Doctoral Dissertation

Effect of semantic activation and episodic inhibition on creative thinking

Efecto de la activación semántica y la inhibición episódica en el pensamiento creativo

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La cultura es el elemento inspiracional más potente que existe.

Mario Tascón

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Introductory Note

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Contents

Preface

Everyone is creative in their own way. Creative achievements can range from painting a vibrant landscape to inventing a new dish that combines unexpected ingredients, to designing a bridge structure that is solid, innovative, and respectful of the environment, to a new scientific discovery that wins a Nobel Prize. The complexity of the topic, far from discouraging interest, has attracted scientific attention and efforts to capture creative performance through experimental paradigms that aim to ensure the precision and utility of the constructs used to describe it (Cortes et al., 2019; Guilford, 1967).

Several theoretical accounts have tried to disentangle the cognitive mechanism underlying creativity, as it is considered a higher-order function responsible for the generation of original, new, and useful ideas or problem solutions (Acar & Runco, 2019). One of the most influential is the dual-process model (Volle, 2018), according to which associative processes would facilitate the activation of remotely related semantic information, while control processes would participate in the downregulation of interfering information and guide the semantic search. Several empirical studies have examined the relevance of semantic memory (associative processes), attentional style, and inhibition (control processes) to creative problem-solving. However, the available evidence does not provide definitive answers.

The central aim of this dissertation was to further investigate the role of semantic memory, attentional style, and inhibitory control of interfering memory representations during creative problem-solving. In addition, we investigated the neural correlates of the semantic and inhibitory components during creative problem-solving. To better understand this goal and our approach, the following section provides a literature review of the major theoretical accounts of creativity and the associated cognitive functions. In the experimental section, we provide a description of the methods and results obtained in four studies that compose this dissertation. Finally, the main findings and implications for semantic and inhibitory processes are discussed.

Part I

Introduction

Creativity

Conceptualization, divergent thinking and convergent thinking

Creativity is considered a high-order cognitive function responsible for the generation of novel and original ideas or solutions to problems that are also effective and relevant in the context in which they occur (Acar & Runco, 2019; Dietrich & Haider 2015; Lubart et al., 2013). This combination of originality and effectiveness makes creativity a critical cognitive ability that is attached to success and development in economic, scientific, or artistic domains and in everyday life (Hennessey & Amabile, 2010). Creative thinking is related to different aspects of human life, enabling people to face problems with original solutions, adapt to unknown situations or achieve goals. Creativity has also been associated with well-being, as individuals who engage in creative activities experience higher levels of positive affect and report greater feelings of personal growth (for a meta-analysis, see Acar et al., 2021).

From the field of cognitive neuroscience, creativity has been explored using different theory-based approaches, such as the Mednick's (1962) associative model, the defocused attention theory of creativity (Mendelsohn, 1976), or the dual-process model (Volle, 2018) as some of the most relevant. Common to most of them is the distinction between convergent and divergent thinking (Cropley, 2006; Guilford, 1967; Runco & Acar, 2012). Divergent thinking (also referred as creative ideation in recent literature, e.g., Benedek et al., 2023) is defined as the ability to generate several candidate ideas or solutions to an open-ended question or problem. Convergent thinking, on the other hand, is described as the ability to explore different ideas or solutions and select the optimal and/or most accurate one for a well-defined problem (Guilford, 1956). However, as will be discussed later, convergent and divergent thinking have been postulated to share certain similarities (for a review, see Zhang et al., 2020) and have even been considered to be part of the same continuous process (Cortes et al., 2019; Eysenck, 2003).

Divergent thinking is the most widely studied component of creativity (Runco & Acar, 2012). The term was first proposed by Guilford (1956; 1967) in his seminal work on the intellect model, in which he described the generation of ideas. Divergent thinking has been associated with other measures of real-world creativity. For instance, enhanced divergent ability has been related to superior performance in music improvisation (Palmiero et al., 2020). Several tasks have been developed to evaluate divergent ability, but the Alternative Uses Task (AUT; Guilford, 1957) is one of the most frequently used. In this task, the primary instruction is to generate as many alternative and original uses as possible for common objects (e.g., a knife, a brick, a shoe).

The primary indices used to measure performance on the AUT are four: ideational *fluency,* which refers to the total number of ideas given; *flexibility,* which refers to the total number of different or unique categories visited when responding to a given stimulus; *originality,* which refers to the uncommonness or uniqueness of the use provided by the participant; and *elaboration,* which refers to the number of details and information provided (i.e., number of words). Despite the well-known utility of the AUT indices as a proxy for divergent thinking and their extensive use in creativity research, several matters remain controversial (Dietrich & Kanso, 2010; for a review, see Acar & Runco, 2019; Barbot et al., 2019). Traditional measures have been criticized for reflecting linear and associative processes rather than divergent thinking style (Acar & Runco, 2015). To illustrate, an individual can reach an original idea by persistently following a single search pathway in semantic memory. Over time, this may result in the identification of remote associates that can be considered original. However, these remote associates are not divergent because they are found by remaining on a single path rather than frequently shifting directions, which is central to the concept of divergence (Acar & Runco, 2019). Another critical point is the strong dependence of flexibility on fluency (i.e., the more categories, the more ideas) and the impact of sample size. Studies have shown that originality decreases with larger sample sizes (Forthmann et al., 2020; Patterson et al., 2023). To overcome these difficulties, subjective scoring evaluation methods have been proposed, including the Consensual Assessment Technique (CAT; Amabile, 1983; Cseh & Jeffries, 2019; Silvia et al., 2008). The CAT is a method

that relies on 'experts' who are asked to provide their personal judgments, often with limited instructions on what they should consider a creative idea or product. In the context of the AUT, the CAT requires evaluators to assign a rating of originality on a scale of 1 (not at all creative) to 5 (highly creative). In the CAT, independent rater agreement is a key indicator of the reliability of a specific creativity assessment. The reliability and validity of subjective scoring methods such as the CAT have been extensively demonstrated in previous research (Kaufman & Baer, 2012; Madore et al., 2015; Silvia et al., 2008;).

Extensive research has also been conducted on convergent thinking, with findings indicating a correlation with other cognitive abilities, including intelligence (Lee & Therriault, 2013). The process of solving convergent thinking tests is often described as *thinking outside the box*. This requires the problem solver to go beyond obvious responses and conventional mental frameworks to look at the problem from an unconventional perspective or explore a new search space where the solution might be discovered (Wiley, 1998). Convergent thinking can be assessed through a variety of tasks, including those that assess visual and verbal creativity.

In the domain of visual tasks, the nine-dot problem and the matchstick problems (Chronicle et al., 2001; Kershaw & Ohlsson, 2004; Öllinger et al., 2008) have been identified as illustrative examples. In the nine-dot problem, participants are presented with nine dots arranged in three columns and three rows, each containing three dots. The goal is to connect all nine dots with four straight lines, without lifting the pen or tracing a line again. The challenge of this task lies in the ability to overcome the self-imposed restriction of moving only through the dots in a linear fashion, without extending the line beyond the figure. In the matchstick problems, participants are presented with false arithmetic problems in Roman numerals created by matchsticks (e.g., III = IX – I). Participants have to correct the statements by moving only one stick from one position to another, without adding or removing another stick (e.g., III = IV – I). There are different types of problems depending on the change to be made: either a change in the numerical values or a change in the operators. The key issue here is that participants are typically trained on one type of problem and then tested on problems that require a different type of solution. However, these classical

tasks usually have a limited set of stimuli and differ in their presentation and levels of difficulty, which limits the ability to compare problem-solving performance across experiments (Aihara et al., 2017).

One of the most important verbal tasks for measuring convergent thinking and creative problem-solving is the Remote Associates Test (RAT; Mednick & Halpern, 1968). In this task, problems formed by three independent words (e.g., *graphic-fashion-interior*) are presented, and the participant have to find a fourth word that is related to all three words in the problem. In the original task, the type of association between each problem cue and the solution can vary (e.g., contextual co-occurrence, synonyms, semantic relatedness, compound word). However, several adaptations of the RAT have been developed, including versions that include only compound word associations between cues and solutions (Bendetowicz et al., 2018; Bowden & Jung-Beeman, 2003), creating new problems based on normative databases (Bieth et al., 2023; Peláez-Alfonso et al., 2020) or translating the problems into different languages (Lazonder et al., 2022; Olteţeanu et al., 2019; Salvi et al., 2020; Shen et al., 2016). The RAT requires participants to integrate multiple pieces of information and connect seemingly unrelated concepts to find a single correct solution. Consequently, it has been considered a task that relies predominantly on convergent thinking (Tik et al., 2018; Wu et al., 2021; Zmigrod et al., 2015).

Despite the conventional distinction between convergent and divergent thinking, there is also evidence of their entwined (Eysenck, 2003; Ovando-Tellez et al., 2023), and some theoretical frameworks suggest that creative performance results from the interplay of divergent and convergent thinking (Allen & Thomas, 2011; Cortes et al., 2019; Sowden et al., 2015). Divergent thinking is considered to expand the representational search space, whereas convergent thinking identifies the best ideas for the task at hand. Consequently, distinguishing between these two constructs based on task performance measures can be challenging. Indeed, in the AUT the initiating process entails the consideration of numerous pieces of information (related to the target object; divergence stage) which are subsequently recombined to come up with a novel use (convergent stage). Similarly, the situation in the RAT is comparable, as participants are not presented with a list of candidate solutions to be selected; therefore, it is not a

purely convergent task. When considering potential solutions, the activation of concepts related to the cues in the problems is initiated (divergence stage) and, subsequently, an evaluation to select the best solution (convergence stage) (Schilling, 2005; Smith et al., 2013; Topolinski & Strack, 2008). Hence, the tasks designed to assess convergent and divergent thinking separately, in fact, entail a combination of both types of thinking to produce creative ideas. Thus, the analysis of the processes involved in RAT and AUT illustrates that the creative process does not represent either convergent nor divergent thinking, but rather the joint work of their dynamic interplay.

Theoretical approaches of creative thinking

What processes lead to the generation of creative ideas in the human mind? The curiosity to describe the cognitive processes and neural mechanisms that underpin creativity has been a topic of interest for almost a century (Ashby and Bassett, 1949; Reitman, 1947; Wallas, 1926). This extensive scientific history has led to the development of various theoretical frameworks that have replaced the old mystical aura of creativity with a more scientific conception of it as *an extraordinary result of ordinary processes* (Abraham, 2013; Lubart, 1996, p. 681). Furthermore, these theoretical proposals have investigated the reasons for individual differences in creative potential (Mednick, 1962; Luchinni et al., 2023), the major cognitive functions and their brain correlates involved in creative thinking (Abraham, 2014; Benedek & Fink, 2019; Chrysikou, 2019; Salvi, 2024; Tik et al., 2018; Zmigrod et al., 2015), and how creative ability can be enhanced (for reviews see Lucchiari et al., 2018 and Weinberger et al., 2017; Scott et al., 2004).

The theoretical frameworks explaining creative performance can be divided into two main categories depending on whether they focus on personality traits or cognitive processes. Regarding the first group, several lines of research have examined the association between creativity and personality, employing the Big Five personality model as a framework (Costa & McCrae, 1992; Feist, 1998; McCrae & Costa, 2008; Puryear et al., 2017; Tan et al., 2016). The most significant

positive influence found for creativity is openness to experience, closely followed by extraversion. This is unsurprising, given the close correlation between the desire to explore ideas and new experiences (novelty seeking) and creativity (Gocłowska et al., 2019). On the other hand, the link between neuroticism and creativity does not show a consistent pattern. Some studies have shown a negative U-shape association (Gao et al., 2020), while other studies revealed that, under the right circumstances, neuroticism may promote the cognitive persistence necessary for success in creativity tasks (Baas et al., 2013).

However, most of the relevant empirical work on creativity has been conducted from a cognitive perspective. In this regard, numerous theoretical proposals have delved into the cognitive processes involved in creative thinking. While each framework has its own relevance and contributions, a comprehensive review of the topic would extend beyond the scope of this dissertation. Thus, we will focus on two main frameworks that have guided recent research and laid the foundations of the studies conducted for this dissertation. The first is the associative model (Mednick, 1962), and the second is the dual-process model (Benedek & Jauk, 2018; Sowden et al., 2015; Volle, 2018).

The associative model

The associative model, first developed by Mednick (1962), posits a strong relationship between creativity and associative processes. The model emphasizes the importance of activating and combining remotely related pieces of information in memory to generate creative outcomes. Therefore, ideas that are closely related are less likely to be creative, while the combination of more distantly associated elements is more likely to lead to the generation of creative ideas or solutions (Gruszka & Nęcka, 2002; He et al., 2020). The associative model is based on the classical idea that concepts and facts are stored and organized in our memory forming interconnected networks with nodes that vary in their degrees of association with others (Collins & Loftus, 1975; McRae & Jones, 2013). For example, when asked to think about creativity, some individuals might associate this concept with imagination, while others might think about problem-solving, art, or a famous scientific, depending on their

previous experiences. Hence, people can differ in their associative abilities (Herault et al., 2024; Nelson et al., 2000).

An additional assumption of the associative model of creativity is that differences in creative capacity among individuals can be attributed to variations in their associative hierarchies among concepts stored in memory. Associative hierarchies are defined as the organization of a set of associations for a given concept on the basis of their associative strength. Thus, more creative individuals are thought to have flatter associative hierarchies, whereas less creative individuals would be characterized by steeper associative hierarchies (Mednick et al., 1964). When less creative people think of associates to a given word, they might produce a few typical strong associations. However, for more remote related concepts, as associative strength diminishes, it would be less probable to retrieve any idea (e.g., presenting the word *fire* to a person with steep associative hierarchies might generate excessively stereotypical responses, such as *flame* or *heat*). In contrast, individuals with a flat associative hierarchy would present more balanced associations enabling them to reach both close and remote associates with equal ease (e.g., presenting the word *fire* to a person with flat associative hierarchies might probably allow them to retrieve remote responses such as *candle*, or *halo*; Kenett et al., 2014; Benedek & Neubauer, 2013). Mednick theorized that creative people would demonstrate higher verbal fluency (i.e., the ability to retrieve many semantic associations for a given word) because of their ability to access both close and remote ideas, resulting in more unusual associations. In this context, Mednick (1968) developed the RAT as a tool to test some predictions from his theory. Given that solving RAT problems relies on the ability to find remote associations to the given cues, individuals with flatter associative hierarchies should be more efficient at finding the appropriate solution (Mednick, 1968).

Limitations of the associative account

Mednick's early proposal was significant in promoting the relevance of associative processes in creativity, and recent empirical evidence also supports the role of associative processes (Becker et al., 2022; Herault et al., 2024; Kenett

et al., 2018). However, some results also suggest the need for additional (control) processes to prevent the most common and usually less original ideas from coming to mind and being produced in response. The effort to create something new is often hindered by the tendency to recall the most common, and therefore unoriginal, information from memory (Benedek & Jauk, 2018; Luft et al., 2018). Hence, creative ideation cannot rely solely on automatic associative processes, but requires control processes to constrain them (Sowden et al., 2015). In this sense, control processes have been proposed to be involved in creativity in several ways, including the downregulation of dominant ideas (Beaty & Silvia, 2012; Nusbaum & Silvia, 2011), the guidance of semantic search to avoid typical thought paths (Baror & Bar, 2016; Luft et al., 2018) or the evaluation of candidate responses (Chrysikou, 2019). In light of these considerations, the dual-process model (Sowden 2015; Volle, 2018) represents a natural progression from associative theories to the cognitive neuroscience of creativity. While the associative model offers valuable insights, it does not fully explain the behavioral and brain-related evidence suggesting additional processes.

The dual-process model

The dual-process model posits a dynamic interplay between associative and control processes in creative thinking (Benedek & Jauk, 2018; Sowden et al., 2015). The general definition of creativity encompasses three main characteristics: novelty, originality, and value. The latter depends on the context in which new ideas or solutions are generated (Mednick, 1962; Guilford, 1957; Sowden et al., 2015). These characteristics imply the relevance of more than just associative processes (i.e., activation, recombination, and integration mechanisms). While generative processes are crucial for producing original ideas, evaluative processes are essential for refining and shaping these ideas into valuable forms. Additionally, during the activation stage, evaluative processes help guide the search for suitable ideas (see also Howard-Jones & Murray, 2003).

In the context of the dual-process framework, the generation of creative ideas (or solutions) would result from associative processes, (as described in section: The associative model) that activate several memory representations

related to a stimulus (externally displayed or internally accessed) through their existing semantic connections. This spontaneous mechanism would facilitate the generation of multiple new ideas based on existing knowledge (Volle, 2018). At the same time, generation of ideas is subject to the influence of control processes, such as inhibition or monitoring. Control processes would prevent habitual thinking by suppressing common ideas, while monitoring that the ideas generated meet the requirements of the task at hand. Inhibitory control might also be engaged to avoid the burden of interference from related ideas that are not relevant to the task (Gabora, 2010; Kenett & Austerweil, 2016; Kleibeuker et al., 2013; Mok, 2014; Zabelina & Andrews-Hannah, 2016).

In summary, the key strength of this proposal is its recognition of the significance of associative processes, which enable spontaneous connections and are influenced by individual differences in the organization of semantic memory (Mednick, 1962), while emphasizing the role of control processes in directing memory search, monitoring idea generation based on task goals, and selecting the most suitable and creative ideas (Cassotti et al., 2016; Volle, 2018). In other words, the dual-process model provides a more comprehensive and nuanced understanding of the cognitive operations involved in creativity, accounting for the dynamic interplay between associative and control processes and fostering a variety of lines of research that have delved into these components involved in creative thinking. In this regard, several characteristics of creative individuals compared to their less creative counterparts have been identified, as well as the cerebral regions and networks engaged during the performance in different creative tasks (Mok, 2014). The following sections discuss the empirical evidence for the relevance of the associative (i.e., semantic memory) and control (i.e., attentional scope and inhibitory control) components of creativity.

The contribution of semantic memory in creativity

Because associative processes implicate the activation, combination, and reorganization of existing knowledge, semantic memory represents an essential component upon which these processes rely (Benedek et al., 2017; Benedek &

Neubauer, 2013; Kenett, 2018; Ovando-Tellez et al., 2022; Smith et al., 2013). However, the connection between creative thinking and memory is puzzling. At first glance, memory may be considered unrelated to creative ideation, given that novelty is a key factor in creative ideas (Runco & Jaeger, 2012). This suggests that such ideas cannot simply be obtained from existing memories. However, creative ideas do not emerge from nowhere. Instead, they are created from existing knowledge, allowing individuals to go beyond what is known through the use of additional processes that operate over activated memory representations (Schacter et al., 2007; Ward, 2007; Weisberg, 1986).

Semantic memory is one of the major memory systems (Tulving, 1972) and refers to our store of conceptual or factual knowledge about the world accumulated over the course of our lives, regardless of time and context (Binder & Desai, 2011). Classical cognitive models assumed information in semantic memory to be organized as semantic networks in which nodes of conceptual information are interconnected (Anderson, 1983). Retrieval of a concept results in activation of the node containing the associated information. Activation spreads automatically to adjacent nodes to a certain degree, depending on the strength of association between the retrieved concept and its neighbors, making such neighbors more accessible (e.g., *match* strongly activates *lighter*, and it can also activate *wood* which would be more remotely associated; Collins & Loftus, 1975; McRae & Jones, 2013).

Associative structure

A growing body of evidence links semantic memory to creativity, considering performance on problem-solving tasks, such as the RAT, analogy tests (Green, 2019; Kenett et al., 2014; Mednick, 1962), or divergent thinking tasks (Ovando-Tellez et al., 2022). In this context, numerous studies have examined how semantic memory structure and search contribute to creative thinking (Beaty & Kenett, 2023). A well-validated tool to estimate semantic memory structure is semantic priming (SP; Hutchison et al., 2013). In SP paradigms, participants are typically presented with a target word (e.g., *chair*) and then asked to respond rapidly to it (usually based on lexical or pronunciation

decision). The target word is preceded by either a semantically unrelated (e.g., *dog*) or related (e.g., *table*) word (McNamara, 2005). The SP effect refers to the fact that participants are faster and more accurate when responding to target words when they are preceded by related words, compared to when they are preceded by unrelated words (Balota & Lorch 1986; Neely, 1976, 1977). Thus, SP effects are seen as a useful tool for studying the organization of semantic memory, as they reflect effortless and automatic (sometimes implicit) access to semantic information (Perea & Rosa 2002; Thompson-Schill et al., 1998). Additionally, the strength of the semantic association between the prime and the target affects the magnitude of the priming effect. Strongly related pairs elicit larger priming effects than weakly related pairs (Anaki & Henik, 2003).

Classic research has demonstrated that participants with higher creative abilities differ from those with lower creative abilities in their semantic memory organization. More creative individuals consider unrelated words to be less semantically distant (Rossmann & Fink, 2010) and are quicker in assessing the relatedness of concepts (Vartanian et al., 2009). In a seminal study by Gruszcka and Nęcka (2002), participants completed a semantic priming task (where prime and target words were either semantically related or unrelated) and a battery of creativity tasks. The results demonstrated that those who scored higher on creative ability were more likely to perceive neutral unrelated words as having a remote semantic relationship than those who scored lower on creativity. These results corroborate the Mednick's proposal (1962) and suggest that the flatter associative hierarchies of creative individuals facilitate access to both remotely and closely related concepts. In the present work, we further examine the relationship between semantic memory structure and creative problem-solving using a semantic priming task and considering individual differences in performance.

Computational methods have enabled researchers to estimate the search processes that operate on semantic memory structure via semantic networks (Siew et al., 2019). It is noteworthy that this technique has been successfully employed to identify structural characteristics that distinguish the semantic memory networks of individuals with high and low levels of creativity (Denervaud et al., 2021; Kenett et al., 2014; Kenett & Faust, 2019; Li et al., 2021). For

example, Kenett et al. (2014) examined the semantic networks of individuals with low and high creativity by analyzing the free associations generated by both groups in response to a list of 96 cue words. They discovered that the semantic networks of individuals with low creativity (as measured by the RAT and other creativity tasks) were less interconnected and more dispersed than those of individuals with high creativity (for a similar result, see Luchini et al., 2023). In another study, Benedek et al. (2017) employed an individual differences approach (rather than considering group-level differences) and used word relatedness judgments to estimate individual semantic networks. Participants rated the relatedness of all possible pairs of 28 cue words, which served as an indicator of the organization of these words in an individual's semantic memory. Their results mirrored the group-based findings of Kenett et al. (2014), indicating that higher levels of creativity (as measured by the AUT) were associated with more interconnected semantic networks with shorter distances between concepts and more efficient structures.

In essence, the existing behavioral research indicates that creative individuals (compared to their less creative counterparts) a) exhibit a semantic memory structure characterized by a greater number of interconnections between concepts, with shorter distances between them (Kenett et al., 2014; Luchini et al., 2023, b) consider pairs of unrelated words as more closely related (Gruszcka & Nęcka, 2002; Rossmann & Fink, 2010), and c) can generate more ideas, faster, accessing more uncommon associations in the process (Benedek & Neubauer, 2013). However, further research is needed to determine the relevance of other semantic memory elements in creative performance, particularly in terms of semantic richness. In a study conducted by Beaty et al. (2022), participants completed the AUT in which the semantic richness of the objects (i.e., the number of semantic associates) was manipulated. The findings revealed that participants generated more ideas for objects with higher semantic richness, although these ideas were less original. This suggests that the structure of semantic memory, particularly the number of interconnected concepts, has a different impact on the participants' capacity to generate creative ideas.

The neural correlates of the semantic component in creativity

A few meta-analyses of neuroimaging results have revealed a number of distributed brain regions that are active during creative performance (Boccia et al., 2015; Gonen-Yaacovi et al., 2013; for a review, see Ovando-Tellez et al., 2019). Given the complex nature of creativity, it is unlikely that a single brain region plays a prominent role. Additionally, there is no clear association between creativity and either the right or left hemisphere of the brain (Dietrich and Kanso, 2010). However, research suggests that the associative processes involved in creativity are mostly related to the default-mode network (DMN; Beaty et al., 2016). The DMN is a set of functionally connected brain regions that shows lower activity during tasks that require focused attention, effort, or control, and higher activity during periods of rest (Greicius et al., 2009; Raichle, 2015). Key brain regions in the DMN that have been related to creative performance are the medial prefrontal cortex, posterior cingulate cortex, medial temporal lobe, and inferior parietal lobe (Buckner et al., 2008).

The DMN may facilitate associative processing that directs the flow of thoughts in a spontaneous manner, thereby promoting creative thinking (Volle, 2018). Specifically, the medial prefrontal cortex is engaged during divergent tasks that require selective retrieval of remotely associated concepts to generate original responses (Wu et al., 2015). For instance, a lesion study by Bendetowicz et al. (2017) found that patients with localized damage to the medial prefrontal cortex showed a reduced ability to spontaneously generate remotely related concepts during a RAT-like task compared to control participants. Moreover, regions of the DMN, such as the rostral prefrontal cortex and posterior parietal cortex, play a relevant role in the retrieval of semantic and episodic memories (Binder et al., 2009; Eustache et al., 2016; Shapira-Lichter et al., 2013; Wirth et al., 2011). Since activation of past-experience associations is determinant for combinatorial processes in creativity tasks, these regions are likely to play a part in the associative activation of semantic and episodic memories, which are essential for the divergent component of creativity. Similarly, the lateral rostral PFC has been shown to be active during the integration of multiple relations in different tasks. This suggests that it may help individuals discover combinatorial

solutions through distant semantic associations or relational similarities (Green et al., 2006; Vartanian et al., 2013).

The generation of an original or new idea inherently requires conceptual expansion (i.e., widen existing conceptual frameworks to encompass new or previously unconnected elements). Conceptual expansion has been related to the inferior frontal gyrus, inferior frontopolar cortex, and anterior temporal lobe (ATL), particularly in the left hemisphere (Abraham et al., 2012; Abraham et al., 2018). A recent study by Bieth et al. (2023) showed an increase in alpha-band activity in left temporal regions and an increase in beta-band activity in right temporo-frontal clusters during RAT performance. These neural changes were linked to the semantic distance between the cues in the RAT problems and their corresponding solutions. Interestingly, semantic cognition has been associated with a network comprising multiple brain regions, with the ATL considered one of utmost significance (Chen et al., 2016; Lambon Ralph et al., 2017). The ATL is a densely interconnected region that plays a crucial role in the construction and maintenance of complex semantic representations (Bonner & Price, 2013; Díez et al., 2017; Lambon Ralph, 2014). While numerous studies appear to indicate that the ATL is bilaterally involved in semantic integration (Lambon Ralph et al., 2017), there is also evidence of functional asymmetry suggesting that left ATL plays a more prominent role in lexical-semantic knowledge (Alonso et al., 2021; Gainotti, 2012; Mion et al., 2010). Since the ATL binds modality-specific information from various cortical areas to form complex conceptual representations, it is plausible that the semantic processing during creative idea integration also recruits the ATL.

The role of control processes in creativity

Control processes are considered critical to the dual-process model of creative thinking, although the evidence is mixed (Hennessey & Amabile, 2010). Some studies suggest that the way in which context is attended can impact semantic search and creativity (Förster & Dannenberg, 2010; Martindale, 1999), while other studies have found no transfer between unrelated tasks (De Luca et

al., 2022). Similarly, inhibition enables the downregulation of irrelevant information and the evaluation of generated ideas or solutions (Cancer et al., 2023; Gupta et al., 2012; Luft et al., 2018). However, in the initial stages of idea generation, when associations are key, control processes may impede creativity by limiting the amount of information considered, particularly in open-ended tasks (for a review, see Amer et al., 2016). In sum, some experts propose that the relative importance of control processes on creative performance depends on the demands of the specific task (i.e., whether the task requires more goal-directed strategies) or the phase of the creative process (Allen & Thomas, 2011; Gilhooly et al., 2007; Silvia et al., 2015).

Attentional scope

The scope of attention becomes relevant when retrieving information from memory to activate and generate specific thoughts for the task at hand (Anderson et al., 1994). In this context, the *scope of conceptual attention* refers to the quantity and diversity of mental representations that are simultaneously activated in long-term memory (Friedman & Förster, 2010). Thus, attentional scope might influence creativity through the memory search process necessary to access remote information. The underlying premise is that when conceptual attention is narrowly focused, activation is limited to nearby mental representations that are most accessible and familiar. Conversely, when conceptual attention is broad, activation spreads to more distant concepts with lower initial accessibility, resulting in simultaneous activation of a diverse set of representations (Chiu, 2015; Friedman & Förster, 2008; Liu, 2016; Wronska et al., 2018). Several studies grant special relevance to the effect of attentional scope in conceptual attention and, subsequently, in creative performance (Förster & Dannenberg, 2010; Martindale, 1999; Mendelsohn, 1976). What is the temperature in your current location? Are there any background noises around you? Unless the environmental conditions are particularly extreme, it is likely that these peripheral and seemingly insignificant stimuli went unnoticed. In fact, paying attention to such stimuli would be a distraction and could interfere with other activities. However, when generating creative ideas, maintaining a broad

attentional scope and recognizing peripheral stimuli can prove advantageous during semantic search in creativity tasks (Wronska et al., 2018). Thus, more creative individuals are characterized by a broader attentional scope which might facilitate the consideration of remotely associated ideas as potential solutions (Finke et al., 1992; Martindale, 1995). Supporting this view, some research has shown that better problem-solving ability is associated with a lower tendency to inhibit apparently irrelevant information, implying a broader scope (Carson et al., 2003; Peterson et al., 2002).

Several studies have explored the influence of attentional scope on creative performance. However, the evidence currently available on this topic is inconclusive. Chiu (2015) manipulated participants' attentional scope to explore its role on creative performance. In the broad-scope condition, participants performed an over-inclusive thinking training (OTT), which required them to organize concepts into broad categories (e.g., locate *strawberry* in one of these categories, *fruit-furniture* or *vegetable-housing spaces*). This was compared to a control condition in which categorizations were based on specific categories (e.g., locate *strawberry* in the category *fruit* or *housing spaces*). After training, they performed a divergent thinking task. The results of three experiments indicated that participants in the OTT had better creative performance than participants in the specific-category training, consistent with the positive effect of broader conceptual attention. In another study, Liu (2016) performed a different manipulation of participants' attentional scope before assessing their creative abilities. Her results indicated that participants in the narrow attention condition (i.e., they performed a category-based fluency task that restricted their focus) exhibited lower levels of creativity than participants in the broad attention condition (who undertook a free association task).

In addition, studies that target the general scope of attention rather than the scope of conceptual representations have found positive outcomes. For example, Colzato et al. (2017) demonstrated that meditation techniques designed to expand the scope of attention were more effective at enhancing creativity than those aimed at narrowing attentional focus. Interestingly, Zmigrod et al. (2015) found a similar correlation between a broader scope of attention and creativity. Participants completed the global-local task (Navon, 1977) to assess their

attentional scope. The task required participants to recognize the global or local features of congruent and incongruent stimulus arrangements (e.g., large letters "S" or "H" formed by smaller letters "S" or "H") in distinct blocks. This task offers three indexes: a) global precedence: participants demonstrate superior performance when responding to the global level of stimuli compared to the local level, indicating a preferential advantage in attending to broader stimuli; b) global interference: incongruent information at the global level hinders performance at the local level, meaning that local processing is obstructed by global features; c) local interference: describes the difficulty in responding to global-level features due to the influence of local-level information. In essence, focusing on specific details interferes with the ability to recognize the 'big picture'. The AUT and RAT were used to evaluate creativity. The findings of Zmigrod et al. (2015) showed that higher global interference was associated with better RAT performance. This indicates that the tendency to perceive global aspects, while focusing on local features, was related to enhanced creativity (as measured by the RAT). In contrast, local interference was negatively associated with flexibility on the AUT. That is, the more participants focused on local details, while the target was the global stimulus, the fewer categories they visited when responding in the AUT. Taken together, these results indicate that better creative performance is related to a broader scope of attention.

While these results appear to support such an association, other studies have found no evidence for an influence of attentional scope on creativity. In a study by Liu and Peng (2018; Experiment 1) no evidence was found to support the hypothesis that attention influences creativity. In their study, participants performed an adaptation of the global-local task and the AUT. In this adaptation, some participants were assigned to the global condition in which they only performed the global block; others were assigned to the local condition, in which they had to complete the local block; and the remainder performed an arithmetic control task. The results demonstrated that manipulating the attentional scope did not have an impact over creative performance. In another study, Zabelina et al. (2016; Experiment 2) found no association between performance on a global-local task and creativity as measured by the Abbreviate Torrance Test for Adults (ATTA: Goff & Torrance, 2002) which includes one verbal and two visual

creativity measures. Finally, De Luca et al. (2022) tested transfer between attentional scope and other tasks (for a review, see Förster & Dannenberg, 2010). The results indicated that transfer effects were only evident for very similar visual tasks. Hence, the mixed findings of prior studies point to the need for further research to determine the role of attentional scope in creativity. Along these lines, in the present work we further explored whether individual differences in attentional scope are related to creative problem-solving.

Inhibitory Control

The dual-process model (Sowden et al., 2015; Volle, 2018) posits that inhibitory control is a critical factor in creative thinking, enabling access to relevant memory representations. A number of studies have examined the role of inhibition during creative performance, but the available evidence is inconclusive. Anyway, some results suggest that inhibitory control might work as a double-edged sword. Thus, in some cases it can reduce interference from competing information, thereby enhancing the creative search. In other cases, however, it can impede creative outcomes by limiting the amount of information considered, which may result in lower originality scores (Chrysikou, 2019).

Smith et al. (2013) examined the strategies that participants used when solving RAT problems. In their study, participants were asked to complete the RAT and to type in any word they considered while attempting to solve the problems, irrespective of whether the word was a potential solution. Analysis of these response protocols revealed that the search process was semantically guided. Participants concentrated on a single RAT cue at a time and progressed sequentially through semantically related words, resulting in responses that typically formed a chain of semantically linked words. Although these results do not directly address the role of inhibition in RAT, they suggest that participants sequentially retrieve responses by focusing on individual cues and selecting or eliminating possible responses. This cue-guided search process (rather than a random walk search) might be associated with control processes and probably with inhibition.

Relevant evidence for the importance of inhibition in semantic search is provided by a study conducted by Marko and Riečanský (2021). This study investigated the relationship between semantic network connectivity (structural properties) and semantic control functions (i.e., semantic inhibition and switching). To assess semantic control processes, participants completed the Associative Chain Test (ACT; Marko et al., 2019), while semantic network structure was estimated using a semantic judgment task (SJT) in which word pairs were presented and participants rated their semantic association. In the ACT, participants generated word chains following defined rules: an associative condition (generating semantically associated words) to assess associative semantic ability, a dissociative condition (generating non-related words) to evaluate inhibitory control, and an associative-dissociative condition (switching the retrieval condition from one word to the next) to measure switching costs during word generation. Results showed that better structural properties of the semantic network (i.e., tighter clustering and shorter average path length between concepts) required greater inhibition of competing information while facilitating flexible switching between clusters.

Other studies have demonstrated a positive correlation between divergent thinking and cognitive control, as measured by the Stroop task (Benedek et al., 2012; Zabelina & Robinson, 2010). Moreover, Edl et al. (2014) obtained similar findings in a sample of design students. The students exhibited higher cognitive control as they did not exhibit Stroop interference effect compared to a control group. Additionally, there was a strong correlation between better inhibitory control and higher creative thinking, as measured by the Torrance Test of Creative Thinking (TTCT; Torrance, 1966). This suggests the relevance of control processes in the downregulation of dominant but irrelevant ideas during creative performance.

However, some empirical evidence challenges the positive role of cognitive control during creative performance (Benedek et al., 2017; Volle, 2018). Specifically, in a study by Radel et al., (2015), participants' inhibitory efficiency was reduced by inducing fatigue through intensive practice of an inhibition-demanding task that did not rely on verbal or semantic information (such as the Simon or Eriksen Flanker tasks). Their creative ability was measured using the

RAT and the AUT. While no differences were found on the RAT as a function of the inhibition demands of the fatigue-inducing task, participants showed greater originality and fluency when exposed to high inhibition demands in the fatigue-inducing task. Similarly, Marko et al. (2019, Experiment 2) tested the relevance of executive function during RAT solution. In this study, participants completed the ACT and a set of RAT problems. Results indicated that the only predictor of reaching remote concepts in the RAT was participants' semantic/associative ability. Thus, inhibition did not account for individual differences in creativity.

Given the complex association between inhibition and creativity, in the present work we use two different approaches to better examine it. One entails the putative inhibition of competitor representations that may hamper the ability to access relevant information later in the problem-solving stage. The other relies on how individual differences in the downregulation of interfering memory representations predict creative problem-solving ability.

Inhibition in fixation resolution

During creative problem-solving, the search for distantly related ideas to create novel responses inevitably activates numerous ideas and concepts. However, these ideas may not always align with the core issue at hand, potentially disrupting the creative process, creating *mental fixation* (i.e., excessive accessibility of irrelevant or not useful ideas) and hindering the ability to find a solution. The ability to inhibit or suppress this competing/potentially interfering information is considered essential to redirect the creative process (Storm & Hickman, 2015). For example, in the RAT problem *archipelago-cage-banana* a strongly related concept that is most likely to become active is *monkey,* due to the close connection between *cage* and *banana*. In this situation, *monkey* acts as a competing representation that causes *mental fixation* because it has no association with *archipelago*. Hence, in order to successfully find a response that aligns with all three cues (e.g., *canary*; Storm & Hickman, 2015), the representation of *monkey* must be inhibited.

Of special relevance, Storm and Angello (2010) investigated whether the capacity to overcome fixation and successfully solve RAT problems is associated

with the ability to inhibit interfering episodic information. Given the importance of competitor downregulation in creative problem-solving, it was hypothesized that superior RAT solution would be associated with greater inhibition of interfering memories, as measured by the retrieval-induced forgetting (RIF) effect that is usually observed with the selective retrieval procedure (SRP; Anderson et al., 1994; for a review, see Anderson & Hulbert 2021). Thus, participants were first involved in studying category-exemplar pairs and selectively retrieving some of them (SRP), and then solved 20 RAT problems. In the SRP, the repeated attempts to retrieve specific exemplars using the categories as cues activate related items (i.e., those of the same category but not targets) that compete for retrieval. In this scenario, inhibitory control would temporarily downregulate related but non-target representations, thereby enabling access to target items. As a result, in a subsequent memory test, the non-target but related items will be less accessible than baseline items (studied items but belonging to non-practiced categories). The RIF effect refers to this memory impairment for items that were competitors during selective retrieval, which is thought to be an aftereffect of an adaptive inhibitory control mechanism that lessen the accessibility of competing items in memory in order to facilitate access to target items (for a review, see Anderson & Hulbert, 2021; Storm & Levy, 2012). Following the SRP, and to generate fixation, half of the participants were exposed to misleading (competing) associates related to the RAT problems, while the rest of the participants were not. Interestingly, Storm and Angello (2010) observed a positive correlation between RIF and creative problem-solving abilities. Thus, the ability to overcome fixation in the RAT was associated with better inhibitory ability as indexed by larger RIF effects.

Capitalizing on this empirical evidence, Storm et al. (2011) further examined the consequences of effective inhibition on RAT solution. Specifically, the study assessed the impact of fixation on RAT performance and how fixation resolution relates to problem-solving success. In Experiment 3, participants were presented with cue-associated words to study. After the study phase, they solved two sets of RAT problems one of which contained impossible-to-solve problems (to boost competition and inhibition). The cues for these problems were derived from the cues used in the study phase. The second set comprised solvable

problems, but the cues for these problems were new in the context of the experiment. The final stage involved a cued-recall test in which participants were asked to recall the previously presented pairs, as well as a set of baseline pairs that had not appeared during the RAT phase. The results revealed a *problem-solving-induced forgetting* effect, such that the recall of associated words was less likely when they were related to cues belonging to impossible-to-solve RAT problems. More interesting, the degree of problem-solving induced forgetting predicted performance on the set of solvable RAT problems. These results suggest that during the RAT solving stage, participants inhibited the misleading words associated with the impossible RAT problems in order to solve them. Consequently, access to these words was impeded during the final test. Thus, evidence from several studies converges to indicate that a) inhibitory control of interfering memories is associated with the ability to overcome fixations during problem-solving tasks, and b) the consequences of overcoming potential fixations during problem-solving may result in lower accessibility of the competitors that produced the fixation when tested in a subsequent retrieval test. Thus, inhibitory control would be the mechanism responsible for suppressing dominant associations or prior unsuitable ideas, and a crucial process for generating new ideas and creative solutions.

