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RESEARCH ARTICLE

Time course of EEG power during creative problem-solving with insight or remote thinking

Théophile Bieth^{1,2}  | Marcela Ovando-Tellez¹  | Alizée Lopez-Persem¹  |
 Béatrice Garcin^{1,3}  | Laurent Hugueville^{1,4}  | Katia Lehongre¹ |
 Richard Levy^{1,2} | Nathalie George^{1,4}  | Emmanuelle Volle¹ 

¹Sorbonne Université, Institut du Cerveau—Paris Brain Institute—ICM, Inserm, CNRS, APHP, Hôpital de la Pitié Salpêtrière, Paris, France

²Sorbonne Université, Institut du Cerveau—Paris Brain Institute—ICM, Inserm, CNRS, APHP, Hôpital de la Pitié Salpêtrière, DMU Neuroscience, Paris, France

³Department of Neurology, Avicenne Hospital, AP-HP, Bobigny, France

⁴Institut du Cerveau—ICM, Inserm U1127, CNRS UMR7225, Sorbonne Université, Centre MEG-EEG, CENIR, Paris, France

Correspondence

Emmanuelle Volle and Théophile Bieth, Sorbonne Université, Institut du Cerveau—Paris Brain Institute—ICM, Inserm, CNRS, APHP, Hôpital de la Pitié Salpêtrière, Paris, France.
 Email: emmanuelvolle@gmail.com and theo_bieth@hotmail.fr

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Abstract

Problem-solving often requires creativity and is critical in everyday life. However, the neurocognitive mechanisms underlying creative problem-solving remain poorly understood. Two mechanisms have been highlighted: the formation of new connections among problem elements and *insight solving*, characterized by sudden realization of a solution. In this study, we investigated EEG activity during a modified version of the remote associates test, a classical insight problem task that requires finding a word connecting three unrelated words. This allowed us to explore the brain correlates associated with the *semantic remoteness* of connections (by varying the remoteness of the solution word across trials) and with *insight solving* (identified as a Eurêka moment reported by the participants). *Semantic remoteness* was associated with power increase in the alpha band (8–12 Hz) in a left parieto-temporal cluster, the beta band (13–30 Hz) in a right fronto-temporal cluster in the early phase of the task, and the theta band (3–7 Hz) in a bilateral frontal cluster just prior to participants' responses. *Insight solving* was associated with power increase preceding participants' responses in the alpha and gamma (31–60 Hz) bands in a left temporal cluster and the theta band in a frontal cluster. Source reconstructions revealed the brain regions associated with these clusters. Overall, our findings shed new light on some of the mechanisms involved in creative problem-solving.

KEYWORDS

creativity, EEG, Eurêka, insight problem-solving, semantic distance, source reconstruction, time-frequency

1 | INTRODUCTION

Solving problems can be a societal challenge, an opportunity for progress, or a personal concern. We constantly have to find solutions to

new problems and adapt ourselves to new situations, from everyday life (e.g., how to reorganize my workspace at home) to worldwide concerns (e.g., how to avoid global warming). Problem-solving requires creativity (called here creative problem-solving) when there is no obvious or previously established rule to solve a newly encountered problem or when the heuristics or rules we spontaneously use are

Nathalie George and Emmanuelle Volle contributed equally to this study.

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inefficient or lead to an impasse. In creative problem-solving, we need to change our mental representation of the problem by recombining the elements of the problem in new ways or by finding new connections between seemingly unrelated elements. In some cases, the solution comes to mind suddenly and spontaneously, with a *Eurêka* phenomenon (Topolinski & Reber, 2010). This type of problem-solving is usually considered as *insight solving* (Kounios & Beeman, 2014; Weisberg, 2013). It relates to the illumination phase of the creative process model developed from the reports of eminent scientific discoveries or artistic creations (Wallas, 1926). Combining remote elements and *insight solving* are considered as central aspects of creative thinking, but the underlying neurocognitive mechanisms are still poorly understood. Are these two aspects of problem-solving related? What happens in the brain when solving a problem requires combining remote concepts or elicits a *Eurêka* experience? Here, we explored these questions using EEG during a problem-solving task assessing creative abilities.

Combining remote elements is a core component of the associative theory of creativity initiated by Mednick (1962). According to his approach, creativity relies on the ability to form new combinations from unusual associations. In this framework, it is not the result that should be considered as creative but the manner in which it has been produced. This theory emphasizes the critical role of associative thinking for creativity, supported by studies showing that more creative individuals can more easily connect remote concepts in memory and show a less rigid and subdivided semantic memory organization (Benedek & Neubauer, 2013; Kenett, 2014; Kenett & Faust, 2019; Ovando-Tellez et al., 2023). Mednick's theory was operationalized in the remote associates test (RAT), which consists in finding a word connecting three given unrelated cue words (Mednick, 1962). The RAT is often used as a creative problem-solving task: it requires forming a new combination of distant elements of knowledge, and it often elicits an experience of insight or *Eurêka* in participants (Bowden et al., 2005; Kounios & Beeman, 2014; Topolinski & Reber, 2010). Solving the RAT has been correlated with various measures of creativity (see Wu et al., 2020 for a review). Several versions of the RAT have been developed using either lexical (compound words) (Bowden & Jung-Beeman, 2003) or semantic associations between the cue words and the solution word (Oltețeanu et al., 2019), or using pictures instead of words (Becker & Cabeza, 2021; Oltețeanu & Zunjani, 2020). Our lab developed a semantic associative version of the task (the combined associates task [CAT]) (Bendetowicz et al., 2017, 2018; Ovando-Tellez et al., 2023) in which we controlled the semantic association strength (SAS) between the expected solution and the three cue words. This operationalized in a unique manner Mednick's hypothesis, according to which the more remote the elements to be combined, the more creative the process (Mednick, 1962). *Semantic remoteness* is central in other approaches of creativity, such as divergent thinking (Beaty & Johnson, 2020; Volle, 2017) and the associative theory of creativity (Beaty & Kenett, 2023; Benedek et al., 2023). However, the effect of *semantic remoteness* is less known in highly constrained creativity tasks, such as the RAT. Our group pioneered the exploration of this question and

found previously that the difference in performance between low and high SAS (respectively, distant and close) trials of the CAT correlated with other creativity measures such as creative behavior (Bendetowicz et al., 2017), divergent thinking (Bendetowicz et al., 2017), or performance in other *insight solving* tasks (Bieth et al., 2021), thus providing ecological support for the CAT. More recently, the role of semantic distance in RAT solving has been described (Becker et al., 2022). Hence, investigating the effects of *semantic remoteness* during the CAT and their related brain correlates can help us better understand some important neurocognitive mechanisms of creative problem-solving. However, although the brain correlates of semantic distance have been studied in divergent thinking tasks (Beaty et al., 2017; Green et al., 2012; Marron et al., 2018, 2020), the role and the neural correlates of the remoteness of the solution in the context of RAT solving remain poorly known.

A previous lesion study identified two distinct brain regions and networks as critical to CAT-solving when *semantic remoteness* increases (Bendetowicz et al., 2018). First, the medial prefrontal cortex (PFC), which is part of the default mode network—a network related to spontaneous cognition and associative thinking (Andrews-Hanna et al., 2010, 2014)—was critical for the spontaneous generation of remote associates. Second, the rostro-lateral part of the PFC, which is involved in the executive control network (Power & Petersen, 2013; Yeo et al., 2011), was critical for combining remote associates. These results are consistent with the associative theory of creativity, but they also emphasize the importance of controlled processes during CAT-solving (Jones & Estes, 2015). They converge with the findings from functional connectivity on divergent thinking in healthy subjects (Beaty et al., 2016), extend these findings to convergent thinking tasks (CAT), and demonstrate the necessity of both default mode and executive control networks in creativity. The interaction of these networks for CAT performance according to the *semantic remoteness* of the trials was recently confirmed in a connectome modeling study in healthy participants (Ovando-Tellez et al., 2023). Hence, our previous findings using CAT shed new light on the neural correlates of combining remote associates, while most previous neurocognitive studies that used RAT-like tasks focused on the insight phenomenon (Wu et al., 2020; but see Becker et al., 2021).

RAT-like tasks are helpful to explore *insight solving* because they provide multiple short trials, allowing to compare trials with and without insight, and fit better the constraints of neuroimaging studies than other insight problem-solving tasks do (e.g., riddles). Currently, the subjective report of *Eurêka* experience during problem-solving on a trial-by-trial basis is the most common measure used to study insight (Laukkonen & Tangen, 2018). *Eurêka* report corresponds to the subjective experience that arises when the solution comes to mind suddenly and effortlessly, without being able to report the mental steps that led to it. According to some insight theories (Sprugnoli et al., 2017), the *Eurêka* moment may follow an initial failure to solve the problem (due to reaching a mental impasse) and the overcoming of it by a reorganization of the problem representation (Ohlsson, 1992).

The critical question of the neural underpinnings of insight problem-solving remains unanswered. A few studies explored the

brain correlates of insight problem-solving using functional MRI. They reported the involvement of frontal regions (anterior and posterior cingulate cortex, inferior frontal gyrus), temporal regions (temporo-polar region, superior and middle temporal gyri, hippocampus) and the insula, during RAT-like tasks (Aberg et al., 2016; Anderson et al., 2009; Becker et al., 2020, 2021; Jung-Beeman et al., 2004; Luo & Niki, 2003; Subramaniam et al., 2009; Tik et al., 2018) or other insight tasks (Aziz-Zadeh et al., 2009; Dietrich & Kanso, 2010; Lin et al., 2018; Qiu et al., 2010; Shen et al., 2016). Electrophysiological methods such as EEG provide invaluable information on the time course of information processing and the brain dynamics associated with cognitive processes. Thus, they have the potential to capture the suddenness of the Eurêka experience (Jung-Beeman et al., 2004; Sandkühler & Bhattacharya, 2008). A pioneering study reported that RAT trials solved with Eurêka (compared to those solved without Eurêka) were associated with a power increase in the alpha band in the right parieto-occipital areas around 1.5 s before the participant's response, followed by a gamma burst in the right antero-superior temporal lobe 0.3 s before the participant's response (Jung-Beeman et al., 2004). Alpha and gamma oscillations have been associated with *insight solving* in other studies that used the RAT (Luft et al., 2018; Sandkühler & Bhattacharya, 2008) and in other insight paradigms (Oh et al., 2020; Rosen & Reiner, 2016; Sheth et al., 2009). Independently of *insight solving*, two studies reported a power increase in the theta band in prefrontal electrodes and in the beta band in fronto-temporal electrodes when contrasting RAT solving with a simple word generation task (Razumnikova, 2007) or a category fluency task (Danko et al., 2009).

