Electrophysiological correlates of interference control at retrieval predict performance on a subsequent analogical reasoning task

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Abstract

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

Keywords: retrieval, analogical reasoning, ERP

INTRODUCTION

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

Successful analogical reasoning is thought to comprise two main component processes; namely, retrieval of significant knowledge from long-term memory, and mapping or transfer from one domain to another (Gentner, 1983; Holyoak & Thagard, 1989). Much of the research to date has focused on mapping (Gentner & Smith, 2012), even though recent work has examined issues involving access to relevant knowledge and memory control processes during this type of inductive reasoning (Bowden, 1985; Keane, 1987; Kurtz & Loewenstein, 2007; Perfetto, Bransford, & Franks, 1983; Valle, Gómez-Ariza, & Bajo, 2019). The solver's ability to access potentially useful information at an appropriate moment is crucial to comprehend and use analogies. Thus, any factor capable of influencing the accessibility of relevant information from memory could affect problem solving as long as this information is required.

In this regard, recent research has shown that both analogical and creative problem solving as well as decision making are sensitive to the degree of accessibility of crucial information in memory (Fawcett & Hulbert, 2020; Gómez-Ariza et al., 2017; Iglesias-Parro, Gómez-Ariza, & Arias, 2009; Koppel & Storm, 2014; Storm & Angello, 2010; Storm, Angello, & Bjork, 2011; Valle et al., 2019). This research has drawn on previous experiments on the role of inhibition as a control mechanism in charge of downregulating competing information in memory during selective retrieval (Anderson, Bjork, & Bjork, 1994) and the retrieval-induced forgetting effect. In a typical variant of the Retrieval Practice procedure, participants encode category exemplar pairs (e.g. FRUIT-Apple; FRUIT-Banana; ANIMAL-Monkey) and later engage in selective retrieval practice on half of the items from half of the categories (RP phase). During this second stage, participants are given the category and a stem (e.g., FRUIT-Ap___) as cues to recall the corresponding studied exemplar. Finally, the participants' memory for the whole set of studied items is tested, for example, by providing the category plus the first letter as recall cues (e.g., FRUIT-B___; ANIMAL-M___). Two main results usually emerge from the final test. One, participants show superior recall for the practiced items (hereinafter, Rp+ items; apple in the example above). More relevant here, unpracticed exemplars of practiced categories (hereinafter, Rp- items; banana in our example) are recalled worse than also encoded exemplars from unpracticed (control) categories (hereinafter, Nrp items; Monkey in our case). This specific memory impairment for Rp- items that follow retrieval practice is known as retrieval-induced forgetting (hereinafter, RIF; Anderson et al., 1994) and is consistent with the idea that competing (Rp-) items were suppressed during retrieval practice to facilitate

selective retrieval and, hence, are harder to retrieve on a later memory test (Anderson, 2003; Levy & Anderson, 2008; see Murayama, Miyatsu, Buchli, & Storm, 2014 for a meta-analytic review; see Weller, Anderson, Gómez-Ariza, & Bajo, 2013, for an elaboration of the specific predictions from an inhibitory account)

Using an adapted RP procedure, Valle et al. (2019; see also Valle, Bajo, & Gómez-Ariza, 2020) showed that some analogical reasoning processes might unconsciously and adversely be affected by reduced access to relevant information. In their study, they influenced the retrievability of relevant information by having participants engage in retrieval practice right before an analogical problem-solving task. First, participants were presented pairs of category-exemplars items (e.g. MA-Maturity, MA-Make-up, DE-Detective) to study. After this, participants engaged in cued-recall of half of the exemplars from half of the categories (e.g., MA-Mak___). Lastly, and after a delay, participants were asked to solve analogies of the format 'A is to B as C is to?'. In these analogies, participants are expected to find the relation between the first pair of words and engage in mapping and relational transfer to come to a solution. Many of the solutions of these analogies matched the words previously studied (e.g. '*GREED is to GENEROSITY as INFANTILISM is to ?*' whose solution was '*Maturity*'), although participants were not told about this coincidence. In addition, the test also included analogies whose solutions were not presented in the context of the study. Interestingly, the results showed that Rp- items (e.g. Maturity) were significantly less produced as solutions than Nrp items (e.g. Detective) but generated as solutions to the same extent as unstudied (baseline) words (hereinafter Up items). Importantly, participants reported not to be aware of the connection between the memory and analogy tasks. This indicates that previous memory operations may impair analogical reasoning without noticing it (for related

results in creative thinking see Gómez-Ariza et al., 2017). As mentioned above, this reduction in accessibility for some (Rp-) items in memory has been interpreted as the result of inhibitory control, which is thought to be largely mediated by the right lateral prefrontal cortex (Kuhl, Dudukovic, Kahn, & Wagner, 2007; Wimber, Alink, Charest, Kriegeskorte, & Anderson, 2015), which acts to reduce activation of competing information during selective retrieval (Gómez-Ariza, Fernandez, & Bajo, 2012; Levy & Anderson, 2002; Weller et al., 2013). Supporting this interpretation, Valle et al., (2020) found that disrupting neural activity in the right prefrontal cortex during selective retrieval by means of tDCS eliminated the specific impairment for Rp- items to be later produced as analogy solutions.

Several studies have explored the neural correlates underlying inhibitory control during selective retrieval by employing brain imaging and electroencephalographical (EEG) techniques. Johansson et al. (2007) recorded EEG during selective retrieval practice and compared event-related potentials (ERP) during a standard competitive retrieval condition with those recorded during a re-learning condition in which retrieval was not required (nor was the need of interference control). They found positive-going ERPs over prefrontal regions to be sensitive to retrieval competition. Importantly, this stronger ERP positivity predicted individual differences in the reduced accessibility to Rp- items in a subsequent memory test. In a more recent study, Hellerstedt and Johansson (2014) manipulated the competition level during retrieval practice by modifying the associative strength between category cue and competitors. The authors reported that strong competitors elicited more positive amplitude onsetting around 300 ms after the category cue presentation over anterior and frontal electrodes. Importantly, this positive-deflection again predicted individual differences in

forgetting. The authors interpreted that this ERP may reflect the reactivation of associates to the category cue, congruent with the FN400 effect observed in previous ERP studies associated with conceptual priming and old/new familiar effects, but also interference and ensuing forgetting of the reactivated competing memories.