Inhibition and the accessibility of memory

In the context of problem solving, the memory system can provide critical pathways for accessing useful information that can facilitate problem solution. Therefore, ensuring that the right information is available at the right time to solve a problem is critical to a successful outcome. Indeed, previous research has shown that prior exposure to relevant information can enhance subsequent performance on a range of tasks (e.g., creative problem-solving: Gauselman et a., 2023; Gómez-Ariza et al., 2017; Howe et al., 2015; decision making: Iglesias-Parro & Gómez-Ariza, 2006). Conversely, when critical information is not accessible to the solver, the probability of successfully solving a problem is reduced (Sternberg, 2012).

In addition, relevant information may be available in memory but temporarily accessible due to a variety of intervening conditions that make it inaccessible. Relevant research has provided compelling evidence that inhibitory control can sometimes play an important role in decreasing the accessibility of potential solutions in a subsequent creative problem-solving stage (Gómez-Ariza et al., 2017; Valle et al., 2019; 2020a; 2020b). While inhibitory control often acts to facilitate the search for a creative solution by suppressing interfering information, recent research has shown that it can also act to limit the accessibility of possible solutions. For example, in a study by Gómez-Ariza et al. (2017), participants underwent a modified version of the SRP that ended with a RAT as the final test. In this adaptation, participants were presented with pairs of lexical category-exemplars (e.g., *FA-Fail, FA-Fantasy, CA-Captain, CA-Canary*). In the subsequent phase, participants were asked to selectively recall half of the words from half of the categories, using the lexical categories as retrieval cues (e.g., *CA-Can_)*. The objective of this manipulation was to enhance the accessibility of practiced words (e.g., *Canary*) while reducing the accessibility of related but competing information (e.g., *Captain*). Selective retrieval has been shown to engage inhibitory control mechanisms that temporarily reduce the retrievability of competitors (Anderson & Hulbert, 2021; see also Bajo et al., 2021). In the final stage, participants completed the RAT that included problems that could be solved using items previously encountered during the SRP (e.g., *Crew-Boat-General*, with *Captain* as the solution). The final RAT phase also included problems whose solution were not presented during the experiment, making them completely new in the context of the experiment. The results of these studies indicated that competitors (words that were inhibited during the second phase as they were associated with practiced words) were less likely to be produced as RAT solutions compared to only studied items (for similar results using analogical reasoning: Valle et al., 2019; 2020a; 2020b and decision making: Iglesias-Parro & Gómez-Ariza, 2006; Lechuga et al., 2012). The reduced access to these representations after SRP was explained as a result of an inhibitory mechanism that downregulates the accessibility of competitor representations in order to access the target items (Valle et al., 2020a; 2020b).

In summary, changes in the accessibility of relevant memory representations are a key factor influencing problem-solving ability. On the one hand, such changes may facilitate the identification of solutions (a kind of priming effect). On the other hand, they may make it more difficult to reach appropriate representations for successful solve problems.

Neural correlates of control processes

The neural underpinnings of control processes during creative performance have been extensively related to the executive control network (ECN; Beaty et al., 2015; Beaty et al., 2016). The ECN encompasses several brain regions including the lateral prefrontal cortex and the posterior parietal cortex. Recruitment of these brain regions is observed in the context of various cognitive functions such as externally directed attention, working memory, relational integration, controlled retrieval of episodic/semantic information, and task-set switching (Burgess et al., 2011; Friedman & Miyake, 2017; Hobeika et al., 2016; Seely et al., 2007).

As noted above, creative idea generation involves goal-directed processes such as inhibition of interfering information, guided memory search, or idea evaluation, and these processes have been associated with brain regions in the ECN neural network. Thus, during guided memory search subregions of the lateral prefrontal cortex are thought to be involved in maintaining focused attention and goals, managing information in working memory, and suppressing irrelevant information (Beaty & Schacter, 2018). In this line, a lesion study by Abraham et al. (2012) examined the creative performance of patients with focal lesions on the basal ganglia, temporo-parietal regions, and lateral prefrontal cortex, and their results indicated that damage to the lateral prefrontal cortex produced lower originality and fluency on a divergent thinking task, although RAT performance was not impaired. In a separate study, Bendetowicz et al. (2017) showed that patients with a focal lesion in the rostro-lateral prefrontal cortex were more likely to rely on more common associations between words when generating responses to a RAT-like task, suggesting that the prefrontal cortex involvement may be related to the requirements of inhibiting

inappropriate common responses, and that dysfunction of this area may underlie the generation of less original ideas.

Another relevant region of the ECN, the inferior frontal gyrus, has also been related to interference resolution (Abraham et al., 2012; Benedek et al., 2014; Chrysikou, 2019). In this sense, patients with lesions in the left inferior frontal gyrus exhibited a) lower suppression of prepotent actions, as they made more errors in a Go/No-Go task using letters as stimuli (Swick et al., 2008) b) lower performance in a verb generation task for words with multiple possible responses (e.g., cat) compared to words with fewer possible responses (e.g., scissors; Thompson-Schill et al., 1998). Interestingly, this evidence aligns with Jung-Beeman's proposal (2005) that the inferior frontal gyrus is related to the ability to select semantic representations and inhibit competing conceptual representations or actions.

Further evidence from clinical data indicates that participants with frontoparietal dementia produce a greater number of ideas, but they have difficulty combining the information to produce original ideas (Fusi et al., 2021). This finding suggests that the impairment in inhibiting interfering information when combining different pieces of information is directly related to damage in the prefrontal cortex (Fusi et al., 2021; Fusi et al., 2021). Additionally, the assessment and evaluation of a new idea and the execution of goal-directed plans for creativity have been associated with activation of the prefrontal cortex broadly, and the inferior frontal gyrus in particular (Abraham et al., 2012; Benedek et al., 2014; Chrysikou, 2019; Dietrich, 2004).

Electrophysiological (EEG) experiments have also shown that specific frequency bands are associated with specific creative processes. Thus, alpha rhythms have been associated with inhibitory processes, although the nature of inhibition varies across brain regions. In frontal and parietal regions increased alpha band activity is linked to the inhibition of external sensory information, which reduces interference and enhances internally oriented processes (Camarda et al., 2018; Fink & Neubauer, 2008). In contrast, alpha activity in the ATL has been associated with inhibition of obvious semantic associations, thereby facilitating access to more remote and creative ideas (Luft et al., 2018). Finally, theta-band power modulations in fronto-temporal regions have been identified

during RAT solution (Bieth et al., 2023; Razumnikova, 2007; Sandkühler & Bhattacharya, 2008). Specifically, Bieth et al. (2023) observed an increase in theta-band power around one second before participant response. This result was interpreted as reflecting the necessary evaluation mechanism during the final idea evaluation stage.

Neural correlates of inhibitory control in the selective retrieval practice

The neural correlates of inhibitory control during SRP have been investigated using brain imaging techniques and EEG recordings (Johansson et al., 2007; Wimber et al., 2015; Wimber et al., 2009; Hanslmayr et al., 2010). Previous research has related the reduced accessibility of inhibited items that occurs after selective retrieval to the dorsolateral prefrontal cortex (DLPFC), ventrolateral prefrontal cortex (VLPFC) and anterior cingulate cortex (ACC; Kuhl et al., 2007; Wimber et al., 2008; Wimber et al., 2009; Wimber et al., 2015). Specifically, the ACC is considered critical for conflict detection, and signaling to the DLPFC, which would be responsible of triggering inhibitory processes (Levy & Anderson, 2002). Thus, Kuhl et al. (2007) observed that the BOLD signal in the ACC was positively related to DLPFC activation during selective retrieval. Moreover, activation of the right DLPFC and VLPFC decreased during selective retrieval cycles, which was interpreted as reflecting a lesser recruitment of these areas after interference detection and inhibition. In a neuromodulation study, Stramaccia et al. (2017) stimulated the right VLPFC during the selective retrieval phase and found that, compared to sham stimulation, real tDCS canceled the reduced accessibility of competitor items. Similarly, Penolazzi et al. (2014) demonstrated that tDCS over the right DLPFC abolished the RIF effect.

Studies using the SRP and focusing on the EEG correlates of memory inhibition have reported interesting results on event-related potentials (ERP) and time-frequency dynamics. For example, in the study conducted by Johansson et al. (2007), participants performed the SRP while their EEG activity was recorded. The event-related potentials (ERPs) in the standard selective retrieval condition were compared with those in a non-retrieval (re-learning) condition in which participants simply studied the target words again (without competition or

interference). The authors reported that positive ERPs over prefrontal regions were sensitive to the differences between conditions. Moreover, individual differences in RIF between participants (i.e., decreased accessibility to competing items) were predicted by this higher ERP positivity. Of special relevance, in another study Hellerstedt and Johansson (2014) recorded ERPs while participants performed selective retrieval. The associative (semantic) strength between the category cue and the competitors was modified to create high and low competition conditions during the selective retrieval phase. Results indicated that ERPs were modulated by the level of competition. Strong competitors resulted in a more positive-going waveform starting approximately 300 ms after the onset of the category cue over frontal electrodes. Again, this outcome was found to be sensitive to RIF. It has been suggested that this outcome reflect the reactivation of previously encoded semantic related with the categories. This interpretation aligns with the FN400 effect in other ERPs studies of familiarity, old/new effects, and conceptual priming as well as interference detection and subsequent inhibition of competing memories (Kwon et al., 2023).

Time-frequency experiments have consistently demonstrated that selective retrieval is related to mid-frontal theta frequency (4-8 Hz; Ferreira et al., 2014; Ferreira et al., 2019; Hanslmayr et al., 2010; Staudigl et al., 2010). Specifically, Ferreira et al. (2014) were able to dissociate the neural correlates of interference detection and inhibition. In their experiment, during the selective retrieval phase, they first presented the category cue followed by the item-specific cue. Importantly, there was a time interval between the two types of cues. The results showed that, during the presentation of the category cue (i.e., when competitor and target items are activated in memory), there was an increase in mid-frontal theta specially related to interference detection in the competitive condition compared to the non-competitive condition. From the presentation of the category cue to the presentation of the item-specific cue, there was a reduction in theta power in the competitive condition compared to the non-competitive condition, which was interpreted as a decrease in interference mediated by inhibitory control.

In summary, inhibitory control of interfering memory representations during selective retrieval seems to be a prefrontally-mediated mechanism indexed by the ERP component FN400 and by changes in theta band frequency.

Objectives and outline of the experimental series

This introduction aims to provide an overview of the current state of the art in creative thinking. It also highlights some key issues that remain unresolved, such as the influence of attentional scope. Additionally, it identifies crucial issues that require further investigation, including the electrophysiological correlates of competition and its downregulation during creative problem-solving, as well as the direct implication of the ATL in semantic processes involved in creativity. Therefore, the experimental research conducted in this dissertation aimed to provide new evidence that sheds light on these questions and contribute to a deeper understanding of creative thinking. This section provides an overview of the objectives of the experiments, the hypotheses to be tested and the tools utilized.

The main goal of our first study was to better understand the impact of individual differences in semantic memory activation, attentional scope, and inhibitory control of interfering memories on creative problem-solving. Although there is a substantial body of evidence indicating that semantic memory structure is one of the building blocks of creativity, a great deal of it has been derived from indexes obtained using the verbal fluency task (i.e., say as many words related to a given one as possible in one minute). This task has been criticized for measuring more than participants' semantic organization. As Volle (2018) points out, the nature of verbal fluency methods lies not only in associative but also in executive processes. Indeed, when considering the words associated with a given word, the selected words must align with the specified criterion. Individuals must maintain awareness of already retrieved words to avoid repetition, or switch between categories to produce as many words as possible (Diamond, 2013; Lee & Therriault, 2013; Marron et al., 2018). Moreover, responses in the verbal fluency task might not reflect the actual organization of semantic memory as downstream processes may modify the access to information before a response is produced. Hence, the structure of semantic memory may be better studied by procedures that examine the initial activation of semantic memory rather than what the person ultimately responds to. (Kounios & Oh, 2023; however, see Beaty &

Kenett, 2023 for a response). Thus, along with those requiring verbal fluency, other tasks (i.e., semantic priming) have been used to assess semantic memory (Kumar et al., 2020; Levy et al., 2021). While some controlled processes might exert influence in semantic priming effects, they are mostly based on automatic and implicit mechanisms (Lerner et al., 2014). Their regulation is determined by the number of associated concepts and their mutual connectivity (Kenett et al., 2017; Nelson et al., 1993).

In Experiment 1, we employed a lexical decision task to obtain measures of semantic priming. Specifically, we computed two semantic priming indexes: one for strong (close) associations and one for weak (more remotely) related concepts. This allowed us to estimate the structure of semantic memory and to account for differences between more and less creative individuals.

Additionally, we considered individual differences between participants in terms of attentional scope and inhibitory control. To assess attentional scope, we used the global-local task (Navon, 1977) to obtain the three main indexes it provides: global precedence, global interference and local interference. To measure inhibitory control, we employed an adapted version of the SRP followed by RAT problems, which allowed us to have two main indexes: one of inhibitory control and the other of creativity. The inhibitory index was calculated by subtracting the percentage of correctly solved RAT problems whose solution was a competitor from those whose solution was a studied item. The creativity index was calculated by averaging participants' performance on completely new problems (i.e., problems whose solution was never presented during the experiment). A key advantage of this task is that it allows us to manipulate the accessibility of relevant information, which can be measured by the inhibitory control index. Additionally, it allows for the isolation of purely creative problem-solving ability, as demonstrated by the presentation of problems whose solution was never presented in the experiment.

In Experiment 1, we expected that the creativity index would show a positive correlation with both semantic priming indexes. Given that enhanced activation of semantic associates is conducive to creative thinking, we expected that individuals exhibiting greater creativity would also demonstrate larger priming effects (in both strong and weak conditions). In particular, the

association between creativity and weak priming would serve as the most reliable indicator of how remote concepts are related in creative individuals. Considering the stablished link between attentional scope and conceptual attention, we expected that stronger global interference and global precedence would align with enhanced RAT problem-solving. The local interference index would be negatively associated with creative RAT performance. Finally, considering the role of inhibitory control in regulating interfering memory representations during creative problem-solving, we expected that greater retrieval-induced impairment (i.e., our inhibitory control index calculated by subtracting correct competitor RAT problems from studied RAT problems) would be associated with enhanced creative performance. Experiment 1 is now published in *Thinking Skills and Creativity* (Lezama et al., 2023).

In Experiments 2 and 3, we focused on the neural underpinnings of semantic processing during RAT problem-solving (Experiment 2) and inhibitory control of relevant information for the subsequent RAT solution stage (Experiment 3). To ascertain the involvement of areas relevant to both processes, we employed a neuromodulation technique, transcranial direct current stimulation (tDCS). Simplifying, tDCS is a noninvasive neuromodulation technique that involves the delivery of a weak, constant electrical current usually applied via surface electrodes positioned on the scalp of participants over a targeted cortical area. The electrical current travels from anode to cathode over a period of time (typically 10–20 minutes) and has the ability to alter cortical excitability (Nitsche & Paulus, 2000) as well as modify brain activity beyond the targeted area (e.g., functional connectivity within brain networks, Kim et al., 2021). Consequently, tDCS is considered as an effective method to study the role of brain regions (and networks) in motor and cognitive functions (Bestmann et al., 2015; Fertonani & Miniussi, 2017; Filmer et al., 2014).

In terms of semantic processing, previous studies have highlighted the significance of the ATL, as evidenced by neuroimaging techniques that have correlated activation of this area with creative performance. In this regard, previous experiments have examined the role of the ATL in creative thinking. However, these studies have not yielded conclusive results. Chi and Snyder (2011; 2012) found that cathodal stimulation over the left ATL, coupled with anodal

tDCS over the right ATL reduced participants' susceptibility to fixation due to prior exposure. This was observed in the matchstick and the nine dot problems. Alternatively, Aihara et al. (2017) observed that tDCS over right ATL (using two different montages) resulted in no discernible impact on creative performance, as measured by the matchstick problems and the RAT (nonverbal and verbal creativity tasks). In another study, Ruggiero et al. (2018) demonstrated that anodal stimulation over the left ATL (while cathodal tDCS was delivered over the right ATL) resulted in a shorter response time for the RAT compared to sham stimulation. No effects on accuracy were observed. However, the sample size for this study was seven participants, which raises serious concerns regarding the interpretation of the results. In conclusion, the variations in sample size, task types, tDCS protocols, and electrode configurations between these studies, make it challenging to draw conclusions about the effects of tDCS on the ATL in the context of creative problem-solving.

In parallel with creativity studies, recent evidence indicates that the left ATL is associated with the generation of semantic-based memory distortions. In fact, this cortical area is thought to be an integration hub within the semantic brain network (Chadwick et al., 2016). Anodal tDCS over the left ATL has been shown to reduce the occurrence of semantic-based false memories (e.g., Boggio et al., 2009; Díez et al., 2017). In a study by Díez et al. (2017), anodal tDCS over the left ATL was found to reduce the formation of semantically-induced false memories. These results indicate that anodal stimulation appears to disrupt the semantic integration process necessary for false memory induction. Given the positive correlation recently found between false memories and creative performance (Thakral et al., 2021; see also Dewhurst et al., 2011), we decided to follow the same tDCS protocol as Díez et al. (2017) for Experiment 2 in order to test the hypothesis that the left ATL is involved in the integration of information required to solve RAT problems.

In Experiment 3, our objective was to test the involvement of the right prefrontal cortex in the downregulation of memory representations that would later be relevant for RAT solution. As mentioned above, the *problem-solving induced forgetting* effect (i.e., the reduced accessibility of memory representations which lately serve as solutions in the RAT phase) occurs as a

result of repeated cycles of practice retrieval of specific items. This selective retrieval triggers control processes that cause related but unpracticed items to be inhibited in order to ensure access to the target items. Prior research has indicated that the right prefrontal cortex (DLPFC and VLPFC) plays a pivotal role in the downregulation of competitor memory representations (Stramaccia et al., 2017; Wimber et al., 2008; 2009; 2015). In line with previous neuromodulation studies, cathodal tDCS was applied over the right DLPFC in Experiment 3 to disentangle the involvement of this area in the downregulation of relevant representations for the creativity task (Stramaccia et al., 2017; Valle et al., 2020a). Finally, in Experiments 2 and 3, resting-state (RS) EEG recordings were obtained before and after the administration of tDCS to better understand its effects. Specifically, we examined changes in power at different band frequencies (e.g., Hertenstein et al., 2019). Experiments 2 and 3 are now published in a single article in the *Creativity Research Journal* (Lezama et al., 2024).

In Experiments 4, we focused on the inhibitory mechanism that might operate during creative problem-solving and its electrophysiological correlates. Specifically, our goal was to capture the behavioral and electrophysiological patterns associated with a) previously induced competition during RAT problem solving, b) its resolution through the downregulation of competitor representations in memory, and c) the subsequent consequences of this downregulation on competitors' neural representations. To induce competition, Experiment 4 first presented the most frequent errors made by participants in a previous study with RAT problems (neutral words were also presented and served as a control condition). In the second phase, participants had to complete the RAT (with competition induced) and a control task, followed by a recognition test. In this experiment, we sought to compare the effects of a competition-inducing task with those of a control task on the representation of competitors. Two ERP components described in the literature on recognition testing were examined (Kwon et al., 2023). One is the FN400, a neural component that shows greater positivity for correctly recognized old (previously seen) items than for correctly rejected new items. This effect typically begins around 300 ms after stimulus presentation and continues until about 500-600 ms, with the strongest activity observed in frontal brain regions (Sanquist et al., 1980; Warren, 1980). The other

component is the Late Parietal Positivity (LPP), a positive shift that occurs later, roughly between 500 and 800 ms following stimulus onset. This component is generally most pronounced over the central-parietal areas of the scalp (Paller & Kutas, 1992; Rugg et al., 1995).

We anticipated that competitors would be recognized worse than baseline and new items. Additionally, in terms of neural correlates, we expected to find differences in the ERP components associated with competitor and control items. Thus, control items would evoke more positivity (in FN400 and LPP) compared to competitors because they were earlier presented but not downregulated. Since competitors are thought to interfere during the RAT solution process, inhibitory control is expected to reduce their accessibility later (during the recognition phase). Experiment 4 is currently in preparation for publication.

Part II

Experimental section

Individual differences in semantic priming and inhibitory control predict performance in the Remote Associates Test (RAT)[1]

Abstract

Creative thinking is a complex cognitive ability that requires the combination and integration of information in the memory to produce original ideas. Previous creativity research has suggested that semantic memory, attentional focus or inhibitory control might be engaged when performing creativity tasks. In the present study, we tested whether stronger global attention, larger semantic priming and better ability to inhibit interfering information were related to performance in a creativity task such as the Remote Associate test (RAT). With this aim, 124 participants performed a lexical decision task in which the degree of semantic association (strong and weak) was manipulated. They also performed Navon's global-local task, in which global precedence and global/local interference indexes were calculated, and an adapted selective retrieval procedure from which an inhibition index was obtained. The results indicated that better creative performance was predicted by larger semantic priming between strong associates and by larger inhibitory effects, while attentional style was not associated with performance in the RAT. These findings support the role of semantic activation and inhibition during creativity.

Keywords: creativity, semantic memory, inhibitory control.

[1] The content of this experiment has been published as Lezama, R., Gómez-Ariza, C. J., & Bajo, M. T. (2023). Individual differences in semantic priming and inhibitory control predict performance in the remote associates test (RAT). Thinking Skills and Creativity, 50, 1–15. https://doi. org/10.1016/j.tsc.2023.101426

Introduction

When facing problems in daily life, we usually rely on previously successful ideas and experiences to solve them (Cushen & Wiley, 2018). However, this strategy does not work when the problem requires novel and creative solutions. Creativity is defined as the ability to generate original, useful and innovative ideas or solutions to problems by accessing and combining distantly associated concepts (Mednick, 1962). Interestingly, people differ in their creative potential, and some individuals are more imaginative and original than others (Beaty et al., 2014; Kenett et al., 2016; Schilling, 2005). Since creativity is a complex process, individual differences in the cognitive functions supporting it might underlie individual differences in creative potential (Abraham et al., 2012; Beaty et al., 2020; Thakral et al., 2021).

Dual-process models suggest that associative and controlled processes play a key role in creativity (Benedek & Jauk, 2018; Sowden et al., 2015). During creative generation, associative processes allow a stimulus (externally presented or internally generated) to activate other stimuli's representations through their already established connections. This kind of spontaneous process allows individuals to come up with new ideas based on previous knowledge (for a review, see Benedek et al., 2023). Controlled processes, such as inhibitory control, are thought to be key to prevent typical thinking paths and facilitate the search for new ideas (Beaty et al., 2014). Hence, the recombination of associated pieces of information and the downregulation of conventional ideas would promote the creation of unusual or original concepts and ideas (Volle, 2018). Following this view, the general goal of the present study is to contribute to our understanding of individual differences in associative and controlled processes underlying creativity. Specifically, we examine the roles of semantic memory structure, attentional scope and inhibitory control (over interfering episodic memories) in producing creative responses in a widely used creativity task such as the Remote Associates Test (RAT; Mednick, 1968).

Associative processes are reliant on semantic memory (Abraham, 2014; Benedek et al., 2023; Friedman & Förster, 2002; Kenett, 2018), which includes concepts, facts and their associations that we have accumulated over the course

of our lives, in interconnected networks (Collins & Loftus, 1975; McRae & Jones, 2013). According to Mednick's associate theory (1962), more creative people have flatter associational hierarchies of concepts, while less creative individuals have steeper associational hierarchies. In this view, creative people have richer and broader associations among concepts that allow them to connect distantly related ideas more efficiently, while less creative people have fewer and more common associations between concepts that may limit these combinations (Rossmann & Fink, 2010). From this perspective, closely related concepts or ideas are less creative than remotely associated concepts (Gruszka & Necka, 2002; He et al., 2020). Recent associative views stress semantic richness as a key factor associated with creativity. In a recent relevant study, for example, Beaty et al. (2022) had participants perform a creativity task, the Alternative Uses Task (AUT), in which they were required to produce as many alternative uses of a common object as possible (e.g., brick, shoe). Critically, the semantic richness (number of semantic associates) of the objects was manipulated. The results indicated that participants produced more ideas for objects with a larger number of semantic associates (high semantic richness), even though these ideas were less original. Hence, semantic memory structure (specifically, the number of interconnected concepts) had a differential impact on participants' ability to generate creative ideas.

From an associative perspective, Mednick (1968) developed the RAT as a tool to assess creative thinking. In this test, three unrelated words (e.g., CHEESE–COMPUTER–ELEPHANT) are presented and the participant has to come up with a single fourth word relating all of them (e.g., MOUSE). The RAT is thought to rely on convergent thinking (it requires finding the correct single solution for a specific triplet) but also on divergent thinking because it requires thinking of alternative, less common meanings of the words to find a possible relationship between them (Cortes et al., 2019). Specifically, when solving RAT problems, participants initiate a semantic search from the provided items that implicitly activates many other associated concepts in semantic memory (divergent stage). This process ends when a weakly associated concept to the three words provided in the problem is selected as a potential solution (convergent stage; Schilling, 2005; Smith et al., 2013; Topolinski & Strack, 2008).

In line with this, a number of studies have shown that individuals who score high in creativity (compared to less creative people) a) have a more interconnected semantic memory with shorter distances between concepts (Luchini et al., 2023; Kenett et al., 2014), b) judge pairs of unrelated words as more semantically related (Rossmann & Fink, 2010), and c) are able to come up with more ideas (and more quickly) and, in doing so, retrieve more uncommon ideas than participants with lower creative potential (Benedek & Neubauer, 2013).

Several studies have used verbal fluency tasks to estimate participants' semantic memory networks and explore their association with creative performance (Kenett et al., 2014; Kenett, 2018; Luchini et al., 2023). However, as highlighted by Volle (2018), verbal fluency relies on associative but also executive processes (i.e., word selection according to a criterion, not repeating words, switching among semantic categories; Diamond, 2013; Lee & Therriault, 2013; Marron et al., 2018). Hence, fluency tasks might not be the most appropriate tool to determine the relevance of semantic memory on creativity. Indeed, other studies have used semantic priming as a tool to measure participants' semantic memory structure (Kumar et al., 2020; Levy et al., 2021). Although controlled processes might also contribute to it, semantic priming is thought to rely, first and foremost, on automatic processes (Lerner et al., 2014) and to be modulated by the number of associated concepts and their interconnectivity (Nelson et al., 1993; Kenett et al., 2017). Hence, in the present study, we focus on strong (between closely related concepts) and weak (between more distant concepts) semantic priming indices to examine the relationship between semantic memory structure and creativity. According to Mednick's (1962) proposal, more creative people would exhibit larger semantic priming effects than less creative people. In support of this, Gruszka & Necka (2002) demonstrated that more creative participants (compared to less creative ones) exhibit a higher predisposition to judge unrelated words as more associated and to exhibit larger priming effects. Similarly, Radel et al. (2015) observed that reducing inhibitory control enhanced priming effects for weakly related word pairs as well as creative performance. In summary, associative processes seem to be involved in creative performance, and semantic priming (especially when the semantic distance between the prime and target is manipulated) emerges as an

interesting tool to investigate the association between semantic memory and creativity.

Regarding controlled processes, some studies support the idea that the way in which the context is attended (and consequently perceived) may affect creativity through the semantic search process (Förster & Dannenberg, 2010; Martindale, 1999; Mendelsohn, 1976). The rationale behind this idea is that a narrow attentional scope might hamper creativity because the spreading activation process from one concept to another is limited, and only stronger and closer concepts are activated (e.g., 'lighter' strongly activates 'match'), while more remote but related concepts are less accessible (e.g., 'halo'; Friedman & Förster, 2008; Wronska et al., 2018). When attentional scope is broad, more concepts are potentially activated, even though the activation level of each piece of information is lower and larger amounts of information become accessible, thus leading to the consideration of remote concepts (Chiu, 2015; Liu, 2016). Consistent with this idea, Colzato et al. (2017) showed that meditation techniques that broaden the scope of attention enhance creativity compared to meditation techniques aiming to narrow attentional scope. Liu (2016) manipulated participants' attentional scope and showed that participants in the narrow attention condition (performing a category-based fluency task that constrained their attention) were less creative than participants in the broad attention condition (performing a free association task).

The results from a study by Zmigrod et al. (2015) also support the idea that attentional scope relates to creativity. They examined whether individual preferences in attending to visual stimuli could predict participants' creative performance. To assess visual attention styles, participants completed the global-local task (Navon, 1977), wherein they were instructed to identify the global or local feature, in separate blocks, of congruent and incongruent stimuli configurations (e.g., large letters S or H composed of small letters S or H). This task provides three behavioural indexes: a) global precedence—participants' performance is better in responding to the global level than the local level of the stimuli, meaning an advantage attending to broad stimulus; b) global interference—incongruent information at the global level hinders performance at the local level, meaning that local processing is hampered by the global aspects;

and c) local interference, which refers to an impairment when responding to the global level generated by the local level or, in other words, how attending to details interferes with perceiving the 'big picture'. To assess creativity, Zmigrod et al. (2015) used two tests: the RAT and the AUT. The results of the study indicated that higher global interference was associated with better performance in the RAT and that better performance in the flexibility measure of the AUT (number of different categories used in responses) was negatively related to local interference, which suggests that enhanced attentional bias to the global aspect of visual stimuli promotes creative responses.

A recent study by Liu and Peng (2018; Exp. 1), however, found no evidence of an association between attentional style and performance in a creative task. In this study, participants first performed an adapted global-local task (Navon, 1977) so that they had to uniquely respond to either local or global conditions, but not to both. Afterwards, they performed the AUT. This manipulation was expected to bias the participants' attentional style to a narrower (local condition) or broader (global condition) scope. However, the results failed to show any effect of the scope of attention over the AUT, suggesting that attentional scope might not be critical for performance in creativity tasks. Other study (Zabelina et al., 2015; Exp. 2) failed to find an association between response times (in a task similar to global-local) and creativity measured with the Abbreviate Torrance Test for Adults (ATTA: Goff & Torrance, 2002). Hence, the mixed pattern of previous results suggests that more research is necessary to determine the extent to which attentional style is involved in creative ability.

Other control processes such as inhibition could also contribute to the production of creative responses, although the available evidence shows mixed results regarding this possibility (Beaty et al., 2019; see Chrysikou, 2019; Gupta et al., 2012; see also Radel et al., 2015). Of special relevance here, a recent study reported data indicating that inhibitory control of memory representations regulates the activation of possible solutions and influence their accessibility during creative problem solution (Gomez-Ariza et al., 2017). In this study, participants performed the adaptation of the selective retrieval task (SRT) followed by RAT solution. First, participants studied a list of category-exemplar words and then repeatedly retrieved some of them before finally solving a set of

RAT problems. Critically, the solutions to the RAT problems were words from the previous phases of the experiment: namely, they could be either only-studied words (baseline), practiced (repeatedly retrieved) or competitor words (words that were related to the practiced ones and thought to be inhibited to prevent them from interfering during selective retrieval). The results showed that practiced words were more often chosen as solutions than the only studied words. More relevant here, competitor (inhibited) words become significantly less produced as RAT solutions compared to baseline items (see also Valle et al., 2019; Valle et al., 2020a, 2020b).This effect resembles the standard retrieval-induced forgetting (RIF) effect that it is usually obtained with explicit memory tests and that have been interpreted as the result of an prefrontally-mediated inhibitory mechanism that reduces the activation level of competing items to facilitate access to target items during selective retrieval (SR; Anderson & Hulbert, 2021; Bajo et al., 2021; Marsh & Anderson, 2022). This experimental procedure and the subsequent inhibitory effect that is usually observed with it are especially relevant to explore the role of inhibition and memory accessibility in the solution of creativity problems.

During RAT solution, the search for weakly related novel responses will necessarily activate multiple ideas and concepts, especially strongly related ones that might interfere with and impair the creative process. The ability to inhibit (or suppress) this interfering information is thought to be crucial in producing creative ideas. Thus, for example, for a RAT problem such as ARCHIPELAGO–CAGE–BANANA, MONKEY might be activated, given its strong association with CAGE and BANANA. However, MONKEY is not related to ARCHIPELAGO, so it should be put aside to facilitate the finding of a more suitable solution (e.g., CANARY; Storm & Hickman, 2015). Further support to the relevance of inhibition during semantic search comes from a study by Marko & Riečanský (2021) in which they investigated the association between semantic network connectivity (structural properties) and semantic control functions (i.e., semantic inhibition and switching). To measure semantic control processes, participants performed the Associative Chain Test (ACT; Marko et al., 2019), whereas a sematic judgement task (SJT) was used to estimate semantic network structure. In the ACT, participants have to generate words' chains under specific criteria: an

associative condition (generate semantically related words) that provides information about associative semantic ability; a dissociative condition (generate unrelated words) that is considered to tap inhibitory control; and an associative–dissociative condition (participants switch the retrieval rule from one word to the next) used to determine switching costs during word generation. The results indicated that better structural properties of the semantic network (i.e., tighter clustering and shorter average path length between concepts) requires more inhibition of interfering information but benefits flexible switching among clusters. Furthermore, as previously discussed, Beaty et al., (2022) showed that semantic richness was associated with an increase in the number of ideas that, however, were less original. Therefore, while associative processes are critical to activate different pieces of information, (inhibitory) control processes might be determinant in the process of selecting original ideas. In this sense, some studies have shown that inhibitory control is a plausible mechanism to facilitate the search for creative responses by reducing interference from highly associated or misleading ideas (Benedek & Neubauer, 2012; Benedek & Fink, 2019; Storm & Hickman, 2015).

Results from other studies, however, suggest that inhibitory control might not be necessary during semantic search (Michalko et al., 2023). Marko et al. (2019; Exp 2) explored the role of lexical-semantic measures and executive functions in solving RAT problems. Specifically, participants were asked to solve these problems after performing an Associative Chain Test (ACT; Marko et al., 2019). The results showed that it was only semantic associative ability that predicted the ability to reach remote associates in the RAT, so that neither inhibition nor switching cost measures were responsible for individual differences in RAT performance. In summary, the role of inhibition in creativity tasks remains an issue that deserves further research.

To sum up, although semantic associative processes, inhibitory control and attentional scope seem to play a role in creativity, the available evidence on this issue is mixed, and further research is necessary. Importantly, no study to date has explored the relative role of these factors on creative performance in the same group of participants. The main goal of the present study was to contribute on this issue.

Aims of the Study

In the present work we aimed to examine the role of semantic memory organisation, attentional styles and inhibitory control in people who differed in creativity. Participants performed a lexical decision task (LDT), wherein we manipulated the degree of semantic relatedness among the primes and targets to obtain two semantic priming indexes (strong and weak). To measure attentional style, we used the global-local task and obtained global preference, global interference and local interference as indexes. Finally, our participants performed the adapted Selective Retrieval Task (SRT) used by Gómez-Ariza et al. (2017), which provides an index of inhibitory control (retrieval-induced impairment in RAT problems) as well as an index of baseline performance in creative responses.

Based on the results of previous studies, we expected that creativity (as measured with the baseline problems of the RAT) would be positively related to the semantic priming indexes (i.e., more facilitation in the semantically related conditions than the control condition in the LDT). In particular, we expected this association to appear for both strong and weak semantic priming indexes, but we were most interested in priming with weakly related associates since it might be a good index for capturing associations among distant semantic concepts. Additionally, assuming that there might be a relationship between conceptual and attentional scope, we expected a positive association between creative potential (higher RAT scores) and global interference and precedence indexes in the global-local task, but a negative association with local interference in this same task. Since previous studies have shown that manipulating the attentional scope in a semantic fluency task influenced performance in a creative task (Liu, 2016), we expected a mediational role of attentional scope so that more global attention might modulate semantic priming and this, in turn, influence RAT scores. Moreover, we expected a mediation effect of the weak semantic priming index in the association between strong priming index and creativity. Finally, if inhibitory control is a key process for reducing interference from irrelevant information, it would be expected that greater retrieval-induced impairment (a

by-product of inhibitory control during selective retrieval) would align with better creative performance.

Method

Participants

A total of 124 undergraduate students (mean age = 21.62 years; SD age = 5.65 years; 107 women) were recruited to participate in the experiment in exchange for course credits. Invitations to participate were sent to students at the University of Granada and at the University of Jaen, two similar and geographically close public universities where the authors are affiliated. Due to the pandemic restrictions of COVID-19 during the data collection process, we used the Gorilla Experiment Builder platform (https://app.gorilla.sc/) to program the tasks and to have participants complete the tasks online. Participants acceded Gorilla using SONA SYSTEMS, an online platform which is used by the University of Granada to provide students with the opportunity to participate in experiments. The sample size was calculated in advance using G*Power (Faul et al., 2009). The analysis indicated that a sample of 98 participants was large enough to detect a medium-sized effect ($f^2 = 0.15$; $\alpha = 0.05$; power = 0.80) with six predictors (the tasks' indexes). Because we expected that some students would not answer the invitation to participate and that some would fail to complete the set of experimental tasks, we sent the invitation to 290 students to ensure an appropriate sample size. From the invited sample, 126 participants abandoned the study (they started the first session but never completed it, did not continue with the second session or interrupted their participation during this session). Since part of the tasks in the second session were completed by verbal response, additional control of participants' performance was applied through audio recordings. Forty additional participants were removed from the analysis for the following reasons: 1) they misunderstood the RAT (they interpreted from the instructions that they had to think of a chaining word to the three provided in the problem or they had to think about something personal being suggested by the words in the problem, n = 5); 2) they discussed possible solutions to the RAT problems with someone else, n = 7); 3)

there were errors in data recording (n = 2); or 4) they noticed that the some of the RAT problems could be solved with words that were previously presented in the experimental session (n = 26). The final sample comprised 124 participants from the Universities of Granada (n = 80 mean age = 22.55 years; SD age = 6.65 years; 67 women) and Jaén (n = 44; mean age = 19.95 years; SD = 2.37; 40 women).

General Procedure

The study was conducted in two sessions that were performed online by the participants (see Figure 1 for a representation of the general procedure). Participants were instructed to be completely alone during their participation in a quiet room. In the first session, participants accomplished the LDT and the global-local task, with their order counterbalanced across participants. About a week later (*M* = 9.3 days; SD = 3.5), participants completed the second session, in which they performed the adaptation of the SRT, followed by the RAT developed by Gómez-Ariza et al. (2017). At the end of the second session, in the debriefing, participants were asked whether they used strategies (and if so, which ones) to memorise the words in the study phase. They were also asked to report whether they noticed any relationship between the two tasks in the session. If they did, they were encouraged to provide further details about the specific time they noticed it. As in Rivera et al., (2023; Exp. 3), to control for participants performance during the online experiment, mandatory fullscreen mode was required. We set 35 minutes as maximum time to complete the first session. In the second session participants had a maximum of 1 hour and 15 minutes to complete.