Solving a creative problem such as the CAT likely involves different neurocognitive mechanisms (Wu et al., 2020), such as combining remote elements (Mednick, 1962) and *insight solving* (Bowden et al., 2005). Overall, the few existing neuroimaging studies of creative problem-solving focused on insight and the effect of the *semantic remoteness* of the elements to be combined has been overlooked. We are unaware of other studies that manipulated the associative remoteness of the solution word in the RAT coupled with neuroimaging. Yet, as mentioned above, investigating the neurocognitive mechanisms of remote elements combination is central to the understanding of creative thinking. In the present study, we jointly investigated the EEG correlates of *semantic remoteness* and *insight solving* using the CAT (Bendetowicz et al., 2017, 2018). The *remoteness* of the solution word was varied across trials and *insight solving* was explored by collecting the subjective reports of Eurêka on a trial-by-trial basis. Most previous EEG studies using RAT-like tasks restricted their analyses to specific frequency bands or groups of electrodes (Dietrich & Kanso, 2010) or did not control the *semantic remoteness*. This did not allow us to form precise whole-brain predictions on the brain correlates of the CAT. However, based on Kounios and Beeman's study (Jung-Beeman et al., 2004), we expected that *insight solving* would be associated with a pattern of alpha activity followed by gamma activity in temporal regions during the period preceding the response. For the *semantic remoteness* of the solution, which likely involves both controlled and semantic processing (Bendetowicz et al., 2018; Ovando-Tellez

et al., 2023), no existing EEG/MEG studies tested it. Alpha activity, which has been associated with remote thinking especially during divergent thinking (Fink & Benedek, 2014), was our main expectation. Therefore, we adopted a data-driven, exploratory approach with no spatial, temporal, or frequency a priori for both aspects. Data were analyzed at the sensor level and then source localized in order to build bridges with the existing fMRI literature. We hypothesized that the effects of *semantic remoteness* and *insight solving* are associated with distinct brain EEG activities in space and time.

2 | MATERIALS AND METHODS

2.1 | Participants

Twenty-three right-handed native French speakers aged from 21 to 25 years old (mean age = 23.04; standard deviation, $SD = 1.15$; 13 women) were included in the study. All participants were healthy adults with MMSE ≥ 28 (Folstein et al., 1975), no history of neurological and/or psychiatric illness, no psychoactive substance abuse or consumption less than 24 h before the experiment. Two participants were excluded because of technical problems during the experiment. The analyzed sample thus consisted in 21 healthy adults (mean age = 22.95, $SD = 1.15$ years old, 12 women). A national ethical committee approved the study. All the participants gave their written informed consent and received financial compensation for their participating in the study.

2.2 | Experimental task

EEG was recorded during the performance of the CAT (Bendetowicz et al., 2017, 2018), which is an adapted version of the RAT (Mednick, 1962). In this task, participants are asked to provide a word that connects three unrelated cue words. Our adapted version varied the SAS between the cue words and the expected solution based on the French associative norm (Bendetowicz et al., 2017, 2018; Debrenne, 2011). Briefly, the SAS quantifies the proportion of participants who produced the word B when given the word A in a free word association task. For instance, if 383 of 538 participants responded "cat" when they were presented with the word "dog," then the SAS between "cat" and "dog" was 71 (i.e., $383/538 \times 100$). CAT trials were designed so that (1) the three cue words were poorly associated with each other in the French associative norm (i.e., from the 100 trials, 68 trials used unrelated cue words, 31 trials used cue word with an $SAS \leq 2$, and one trial had two cue words with an $SAS = 25$, based on the French associative norm) and (2) had variable SAS with the solution word. We selected words from the French associative norm tested on at least 450 adult native French speakers. We considered the average SAS between the expected solution and each of the three cue words within each trial. Hence, every trial was characterized by an SAS value: the lower the SAS value, the more remote the solution was from the cue words (an example trial with a low SAS

value—hence distant solution—is “Bridge-Social-To tie,” where the solution is “Link”; an example trial with a high SAS value—hence close solution—is “Street-Countryside-Centre,” where the solution is “Town”). Previous studies using the CAT (Bendetowicz et al., 2017, 2018) have shown that the performance in this task, especially for distant trials, correlated with other creative assessments, supporting its external validity. Following the same principles as in the original CAT, we built 28 additional trials for the current study in order to anticipate the loss of analyzable trials due to EEG experimental constraints and artifacts. In total, each participant performed 100 trials (median SAS value 6.5, range from 0.3 to 38.8). We aimed to build trials in which the solution was as much as possible equidistant (or equifrequent) from the cue words. The limited number of the French associative norm allowed us to partially achieve this goal. Overall, the variability measured by the standard deviation (SD) of the cue-solution words' SAS was on average 2.43 in distant trials (i.e., trials with SAS < median SAS value) and 12.26 in close trials (i.e., trials with SAS > median SAS value).

During the experiment, the participants were seated comfortably in front of a computer screen. Before starting the task, the examiner explained the general design and instructions with written support. Explanations on Eurêka were particularly detailed. It was described as “the subjective experience you can have when you solve a problem, and the solution comes to mind suddenly, it is not the result of cognitive efforts, and you are not able to report the mental steps leading to this solution.” It was opposed to analytic solving in which “you have a strategy and the feeling of gradually getting closer to the solution.” We clarified that these two solving methods were not incompatible or exclusive and instructed the participants to consider only a few seconds before their response. To ensure the participants understood the instructions correctly, they completed 10 practice trials, and the

instructions were repeated when needed. After instructions and training, the participants performed 100 trials in random order while EEG was recorded. Breaks were proposed to the participants every 25 trials to limit fatigue.

The CAT was computerized and programmed using Psychtoolbox (version 3.0.11) running in MATLAB (version 9.0, R2016a) (Figure 1). For each trial, the three cue words were displayed on the center of the screen, one above the other, to limit eye movements as much as possible. The participants were asked to give a unique word related to all three cue words and had up to 30 s to respond. They were aware that the response could be a noun, a verb, or an adjective, but neither a proper noun nor a compound word. As soon as they thought they had found the correct answer, they pressed the space button on the keyboard. This made the three cue words disappear, and the participants had then a fixed time of 2.5 s to tell their response verbally. The screen remained blank during this period. The examiner wrote down the participant's response. In addition, as classically performed in previous studies using similar tasks, we collected the self-reported Eurêka experience on a trial-by-trial basis (Kounios & Beeman, 2014). Thus, after the 2.5 s response period, the question “Eurêka?” was displayed on the screen. The participants had to indicate whether the solution they gave came to their mind with a Eurêka by pressing the keyboard letters “V” (Eurêka) or “N” (no Eurêka) within a time limit of 5 s. A central fixation cross was displayed during the intertrial interval of jittered duration (mean = 1.5 s, range between 1.2 and 1.8 s).

2.3 | Behavioral measures and analyses

Accuracy (correct or incorrect responses) was determined based on the French associative norm (Bendetowicz et al., 2017; Debrenne, 2011).

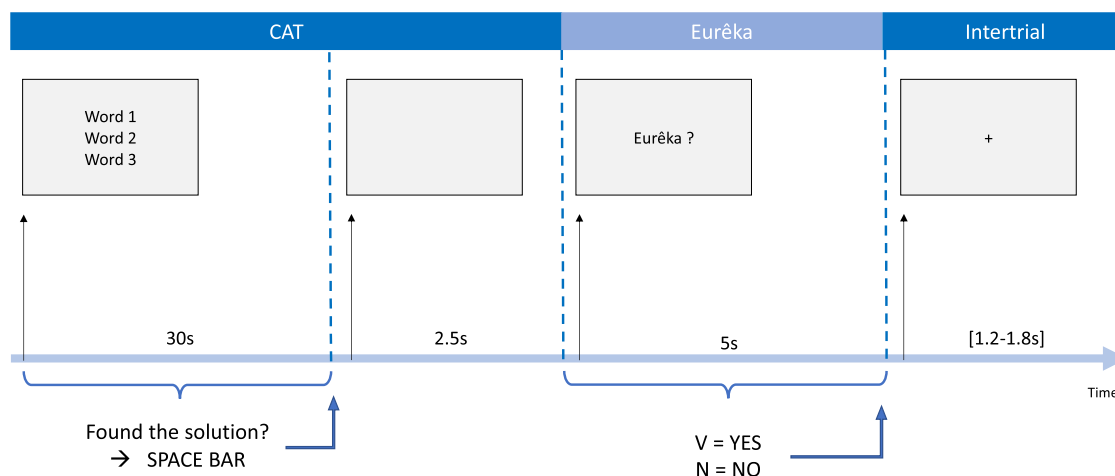


FIGURE 1 Combined associates task (CAT) procedure. Each trial started with presenting three unrelated words, vertically displayed on a gray screen for up to 30 s. The participants pressed the space bar as soon as they thought they had the solution, triggering the display of a blank screen during 2.5 s. They verbalized their response during this period. Then, the question “Eurêka?” was displayed on the screen, and the participants indicated whether the solution that they just had gave came to their mind with a Eurêka, using the keyboard letters “V” (yes) and “N” (no), within a time limit of 5 s. Finally, a fixation cross was displayed on the screen for a random interval before a new trial began (intertrial interval between 1.2 and 1.8 s).