EEG measures have also been used to examine the neural correlates of analogical reasoning (Kmiecik, Brisson, & Morrison, 2019; Long et al., 2015; Maguire, McClelland, Donovan, Tillman, & Krawczyk, 2012; Qiu, Li, Chen, & Zhang, 2008; Zhao et al., 2011). These studies typically employ four-term analogies of the form 'A:B::C:D' and participants are generally asked to verify whether the given 'D ' term ' is related to C in the same way than 'A' is related to 'B'. These analogy problems are presented into isolated substages to better evaluate the involvement of encoding (base stimuli or 'A:B' terms), mapping (target stimuli or 'C' term) and response production (conclusion or 'D' term) processes. In a non-semantic analogy task (e.g., abc:abd::ijk:ijl), Qiu, Li, Chen, et al. (2008) reported that the 'A:B' stage elicited a negative ERP deflection (N500–1000) with dipole localization at the left thalamus and a positive component (P600–1000) with dipole localization at the medial prefrontal (BA10) and the left frontal cortex (BA6) possibly reflecting encoding and schema induction. Following the presentation of the 'C' term, a greater negativity (N400-600 component) over frontal electrodes is typically elicited that has been associated with activation of the schema and analogical mapping (Maguire et al., 2012; Qiu et al., 2008; Zhao et al., 2011). Altogether, these results suggest that the encoding and mapping processes appear to be well differentiated since different components are evoked. Nevertheless, although these studies have attempted to temporally disentangle the processes involved during the different stages of

analogical reasoning, none of them has examined memory dynamics making it difficult to understand its involvement during analogical processing.

The present work aims to examine the neural signatures of the effects of prior selective retrieval on analogical reasoning. Specifically, we wanted to learn to what extent reducing the accessibility of some target memories impact the mapping and/or retrieval processes of analogical problem solving. Because EEG provides high temporal resolution, we aimed to track temporal dynamics of the selective retrieval mechanism during both the retrieval practice phase, when inhibitory control of competing information is assumed to operate, and during the analogical reasoning task, when its detrimental effects should be observed. To this end, we adapted the procedure employed in Valle et al. (2019; see also Valle et al., 2020), in which the retrieval practice paradigm was introduced right after an analogical reasoning task, to influence the accessibility of potential solutions while electrophysiological brain activity was recorded. At a behavioral level, we expected to replicate the main results obtained by Valle et al. (2019): namely, those solutions that putatively had been the target of inhibitory control (Rp- words) were significantly less provided as solutions than control words (Nrp) in the subsequent analogy test. In addition, inhibited solutions were expected to be generated to the same degree than unstudied or unprimed (Up) words. As in Valle et al.'s (2019) experiments, specific efforts were made to minimize participants' awareness about the relationship between the memory and the analogical reasoning tasks. This would support the idea that the recruitment of inhibitory control during retrieval may have an effect on a subsequent reasoning task that requires this information to be accessible without awareness of the episodic nature of the provided solutions.

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

We further aimed to investigate the time course of these retrieval effects during analogical reasoning by isolating the stages of problem solving. Thus, we presented sequentially the A:B, C, and ? terms of the analogy to temporally separate the neural correlates of the distinct processes involved in the reasoning task. Previous research has linked the P600-1000 components elicited during the A:B stage to scheme induction processes (Qiu et al., 2008; Zhao et al., 2011), whereas the N400 component evoked during the C:? stage has been associated with analogical mapping (Maguire et al., 2012). Nevertheless, these studies have focused on mapping and integration processes by employing analogy decision tasks, in which the ERP correlates of solution retrieval were unclear. Electrophysiological studies examining the temporal dynamics of a target memory after the presentation of a retrieval cue have observed more positive-going ERPs for previously studied words relative to unstudied words approximately 400 ms after the onset of the stimulus

(Allan, Doyle, & Rugg, 1996; Allan, Wolf, Rosenthal, & Rugg, 2001; Angel, Fay, Bouazzaoui, & Isingrini, 2010; Osorio, Ballesteros, Fay, & Pouthas, 2009). This effect has been interpreted as an ERP correlate of successful episodic retrieval. In this regard, we hypothesized that the production of Nrp control solutions should evoke more positive-going frontal ERPs relative to baseline Up solutions since the Nrp items were previously experienced during the study phase, and the Up solution had never been presented in the context of the experiment. In contrast, and in accordance with behavioral data, we expected no differences between the amplitudes elicited by the generation of Rp- solutions and baseline Up solutions. This might reflect the weakening of the Rp- representations in memory at a similar level to that of Up items, which were never presented in the context of the experiment. We expected these ERPs patterns to be evident after the presentation of the C target and during the response time window (related to the retrieval of solutions). We also expected that reduced accessibility of specific Rp- items should not affect the mapping stage of analogical reasoning since inhibition was directed to specific items and not to the more abstract relational information needed for successful mapping. Accordingly, our approach would allow us to temporally disentangle the processes of mapping and solution retrieval during analogical reasoning.

METHOD

Participants

46 undergraduate students (mean age = 20.97 years; *SD* = 2.56) from the University of Granada participated in the experiment. A sample size greater than 30 participants was determined before conducting the study on the basis of the sample

sizes of two relevant previous experiments; namely, the one by Valle et al., 2019 that examined the effect of selective retrieval on a subsequent analogical reasoning task (with n = 30), and the one by Hellerstedt and Johansson (2014) that examined the electrophysiological correlates of competitor activation that predict retrieval-Induced forgetting (with n = 28). Because 46 participants contacted the experimenter after calling for participation, they all formed the original sample. One participant was excluded from the study because of excessive noise in the EEG recording and an insufficient number of trials for stable ERPs. Another participant was eliminated from the analysis because he/she indicated in the post-experimental assessment that he/she had noticed the relationship between memory and analogy tasks and applied explicit retrieval strategies to solve the analogical reasoning problems. Participants received either course credit or 12 euros for their participation, and they all signed informed consent previous to their participation. The study was approved by the ethics committee of the University of Granada in accordance with the standards of the Declaration of Helsinki.