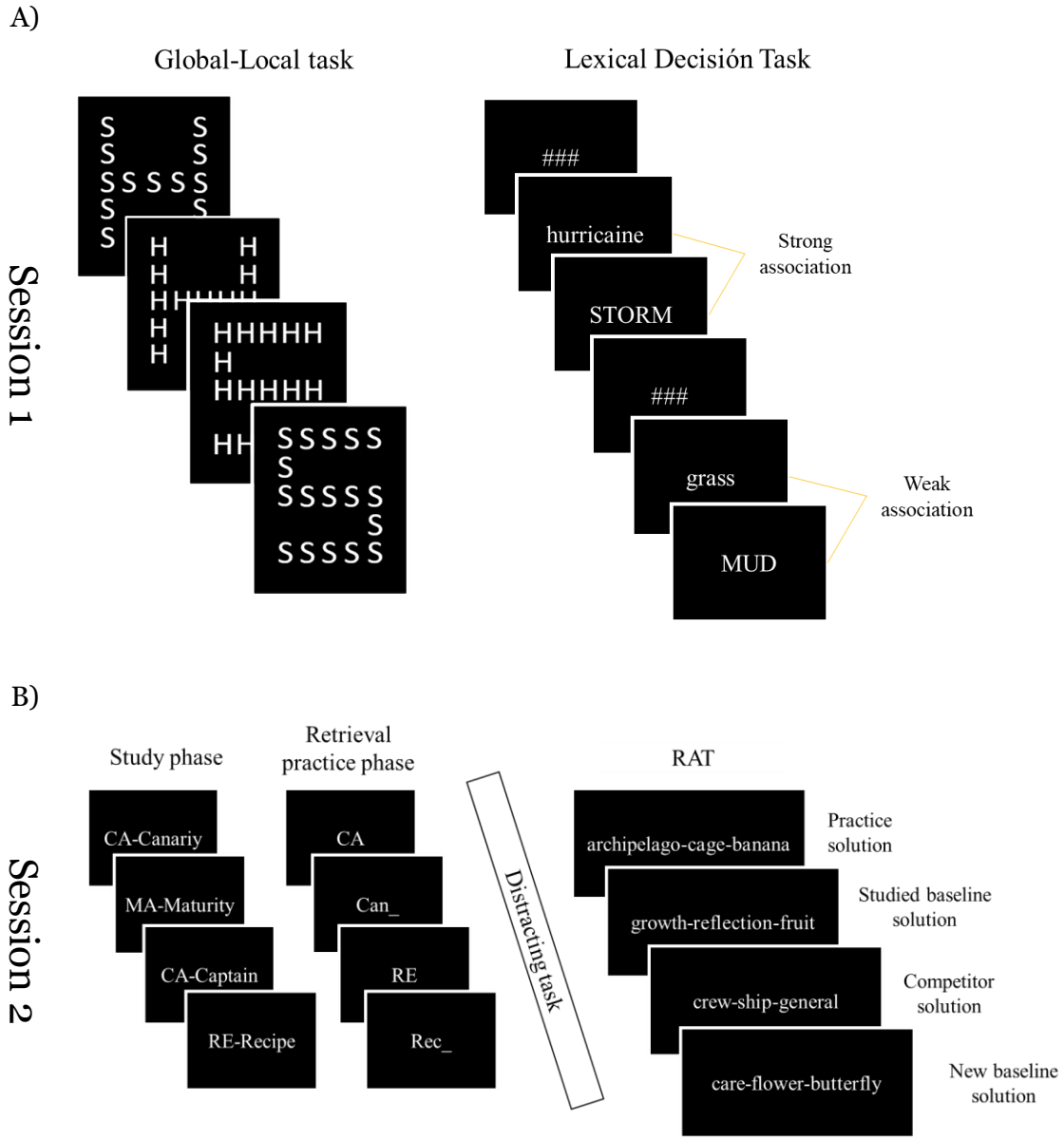

Figure 1. Graphic representation of the experimental procedure. A) In session 1 participants performed the lexical-decision task and the global-local task, counterbalance order was applied across participants. B) In session 2, participants performed the selective retrieval practice followed by the RAT.

Materials

Lexical Decision Task

We used the same materials as the study by Sánchez-Casas et al., (2006). In their study, they firstly selected pairs of semantically related words to be used as primes and targets using a similarity rating task and a feature generation task. Through these two tasks they obtained prime-target pairs that varied in semantic relatedness (weakly related and closely related pairs). Afterwards, they performed a lexical decision task (Experiment 1) and a semantic decision task (Experiment 2) to test the pairs in different set of participants. The results revealed that both types (closely related and weakly related) generated semantic priming effects. Moreover, they observed that the priming effect of closely related pairs was larger than in weakly related pairs. These materials contained 72-word triplets in which one word was the target and the other two were the primes, one with a strong semantic association (semantic distance, mean = 0.73; SD = 0.21) and the other with a weak semantic association (semantic distance, mean = 1.03; SD = 0.15) with the target (e.g., swallow–sparrow and swallow–squirrel). During the task, each target word appeared only once and was presented under one of the four possible counterbalanced experimental conditions: a) identity condition, prime and target were the same (e.g., sparrow-SPARROW); b) control condition, prime and target did not have semantic relationship and prime and target words from different triplets were selected (e.g., trousers-SPARROW); c) weak semantic association condition, the target and prime had a weak semantic association (e.g., squirrel-SPARROW); or d) strong semantic association condition, the target and prime had a strong semantic association (e.g., swallow–SPARROW).

In addition to the original experimental materials, we created 72 new fillers prime–target pairs with no semantic association. We then reduced the percentage of semantically associated pairs by approximately 25%. Finally, we created 144 prime and nonword target pairs with a similar structure to the original experimental set. Specifically, we created triplets that were formed with words that were similar in lexical frequency and letter numbers (primes: mean frequency = 41.2, SD = 104.22; mean letter number = 6.3, SD = 1.79; targets:

mean frequency = 56.1, SD = 99.77; mean letter number = 6.3; SD = 1.76). Subsequently, we selected 288 concrete words from the Spanish frequency dictionary to work as distracters and took special care to create pairs similar in lexical frequency and number of letters to those in the experimental set.

Similar to Sánchez-Casas et al. (2006), we designed four experimental versions with 288 trials each. Hence, no prime–target pair was presented twice to any participant, but each experimental target was presented across the four possible experimental conditions of counterbalance. The filler pairs and the word–nonword pairs were the same for the four experimental conditions.

At the beginning of each trial, a "#" symbol appeared for 1,000 ms. Then, the prime word in lowercase was shown for 250 ms followed by the target word in uppercase for 1,000 ms. As in Sánchez-Casas et al. (2006), the SOA was of 250 ms. The words appeared in the centre of the screen in white font on a black background. Participants were instructed to respond whether the string letter in uppercase was a word or not as quickly and accurately as possible. They responded by pressing the keyboard buttons 'z' or 'm'. The yes and no response buttons were counterbalanced across participants. The task started with a practice block of 12 trials containing all the different kinds of conditions in the same proportions as the experimental block. After practice, the experimental block took place, in which word pairs were presented in random order and feedback was provided after every trial.

From each participant's responses, we calculated two semantic indexes. One was computed by subtracting the mean response times (RTs) in the weak semantic condition from the mean RT in the control condition (weak semantic index), and another (strong semantic index) was computed by subtracting the mean RT in the strong semantic condition from the RT in the control condition.

Global-Local Task

For this task, we followed the procedure developed by Zmigrod et al. (2015). Two large letters, S and H, were created from 5 x 5 matrixes that also included the small letters S and H. The stimuli were congruent when the same letter was contained in the local and global levels (i.e., large S formed by little S)

or incongruent when the letter at the local level was different from the global level (i.e., large H formed by little S).

First, a fixation cross was presented in the centre of the screen for 500 ms, after which the stimulus was shown for 3,000 ms. Participants were instructed to identify the global (large) or local (little) letter in two separate blocks. Each experimental block contained 72 trials. Before the task, there was a practice block, and participants received feedback after each trial. The stimuli were randomly presented in the centre of the screen in a white font on a black background, and the presentation of the two blocks was counterbalanced across participants.

From the global-local task, we obtained three different indexes of attentional style: the global precedence index, calculated as the subtraction of mean RT to trials in the global block from those in the local block; and the global and local interference indexes, estimated by subtracting the mean RT to congruent trials from incongruent trials in local and global blocks, respectively.

Selective Retrieval Practice and Remote Associates Test

Study Phase

Participants were told to memorise pairs of syllable-exemplars of orthography-based categories (e.g., CA-Canary, MA-Maturity, CA-Captain, RE-Recipe; See Figure 1B) because afterwards they would be tested. Each pair was presented for five seconds, with a one-second interval between pairs. They watched 36 pairs of stimuli (category-exemplar) twice in random order, always using the same four filler pairs at the beginning and at the end.

Selective Retrieval Phase

Here, the participants had to repeatedly recall half of the items of half of the categories presented in the encoding phase. As can be seen in Figure 1B, every trial began with the presentation of a category cue (e.g., CA) for two seconds; after a one-second interval, a three-letter exemplar-fragment appeared for five seconds (e.g., Can_). Participants were asked to say aloud a single word from the previous phase that matched the fragment. Participants' voice was recorded through a specific setting available in Gorilla that allows researchers to record audios using computer microphones. Previous consent regarding this issue was always

obtained before starting the experiment. The words were divided into blocks of three items, always with a filler word at the beginning and at the end of each block. Each trial was practiced five times in the above-mentioned blocks pseudo-randomly, in which only one category appeared at a time. Subsequently, the participants performed a distracting task. They had to circle two different letters (k and w) in a text written in a foreign, unfamiliar language for five minutes.

Remote Associates Test (RAT)

Participants solved creative problems composed of three words with no apparent association between them. They were instructed to come up with a fourth word related to all of them under different kind of association; contextual co-occurrence, descriptions, synonyms, semantic association, and compound words. Before starting, they were presented with two pre-solved RAT problems to familiarise them with the process. To avoid creativity constrains (Smith et al., 1993) and to assure that participants would not try to mimic the same type of relationship, different kind of associations were used in the examples. In one of the examples (*carbon-humor-pelo*; coal-mood-hair) the association between the solution (*negro;* black) and the problem cues was description for two, and compound word for the other, in the other problem (football-quotient-cellular) the association with the answer (*division*; division) was contextual co-occurrence for two cues and compound word for the last. Subsequently, participants had to solve 18 filler RAT problems that were selected from the normative study of Peláez-Alfonso et al. (2020) to enhance the implicitness of the task. Then, they solved 54 problems in random order (see RAT in Figure 1B), divided into two different blocks based on lexical frequency. In the first block, the solutions to the problems were high-frequency words (competitors and items from both baseline conditions: studied and new). In the second block, problems were presented that could be solved with low-frequency items (practiced and items from the studied and the new baseline conditions). Participants were given one minute per problem and pressed the space bar to continue once they had said their responses. To record participants' response, the same protocol as the previous phase was followed. When no response was provided, the next problem appeared automatically after one minute.

From the RAT that followed the SRT, we computed two scores for each participant: 1) an inhibition index (calculated by subtracting correct solutions to problems to be resolved with competitors from correct solutions to problems to be solved with studied baseline items, in which higher values above zero reflect better inhibitory control); and 2) a basic creativity index (correct responses to problems that could be solved with never-presented solutions; averaged performance to medium-low and medium-high-frequency from new baseline items) that was independent of previous presentations of solutions. All participants went through the three main phases of the SRT: study phase, retrieval practise phase and RAT. Participants were instructed that they would perform two different and unrelated tasks: A memory task first and then a creativity task.

Regarding the stimuli, we used the list of items used by Bajo et al. (2006; see also Gómez-Ariza et al., 2017). The experimental set consisted of 54 words belonging to nine different orthographic categories (e.g., DI, RE, TA). Additionally, two filler categories with two words each were created to be used at the beginning and end of the presentation to avoid primacy and recency effects. Each orthographic category included six words that shared the first two letters (e.g., rebaño, receta, relámpago, regalo, reserva, retrato, for the category RE). Each word was chosen according to its lexical frequency from the normative database of Alameda and Cuetos (1995). All categories included three medium-high-frequency words (range = 34–98, M = 58.7) and three medium-low-frequency words (range = 10–34, M = 20.1). Moreover, the included words met the following criteria: a) between two and five syllables long; b) no semantic or associative relationship with the other words; and c) uniqueness in the third letter within the category.

The medium-high lexical frequency words were counterbalanced across the following experimental conditions to assess the effect of inhibitory control during selective retrieval (SR) on the solution of RAT problems: a) competitors during SR (items that were presented during the first phase of the experimental session but belonged to the same lexical category as the practiced items, although they were never practiced themselves); b) studied baseline (items that were presented during the first phase of the experimental session but neither belonged

to the same lexical category as the practiced items nor were practiced themselves) that served as the standard control condition to assess the negative (inhibitory) effect of selective retrieval on RAT problems solving; and c) new baseline (items that were not presented during the first phase of the experimental session, nor belonged to the same lexical category as the practiced items, nor were practiced themselves) that served as the control condition for the studied baseline items to determine the effect of the previous presentation of solutions to RAT problems.

Medium-low lexical frequency words were counterbalanced across the following conditions: a) practiced (targets) during SR (items that were presented during the first phase of the experimental session and were to be repeatedly retrieved during SR); b) studied baseline (items that were presented during the first phase of the experimental session but neither belonged to the same lexical category as the practiced items nor were practiced themselves), which served as the standard control condition to assess the positive (facilitatory) effect of selective retrieval on RAT problem solving; and c) new baseline (items that were not presented during the first phase of the experimental session, nor belonged to the same lexical category as the practiced items nor were practiced themselves). Again, these baseline items served as the control condition for the studied baseline items to determine the effect of the previous presentation of solutions to RAT problems.

Six different counterbalanced sets were created to rotate every category across the practiced, non-practiced and non-presented conditions. In each counterbalanced set, three categories were studied and practiced (e.g., DI, RE, TA), so they generated the practiced and competitors' items during SR, while the three categories were studied but not practiced (e.g., BA, MA, DE) and they brought out the studied baseline items; the three remaining categories were not studied (e.g., CA, PE, FA) and produced the new baseline items.

For the RAT, 54 problems were created. Each problem could be solved with one of the 54 words from the nine categories previously described (e.g., growth-reflection-fruit for maturity). Prior to these problems, we presented 18 additional filler problems extracted from the normative study of Lechuga et al. (2020) to minimise the probability of participants recognising the connection between the RAT and the previous (memory) task. As in Gómez-Ariza et al. (2017), the

associative strength between RAT problems' words and their solutions was moderate (forward/backward associative strength < .20). The nature of the relationship could be synonymy, compound word, contextual co-occurrence or semantic relatedness.

Statistical Analysis

To analyse performance in the LDT, we took error rates and (logarithmic, log) response times to correct trials as dependent variables. We used a repeated-measures analysis of variance (ANOVA) with conditions (identity, control, weak and strong semantic associates) as the within factor for each dependent variable. In the global-local task, we considered hits and log RTs to correct trials as dependent variables. A factorial ANOVA was performed with block (global, local) and congruency (congruent, incongruent) as the within factors for each dependent variable. For the SRT, we calculated the mean percentage of correct recall across retrieval attempts. Performance in the RAT was analysed on correct responses to the different conditions of the solutions to the problems (i.e., practiced, competitors, studied baseline and new baseline) by using ANOVAs and t-tests. Analyses were conducted by considering two different scoring criteria: a strict criterion (only solutions that matched the items studied in the first phase were considered correct) and a lenient criterion [solutions that were similar (i.e., synonyms) to the correct solutions and served as plausible solutions were considered correct). To accept solutions following the lenient criteria, plausible solutions were first selected (words with the same meaning as the primary correct solution and that maintained the same type of relationship with the words in the problem, such as compound word, semantic relationship, description, etc.). Thus, for example, for the problem "border-limit-fence" with the primary solution being "barrier," the accepted alternative solutions were "division," "wall," or "separation." As a second stage in the process, the proposed alternative solutions were agreed upon by the authors to ensure a standard criterion. The words accepted as solutions by the lenient criterion, as well as the problems and primary correct solutions, are shown in the supplementary material.

For descriptive purposes, bivariate correlations between all the variables were run using the Benjamini-Hochberg method to correct for multiple comparisons (false discovery rate = 0.15). The results from these analyses have been included in the appendix. To test our hypothesis that strong creative performance is associated with semantic memory organisation, inhibitory control and global attentional style, we performed stepwise multiple regressions analyses over the creativity performance by entering as predictors our indexes of semantic structure, global attentional style and inhibition. Descriptive statistics for these indexes are reported in Table 1.

Table 1. Descriptive statistics (means and standard deviations) of the indexes obtained from the three experimental tasks

Lexical Decision Task		Global-local Task		Selective Retrieval Task/RAT	
Strong semantic priming log-RT index	0.006 (0.03)	Global precedence RT index	-0.30 (0.04)	Inhibitory Index	0.06 (0.24)
Weak semantic priming log RT index	0.008 (0.03)	Global interference RT index	0.017 (0.03)	Creativity index	0.27 (0.14)
		Local interference RT index	0.047 (0.02)		

Results

Lexical decision task

Errors: The ANOVA performed on errors showed a significant effect of type of prime, $F(3,123) = 11.07$, $p < 0.001$, $\eta^2 = 0.08$. Planned comparisons revealed statistically significant differences between the identity condition and the control unrelated condition, $t(123) = 5.63$, $p < 0.001$, $d = 0.50$. Participants made fewer errors in the identity condition ($M = 0.02$; $SD = 0.04$) compared to the control condition ($M = 0.06$; $SD = 0.07$). Similarly, participants made fewer errors in the strong semantic prime condition ($M = 0.04$; $SD = 0.063$) compared to the control condition ($M = 0.06$; $SD = 0.07$), $t(123) = -3.11$, $p = 0.01$, $d = -0.28$. However, there was no difference between the weak prime condition ($M = 0.05$;

SD = 0.06) and the control condition (*M* = 0.06; *SD* = 0.07), t(123) = 1.99, p = 0.28, or between the strong and weak conditions, *t*(123) = 1.12, *p* > 0.9.

Response times: The ANOVA on response times revealed a significant main effect of priming, *F*(3, 123) = 105.67, *p* < 0.001, η^2 = 0.46. There were significant differences between the identity condition (*M* = 2.77; *SD* = 0.07) and the control condition (*M* = 2.82; *SD* = 0.06), *t*(123) = 15.96, *p* < 0.001, *d* = 1.43, and between the weak prime and the control condition (*M* = 2.81; *SD* = 0.06) and strong conditions (*M* = 2.82; *SD* = 0.06), *t*(123) = 2.67, *p* = 0.04, *d* = 0.24. The difference between the strong prime and the control conditions did not reach statistical significance (*t*(123) = -2.14, *p* = 0.19)[2].

Global-Local Task

Accuracy. Analyses on the correct responses revealed a reliable congruency effect *F*(1,123) = 42.84, *p* < 0.001, η^2 = 0.11. Participants were more accurate when responding to congruent (*M* = 0.97; *SD* = 0.04) than to incongruent stimuli (*M* = 0.91; *SD* = 0.10). The interaction between block and congruency approached to statistical significance and we followed it up, *F*(1,123) = 3.70, *p* = 0.06, η^2 = 0.008. Post-hoc analyses indicated that participants showed better performance in the global block for congruent (*M* = 0.97; *SD* =0.04) than for incongruent trials (*M* = 0.90; *SD* = 0.10), *t*(123) = 6.12, *p* < 0.001, *d* = 0.68. In a similar vein, in the local block participants exhibited better performance when responding to congruent (*M* = 0.96; *SD* = 0.06) than to incongruent trials (*M* = 0.93; *SD* = 0.15), *t*(123) = 3.52, p = 0.003, *d* = 0.27.

Response times. The analyses on the log-response times to correct responses showed a reliable block effect *F*(1,123) = 51.19, *p* < 0.001, η^2 = 0.179. Participants were slower responding to local (*M* = 2.71; *SD* = 0.05) than to global trials (*M* = 2.68; *SD* = 0.05). There also was a reliable congruency effect, *F*(1,123) = 320.13, p < 0.001, η^2 = 0.18, which was modulated so that participants were

[2] Since we were interested in individual differences, no measures were taken to minimize the influence of outliers to estimate priming effects at the group level. However, an analysis after winsorizing outliers (from 4 participants) revealed a reliable strong priming effect, *t*(123) = 3.07, *p* < 0.01, *d* = 0.20.

faster responding to congruent (*M* = 2.68; *SD* = 0.05) than to incongruent trials (*M* = 2.71; SD = *0.05*). The interaction between block and congruency also was statistically significant $F(1,123) = 59.50$, $p < 0.001$, $\eta^2 = 0.042$. Further analyses on every simple effect yielded statistically significant results. Thus, participants were faster in congruent (*M* = 2.69; *SD* = 0.05) than in incongruent trials (*M* = 2.73; *SD* = 0.06) in the global block [$t(123) = -17.61$, $p < 0.001$, $d = 1.70$]. In the local block participants were faster to congruent (*M* = 2.67; *SD* = 0.06) than to incongruent trials (*M* = 2.68; *SD* = 0.06) $t(123) = -6.26$, $p < 0.001$, $d = -0.52$. Additionally, participants were faster responding to the global (*M* = 2.69; *SD* = 0.05) compared to the local block (*M* = 2.67; *SD* = 0.06) in the congruent trials ($t(123) = 4.09$, $p < 0.001$, $d = 0.37$) and they have the same pattern on incongruent trials so that they were faster in the global block (*M* = 2.73; *SD* = 0.06) compared to the local block (*M* = 2.68; *SD* = 0.06; $t(123) = 8.37$, $p < 0.001$, $d = 0.75$). Despite that the all comparisons yielded significant differences, the interaction effect is due to that the effect size between congruent and congruent conditions in the global block is more than three times larger than in the local block.

Selective Retrieval Phase and RAT

The mean proportion of correct responses during the retrieval practice phase was 0.57 (SD = 0.20). All participants included in the analyses reached a minimum of 15% correct responses to ensure their engagement during the task.

We performed analyses to determine if participants exhibited the expected retrieval-induced impairment (our inhibitory index) when solving RAT problems (see Gómez-Ariza et al., 2017). This was done by comparing the proportion of correct responses to problems whose solutions were competitor items during the selective retrieval phase (i.e., problems whose solutions did not appear during the selective retrieval phase but belonged to the practiced category) with the proportion of correct responses to baseline studied problems (whose solutions were studied items belonging to categories that were not presented during the practice phase).

Retrieval-induced impairment: When considering a strict scoring criterion, the analysis indicated that participants solved fewer problems whose solutions were competitors during the selective retrieval phase (M = 0.27; SD = 0.17) than problems whose solutions were baseline items (M = 0.34; SD = 0.20), t(123) = 2.96, p = 0.004, d = 0.26. The same pattern of results was obtained when the analysis was performed considering a lenient criterion to score the responses (competitors with M = 0.33 and SD = 0.16; baseline with M = 0.40 and SD = 0.18), t(123) = 3.58, p < 0.001, d = 0.32).

Regression analyses

We ran a stepwise multiple regression analysis over the creativity performance (in non-studied solution problems). In the regression analysis, we included the strong semantic priming index, the inhibition index, the weak semantic priming index, and global precedence as predictors. Importantly, because the global precedence and global interference indexes were correlated (see supplementary material), we only included global precedence as the index of global attentional style. As seen in Table 2, the results of the regression model revealed that only the strong semantic priming index and the inhibition index significantly accounted for variability in the creativity index, which suggests that only semantic priming and inhibitory control (see Figures 2 and 3) would contribute to creative performance.

Table 2. Summary of the stepwise regression analysis with the creativity index (new baseline) as the outcome and the semantic priming, inhibitory control and global attentional style indexes as predictors.

Model	R^2	B	β	*SE*	F	*P*
SPP	0.05	0.98	0.23	0.38	6.67	0.01
SPP + Inhibitory index	0.09	1.03 0.11	0.24 0.18	0.37 0.05	5.63	0.0 4

Note. SSP index = Strong semantic priming index. Weak semantic priming and global precedence indexes did not reach statistical significance as predictors *ps* > 0.3.

The same analyses were conducted on correct responses to RAT problems after using a lenient scoring criterion, with the results remaining essentially the same. Again, Pearson correlations between the tasks' indexes and performance in the RAT revealed that only the strong semantic priming and the inhibition indexes correlated with RAT performance and that both contributed to accounting for the variance in creative performance.

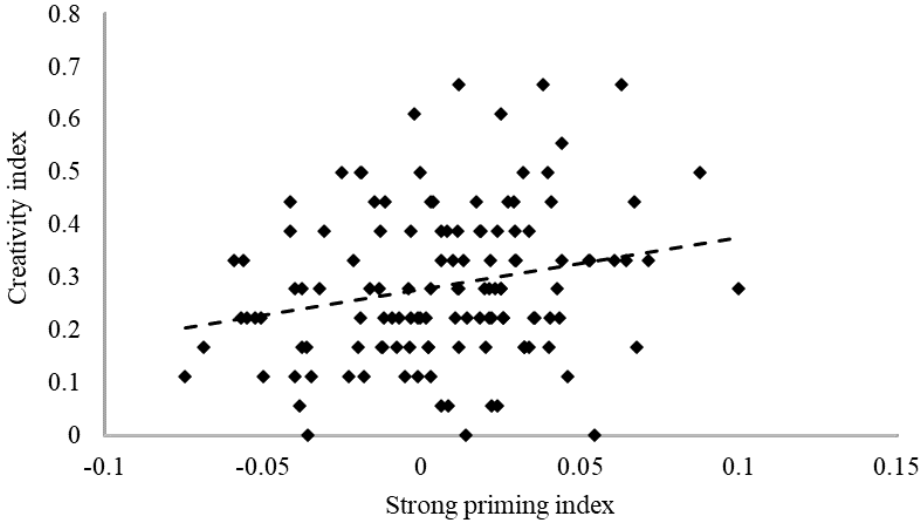

Figure 2. Creativity performance plotted against the strong priming index.

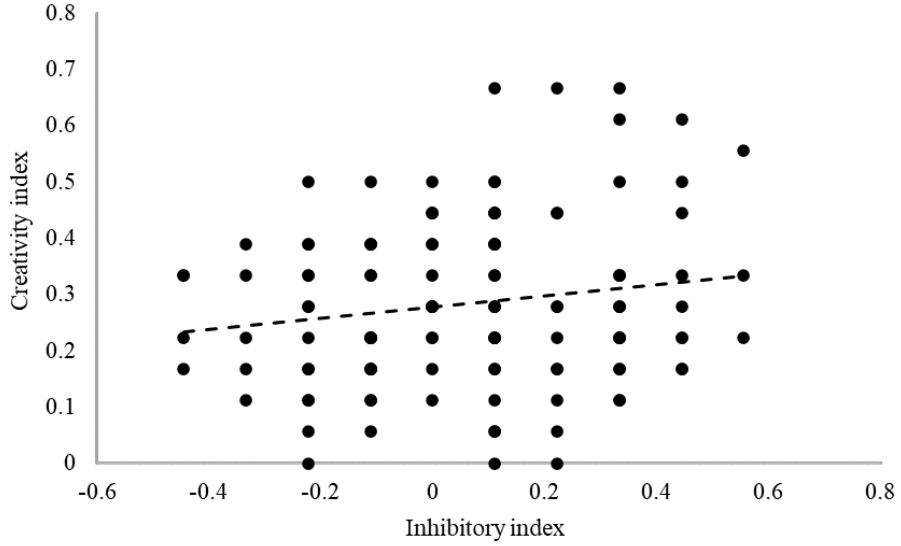

Figure 3. Creativity performance plotted against the inhibitory index.

Mediation analyses

We also conducted analyses to test whether attentional style and weak semantic priming played a mediating role in creativity performance. We used strong semantic priming and inhibition as predictors, global precedence and weak semantic priming as mediators, and creativity as the outcome variable. However, the results failed to confirm a mediation effect for global attentional style or weak semantic priming (*Bs* < 0.09; *ps* > 0.1).

Discussion

Current theories envision creativity from an integrative perspective in which associative and controlled processes might play a role in producing innovative and original ideas (Beaty et al., 2022; Benedek & Fink, 2019). In the present work, we specifically aimed to investigate the relative weight of semantic memory structure, attentional style and inhibitory control on creative thinking from an individual differences approach. To do this, 124 participants were enrolled in a two-session online study in which they performed three different tasks: a lexical decision task, the global-local task and an adapted selective retrieval paradigm followed by the RAT.

In line with previous studies (Kenett et al., 2014; Rossmann & Fink, 2010), we predicted that semantic memory, as measured by semantic priming for strong and weak associates, would correlate with better performance on the RAT. Specifically, we expected that participants with better performance in the new baseline problems would exhibit larger semantic priming for strong and weak associates. We also expected that semantic priming for weaker associates would more strongly predict RAT performance than semantic priming for strong associates. The results supported our predictions, but only partially. We found evidence for a relationship between the strong semantic priming index and performance on the new baseline problems, but there was no evidence of an association between priming with weak associates and RAT performance, which suggests that the general level of activation in the network might contribute more to RAT performance than the spread of activation to weaker associates.

The finding of an association between semantic priming (strong associates) and RAT performance is in line with the results of a recent meta-

analysis on the interplay between semantic memory and creative thinking. In fact, this meta-analysis reveals correlations of similar magnitude to the one reported in this study between semantic priming and creativity (Gerver et al., 2023). Thus, our results support previous work indicating that the structure of semantic memory is critical for creative thinking (Kenett, 2018; Mednick, 1962). In the LDT, the presentation of a prime word related to the target word 'preactivates' the target representation so that its recognition is facilitated when it is later presented (Balota & Lorch, 1986; Neely, 1976). Similarly, when participants face creative RAT problems, the processing of the problem cues initiates a guided search through semantic memory, which facilitates responding to the problems. This activation might constrain the semantic search and make it more efficient (Kenett et al., 2014). Thus, our results show that people with larger sematic activation effects are also better at finding RAT solutions. Interestingly, Smith et al. (2013) investigated how the search process in the RAT takes place. In their study, the participants were asked to perform the RAT, but they were instructed to type each word that came into their minds while trying to solve the problems, regardless of whether the word was considered a solution. The analysis of the response protocols indicated that the search was semantically guided. Thus, participants focused on one RAT cue at a time, and the search for that cue proceeded sequentially through semantically related words so that responses tended to show a chain of semantically related words. This evidence suggests that the search proceeds semantically so that strong semantic activation may facilitate the semantic search.

The fact that priming with weak semantic associates did not facilitate performance in RAT problems may be due to several reasons. Our expectations were that participants with better creative potential would exhibit more priming effects of weak associates due to the more interconnected structure of their semantic network (Beaty et al., 2020; Li et al., 2021). That is, more interconnected semantic structures would facilitate the semantic search process and, if so, would also facilitate RAT performance. On the one hand, the weak semantic index is calculated between distant associate prime and target words. However, it is possible that more remote associations might not be beneficial due

to the possible interference generated by multiple other concepts related to the prime and the target (Anaki & Henik, 2003; de Groot, 1983).

Mednick's (1962) model of creativity assumes that, to reach creative ideas, there must be a spontaneous activation and new combination of concepts. Specifically, the recombination of further associated concepts stored in memory would be the building blocks of more creative outcomes. According to more recent versions of the theory, a structural organization of semantic memory, wherein nodes of information are more interconnected and have shorter path lengths, would enhance associative processes (Benedek et al., 2023). The present results, however, do not seem to entirely align with this model. During the LDT, the advantage of responding to targets strongly related to primes is thought to be due to the closeness between both representations in participants' semantic memory network, which would benefit the search for creative responses while completing the RAT. However, our failure to observe an association with the weak semantic priming index limits the implications of remote associations in producing creative responses.

Nevertheless, generating and evaluating possible solutions could not be a necessarily fast process. In fact, response times are not usually considered in creative thinking tasks (Kenett, 2018; Zmigrod et al., 2015). If so, it is possible that to be creative does not necessarily involve fast semantic access to weak associates (as represented by semantic priming with weak associates), but slower access to and evaluation of concepts until remote concepts are reached. Thus, reaching far concepts may be what enhances the creative potential, and this might be facilitated by the stronger semantic activation represented by priming with strong associates and not so much by the fast-spreading activation of remote concepts represented by semantic priming with weaker associates. In this sense, Benedek and Neubauer (2013) observed that participants with higher creative potential were able to retrieve more associated concepts during a verbal fluency task (higher associative fluency) in which they had to produce as many words related to a target word as possible. This is considered a measure of creative potential given that associative fluency has been strongly linked to ideational fluency, an indicator of creativity (Benedek & Neubauer, 2012). Similar to their results, our participants with higher RAT scores were indeed faster answering the

strong related condition due to the close association between prime and target, which, eventually, might allow them to reach remote relationships when facing creative problems. Hence, it is possible that strong semantic priming, like high verbal fluency, mirrors efficient access to related ideas that can influence creativity on the basis of how information is associated/interconnected.

Regarding attentional style, we did not find any association between global interference, global precedence or local interference with creative performance. A number of previous studies have provided evidence that a global attentional style aligns with more original responses in creative tasks, supporting the idea that a wider focus of attention facilitates the activation of remote concepts, which might be out of focus when a narrower attentional style is predominant (Finke et al., 1992; Martindale, 1995). However, it has been suggested that the relationship between attentional style and creative thinking might not be general but task dependent. First, recent studies (e.g., De Luca et al., 2022) have shown that global/local attentional styles captured through a given task transfer to other tasks that also require global/local processing only if the two tasks are closely related and resemble each other. Substantial changes from one task to the other reduce or eliminate transfer. Hence, it is possible that the evident differences between the global/local task and the RAT might reduce the potential predictive power of global/local attention.

Second, some research has suggested that the type of attentional processing required varies for different creative tasks. For example, invent a creative title for a picture or a story (Förster & Denzler, 2012) or imagining an animal that lives on another planet (Liu, 2016) might not require the same processes as solving creative problems with a single correct solution like the RAT. While in the first task, correctness might not be a relevant feature of the response, in the case of RAT, it is determinant, and narrower attention might be important to evaluate whether a solution is optimal or not (e.g., Simon, 1985). Simultaneously, however, in this task, a wider attentional focus might favour reaching distantly related solutions, so global styles might also benefit performance. In other words, during RAT solution, the participant starts by conducting a semantic search in which a wide attentional style might help find a remote concept related to the problem words. However, once activation has

occurred, a narrower attentional style might be more helpful in selecting the correct solution than a broader attentional style. Hence, it is possible that the lack of association between attentional styles and creative performance is a consequence of the joint engagement of the two types of attentional processes related to attentional styles in different ways. In the idea generation phase, a wide attentional style benefits the process, but during the idea evaluation of the candidates, focused attention enhances the decision. Further research should be directed towards addressing this possibility and disentangling the relative role of attention in the search and selection processes.

Finally, a relevant additional observation in this study is the positive association between our inhibitory control measure and the creativity index. When participants try to solve RAT problems, several ideas are considered potential solutions, while strongly related inappropriate responses must be discarded. To do this, participants may have to trigger inhibitory processes to reduce the level of activation of these activated competing concepts. Our results indicate that the ability to inhibit misleading information to reduce its accessibility is positively related to performance in a creative task such as the RAT. Although the nature of our study does not allow us to draw conclusions about the causality of inhibitory control and RAT performance or about the exact nature of the inhibitory mechanisms underlying selective retrieval and selection in RAT problems, the idea of inhibition during selection is consistent with other studies in which the ability to suppress strong semantic associations is related to creativity (Abraham, 2014; Chrysikou, 2019; Gupta et al., 2012). For example, Storm & Angello (2010) explored whether a stronger ability to overcome memory interference was related to the ability to overcome induced interference in creative problem-solving. They correlated their inhibitory index (retrieval-induced forgetting) with RAT performance. Critically, the participants had previously been exposed to incorrect associates of half of the RAT problems they had to solve. The activation of these incorrect responses was shown to produce fixation effects and hamper the search for the correct response (Smith & Blankership, 1991). The researchers observed that RIF was related to performance in the fixated problems of the creativity task (RAT), but not in the

control RAT problems, suggesting that inhibition is triggered to suppress strong competitor responses and to facilitate creative performance.

From another perspective, our study joins others in demonstrating that inhibitory control might also impair performance in RAT problems. In the present study, studied baseline words were more often selected as a solution to the RAT problems than competing RP-related words. This effect suggests that the repeated cycles of retrieval attempt during the practice phase made competing words less accessible in the subsequent RAT solution phase. This effect was described by Gómez-Ariza et al. (2017) and further replicated in analogy problems (Valle et al., 2019, 2020a, 2020b; see also Bajo et al., 2021). From an inhibitory theory account (Anderson & Hulbert, 2021), our results align with previous evidence showing that inhibitory control is the mechanism responsible for competitive memory selection.

The present study has some limitations. First, we did not collect measures of complexity or connectivity to estimate semantic memory structure, which could be of relevance to delve into the link between semantic memory and creativity (Beaty et al., 2022). Future research should consider more complex measures of semantic networks. A second limitation has to do with the type of task used to tap attentional scope that could have contributed to make it difficult to observe an association between attentional scope and creativity. While this null finding adds to previous ones (De Luca et al., 2022), it is possible that other tasks (e.g., inducing mental sets) can be more sensitive and suitable to examine such an association (see Madore et al., 2015, 2016 for a related approach).

Conclusions

To summarise, the results of this study support the idea that creativity involves a number of cognitive processes that involve semantic memory and executive control. People with stronger semantic activation, as reflected by larger priming effects, are also better at performing creativity tasks, and we suggest that this might be because stronger activation facilitates the search process in semantic memory. Second, inhibitory control also seems to be related to better performance in the RAT. People with larger inhibitory indexes also obtained

larger creativity scores, suggesting that the inhibition of competitors might be a critical function of creative problem-solving. Finally, attentional styles do not seem to predict performance in the RAT, which might suggest that this is not an important factor underlying individual differences in creativity. However, the lack of relationship between global/local style and performance in creativity tasks, in our view, should be taken with caution, since it is possible that a global attentional style benefits the idea generation process, whereas a local style of attention might facilitate the selection and evaluation processes that are also needed for a task such as the RAT (Martindale, 1999). Further research should attempt to disentangle the role of these processes in explaining individual differences in creativity.

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Conflict of interest

The authors declare that the research was conducted in the absence of any
commercial or financial relationships that could be construed as a potential conflict of interest.

Data availability statement

The full data set is openly available on
https://osf.io/my2kv/?view_only=cc279d8931ae477a8df387c5288bd04d

Supplementary materials

RAT problems, the primary correct solutions and the words accepted as solutions by the lenient criterion.

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Appendix

	Creativity index	Creativity overall index	Inhibition index	Strong priming index	Weak priming index	Global precedence index	Global interference index	Local interference index
Creativity								
Creativity overall	0.89***							
Inhibition index	0.17	0.05						
Strong priming index	0.23*	0.26**	-0.06					
Weak priming index	0.07	0.11	-0.01	0.55***				
Global precedence index	-0.05	0.01	-0.014	0.07	0.04			
Global interference index	0.05	-0.001	0.03	0.11	0.13	0.24**		
Local interference index	-0.01	-0.07	0.18	-0.11	-0.08	-0.34**	-0.11	

Note. * p < 0.05, ** p < 0.01, *** p < 0.001, ^ p = 0.06. *Table 2* reports the correlations between the semantic priming (weak and strong), global-local and inhibitory indexes, and the creativity indexes. The creativity index always refers to correct responses to RAT problems whose solutions were neither targets nor competitors during retrieval practice. Because there were two types of RAT problems as a function of whether or not their solutions were previously studied, correlation analyses were performed considering them as a single variable (creativity overall index), but also considering only new baseline items. Because the latest was not contaminated by episodic retrieval (the problems were never presented in the context of the experiment), we used new baseline items (creativity index) for further analysis. Only strong semantic priming positively and reliably correlated with the two measures of creativity while inhibitory index was marginally correlated with the creativity index .