Responses were also considered valid if they were lexically similar (e.g., “a stop” and “to stop”) or synonyms (e.g., “wizard” and “sorcerer”) to the one defined by the French associative norm. Finally, a few additional answers were accepted if they provided semantic similarities with the cue words but were not in the French associative norm. In this case, we asked five external judges to assess whether the new response was related to all the cue words of the considered trial. The new response was considered correct if at least two judges evaluated that a relationship existed. We defined response time (RT) as the time between the onset of the display of the cue words and the space bar press.

Each trial was characterized by its *SAS* value (a continuous variable determined by the material and fixed across participants) and was also categorized according to how the participant solved it (with or without *Eurêka*, a binary variable that varied across trials and participants). To estimate the effect of *semantic remoteness* (*SAS*, independent continuous variable) on accuracy (binary dependent or outcome variable) and RT (continuous dependent or outcome variable), we first computed individual logistic regression (*glmfit* function with binomial distribution in Matlab) and individual linear regression (*glmfit* function with normal distribution in Matlab) respectively. Then, we computed one-sample two-tailed *t* tests (against zero) on the resulting individual regression coefficients in order to test the statistical significance of the effect of *SAS* on accuracy and RT—respectively—at the group level.

To estimate the effect of *insight solving* (*Eurêka*, independent binary variable), we explored how many trials were solved with and without a *Eurêka*. To examine whether trials solved with a *Eurêka* differed from those without a *Eurêka*, we compared the average percentage of *Eurêka* and no *Eurêka* trials and the average RT of trials with and without *Eurêka* across participants, using nonparametric paired Wilcoxon tests. We focused on correct trials, as incorrect ones were excluded from the EEG analysis.

Finally, we explored the link between the effects of *SAS* and *Eurêka* using a two-level modeling approach. First, we ran a generalized linear regression (*glmfit* function in Matlab) at the individual level, including only the correct trials. We used logistic regression to explore whether the *SAS* (continuous independent variable) predicted the *Eurêka* trials (binary dependent variable). As we expected the *SAS* to be correlated with RT, we removed the variance explained by RT from the *SAS* variable before running this regression. Then, we performed group level analysis. We computed a one-sample two-tailed *t* test (against zero) on the obtained individual regression coefficients reflecting the relation between *SAS* and *Eurêka* across participants.

2.4 | EEG

2.4.1 | EEG recording

EEG data were recorded using BrainAmp DC system (Brain Products GmbH, Munich, Germany) with 64-active electrodes mounted in an elastic cap (actiCAP) according to the extended International 10–20 system and including a row of low fronto-temporo-occipital electrodes (PO9/10, TP9/10, FP9/10). Two additional electrodes were

used as reference (FCz electrode) and ground (AFz electrode). Disposable electrodes placed above and below the right or left eye and lateral to the outer canthus of both eyes recorded vertical and horizontal EOG, respectively. Electrode impedances were at or below 10 kOhm. The EEG data were recorded at 1 kHz with an online 0.016–250 Hz band-pass filter.

2.4.2 | EEG preprocessing

All EEG preprocessing and analyses were performed using the FieldTrip toolbox (Oostenveld et al., 2011), completed by homemade scripts, and Brainstorm (version 09-Sep-2020) (Tadel et al., 2011), running under MATLAB (version 9.0, R2016a).

EEG signal was downsampled offline to 128 Hz, and filtered with zero phase, third order, high-pass and low-pass, Butterworth filters (set at 0.5 and 63 Hz, respectively). Independent component analysis (ICA) was used to detect and remove artifacts caused by eye blinks. On average, two independent components (IC) were removed after the visual inspection of the time series and topographies of the IC. Then, the EEG signal was visually inspected to exclude artifacts related to muscles or movements. Next, noisy channels were interpolated using the averaged signal of adjacent channels. A mean of seven electrodes ($SD = 2.1$) was interpolated across participants. Trials containing more than 10% of bad channels were removed (11 trials per participant on average, $SD = 6.5$). Finally, the signal was rereferenced to the average of all electrodes (recovering the FCz channel).

We segmented the EEG signal for each trial in two time windows of interest. First, the “initial time window” corresponded to the 2 s period following the onset of the cue word display on the screen. Second, the “RT window” corresponded to the 2 s period preceding the space bar press (i.e., the participant's response). We considered only correct trials for EEG data analysis. We chose not to analyze incorrect trials since the cognitive involvement of the participants in incorrect trials is uncontrolled. We excluded the trials with an RT shorter than 4 s to avoid the overlapping of our two time windows of interest (14 trials excluded on average per individual, $SD = 9.5$).

The average number of analyzed trials across individuals is presented in Table S1. In addition, supplementary analyses are provided to ensure that there was no unbalance between the number of trials analyzed across the experimental conditions of *semantic remoteness* (*SAS*) and *insight solving* (*Eurêka*/no *Eurêka*) (see *Supplementary material* and Figure S1).

2.4.3 | Time-frequency analysis

Time-frequency maps were computed for each electrode, trial, and time window (initial and RT windows) in a frequency range between 3 and 60 Hz. We used a multitaper time-frequency transform (Slepian tapers, lower frequency range: 3–32 Hz, six cycles and three tapers per window; higher frequency range: 32–60 Hz, fixed time-windows of 240 ms, and 4–31 tapers per window). This approach allows better control of time and frequency smoothing. It uses a constant number

of cycles across frequencies up to 32 Hz (hence, a time window with a duration that decreases when frequency increases) and a fixed time window with an increasing number of tapers above 32 Hz in order to obtain more precise power estimates by adaptively increasing smoothing at high frequencies. Hence, the resulting EEG power represents the signal amplitude in a given frequency after its spectral decomposition. Time courses were aligned to the onset of the cue word display for the initial time window (corresponding to time 0 for the initial time window epochs) and to the space bar press for the RT window (corresponding to time 0 for these latter epochs). We performed a z-score baseline correction of time-frequency maps using the time interval from -1.2 to -0.1 s before the onset of the display of the cue words on each trial (same baseline time window for both the initial and response epochs). Finally, time-frequency maps were averaged along the frequency dimension according to the four frequency bands: theta 3–7 Hz, alpha 8–12 Hz, beta 13–30 Hz, and gamma 31–60 Hz.

2.4.4 | Task-based statistical analysis of time-frequency data

As for the behavioral analysis, we used a two-level statistical analysis approach at the sensor level. First, we used individual linear regressions to evaluate the relation between EEG power and task-related experimental variables at the participant's level. To explore EEG correlates of *semantic remoteness*, we used EEG power as the dependent (or outcome) variable, and SAS as the independent variable. To explore *insight solving*, EEG power was the dependent variable (or outcome) and the Eurêka report was the independent variable. These two analyses were performed independently at the individual level for each point in time and sensor space, in each frequency band (theta, alpha, beta, gamma), and for each time window (initial and RT window). This first level of analysis allowed us to obtain regression coefficients at the individual level. Then, at the second (group) level, the resulting individual regression coefficients were analyzed across participants with cluster-based permutation tests (Maris, 2012; Maris & Oostenveld, 2007). These tests were performed for each frequency band (theta, alpha, beta, and gamma) and time window of interest (initial and RT window). They allowed us to correct for multiple comparisons across the time and space (electrode) dimensions (Maris, 2012; Maris & Oostenveld, 2007) and consisted of the following steps. First, we compared the obtained individual regression coefficients against vectors of zero (of length equal to the number of participants) at each time point and on each electrode, using the two-sample paired t test across participants implemented in Fieldtrip. This allowed us to test our regression coefficients against zero since one-sample t test as such is not implemented in Fieldtrip toolbox. The (electrode, time) pairs yielding significant results ($p < 0.0125$) were grouped together based on their spatial and temporal adjacency. This p -value was chosen because we did not cluster our data across the frequency dimension and performed our analysis separately in each of the four frequency bands of interest ($0.05/4 = 0.0125$). It allowed reducing the risk of false positives during the cluster formation. We computed

the sum of the t -test statistics for each obtained cluster ($\text{sum}(t)$). Then, we used a Monte Carlo procedure to build the distribution of the cluster-based $\text{sum}(t)$ statistics under the null hypothesis. The individual regression coefficients were randomly permuted with the zero vector values for each participant. This permutation was performed at the participant level, that is, it was applied to all (electrode, time) points. The previously described two-sample t test and clustering procedure was applied to the permuted data, the $\text{sum}(t)$ of the clusters obtained was computed, and the maximum $\text{sum}(t)$ value was retained. This permutation procedure was repeated 1000 times to obtain the distribution of the cluster statistics under the null hypothesis, effectively corrected for multiple comparisons. Finally, the $\text{sum}(t)$ values of the clusters obtained from the original data were compared to this distribution and considered significant if they were within or beyond the 5% highest values of the $\text{max}(\text{sum}(t))$ obtained across the 1000 permutations, corresponding to a corrected p -value (p_{corr}) of .05.

Finally, as we performed a cluster-based permutation test for each frequency band, we checked whether the resulting clusters survived a Bonferroni correction for multiple comparisons, that is, whether each cluster's p_{corr} value was lower than $.0125 (=0.05/4)$.

2.4.5 | Source reconstruction

Using source localization, we explored the brain regions related to the significant clusters observed at the sensor level. We analyzed the cortical sources in the time windows and the frequency bands in which significant clusters were found. We used the Brainstorm software that is freely available for download online under the General Public License (<http://neuroimage.usc.edu>; Tadel et al., 2011).