Design

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

Material

In order to obtain stable ERP waveforms, we doubled the number of items used by Valle et al. (2019) in a similar behavioral experiment. Therefore, we employed two study lists (one per block), each list contained 54 words (108 total words) from

orthography-based categories (e.g., Maquillaje, Marinero, Matanza, Madurez, Maleta, and Manual for the category MA). These exemplars were to be used as practiced (Rp+) items, unpracticed items from practiced categories (Rp-) items, unpracticed-control items from unpracticed categories (Nrp), and unstudied-baseline (Up) items that were never presented in the context of the experiment. For one of the lists, we employed the same material used by (Valle et al., 2019). The other list was constructed according to the same criteria: (a) they started with their same two first letters (b) their third letter was unique (c) they were two to five syllables in length (d) they had no semantic associations with words belonging to the same category. We selected them from the Alameda and Cuetos (1995) database. As in the experiments by Valle et al. (2019), the lexical frequency of the items was controlled to ensure that the Rp- items were competitive enough to demand inhibitory control during retrieval practice (Anderson et al., 2004; Bajo, Gómez-Ariza, Fernandez, & Marful, 2006). Thus, each category consisted of three medium-low lexical frequency words (range= 10-36, *M*= 20.04) selected to be used as practiced (Rp+), unpracticed control (Nrp+) and unstudied (Up+) items and three medium-high lexical frequency words (range= 34-98, *M*= 59.91) selected to be used as unpracticed (competing) (Rp-), unpracticed control (Nrp-) and unstudied (Up-) items. The "+" and "-" designators are also used here to differentiate items as a function of their lexical frequency and for counterbalancing/matching purposes. Thus, high-frequency items (Rp-, Nrp- and Up-) were matched and analyzed separately from low-frequency items (Rp+, Nrp+, Up+). Nevertheless, participants were not aware that they would have to study words from different frequency ranges. In order to reduce primacy and recency effects, four additional categories were used as fillers.

We used 108 analogical reasoning problems of the form 'A is to B as C is to ?'. Verbal analogies are commonly used in verbal aptitude and standardized psychometric assessment tests (Meagher, 2006; Schalkwyk, 2011). Part of the analogies was the same as the ones Valle et al. (2019) employed in their experiments with the addition of new ones. The relationship between the pairs of terms was based on synonymy, antonymy, part to whole, object/action, cause/effect, degree, exemplar/category among others. The solutions to the analogies matched with each of the 108 target words described above (AVARICIA es a GENEROSIDAD como INFANTILISMO a..., whose solution would be MADUREZ; GREED is to GENEROSITY as INFANTILISM is to…, MATURITY). The set of new analogies were constructed taking into account the same criteria as Valle et al. (2019): both forward and backward associative strengths were < .20 according to Spanish free association norms (Fernandez, Díez & Alonso, 2014; Fernandez, Díez, Alonso, & Beato, 2004). This set of analogies was developed using a selection process in which the list of words to be used as solutions were compiled first, and then analogies whose solutions matched with this set of words were selected. We conducted a pilot norming study to make sure that the words to be used as solutions to the analogies matched with the other terms of the analogy and were really used as solutions by the participants. Thus, in this norming study preliminary test 45 participants were asked to produced solutions to the A:B :: C: ? analogies. We only selected those analogies that felt between 20% and 80% accuracy rates. These materials were assigned to two different lists each containing fifty-four cue-response pairs and fifty-four verbal analogies. The order of presentation of the lists was counterbalanced as well as the cue-response pairs to ensure that every category rotated throughout the different practiced conditions: practiced, unpracticed (competing and control) and unprimed.

Procedure

Participants went through two experimental blocks. Each block lasted around 1h (depending on the participant's performance) and was composed of a study phase, a retrieval practice phase, and an analogical test phase. The rationale of this division of the task was to prevent participants from studying, recalling and solving a large set of material without a break. Hence, we introduced a short break between the two blocks during which participants were told to rest and remain sited until new instructions were given. Both blocks differed in the set of materials assigned and the number of analogies. While the first block only included analogies that could be solved with Rp-, Nrp- and Up- items (9 items per condition, 27 analogy problems in total), the analogies in the second block could be solved with the Rp-, Nrp-, Up-, Rp+, Nrp+, and Up+ items (9 items per condition, 54 analogy problems in total). The rationale for not adding all the analogies during the first block was that we wanted to ensure participants were not aware of the relationship between the memory and analogical tasks until the end of the experiment (Valle et al., 2019). This has the consequence that the number of Rp+/Nrp+/Up+ items was relatively small (9 total trials per condition) in comparison to the number of Rp-/Nrp-/Up- items (18 trials per condition). Before the beginning of the actual experiment, participants were told that they would participate in two different experimental tasks: the first related to memory and the second with analogical thinking. They were also told that the session will be divided into two parts, each of them containing a memory and an analogical test. They were also informed that EEG will be recorded while they were performing the experimental tasks. Informed consent was obtained from all the participants. The whole experimental session lasted around 2h 30 min including the electrodes cap setting and removal and debriefing.

Study Phase

Participants were instructed to memorize category-exemplars pairs (MA-Madurez; MA-Maturity) for an upcoming memory test. Each pair (36 items per experimental block) appeared in the center of the screen for 5 s with a 1-s interstimulus interval. Filler pairs were presented at the beginning and at the end of the list to control for primacy and recency effects. The rest of the items were presented in a randomized order.

Retrieval Practice Phase

Participants had to repeatedly (three different cycles of practice) retrieve half of the exemplars from half of the categories by a given cue (e.g., MA-Mad___). The trials started with a fixation cross, followed by the category for 2 s (e.g., MA), a black screen for 1 s, the first three letters cue (e.g., Mad___) for 3 s, and a question mark during which participants were instructed to retrieve and then say aloud the corresponding word in order to prevent EEG speech artifacts. Each word was displayed three times pseudorandomly (9 items per cycle). At the end of the task, participants engaged in an arithmetic distractor task (they had to solve basic mathematic operations; e.g., 133 – 55) for 5 minutes.