Supplementary Material

RAT Problem	Correct Answer	Accepted response in the lenient criteria
frontera-límite-valla	Barrera	Borde, división, cerco, separación, muro
contrato-bolsa-televisión	Basura	
campo-ejército-estratégica	Batalla	Guerra, lucha, maniobra
música-ahumado-ruta	Bacalao	
equilibrio-libra-justicia	Balanza	
espuma-pato-cortina	Bañera	Baño, ducha
archipiélago-jaula-plátano	Canario	
tripulación-barco-general	Capitán	Marine
lento-cuernos-sol	Caracol	
ángel-champú-caída	Cabello	
pajarita-barra-bandeja	Camarero	
iglesia-enorme-monumento	Catedral	Monasterio, vaticano, templo, Notre Dâmme, Sagrada Familia
constitución-gobierno-igualdad	Democracia	
ejercicio-afición-entretenimiento	Deporte	Gimnasia, fútbol
desorden-catástrofe-natural	Desastre	Destrozo, crisis
discusión-político-tertulia	Debate	Disputa, enfrentamiento, conflicto
cuidado-flor-mariposa	Delicadeza	Frágil, fragilidad, sensible
investigador-lupa-sospecha	Detective	Inspector, policía
calendario-uvas-inocente	Diciembre	
homenaje-entierro-esposo	Difunto	Muerte, funeral, velatorio
gráfico-moda-interior	Diseño	
intestino-corte-pesada	Digestión	
disyuntiva-moral-existencial	Dilema	Duda
cónyuges-papeles-ruptura	Divorcio	Separación
producción-defecto-industria	Fábrica	
ídolo-modelo-entrevista	Famoso	Actor, actriz, celebridad, influencer, cantante, referente
cuento-imaginación-dragón	Fantasía	Ficción
descuido-error-olvido	Fallo	Despistado, despiste, equivocación

laboratorio-receta-medicina	Farmacia	Farmacéutico, fármaco, farmacología
flora-animal-exótico	Fauna	
crecimiento-reflexión-fruta	Madurez	
consigna-pasajero-ruedas	Maleta	Equipaje
libro-habilidad-artesano	Manual	
payaso-polvos-coqueta	Maquillaje	Pinturas
nudo-traje-puerto	Marinero	Navegante
cerdo-brutal-ametralladora	Matanza	
juego-deshinchada-adulador	Pelota	
ibérica-tierra-saliente	Península	
cama-pecado-estirarse	Pereza	Vagueza
derrota-negro-depresión	Pesimismo	Tristeza, triste, fracaso, fracasar, malestar
mano-reclamo-favor	Petición	
porción-añico-tarta	Pedazo	Trozo
pastor-agrupación-control	Rebaño	Ganadería
médica-libro-postre	Receta	
resplador-rápido-miedo	Relámpago	Trueno, rayo
papel-sospresa-promoción	Regalo	
natural-vino-encargo	Reserva	
robot-artista-vivo	Retrato	
sentido-mano-roce	Tacto	Contacto, caricia, tocar, acariciar
baile-acordeón-argentino	Tango	
felicitación-invitación-crédito	Tarjeta	
cartón-camello-cigarro	Tabaco	Porro
mecánica-curso-artesanía	Taller	
café-váter-cuenco	Taza	

Dissociating semantic integration and inhibitory control in the Remote Associates Test: a tDCS-EEG study[3]

Abstract

Neuromodulation was utilized here to investigate the distinct involvement of two recognized cortical hubs for semantic integration (the left anterior temporal lobe, lATL) and inhibitory control (the right dorsolateral prefrontal cortex, rDLPFC) in creative problem-solving. Participants were presented with a list of category-exemplar words, selectively recalled some of them, and then solved a set of RAT problems. Selective retrieval was introduced to trigger inhibitory control over competitors. Critically, some RAT problems could be solved with words from the previous phases of the experiment, including words that might be less accessible due to inhibition. Other problems, however, could only be solved with unpresented words. Experiment 1 showed that anodal tDCS over the lATL had a negative effect on the production of correct responses to baseline RAT problems, but not on those that required inhibited solutions. Experiment 2 produced the reverse pattern with cathodal tDCS over the rDLPFC. Resting-state EEG recordings were obtained before and after delivering tDCS, which also revealed specific tDCS-induced changes in frequency bands depending on the site of stimulation. Overall, these findings provide support for the involvement of semantic and control processes in creative problem-solving that are linked to different brain networks.

[3] The content of this experiment has been published as Lezama, R., Gómez-Ariza, C. J., & Bajo, M. T. (2024). Dissociating Semantic Integration and Inhibitory Control in the Remote Associates Test: A tDCS-EEG Study. *Creativity Research Journal*, 1–27. https://doi.org/10.1080/10400419.2024.2373593

Keywords: creativity, semantic integration, inhibitory control, anterior temporal lobe, dorsolateral prefrontal cortex.

Introduction

Creativity is thought to be a hallmark of human beings and closely linked to success and evolution (Lindell, 2010). Hence, significant interest has been directed towards comprehending the neurocognitive underpinnings of creative thinking (Gerver et al., 2023; Cogdell-Brooke et al., 2020; Wu et al., 2020). Creativity is defined as the ability to generate novel, original and useful ideas or solutions to problems (Mednick, 1962). Relevant theoretical accounts on creativity, such as the dual-processes model, acknowledge the dynamic interplay between associative and controlled processes (Sowden et al., 2015; Volle, 2018). During the creative ideation, it is assumed that associative and spontaneous processes are responsible for the semantic activation of remotely related pieces of information, which are then combined into new ideas (or solutions; Beaty & Kenett, 2023; Kounios & Beeman, 2014). However, for these ideas to genuinely exhibit novelty and originality, it is necessary to avoid habitual thinking paths and dominant information in memory (Luft et al., 2018). Consequently, controlled and goal-directed processes are thought to play a central role in the downregulation of prepotent or interfering information/responses (Benedek et al., 2012; Lezama et al., 2023). Hence, semantic activation/integration and (inhibitory-like) control processes are thought to play an essential role during creative thinking (Benedek & Jauk, 2018).

Previous studies have underscored the importance of semantic memory structure in associative search processing and the role of inhibitory control in selecting original ideas (Beaty et al., 2022; Ovando-Tellez et al., 2022). When tackling creative problems, a search in semantic memory is initiated to find suitable pieces of information that can be integrated to reach a proper solution (Smith et al., 2013). A number of studies suggest that individuals with higher creativity tend to have semantic networks characterized by more broadly and strongly interconnected nodes of information (Benedek et al., 2017; Kenett et al.,

2016) and fewer modules of distinct subnetworks, compared to less creative individuals (Denervaud et al., 2021; He et al., 2020). In addition, the ability to circumvent evident and irrelevant ideas that usually arise during the search process appears to facilitate the generation of more creative solutions (Lezama et al., 2023; Smith & Blankenship, 1991; for a review, see Cassotti et al., 2018). Thus, for example, Storm and colleagues (Storm et al., 2010; Storm et al., 2011) demonstrated that individuals who exhibited enhanced inhibition of interfering episodic information also exhibited superior performance on a creativity test.

Of special interest here, Lezama et al. (2023) have recently demonstrated that better semantic activation of strong associates and better ability to inhibit episodically interfering information predicted superior performance on the Remote Association Test (RAT). The RAT is a verbal creativity task wherein triplets of unrelated words (e.g., manners-tennis-round) are presented and participants have to find a fourth word which relates to all of them (e.g., table) (Mednick, 1968). In Lezama et al.'s study, participants firstly performed a lexical decision task with strong and weak semantic associations between primes and target as well as an attentional (global-local) task. Participants then completed an adapted version of the selective retrieval (SR) procedure; for a recent review see Anderson & Hulbert 2021), which included a RAT as the final test (see Gómez-Ariza et al., 2017). Specifically, participants studied pairs of lexical category-exemplar (e.g., FA-Famous, FA-Factory, CA-Cathedra, CA-Canary) and, in a second phase, they selectively retrieved half of the words of half of the categories when the categories and word stems were provided as retrieval cues (e.g., CA-Can__). Since selective retrieval has been shown to trigger inhibitory control over competitors, making them less retrievable temporarily, this manipulation was introduced to increase the accessibility of practiced words (e.g., Canary) while limiting the accessibility of related but competing words (e.g., Cathedra) that were not practiced (Anderson & Hulbert, 2021; see also Bajo et al., 2021). Finally, participants performed the RAT in which some of the problems could be solved with items that had formed part of the SR stage (e.g., Church-Enormous-Monument, with Cathedra as the solution). The RAT also included problems whose solutions were completely new (they had never been presented during the

experiment). The results showed that participants' priming effect (with strong semantic associations only) was the best predictor of performance on the RAT, such that more semantic priming was associated with better creative performance. Importantly, the second-best predictor of RAT performance was the participants' inhibitory control as measured by the relative impairment in producing solutions that were competitors during the selective retrieval phase. As noted above, this retrieval-induced impairment (retrieval-induced forgetting, RIF, in the episodic memory literature) has been attributed to inhibitory control processes that downregulate the activation of competing information to overcome interference during selective retrieval (see Anderson & Hulbert, 2021 and Bajo et al., 2021). As a result, successful activation of former competitors during subsequent RAT problems solving became more difficult, and these competitors are significantly less produced as solutions (for related findings in decision making and analogical reasoning see Iglesias-Parro & Gómez-Ariza, 2006, and Valle et al., 2019; 2020a; 2020b, respectively). Interestingly, Lezama et al. found that individual differences in retrieval-induced impairment showed to be associated with RAT performance, such that better inhibitory control predicted enhanced performance on the RAT. Thus, the results of this study by Lezama et al. (2023) support the idea that both semantic associative processes and inhibitory control play significant roles in creativity.

Semantic processes and inhibitory control have been associated with different neural networks. Thus, although semantic cognition requires multiple processes and brain systems, the anterior temporal lobe (ATL) is usually considered a core region for semantic processing (Chen et al., 2016; Lambon Ralph et al., 2017). Specifically, the ATL is a highly interconnected area that plays a critical role in the creation and maintenance of complex semantic representations (Bonner & Price, 2013; Díez et al., 2017; Lambon Ralph, 2014). Moreover, the ATL is thought to serve as an integration hub responsible for binding modality-specific information from distributed cortices to create amodal conceptual representations (Farahibozorg et al., 2022; Lambon Ralph, 2014; Snowden et al., 2018; Zhao et al., 2017). Importantly, while a number of findings seem to support the bilateral involvement of the ATL as a semantic integration

hub (Lambon Ralph et al., 2017), some lines of evidence suggest a functional asymmetry, indicating that the role of the left ATL is more evident when lexical-semantic knowledge is concerned (Alonso et al., 2021; Gainotti, 2012; Mion et al., 2010). Interestingly, some studies have linked the activity in the left ATL with the exploration of conceptual structures stored in memory to generate creative ideas (e.g., Abraham et al., 2012; Abraham et al., 2018; Aihara et al., 2017; Chi & Snyder, 2011, 2012).

Executive control processes thought to contribute to the production of creative ideas have been associated with prefrontal regions such as the inferior frontal gyrus (IFG) and the dorsolateral prefrontal cortex (DLPFC) (Becker et al., 2020; Benedek et al., 2014; Beaty et al., 2017; Cassotti et al., 2016). These areas are thought to be involved in the implementation of top-down control over different cortical and subcortical regions, depending on the specific task being performed (Beaty et al., 2015; Anderson & Hulbert, 2021). For example, the downregulation of interfering information during selective retrieval has been shown to be associated with the right dorsolateral and ventrolateral prefrontal cortices (Kuhl et al., 2007; Stramaccia et al., 2017; Valle et al., 2020a; Wimber et al., 2015). Interestingly, the IFG and DLPFC have also been proposed to play a role in the regulation of semantic processing and access to meaning (Green et al., 2017; Noonan et al., 2010; Sela et al., 2012). Thus, for example, Bendetowicz et al. (2018) observed that patients with brain damage in right prefrontal regions were less creative because they relied on more common links when generating semantic associations in the RAT. Overall, the lateral prefrontal cortex seems to be particularly involved in interference control and, in the case of creativity, in gaining accessibility to original ideas by inhibiting dominant but non-original ones and orienting the semantic search towards task-appropriate semantic knowledge (Benedek & Fink 2019; for a review, see Chrysikou, 2019; Öllinger et al., 2008).

Despite the evidence for a role of semantic processes and inhibitory control in creative performance and their association with activity in temporal and prefrontal regions, to our knowledge no previous study has examined the contributions of both processes in creativity tasks. Therefore, the aim of the

present research was to dissociate semantic and inhibitory control processes by using transcranial direct current stimulation (tDCS) to modulate activity in the left ATL (semantic processing/integration) and the right DLPFC (inhibitory control) during creative thinking. TDCS usually involves the delivery of a constant weak electrical current (usually 1-2 mA) typically applied through surface electrodes placed on the participant's scalp over a region of interest. The current flows from anode to cathode over a period of time (usually 10-20 min) and has the potential to modulate cortical excitability (Nitsche & Paulus, 2000) and change brain activity beyond the stimulated area (i.e., functional connectivity within brain networks, Kim et al., 2021). Therefore, tDCS is considered a valuable technique for understanding the involvement of brain areas (and networks) in motor and cognitive functions (Filmer et al., 2014; Bestmann et al., 2015; Fertonani & Miniussi, 2017).

Some studies have already explored the role of the ATL during creative problem-solving, particularly in relation to insight, but with mixed results (Aihara et al., 2017; Chi & Snyder, 2011, 2012; Ruggiero et al., 2018). Chi and Snyder (2011, 2012) showed that cathodal tDCS delivered over the left ATL (while anodal tDCS was delivered over the right ATL) reduced participants' susceptibility to functional fixation induced by prior exposure while completing insight problems. In contrast, Aihara et al. (2017) found no evidence that anodal tDCS over the right ATL (with two different electrode montages) influenced performance in creative tasks (matchsticks arithmetic problems and RAT). More recently, Ruggiero et al., (2018) observed that anodal stimulation of the left ATL (coupled with cathodal tDCS of the right ATL) reduced response times in the RAT relative to sham, but this effect did not reach statistical significance in accuracy (note that the sample size in this study was very small: n = 7). In few words, because these studies varied in sample sizes, type of tasks, tDCS protocols and electrode montages, it is still difficult to interpret the effects of tDCS over ATL when solving creative problems.

Regarding the role of the DLPFC in creativity, there seems to be a general consensus on the predominant role of the left DLPFC relative to the homologous region in the right hemisphere, even when the available evidence is also mixed.

Cerruti and Schlaug (2009) showed that anodal stimulation over the left DLPFC improved RAT solution compared to cathodal or sham stimulation, whereas tDCS delivered over the right DLPFC did not change RAT performance (see Zmigrod et al. 2015; Exp. 1 for similar results). More recently, however, Li et al. (2022) observed that, compared with sham stimulation, anodal left/cathodal right tDCS improved the originality of responses in the Alternate Uses Task (AUT) but had no effect on performance in the RAT (for a similar finding see Xiang et al., 2021), which might suggest that divergent thinking may be more easily modulated by tDCS over the DLPFC than convergent thinking.

In summary, previous work has demonstrated the importance of semantic and inhibitory processes in creative problem-solving. However, causal evidence for the involvement of anterior temporal and lateral prefrontal areas in RAT problem solving remains to be elucidated. With the aim of clarifying and dissociating the role of the (1) left ATL in semantic integration during creative problem-solving (Experiment 1) and (2) the right DLPFC in the downregulation of interfering memory representations that could potentially contribute to creative RAT problem solving (Experiment 2), we report two tDCS experiments using the SR-RAT procedure used by Gómez-Ariza et al. (2017). In this procedure, participants initially studied a list of items consisting of orthography-based categories pairs (e.g., CA-Canary, CA-Cathedra). In the following phase, they had to repeatedly recall half of the items from only half of the previously presented categories (e.g., CA-Can_). Finally, they were engaged in solving RAT problems, wherein some of the solutions were words presented in the previous phases, and the rest were entirely new words. The advantage of this behavioral procedure is that it provides indices to assess the relative role of semantic processing (from hits in RAT problems whose solution is a new word) and memory inhibition (from hits in RAT problems whose solutions were competitors during selective retrieval). Although both, semantic processing and inhibitory control, should operate in the search for a RAT solution, in the SR-RAT procedure some RAT problems have a potential solution that has been previously studied and inhibited and, therefore, trying to solve such problems has a strong episodic component. In contrast, RAT problems with new solutions would more probably reflect the

result of semantic processing (semantic integration over the presented word triplet to arrive at correct solution). Hence, in the present experiments, the index of creativity (assumed to be more dependent on semantic activation/integration) was the percentage of correct responses to problems whose solution had not been presented previously (new problems). As in previous related studies (see Bajo et al., 2021), inhibitory control was operationalized as the difference between responses to problems that could be solved with competitors and responses to problems that could be solved with studied only items (retrieval-induced impairment; see Bajo et al., 2021).

Importantly, the processes targeted by tDCS in each of the experiments are thought to operate in different time windows. Associative and integration processes are thought to play a role during creative generation (i.e., during RAT problems solving) (Benedek et al., 2023), whereas inhibitory control is thought to operate during retrieval (Bajo et al., 2021). Thus, in Experiment 1 tDCS was applied before the target process (semantic integration) is thought to play its role. This specific timing was chosen based on the results of Díez et al. (2017; see also Boggio et al., 2009), who showed that applying anodal tDCS over the left ATL during the encoding phase of a DRM paradigm generated a reduction in semantically based memory distortions (a behavioral effect thought to depend on the left ATL and its role as an integration hub). However, in Experiment 2, tDCS was intended to hamper inhibitory control of competing memories which could subsequently be solutions in the RAT phase, while leaving semantic integration unaffected. Importantly, previous tDCS studies have shown that cathodal stimulation over the right DLPFC during selective retrieval disrupts inhibitory control of competitors (Stramaccia et al., 2017; Valle et al., 2020b). Hence, in Experiment 2, the tDCS protocol was based on studies showing successful disruption of inhibitory control of competing memories.

In both experiments the potential effects of tDCS were assessed using behavioral and electroencephalography (EEG) measures. In Experiment 1, anodal tDCS over this region was expected to reduce the number of responses to new problems compared to sham stimulation. In Experiment 2, it was predicted that cathodal tDCS over the right DLPFC would specifically increase the

production of competitor solutions during selective retrieval. Because previous studies have shown that it disrupts inhibitory control over competing memories (e.g., Valle et al., 2020a), it was expected that former competitors would be more accessible as solutions in the real tDCS group than they would be in the sham group, in which inhibition was expected to act on competitors during selective retrieval. For EEG, resting-state (RS) brain activity was recorded before and after stimulation. Previous studies of RS-EEG and creativity tasks have focused on resolution style (insight/analysis) rather than on how different band frequencies relate to mean performance, and have yielded mixed results using different creativity tasks (Erickson et al., 2018; Kounios et al., 2008; Wu et al., 2014). To the best of our knowledge, only one previous study considered pre-post EEG recordings when tDCS was delivered over bilateral DLPFC during RAT performance (Hertenstein et al., 2019). Although this study found an increase in beta-band power after stimulation, tDCS did not affect performance, nor was beta power associated with creative responses. In the present experiments, RS-EEG was recorded to examine whether there were tDCS-induced changes in power at different frequency bands, as well as possible associations between this activity and RAT performance (e.g., Hertenstein et al., 2019).

Experiment 1

The main goal of Experiment 1 was to determine whether applying anodal tDCS over the left ATL would modulate creative responses in the RAT. Because RAT performance has been shown to be sensitive to individual differences in both associative/semantic and inhibitory processes (Lezama et al., 2023), RAT could also be an appropriate task to target the modulation of such processes using tDCS. The ATL is thought to serve as a semantic integration hub of utmost significance in the establishment and maintenance of complex semantic representations (e.g., Bonner & Price, 2013; Lambon Ralph, 2014), which play a relevant role in creativity (Abraham et al., 2018; Aihara et al., 2017). However, previous studies investigating the effect of anodal stimulation of the left ATL on creativity have yielded mixed results (see Chi & Snyder, 2011, 2012; Ruggiero et al., 2018). Thus,

the present experiment aimed to shed light on the involvement of the left ATL in associative/integration processes that are thought to contribute to creative problem-solving.

The left ATL has been shown to be involved in the formation of semantically- based false memories due to its role as an integration hub within a semantic brain network (Chadwick et al., 2016). Indeed, anodal tDCS over the left ATL has been shown to reduce semantically based memory distortions (e.g., Boggio et al., 2009, Diez et al., 2017). As mentioned, Díez et al. (2017) observed that semantically-induced memory distortions were reduced after anodal but not cathodal tDCS over the lATL, suggesting that anodal stimulation seemed to disrupt the semantic integration process necessary to induce false memories. Thus, in the present experiment, the same tDCS protocol as Díez et al. (2017) was followed because the main goal was to learn whether the impairment of semantic integration by tDCS would selectively affect the ability to solve creativity problems. For this reason, and because RAT scores have recently been shown to positively correlate with semantically induced false recognition (Thakral et al., 2021; see also Dewhurst et al., 2011), it was expected that anodal tDCS, relative to sham tDCS, over the left ATL would impair RAT performance in the present experiment, particularly for problems whose solution had not been presented previously in the experimental session (i.e., new problems). New problems would more clearly involve semantic processes than problems whose solutions had been previously studied, which would necessarily involve episodic memory because they were previously presented (and studied) during the encoding phase. Therefore, we expected that stimulation would be more likely to affect solutions to new problems than solution to studied problems.

On the other hand, it was hypothesized that solutions that were competitors during selective retrieval would be produced less frequently than studied solutions during the RAT phase (i.e., a retrieval-induced impairment in the RAT). Importantly, because tDCS was applied over left the anterior temporal region, which is not directly associated with inhibitory control, no difference in retrieval-induced impairment was expected between real and sham tDCS. In

conclusion, in Experiment 1, tDCS should modulate the creativity index but not the inhibitory index.

Method

Participants

The minimum sample size was determined in advance based on the effect sizes observed in two previous studies (Díez et al., 2017; Gómez-Ariza et al., 2017). Given the similarity of the materials and procedure to those used by Gómez-Ariza et al. (2017), the (large) effect size of the retrieval-induced impairment (inhibition index) observed in their Experiment 2 (d= 1.37) was assumed. The analysis conducted by using G*Power 3.1 (Faul et al., 2009) indicated that a sample size of 18 participants per group was large enough to detect a statistically significant retrieval-induced impairment (power = 0.80%; alpha = 0.05). Additionally, the effect size (false recognition of critical words in associative lists; anode vs. sham; d = -0.85) observed in the tDCS study by Diez et al. (2017), who also stimulated the left ATL, was considered. The corresponding analysis determined that a sample size of 22 participants per group was large enough to detect group differences. Finally, the sample size included 32 participants per group (mean age = 20.3 years; SD = 3.6, females = 44) to complete the counterbalancing conditions. In order to assess the implicitness of the relationship between some of the solutions to the RAT problems and the previous stages wherein they could appear, participants were asked at the end of the experiment to report whether they had noticed this association (i.e., Have you noticed any association or relationship between the memory task and the RAT?). Only participants who reported that they were not aware of the relationship between the two phases or became aware only during the second block of the RAT, were included in the analysis. Thus, at the end of the experimental session, participants were included in the final sample only on the basis of their response. The total sample collected for Experiment 1 was actually 77 participants, but 13 of them were excluded (10 from the real tDCS group and 3 from the sham group)

(Table 1 in the Appendix shows the actual sample sizes in both experiments for behavioral and EEG results). All participants were right-handed according to the Edinburgh Handedness Inventory (Oldfield, 1971), had normal or corrected vision and reported no history of neurological or psychiatric disorders, migraines, metal implants, head injuries, seizures, epilepsy or active medication (except oral contraceptive pills). Participants were randomly assigned to the stimulation conditions and remained unaware of their specific tDCS group and the main hypotheses until the end of the experimental session. Ethical approval for the study was granted by the Ethics Committee of the University of Granada (code: 84/CEIH/2015). Participants participated in the study in exchange for course credits.

Materials

The materials were the same as in Gómez-Ariza et al. (2017) and Lezama et al. (2023). The stimuli were 54 words belonging to nine different orthographic categories, with each category containing six words (i.e., maquillaje, marinero, matanza, madurez, maleta, and manual for the category MA). Additionally, there were two extra categories; of two words each that were used as fillers to minimize primacy and recency effects during the presentation of the material.

Within each category, there were three words of medium-high lexical frequency (range = 34-98, M = 58.7) and three words of medium-low lexical frequency (range = 10-34, M = 20.14). All exemplars were selected from the normative database of Alameda and Cuetos (1995) according to their lexical frequency. Importantly, the selected words adhered the following standards: a) they had no associative or semantic connections with other words in the category; b) they were two to five syllables long; c) each word had a unique third letter.

The medium-high lexical frequency words were counterbalanced across conditions to form: a) competitor items (words presented during the study phase and belonging to the same category as the practiced words during the SR phase, but never retrieved); b) studied items (words presented exclusively during the study phase and belonging to a different category than the practiced words); c)

new items (words neither presented during the study phase nor during the SR phase; and belonging to a different lexical category than the practiced words). Similarly, the words with medium-low lexical frequency were counterbalanced to generate: a) practice words during the SR phase (words presented during the study phase and retrieved during the SR phase); b) studied items (words presented only during the study phase, and belonging to a different lexical category than the practiced words); c) new items (words that were neither presented in the study phase nor in the SR phase and that belong to a different lexical category than the practiced words).

Six task versions were created to counterbalance the material across participants. Within each version, three categories (e.g., CA, PE, FA) were both studied and practiced, resulting in competitors and practiced items. Another set of three categories were studied only during the initial phase (e.g., BA, MA, DE), yielding only studied items. The remaining three categories (e.g., DI, RE, TA) were not studied and corresponded to the new solutions. In the RAT phase, the solution of each problem corresponded to one of the 54 exemplars previously described (e.g., Growth-Reflection-Fruit for Maturity). Similar to Gómez-Ariza et al. (2017) and Lezama et al. (2023), the associative strength between the solutions and the words of the RAT problems was controlled (forward/backward associative strength <.20).

Resting-State EEG acquisition and processing

Two five minutes eyes-closed resting-state EEG recordings were obtained at the beginning and end of the experimental session using a 40-scalp electrode cap (Quick-Cap, Neuroscan, Inc.) using the 10-20 system. The electrical signal was amplified by a Scan NuAmps system (Compumedics Ltd., VIC, Australia). The sampling rate was set to 1000 Hz with an online filter (high pass: 0.5 Hz; low pass: 70 Hz). Impedance of all electrodes was kept below 10 kΩ, and the EEG signal was referenced to the Cz electrode during data acquisition. The preprocessing and analysis procedures followed the methods described in Prat et al. (2016) and Aguerre et al. (2021). Prior to data analyses, a high-pass filter at 1

Hz was applied and the five minutes recording was segmented into second-s epochs with 0.5s overlap. Artifacts were manually removed using Fieldtrip toolbox on Matlab (Oostenveld et al., 2011) through thorough data inspection. Bad channels, with high level of artifacts (always less than 10% of the total) were identified and interpolated from neighboring electrodes using triangulation method. The average log power spectrum was then calculated over the frequency range from 4 Hz until 40 Hz. To do this, the power spectrum of each epoch was calculated using the Fast Fourier Transform, then log-transformed, and finally; the resulting power spectra were averaged over all epochs. To diminish spectral leakage, a Hanning window was applied to each epoch before the Fast Fourier transform. Finally, the mean log power was calculated across theta (4-7.2 Hz), alpha (8-12.5 Hz), beta (13-29.5 Hz), and low gamma (30-40 Hz) frequency bands for each channel and participant in the two recording times.

Transcranial direct current stimulation. TDCS was delivered using a DC Brain Stimulator Plus (NeuroConn, Ilmenau, Germany) via two saline-soaked surface sponge electrodes. Saline solution with a sodium chloride saturation of 0.9% was used (ERN Laboratories, S.A.) In the anodal group (real tDCS), a constant current of 1.5 mA (0.06 mA/cm^2) was delivered for 20 minutes using a 30 s fade-in and fade-out ramp. The anode (5x5 cm) was positioned on FT9 according to the international 10-10 system for EEG electrode placement. FT9 was chosen because it is considered the closest electrode to the left ATL (BA 38) (Acharya et al., 2016; see also Díez et al., 2017). The reference electrode (5x7 cm) was placed on the contralateral deltoid muscle to minimize its effect on the brain. For the sham group, the montage mirrored that of the active group, but the current intensity was reduced to 0.75 mA and lasted 30 seconds, with an eight seconds fade-in and fade-out ramp. Figure 1 depicts the electrode montage and simulated current flow using SimNIBS (4.0.1) software (Thielscher et al., 2015).

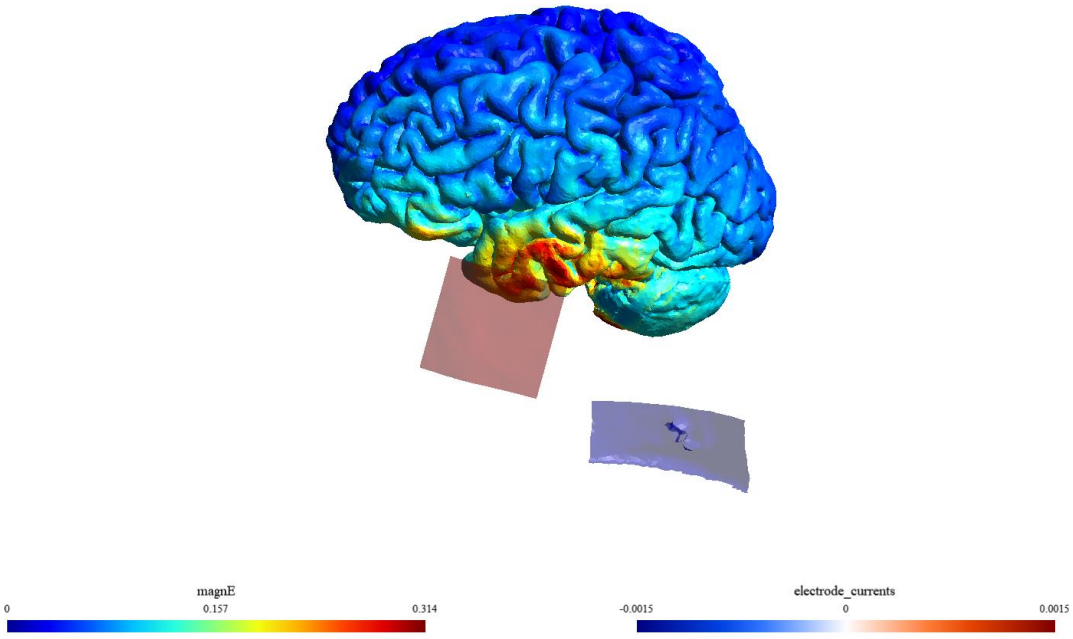

Figure 1. tDCS electrode montage and simulation of the current flow performed using SimNIBS 4.0.1 (Thielscher et al., 2015). The 5x5 cm anode electrode was positioned over the left anterior temporal lobe (FT9). The 7x5 cm cathode electrode was positioned over the contralateral shoulder. The strength of the induced electrical field (magnE) is depicted in V/m and the current generated by each electrode in presented in mA.

As is common in neuromodulation research, participants were asked to remove metal objects from their bodies. Elastic bands were used around the participants' chest and head to prevent displacement of the electrodes in case of movement. Importantly, the stimulator was always manipulated between tasks to disguise the stimulation assignment; and was always out of reach for participants. They could never see the screen of the device (which was covered with paper) or press any buttons.

Procedure

The experimental procedure was very similar to that used by Gómez-Ariza et al. (2017), albeit with adaptations to include the tDCS and resting EEG recording protocols. The experimental session lasted approximately two and a half hours. Once participants read and signed the written consent, the pre-task resting-state EEG recording began. Participants were instructed to close their

eyes, relax, and avoid movement for five minutes. The tDCS electrode montage was then prepared. Figure 2 shows a schematic representation of the experimental procedure.

Participants then performed the adapted SR task followed by the RAT. During the encoding phase, a sequence of orthography-based categories and exemplars pairs (e.g., CA-Canary) was presented for five seconds, with a one-second interval between pairs. Participants were required to memorize each syllable-exemplar pair. The 36 pairs of stimuli were presented twice in random order, with the same two filler categories (FI y LE) always presented at the beginning and end of the list. After the instructions were explained, the tDCS (anodal or sham) started and continued through the study phase (approximately 12 minutes), and the eight minutes distractor task that participants performed after the study. In this task, participants had to circle three different letters (k, w, and z) within a text written in an unfamiliar foreign (Polish) language. Then, in the selective retrieval phase, participants were asked to repeatedly recall half of the items from half of the studied categories. Each trial began with the presentation of a category cue (e.g., CA) for two seconds, followed by one-second interval during which a three-letter exemplar fragment appeared (e.g., Can_) for five seconds. Participants were asked to say aloud the unique word from the preceding phase that matched the fragment. Each trial was practiced three times in random blocks of three items, with each category appearing only once. Filler categories were always presented at the beginning and end of each block. Participants then performed another distraction task involving arithmetic operations for five minutes.

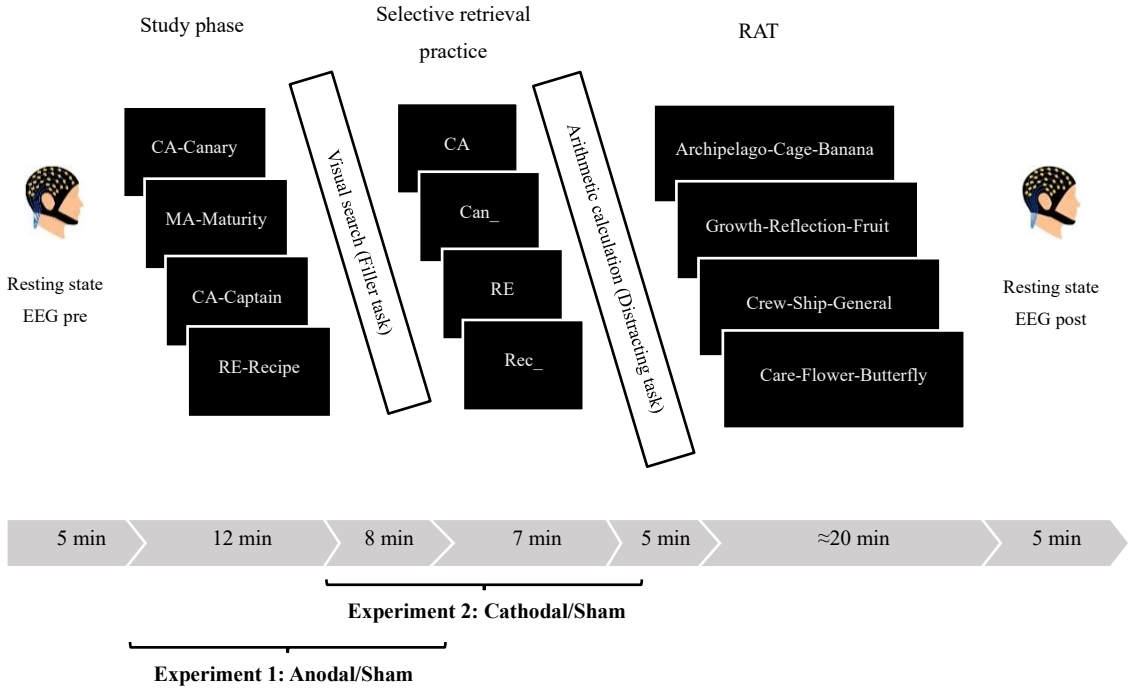

Figure 2. Schematic representation of the experimental procedure. The same procedure was followed in Experiments 1 and 2, except for the tDCS protocol. In Experiment 1, anodal tDCS was applied over the left ATL during the study phase. In Experiment 2, cathodal tDCS was applied over the right DLPFC during the selective retrieval phase. In both cases, real tDCS lasted for 20 minutes.

Finally, participants completed the RAT problems. Participants were told that they had to solve creative problems consisting of three words lacking an apparent association between them. They were instructed to find a fourth word that was related to all three. Additionally, they were informed that the relationship could be based on context, semantic field, synonymy, descriptions, etc. Before starting the experimental task, two RAT problems were presented to familiarize the participants with the procedure. The 54 problems were divided into two different blocks according to the lexical frequency of the solutions, and presented in a random order within each block. The first block contained problems whose solutions were high-frequency words (i.e., competitors during the SR phase, only-studied words or new solutions). In the second block, problems could be solved with low-lexical frequency words (i.e., targets during SR, only-studied words, and new solutions). Participants had up to one minute to produce a solution to each problem. If participants did not provide an answer, the next problem appeared automatically after one-minute time limit. At the end of

the task, a post-task questionnaire was administered to assess participants' awareness of the relationship between encoding/SR and RAT. Before the stimulation began, participants were instructed to inform the experimenter if they felt any discomfort. At the end of the experimental session, participants were asked which tDCS condition they thought they had been assigned to and finally they completed a questionnaire on potential adverse effects of tDCS (Brunoni et al., 2011).

Results

The results of analyses of variance (ANOVAs) on performance in the selective retrieval phase and the RAT are reported below. In all cases, stimulation (real vs. sham) was introduced as a between-groups factor. RAT performance was analyzed considering correct responses to problems with different solution type (new, competitor, studied). Specifically, to examine the effect of tDCS on creativity (without the influence of the selective retrieval manipulation), the focus was on correct responses to new and studied problems (collapsing both blocks of RAT problems). As for the retrieval-induced impairment, it was analyzed by considering correct responses to problems whose solutions were competitors during selective retrieval and correct responses to problems with studied solutions (all presented during the first problem block).

EEG activity was analyzed by considering averaged power in each band frequency (i.e., theta, alpha, beta, and low gamma; see previous section for detailed EEG data processing). A mixed ANOVA with stimulation (real vs. sham) as the between-group factor and recording time (pre-task vs. post-task) as the within-subject variable was performed as well as correlation analyses (Spearman's rho) between pre-task and post-task power. Finally, the differential resting-state activity for each band frequency was obtained (by subtracting the pre-task EEG measurements from the post-task EEG measurements), and correlation analyses (Spearman's rho) between this measure and correct responses to new problems (the only ones modulated by tDCS) were performed for both stimulation groups.

Responses to the adverse effects questionnaire indicated that none of the participants experienced major complaints or discomfort associated with stimulation. Table 2 in the Appendix summarizes the self-reported frequency of effects in both groups and the incidence of correct guessing of group assignment, along with *p* values for between-groups comparisons.

Behavioral results

Effect of neuromodulation and prior exposure on creative responses

To examine the potential effect of tDCS over the left ATL on creative performance, only responses to problems that could be solved with new solutions (items never presented during the experimental session) and studied solutions (i.e., studied items that were neither targets nor competitors during retrieval practice) were considered. Thus, a 2 (tDCS: Real vs. Sham) x 2 (type of solution: Studied vs. New) mixed ANOVA on correct responses to RAT problems was conducted. The analysis revealed a main effect of type of solution, $F(2,62) = 29.13$, $p < 0.001$, $\eta^2_p = 0.32$, indicating that participants resolved more RAT problems whose solution had been previously studied (Studied: $M = 44.20$; $SD = 14.70$; New: $M = 34.10$; $SD = 11.20$). There was also a main effect of tDCS, such that participants who received real stimulation ($M = 37.33$; $SD = 10.92$) produced fewer responses than participants in the sham group ($M = 42.55$; $SD = 10.93$; $F(2,62) = 7.59$, $p = 0.008$, $\eta^2_p = 0.10$). More importantly, the interaction reached statistical significance, $F(2,62) = 5.21$, $p = 0.02$, $\eta^2_p = 0.07$. Simple effects analyses revealed that there was no difference between real and sham tDCS when participants solved problems whose solution had been previously studied (M_{Real}= 42.90; SD_{Real} =14.30; M_{Sham}= 45.50; SD_{Sham}= 15.23, $F(1,62) < 1$, $\eta^2_p < 0.01$). In contrast, in the case of problems to be solved with unstudied solutions real tDCS led to fewer correct responses ($M = 28.50$; $SD = 7.82$) than Sham tDCS ($M = 39.64$; $SD = 11.33$), $F(1,62) = 21.08$, $p < 0.001$, $\eta^2_p = 0.25$ (see Figure 3).

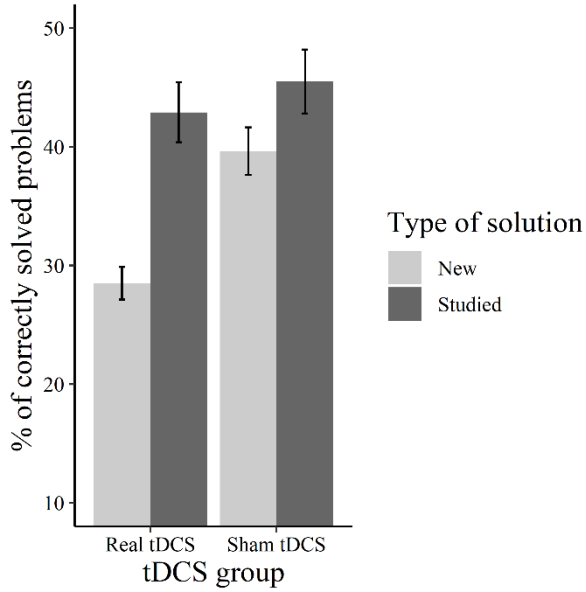

Figure 3. RAT performance in Experiment 1 as a function of stimulation and type of solution. Studied: Problems whose solution was studied in the first phase of the experimental session but was not target nor competitor during retrieval practice. New: Problems whose solution was never presented in the experimental session. Error bars represent standard errors of the mean.