For each individual, first, a head model was computed using the symmetric boundary element method from OpenMEEG open-source software (Gramfort et al., 2010), based on the template MRI normalized in the Montreal Neurological Institute (MNI) system, available in Brainstorm software (MNI/Colin27), and coregistered with the 65 electrodes considering standard 10–10 electrode coordinates. Next, the noise covariance matrix was computed from all trials considering the baseline time period preceding the onset of the word triplet (-1.2 to -0.1 s). Sources were then computed at the trial level using preprocessed EEG signal (i.e., 128-Hz, ICA-corrected, average-referenced EEG signal). We applied a weighted minimum norm imaging method with current density map measures computed for 15,000 trihedral dipoles—total of 45,000 elementary dipoles, equivalent to sources unconstrained in their orientation—distributed over the cortical mantle of the brain model obtained from the standard MNI/Colin 27 brain template. Then, we computed the power within the considered frequency band using a Hilbert transformation at the source level for each cluster identified at the sensor level (i.e., in each time window and frequency band of interest). Since we used unconstrained orientations for the sources, we computed the time-frequency decompositions for all 45,000 elementary dipoles and summed the power for the three orientations at each source location (or vertex) as recommended. Finally, power was averaged within the time window of the cluster and then averaged across trials separately for each studied

experimental condition. This procedure was repeated for each participant. The obtained cortical current power maps were averaged across participants for trials with a lower and higher SAS than the median SAS value (6.5) (distant and close conditions, respectively) and for trials solved with or without a Eurêka (Eurêka and no Eurêka conditions, respectively). Then, we contrasted the maps between conditions (Distant minus Close conditions or Eurêka minus no Eurêka conditions) according to the considered cluster. We did not run further statistical analysis at the source level to avoid double-dipping. The cortical current power maps were thresholded to visualize only sources with activity higher and lower than 10% of the absolute maximal source.

3 | RESULTS

3.1 | Behavioral data

Overall, mean accuracy across individuals was 57.4% (SD = 12.0), and mean RT was 8.4 s (SD = 1.0).

We found a significant relationship at the group level between the SAS and accuracy ($\beta_{\text{mean}} = .11$, SD = 0.04, one sample t test: $t(20) = 12.04$, $p = 1.29 \times 10^{-10}$) and the RT ($\beta_{\text{mean}} = -.07$, SD = 0.07, one sample t test: $t(20) = -4.64$, $p = 1.58 \times 10^{-4}$). These results suggest that the closer the solution was from the cue words, the higher the solving rate was (Figure 2a). Of note, these results were unchanged after excluding trials with outlier values of SAS (see Supplementary Data S1).

On average, the participants reported a Eurêka in 55.6% (SD = 20) of the correct trials (and in 22.7% (SD = 16.4) of the incorrect trials), whereas they declared no Eurêka in 44.1% (SD = 21.1) of the correct trials (and in 49.1% (SD = 20.5) of the incorrect trials). The percentages of Eurêka and no Eurêka did not statistically differ within the correct trials ($W = 149$, $p = .26$). However, the mean RT were significantly shorter in the trials correctly solved with Eurêka than in the trials correctly solved without Eurêka (respectively, 6.8 s [SD = 2.1] and 11.4 s [SD = 3.8], $W = 216$, $p = 1.31 \times 10^{-4}$, Figure 2b).

We examined how *semantic remoteness* related to Eurêka reports by computing logistic regressions at the individual level (see Section 2). The results showed no significant effect of SAS (orthogonalized from

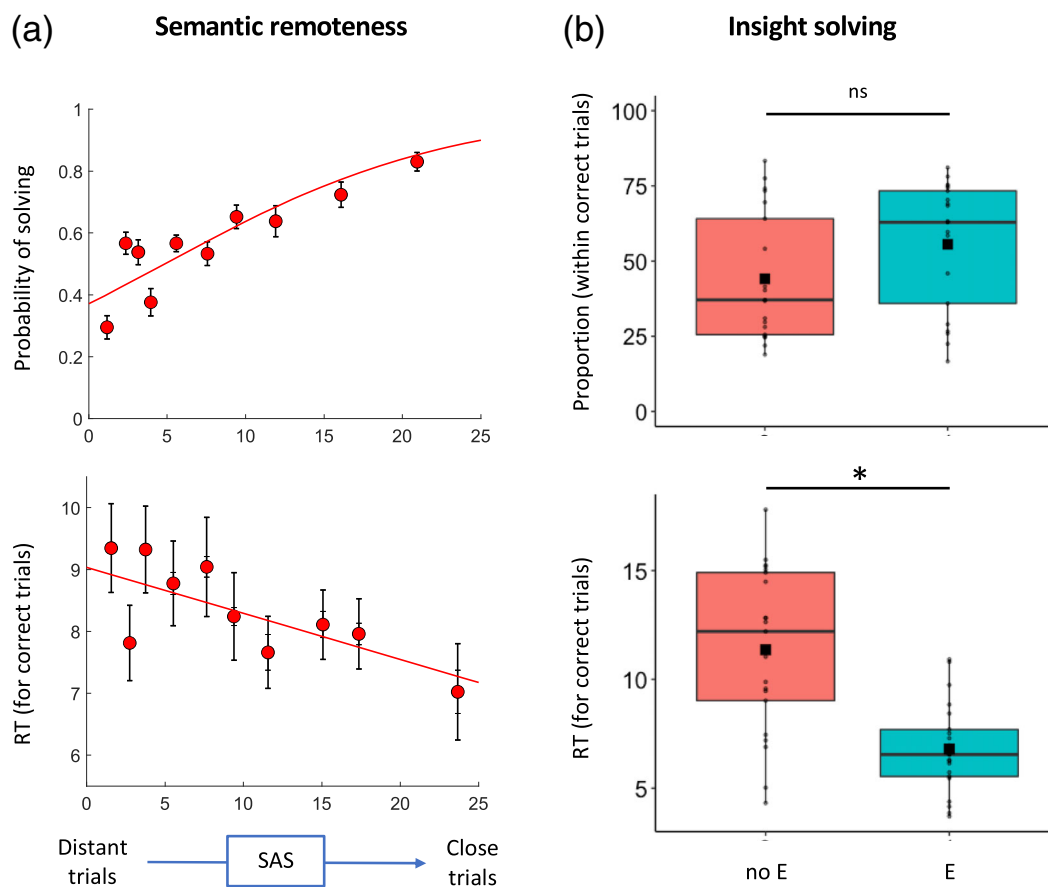


FIGURE 2 Behavioral results. (a) Probability of solving (top) and response time (RT) (bottom) as a function of semantic association strength (SAS). Each dot indicates binned data averaged across participants, with error bars corresponding to inter participant SEM. Solid red lines represent the averaged logistic (probability of solving) or linear (RT) regression fit across participants that are significant at the group level ($p < .05$). (b) Averaged proportion (top) and RT (bottom) for correct trials solved without Eureka (no E, in red) and with Eureka (E, in blue). Each dot represents an individual value, color boxes represent the upper and lower quartiles, the black horizontal line within the boxes symbolizes the median, and the filled square is the mean value across participants. ns: nonsignificant, $*p < .05$.

RT) on Eurêka reports in any individual. At the group level, the one-sample t test on the individual regression coefficients was not significant ($\beta_{\text{mean}} = .004$, $SD = 0.01$, $t(20) = 0.4$, $p = .70$). These results remained nonsignificant after removing the trials with outlier values of SAS (see Supplementary Data S11).

3.2 | EEG

Time-frequency analyses were computed between 3 and 60 Hz during the 2 s period following the onset of the cue word triplet (initial time window) and the 2 s period preceding the participant's response (RT window; see Section 2). Time-frequency maps were averaged along the frequency dimension according to four frequency bands (i.e., theta 3–7 Hz, alpha 8–12 Hz, beta 13–30 Hz, and gamma 31–60 Hz).

The average number of trials included in the EEG analyses (non-artifacted correct trials with $RT > 4$ s) for the initial and RT windows was, respectively, 32.1 ($SD = 11.5$) and 32 trials ($SD = 11.7$) for *semantic remoteness* condition, and 30.3 ($SD = 12$) and 29.4 trials ($SD = 11$) for the *insight solving* condition. The time-frequency maps of EEG power across all trials are shown in Figure S2 for each time window of interest, including topographical maps for each frequency band.

We used a two-level statistical analysis approach to explore the neurophysiological correlates of *semantic remoteness* and *insight solving*. First, individual linear regressions assessed the relationship between EEG power in each frequency band and behavior with EEG power as the dependent variable and (i) semantic distance as the independent variable to explore the effect of *semantic remoteness*, (ii) Eurêka self-report as the independent variable to explore *insight solving*. Then, the resulting individual regression coefficients were tested at the group level (one-sample t tests) with cluster-based corrections for multiple comparisons in spatial (65 electrodes) and time dimensions. These analyses were performed for each time window (see Section 2).

Finally, we used source localization to explore the brain regions associated with the significant clusters observed at the sensor level. We analyzed the cortical sources in the time windows and the frequency bands in which significant clusters were found.

3.2.1 | Semantic remoteness in associative combination

We found three significant negative clusters in the alpha, beta, and theta bands (i.e., the lower the SAS, i.e., the more remote the solution, the higher the power in the considered frequency band) (Figure 3). No positive clusters were found.

Two significant clusters were observed during the initial time period. A first negative cluster surviving the Bonferroni correction was observed in the alpha band on left temporal and parietal electrodes, from 1.29 to 1.99 s after the onset of the cue words (11 electrodes, $\text{sum}(t) = -1523$, $p_{\text{corr}} = 5.99 \times 10^{-3}$) (Figure 3, “alpha” in orange). We performed a source reconstruction of alpha band activity

during the cluster time window and contrasted the cortical source maps between distant and close trials. The largest source differences in alpha band between 1.29 and 1.99 s were located in the left inferior temporal gyrus and the left anterior part of the middle temporal gyrus. We also observed source differences in alpha band activity in the right hemisphere in the anterior part of the inferior and middle temporal gyrus and the right pre- and post-central gyrus (Figure S3a).