Analogy test phase

During this phase, participants were asked to solve a set of verbal analogies. The presentation of each analogy involved three parts: first, the A:B terms (e.g., AVARICIA GENEROSIDAD; GREED GENEROSITY) were presented for 3 s; then after a short interval, the C term (e.g., INFANTILISMO; INFANTILISM) appeared for 3 s as a target stimulus; finally, a question mark was presented. Participants were asked

to find a solution and wait to respond until the question mark appeared. This was done in order to control for speech artefacts during the recording of the EEG signal. Before starting the analogical reasoning test, four practice trials were provided to solve the analogical problems and participants received feedback on these trials. In the second block, and in order to control for output interference, participants were presented first with the set of analogies whose potential solutions corresponded with Rp-/Nrp-/Up-. Then, they were presented with the set containing the remaining Rp+/Nrp+/Up+ items. As previously described, the first block only contained problems that could be solved with Rp-/Nrp-/Up- items. Within each set, the analogies were presented in random order for each participant. To prevent participants from attempting to solve the problems simply thinking back to the previously studied/practiced words, they were told that they were going to participate in two different experiments: One concerning memory and another one concerning analogical reasoning. Figure 1 depicts the experimental procedure for the two tasks.

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

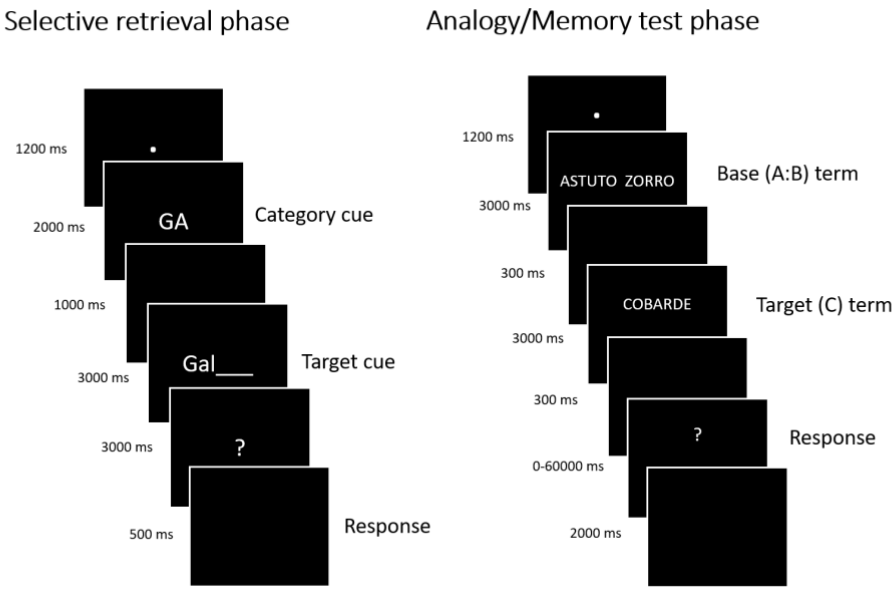

Fig. 1. Schematic representation of events during the selective retrieval phase and the analogy test.

EEG recording

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

ERP analyses

Different ERP analyses were conducted for the different phases in which EEG was recorded: the selective retrieval phase and the analogical reasoning test. In both

cases, before data analyses a high-pass filter at 1 Hz was applied and blinks, ocular movements and EKG artifacts were corrected by means of independent component analyses using the 'runica' function that can be found within the EEGLAB toolbox. The remaining artifacts were corrected by visual inspection. Bad channels with a high level of artifacts were detected by careful visual inspection and interpolated from neighbor's electrodes. Waveforms were low-pass filtered at 30Hz. Epochs were segmented into 1000 ms, including a 200 ms pre-stimulus period used as baseline correction. On the resulting epochs, we applied an automatic artifact rejection with an amplitude threshold of ±100 μV. Finally, epochs were averaged separated for each participant and trial type. Based on previous EEG research on retrieval-induced forgetting (Johansson et al., 2007), we extracted 8 regions of interest (ROI) from the 64 channels: anterior-frontal (FP1, FPZ, FP2), left-frontal (F7, F5, F3), right-frontal (F4, F6, F8), left-central (T7, C5, C3), right-central (C4, C6, T8), left-parietal (P7, P5, P3), right-parietal (P4, P6, P8), and occipital (O1, OZ, O2).

The rationale behind our ERP analysis is as follows. On the one hand, we expected the neural mechanisms underlying selective retrieval to change across retrieval attempts. In particular, the category cue should more readily reactivate competing associates during the first cycle of practice relative to the second or third cycles, when interference would have been overcome by inhibitory control (Johansson et al., 2007; Kuhl et al., 2007; Wimber et al., 2015). These differences were expected to be evident in an FN400, given that this ERP component has been associated with the reactivation of associates in cued recall (Hellerstedt & Johansson, 2014) and recognition memory tests (Opitz & Cornell, 2006). Thus, a Cycle (Cycle 1 vs. Cycle 2 vs. Cycle 3) x Region (anterior-frontal vs. left-frontal vs. right-frontal vs. left-central

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

Rp+ trials, our interest in getting stable and reliable ERP effects and our focus on the aftereffects of inhibitory control, we did not analyze the EEG recordings associated with the facilitation effect.

Finally, we correlated the magnitude of the ERPs observed during the selective retrieval phase and the subsequent retrieval-induced impairment (as the difference between problems solved with Nrp- items and those solved with Rp- items) in analogical reasoning. To this end, we calculated the ERP amplitude differences between cycles during the relevant time window and the cluster of electrodes with a reliable effect.

RESULTS

Behavioral results

Selective Retrieval Phase

Mean accuracy for the retrieval practice phase was 61.21% (*SD* = 14.82). A repeated-measures ANOVA performed on accuracy revealed a statistically significant effect of retrieval cycle, $F(2, 90) = 6.904$, $MSE = 1854.859$, $p = .002$, $\eta_p^2 = .133$. Bonferroni corrected post-hoc comparisons showed that retrieval success was higher in both the first (*M* = 65.82; *SD* = 19.73) and the third practice cycles (*M* = 64.21 *SD* = 19.57) than in the second one (*M* = 54.11, *SD* = 20.60; *p* = .009 and *p* = .014 respectively).