Selective retrieval and retrieval-induced impairment in RAT performance

The overall mean percentage of successful recall during the SR phase was 89.45 (*SD* = 12.01). Performance was not significantly different between the two stimulation groups (M_{Sham} = 89.50, SD_{Sham} = 12.02; M_{Real} = 89.41; SD_{Real} = 12.20; $F(1,62) < 1$, $\eta^2_p < 1$). For the RAT phase, the overall mean percentage of correctly solved problems was 39.94 (*SD* = 11.20), with the difference between real and sham groups only approaching statistical significance (M_{Sham} = 42.55, SD_{Sham} = 10.93; M_{Real} = 37.33; SD_{Real} = 10.92; $F(1,62) = 3.66$, $p = 0.06$, $\eta^2_p = 0.06$).

To test whether tDCS modulated the retrieval-induced impairment in the RAT (which was not expected in Experiment 1), a 2 (tDCS: Real vs. Sham) x 2 (type of solution: Competitors vs. Studied) mixed ANOVA was performed. It should be noted that for this analysis and following the procedure from previous studies on retrieval-induced impairments (e.g., Bajo et al., 2006; Gómez-Ariza et al., 2012; Gómez-Ariza et al., 2017; Valle et al., 2020a; Weller et al., 2013), the studied solutions considered belonged to the high-medium lexical frequency

items. The results revealed a main effect of solution type indicating that competitor items (those that were competitors during the SR phase; M = 33.20; SD = 17.70) were produced less as solutions than studied items (M = 40.50; SD = 17.64), $F(2,62) = 7.86$, $p = 0.007$, $\eta^2_p = 0.11$, (see Figure 4: see also Table 3 in the Appendix for descriptive statistics). However, there was no main effect of tDCS, $F(2,62) < 1$, $\eta^2_p = 0.00$ or interaction, $F(2,62) < 1$, $\eta^2_p = 0.014$. This pattern of results indicates that tDCS over the left ATL did not modulate retrieval-induced impairment.

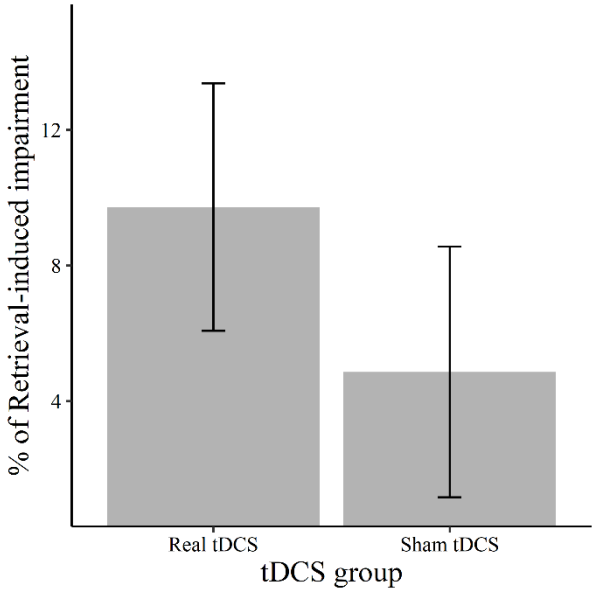

Figure 4. Retrieval-induced impairment (percentage of problems correctly solved with competitors subtracted from the percentage of problems correctly solved with studied only solutions) as a function of stimulation group. Error bars represent standard errors of the mean.

EEG results

Effects of neuromodulation in resting-state EEG

Due to technical failures, data from three participants (two real and one sham) were missing from the pre-task recording and further three from the post-task one (all from the sham group). To determine whether there were group differences in resting-state brain activity, a 2 (tDCS: Real vs. Sham) x 2 (recording time: pre-task vs. post-task) mixed ANOVA on mean power for each frequency band was conducted considering the following clusters from the 40 channels:

anterior-frontal (FP1, FP2), left-frontal (F3, F7, FC3) right-frontal (F4, F8, FC4), left-parietal (P3, P7) right-parietal (P4, P8) left-temporal (FT7, FT9, T7) right-temporal (FT8, FT10, T8) and occipital (O1, OZ, O2) and the whole set of electrodes). No statistically significant effects were found (all *Fs* <1; *ps* > 0.45). Descriptive statistics in each band frequency of the whole set of electrodes are summarized in Table 1.

Table 1. Means (and standard deviations) of power in each band frequency as a function of tDCS and recording time in Experiment 1.

tDCS group	Band frequency	Pre	Post
Sham tDCS	Theta	2.39 (3.68)	2.55 (2.26)
	Alpha	2.61 (3.76)	2.86 (2.26)
	Beta	2.24 (3.34)	2.34 (1.87)
	Gamma	1.83 (3.06)	1.81 (1.58)
Real tDCS	Theta	2.42 (2.14)	2.62 (1.61)
	Alpha	2.68 (2.15)	2.94 (1.58)
	Beta	2.33 (1.85)	2.52 (1.33)
	Gamma	1.95 (1.65)	2.04 (1.16)

Pre and post EEG activity was then correlated separately for each group to examine the consistency of power. For the sham group, the analyses showed positive and reliable associations across all frequency bands. For the real tDCS group, however, there were statistically significant correlations for alpha, beta and gamma, but not theta [see Table 2; see and also Figure 1(a) in the Appendix], suggesting that real tDCS induced changes in theta band power that were not present in the sham group.

Table 2. Pre-post correlations in power as a function of tDCS and band frequency in Experiment 1.

Band frequency	**Sham tDCS**	**Real tDCS**
	Spearman 's rho (ρ)	Spearman 's rho (ρ)
Theta	0.59**	0.25
Alpha	0.53**	0.46**
Beta	0.55**	0.51**
Gamma	0.45*	0.39*

*p < 0.05, ** p < 0.01

Differential EEG resting-state activity and performance in new problems

To determine whether performance on problems with new solutions, the problems on which tDCS was shown to have a behavioral effect, was associated with resting-state EEG activity, post-pre differences in power for each frequency band were correlated with correct responses in each tDCS group. Spearman's correlation analyses revealed a different pattern of associations in each group. In the sham group, the number of correct responses was positively associated with the change in theta band (r = 0.42; p < 0.05; see Figure 5). That is, the greater the change in resting power from pre to post, the higher the rate of correct responses to problems. In the real stimulation group, however, no reliable correlation emerged (ρs < 0.1, ps > 0.43).

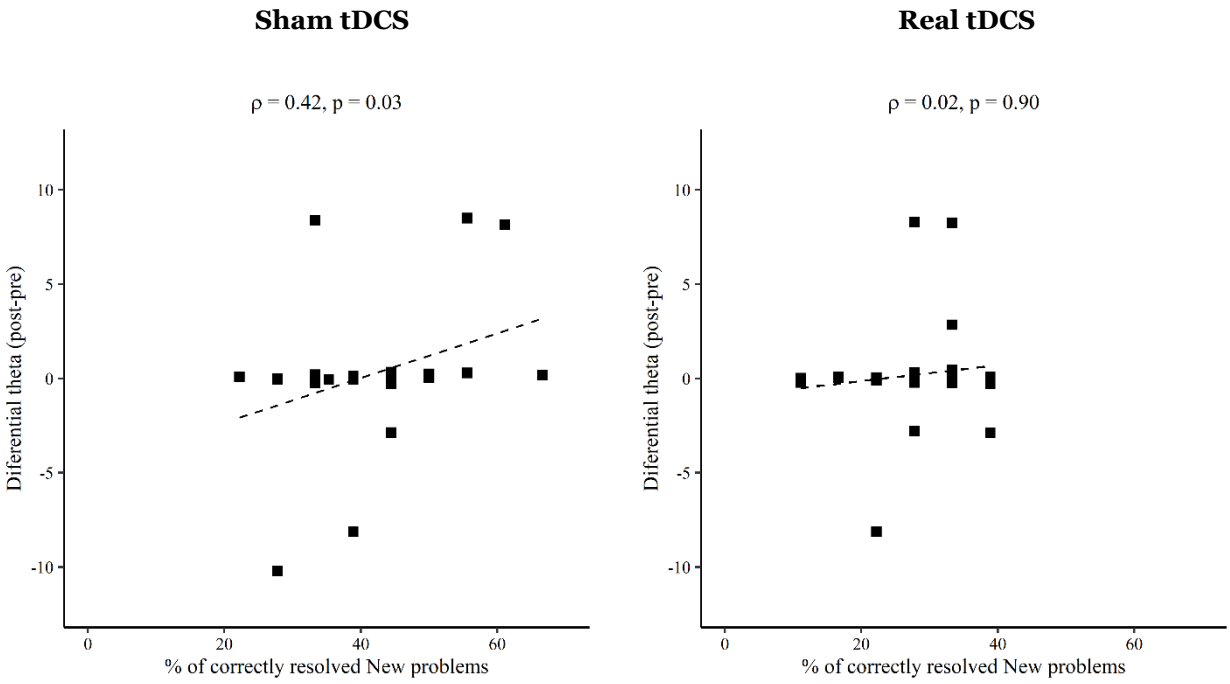

Figure 5. Scatterplots of the relationship between differential theta and creative performance (correct responses to problems with new solution) in both tDCS groups in experiment 1. Spearman's coefficients and associated p-values are also shown.

Interim discussion

Experiment 1 aimed to test the implication of the left ATL in solving RAT problems using anodal tDCS, which has previously been shown to be effective in disrupting performance on cognitive tasks that also require the contribution of the ATL as a semantic integration hub (Abraham et al., 2018; Díez et al., 2017; Ruggiero et al., 2018). Consistent with such an implication, participants in the real tDCS group exhibited a reduced ability to accurately solve RAT problems compared to their sham counterparts. Importantly, this behavioral effect was uniquely observed in the (new) problems whose solutions were words that were never presented in the experimental session, mimicking the standard problems usually included in the RAT. It should be noted that these solutions were unaffected by prior exposure during the study phase or by inhibitory control during selective retrieval, and are therefore the most appropriate index to assess

the potential effect of tDCS on the left ATL and its contribution to creative problem-solving.

Importantly, no other performance differences between the stimulation groups emerged. Selective retrieval success was comparable in both groups. Similarly, performance in the remaining problem conditions (to be solved with competitors and studied items) was comparable in both tDCS groups, replicating previous findings in the literature on selective retrieval and its consequences for decision making and problem solving (Gómez-Ariza et al., 2017; Iglesias-Parro & Gómez-Ariza, 2006; Lechuga et al., 2012; Valle et al., 2019, 2020b). This strongly supports the notion that the left ATL is not involved in the downregulation of competing responses. Previous exposure to some of the (studied) items prevented anodal tDCS from interfering with their generation as solutions. Thus, it is possible that increased activation and accessibility of these items minimized their dependence on brain regions (such as ATL) involved in complex semantic integration. If so, these solutions would be less susceptible to the disruption of neural activity in the left ATL by tDCS.

Of relevance, tDCS did influence the pre-post correlation in theta power. Thus, while the sham group showed reliable correlations in power across frequency bands between the two sessions of RS-EEG recording, this was not the case for theta band after real tDCS. Interestingly, it was only in the sham group that differential theta power (post-pre differential activity) was associated with improved performance on the new RAT problems, suggesting that the behavioral effect of anodal tDCS might be mediated by changes in the theta band.

Experiment 2

This experiment involved the same procedure as Experiment 1 except for the tDCS protocol. The main goal was to examine whether inhibitory control (which has been associated with activity in the right DLPFC) is involved in modulating the accessibility of relevant memory representations for the creativity task. In this case, the hypothesis was based on findings from previous tDCS studies using the selective retrieval paradigm (Stramaccia et al., 2017; Valle et al.,

2020a). These studies showed that cathodal tDCS over the right DLPFC during the SR phase disrupts the downregulation of competing memories, making them as accessible as baseline memories in subsequent memory or problem-solving tests. Thus, compared to the sham condition, cathodal tDCS during selective retrieval was expected to disrupt inhibitory control over competitors' memories (those of items that were not to be retrieved but were related to targets during the SR phase) (Penolazzi et al., 2014; Valle et al., 2020a), as this process is thought to occur during selective retrieval (Anderson & Hulbert, 2021). Therefore, and closely following the tDCS protocol used by Valle et al. (2020a), it was expected that real tDCS, but not sham tDCS, would prevent the retrieval-induced impairment from manifesting in the RAT. In other words, it was predicted that cathodal tDCS would cause participants to produce competitors and studied solutions similarly. In contrast, tDCS was expected to have null or a smaller effect over new problems because the RAT problems employed in the present studies were not created to be solved under conditions of high competition. In addition, previous studies have shown changes in RAT performance (i.e., improvements) after tDCS of the left DLPFC but not of the right DLPFC (Cerruti & Schlaug 2009; Zmigrod et al., 2015).

Method

Participants

The required sample size for this study was calculated using G*Power 3.1 (Faul et al., 2009) and assuming a medium effect size (partial squared eta = 0.06[4]) of a 2 x 2 interaction in a mixed ANOVA (tDCS group x type of items on which retrieval-induced impairment was calculated). A total sample of 34 participants was sufficient to detect a statistically significant interaction (power = 0.80%; alpha = 0.05). The final collected sample consisted of 40 participants

[4] In a related study in which cathodal tDCS was shown to eliminate retrieval-induced impairment in analogy problem solving (Valle et al., 2020a), the effect size of the interaction was large (partial squared eta = 0.16). For the present study, however, a more conservative approach was preferred, and we predicted only a medium effect size even though it would demand a larger sample size.

who met the same requirements as in Experiment 1 and were randomly assigned to the stimulation groups. As in the previous experiment, participants were completely blind to their assignment and to the hypothesis of the study and agreed to participate in exchange of course credits or economical compensation (15€).

Materials

The same as in Experiment 1.

Resting-State EEG acquisition and processing

The EEG recording was similar to Experiment 1 except that a 32-scalp electrodes cap (Quick-Cap Neo net, Neuroscan, Inc.) was used. The electrical signal was amplified by a Grael system (Compumedics Ltd., VIC, Australia). The sampling rate was set to 2050 Hz with an online filter (high pass: 0.5 Hz; low pass: 70 Hz). The raw signal was downsampled to 1000 Hz, and the same protocol as in Experiment 1 was followed to process and analyze the data.

Transcranial direct current stimulation

The stimulation protocol was identical to that used in Experiment 1, except for the timing of current application (the SR phase rather than the encoding phase), the site of stimulation and the polarity of the electrode of interest. As in Valle et al. (2020a), the cathodal electrode was placed over the right DLPFC (BA 46/9) centered on F4 according to the international 10-10 system for EEG electrode placement. The reference electrode was placed on the contralateral deltoid muscle. Figure 6 depicts the electrode montage and simulated current flow using SimNIBS (4.0.1) software (Thielscher et al., 2015).

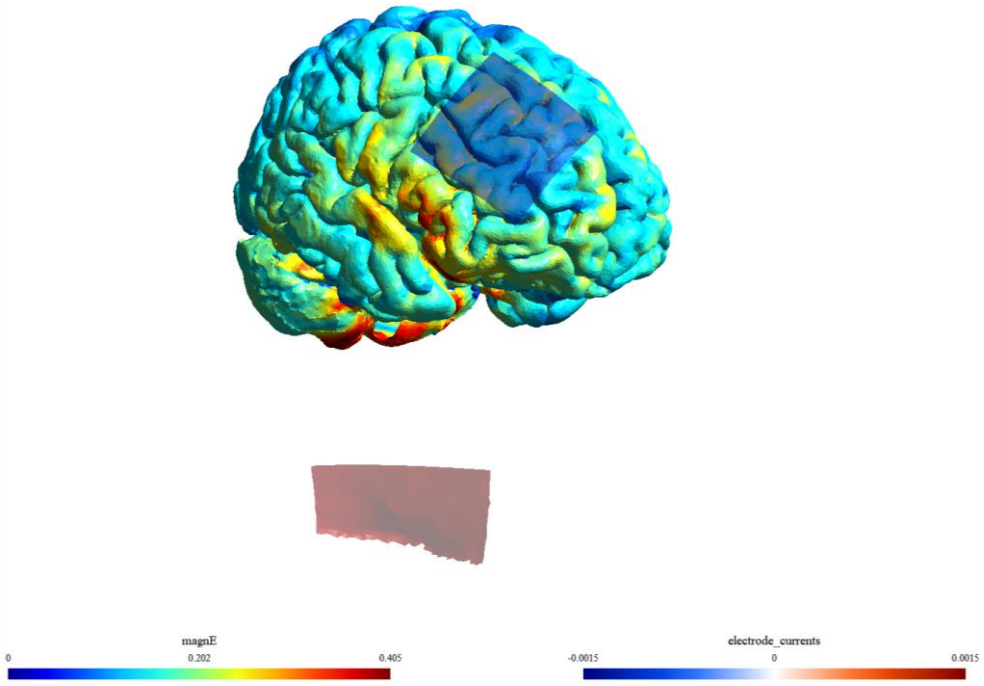

Figure 6. tDCS electrode montage and simulation of the current flow performed using SimNIBS 4.0.1 (Thielscher et al., 2015). The 5x5 cm anode electrode was positioned over the right dorsolateral prefrontal cortex (F4). The 7x5 cm cathode electrode was localized over the contralateral shoulder. The strength of the induced electrical field (magnE) is depicted in V/m and the current generated by each electrode in presented in mA.

Procedure

The experimental procedure was the same as in the previous experiment and also lasted approximately two hours and a half (see Figure 2, Experiment 2, for a schematic representation of the procedure). Since the goal of tDCS was to disrupt inhibitory control-related activity in the right prefrontal cortex, current delivery (either sham or real) was started during the first distracting task, after the study phase that lasted eight minutes, continued throughout the SR phase (seven minutes) and was finished during the second distracting task. As in Valle et al. (2020a), the RAT problems whose solution was a practiced word were not presented in order to minimize participants' awareness of the associations between experimental tasks.

Results

The analytical approach to the data of the present experiment was identical to that of Experiment 1. The adverse effects questionnaire indicated that participants did not experience any major discomfort related to the stimulation, nor were they able to guess their stimulation condition (see Table 4 in the Appendix).

Behavioral results

Effect of neuromodulation on creative responses and type of solution

To examine whether tDCS modulated creative performance, a 2 (tDCS: Real vs. Sham) x 2 (type of solution: Studied vs. New) mixed ANOVA was performed on correct responses. The results revealed a main effect of type of item, so that studied items (M = 45.28; SD = 14.54) were produced as solutions more often than new items (M = 33.06; SD = 12.32; See Figure 7). Neither the main effect of tDCS $F(1,38) < 1$, $p = 0.6$, $\eta^2_p < 1$) nor the interaction reached statistical significance $F(1,38) = 3.03$, $p = 0.09$ $\eta^2_p = 0.07$).

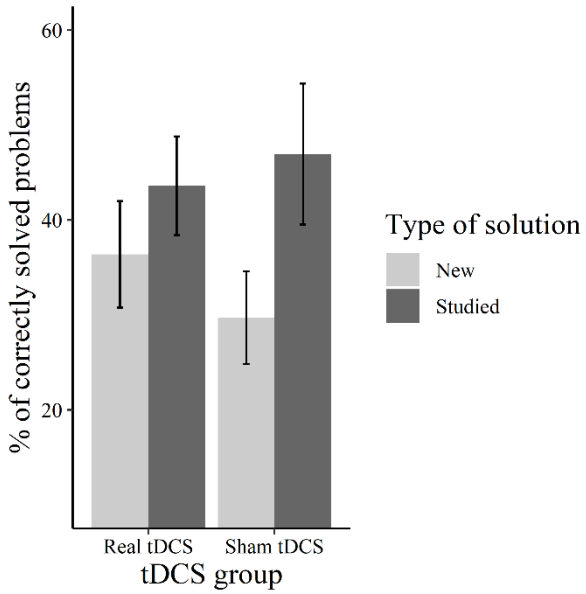

Figure 7. RAT performance in Experiment 2 as a function of stimulation and type of solution. Studied: Problems whose solution was studied in the first phase of the experimental session but was not target nor competitor during retrieval practice. New: Problems whose solution was never presented in the experimental session. Error bars represent standard errors of the mean.

Selective retrieval and retrieval-induced impairment in RAT performance

A one-way ANOVA indicated that performance during selective retrieval did not differ as a function of stimulation (M_{Sham} = 55.14, SD_{Sham} = 14.92; M_{Real} = 53.51; SD_{Real} = 13.46; $F(1,38) < 1$, $\eta^2_p < 1$).

A 2 (tDCS: Real vs. Sham) x 2 (Type of solution: Studied vs. Competitor) mixed ANOVA on correct responses was conducted to examine the effect of tDCS over the right DLPFC on retrieval-induced impairment in the RAT (see Table 5 in the Appendix for descriptive statistics). A main effect of type of solution was found, $F(2,38) = 4.20$, $p = 0.04$, $\eta^2_p = 0.09$, showing that participants correctly solved more problems whose solution was a previously studied word (M = 44.17; SD = 18.40) compared to problems whose solution was a competitor during selective retrieval (M = 34.44; SD = 23.84). The main effect of tDCS was not significant, $F(1, 38) = 1.91$; $p > 0.1$; $\eta^2_p = 0.05$). However, there was a reliable interaction between tDCS and type of solution, $F(2,38) = 8.90$, $p < 0.01$, $\eta^2_p = 0.19$. Follow-up analyses revealed that participants in the sham group exhibited a reliable retrieval-induced impairment such that they solved fewer problems

with competitors (M = 24.44; SD = 18.94) than with studied solutions (M = 48.33; SD = 17.76); $t(19) = 4.66$; $p < 0.001$; $d = 1.04$). On the contrary, participants in the real tDCS group produced similarly solutions that were competitors (M = 44.44; SD = 24.45) and solutions that were not (M = 40.00; SD = 18.52; $t(19) = -0.56$; $p > 0.5$, $d = -0.12$). Figure 8 shows the mean retrieval-induced impairment in each stimulation group.

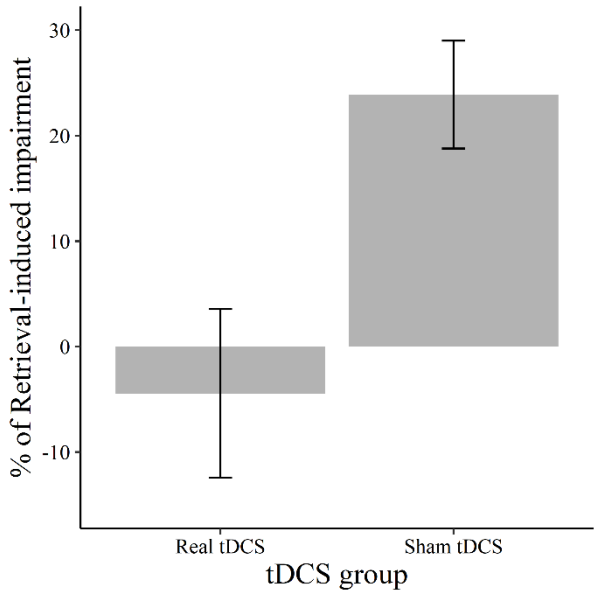

Figure 8. Retrieval-induced impairment (percentage of problems correctly solved with competitors subtracted from the percentage of problems correctly solved with studied only solutions) as a function of stimulation group. Error bars represent standard errors of the mean.

EEG results

Effects of neuromodulation on resting-state EEG

The 2 (tDCS: Real vs. Sham) 2 x (recording time: pre-task vs. post-task) mixed ANOVAs on power for each frequency band indicated that there were no statistically significant differences in any frequency band (all $Fs < 1$; $p > 0.6$). Descriptive statistics are summarized in Table 3. Correlational analyses were performed between pre and post EEG activity in each group. While the sham group showed a positive association for each band frequency between pre and post measurements, the real tDCS group showed significant correlations for theta and beta but not for alpha and gamma [see Table 4, and Figure 2(b) and Figure

2(c) in the Appendix]. This suggests that cathodal tDCS over the right lateral prefrontal cortex specifically induced changes in alpha and gamma power.

Table 3. Means (and standard deviations) of power in each band frequency as a function of tDCS and recording moment in Experiment 2.

tDCS group	Band frequency	Pre	Post
Sham tDCS	Theta	1.98 (2.62)	1.62 (3.04)
	Alpha	2.25 (2.60)	1.94 (3.00
	Beta	1.87 (2.18)	1.53 (2.50)
	Gamma	1.54 (1.97)	1.21 (2.24)
Real tDCS	Theta	1.98 (2.62)	1.92 (2.67)
	Alpha	2.33 (2.60)	2.43 (2.73)
	Beta	1.82 (2.11)	1.81 (2.15)
	Gamma	1.55 (1.90)	1.46 (1.93)

Table 4. Correlations between pre-task and post-task power as a function of group and band frequency in Experiment 2.

Band frequency	Sham tDCS	Real tDCS
	Spearman 's rho (ρ)	Spearman 's rho (ρ)
Theta	0.47*	0.65**
Alpha	0.53*	0.18
Beta	0.59**	0.55**
Gamma	0.51*	0.31

*p < 0.05, ** p < 0.01

Differential EEG resting-state activity and performance in creative problems

It was also examined whether resting-state EEG activity was associated with performance during problem solving. Specifically, the focus was on the behavioral index that was affected by tDCS (retrieval-induced impairment). Thus, the post-pre difference in power for each frequency band across participants was correlated with their retrieval-induced impairment. The sham group showed a correlation between change in alpha and retrieval-induced impairment that only approached statistical significance (ρ = -0.42, p = 0.06), such that the smaller the change in alpha from pre to post, the greater the impairment participants showed in producing competitors as solutions. Analyses in the real tDCS group revealed

no associations between differential power in any frequency band and the magnitude of retrieval-induced impairment (all *ps* > 0.5; see Table 5).

Table 5. Correlation coefficients (Spearman's rho) between differential power (post-pre) and retrieval-induced impairment as a function of frequency band and group in Experiment 2.

Band frequencies	**Sham tDCS**	**Real tDCS**
Theta	-0.23	-0.02
Alpha	-0.42*	0.10
Beta	-0.38	0.12
Gamma	-0.25	0.16

*p = 0.06

Interim discussion

The goal of the present experiment was to determine whether disruption of inhibitory control (during selective retrieval) by cathodal tDCS over the right prefrontal cortex alters performance in the RAT. Specifically, it was expected that real tDCS would increase correct responses to problems that could be solved with solutions that were competitors during the SR stage, since the disruption of inhibitory control should make competitors comparable to only-studied items in accessibility and production as solutions (thus diminishing the otherwise expected retrieval-induced impairment in the RAT). The results clearly supported this expectation. While a reliable retrieval-induced impairment was present in the sham group, no such effect was evident in the real tDCS group. No other tDCS-related differences in performance were observed (importantly, problems with new and studied solutions were solved similarly in both stimulation groups).

Resting-state EEG analyses also revealed a tDCS-induced change in power in two frequency bands. All pre-post correlations were statistically significant in the sham group, suggesting stability across participants between the two recording sessions. In addition, changes in alpha band marginally predicted the relative production of competitors as solutions. In the real tDCS group, however,

the consistency of alpha and gamma power was altered and no association between differential power and retrieval-induced impairment was observed.

General discussion

Although previous neuromodulation studies have already investigated the implication of temporal and prefrontal regions in creative thinking, the results regarding the left ATL and the right DLPFC remained inconclusive (Koizumi et al., 2020; for a review, see Weinberger et al., 2017). Hence, the main goal of the present study was to test the hypotheses that 1) the left ATL plays a role in the production of creative responses requiring semantic integration (Experiment 1), and 2) the right lateral prefrontal cortex is involved in the inhibition of competing information, which might subsequently contribute to the production of creative responses (Experiment 2). Both studies worked as reciprocal control experiments to examine if tDCS over each region of interest differentially modulates different neural networks and cognitive processes associated with creative thinking. In the present experiments, participants performed an adapted selective retrieval task followed by a RAT containing problems that could be solved with studied (some of which also became competitors during selective retrieval) and new words. This is a procedure that allows the dissociation between semantic processing (from hits to RAT problems whose solutions are new words) and memory inhibition (from hits to RAT problems whose solutions were competitors during selective retrieval). Although solving RAT problems involves both semantic processing and inhibition (e.g., Lezama et al., 2023), in the SR-RAT procedure semantic processing is better captured by solutions to new problems since they are not primed by episodic processing during study and/or selective retrieval. In contrast, the production of solutions that were competitors during selective retrieval is a good marker of memory inhibition, since their reduced presence in responses to RAT problems would index the consequences of inhibitory control.

Thus, in Experiment 1, it was expected anodal tDCS over the left ATL to hamper RAT problems solving, particularly for problems whose solutions were not previously presented in the context of the experiment. Additionally, it was

hypothesized that the impairment typically observed after selective retrieval (Gómez-Ariza et al., 2017; Lezama et al., 2023) would not be affected by stimulation of the left ATL. In Experiment 2 the hypothesis was that cathodal tDCS of the right DLPFC applied during selective retrieval would interfere with the inhibitory mechanism acting on competing items, preventing them from being downregulated but consequently making them more accessible as solutions during the RAT phase. Thus, less retrieval-induced impairment was expected compared to the sham condition. Finally, real tDCS was expected to modulate resting-state EEG in both experiments.

The pattern of results from Experiment 1 indicated that real tDCS led participants to produce fewer responses to new RAT problems than sham tDCS. Solving new RAT problems requires access to information that is semantically related to the cue words in the problem as well as the combination of this information to generate candidate solution ideas (Smith et al., 2013). Hence, the main finding of Experiment 1 suggests that the left ATL, as an integration hub within the semantic memory network (Bonner & Price, 2013; Lambon Ralph, 2014), plays a relevant role in the generation of possible solutions to RAT problems which was disrupted by anodal tDCS. This finding is consistent with results from neuroimaging studies that have identified enhanced activation of the left ATL linked to semantic processing during creative tasks such as the AUT and RAT (Abraham et al., 2012, Abraham et al., 2018; Tik et al., 2018). Interestingly, the finding also fits with theoretical frameworks that point to the left ATL as a hub specialized in binding information from different brain areas to form coherent conceptual representations (Lambon Ralph, 2014). The left ATL seems to play a particularly significant role in the processing of verbal information (Jefferies, 2013; Díez et al., 2017) and in situations where complex conceptual constructions are required (Baron & Osherson, 2011).

However, this main finding differs from the results of previous studies in which tDCS was delivered over the ATL. In two studies, Chi and Snyder (2011, 2012) found that bilateral (right anodal) tDCS increased participants' creative performance that relied heavily on visuospatial information (matchsticks and 9-dot problems). A similar bicephalic montage was used in the study by Aihara et

al. (2017), wherein matchsticks and RAT problems were used to examine the effect of tDCS on creativity. No effect, however, was observed, in contrast to the present finding. These differences are likely due to methodological factors. First, there is some evidence that the right ATL is more involved in processing of visuospatial information than the left ATL (e.g., Alonso et al., 2021; Mion et al., 2010). Hence, variations in the tasks (visual versus verbal) used to capture the effect of tDCS on creativity might explain the differences. Second, the electrode montage used here was aimed to specifically modulate activity in the left ATL, whereas in the aforementioned studies both ATLs were the target of stimulation. This divergence suggests that the impact of anodal tDCS on RAT problem solving arises specifically when the left ATL is the target of stimulation. In support of this idea, Ruggiero et al. (2018) observed that anodal stimulation of the left ATL coupled with cathodal tDCS of the right ATL reduced RTs relative to sham, even though there was no change in accuracy. Hence, the present study seems to indicate that tDCS montages targeting the left ATL may be able to change performance in the RAT, particularly with anodal stimulation. Further research should be directed to replicate the present finding and to establish the role of right (or bilateral) ATL stimulation and its relation to the type of information required by the creativity task.

In Experiment 2, cathodal stimulation of the right lateral prefrontal cortex resulted in participants having comparable access to both competitors and studied items during the RAT phase, in contrast to the sham group which exhibited the expected impairment following selective retrieval (for related results see Gómez-Ariza et al., 2017; Iglesias-Parro & Gómez-Ariza, 2006; Lezama et al., 2023; Valle et al., 2020a). This finding supports the notion that altering neural activity in the right prefrontal cortex during selective retrieval disrupts inhibitory control over competitors, making them as accessible as non-competitors when it comes to generating solutions. Accessibility to relevant information becomes critical throughout the problem-solving process (e.g., Gómez-Ariza et al., 2017; Gupta et al., 2012; Luft et al., 2018). The present findings contribute to the understanding of how prior inhibition of relevant information may modulate RAT performance (see also Lezama et al., 2023).

Furthermore, this tDCS-related finding offers converging evidence supporting the causal role of the right lateral prefrontal cortex in selective retrieval as a source of top-down control that influences memory accessibility and problem solving, including convergent thinking (Penolazzi et al., 2014; Stramaccia et al., 2017; Valle et al., 2020a).

Anodal tDCS over the left ATL was also linked to changes in the pattern of pre-post consistency in theta power observed in the sham group. This suggests that real stimulation specifically modulated theta rhythms. In addition, better solution of new RAT problems was associated with larger post-pre differences in theta power in the sham but not the real tDCS group, suggesting that tDCS could have changed performance by modulating the pattern of activity in the theta band. Previous studies have related theta oscillations to higher order cognitive functions such as episodic and working memory (WM) processes (Klimesch et al., 2007; Sammer et al., 2007; for a review, see Sauseng et al., 2012) and semantic retrieval (Marko et al., 2019). Moreover, in a transcranial alternating current stimulation (tACS) experiment, Marko et al. (2019) induced theta oscillations over the left prefrontal and posterior perisylvian cortex to be either in-phase or anti-phase while participants performed a series of semantic retrieval tasks. Their results indicated that variations in theta-band synchrony modulated semantic retrieval performance (in-phase tACS negatively affected controlled semantic retrieval, while anti-phase tACS improved controlled retrieval but hindered performance on automatic semantic tasks). These results were taken as evidence for the role of theta oscillations in binding semantically related representations, and might support the interpretation that the changes observed here in RS theta after tDCS might be reflecting disturbances in the integration process during RAT problems solving.

Resting-state EEG in Experiment 2 also revealed changes in the pattern of power consistency as a function of tDCS condition. Specifically, prefrontal neuromodulation appeared to eliminate the pre-post stability in the alpha and gamma bands that prevailed in the sham group (as a matter of fact, all frequency bands exhibited consistency across the two RS recordings in this group). Considering the well-established association of the gamma band (along with

theta) with episodic encoding and retrieval processes (e.g., Nyhus & Curran, 2010; Griffiths et al., 2019), variations in gamma power after cathodal tDCS of the right DLPFC may arise from the disruption of retrieval-related brain activity. Furthermore, alpha band has been associated with controlled access to information in long-term memory and inhibition of distracting information (Klimesch, 2012). Hence, it is entirely possible that the tDCS-induced changes in cortical excitability are responsible for the loss of pre-post consistency in alpha and gamma and that this can mediate the reduction in inhibitory control during selective retrieval. While these are only speculations about the cognitive correlates of these specific changes in brain rhythms in Experiments 1 and 2, they provide complementary evidence (along with performance changes) for specific effects of stimulation over distinct cortical regions of interest for creative thinking.

It is worth mentioning that stimulation of the left ATL did not lead to changes in retrieval-induced impairment (reduced production of competitors as solutions). This result a) replicates previous findings on how inhibitory control during selective retrieval may impact on subsequent problem-solving tasks even unconsciously (creativity: Gómez-Ariza et la., 2017; decision making: Iglesias-Parro & Gómez-Ariza, 2006; Lechuga et al., 2012; analogical reasoning: Valle et al., 2019, 2020a, 2020b) and, more relevant here, b) is consistent with the idea that the left ATL (and its interconnected nodes within the semantic network) do not play a relevant role in exerting top-down control over competing information during episodic retrieval. Thus, only those problems whose solution was never presented (new) were sensitive to the effect of ATL stimulation, so that prior exposure to items (in the case of studied problems) seemed to prevent anodal tDCS from hindering their generation as solutions. While studied words were provided as responses more frequently than unstudied (new) words (this is an expected priming effect; see Valle et al., 2019 for a similar finding in analogical reasoning), they were not affected by anodal tDCS which, however, uniquely disrupted the process of generating unprimed solutions. It is important to note that the problems to be solved with new words in the present experiments essentially correspond to the standard condition in other RAT studies, in which

participants solve problems with unprimed solutions (Luft et al., 2018; Zmigrod et al., 2015), and in which neuroimaging and neuromodulation studies have suggested the implication of anterior regions of the left temporal lobe in the generation of creative ideas (e.g., Abraham et al., 2018; Aihara et al., 2017; Chi & Snyder, 2011, 2012; Tik et al., 2018). Hence, it is plausible that prior exposure to solutions, which would increase their activation, may reduce the need to rely on brain regions (such as the ATL) that contribute to semantic integration, which would result in these solutions being less affected by the disruption of neural activity in such regions.

Unlike Experiment 1, participants in in Experiment 2 exhibited a comparable rate of correct responses to new and studied problems regardless of stimulation condition. This shows that right DLPFC stimulation uniquely altered inhibitory control during selective retrieval, which impacted RAT solutions that were competitors. Although previous research has shown that enhanced inhibitory control during retrieval predicts RAT performance (Lezama et al., 2023; Storm et al., 2011), and that inhibition itself may contribute to creative thinking (Palmiero et al., 2022), Experiment 2 failed to provide evidence that disrupting neural activity in the right lateral prefrontal cortex changes RAT performance outside of the specific problems with former competitors as solutions. However, this lack of effect of prefrontal neuromodulation on the production of solutions that had not been previously competitors is not unexpected since previous studies with different tDCS protocols to the one used here also failed to observe general changes in RAT performance (Li et al., 2022; Xiang et al., 2021). It is important to note that none of these previous studies directly assessed or manipulated the strength or presence of competing solutions during problem-solving tasks. Hence, it is possible that the neuromodulation of inhibitory control did not lead to changes in creative performance because the employed creativity tasks did not sufficiently demand such a type of executive control. Additionally, it would be beneficial to examine if the monopolar montage used in Experiment 2 (cathode over the right DLPFC) is effective in modulating RAT performance when tDCS is delivered online (while participants are engaged in problem solving) rather than offline (as was the case in Experiment 2).

To conclude, an important contribution of the present experiments is that it provides causal evidence of a) the involvement of the left ATL (presumably via integration/combination of ideas) in solving RAT problems and of b) the role of the right lateral prefrontal cortex in downregulating relevant information that could contribute to the generation of creative solutions. It is noteworthy that the present findings support a functional dissociation between the left ATL (as part of a semantic brain network) and the right lateral prefrontal cortex (as part of a cognitive control network). The results from Experiment 1 support the relevance of temporal areas to creativity while opening a door to questioning the possible functional dissociation (or collaboration) between the left and the right ATL, which might also depend on the nature of the creativity task. Along these lines, Salvi et al. (2020) applied HD-tDCS over either the right temporal region (BA22; which is not precisely the same contra-hemispheric region targeted here) or the frontopolar region to compare the effect of this stimulation to that of sham tDCS on performance in the RAT. Their results revealed that, in comparison to sham and left frontopolar stimulation, right temporal stimulation increased hits as well as the use of insight as a resolution strategy. Although Salvi et al. (2020) used a different neuromodulation technique in a more posterior region, which complicates the comparisons between their results and those from our Experiment 1, it suggests an implication of the right ATL during RAT solution. Finally, Experiment 2 further demonstrated how changes in accessibility of relevant information in memory can subsequently affect the ability to solve creativity problems, as well as the involvement of right prefrontal areas in regulating such accessibility.

While offering valuable insights into the involvement of the left ATL and the right prefrontal cortex in processes that contribute to creative thinking, the present study is not without limitations. Firstly, creativity was only assessed with the RAT. Consequently, it would be necessary to test the generalizability of the present findings in creativity tasks other than the RAT, provided that they require semantic and inhibitory control processes (e.g., story completion task, Lam & Comay, 2020). Second, a dual-electrode (conventional) tDCS montage was used in the present experiments. Even when an extracephalic reference electrode was

utilized to minimize its effects on the brain and an active electrode of relatively small size was employed, HD-tDCS could be more suitable for achieving higher spatial precision. Additionally, and following the procedure of previous tDCS studies in our laboratory, both experiments employed a single-blind stimulation protocol. Even when a counterbalance procedure was employed, which precluded the experimenter from being aware of the specific condition to which each problem belonged, a double-blind protocol would have been the preferable option.