A second negative cluster (not surviving the Bonferroni correction) was observed in the beta band during the initial time window. It was formed from two subsets of electrodes over time. Beta activity increased with *remoteness* first on central electrodes from 1.47 to 1.70 s after the cue words onset (six electrodes, $\text{sum}(t) = -421$, $p_{\text{corr}} = .03$) (Figure 3, “beta” in light green) and second on temporofrontal electrodes from 1.78 to 1.99 s (seven electrodes, $\text{sum}(t) = -554$, $p_{\text{corr}} = .02$) (Figure 3, “beta” in dark green). We separately performed source reconstruction in the beta band during these two time periods. Between 1.47 and 1.70 s, the distant versus close contrast revealed sources located in bilateral posterior middle temporal gyrus. In addition, there was reduced beta activity for distant than close trials in the left anterior part of the middle frontal gyrus (Figure S3b). Between 1.78 and 1.99 s, the sources showing differentiated beta band activity for remote versus close trials were located in similar regions (Figure S3c): beta power was higher in distant than close trials in a potential source located in the left posterior inferior temporal gyrus and was lower in the left posterior and inferior gyrus encompassing the left inferior frontal sulcus.

The third negative cluster (surviving the Bonferroni correction) was observed in the theta band during the RT window (-1.80 to -1.06 s before the response) on prefrontal electrodes (15 electrodes, $\text{sum}(t) = -2574$, $p_{\text{corr}} = 2.00 \times 10^{-3}$) (Figure 3, “theta” in yellow). As for the previous clusters, we reconstructed the sources of theta band activity in the cluster time period. Contrasting distant versus close trials revealed sources located in the right inferior part of pre- and post-central gyrus and in several regions in the left hemisphere, including the lateral part of the orbital gyrus and the anterior part of the inferior frontal gyrus, the inferior pre- and post-central gyrus, the posterior part of the superior temporal gyrus and posterior and anterior temporal areas (Figure S3d).

Of note, the EEG power average within each of the three reported clusters was not significantly correlated to accuracy at the inter individual level (Spearman correlations; alpha cluster: $\rho = 0.11$, $p = .63$; first beta cluster: $\rho = 0.11$, $p = .64$; second beta cluster: $\rho = -0.05$, $p = .82$; theta cluster: $\rho = 0.13$, $p = .58$). These results suggest that brain activity in the reported clusters related to the effect of the SAS, independently of the accuracy.

3.2.2 | Insight problem-solving

We found three significant positive clusters, where trials solved with a Eurêka were associated with significantly higher activity amplitudes than those solved without a Eurêka. All clusters were observed in the RT window (Figure 4) and remained significant after Bonferroni correction. No negative cluster was found.

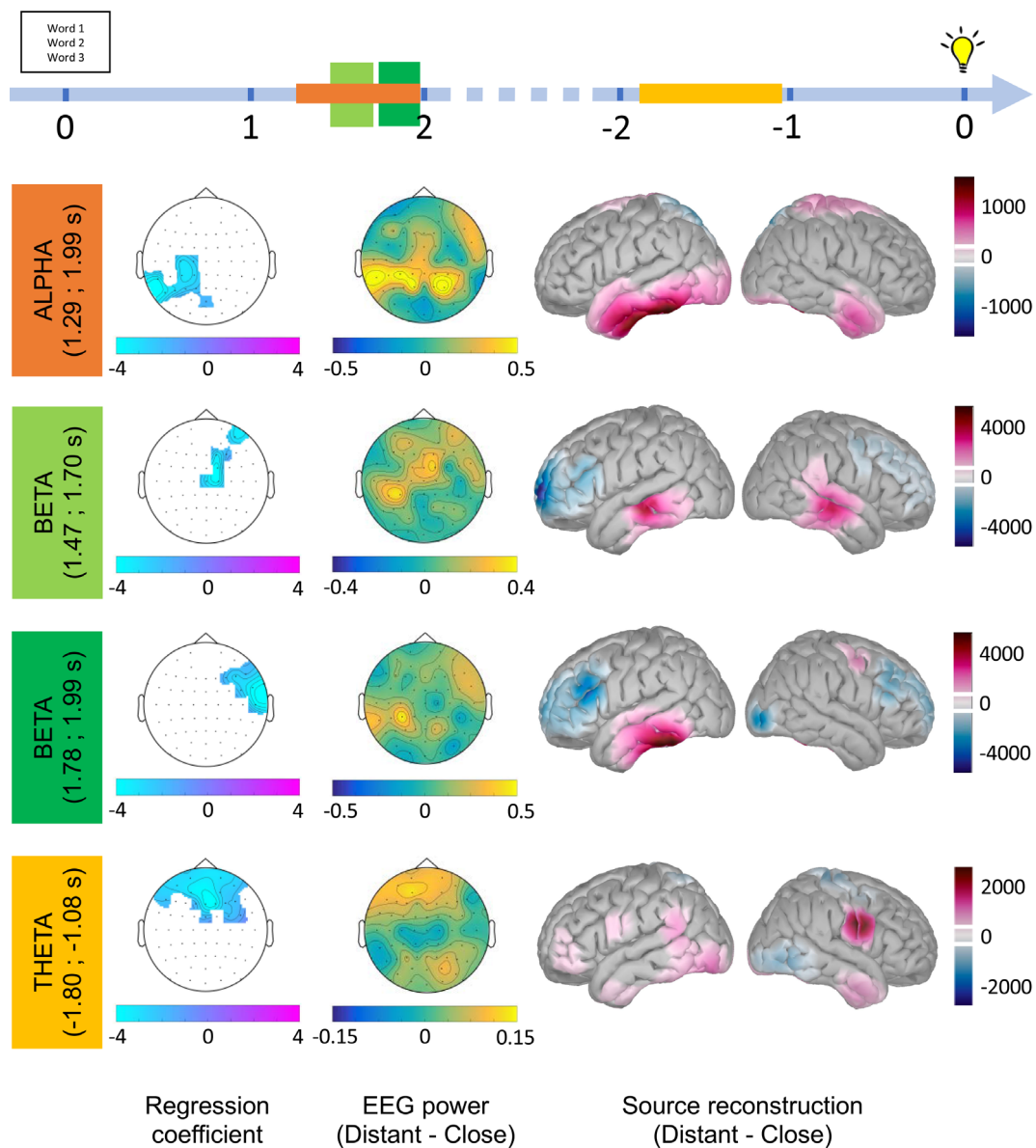


FIGURE 3 EEG effects related to the *remoteness* of semantic associations. Top: Time course (in seconds) of the task in the two time windows of interest (initial time window between 0 and 2 s after the onset of the cue words, and response time window between -2 and 0 s before the response). Colored rectangles symbolize the time periods of the clusters where EEG power was significantly associated with the *remoteness* of semantic associations in the alpha band (in orange), the beta band (in light and dark green), and the theta band (in yellow). For each cluster, the results are further detailed in lower rows as follows. First column: Topographical maps of the clusters. The significant clusters ($p_{\text{corr}} < .05$) are represented for each frequency band. All clusters survived after the Bonferroni correction, except the beta clusters. The color codes the regression coefficient values in the significant clusters (color bar from negative values in light blue to positive values in purple). Second column: Topographical maps of the EEG power in each band contrasted between distant (low SAS) minus close (high SAS) trials, averaged across participants and in the time-windows of the clusters (as indicated in the colored rectangles on the left). Color bars indicate EEG power (in z-score) from negative (in blue, distant < close) to positive (in yellow, distant > close) values. Third column: Source reconstruction of EEG activity in the considered frequency band during the significant cluster time periods. The cortical source maps were contrasted between conditions (distant–close), and we represent the difference in source activity averaged in the time window of the cluster. The color bar indicates the power (in pA.m) from negative (in blue) to positive (in purple) values. The white lines in the color bars indicate the threshold used to visualize the source on the normalized cortical surface rendering.

The first positive cluster was observed in the alpha band frequency in left central and temporal electrodes, between -1.96 and -1.55 s before the response button press (13 electrodes, $\text{sum}(t) = 1174$, $p_{\text{corr}} = .01$) (Figure 4, “alpha” in orange). The source

reconstruction of EEG activity in the alpha band during the time window of this cluster showed increased alpha activity of sources mainly located in the left superior parietal lobule and posterior part of the inferior and middle temporal gyrus. Additionally, alpha activity at