Analogy test phase

Mean accuracy for the analogy test was 42.99% (*SD* = 8.89). In order to check for an inhibitory effect, we conducted a repeated-measures ANOVAs as a function of the status practice/exposure of items (Rp- vs. Nrp- vs. Up-) on accuracy. Table 1 shows

the mean percentages of correctly solved analogies. In addition, and although the main focus of the experiment was not on the facilitation effect, for completeness we also performed a repeated-measures ANOVA to check for it (Rp+ vs. Nrp+ vs. Up+), since the number of Rp+ items and their controls was sufficient for behavioral analyses.

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

We also looked whether retrieval practice success predicted performance at test. However, Pearson correlation analyses failed to showed reliable relationships between mean accuracy during the RP phase and a) retrieval-induced impairment in solving analogies (r = .035, p = .819), b) analogies correctly solved in the control (Nrp-) condition (r = .127, p = .399), and c) analogies correctly solved in the baseline (Up-) condition (r = .250, p = .094).

Facilitation effect. The ANOVA showed a main effect of type of item, $F(2, 90) = 8.826$, $MSE = 1828.592$, $p < .001$, $\eta_p^2 = .164$. Bonferroni corrected post-hoc comparisons revealed that both Rp+ and Nrp+ words were significantly more generated as

solutions than Up+ words (both with $p < .001$). However, the difference between Rp+ and Nrp+ did not reach statistical significance ($p = .269$), even though there was a trend towards a benefit for Rp+ items. This lack of a facilitation effect does not come to a surprise since some previous RIF experiments have reported similar null findings (e.g., Gómez-Ariza et al., 2012; Valle et al., 2019; see also Levy & Anderson, 2008), especially when the testing procedure at the final test largely differs from the one used during the retrieval practice phase. In addition, the fact that success during the RP phase was relatively low (61.21%) probably left little room for Rp+ items to be much more produced than Nrp+ items as solutions.

Table 1

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

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

ERP data results

ERP Correlates of Cue presentation during Selective Retrieval

Grand means of ERPs evoked by the presentation of the category cue during the selective retrieval phase are plotted in Figure 2. There was a remarkable difference in amplitude over anterior frontal, left-parietal and occipital regions between ERPs elicited after the presentation of the category cue during the first cycle and the

presentation of the same category cue in the second and third cycle. This amplitude difference had its onset about 200 ms after the cue presentation and lasted approximately until 500 ms. Based on visual inspection of the grand average waveforms, we selected the 200-400 ms time window for analyses. These analyses revealed a statistically significant interaction between Cycle and Region [F(2.499, 112.437) = 3.744, MSE = 33.266, p = .019, η_p^2 = .077]. Planned comparisons on these results showed that the first cycle elicited stronger positivity than the second cycle F(1, 45) = 5.927, MSE = 22.057, p = .019 and the third cycle F(1, 45) = 5.635, MSE = 14.376, p = .021 over anterior frontal sites. Post-hoc comparisons revealed that there was also a stronger negativity over left parietal (p = .023, p = .014, respectively) and occipital (p = .039, p = .025, respectively) regions. The enhanced positivity associated with the presentation of the category cue during the first cycle, relative to the second and third cycle, is consistent with the interpretation that the FN400 effect reflects the reactivation of competitors. In addition, the enhanced negativity over left parietal and occipital locations across cycles may be related to the N300 component (a negative deflection over parietal and occipital areas that emerges between 300 and 400 ms after the onset of a stimulus) that it is thought to reflect perceptual cue detection (West, Herndon, & Crewdson, 2001). We also explored the time window ranging from 600 and 800 ms. since it might have reflected some type of recollection effects (Allan & Rugg, 1997). However, we failed to observe significant effects of Cycle (F(1.472, 66.247) = 2.015, MSE = 1.638, p = .153, η_p^2 = .043) or the interaction between Cycle and Region (F(2.907, 130.798) = 1.327, MSE = 15.334, p = .269, η_p^2 = .029).

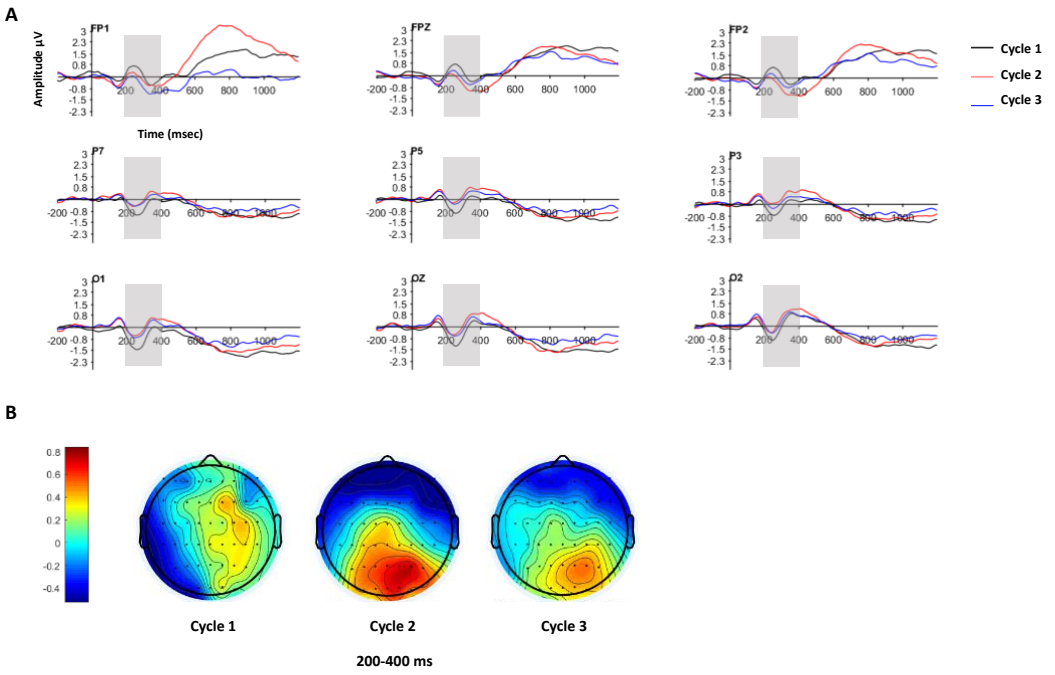

Fig. 2. (A) Plot of the ERPs waveforms elicited by the presentation of the category cue in cycles 1, 2 and 3 during the retrieval practice phase for anterior frontal, left parietal and occipital electrodes (FP1, FPZ, FP2, P7, P5, P3, O1, OZ, and O2). (B) Scalp maps show grand average topographies of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