Future studies on neuromodulation and creative thinking should include simultaneous recording of electrophysiological brain activity (i.e., EEG/magnetoencephalography) to more precisely determine the neural changes that underlie RAT solution. Connectivity analyses within and between the different brain networks involved in creative thinking would assist in elucidating of the neurocognitive processes underlying the generation of innovative ideas.

Author contribution

RL: Conceptualization, methodology, data curation, formal analyses, writing – original draft.

CJGA: Conceptualization, methodology, supervision, funding acquisition, writing - review & editing.

MTB: Conceptualization, methodology, supervision, funding acquisition, writing - review & editing.

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Data availability statement

The data that support the findings of both experiments are openly available in OSF at https://osf.io/zyxw2/?view_only=9c5b67b817d14fdbab6d0a592c381812

Supplementary materials

Supplementary materials (Appendix) associated with this research can be found at https://osf.io/zyxw2/?view_only=9c5b67b817d14fdbab6d0a592c381812

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Appendix

Table 1. Mean (and standard deviations) of the responses to the questionnaire on tDCS adverse effects in the two stimulation groups in Experiment 1. The lowest row reports the proportion of correct guessing. Participants rated the side-effects on a scale ranging from 1 to 4 (1: absent; 2: mild; 3: moderate; 4: severe).

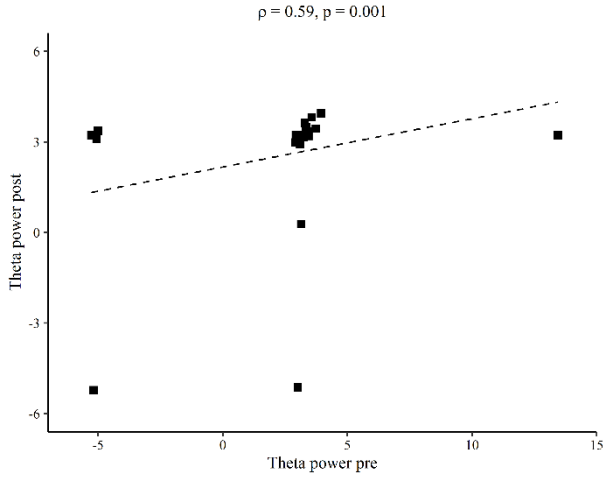
Side effect	**Real tDCS**	**Sham tDCS**	***p***
Headache	0.35 (0.55)	0.16 (0.37)	0.11
Neckache	0.25 (0.44)	0.15 (0.37)	0.36
Scalp pain	0.06 (0.25)	0.18 (0.40)	0.13
Tingling	1.06 (0.80)	0.62 (0.71)	0.02
Itching	1.19 (0.82)	0.75 (0.80)	0.03
Skin redness	0.06 (0.35)	0 (0)	-
Burning sensation	0.63 (0.87)	0.12 (0.42)	0.005
Trouble concentrating	0.75 (0.67)	0.66 (0.79)	0.61
Drowsiness	0.34 (0.55)	0.47 (0.62)	0.40
Acute mood change	0 (0)	0 (0)	-
Stimulation group guessing	0.69	0.50	0.13

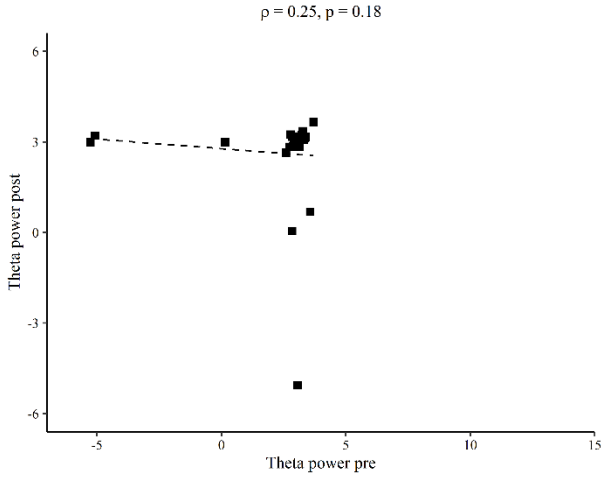
Table 2. Mean percentage (and standard deviation) of hits in each RAT condition for both tDCS groups in Experiment 1.

tDCS groups	**Conditions**	**% of hits**
Sham tDCS	Competitors	34.34 (17.50)
	New	39.64 (11.33)
	Studied	41.67 (17.17)
Real tDCS	Competitors	31.95 (18.01)
	New	28.50 (7.82)
	Studied	39.24 (17.48)

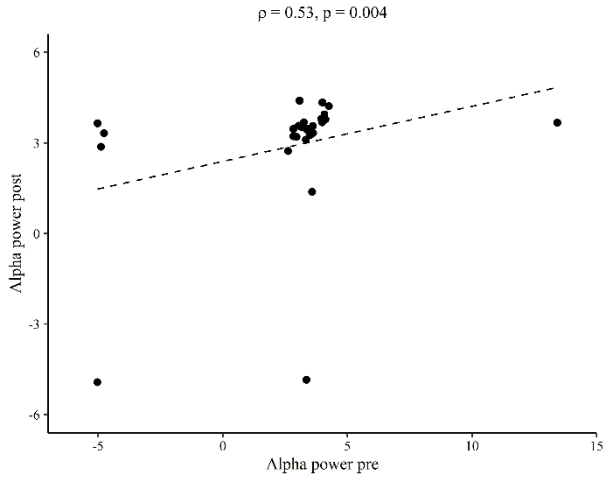
Sham tDCS group	Real tDCS group

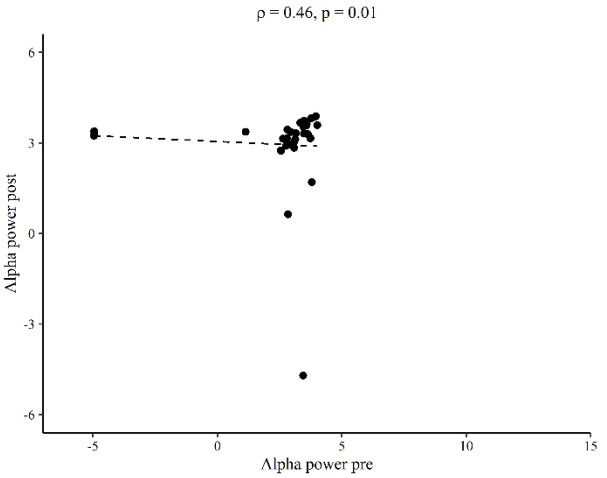
a)



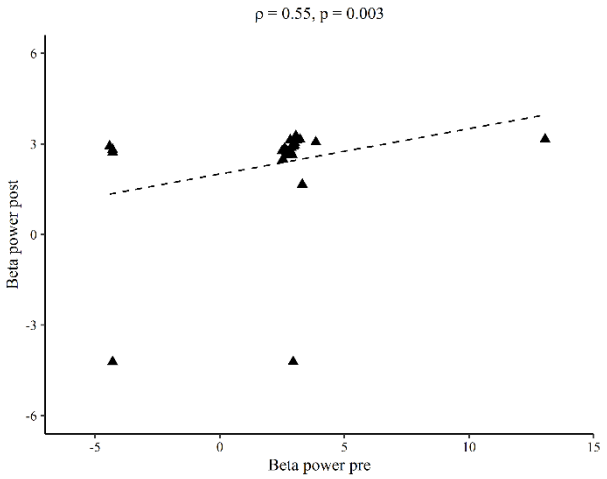


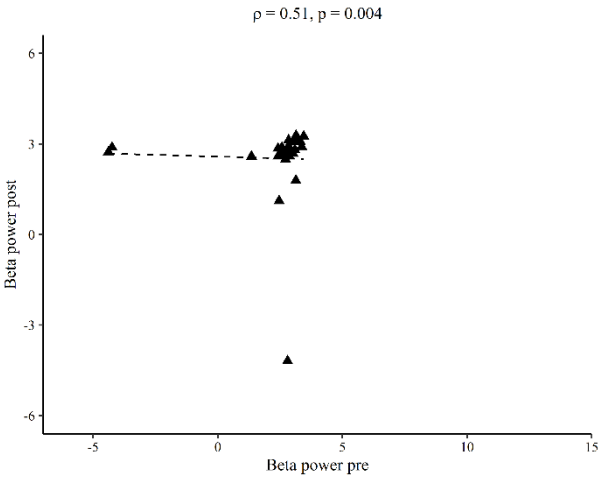
b)





c)





d)

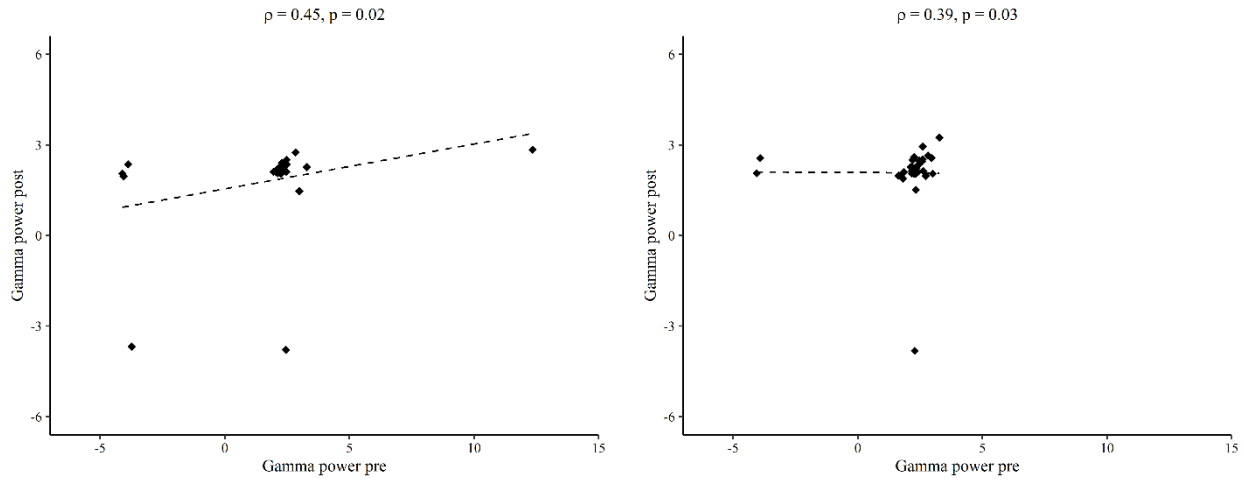


Figure 1. Dispersion graphics of the correlation between power in each band frequency (pre and post measure) in each tDCS group in Experiment 1.

Table 3. Descriptive statistics (mean and standard deviations) of the responses to the questionnaire on tDCS adverse effects in Experiment 2. The lowest row reports the proportion of correct guessing. Participants rated the side-effects on a scale ranging from 1 to 4 (1: absent; 2: mild; 3: moderate; 4: severe).

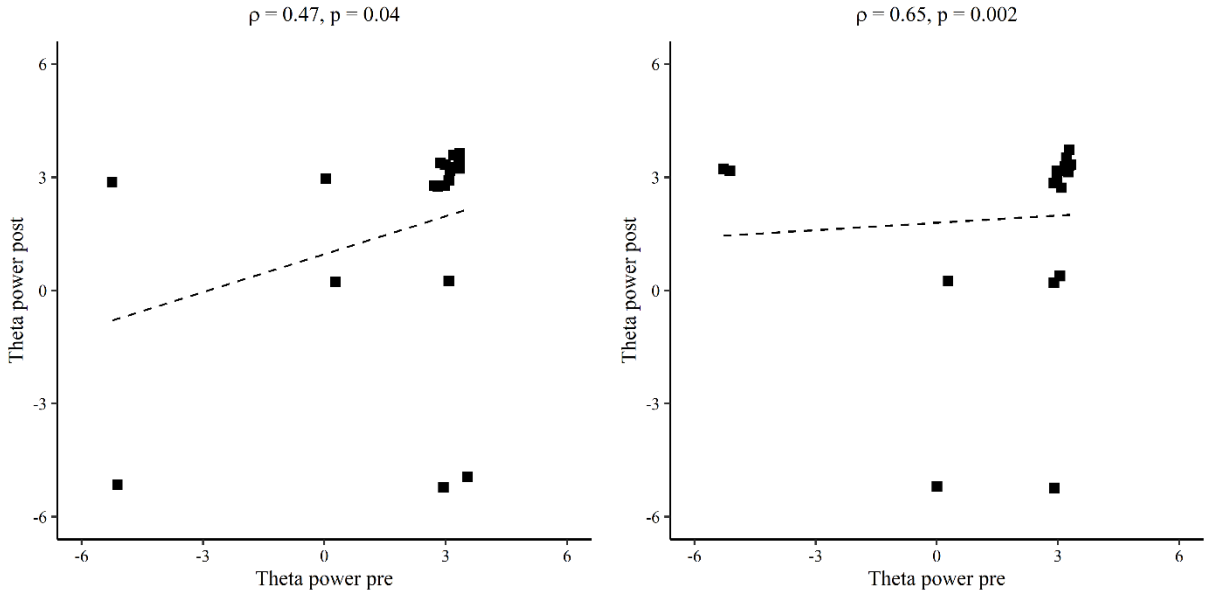
Side effect	Real tDCS	Sham tDCS	*p*
Headache	0.10 (0.30)	0.25 (0.44)	0.22
Neckache	0.10 (0.30)	0.25 (0.55)	0.29
Scalp pain	0.05 (0.22)	0.10 (0.31)	0.56
Tingling	0.25 (0.44)	0.20 (0.41)	0.71
Itching	0.45 (0.6)	0.20 (0.41)	0.13
Skin redness	0.15 (0.36)	0.10 (0.31)	0.64
Burning sensation	0.30 (0.47)	0.15 (0.37)	0.26
Trouble concentrating	0.45 (0.68)	0.55 (0.60)	0.63
Drowsiness	0.50 (0.51)	0.80 (0.76)	0.15
Acute mood change	0 (0)	0 (0)	-
Stimulation group guessing	0.55	0.55	1

Table 4. Mean percentage (and standard deviation) of hits in each RAT condition for both tDCS groups in Experiment 2.

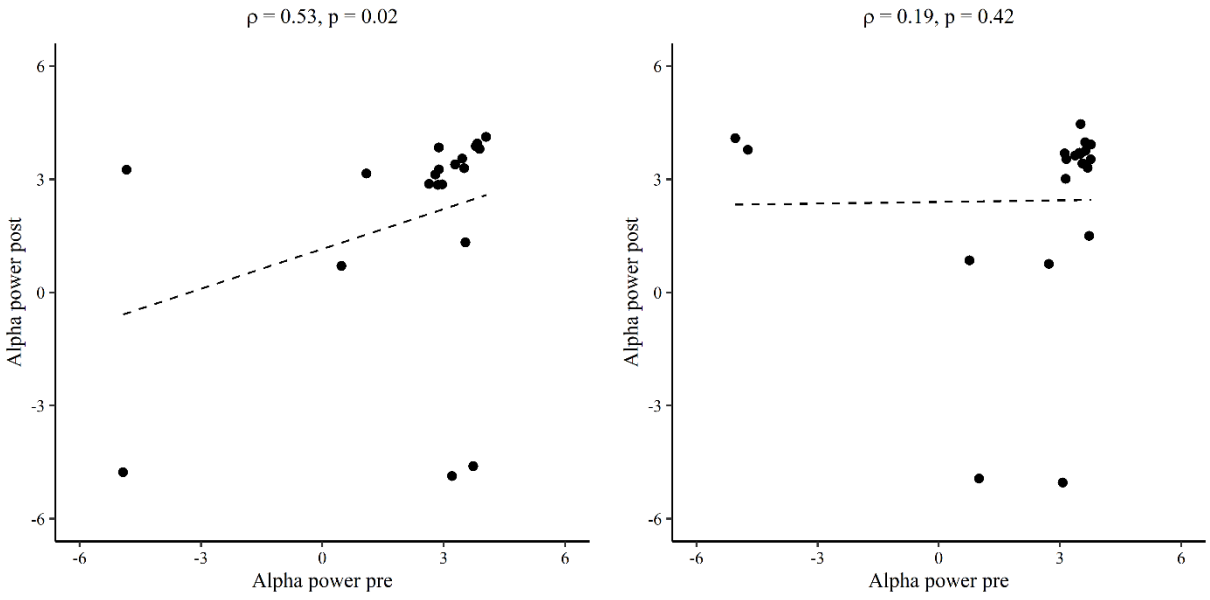
tDCS groups	Conditions	% of hits
Sham tDCS	Competitor	24.44 (18.94)
	New	29.72 (11.15)
	Studied	48.33 (17.76)
Real tDCS	Competitors	44.44 (24.45)
	New	36.39 (12.81)
	Studied	40.00 (18.52)

Sham tDCS group **Real tDCS group**

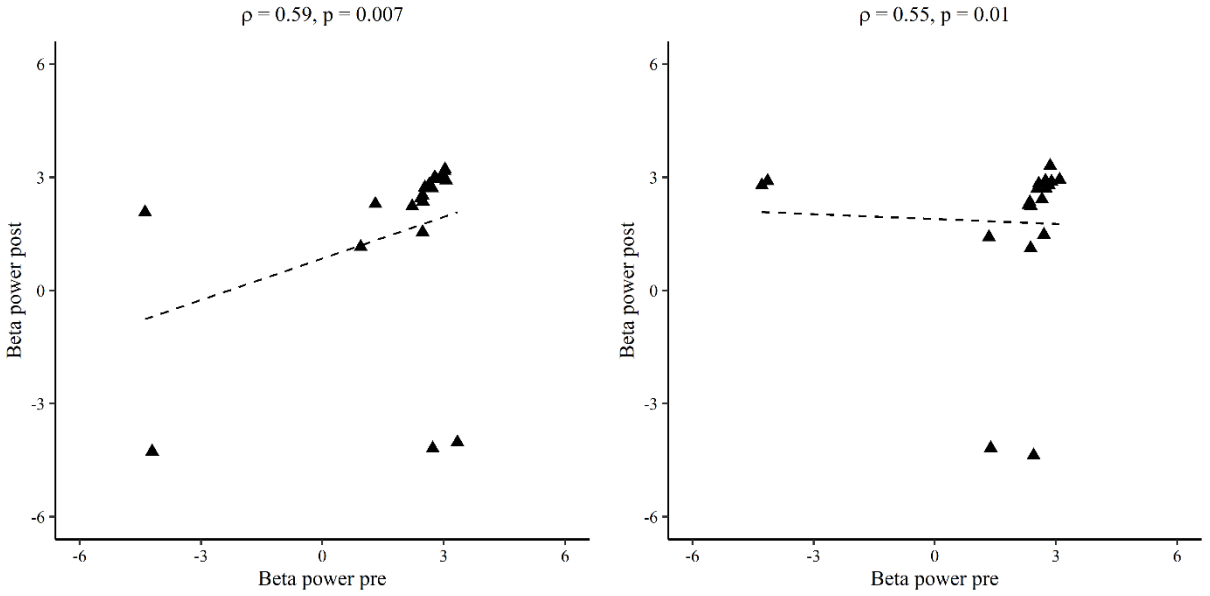
a)



b)


ρ = 0.53, p = 0.02
ρ = 0.19, p = 0.42
Alpha power post
Alpha power pre
6
3
0
-3
-6

c)


ρ = 0.59, p = 0.007
ρ = 0.55, p = 0.01
Beta power post
Beta power pre
6
3
0
-3
-6

d)

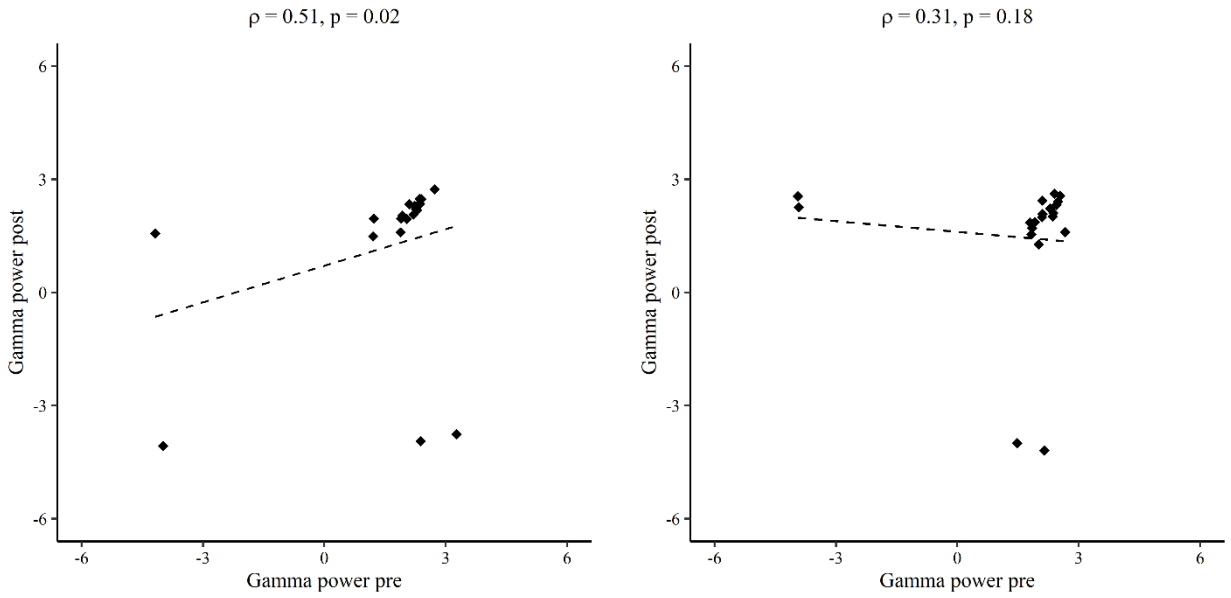


Figure 2. Dispersion graphics of the correlation between power in each band frequency (pre and post measure) in each tDCS group in Experiment 2.

Electrophysiological correlates of the consequences of competition in RAT problem-solving[5]

Abstract

Creative problem-solving requires the downregulation of competing memory representations that arise during the search for a solution. The present study examines the behavioral and electrophysiological consequences of the downregulation of competing information during the solution of a series of Remote Associates Test (RAT) problems. Participants were exposed to the most common error produced by others in previous studies requiring the solution of RAT problems and to baseline words (studied words only). They then solved a series of RAT problems and performed a control task. Retrieval of the competitor and baseline words against a set of novel words was tested in a final recognition test. Results showed that participants were slower to identify competitor items than baseline items, but no differences were found in terms of correct responses. Brain activity revealed differences in classical event-related potentials (ERP) associated with interference detection and old/new effects; the FN400 and late parietal positivity (LPP). Competitor items elicited a stronger FN400 than baseline items, whereas baseline items elicited a stronger LPP than competitors.

Keywords: competition, inhibition, EEG, creative problem-solving.

[5] Lezama, R., Gómez-Ariza, C. J., Bramão, I., Johansson, M., & Bajo, M. T. Electrophysiological correlates of competition in RAT problem-solving. (In preparation).

Introduction

The ability to solve problems is one of the fundamental human skills. When confronted with everyday challenges, we often use past effective solutions and prior experience to address them, even though some problems require novel and creative solutions (Ramey & Zabelina, 2023). Creativity is the ability to create novel associations between distantly associated concepts, leading to the generation of original and practical ideas or solutions to problems (Amabile, 1983; Runco & Jaeger, 2012).

Current theories of creativity, such as the dual-process model, consider that creative outcomes emerge from a dynamic interaction between associative, spontaneous processes, and control, goal-directed processes (Benedek et al., 2023; Kleinmintz et al., 2019). Associative processes promote the activation of distantly related pieces of information stored in our memory which can later be combined to produce a novel response (George & Wiley, 2019; He et al., 2020; Beaty & Kennet, 2023). However, along with relevant information, dominant but inadequate associations or obvious ideas and past experiences are also activated, which might hinder the creative ideation process (Chrysikou, 2019; Dietrich & Kanso, 2010). The fact is that although memory is the fundamental scaffold from which one generates creative ideas, the retrieval of dominant and unoriginal pieces of information may impasse the creative process (Gerver et al., 2022; Kleibeuker et al., 2013b; Schacter et al., 2007). To overcome these impasses, control and goal-directed processes (i.e., inhibitory control) can operate to downregulate competitive and interfering information and facilitate the search for original ideas (Cancer et al., 2023; Luft et al., 2019; Gupta et al., 2012; Koppel & Storm, 2014). Impasses occur when the solver faces obstacles in reaching the key information, possibly due to insufficient activation of the target information or interference from fixations on inappropriate strong associations (Storm & Hickman, 2015; Gauselman et al., 2023; Beda & Smith, 2018). Here, the inhibition of irrelevant information may promote creative problem-solving as a mechanism to overcome the impasses (Storm & Angello, 2010).

Previous studies have investigated the role of inhibition by manipulating competition during creative problem-solving using the Remote Associates Test (RAT) developed by Mednick (1962) (Beda & Smith, 2018; Smith & Beda, 2020; Storm & Bjork, 2011; Storm & Angello, 2010). In this task, problems formed by three apparently unrelated words are presented (e.g., *graphic-fashion-interior*), and participants have to generate a fourth word that connects to all of them (*design*). During the candidate generation stage, several concepts related to the problem cues are activated and the participant have to actively inhibit the related but inappropriate ideas in order to keep searching for the best response (e.g., *underwear* related to *fashion* and *design* but not to *graphic*; Beda & Smith, 2018; Cassotti et al., 2016). If the participant experiences difficulties in dismissing those inappropriate solutions, mental fixation might emerge (i.e., when irrelevant or unhelpful ideas are strongly accessed which might block the retrieval of other possible ideas and impede the creative problem-solution; Storm & Hickman, 2015).

Storm and Angello (2010) examined whether the capacity to downregulate episodic interfering information was positively related to the ability to overcome mental fixation in a set of RAT problems. Considering the significance of downregulation of competitors in creative problem-solving, the hypothesis was that greater inhibition of competing memories in an episodic memory paradigm would correlate with enhanced performance in the RAT. This relationship was assessed through the retrieval-induced forgetting (RIF) effect. Hence, Storm and Angello (2010) used the selective retrieval procedure (SRP; Anderson et al., 1994) to obtain a measure of episodic inhibition, while measuring the ability to overcome fixation by having participants solve a set of RAT problems.

In the SRP, following an encoding phase involving category-exemplar pairs, repeated attempts to retrieve specific exemplars is assumed to produce retrieval competition from related but non-practiced items within the same category. In this context, inhibitory control acts to temporarily reduce the activation of related but non-target representations, thereby facilitating access to target items. As a result, the non-target items become temporarily less accessible than baseline items (which are also studied but belong to unpracticed categories

during the selective retrieval phase). The RIF effect specifically refers to this below-baseline temporary reduction in accessibility of items that were the target of inhibitory control (for a review, see Anderson & Hulbert, 2021; Storm & Levy, 2012). Finally, participants are tested on the complete set of studied items to assess differential item accessibility as a function of the retrieval status in the SRP phase.

In the experiment by Storm and Angello (2010), after performing selective retrieval, participants solved a set of RAT problems. Specifically, half of the participants were exposed to competitor words beforehand (i.e., misleading associates to the words in the RAT problems; fixation group), while the other half solved a set of neutral RAT problems (control group with no pre-exposure). Storm and Angello (2010) found that RIF did not correlate with problem solving ability in the control group, whereas there was a positive association between RIF and performance on the RAT in the fixation group (for similar results see Kopper & Storm, 2014).

Building on Storm and Angello's (2010) findings highlighting the relationship between inhibitory control and creative problem-solving, Storm et al. (2011) examined the behavioral aftereffects of downregulating fixated information during RAT solution and how these aftereffects relate to problem solving ability. In their Experiment 3, there were two main phases; in the first, participants encoded pairs of cue-associate words (e.g., *playing-fun, credit-union, report-paper*). Afterwards, they solved a set of RAT problems in which the three words that formed each problem (i.e., problem cues) were the first words in the pairs from the previous phase (e.g., *playing-credit-report*). Subsequently, participants again encoded pairs of cue-words as before, and then encountered two sets of RAT problems: one set of unsolvable problems (designed to increase competition and inhibition) and another set of solvable problems. In both sets, the problem cues were cues from the encoding task. Finally, a cued-recall test was administered to test participants' memory for the previously studied responses. Importantly, one set of cues belonging to the encoding phase was not used during the RAT phase, and serve as baseline pairs in the final recall test. Results showed a problem-solving induced-forgetting effect, i.e., participants were less likely to

recall words associated with cues from unsolvable RAT problems than baseline items. Interestingly, this forgetting effect was positively associated with the ability to solve problems, suggesting that participants suppressed the misleading associates while attempting to solve unsolvable RAT problems, which in turn made these words more difficult to recall later in the final test.

Some studies have used EEG to investigate the brain dynamics associated with the cognitive processes involved in RAT problem-solving (Jung-Beeman et al., 2004; Sandküler & Bhattacharya, 2008; Bieth et al., 2023; for a review, see Stevens & Zabelina, 2019). RAT solution involves cognitive operations that unfold over time and require complex interactions between brain networks (Becker et al., 2023). For example, results from some studies report an increase in alpha-band frequency, which has been related to the inhibition of non-relevant stimuli to facilitate endogenous processing and semantic memory search during creative problem-solving (Camarda et al., 2018; Luft et al., 2018). In a recent study, Bieth et al. (2023) registered EEG activity while participants solved RAT problems in which the semantic distance between cue and correct responses was experimentally manipulated. Interestingly, they observed an increase in theta power in fronto-temporal regions around one second before the participants response. Since theta activity over frontal areas has been largely related to executive functioning (Cavanagh & Frank, 2014; Hanlsmayr et al., 2010), this result was interpreted as reflecting executive processes (e.g., inhibitory control engaged in rejecting inappropriate solutions or evaluating and validating potential responses).

From a different perspective, others have studied inhibitory control by manipulating the activation level of potential solutions and observing their accessibility in a subsequent creative problem-solving stage (Gómez-Ariza et al., 2017; Lezama et al., 2023; Lezama et al., 2024; analogical reasoning: Valle et al., 2019; 2020b). In the studies by Gómez-Ariza et al. (2017) and Lezama et al. (2023), participants underwent a version of the SRP that included a RAT as a final test of accessibility. Specifically, participants went through the two main phases of encoding pairs of lexical cue-exemplars (e.g., *FA-Famous, FA-Fantasy, CA-Cathedra, CA-Captain*) and selective retrieval using the lexical categories as

cues (e.g., *CA-Cat_*). Finally, participants completed the RAT in which some problems could be solved using items previously encountered during the encoding phase (e.g., *Crew-Boat-General*, with *Captain* as the solution). The final RAT phase also comprised problems whose solutions were not presented during the experiment, so they were completely new. Overall, the results of all these studies replicated the RIF effect, in that competitors (non-target items that were associated with targets during selective retrieval) were produced less often as RAT solutions compared to baseline items (for similar results using analogical reasoning, see Valle et al., 2019; 2020a, 2020b). As with RIF effects observed in other explicit memory tests, the impairment for competitor solutions can be explained as the aftereffect of a prefrontally-mediated inhibitory mechanism in charge of downregulating the accessibility of competitor representations in order to facilitate access to target items (Lezama et al., 2024; Valle et al., 2020a; 2020b). Interestingly, Lezama et al. (2023) found that such a retrieval-induced impairment in the production of creative solutions was associated with better performance on RAT problems whose solution was completely new. Overall, these findings (and those from of Storm and colleagues) suggest that the downregulation of interfering episodic memory representations during selective retrieval and the competition resolution of misleading associates during creative problem-solving might share a common inhibitory control component.

Some studies have also investigated the brain correlates underlying inhibitory control using SRP (Johansson et al., 2007; Wimber et al., 2015; Wimber et al., 2009; Hanslmayr et al., 2010). Johansson et al. (2007) conducted an EEG experiment to identify ERP components of selective retrieval. In their experiment, they compared the electrophysiological activity associated with the selective retrieval phase of the standard SRP with a re-learning (control) condition in which participants were re-exposed to some of the exemplars of some categories. Since this condition did not involve retrieval, neither competition/interference nor inhibition was expected. The results of the study showed that prefrontal ERPs in anterior, left and central regions in a time-window of 1000 ms were sensitive to differences between the two conditions. Specifically, these ERPs were more sustained and positive-going during selective

retrieval than during re-exposure. Moreover, greater positivity was predictive of a larger RIF. In another study, Hellerstedt and Johansson (2014) manipulated the degree of semantic association between category cues and competitors to generate high versus low competition during the selective retrieval phase. The results showed that ERPs were influenced by the strength of the competition, with stronger competitors producing a more positive response from about 300 ms after the onset of the category cue, especially over frontal electrodes. This effect was again correlated with RIF. This result was interpreted as reflecting the reactivation of previously encoded semantic associations within categories. This interpretation is consistent with similar effects observed in other ERP studies, including those investigating familiarity, old/new recognition effects, conceptual priming, and interference detection and competing memory inhibition (Kwon et al., 2023).

While there is a considerable body of research on the neural correlates of inhibitory control in memory, there is scarce empirical evidence on the electrophysiological correlates of competition and fixation resolution in RAT problem-solving. To fill this gap, the present research was directed to 1) identify the neural correlates of prior exposure to competitors on creative problem-solving (RAT problems) compared to a control task, and 2) identify the neural correlates of effective inhibition over competitor representations during a subsequent recognition task. Thus, competition was first generated to determine neural patterns of competition during RAT solution and its resolution by inhibition. Additionally, we wanted to explore what happens to competitor representations during a subsequent recognition task, when they are inhibited during the problem-solving phase. EEG was used to study the temporal dynamics of competition resolution and its aftereffects.

For this purpose, we used a methodological approach similar to that of Storm et al. (2011), except for some details necessary to adapt the procedure for EEG recording. Specifically, participants encoded a list of items (some of which later became competitors). Participants then completed two tasks; solution of a set of RAT problems (whose competitors were presented beforehand) and a control task in which they had to identify the longest word in the triad. These

tasks were performed twice. Finally, an old/new recognition test was performed. Behavioral and time-locked neural activity was examined in the recognition task for three types of items: a) competitors (presented during the training phase and competing with the correct solution during the RAT), b) baseline (presented only during the first phase and attached to the problems presented in the control condition, which included a task that did not generate competition), and c) new, (i.e., completely new words). While the paradigm used here is similar to the one used by Storm et al. (2011), our competitors were selected from the most common errors made by other participants in previous RAT studies (Lezama et al., 2023; Lezama et al. 2024).

At the behavioral level, similar to Storm et al. (2011), we expected that after the encoding phase, competitor representations should be reactivated when the associated RAT problem was presented. Thus, as a consequence of solving the problems, the competitor representation (i.e., the most common incorrect answer) would get activated and then downregulated by inhibitory control. We expected the aftereffect of this solution to be detected in the recognition phase. Specifically, we expected responses to competitors to be less accurate and slower than responses to baseline and new items (Anderson & Hulbert, 2021; Storm et al., 2011).

Regarding the neural underpinnings, we expected to detect ERP components sensitive to competition (and its resolution), as well as to familiarity (baseline versus new items), during the recognition phase. In this sense, it was expected to observe two well-documented ERP components associated with old/new recognition. First, we expected to find the FN400 component, with more positivity for correct responses to baseline (old) items than for correctly rejected new items over frontal regions in the 300-600 ms time window. Second, we also expected to find the late parietal positivity (LPP or P600), an ERP component that is linked to successful recognition of old items eliciting more positivity than correct rejection of new items over left or central parietal regions around 300-600 ms after stimulus onset as a consequence of effective memory (for a meta-analysis see Kwon et al., 2023; Paller & Kutas, 1992; Rugg et al., 1995). Additionally, the comparison between baseline words (presented in the first

phase) and competitors (attached to the RAT problems in the second phase) would allow us to find out whether there is an observable consequence of the induced competition and its resolution in the recognition phase. As previously mentioned, the FN400 is usually observed during the reactivation of competitors during selective retrieval (Hellerstedt & Johansson, 2014). Therefore, in the present study, we predicted an FN400 component of reduced amplitude over anterior frontal regions during the presentation of competitors compared to baseline items (all during the recognition phase). Finally, because competitor representations were expected to be downregulated, we predicted differences between baseline and competitors in the LPP that would reflect lower recollection process.

Method

Participants

Thirty-six undergraduate students (*mean age* = 22.35; *SD* = 2.65 years; women = 26) were recruited to participate in exchange for economic compensation (12€). The sample size was determined prior to the experiment using G*power (Faul et al., 2009). The analysis indicated that 34 participants were an appropriate sample to detect a medium-size effect (d = 0.5; α = 0.05; power = 0.8). Because EEG recordings are sometimes very noisy and some participants' data are sometimes lost, we decided to keep 36 participants who contacted us after advertising for participation. Participants included in the analyses were right-handed, had normal or corrected vision and reported no history of neurological or psychiatric disorders, migraine, metal implants, head injuries, seizures, epilepsy, or active medication (except oral contraceptive pills). The research received approval from the ethics committee at the University of Granada, following the guidelines set forth in the Declaration of Helsinki.

Materials

The stimuli used to generate the competition were 48 words obtained from a database containing the most frequent errors made by 156 participants on 48 RAT problems. Four filler words were also included, to be presented at the beginning and end of the first phase to avoid primacy and recency effects. The RAT problems and their correct solutions were the same items used in Gómez-Ariza et al. (2017), Lezama et al. (2023; 2024) except that we decided to eliminate six problems whose accuracy was lower than 8.3%. The solutions belonged to nine different orthographic categories (e.g., *CA, PE, TA*). Each category had six associated exemplars (except for the categories whose related RAT was eliminated, DI; 5, RE; 4, BA; 5, PE; 4). The exemplars within each category shared the first two letters (e.g., maquillaje, marinero, matanza, madurez, maleta, manual for the category MA). The sample words were chosen from the normative database of Alameda and Cuetos (1995) on the basis their lexical frequency. Each category comprised three words of medium-high frequency (range = 34–98, mean = 58.7) and three words of medium-low frequency (range = 10–34, mean = 20.1). Importantly, the chosen words met the following criteria: a) they lacked any associative or semantic links to other words within the category; b) they ranged from two to five syllables in length; c) each word had a distinct third letter.

Each of the 48 RAT problems could be solved with one of the 48 words belonging to the previously described categories (e.g., *spouse, papers, break-up* for *divorce*). Similar to Gómez-Ariza et al. (2017), the associative strength between the words in RAT problems and their solutions showed a moderate level of associative strength (forward/backward associative strength < 0.20). This relationship could be synonymy, compound words, contextual co-occurrence, or semantic relatedness. Six different counterbalanced versions of the task were created to rotate the material through the different experimental tasks in the first and second phase. Additionally, another 48 words were selected to be presented as completely new words in the recognition phase. The selected words were obtained from the Spanish Lexical Database (Duchon et al., 2013), and were matched to the competitor words in terms of number of letters, relative frequency, familiarity, imaginability, and concreteness (*ps* > 0.44).

Procedure

Training phase

After participants read and signed the informed consent, the EEG cap was placed on the head and the training phase began. The encoding protocol used by Kerrén et al. (2021) was followed. In the first phase, the 48 words (24 competitors and 24 baseline words) were presented in two possible encoding tasks. In the like task, participants rated how much they like the presented item on a 3-point scale (1 = nothing, 2 = some, 3 = a lot). In the artist task, participants had to rate on a 3-point scale (1 = nothing, 2 = some, 3 = a lot) how easy it would for an artist to paint them. Here, half of the items were encoded using the artist task and the other half using the like task. Competitors and baseline words were grouped so that in both tasks, half of the items were competitors and half were baseline words. The items presented in the task were counterbalanced across experimental versions, and the stimuli were presented in random order. Each trial began with a fixation cross (1500 ms) followed by either a G (*gustar,* like) or an A (*artista,* artist) for 600 ms. This indicated to the participant what their task was during the encoding. Then, the item (competitor or baseline word) was presented for 6 seconds, and after 4 seconds the rating scale appeared at the bottom of the screen and remained until the end of the trial.