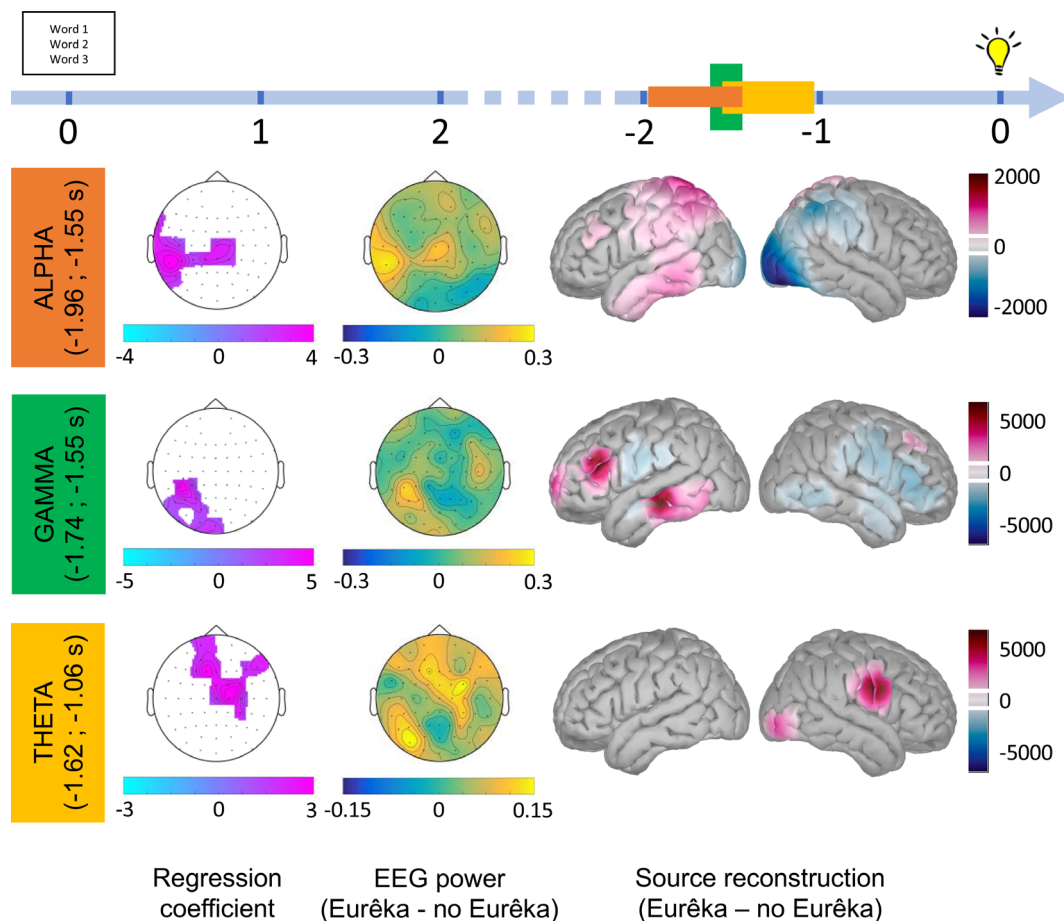


FIGURE 4 EEG effects related to *insight solving*. Top: Time course (in seconds) of the task in the two time windows of interest (initial time window between 0 and 2 s after the onset of the cue words, and RT window between -2 and 0 s before the response). Colored rectangles symbolize the time periods of the clusters where EEG power was significantly associated with Eurêka reports in the alpha band (in orange), the gamma band (in green), and the theta band (in yellow). For each cluster, the results are further detailed in the lower rows as follows. First column: Topographical maps of the cluster. The significant clusters ($p_{\text{corr}} < .05$) are represented for each frequency band. All clusters survived after the Bonferroni correction. The color codes the regression coefficient values in the significant clusters (color bar from negative values in light blue to positive values in purple). Second column: Topographical maps of EEG power in each band contrasted between trials with Eurêka minus those without Eurêka, averaged across participants and in the time windows of the clusters (as indicated in the colored rectangles on the left). Color bars indicate EEG power (in z-score) from negative (in blue, Eurêka < no Eurêka) to positive (in yellow, Eurêka > no Eurêka) values. Third column: Source reconstruction of EEG activity in each frequency band during the time periods of the significant cluster. The cortical source maps were contrasted between conditions (Eurêka–no Eurêka), and we represent the difference in source activity, for each frequency, averaged across the time window of the cluster. The color bar indicates the power (in pA.m) from negative (in blue) to positive (in purple) values. The white lines in the color bars indicate the threshold used to visualize the source on the normalized cortical surface rendering.

source level was reduced in the right occipital polar cortex when participants reported a Eurêka (Figure S4a).

The second positive cluster overlapped temporally with the end of the first cluster during the RT window (-1.74 to -1.55 s before the response) and was found in the gamma band in left parieto-temporal electrodes (nine electrodes, $\text{sum}(t) = 372$, $p_{\text{corr}} = 7.99 \times 10^{-3}$) (Figure 4, “gamma” in green). The source reconstruction of EEG activity in the gamma band during the time period of this cluster showed increased gamma activity for Eurêka relative to no Eurêka trials in the left anterior superior frontal gyrus, around the inferior frontal sulcus (encompassing posterior part of the inferior and middle frontal gyrus) and left middle temporal gyrus (Figure S4b).

The last positive cluster was observed in the theta band on centro-frontal electrodes from -1.62 to -1.06 s before the response (14 electrodes, $\text{sum}(t) = 1377$, $p_{\text{corr}} = 7.99 \times 10^{-3}$) (Figure 4, “theta” in yellow). During the cluster time window, the source reconstruction of EEG activity in the theta band showed greater theta activity in the inferior part of the right pre- and post-central gyrus (Figure S4c).

4 | DISCUSSION

This study explored the neurophysiological correlates of two cognitive components of creative problem-solving. Using an adapted version of the RAT (Bendetowicz et al., 2017, 2018; Mednick, 1962), we

examined the time course of EEG power related to *insight solving* and, for the first time, the effect of the *semantic remoteness* of the solution to be found in the context of a semantic associative combination. Whereas most of the previous EEG studies using a similar task averaged signal across long time windows or large sets of electrodes, or were restricted to specific electrodes or frequency bands (Danko et al., 2009; Jung-Beeman et al., 2004; Luft et al., 2018; Razumnikova, 2007), here, we employed a data-driven time-frequency approach. This approach revealed distinct patterns of activity associated with *semantic remoteness* and *insight solving* in several frequency bands. Three clusters showed increased EEG activity with *semantic remoteness*: a left temporo-central cluster in the alpha band and a right fronto-temporal cluster in the beta band during the initial phase of the task (although uncorrected), and a later frontal cluster in the theta band just before the response.

EEG activity changes related to *insight solving* were observed only in the period just preceding the response. They included an increase in alpha activity in a left temporo-central cluster, followed by a gamma activity increase in a left parietal cluster, and finally, an increase in theta band activity in a fronto-central cluster. Overall, these EEG findings provide new insights into the mechanisms involved in creative problem-solving.

In the following sections, we discuss each result, first, at the sensor level (where robust two-level statistical analyses corrected for multiple comparisons allowed us to identify clusters with specific differences in several frequency bands of EEG activities), then at the source level (the brain areas that showed differences in activity in the frequency bands and time windows of sensor level clusters).

4.1 | Semantic remoteness in associative combination

An increase in alpha activity was significantly associated with the *remoteness* of semantic associations about 1.5 s after displaying the cue words. Alpha is the most reported EEG correlate in creativity studies using various tasks (Fink et al., 2009; Fink & Benedek, 2014; Fink & Neubauer, 2006; Jauk et al., 2012; Mastria et al., 2021; Mölle et al., 1996; Shemyakina et al., 2007; Zhou et al., 2018), including the RAT (Jung-Beeman et al., 2004; Luft et al., 2018; Sandkühler & Bhattacharya, 2008). Alpha activity increases with the creative requirements of the task (Fink & Benedek, 2014). It has been interpreted as an active inhibition (Klimesch, 2012; Klimesch et al., 2007) of external, nonrelevant stimuli, facilitating internal processing (Cona et al., 2020; Cooper et al., 2006) and internally oriented attention (Fink & Benedek, 2014; Lustenberger et al., 2015). Alternatively, Klimesch (2012) postulated that alpha-related inhibition is needed to explore and navigate in semantic memory, which is organized as a network. More precisely, access to remote knowledge may require that closely related, but not relevant memory information, is inhibited. Distant CAT trials likely required an extended access to the knowledge stored in semantic memory as participants had to find a remote solution and inhibit close but irrelevant associations. The increase in alpha

band activity during the initial time may reflect this process. The source reconstruction suggested that the effect of *semantic remoteness* in the alpha band involved the left (and to a lesser extent to the right) inferior and middle temporal gyrus. Previous studies have identified different temporal regions as key brain areas for semantic processing (Binder et al., 2009; Hickok & Poeppel, 2004; Ralph et al., 2017; Visser et al., 2012) with distinct roles for regions along the rostro-caudal and supero-inferior axes (Ralph et al., 2017). The anterior temporal lobe appears as a transmodal hub in semantic processing in interaction with more posterior temporal areas. The left inferior temporal gyrus plays a role in semantic representation and word meaning (Whitney et al., 2011). The left posterior middle temporal gyrus is involved in a semantic control network (Evans et al., 2020; Noonan et al., 2013; Teige et al., 2019; Vatanserver et al., 2021). Semantic control is likely involved in CAT, especially in distant trials where participants had to retrieve and combine remote associations. Neuroimaging studies using RAT-like tasks have reported the involvement regions of the semantic control network (Anderson et al., 2009; Becker et al., 2020; Gonen-Yaacovi et al., 2013; Jefferies & Wang, 2021; Ovando-Tellez et al., 2023). The involvement of semantic control in CAT is also consistent with previous research linking alpha activity with cognitive control (Sadaghiani & Kleinschmidt, 2016). Overall, the initial alpha activity that we found may reflect enhanced controlled access to the knowledge required by distant trials.

Beta power was also related to *semantic remoteness* in the form of a right centro-temporal and temporo-frontal cluster of beta activity that significantly increased with the remoteness of the associative combination. This beta activity temporally overlapped with the alpha cluster described above. Although this cluster did not survive Bonferroni correction, its role in creativity may be discussed. Variation of beta activity during creative thinking or problem-solving is not classically reported. A few studies reported an increase in beta activity in frontal and temporal electrodes associated with the RAT (Razumnikova, 2007) or during other creativity tasks (Rosen & Reiner, 2016; Zioga et al., 2020), but its functional role in the context of creativity is not understood. Beta activity is usually associated with motor preparation, but in regions and time windows different from our study (da Silva, 2009; Weiss & Mueller, 2012). In addition, if beta activity reflected a motor preparation, it is unclear why this EEG activity should be stronger for trials with higher SAS, why it was not located in the left hemisphere (as all participants answered with their right hand), and why it was not found when analyzing *insight solving* (as it was the same conditions to respond). Hence, higher beta activity for more remote combinations may reflect non-motor cognitive processes. Enhancement of beta-band activity has been related to various aspects of language processing (Weiss & Mueller, 2012), such as the maintenance of a mental state during a cognitive task requiring language (Engel & Fries, 2010) or of visual object representation in short-term memory (Tallon-Baudry et al., 1999). The role of beta activity increase in distant CAT-solving is not obvious. One can speculate that when the cue words to be combined are not quickly converging to a solution, the current mental activity (i.e., active exploration of semantic memory related to the alpha activity) should be maintained, increasing beta activity in more distant trials.