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

Figure 3 displays the grand average waveforms evoked during the production stage of the analogy test as a function of the practice status of the solutions (Rp-, Nrp-, and Up-). Visual inspection of these waveforms showed that the most striking effect was a positive-going increase over anterior frontal electrodes when producing Nrp- items compared with Rp- and Up- items production. This effect began at approximately 300 ms and peaked at about 400 ms. For this reason, a time window

ranging from 400 to 600 ms was selected for the statistical analyses that revealed a significant interaction between Status of Practice and Region (F(2.142, 96.389) = 3.114, MSE = 44.472, p = .046, η_p^2 = .065). Follow-up analyses showed that the effect was restricted to anterior frontal (p < .01) and left-parietal electrodes (p = .05) indicating that Nrp- analogies elicited more positive going amplitudes than Up-problems. By contrast, in accordance with behavioral results, no statistically significant differences between Rp- and Up- solutions emerged.

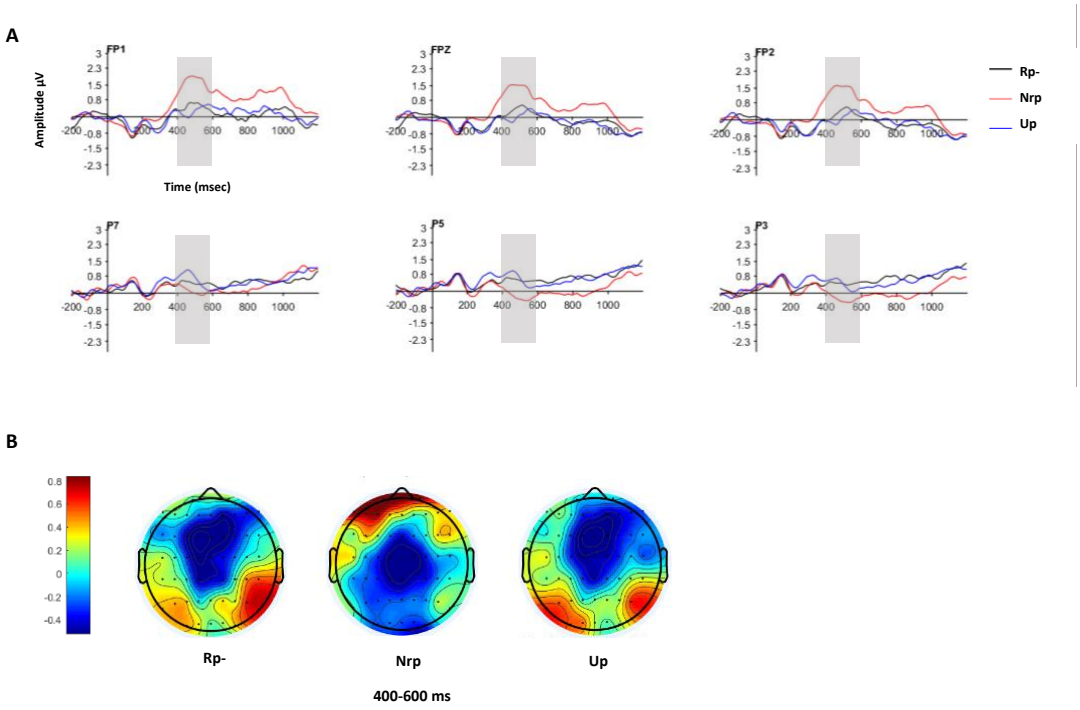

Fig. 3. (A) Grand-average ERPs results for conditions Rp-, Nrp- and Up- after participants solved the analogies over anterior frontal and left parietal electrodes (FP1, FPZ, FP2 and P7, P5, P3, respectively (B) Scalp maps show grand average topographies for Rp-, Nrp- and Up- analogies during the response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

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

Figure 4 displays the grand averages waveforms elicited by the presentation of the C term during the analogical reasoning task as a function of practice status (Rp-, Nrp-, Up-). As is evident from the visual inspection of the grand average waveforms, there were no differences in amplitude for Rp-, Nrp- or Up- analogies. Consistent with our predictions, in a time window ranging from 400 to 600 ms we failed to observe a significant main effect of Status of Practice (F(1.956, 88.001) = .254, MSE = .030, p = .771, η_p^2 = .006) or the interaction between Status of Practice and Region (F(3.928, 176.779) = 1.039, MSE = 2.686, p = .388, η_p^2 = .023). The later time window between 600 to 800 ms also failed to show significant effects [main effect: F(1.878, 84.497) = 2.023, MSE = .344, p = .141, η_p^2 = .043; interaction: F(3.151, 141.801) = 1.784, MSE = 8.985, p = .150, η_p^2 = .038].