Problem solution phase

After the encoding phase, the retrieval practice phase started. Participants were instructed to perform two different tasks twice, in different blocks. In the RAT condition, participants had to solve 24 RAT problems. Here, problems comprising three unrelated words were presented and they had to find a fourth one that related all of them. In the longest condition, participants had to determine the longest word in the 24 triplets presented. Critically, the words presented during the encoding phase in both the RAT and the longest condition were the most common errors made by other participants (N = 155) for each of the triplets in previous RAT studies. The problems were presented in random

order within each task condition; however, the tasks were presented in counterbalanced blocks across experimental versions. Each trial began with a fixation cross (1500 ms) followed by the triplets, and participants had up to one minute to solve each problem (either the RAT or the longest task). To avoid the voice artifact in the EEG recording, participants were instructed to search for the solution and, when they had it in mind, to press the space bar. As soon as a question mark appeared on the screen, they said their response aloud. Finally, a blank screen remained for 500 ms. Due to a programming error, the order of presentation in the second block was sequential for each task. At the end of the second phase, participants performed a distracting arithmetic task for five minutes.

Recognition phase

After the problem solution phase participants performed a recognition test. They had to determine whether the words appearing in the screen had been presented during the encoding phase by pressing yes or no response buttons (z and m) which were counterbalanced across experimental versions. The test included the 48 words presented during the encoding phase (competitors and baseline) and 48 new words. The order of presentation was completely random. Each trial started with a fixation cross (1000 ms), and the target word appeared and remained for a maximum of 3000 ms or until the participant responded. Then a blank screen then remained for 500 ms at the end of the trial. Participants were instructed to respond as correctly and fast as possible.

EEG acquisition and preprocessing

Electroencephalographic activity was recorded throughout the experimental session using a 64-scalp elastic electrode cap (Quick-Cap, Neuroscan Inc.) according to the 10-20 system. Electrical activity was recorded continuously at a sampling rate of 1000 Hz and amplified using a Neuroscan Synamps2 amplifier (El Paso, TX). Electrical activity was referenced online to a

midline electrode (halfway between Fz and Cz) and re-referenced offline to a common average. Impedance was kept below 10 kΩ. The ground electrode was positioned on the vertex. For ERP preprocessing the pipeline was similar that of Valle et al. (2020) except for time segmentations. Preprocessing analyses were performed using the EEGLAB toolbox in MATLAB (version 9.1, R2016b). In the preprocessing analyses, the signal was downsampled to 500 Hz and a high-pass filter at 0.1 Hz was applied. Bad channels with high artifact levels were detected by visual inspection and interpolated using neighbor electrodes and spherical as the interpolation method. Artifact correction of ocular movements and blinks was performed by means of independent component analyses (ICA) using the EEGLAB toolbox's function 'runica'. The remaining artifacts were corrected by careful visual inspection. Waveforms were low-pass filtered at 30 Hz. Epochs were segmented into 1500 ms, including a 200 ms period pre-stimulus presentation which was used as baseline correction. Finally, an automated artifact removal process was implemented using an amplitude threshold of ± 100 μV. Separate averages were then calculated for each participant and condition. Three participants were excluded from the analyses due to excessive final epoch rejection (>20%).

Data analyses

Behavioral analyses

Correct responses (hits and correct rejections) and response times during the recognition task were the dependent variables considered. Data from 3 participants were discarded due to low accuracy during the recognition phase (< 52%). Descriptive statistics for the recognition phase are shown in Table 1. Performance during recognition was analyzed using a repeated-measures ANOVA, with type of item (competitor and baseline) as the independent variable and hits and (logarithmic) response times for hits respectively as the dependent variables. Additionally, an index of the consequences of inhibitory control was calculated by subtracting the competitor's RT from the baseline RT in the

recognition phase. The index was based on response times because this measure showed to be more sensitive than accuracy. Additionally, RT is a continuous variable offering more fine-grained information. The index was correlated with accuracy during the RAT problem-solving phase to check whether better inhibition of competitors was associated with better RAT performance.

Finally, conditional analyses were performed. Because performance on the previous RAT solution phase is not considered in the analysis of recognition performance itself, correct responses to competitors are blind to whether or not the RAT problem attached to these items was effectively solved. Thus, only some of the competitors presented during recognition might have been previously inhibited during problem solving. Hence, and with the aim of improving the sensitivity of the recognition test, we also conducted a conditional analysis by considering only those competitors whose attached RAT problem was successfully solved.

EEG analyses

To explore ERP modulation as a function of type of item during the recognition phase two components linked to familiarity and recollection effects for old/new judgements were determined (for a metanalysis see Kwon et al., 2023; Sanquist et al., 1980; Warren, 1980). First, the FN400, a more positive-going component for correctly identified "old" (baseline) items compared to correct rejection of new items. This phenomenon starts around 300 ms post-stimuli presentation and offsets at approximately 500/600 ms in recognition tests and tends to be maximal over frontal regions (Düzel et al., 1997; Rugg et al., 1998a). The second component of interest was late parietal positivity (LPP), a later positive deflection occurring approximately 500–800 ms after stimulus onset and has been linked to recollection processes for studied (as compared to new) items. LPP is most prominent over central parietal regions of the scalp (Paller & Kutas, 1992; Rugg et al., 1995).

Non-parametric cluster-based permutation tests were conducted on the EEG data using the FieldTrip toolbox (Oostenveld et al., 2011), with time-averaged data. The Monte Carlo method was applied with 1000 permutations to

assess statistical differences. In the initial analysis, the goal was to detect the two well-established old/new effects (FN400 and LPP) that have been consistently reported in the recognition literature (for a meta-analysis see Kwon et al., 2023). The analyses were performed for each time window (300-600 ms and 600-1000 ms respectively) to identify the electrodes that maximized the difference between baseline (studied) and new items (old/new effect). Regions of interest (ROIs) were selected using a data-driven approach for both components. For each ERP component, the mean amplitude in the detected ROIs was introduced into a within-subject ANOVA with type of item in the recognition phase (competitor, baseline and new) as the independent variable.

Results

Behavioral results

The mean percentage of successful solution of RAT problems was 36.81 (*SD* = 13.81; Cycle 1 *M* = 36.81; *SD* = 14.48; Cycle 2 *M* = 38.00; *SD* = 14.049). The percentage of correct responses in the longest (control) condition was of 97.22 (*SD* = 3.71%: Cycle 1 *M* = 96.72; *SD* = 4.39 ; Cycle 2 *M* = 97.73; *SD* = 4.05).

The ANOVA performed on hits showed no significant differences between competitors and baseline items, $F(1, 32) = 0.05$, $p = 0.81$, $\eta^2_p = 0.003$. However, the analysis on the log-response times of correct responses revealed a statistically significant difference between both types of items, $F(1, 32) = 4.06$, $p = 0.05$, $\eta^2_p = 0.11$. Participants were faster when responding to baseline items (*M* = 3.03; *SD* = 0.08) than to competitors (*M* = 3.04; *SD* = 0.08).

The Pearson correlation analysis between the RT index and accuracy in the RAT phase failed to show a reliable association ($r = 0.08$; $p = 0.65$).

Table 1. Descriptive statistics (means and standard deviations) for correct responses and RT as a function of type of item

	Correct responses	RT	Conditional correct responses	Conditional RT
New	0.88 (0.09)	3.04 (0.1)	-	3.04 (0.1)
Competitor	0.75 (0.13)	3.05 (0.08)	0.73 (0.17)	3.04 (0.09)

Baseline	0.76 (0.15)	3.03 (0.08)	-	3.03 (0.08)

Note: In the case of competitor and baseline items correct responses refer to hits. In the case of new items, it refers to correct rejections.

Conditional analyses

The ANOVA on hits again failed to show a significant effect of type of item, $F(1, 32) = 0.97$ $p < 0.33$, $\eta^2_p = 0.02$, as also did the one on log-response times, $F(1, 32) = 1.42$, $p = 0.24$, $\eta^2_p = 0.04$.

EEG results

FN400: The cluster-based permutation involving baseline and new items revealed a significant positive cluster ($p_{corr} = 0.03$) around 300-600 ms over left lateralized frontal electrodes (FP1, FPZ, FP2, F7, F5, FT7, FC5). This result indicated that baseline items exhibited more positive-going ERPs compared to new items in this ROI, see Figure 1 for the ERP waveform.

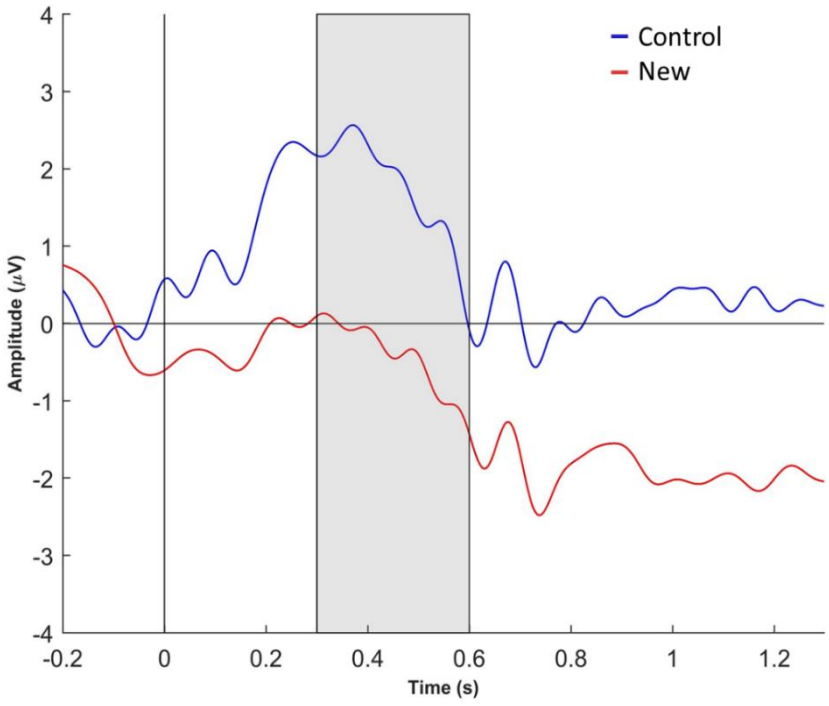


Figure 1. Grand-averaged ERPs at left frontal electrodes (FP1, FPZ, FP2, F7, F5, FT7, FC5), showing the FN400 for baseline and new items in the recognition phase.

Thus, an averaged ERP in the obtained ROI with type of item as factor was introduced in a repeated-measure ANOVA. We performed this analysis in order to be able to directly compare the amplitudes for the three types of items with the same set of electrodes (assuming there were no topographical changes). The analysis revealed a main effect of type of item, $F(2, 58) = 6.09$, $p = 0.003$, $\eta^2_p = 0.17$. Planed comparisons showed statistically significant differences between new ($M = -0.46$; $SD = 2.76$) and baseline items ($M = 1.14$; $SD = 3.50$), $t(29) = -2.97$, $p = 0.01$, $d = 0.53$) and between new ($M = -0.46$; $SD = 2.76$) and competitor items ($M = 1.19$; $SD = 2.73$), $t(29) = -3.07$, $p = 0.01$, $d = -0.55$). However, the contrast between competitor ($M = 1.19$; $SD = 2.73$) and baseline items ($M = 1.14$; $SD = 3.50$) did not reach statistical significance, $t(29) = -0.1$, $p = 1$, $d = -0.02$.

Because the initial analyses assuming identical topographies for the differences between competitor and baseline items and for the differences between baseline (studied) and new items (old/new effect) did not yield significant results, we performed additional cluster analyses comparing baseline and competitor conditions to identify the potential topography for this effect. The results of the cluster-based permutation tests within the 300-600 ms time window indicated a significant positive cluster ($p_{corr} = 0.004$) located over fronto-central electrodes (F1, FZ, FC1, FCZ, FC2, FC4, CZ, C2, C4), so that ERPs elicited by competitor items presented more positivity than baseline items (see Figure 2 for the ERP waveforms).

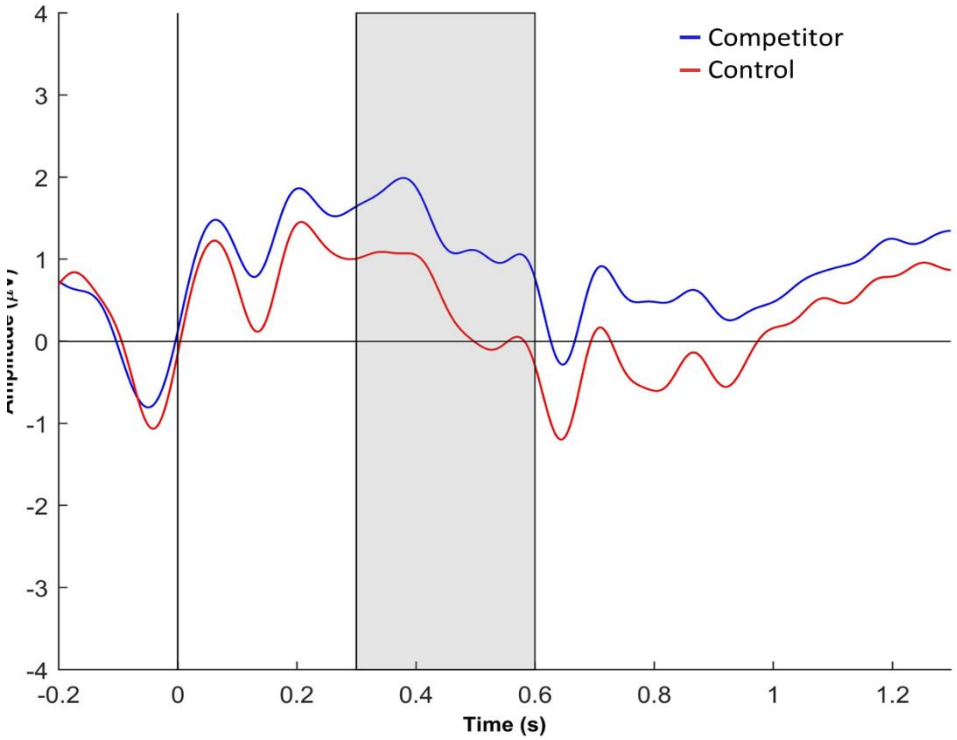


Figure 2. Grand-averaged ERPs at fronto-central electrodes (F1, FZ, FC1, FCZ, FC2, FC4, CZ, C2, C4) electrodes for competitor and baseline items in the recognition phase, in the 300-600 ms time window.

LPP: The cluster-based permutation comparison between baseline and new items identified a significant positive cluster (p_{corr} = 0.01) between 600-1000 ms located over right temporo-parietal electrodes (T8, TP8, P8, PO6, PO8, OZ, O2; see Figure 3 for the ERP waveform).

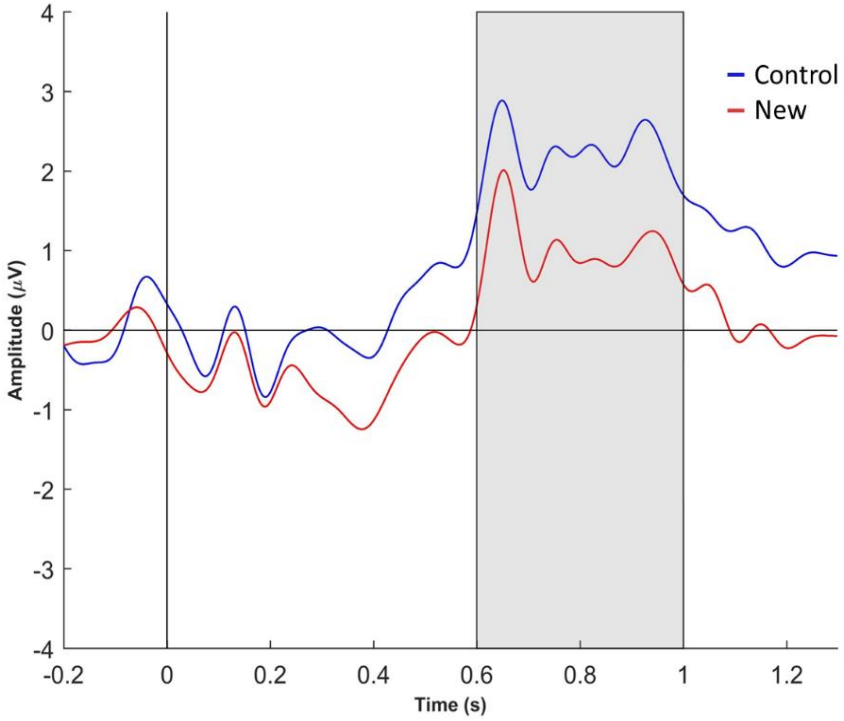


Figure 3. Grand-averaged ERPs at right temporo-parietal electrodes (T8, TP8, P8, PO6, PO8, OZ, O2), showing the LPP for baseline items and new items in the recognition phase.

Following the same previous rationale, the averaged ERPs in the obtained ROI per participants and type of item were introduced in a repeated-measure ANOVA. The results from this analysis showed a main effect of type of item $F(2, 58) = 9.22$, $p < 0.001$, $\eta^2_p = 0.24$. Post-hoc analyses indicated more positive activity for baseline items ($M = 1.87$; $SD = 1.68$) than new items ($M = 0.80$; $SD = 1.60$), $t(29) = 4.23$, $p < 0.001$, $d = 0.58$). Similarly, the contrast between new ($M = 0.80$; $SD = 1.60$) and competitor items ($M = 1.49$; $SD = 2.17$) showed statistically significant differences $t(29) = -2.74$, $p = 0.02$, $d = -0.38$). Finally, there were no differences in the ERPs elicited by competitor ($M = 1.49$; $SD = 2.17$) and baseline items ($M = 1.87$; $SD = 1.68$), $t(29) = -3.07$, $p = 0.01$, $d = -0.55$).

Again, because the comparison between baseline (studied) and new items reflects an old/new effect that may have a different topographical distribution to the competitor versus baseline effect, a cluster-based permutation test in the 600-1000 ms time window was performed. Results indicated that there was a significant positive cluster ($p_{corr} = 0.007$) located over left parieto-occipital

electrodes (PO7, POZ O1, OZ, O2). This contrast indicated that baseline items elicited more positive-going ERPs than competitor items (see Figure 4 for the ERP waveform).

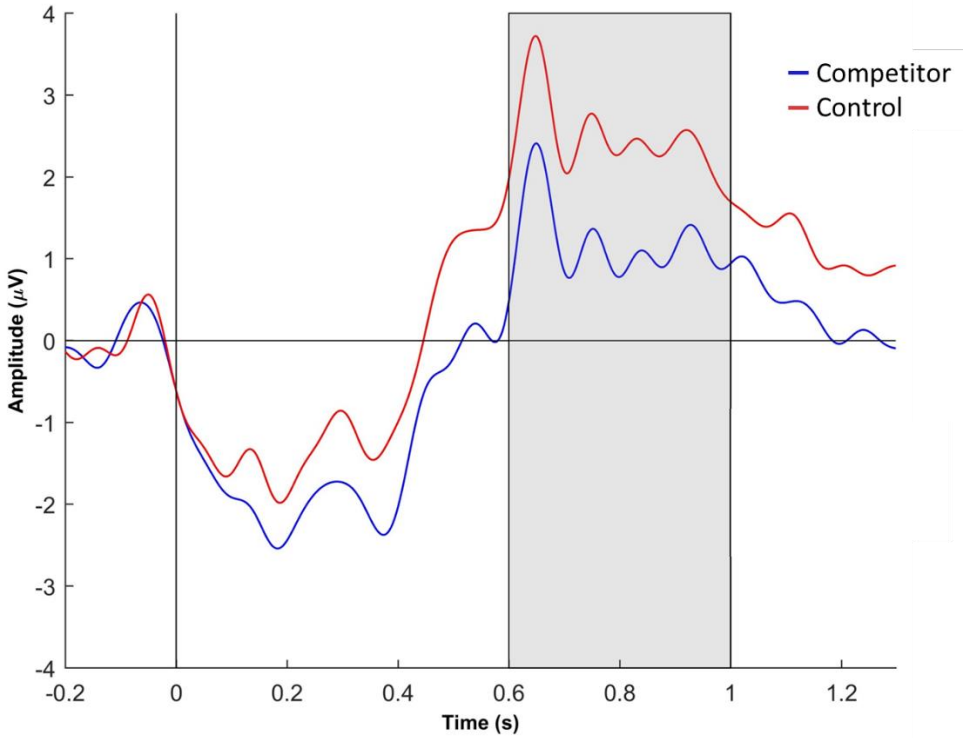


Figure 4. Grand-averaged ERPs at left parieto-occipital electrodes (PO7, POZ O1, OZ, O2) electrodes, ERPs of competitor and baseline items in the recognition phase, in the 600-1000 ms time window.

Discussion

As creative problem-solving requires the activation of associated pieces of information stored in our memory, related irrelevant information may come to mind as a possible solution making it necessary to discard this inappropriate information in order to reduce interference and find the proper solution (Sowden et al., 2015). However, reducing interference can prove challenging at times, and fixation might occur (Beda & Smith, 2018). In order to overcome interference and fixation, control processes, such as inhibitory control, have been proposed to play a role in downregulating interfering representations thereby facilitating solution search (Volle, 2018).

The main aim of the present study was to examine the behavioral and electrophysiological correlates of interference resolution during RAT problem solving and its aftereffects. To this end, participants first underwent an implicit encoding phase, in which they made naïve judgements about words appearing on the screen. They then underwent two cycles of solving RAT problems and a control task (i.e., saying the longest word in a triad). Critically, some of the words presented in the first phase were the most frequent errors made by 155 participants who had attempted to solve the RAT problems in previous experiments (these items served as competitors), together with only studied words that were the solution to the RAT appearing in the control task (baseline items; Lezama et al., 2023; 2024). Finally, participants completed an old/new recognition test that included competitor, baseline and completely new words. To investigate the neural correlates associated with representations of the competitor and baseline items, EEG was recorded throughout the experimental session.

The implicit encoding of competitors during the first phase was expected to increase their activation so that later, when participants were faced with the RAT problems, these competitors might interfere with other concepts during the solution search and generate fixation (Storm & Angello, 2010). Hence, inhibitory control was expected to be triggered to overcome such competition during problem solution to get the problems successfully solved. Thus, we hypothesized poorer performance during the recognition test for competitors than for baseline items (fewer hits and longer response times). However, the results of this study only partially support this hypothesis. While there was no difference between both types of items in terms of hits, participants responded significantly slower to competitors than to baseline items, a result consistent with the findings of Storm et al. (2011). In Experiment 3, Storm and cols. (2011) observed a problem-solving-induced forgetting effect, such that competitor words were more difficult to retrieve as a consequence of the fixation generated during the intermediate (impossible) RAT solution block. These results were interpreted in terms of inhibitory control theory (Anderson, 2005). According to this theory, participants use inhibitory mechanisms to reduce the interference of misleading pieces of

information during RAT solution, which may make this information less accessible later. In the present experiment, participants were significantly slower in their identification of competitors (in comparison to baseline items) as old items, which fits well with the assumptions of the theory and extends previous results on resolution of interference and RAT. Hence, the present results are consistent with previous studies supporting the relevance of inhibitory control as a key mechanism for reducing the accessibility of misleading interfering representations during creative problem-solving (Anderson & Hulbert, 2021; Lezama et al., 2023; Storm et al., 2010; Storm et al., 2011).

However, we also found some differences in the results with respect to the study by Storm et al. (2011) since we did not find any differences in accuracy between competitors and baseline items. Some dissimilarities between the experimental protocols might explain differences in the observed results. First, and differently to their materials, we did not use strong associates to the cue as competitors during the RAT. Instead, we used words that were the most common errors made by participants who had previously attempted to solve the same RAT problems with the idea that the inclusion of these particular items would help increase competition. However, it should be noted that we did not have normative data on the relation between the selected items and the cues in the problems, and therefore the overall level of competition from these items might have been lower than expected. Second, Storm et al. (2011) used a cued-memory test, whereas a recognition test was employed here, so it is possible that, in this context, recognition accuracy does not capture the effect of inhibition, however, is better detected by response times. Third, in the experiment by Storm and colleagues' participants underwent a training phase to ensure recall of each item, whereas in the present study an implicit task was used in which participants had to encode competitor and baseline items with only one presentation cycle. Interestingly, and despite these differences in procedure, we were able to observe a reliable effect in response times raising the possibility that increasing the number of encoding cycles in future studies might enhance the effects found here and also extend them to accuracy measures.

Finally, and in contrast to Storm et al. (2011), the correlation between the RT index of problem-solving-induced forgetting and RAT accuracy was not statistically significant. As in Experiment 1 of Storm et al. (2011), it is possible that participants who struggled more in the RAT (lower accuracy) did so because they experienced higher levels of fixation, which increased the need to suppress competitors. This would explain the lack of such a correlation; it is possible that using a control set of RAT problems to test this correlation might yield different results. Unfortunately, these were not included in the present experiment.

Regarding the electrophysiological data, we expected to find differences between competitors, baseline and new items in the familiarity-related ERP component FN400 and in the recollection-related component LPP (Düzel et al., 1997; Rugg & Curran, 2007; Rugg et al., 1995). Thus, a first cluster-based permutation test between baseline (studied) and new items was performed in both time-windows to test the basic old/new effects observed in the literature related to familiarity and recollection processes and their topographical distribution. These analyses indicated statistical differences between baseline and new items in both time windows showing the classical effects of stronger positivity for old (studied) items compared to new items in the frontal ROI between 300-600 ms (FN400) and in the parietal region between 600-1000 ms (LPP). Although analyses contrasting the three types of items on the same electrodes did not show differences between competitor and baseline items (only for the comparisons between new and competitor items, and between new and baseline items), further analyses for the specific comparison between competitor and baseline items yielded statistically significant clusters for both time intervals. For example, in the first time-window a cluster of frontal electrodes yielded significant differences between both item conditions with competitors showing a more positive-going component compared to baseline items. According to the memory inhibition literature, this greater positivity might also reflect an interference detection mechanism (Valle et al., 2020b). In a previous related study, Johansson and Hellerstedt (2014) observed that during the presentation of the category cue in the first retrieval practice cycle there was a stronger FN400 component than in subsequent cycles, suggesting interference detection and

subsequent resolution by inhibitory control. Although there was only one recognition trial for each item in the present study, it is plausible that there was a reactivation of competitors that increased interference.

On the other hand, cluster analyses in the second time window indicated a significant left parietal cluster in which baseline items had more positive-going components compared to competitor items. This result suggests that competitors might have more difficult retrieval processes. Because competitors were related to the RAT phase in which they competed for accessibility as potential solutions, the interference resolution mechanism would have suppressed their representations as reflected in the reduced LPP component which is usually related to recollection processes.

While this study provides interesting insights, it also reveals numerous opportunities for future research and advancement. For example, to ensure that competition is induced during the problem-solving phase, an additional block of problems without (induced) competition should be added as a control condition. In this way, the comparison between competitive and non-competitive RATs would shed light on whether there is a fixation effect. In this line, the addition of several encoding cycles might increase this competition. The RAT problems presented in this experiment had a low average solution success, so it would really be valuable to reduce the difficulty of the problems in order to gain variability.

To conclude, in the present study we found mixed evidence for competition and subsequent solution in RAT problem solving. There was a statistical difference in response time between competitor and baseline items suggesting an impairment caused by the fact of solving RAT problems, such that competitors were recognized more slowly than baseline items presumably due to their previous downregulation. Regarding ERP components, our evidence suggests that inhibition may result in lower accessibility during recollection.

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Part III

General Discussion and Conclusions

Discussion and Conclusions

In this dissertation, our primary goal was to further contribute to the understanding of the cognitive functions involved in creative problem-solving, as well as their neural underpinnings. In Experiment 1, we adopted an individual differences approach to investigate the relative contribution of semantic memory structure, inhibitory control of interfering information and attentional scope to creative problem-solving. A lexical decision task was used to obtain two semantic priming indexes, while the Global-Local task (Navon, 1977) provided three attentional scope indexes. Additionally, an adaptation of the selective retrieval practice paradigm followed by the Remote Associates Test (RAT; Gómez-Ariza et al., 2017) was employed to obtain a memory inhibition and a creative problem-solving index.

Experiment 1 confirmed the significance of semantic memory and inhibitory control for creative performance (at the behavioral level), so that in Experiments 2 and 3 we shifted our attention to examining the role of cortical regions, from different brain networks thought to be involved in semantic integration and inhibitory control, in creative problem-solving. Given that tDCS can be a valuable tool for establishing causal relationships between brain activity and cognitive processes, in Experiment 2 we delivered anodal tDCS over the left ATL to seek causal evidence for its involvement in semantic integration, which is essential for solving RAT problems. In Experiment 3, we delivered cathodal tDCS over the right DLPFC to determine its involvement in memory control processes already shown to influence RAT performance. Finally, in Experiment 4, we aimed to examine the electrophysiological dynamics underlying the interference of competing information during RAT problems solving and its downregulation by inhibition.

Across this experimental series, we tried to demonstrate that semantic integration and episodic inhibition are two dissociable and relevant processes that are associated with different cortical regions contributing to brain networks that work collaboratively during creative problem-solving. In the following sections, the main findings obtained across the experimental series is

summarized while discussing the main implications for current theoretical proposals on creative problem-solving, and a general conclusion is drawn.

Semantic memory contributions to creative problem-solving

Creativity has attracted considerable scientific interest, and a few different theoretical proposals have attempted to shed light on the cognitive functions and processes involved (Hills et al., 2012; Martindale, 1995; Mednick, 1962; Volle; 2018). From the viewpoint of the associative model proposed by Mednick (1962), associative processes would be fundamental ones for creativity. That is, the ability to bring together different and distant pieces of information is the core component required to generate a creative outcome. Thus, more creative individuals would exhibit flatter (larger and more diverse associations to a specific concept) associative hierarchies among concepts stored in memory in comparison to the steeper hierarchies of their less creative counterparts. Because flatter associative structures would allow distant concepts to be reached as easily as closely related ones, creative individuals would be able to connect ideas more quickly and in a more efficient fashion, thereby improving search processes (Mednick, 1968). According to this proposal, more creative individuals would exhibit greater verbal fluency because the organization of their semantic memory structure would be arranged in networks of more accessible concepts. The most recent dual-process models (Sowden et al., 2015; Volle, 2018) also recognize the relevance of associative processes, but also emphasize the importance of control mechanisms that promote the search for relevant ideas by reducing the burden of related but inappropriate concepts (Luft et al., 2018). The results obtained in this dissertation add to the already existing evidence supporting the dual-process model (for a review see Benedek & Jauk, 2018). Specifically, our first study revealed that creative problem-solving ability (as measured by the RAT) is predicted by stronger semantic priming and better episodic inhibition. This supports the idea that semantic memory and inhibitory control are cognitive functions relevant to creativity. Surprisingly, neither weak semantic priming nor attentional scope correlated with creative problem-solving ability.

A straightforward consideration from our results is that automatic activation processes (at least between strong associates) benefit creative problem-solving. As observed in a study by Smith et al. (2013), RAT problem solving requires chain-like access to different concepts that are semantically related to cues in the problem. Therefore, better ability to retrieve these associations shares a common underlying process with faster responses to targets that are strongly associated with primes. Consistent with this result, other relevant empirical findings have shown that creative individuals exhibit semantic networks with more interconnected concepts (Kenett et al., 2014; Luchini et al., 2023). Vartanian et al. (2009) observed that individuals who scored high on creativity were faster at evaluating the association between concepts. However, although the association between strong priming and RAT solution is to some extent consistent with the dual-process model (Sowden, 2019; Volle, 2018; Benedek and Jauk, 2018) and the associative model (Mednick, 1962), the fact that weak semantic priming was not associated with creative problem-solving raises questions and seems to partially contradict the predictions of these models.

For a number of reasons, we expected weak semantic priming to be the best predictor of RAT performance. This index was used as a direct marker of flatter associative hierarchies, which are thought to characterize more creative individuals. If more creative individuals have similar access to strong and distant associations due to their associative structure, then enhanced weak priming might be expected to predict creative RAT performance. On the contrary, this lack of correlation (along with the positive correlation found for strong priming) might suggest that one of the necessary processes for creative problem-solving is simply the activation of strongly related concepts. However, more creative individuals do not appear to have a semantic memory structure with very different organizational properties (i.e., remotely related concepts organized similarly to closely related concepts). Some previous evidence is consistent with our results. Levin (1978) measured associative abilities using a verbal chaining task (i.e., saying a related word to the preceding one) and related this measure to RAT performance. The results indicated that better chaining abilities were associated with better creativity. More recently, Benedek and Neubauer (2013) found that more creative individuals generated more associated responses and, in doing so,

retrieved more uncommon ideas. Bernard et al. (2019) employed computational modeling and network analysis to investigate the characteristics of participants' semantic memory structure in relation to creative problem-solving. In their study, participants made association judgments between pairs of words from which participants' semantic networks were derived, and then performed a RAT-like task. In this version, there were *close* problems (low semantic distance between the words in the problem and the solution was close) and *remote* problems (high semantic distance between the words in the problems and the solution). According to the associative model, the prediction was that individuals' semantic metrics indicating that more remote concepts were judged as more closely related would be associated with better RAT performance. However, their results indicated that stronger pairs were the only pairs judge to be close, and that these closely-related pairs were the pairs associated with better overall RAT performance and with better RAT performance.

Thus, from these studies and from our own empirical evidence, it can be concluded that even when semantic activation of related concepts is critical for solving RAT problems, the ability to access distant ideas is not a structural characteristic of creative individuals. According to this argument, a relevant constraint in RAT problems is that the selected solution must be related to three words in the problem. Hence, rather than being beneficial, as expected from the associative model, weak semantic priming could become an obstacle when many possible pieces of information are activated and cause interference (Anaki & Henik, 2003; de Groot, 1983; de Groot et al., 1982). It is important to emphasize, however, that we are not suggesting that reaching further during semantic search is irrelevant to creative problem-solving. Rather, we are suggesting that, according to the evidence, the possibility of reaching remote concepts is possible by traveling through close connections, through of guided semantic search, starting from the cues contained in the problem (Gupta et al., 2012; Smith et al., 2013).

In addition, the differences between more and less creative individuals do not seem to rely on semantic structural properties per se, as they are not sufficient by themselves to explain semantic cognition (i.e., the ability to use stored knowledge in an adaptive manner to generate appropriate thoughts or behaviors;

Jefferies, 2013; Lambon Ralph et al., 2017). Control processes are also necessary. In fact, people with different creative potential retain many different attributes and associations for different concepts in their semantic memory, but only a reduced subset of them will be crucial to generate the creative response during creative problem-solving. For example, when faced with the problem *archipelago-cage-banana*, information associated with the semantic-perceptual information of banana (i.e., color, shape, taste) should be suppressed in order to focus on an appropriate set of features and solve the problem. Thus, it is possible that the interaction between stored semantic representations and semantic control allows individuals to dynamically retrieve relevant information for creative problem-solving. The results of Experiment 2 provide evidence for this idea. In this study, changing the neural activity in a brain network relevant to semantic cognition (by stimulating the left ATL), undermined participants' ability to solve completely new RAT problems (i.e., problems whose solution never appeared during the experiment).

While there are several theoretical proposals that attempt to explain how semantic knowledge is represented, as well as the neural bases of these representations, one of the most relevant in this context is the Hub and Spoke theory (Patterson et al. 2007; see Jefferies & Wang, 2021 for a review). In this proposal, both verbal and nonverbal experiences from multiple modalities serve as the fundamental "building blocks" for concept formation. These experiences are encoded in modality-specific regions of the cortex (the *spokes*). The ATL would function as a heteromodal convergence area (the *hub*) involved in processes that allow the formation of integrated representations by binding together the different features from the spokes (Bonner & Price, 2013; Chen et al., 2016; Farahibozorg et al., 2022). Thus, it is entirely possible that delivering tDCS over the left ATL disrupted the natural binding processes involved in the formation of complex semantic representations, thereby disrupting participants' ability to integrate semantically associated features of the concepts (words) in the problems. Consequently, this disruption led to lower performance on those RAT problems whose solutions had not been episodically encoded in previous phases of the experiment (i.e., new problems). Additional support for this claim comes from the EEG results obtained in Experiment 2, in which the pre-post correlation

in the theta band frequency was disrupted in the real tDCS group, while it was evident in the sham group. In addition, differential theta power (post-pre measures) was associated with better performance on new problems in the sham group but not in the tDCS group. Oscillations in the theta band are essential for language processing and semantic memory retrieval (Bastiaansen et al., 2005, Bastiaansen et al., 2008; Hanouneh et al., 2018; Marko et al., 2019).

Previous studies have shown increments in left hemisphere theta activity for words associated with extensive semantic memory representations (e.g., nouns, verbs, adjectives) compared to basic syntactic units (e.g., or, the; Bastiaannsen et al., 2005), providing an indication of the role for theta rhythms in distributed semantic activation. Prior research has shown that transcranial alternating current stimulation (tACS) at theta frequency seems to modulate retrieval performance in a phase-dependent manner, suggesting that theta oscillations support the binding of semantically related representations (Marko et al., 2019). Thus, it is possible that theta oscillations are the necessary mediating mechanism for the observed behavioral outcome of poorer solution of new RAT problems after delivering anodal tDCS over the left ATL, suggesting that the disruption of the processes necessary to bind semantic features in complex representations underlies poorer RAT performance.

Another interesting fact derived from Experiment 2 is that while most prominent theoretical accounts of creative problem-solving assume that its underlying neural process involves right-lateralized neural activity (Kounios & Beeman, 2014; for a review see Salvi, 2023), Experiment 2 provides evidence for the critical involvement of the left hemisphere. According to the insight model first proposed by Jung-Beeman et al. (2004), creative problem-solving entails two possible and distinct processes; insight and analysis. Analysis implies a conscious and deliberate line of thought in which the uncovering of solutions occurs through progressive awareness of the best solution (Smith & Kounios, 1996). In contrast, insight is a sudden understanding of the solution that relies on a reorganization of the features composing the mental representation of the problem, giving rise to nonobvious, unexpected interpretations. Research on the neural basis of these processes suggests that the right hemisphere is more

involved in insight solutions, while the left hemisphere contributes more to analytical solutions (Salvi et al., 2020; Santanercci et al., 2018).

This asymmetry would derive from the nature of the semantic relations under consideration, such that the right hemisphere would be expected to activate a wider range of semantic features, including those more loosely related to the word or context. Conversely, the left hemisphere would strongly activate a narrower, more focused set of semantic features, specifically those most relevant to the dominant meaning or current context. Although we did not examine the process by which participants arrived at solutions, it is arguable that all participants engaged in analytical processing, and that tDCS over the left ATL impaired these problem-solving processes. Rather, it seems more plausible that remote associations are reached through the initial activation of closely related semantic representations that pave the way and facilitate the activation of remote associates, which requires a more prominent participation of the left hemisphere. Thus, activation of strong associates allows the more distant ones to be reached, in which case the right hemisphere would be activated, explaining the bilateral participation of both hemispheres. This explanation would be consistent with results of neuroimaging studies using divergent thinking tasks (Abraham et al., 2012; Abraham, 2014) and insight problem solving (Tik et al., 2018) where the participation of both hemispheres was observed.

Control processes contributions to creative problem-solving

According to the dual-process model (Benedek & Jauk, 2018; Sowden, 2019), control processes are of special relevance for creative problem-solving. In this context, attentional scope (a source of individual differences) has been proposed as a possible modulatory mechanism for creativity. Along these lines, Mendelsohn (1976) proposed that creative individuals are characterized by a broader attentional scope (i.e., a tendency to attend to unexpected or seemingly unrelated features) than less creative individuals. This broader scope may facilitate the consideration of apparently irrelevant information to capture attention, which could provide relevant cues for original solutions. Martindale (1999) proposed that rather than having a fixed tendency for a broad scope of

attention, creative individuals may be superior at shifting their attentional focus based on the specific requirements of a task. In this sense, during the early stages of the problem-solving situation, a broad scope would benefit associative processes by opening the focus of the search process. In contrast, later stages, such as the idea evaluation process, may benefit from a more focused attentional scope that allows to reduce the interference of irrelevant activated information and to select of the best candidate solution. Despite the relevance of both proposals, a large body of research has failed to find conclusive results (De Dreu et al., 2011; Förster & Dannenberg, 2010; Lui, 2016; Vartanian et al., 2007). Experiment 1 was designed to further clarify the role of attentional scope in creative problem-solving, although we did not find a correlation between attentional scope indexes and RAT solution.