Finally, theta activity was associated with *semantic remoteness* 1 s before the participant's response, involving fronto-temporal regions. Theta activity in creative problem-solving has been scarcely reported (Razumnikova, 2007; Sandkühler & Bhattacharya, 2008). The role of theta activity in cognition is debated. Prefrontal theta activity has been associated with several aspects of executive control functions. Cavanagh et al. (2012); Cavanagh and Frank (2014) proposed that theta rhythm generated by the medial PFC region is involved in monitoring novelty, conflict, and surprise. Theta activity increases when information is accumulated (Cavanagh et al., 2012; Cavanagh & Frank, 2014). When controlled processes are engaged during goal-directed behavior, theta band coherence between frontal and other relevant brain regions increases (Zavala et al., 2018). Several studies have also associated theta activity with other controlled processes and functions such as inhibition (Adelhöfer & Beste, 2020), planning (Domic-Siede et al., 2020), prioritizing relevant information in working memory (Riddle et al., 2020), or analytical reasoning (Williams et al., 2019). These data may suggest that control processes (Cavanagh & Shackman, 2015) may be required in this highly constrained task for monitoring candidate solutions, evaluating and verifying that an idea satisfies all criteria, and/or selecting the right one through inhibition of other unappropriated propositions.

Importantly, theta activity has been related to memory retrieval and encoding (Düzel et al., 2010) and may reflect integration processes that allow us to build new connections between elements of knowledge in semantic memory (Backus et al., 2016; Nicolás et al., 2021). Hence, theta band activity associated with distant CAT may reflect controlled retrieval and integration in semantic memory. Consistent with this interpretation, the central contribution of executive and memory processes in creativity is now well established (Beaty et al., 2016; Benedek & Fink, 2019; Benedek & Jauk, 2018; Cassotti et al., 2016; Volle, 2017). Recent studies have demonstrated the important role of the executive control network for creative thinking (Beaty et al., 2016, 2017; Bendetowicz et al., 2018). The executive control network supports several control processes involved in creative thinking, such as working memory, attentional control, including inhibition processes, planning, flexibility, and control and selection in memory retrieval. The source reconstruction of our theta-related cluster revealed a set of left regions largely coherent with the executive control network, such as the rostro-lateral PFC, parieto-temporal junction, and temporal regions. The rostro-lateral part of the PFC is a node of the executive control network that has been shown to be critical for solving CAT in frontal patients, especially in distant trials (Bendetowicz et al., 2018). Additionally, the gray matter volume in this region was also correlated with performance in this task (Bendetowicz et al., 2017). The particular role of the left rostro-lateral PFC in the CAT may be to combine the retrieved associates or integrate the result of the search from each cue word, that is, in the relational integration of distant items (Aichelburg et al., 2016; Green et al., 2016; Urbanski et al., 2016). Thus, observing theta power increase during the RT window is consistent with previous studies using different methods showing the involvement of the left rostro-lateral PFC and executive control network in creativity (Beaty

et al., 2015, 2016, 2018; Bendetowicz et al., 2018; Ovando-Tellez et al., 2022, 2023), in interaction with other networks (such as the default mode network). The source reconstruction also located theta activity in the right inferior pre- and post-central gyrus. This result showed similarities between *semantic remoteness* and *insight solving* analyses and is discussed below.

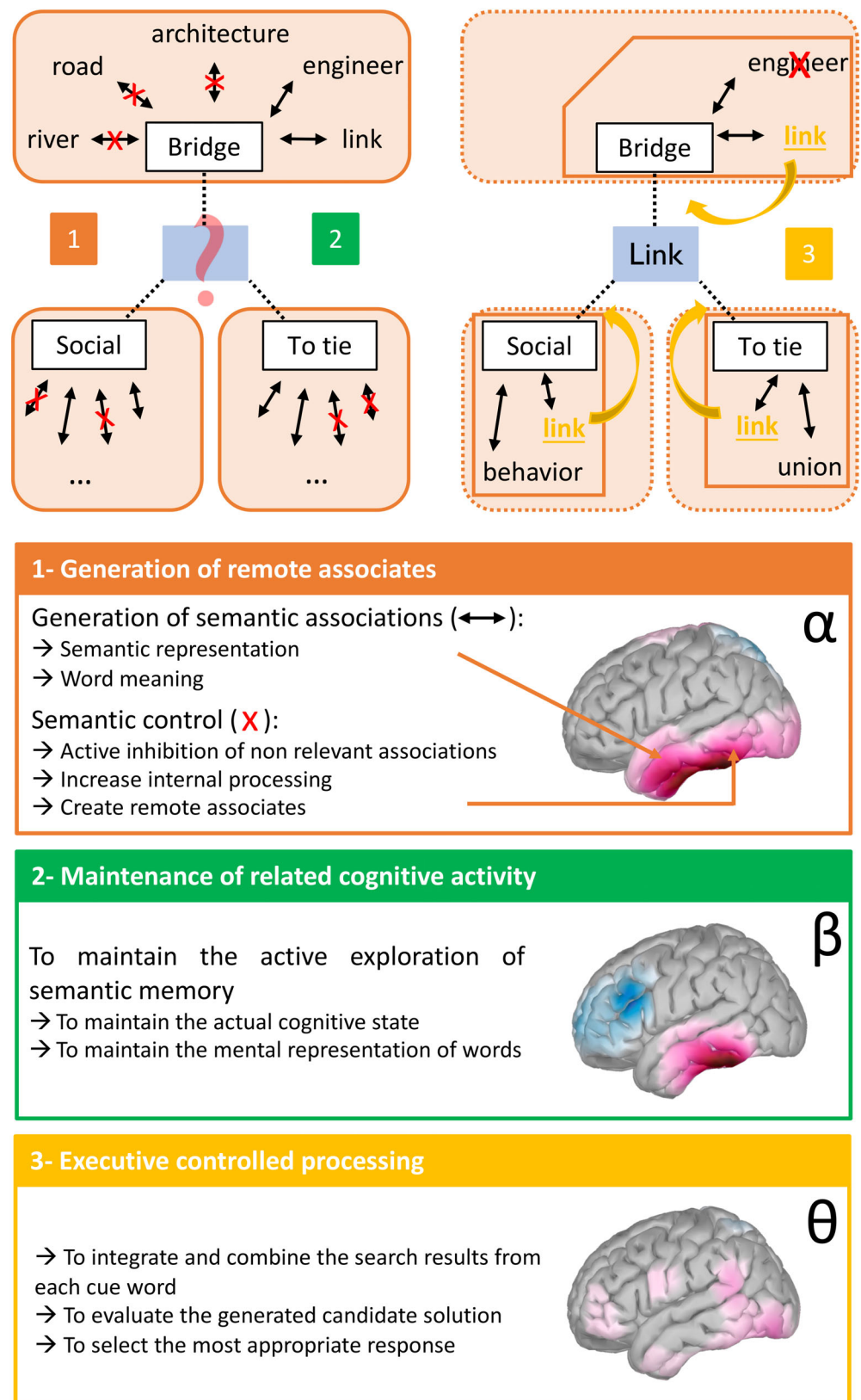
Overall, our results, combined with the existing literature, suggest that the combination of remote associates relied on several controlled processes in distinct periods of CAT-solving (Figure 5). Hypothetically, in the initial phase of the task, semantic control (supported by alpha activity in the posterior middle temporal gyrus) may enable the exploration of semantic memory in search of remote associates (in relation to alpha activity in infero-temporal regions, including the temporal pole). The maintained semantic search or search space might be reflected in the overlapping beta activity, which is associated with the maintenance of a current mental state or representation. Finally, just before the response, the increased prefrontal theta activity may reflect the involvement of other executive controlled processes, allowing integrating and combining of the search results from each cue word, evaluating the generated candidate solutions, and finally selecting the most appropriate response.

4.2 | Insight solving

The second aspect of the CAT that we analyzed, *insight solving*, modulated distinct EEG activity compared to the remote associative combination. Eurêka-related EEG differences were observed only during the RT window, suggesting that the early stages of problem-solving were similar for trials with or without Eurêka. It might be explained by the fact that the two solving modes (with and without Eurêka) are not exclusive and may co-occur within a trial. It is possible that people initially used analytical thinking until they reached an impasse and finally solved the problem with insight. Cognitive theories link insight with the need to experience a mental impasse and restructure the problem representation before solving it with insight (Ohlsson, 1992; Sandkühler & Bhattacharya, 2008). It may thus not be surprising that insight and non-insight trials only differed in the period just preceding the response. Nevertheless, we examined only the first and last 2 s of problem-solving. We cannot exclude that differences between trials with Eurêka and without Eurêka occurred in between these time windows.

Consistent with our expectations, just before the response, we observed successive modulation of alpha- and gamma-band activities for trials with Eurêka (compared to those without Eurêka), which is consistent with previous EEG studies (Jung-Beeman et al., 2004; Oh et al., 2020; Sandkühler & Bhattacharya, 2008; Sheth et al., 2009). The source reconstruction suggested that alpha activity related to Eurêka involved the left posterior inferior and middle temporal gyrus and the parietal region. Although the alpha activity associated with the *semantic remoteness* and *insight solving* effects showed some similarities, they occurred in different time periods (initial vs. RT windows), suggesting that they reflected distinct mechanisms. Given the role of

FIGURE 5 Hypothetical model of remote associative combination. Combined with the existing literature, our results suggest that solving a distant CAT (relative to a close one) requires generating remote semantic associates to each of the three cue words. This is supported by alpha activity in temporal areas (in orange). Overlapping beta activity might facilitate this process by maintaining related cognitive activity (in green). Then, executive controlled processing is needed to integrate, combine, evaluate, and select the appropriate response. This final step is supported by theta activity found in brain regions involved in the executive control network. Please note that this model is hypothetical and based on our interpretations of the results.



alpha in inhibition processes and the involvement of the left inferior and middle temporal gyrus in semantic processing discussed above, the Eurêka-related alpha increase may reflect the inhibition of nonrelevant information to overcome the mental impasse and restructure

the problem (Sandkühler & Bhattacharya, 2008). The source reconstruction also suggested that the superior parietal lobule, a region often showing alpha activity in relation to creativity (Fink & Benedek, 2014), played a role in *insight solving*. Given the classical role

attributed to alpha activity in parietal areas in creativity research, this cluster might alternatively or additionally reflect an increased state of internally oriented attention during trials with *insight solving* (Fink & Benedek, 2014).