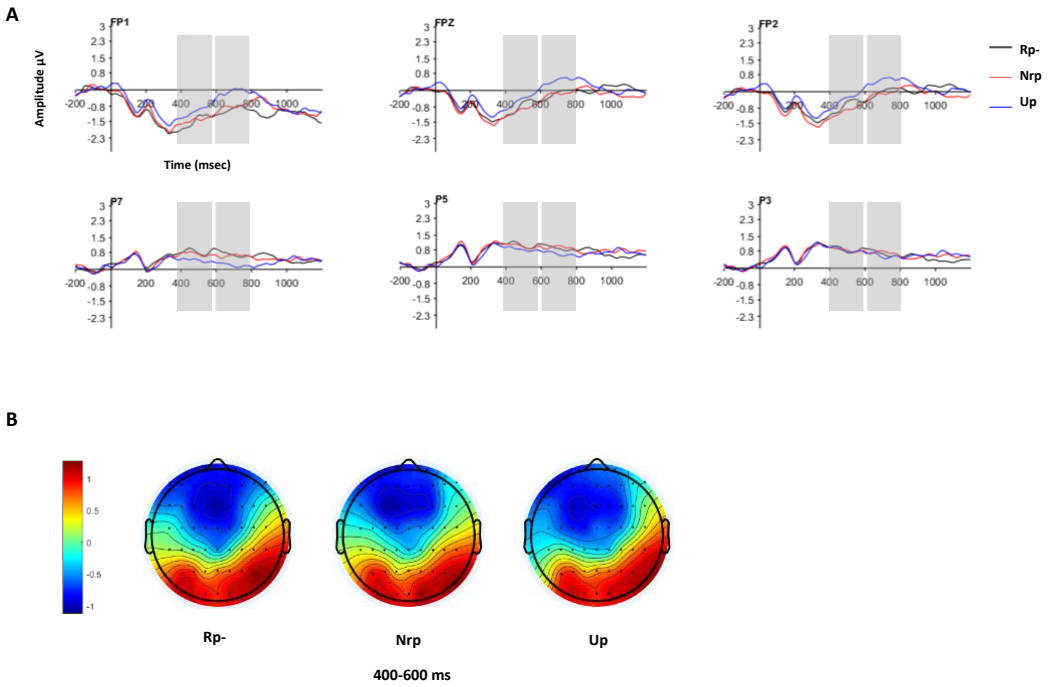

Fig. 4. (A) Grand-average ERPs results of conditions Rp-, Nrp and Up after the presentation of the C term during the analogical reasoning test for anterior frontal

and left parietal electrodes sites (FP1, FPZ, FP2 and P7, P5, P3). (B) Scalp maps show grand average topographies of Rp-, Nrp and Up analogies during the mapping stage of the analogy test.

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

We further explored whether the ERP amplitude differences over anterior frontal, left parietal and occipital regions between the first and third cycles during retrieval practiced predicted the amount of subsequent impairment in the reasoning task (see Figure 5). We calculated for each participant a RIF index by subtracting the percentage of Rp- correct solutions generated from the percentage of Nrp- solutions provided to the problems. This difference was then divided by the percentage of correct Nrp- solutions to obtain a relative measure of performance [((Nrp- – Rp-)/Nrp-) × 100]. Prior to analysis, scores above or below 2 standard deviations (SD) were winsorized by replacing each outlier with the next adjacent (non-outlier) value of the distribution (Wilcox, 2005). Interestingly, we observed a reliable positive correlation between ERP amplitude differences across cycles in the anterior frontal region and the retrieval-induced reasoning impairment (r = .333, p = .024). Nevertheless, no statistically significant effects were found when analogical performance was correlated with amplitude differences in the left parietal (r = -.042, p = .780) and the occipital (r = -.076, p = .617) regions.

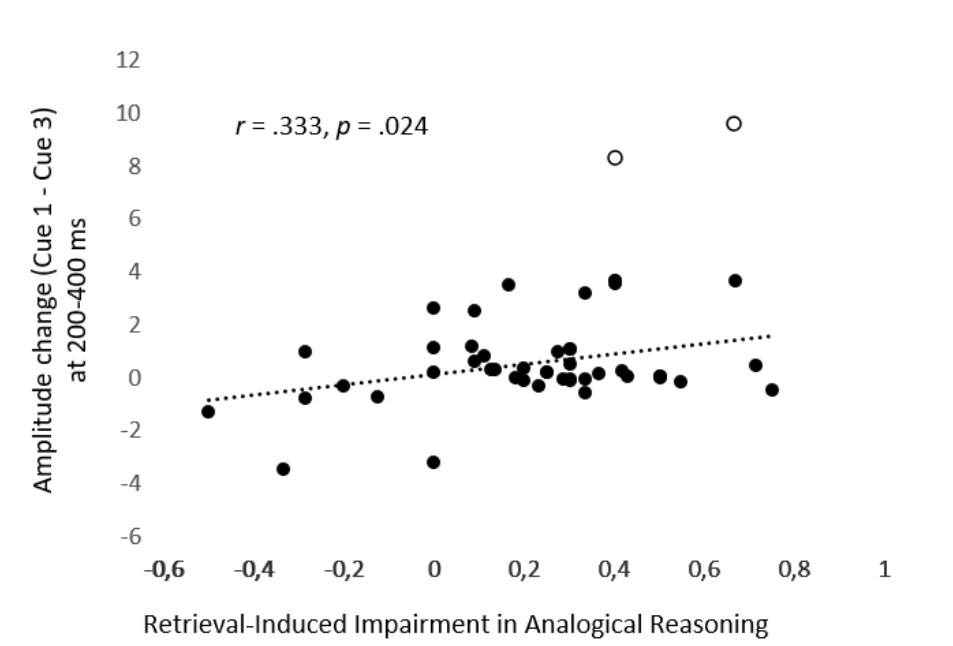

Fig. 5. Relationship of the brain-behavior results. The plot depicts the correlation of the amplitude difference elicited by the presentation of the category cue during the first and the third cycle over anterior frontal electrodes with the retrieval-induced forgetting effect on analogical reasoning. White points depict (winsorized) outliers.

DISCUSSION

The purpose of the present study was to track the neural correlates of selective retrieval and its possible differential effects on analogical mapping and retrieval in the subsequent reasoning task. Since EEG can reveal changes in patterns of brain activation with a high temporal resolution, we examined ERPs to investigate the time course of control processes during selective retrieval as well as to identify the extent to which externally induced reduced accessibility to relevant information differentially affected mapping and retrieval during analogical problem solving.