This is not surprising, as several empirical studies have failed to find this association (Liu & Peng, 2016; Zabelina et al., 2016). Furthermore, Luca et al. (2022) have also shown that the attentional scope (broad/focus) identified in one task transfers to other tasks involving broad/focus processing only when the tasks are highly similar and closely related. Significant differences between tasks weaken or eliminate this transfer. Therefore, the many differences between the Global-Local task and the RAT might account for the reduction in the predictive value of global/local attention on RAT creative performance. In addition, and considering Martindale's (1999) proposal, it can also be argued that our approach has not been sensitive enough because the attentional indexes obtained from the Global-Local task did not capture participants' ability to dynamically change scope to meet the demands of the different stages of creative problem-solving. It is possible that other indexes capturing individual differences in participants' attentional scope with respect to these dynamic fluctuations may better predict RAT performance. On the other hand, studies that observed the influence of attentional scope on creative performance did not measure general scope, but rather introduced specific induction procedures to enhance a specific attentional scope (e.g., Chiu, 2015; Colzato et al., 2017; Liu, 2016). Therefore, we speculate that similar to other types of interventions (e.g., Abraham et al., 2019; Beda et al., 2020; Madore & Schacter, 2014), attentional scope inductions may have an impact on creativity. Thus, depending on the demands of the creative task at

hand, inductions of a broad attentional scope may enhance associative processes whereas inductions of a narrow attentional scope may benefit control processes. Further research should explore these possibilities.

A relevant process examined in this experimental series is inhibitory control. According to the dual-process model, inhibitory control would be of particular relevance at different stages of the creative problem-solving process (Benedek & Fink, 2019, but see Chrysikou, 2019). Specifically, inhibition would be the mechanism regulating semantic search during the initial conceptual activation of related information (Luft et al., 2019). Subsequently, other studies have emphasized the role of inhibition during the evaluation of candidate solutions in the final stage, before producing a response (Bieth et al., 2023). Since many ideas can be considered as potential solutions, inhibition would be the mechanism responsible for limiting the interference of different candidates. However, other studies have found evidence for the involvement of inhibitory control in limiting semantic search and, consequently, hindering creative ideation and performance (Benedek et al., 2017, Marko et al., 2019).

To provide insight into this controversy, we studied the relevance of the ability to inhibit interfering episodic information for creative problem-solving and its neural correlates (Experiments 1, 3, 4). In Experiment 1, we introduced an experimental manipulation to vary the accessibility of previously encoded representations. Importantly, the manipulated representations could subsequently be used as solutions in the final RAT solution phase (Gómez-Ariza et al., 2017). This manipulation allowed us to obtain an inhibition index from RAT performance. The evidence obtained suggests that an enhanced ability to suppress interfering information during selective retrieval (and reduce its accessibility) is associated with better performance in creative problem-solving tasks, such as the RAT. This would be in line with previous studies observing that a better capacity to reduce the accessibility of strongly related concepts benefits creative performance (Abraham, 2014; Gupta et al., 2012). At the same time, the association between the inhibition index and RAT performance aligns with the experimental findings of Storm and Angello (2010) and Storm et al. (2011) and extends current knowledge by providing additional understanding. While Storm and Angello (2010) correlated an independent episodic inhibition index with RAT

problem-solving ability, in the present experiment the inhibition index was embedded in the main problem-solving task (Gómez-Ariza et al., 2017), providing valuable information on how episodic manipulations can subsequently influence creative performance and how episodic inhibition in the task itself is related to RAT solution.

Moreover, Experiment 3 investigated the neural correlates associated with this episodic inhibition, that are responsible for modulating the accessibility of relevant information required to solve the RAT. Previous neuroimaging studies have highlighted the role of the lateral prefrontal cortex in the implementation of inhibitory control during selective retrieval (for a review, see Anderson & Hulbert, 2020). Specifically, the right DLPFC (along with the ventrolateral prefrontal cortex and the anterior cingulate cortex) participates in the downregulation of interfering information during selective retrieval (Kuhl et al., 2007; Valle et al., 2020a; Wimber et al., 2015). Valle et al. (2020b), who used a selective retrieval paradigm but with an analogical reasoning test as the final task (i.e., A is to B as C is to…) that replaced the usual memory test, found that cathodal tDCS over the right DLPFC during selective retrieval eliminated the RIF effect. Thus, participants were able to use the competitor items as solutions in the analogical reasoning test to a similar extent as the baseline items. This result suggests that altering the natural functioning of the right prefrontal cortex disrupts the inhibitory processes that occur during selective retrieval, making previous competitors still accessible and retrievable for use in subsequent tasks.

In a similar vein, we wanted to explore whether modulating activity in the right prefrontal cortex may also change performance during creative problem-solving. In Experiment 3, cathodal tDCS was applied over the right DLPFC during the selective retrieval phase to disrupt inhibitory control. Our findings indicate that we conceptually replicated and extend the main results obtained by Valle et al. (2020a). TDCS seemed to disrupt a downregulation mechanism so that participants were able to use competitors as solutions to a similar extent as baseline solutions. However, the sham group showed the expected retrieval-induced impairment effect in the RAT. Importantly, the participants included in the analyses were only those who did not notice that the RAT problems could be solved with words from the first two experimental phases (Experiment 3). In

Experiments 1 and 2, the included participants had reported that they were unaware of this (or that they only noticed the connection during the last RAT problems). This suggests that participants did not use direct recollection strategies to solve the problems which would compromise an inhibitory interpretation of the retrieval-induced impairment in creative performance.

Resting-state EEG results in Experiment 3 support the idea that tDCS modulates retrieval-related processes. TDCS over the right DLPFC disrupted pre-post correlations for alpha and gamma band power that were present in the sham group. The alpha band has been associated with the regulation of access to information stored in long-term memory and the suppression of irrelevant or distracting information (Klimesch, 2012). Moreover, a study by Waldhauser et al. (2012) examined the electrophysiological correlates of selective retrieval using visual material. They manipulated the location of the presented items to control which hemisphere processed the memory representation. Their results showed an increase in alpha power in the hemisphere hosting the competitor representation. Alpha activity was associated with the activation of competitor memory traces during selective retrieval. This increase (along with the increase in beta power) was predictive of the amount of RIF found in the final memory test. On the other hand, gamma oscillations have been extensively associated with the formation and subsequent retrieval of episodic memories, and nested within theta rhythms, gamma oscillations help encode and retrieve sequences of events, supporting the temporal structure of episodic memories (see for a review Griffiths & Jensen, 2023; Griffiths et al., 2019; Heusser et al., 2016). Consistent with this, our resting-state EEG results in Experiment 3 may indicate that tDCS-induced changes in cortical excitability may be responsible for the disruption of pre-post consistency of alpha and gamma activity, which may contribute to a decrease in inhibitory control during selective retrieval.

A final consideration of the evidence obtained in Experiments 2 and 3 regarding episodic inhibition is that the information used in a memory task can later influence how accurately individuals solve creative problems (Gómez-Ariza et al., 2017). In this sense, previous studies highlight how the way concepts are dynamically represented can be shaped by long-term experiences, recent encounters, or the current context (Yee & Thompson-Schill, 2016). In this

dissertation, we provide evidence for how episodic memory dynamics can affect performance in an apparently independent task that relies primarily on semantic processes.

Finally, electrophysiological evidence in Experiment 4 supports the role of inhibition in creative problem-solving using a different approach. In this study, the focus was on the control of competition during the actual creative problem-solving task. Thus, instead of manipulating the accessibility of potential solutions, participants were exposed to competitive information that could induce fixation. That is, following an approach similar to Storm et al. (2011), participants encoded words that were related to the problems but were not the correct solution (misleading information) before attempting to solve RAT problems. The rationale here was that these misleading words would increase competition, and inhibitory control should be triggered to discard these interfering representations to facilitate correct problem-solving. The aftereffects of this downregulation were examined in a recognition test with only studied (not competitor), competitor and new words. Behaviorally, participants were slower to respond to competitor items than to studied items, suggesting poorer retrieval of these representations. EEG results indicated that competitor representations elicited a more positive FN400 component compared to that elicited by studied words. In addition, the late parietal positivity (LPP) component indicated stronger positivity for baseline words compared to competitor words. These results might indicate that although competitors were effectively recognized as earlier presented items (no differences in accuracy were found and they elicited stronger FN400), some difficulties were encountered during recognition as showed by their reduced LPP and slower response times. This result can also be interpreted in a similar way to those by Johansson and Hellerstedt (2014). In their study, during the first cycle of selective retrieval, there was a stronger FN400 elicited by the interference detection. Thus, one possible interpretation is that the stronger FN400 elicited by the competitors compared to studied items might be due to the reactivation of competitor representations. Finally, the reduced LPP generated by the competitors (in comparison to studied items) might indicate that, similar to other recognition experiments (Rugg et al., 1998), the retrieval of competitors was less efficient than the retrieval of studied items (Paller & Kutas, 1992).

Overall, the results obtained in Experiments 1, 3, and 4 highlight the relevance of inhibition during creative problem-solving either by producing changes in memory accessibility that occur prior to the problem-solving stage or during the actual problem-solving process by facilitating the achievement of a solution through competition resolution. This is consistent with the idea that inhibition plays a key role during creative problem-solving. Although the involvement of inhibition is controversial in the literature on creativity (Chrysikou, 2019), several considerations might help explain the lack of consistency. First, the definition of inhibition and the procedures used to assess it in the context of creativity are not consistent and/or appropriate. For example, one of the most commonly used tasks to measure inhibition during creative thinking is the Stroop task and its variants (Benedek et al., 2012; Edl et al., 2014; Groborz & Necka, 2003; Zabelina & Robinson, 2010). In the classic version of the Stroop task, participants are presented with a list of color words (e.g., *red, blue, green*) printed in different colors of ink. The task requires participants to name the color of the ink rather than reading the word itself. For example, the word *blue* might be printed in *red* ink, and the participant should say *red*. The *Stroop effect* occurs when there is a mismatch between the word and the ink color, resulting in slower response times and increased errors presumably due to the difficulty of inhibiting the automatic tendency to read the word rather than report the ink color. However, this task primarily measures interference (assumed to be the inverse of inhibition as defined in the context of creativity), which occurs when the meaning of a word conflicts with the task of naming the ink color (Parris et al., 2022; Naber et al., 2016). To claim inhibition as the mechanism mediating the effect, an independent measure of the difficulty of retrieving the inhibited information is needed. Thus, the Stroop task provides information about cognitive interference and the ability to manage conflicting information, but not necessarily about inhibition.

Another controversial point is that inhibition might have a flexible association with creativity, depending on the creativity task at hand (Allen & Thomas, 2011; Gilhooly et al., 2007). As shown here, the ability to inhibit interfering information is key to a specific creative problem-solving task; the RAT. However, the association with other divergent thinking tasks might not be

the same because the processes required to generate a solution are different. For example, generating an alternative use for a *brick* in the AUT does not present the same challenges as solving a RAT problem or imagining an animal living on another planet (Abraham et al., 2012; Benedek et al., 2012). Overall, in this dissertation we have provided evidence for the necessary inhibition of interfering information for successful RAT problem solving, however, additional studies are warranted to better understand the relationship between inhibitory control mechanisms and creativity across methodological approaches.

Conclusions

The ability to overcome challenges and face new problems is usually supported by the ability to retrieve previous useful experiences and solutions. However, in some situations this approach does not work and we need to think creatively to find an appropriate and correct solution. In this situation, associative and control processes have been described to participate in a dynamic interplay to come up with creative solutions. Our main goal in this dissertation has been to disentangle this interaction by focusing on cognitive functions relevant for creative problem-solving such as semantic memory, inhibitory control, and attentional scope using different approaches (i.e., individual differences perspective and using neuroscience techniques). Across four experiments, we have determined that semantic memory would be of particular importance for activating highly related information to be used for creative problem-solving. However, we found that more creative individuals (as measured by the RAT) do not exhibit a different semantic memory organization in which remote concepts are more easily activated. In addition, the evidence obtained here suggests that the semantic processes to generate creative solutions (at least in the RAT) are supported by a semantic network in which the left ATL plays an important role as a relevant integration hub (within a broader semantic brain network) responsible for binding semantic information into complex representations, and that theta band frequency is associated with this. Regarding other processes, it was observed that attentional scope has no discernible effect on creative problem-solving. The ability to inhibit episodic interfering information was related to

better creative problem-solving. As for the brain regions associated with episodic inhibition, the right DLPFC, and more broadly the right prefrontal cortex, is thought to be a hub within the control network that participates in the effective downregulation of interfering episodic information which lately turns out to be relevant to creative problem-solving, possibly through alpha and gamma oscillations. Finally, we showed that the downregulation of misleading information during creative problem-solving process has behavioral and electrophysiological consequences over this competing information.

Several questions remain unresolved and provide intriguing avenues for future research. For instance, further work is needed to clarify whether attentional scope exerts some kind of influence on creative problem-solving, possibly through the manipulation of the attentional breadth. Another compelling question is whether the distortions found in resting-state electrophysiological band frequencies are directly responsible for the behavioral differences found after neuromodulation. As a follow-up study of Experiment 4, new evidence is needed regarding the brain activity in terms of band frequency power associated with competition detection during RAT solution and its downregulation.

Resumen y conclusiones

La creatividad se considera una función cognitiva de orden superior, responsable de la generación de ideas o soluciones novedosas y originales a problemas, que además sean efectivas y relevantes en el contexto en el que aparecen (Acar & Runco, 2019; Dietrich & Haider 2015; Lubart et al., 2013). Cada persona es creativa a su propia manera. La creatividad puede manifestarse pintando un paisaje vibrante, cocinando un plato nuevo combinando ingredientes de forma inesperada, diseñando un puente sólido, innovador y además respetuoso con el medio ambiente, o descubriendo un fenómeno desde la ciencia que acabe siendo galardonado con un premio Nobel. Esta complejidad, lejos de desalentar su estudio, ha atraído considerable interés científico. Además, se han realizado grandes esfuerzos por diseñar paradigmas experimentales que capturen adecuadamente el desempeño creativo para asegurar que los constructos que la definen sean los apropiados y resulten útiles (Cortes et al., 2019; Guilford, 1967).

La curiosidad por conocer los procesos mentales que conducen a la generación de ideas creativas comenzó hace casi un siglo (Wallas, 1926). Diferentes modelos teóricos han tratado de describir estos procesos y sus correlatos cerebrales, y también cuáles son las razones por las que unas personas son más creativas que otras. En este sentido, un importante cuerpo de evidencia científica ha reemplazado nuestra concepción de la creatividad como una habilidad casi mística por otra más científica, como *un resultado extraordinario de procesos ordinarios* (Lubart, 1996, p. 681). Desde el estudio de la creatividad basada en una perspectiva cognitiva, cobran especial relevancia dos propuestas teóricas en las que se puede encuadrar esta investigación; el modelo asociativo de Mednick (1962) y el modelo de doble proceso (Sowden, 2019; Volle, 2018).

En su primera propuesta, Mednick postuló que los mecanismos claves para generar ideas o soluciones creativas son los asociativos. Es decir, una idea será creativa en tanto que las piezas de información activadas y combinadas para originarla estén distantemente relacionadas entre sí. El modelo se fundamenta en la clásica idea de que los conceptos y los hechos (nodos) se almacenan en

nuestra memoria formando redes interconectadas entre sí y que varían en los grados de asociación (Collins & Loftus, 1975). Por ejemplo, si presentamos la palabra *creatividad* a diferentes personas y les pedimos que digan la primera palabra que les viene a la mente, unos dirán *arte,* otros *solución de problemas,* otros *originalidad,* y es posible que alguno mencione a *un científico famoso*. Esto va a depender de sus propias experiencias, ya que diferimos en nuestras habilidades asociativas (Nelson et al., 2000). De aquí se deriva que las variaciones en capacidades asociativas son debidas a diferencias en las jerarquías asociativas entre conceptos, y que estas determinarían el potencial creativo. Personas con mayor potencial creativo tendrían una estructura asociativa más plana mientras que las personas con menor creatividad la tendrían más inclinada. Es decir, las personas menos creativas generarían menos conceptos, aunque fuertemente asociados a una palabra concreta. Y, a medida que la fuerza asociativa entre conceptos se reduce, menos probable sería que activen palabras lejanamente relacionadas. Por otro lado, las personas más creativas tendrían una estructura jerárquica más equilibrada en la que una palabra activa conceptos fuerte y remotamente relacionados de forma similar.

La propuesta de Mednick (1962) ha recibido una gran cantidad de apoyo empírico (Becker et al., 2022; Herault et al., 2024; Kenett et al., 2018). No obstante, resultados recientes defienden la necesidad de procesos adicionales, de regulación y control, que complementarían los procesos asociativos. El esfuerzo por crear algo nuevo se ve a menudo obstaculizado por la tendencia a recuperar información común y poco original (Benedek y Jauk, 2018; Luft et al., 2018). Por tanto, la ideación creativa no puede basarse únicamente en procesos asociativos, requiere procesos de control para restringirlos (Sowden et al., 2015). Se ha propuesto que los procesos de control intervienen de varias formas, entre ellas la supresión de ideas dominantes (Beaty y Silvia, 2012; Nusbaum y Silvia, 2011), la orientación de la búsqueda semántica (Baror y Bar, 2016; Luft et al., 2018) o la evaluación de respuestas candidatas (Chrysikou, 2019). De esta forma, el modelo de doble proceso (Sowden 2015; Volle, 2018) representa una progresión natural desde las teorías asociativas hacia la neurociencia cognitiva de la creatividad.

El modelo de doble proceso plantea una interacción dinámica entre procesos asociativos y de control en el pensamiento creativo (Benedek & Jauk,

2018; Sowden et al., 2015). En este contexto, la generación de ideas o soluciones creativas surge de un proceso asociativo (similar al propuesto por Mednick, 1962), en el cual se activan diversas representaciones almacenadas en la memoria y relacionadas con un estímulo a través de sus conexiones semánticas preexistentes. Al mismo tiempo, la generación de ideas está sujeta a la influencia de procesos de control, como la inhibición o la monitorización. Los procesos de control suprimirían las ideas comunes, al tiempo que supervisan que las ideas generadas cumplan con los requisitos de la tarea en cuestión. El control inhibitorio también podría evitar la interferencia de ideas relacionadas pero irrelevantes para la tarea (Gabora, 2010; Kenett y Austerweil, 2016; Kleibeuker et al., 2013; Mok, 2014; Zabelina y Andrews-Hannah, 2016). En definitiva, el modelo de doble proceso ofrece una explicación más completa y matizada de la creatividad, dando cuenta de la interacción dinámica entre los procesos asociativos y de control.

Como principal objetivo en esta tesis quisimos determinar la contribución relativa de procesos de activación e integración semántica y de control en el pensamiento creativo. Dentro de los procesos asociativos, nos focalizamos en la estructura de la memoria semántica como factor de especial relevancia (Kenett, 2018; Ovando-Tellez et al., 2022). En este sentido, diferentes líneas de investigación han demostrado que las personas creativas (comparadas con otras menos creativas) a) tienen una estructura de la memoria semántica con un mayor número de interconexiones entre conceptos, siendo menores las distancias entre ellos (Kenett et al., 2014; Luchini et al., 2023, b) consideran pares de palabras no relacionadas como más estrechamente asociadas (Rossmann & Fink, 2010; Gruszcka & Nęcka, 2002), y c) pueden generar más ideas, más rápidamente, y acceder a más asociaciones poco comunes en el proceso (Benedek & Neubauer, 2013).

Respecto a otros procesos no asociativos, nos centramos en el tipo de foco atencional y la inhibición de información interferente. Algunos estudios sugieren que la forma en cómo se atiende el ambiente puede afectar a la búsqueda semántica y la creatividad (Förster y Dannenberg, 2010; Martindale, 1999), mientras que otros estudios no han encontrado tales asociaciones (De Luca et al., 2022). La idea es que el tipo de foco atencional determina la cantidad de

estímulos que se procesan en el ambiente y también determina la cantidad y diversidad de información que se activa durante la búsqueda semántica para encontrar asociados remotos, afectando a la creatividad. Un foco atencional restringido haría que únicamente los conceptos muy estrechamente relacionados y familiares se activen. En cambio, un foco atencional amplio permitiría que se activen también conceptos más remotamente relacionados y con una accesibilidad inicial más baja, lo que aumentaría la diversidad de representaciones activas en accesibles (Chiu, 2015; Friedman & Förster, 2008; Liu, 2016; Wronska et al., 2018). Mantener un foco atencional amplio permite reconocer estímulos periféricos, lo que puede ser ventajoso durante la búsqueda semántica en tareas de creatividad (Wronska et al., 2018). Así, los individuos más creativos se podrían caracterizar por un foco atencional más amplio que podría facilitar la consideración de ideas remotamente asociadas como una posible solución (Finke et al., 1992; Martindale, 1995). En apoyo de esta idea, algunas investigaciones han demostrado que una mejor capacidad de resolución de problemas se ha asociado con una menor tendencia a inhibir información aparentemente irrelevante, lo que implica un foco atencional más amplio (Carson et al., 2003; Peterson et al., 2002). Sin embargo, también hay estudios que muestran que el foco atencional no influye sobre el desempeño creativo (Liu & Peng, 2018; Zabelina et al., 2016). Es más, De Luca et al. (2022) estudiaron en qué medida el foco atencional se transfería entre tareas (para una revisión, véase Förster y Dannenberg, 2010). Los resultados indicaron que los efectos de transferencia solo aparecieron para tareas visuales muy similares. Por lo tanto, este diverso abanico de hallazgos apunta a la necesidad de más investigaciones para determinar el papel del foco atencional en la creatividad.

Por otro lado, durante la resolución de problemas creativos la inhibición participaría en la supresión de la información irrelevante y la evaluación de las ideas o soluciones generadas (Cancer et al., 2023; Gupta et al., 2012; Luft et al., 2018). Varios estudios han examinado el papel de la inhibición durante el desempeño creativo, pero los resultados no son concluyentes. Es posible que el control inhibitorio funcione como un arma de doble filo; en algunos casos podría reducir la interferencia causada por la información competitiva, mejorando la búsqueda controlada. Sin embargo, durante las etapas iniciales de la generación

de ideas, donde las asociaciones son clave, los procesos de control podrían obstaculizar la creatividad, al limitar la cantidad de información considerada, (especialmente en tareas de final abierto; para una revisión, véase Amer et al., 2016). En definitiva, los expertos proponen que la importancia relativa de los procesos de control en el desempeño creativo dependería de los requisitos de la tarea específica (si la tarea requiere más estrategias dirigidas a objetivos) o de la fase del proceso creativo (Allen y Thomas, 2011; Gilhooly et al., 2007; Silvia et al., 2015).

Objetivos y consecución de los experimentos

Nuestro principal objetivo en esta tesis ha sido determinar la participación relativa de procesos asociativos y de control durante la solución de problemas creativos. Por ello, en el primer estudio titulado *Individual differences in semantic priming and inhibitory control predict performance in the Remote Associates Test (RAT*), nos focalizamos en determinar en qué medida la estructura de la memoria semántica, el foco atencional y la capacidad para inhibir información irrelevante predecían el desempeño en una tarea de solución de problemas creativos. Hasta ahora los estudios previos se han centrado en explorar la importancia de procesos asociativos y de control de forma independiente. En este estudio adoptamos una perspectiva basada en las diferencias individuales para determinar el peso relativo de cada factor.

Por ello, el primer experimento requería dos sesiones y donde en la primera los participantes realizaron una tarea de decisión léxica, para medir la estructura de la memoria semántica, y una tarea global-local (Navon, 1977), para medir su foco atencional. En la segunda sesión (separada de la primera por al menos una semana), los participantes realizaron la adaptación de la tarea de recuperación selectiva (SRP) seguida de la tarea de asociados remotos (RAT, por sus siglas en inglés; Gómez-Ariza et al., 2017). En la tarea de decisión léxica se manipuló el grado de asociación entre palabra primada y objetivo para obtener dos índices; uno de priming semántico fuerte y otro de priming semántico débil. De la tarea global-local, se obtuvieron los conocidos índices de precedencia global, e interferencia global y local. Respecto a la adaptación de la SRP, comparte

con la tarea clásica la inclusión de una fase de estudio de pares formados por una categoría y un ejemplar de la misma (e.g., CA-Canario, BA-Balanza, CA-Catedral). Después hay una fase de recuerdo selectivo, donde repetidamente se recuperan parte de los ejemplares de parte de las categorías, utilizando las iniciales como clave de recuerdo (e.g., CA-Cat_). La tarea estándar de SRP suele incluir una prueba de memoria (recuerdo señalado o reconocimiento), con la que se ha encontrado de forma robusta que los ejemplares asociados que compiten durante la práctica (e.g., Canario) tienden a ser peor recordados o reconocidos. La interpretación es que la recuperación selectiva activa mecanismos de control inhibitorio que reducen la accesibilidad de los ejemplares asociados que compiten con los objetivos del recuerdo (e.g., Canario) para facilitar la recuperación de estos últimos (e.g., Catedral). Sucesivos ciclos de recuperación generan que, posteriormente, aquellos ítems relacionados, pero no practicados se recuerden menos en comparación con los de la línea base (de categorías estudiadas, pero no practicadas), como consecuencia del efecto de esa inhibición producida durante la fase de recuperación selectiva. Este impedimento en el recuerdo o reconocimiento de los ítems competidores es conocido como *olvido inducido por la recuperación* (RIF, por sus siglas en inglés). En vez de tener una fase final de memoria, nosotros introdujimos una tarea creativa; el test de asociados remotos (RAT). En el RAT, los participantes tienen que tratar de resolver problemas formados por tres palabras que no tienen relación aparente entre sí, tratando de encontrar una cuarta palabra capaz de relacionarse con las tres del problema. La clave es que, para parte de los problemas, su solución fue una palabra de la fase previa, teniendo soluciones de categorías no practicadas y de categorías practicadas. De estas últimas, la mitad fueron competidoras y potencialmente inhibidas durante la fase de recuperación selectiva. Además, también se incluyó un set de problemas cuya solución era una palabra completamente nueva (problemas nuevos). Basándonos en el efecto RIF, calculamos un índice de inhibición episódica en creatividad a partir de la sustracción de los aciertos en problemas de la condición de línea de base menos los de competidores. Por otro lado, obtuvimos un índice de creatividad a partir de las respuestas correctas a problemas nuevos.

En este estudio esperábamos que el índice de creatividad correlacionara positivamente con los índices de priming semántico. En particular, esperábamos que esta asociación apareciera tanto para índices de priming semántico fuerte como débil, pero estábamos más interesados en el priming semántico con asociados débilmente relacionados ya que podría ser un buen índice para capturar asociaciones entre conceptos distantes (de acuerdo al modelo asociativo de Mednick). Además, asumiendo que podría haber una relación entre el tipo de organización en memoria semántica (más focalizado o más amplio) y el tipo de foco atencional, esperábamos una asociación positiva entre el potencial creativo (puntuaciones más altas en el RAT) y los índices de interferencia global y precedencia de la tarea global-local, pero una asociación negativa con la interferencia local en esta misma tarea. Estudios anteriores han demostrado que manipular el foco atencional en una tarea de fluidez semántica influía en el desempeño en una tarea creativa (Liu, 2016). Así, esperábamos un papel mediador del foco atencional de modo que una atención más global pudiera modular la preparación semántica y esto, a su vez, influir en el desempeño en el RAT. Además, esperábamos un efecto mediador del índice de priming semántico débil en la asociación entre el índice de priming fuerte y la creatividad. Finalmente, si el control inhibitorio es un proceso clave para reducir la interferencia de la información irrelevante que compite durante la recuperación, sería de esperar que un mayor deterioro inducido por la recuperación (un subproducto del control inhibitorio durante la recuperación selectiva) conllevara un mejor desempeño en la tarea de creatividad.

En los Experimentos 2 y 3, agrupados en el segundo estudio titulado *Dissociating Semantic Integration and Inhibitory Control in the Remote Associates Test: A tDCS-EEG Study*, nuestro objetivo fue determinar la participación de ciertas áreas cerebrales (de importancia para distintas redes) en los procesos de integración semántica e inhibición episódica durante la resolución de problemas RAT. Los estudios previos señalan el papel del lóbulo temporal anterior (por sus siglas en inglés ATL) como un centro de integración semántica que conecta información específica de modalidad almacenada en la corteza cerebral para crear representaciones conceptuales de carácter más amodal (Farahibozorg et al., 2022; Lambon Ralph, 2014; Snowden et al., 2018;

Zhao et al., 2017). Además, algunas líneas de evidencia sugieren una asimetría funcional, donde el ATL izquierdo es más relevante cuando se trata de información léxico-semántica (Alonso et al., 2021; Gainotti, 2012; Mion et al., 2010). Otros estudios han vinculado la actividad en el ATL izquierdo con la exploración de estructuras conceptuales para generar ideas creativas (e.g., Abraham et al., 2012, 2018; Aihara et al., 2017; Chi et al., 2011, 2012). Respecto a la inhibición episódica, se ha demostrado que la reducción de accesibilidad de la información que interfiere durante la recuperación selectiva está asociada con las cortezas prefrontales dorsolateral y ventrolateral derechas (por sus siglas en inglés DLPFC y VLPFC, respectivamente; Kuhl et al., 2007; Stramaccia et al., 2017; Valle et al., 2020; Wimber et al., 2015).

De esta forma, en los Experimentos 2 y 3 quisimos comprobar por medio del uso de la tDCS (estimulación transcraneal por corriente continua), si la alteración independiente de la actividad en el ATL izquierdo y en el DLPFC derecha podría afectar al desempeño en los problemas RAT, modulando los procesos de integración semántica e inhibición episódica, respectivamente. La tDCS implica la administración de una corriente eléctrica capaz de modular la excitabilidad cortical (Nitsche y Paulus, 2000), lo que podría permitir el establecimiento de relaciones causales entre actividad cerebral y procesos cognitivos. De esta forma, en dos experimentos diferentes se utilizó de nuevo el paradigma desarrollado por Gómez-Ariza et al. (2017) de recuerdo selectivo seguido del RAT y la tDCS (grupo activo o control) en ambas regiones, ATL izquierdo y DLPFC. Además, en ambos estudios se realizaron dos registros de electrofisiología (EEG) en estado de reposo, de una duración de 5 minutos cada uno, antes y después de la realización de la tarea, con la idea de tener medidas independientes de los efectos a nivel cortical de la neuromodulación.

En el Experimento 2, la tDCS se aplicó sobre el ATL izquierdo durante la fase inicial de estudio. La resolución de problemas nuevos necesariamente requiere de procesos semánticos más claramente que los problemas cuyas soluciones se han estudiado previamente, y que se basa en mayor medida en la memoria episódica. Por ello, se esperaba que la tDCS (anódica), en comparación con la tDCS placebo (control), sobre el ATL izquierdo afectara el desempeño de los problemas RAT cuya solución no se había presentado previamente en la sesión

experimental (problemas nuevos) en comparación a los problemas cuya solución había sido estudiada. Por otro lado, debido a que la tDCS se aplicó sobre ATL izquierdo, que no está directamente asociada con el control inhibitorio, no se esperaba ninguna diferencia en la inhibición episódica (comparativa en desempeño entre problemas estudiados y competidores) entre la tDCS real y la control.

En el Experimento 3, la neuromodulación se aplicó sobre el DLPFC derecho durante la fase de recuperación selectiva. En otros estudios, la tDCS real (catódica) sobre el DLPFC derecho durante la fase de recuerdo selectivo afecta negativamente al control inhibitorio que suele actuar sobre las representaciones que compiten, lo que las hace tan accesibles como las de las representaciones de las palabras de línea de base en posteriores pruebas de memoria o resolución de analogías (i.e., A es a B, como C es a ?; Valle et al., 2020a). Por ello, se esperaba que la tDCS real, pero no la de placebo, evitara las diferencias en el desempeño ante problemas cuya solución es una palabra competidora en comparación a los problemas cuya solución es una palabra sólo estudiada. Por el contrario, se esperaba que la tDCS tuviera un efecto nulo o menor sobre los nuevos problemas porque los problemas de RAT empleados en los estudios actuales no se crearon para ser resueltos en condiciones de alta competición (donde más claramente podría participar el DLPFC derecho).

Finalmente, en el Experimento 4 *Electrophysiological correlates of the consequences of competition in RAT problem-solving,* nos interesamos por los correlatos fisiológicos relacionados con los efectos de resolver la competición de representaciones durante la solución de problemas RAT. En este estudio, durante la primera fase, los participantes fueron expuestos de forma implícita a los errores más comunes cometidos por otros participantes en estudios previos durante la resolución de problemas RAT. En la fase de codificación, los participantes evaluaban del 1 al 3 las palabras (competidoras y control) en función de dos posibles tareas: juzgar cuánto les gustaba la palabra que aparecía en la pantalla o cómo de difícil opinaban que sería para un artista pintarla. Seguidamente, los participantes pasaban por dos ciclos de dos tareas diferentes, una de solución de problemas RAT y otra (de control) que les requería decir la palabra más larga en una triada. Finalmente, los participantes pasaron por una

prueba de reconocimiento con todas las palabras presentadas en el estudio y un set de palabras completamente nuevas. Se registró EEG durante toda la sesión experimental.

A nivel comportamental, esperábamos que tras la fase de codificación las representaciones de los competidores se reactivaran cuando se presentara el problema RAT asociado. A su vez, asumíamos que el intento de resolución de los problemas conllevaría la puesta en marcha de control inhibitorio para suprimir la interferencia causada por los competidores (una respuesta incorrecta muy común). Por ello, en la fase de reconocimiento esperábamos que las respuestas a los competidores fueran menos precisas y más lentas que las respuestas a las palabras de la condición de control y las nuevas (Anderson y Hulbert, 2021; Storm et al., 2011).

A nivel electrofisiológico nos centramos en los potenciales evocados relacionados (ERP por sus siglas en inglés). Esta medida ha sido ampliamente utilizada en estudios en el ámbito de la neurociencia cognitiva como marcadores de ciertos procesos cognitivos. Esperábamos detectar componentes ERP sensibles a la competición (y su resolución), así como a la familiaridad (palabras estudiadas frente a nuevas), durante la fase de reconocimiento. En este sentido, se esperaba observar dos componentes ERP bien documentados asociados con el reconocimiento antiguo/nuevo: el FN400 y la positividad parietal tardía (LPP).

Resultados

Los resultados obtenidos en estos estudios muestran de forma consistente que tanto la memoria semántica como la inhibición de información interferente son funciones implicadas en la solución de problemas creativos. Respecto a la modulación de la estructura de la memoria semántica (la forma en cómo se organizan los conceptos esa memoria) sobre la solución de problemas creativos, en el Experimento 1 encontramos que únicamente el índice de priming semántico fuerte predecía el desempeño creativo. El priming semántico débil no correlacionaba con la solución de problemas RAT. Por otro lado, el modelo de mediación realizado para determinar si el priming semántico fuerte explicaba una posible relación del priming semántico débil y la creatividad dio también

resultados nulos. Seguidamente, en el Experimento 2, se observó una diferencia significativa entre la solución exitosa de problemas completamente nuevos en función del grupo de neuromodulación al que pertenecían los participantes. Así, los participantes del grupo activo de tDCS sobre el ATL izquierdo resolvieron una menor cantidad de problemas completamente nuevos en comparación con el grupo control. Por otro lado, no hubo diferencias entre los grupos a la hora de resolver problemas cuya solución era una palabra sólo estudiada o una palabra competidora durante la recuperación selectiva. Así, replicamos el efecto RIF pues en ambos grupos los problemas cuya solución era una palabra solo estudiada se resolvían mejor que los problemas cuya solución era una palabra competidora. Seguidamente, y respecto al registro de EEG, mientras que las medidas de todas las bandas de frecuencia se mantuvieron estables para el grupo control (antes y después de la aplicación de la tDCS), para el grupo de tDCS real se perdió la correlación pre-post en la banda de theta. Es más, análisis de correlación entre el poder diferencial de theta y el desempeño para los problemas cuya solución era nueva (donde se había observado un efecto comportamental) revelaron que, para el grupo control, más cambio post-pre en theta estaba asociado con una mejor ejecución en los problemas nuevos. Esta correlación no se mantuvo en el grupo de tDCS real.

Respecto al componente de control inhibitorio, en el Experimento 1 encontramos que el índice de inhibición se asociaba positivamente con el desempeño en los RAT completamente nuevos. En relación al Experimento 3, los resultados indicaron una diferencia significativa en la habilidad de los participantes para resolver RAT cuya solución era una palabra que había sido competidora. De esta manera, la estimulación del DLPFC derecha hizo que, en comparación con el grupo control, los participantes fuesen capaces de resolver los problemas cuya solución fue una palabra competidora en similar medida que los problemas cuya solución se había solo estudiado. En cambio, el grupo control exhibió un efecto parecido al RIF en el contexto de la resolución de problemas, ya que resolvían más problemas cuya solución era solo estudiada que problemas con soluciones que habían competido durante la recuperación selectiva. Respecto a los problemas completamente nuevos, no se observaron diferencias entre ambos grupos de tDCS. Los análisis de los registros de EEG por bandas de frecuencia

mostraron un mantenimiento de la consistencia para el grupo control en las asociaciones pre-post para todas las bandas de frecuencia. Para el grupo tDCS real, sin embargo, esas correlaciones no emergieron para alfa y gamma.

Finalmente, y respecto al Experimento 4, durante la fase de reconocimiento no hubo diferencias entre palabras solo estudiadas y competidoras en cuanto a los aciertos, si bien los participantes respondieron significativamente de forma más lenta a los ítems competidores que a los únicamente estudiados. Este resultado es consistente con los hallazgos de Storm et al. (2011) y con la idea de que las representaciones de los ítems competidores son menos accesibles. Respecto a los datos de electrofisiología, fuimos capaces de replicar el clásico efecto viejo/nuevo en el test de reconocimiento, de forma que los ítems estudiados generaron una mayor positividad que los ítems completamente nuevos en el componente FN400 en regiones frontales. También se observó una mayor positividad en el componente LPP para los ítems estudiados en comparación con los nuevos que se ha asociado con procesos de recuperación. La comparación entre los ítems estudiados y los competidores reveló que los últimos estaban asociados a una mayor positividad en el efecto del FN400 en la zona frontal en comparación con los ítems nuevos. Por otro lado, y respecto al componente LPP, los ítems estudiados produjeron una mayor positividad en zona parietal en comparación con los ítems competidores.

Conclusiones

Nuestro objetivo principal en esta tesis ha sido desentrañar la interacción dinámica entre procesos asociativos y de control en la creatividad, centrándonos en la memoria semántica, el control inhibitorio y el foco atencional, y utilizando diferentes enfoques (diferencias individuales y comparaciones a nivel de grupo mediante el uso de técnicas de la neurociencia cognitiva). A lo largo de cuatro experimentos, hemos determinado que la memoria semántica sería de particular importancia para activar información fuertemente relacionada que se utilizará para la resolución de problemas de creatividad. Sin embargo, encontramos que los individuos más creativos (de acuerdo a medidas proporcionadas por el RAT) no exhiben una organización de memoria semántica diferente a los menos

creativos en la que los conceptos remotos se activen más fácilmente. Además, la evidencia obtenida aquí sugiere que los procesos semánticos necesarios para generar soluciones creativas dependen de una red cerebral que tiene como nodo importante el ATL izquierdo, un centro de integración responsable de la creación de representaciones complejas y, probablemente, ligado a frecuencias en la banda de theta. Con respecto al foco atencional, no se observó foco atencional una relación con la resolución creativa de problemas. Sin embargo, la capacidad para inhibir la información episódica interferente se relacionó con una mejor resolución de problemas. En cuanto a las regiones cerebrales asociadas con la inhibición episódica, la corteza prefrontal (dorsolateral y previsiblemente ventrolateral, como partes sustanciales de una red amplia de control cognitivo), parece estar directamente implicada posiblemente a través de oscilaciones en alfa y gamma. Finalmente, la regulación negativa de la información inapropiada durante el proceso de resolución creativa de problemas tiene consecuencias conductuales y electrofisiológicas sobre esta información competidora.

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