The present behavioral results are similar to those observed by Valle et al. (2019; 2020) showing that, after engaging in selective episodic retrieval, participants were less likely to produce Rp- solutions in comparison to Nrp- control solutions during the reasoning test. Critically, there was no difference between the generation of Rp- and Up- solutions that were not previously presented in the context of the experiment. This finding, together with the one obtained by Valle et al. (2020) after delivering cathodal tDCS over the right prefrontal cortex (which canceled out the impairment for Rp- items during the analogy test), suggests that control mechanisms during selective retrieval modulated the accessibility of a subset of items (those competing for retrieval during practice) that led to worse performance in those analogy problems that required the use of this information.

EEG recordings during the intermediate phase of the retrieval practice procedure enabled us to explore the neural mechanisms underlying selective retrieval throughout subsequent cycles of recall attempts. Growing evidence supports the idea that retrieval-induced forgetting relies on the reactivation of competing memory representations and their active suppression (Hellerstedt & Johansson, 2014; Johansson et al., 2007; Kuhl et al., 2007; Wimber et al., 2015). When higher levels of interference are thought to be elicited during the first retrieval attempt, repeated retrieval results in a lower level of interference across cycles (Anderson, 2003; Bäuml, Pastötter, & Hanslmayr, 2010; Staudigl, Hanslmayr, & Bauml, 2010). Along these lines, prior work has suggested that the detection of interference and its resolution during retrieval practice is related to theta oscillations (~4-8 Hz). For instance, Staudigl et al. (2010) found a reduction in theta amplitude when comparing the first and the second cycle of retrieval that predicted the amount of retrieval-induced forgetting. Similarly, in a recent study, Ferreira, Maraver,

Hanslmayr, and Bajo (2019) found that theta power decreased gradually across retrieval cycles. This would presumably reflect the successful down-regulation of interference. Interestingly, our results are consistent with this idea. The presentation of the category cue elicited more frontal activation in the first cycle than it did in the second and third cycles. Moreover, this positive-going deflection was observed in a time window that was similar to that of previous ERP studies, but it was elicited with an anterior frontal topographical distribution that parallels the FN400 component that has been associated with the reactivation of competitor associates and interference (Hellerstedt & Johansson, 2014).

The FN400 component has been also related to enhanced semantic memory representations after repeated exposure (referred to as conceptual priming; Paller, Voss, & Boehm, 2007) and old/new familiarity effects caused by the reactivation of memories previously associated with a retrieval cue in recognition tasks (Opitz & Cornell, 2006). However, in the present study, the observed FN400 effect elicited by the presentation of the category cue was sensitive to the repetitions showing less positive-modulation across cycles and, therefore, this finding is more consistent with the idea that the observed FN400 is related to interference. Thus, during the first retrieval attempt the category cue more readily reactivated competing associates relative to the second or third attempts, when interference would have been overcome by inhibitory control. Furthermore, the fact that the magnitude of the FN400 component correlated positively with the retrieval-induced impairment observed in analogical reasoning mimics previous results showing that the FN400 predicts the ensuing forgetting of the reactivated memories (Hellerstedt & Johansson, 2014). Overall, this indicates that the FN400 effect may be a marker of

the memory reactivation that is crucial to triggering inhibitory control mechanisms to prevent competing items from interfering over target memories retrieval.

An additional goal of this study was to explore the EEG correlates of the detrimental effect that previous inhibitory control may have on analogical reasoning. With this purpose, we sought to disentangle analogical mapping and solution retrieval processes through the sequential presentation of the A:B, C and D terms. Remarkably, the mapping phase failed to reveal significant amplitude or latency differences as a function of the practice status of the solutions. This indicates that analogical mapping was not noticeably affected by the accessibility level of candidate solutions to the analogies. Note that mapping in analogical problem solving requires access to the more abstract relationship between the two domains, while our manipulation reduced the accessibility to the specific item's representations that were needed to solve the problems. Thus, the ERPs elicited during the response production stage and captured by anterior frontal and left parietal electrodes differed according to the items' practice status (induced by selective retrieval). In particular, Nrp- solutions elicited a more positive deflection than Up solutions. By contrast, the comparison of the waveforms elicited from Rp- and Up- items failed to reveal statistically significant differences in the same time window. Similar ERP amplitudes for Rp- and Up- solutions are indicative of how deeply inhibitory control during selective retrieval specifically affected competing memory representations, without influencing more abstract relational information needed for successful mapping. Thus, these findings suggest that the response production phase of analogical reasoning is particularly sensitive to changes in memory accessibility and further expands our understanding of the temporal

aspects of retrieval processes influencing analogical reasoning during the response stage, but not during the mapping stage.

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

Although it was not a goal of the present study to test the inhibitory account of RIF, a final point that deserves attention is whether a non-inhibitory interpretation of RIF phenomena might account for the present results. The below-baseline accessibility that Rp- items exhibit after selective retrieval can, in principle, be accounted for associative blocking (Raaijmakers & Jakab, 2013; Verde, 2012). From this view, selective retrieval specifically strengthens the association between the practiced (Rp+) items and the retrieval cues (i.e., the category label) used. As a result, if at test Rp- items are cued with such retrieval cues, Rp+ items would be facilitated so blocking the access to Rp- items. It is to note, however, that finding

retrieval-induced impairment with a testing procedure as the one used here (problem solving; see also Gómez-Ariza et al., 2017; Valle et al., 2020, 2019) is a unique prediction from an inhibitory framework (for an elaboration of the cue-independence property of RIF, see Weller et al., 2013). Since accessibility to memory representations was assessed with cues and a task set different from the ones employed during selective retrieval, the first block of reasoning problems circumvented the potential interference from Rp+ solutions over Rp- ones (for similar arguments on a related inhibitory paradigm, see Wang, Luppi, Fawcett, & Anderson, 2019). Hence, altogether, the present behavioral and electrophysiological results directly support a frontally-mediated inhibitory account of retrieval-induced forgetting (Hellerstedt & Johansson, 2014; Johansson et al., 2007; Kuhl et al., 2007; Román, Soriano, Gómez-Ariza, & Bajo, 2009; Valle et al., 2020; Wimber et al., 2015).

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

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

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