Succeeding to alpha modulation, we observed a gamma activity increase in left parietal electrodes, which involved the left anterior superior frontal gyrus, left posterior inferior, middle frontal gyrus, and left middle temporal gyrus. An increase in gamma activity is often reported by studies exploring insight problem-solving (Jung-Beeman et al., 2004; Oh et al., 2020; Rosen & Reiner, 2016; Sandkühler & Bhattacharya, 2008; Sheth et al., 2009) and has been related to the suddenness of the solution (Sandkühler & Bhattacharya, 2008). Gamma burst may reflect the sudden awareness of a mental representation from memory (Engel et al., 2001; Engel & Singer, 2001; Tallon-Baudry et al., 1999). The gamma activity observed during the CAT-solving with *insight* may reflect the awareness of a solution that popped up suddenly in mind, yielding the subjective Eureka experience. Besides, previous studies revealed gamma activity in frontal and temporal regions (Gueguen et al., 2021) associated with reward or prediction error signals, which have been showed recently tightly linked with insight or Eureka moments (Becker et al., 2023; Dubey et al., 2021; Laukkonen et al., 2023; Oh et al., 2020). Hence, whether gamma activity can reflect prediction error in our study remains an open question.

The similar alpha followed by gamma synchronization associated with insight reported by previous studies involved distinct electrodes than the ones we observed, especially in the right hemisphere (Jung-Beeman et al., 2004; Sandkühler & Bhattacharya, 2008; Sheth et al., 2009). The reasons for this left–right difference in our results are unclear. They might relate to the use of different paradigms. Previous studies mostly used the compound remote associate task, requiring finding a word that forms a compound word with each cue. Instead, we used a version where the solution is associatively related to the cue words. Thus, our task may rely more on semantic processing than the compound remote associate task, thus recruiting more left-brain areas (del Jesus Gonzalez Alam et al., 2019; Hickok & Poeppel, 2004). Another methodological difference is that previous EEG studies on insight focused on specific scalp regions or frequency bands based on a priori hypotheses. In contrast, we used a data-driven approach, considering all the electrodes and frequencies in our analyses while controlling for multiple comparisons. It potentially revealed new brain correlates of insight problem-solving. In addition, as in other EEG studies based on the RAT (Oh et al., 2020; Sandkühler & Bhattacharya, 2008), we observed alpha and gamma effects earlier than in Jung-Beeman et al.'s (2004) study. This difference may relate to the instructions given to our participants of pressing the space bar when they thought the solution they had in mind was correct. It may have encouraged the participants to evaluate their solution more carefully and added a delay between the insight moment and button press.

Finally, like remote trials, insight trials were associated with higher theta activity in frontal electrodes. As discussed before, theta activity had been related to several mechanisms, that is, conflict monitoring processes, generic control processes, and memory retrieval and

encoding processes. In *insight solving*, the theta activity that occurred just after the increase of gamma activity may reflect conflict monitoring because when the solution arises suddenly in consciousness, a conflict (or surprise) with ongoing mental representations or ideas can arise, signaling a need for monitoring and selection. However, it is also possible that as for *semantic remoteness*, theta activity reflects here generic control processes required for evaluating and verifying that the solution meets the constraints of the task. Finally, because it was the last activity change we observed, it is less likely that theta activity reflects control processes, signaling a mental impasse that needs to be overcome.

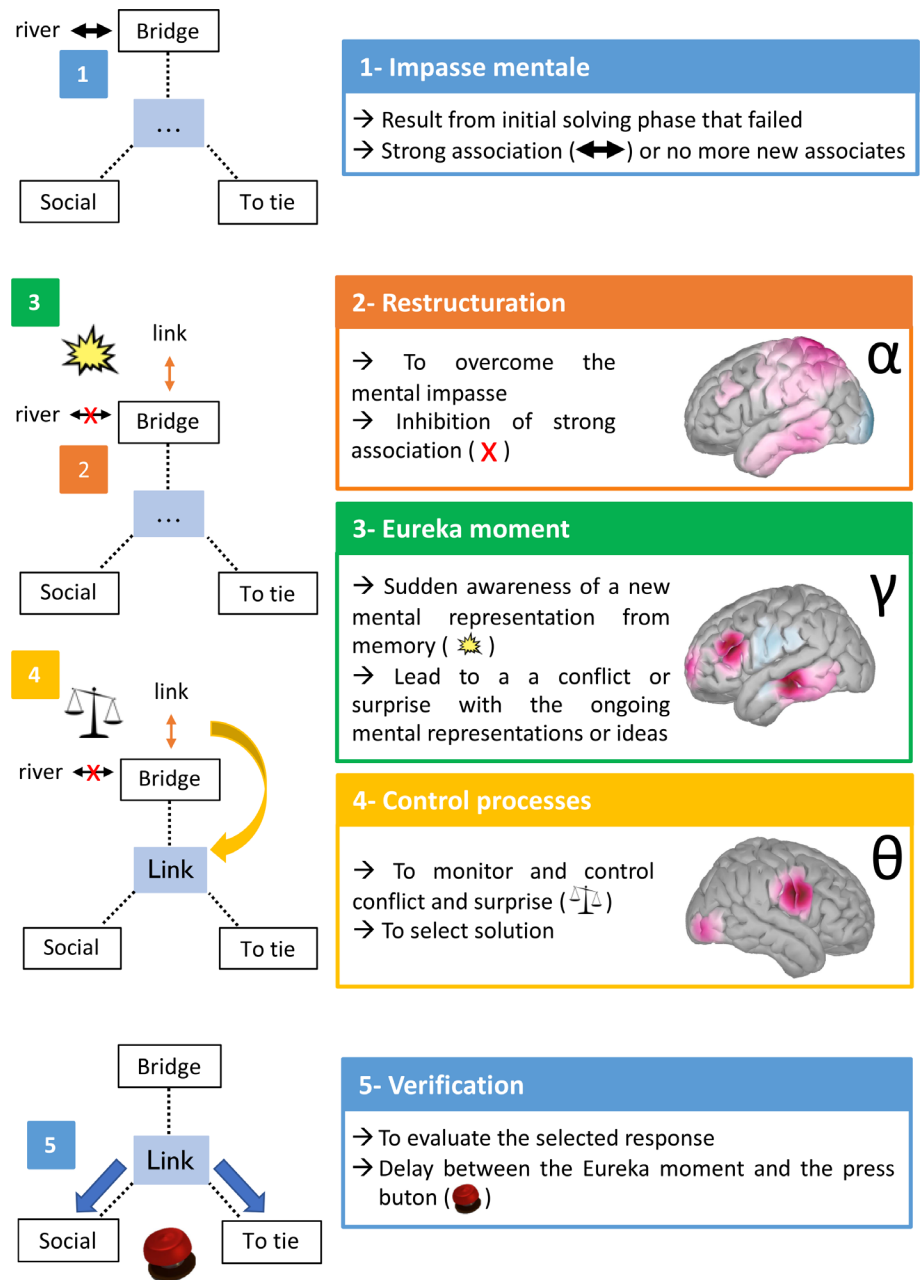
The source reconstruction located a potential source in the right inferior part of the pre- and post-central gyri. Although sensorimotor regions in creativity have already been described (Matheson & Kenett, 2020), their role remains challenging to interpret. Interestingly, this region was also a candidate source for the theta activity associated with *remoteness* during the same time window. *Remoteness* in associative combination and *insight solving* are often confused in previous studies (Dietrich & Kanso, 2010), leading to an unclear link between them. According to some theory (Bowden et al., 2005; Ohlsson, 1992; Öllinger et al., 2014), they are both resulting in overcoming a mental impasse, suggesting that they might share similar thread in the time course of EEG power. In our study, we explored both components with the same task. Overall, our results did not suggest a link between *insight solving* and *remoteness* (no significant interaction at the behavioral level, distinct brain clusters at the sensor level). The shared theta activity cannot be explained by an imbalance in the distribution of trials between the two conditions (for instance, more Eureka reports in distant trials) as the average number of trials included in the EEG analyses did not significantly differ between conditions (see Supplementary Data S12). However, we cannot exclude that *remoteness* and *insight solving* effects are associated with some similar brain events occurring just before the response. Further studies are needed to clarify this question.

To summarize (Figure 6), we show that alpha, gamma, and theta power successively increased just before successful *insight solving*. Alpha activity could help to overcome strong, obvious associations of ideas. The solution could hence suddenly emerge in the individual's mental representation and lead to a gamma activity. Then, a conflict might occur between the Eureka-mediated solution and the previously ongoing mental thinking. This conflict needs to be monitored and controlled, which may be reflected by the increase in theta activity. Alternatively, this activity may be related to a solution check.

4.3 | Limitations

This study is not without limitations. First, the CAT is a difficult task with a low correct response rate, often around 60%. Added to the constraints related to EEG artifact cleaning, this led to the analysis of a limited number of trials per participant. We chose not to analyze incorrect trials since the cognitive involvement of the participants in incorrect trials is uncontrolled. However, incorrect responses were

FIGURE 6 Hypothetical model of *insight solving* related results. After reaching a mental impasse (in blue), restructuring is needed to break out it. Inhibition of strong associations can be supported by alpha activity in temporal areas (in orange). When a new association suddenly arises in consciousness, a realization of the solution occurs (supported by gamma activity, in green). It ensures a conflict or surprise that needs to be monitored to select the appropriate association (supported by theta activity, in yellow), verified before answering (in blue). Please note that these models are hypothetical and based on our interpretation of the results.



manually inspected. They corresponded either to a strong associate of one of the three cue words, an obviously inappropriate response, one of the cue words, or resulted from noncompliance with task instructions. Thus, incorrect responses in this study did not seem to result from the creative process we aim to explore.

Second, the usually long RT in such a task led us to analyze fixed time windows at the beginning and end of each trial without considering the time in between. It does not allow us to comprehensively characterize the dynamic time course of EEG power during creative problem-solving. However, it allows to separate nonoverlapping events of the task at a time scale adequate to the high EEG temporal resolution. In addition, the average RT was 8.4 s (SD = 1 s), indicating that even though participants were allowed 30s to answer, they did it in a much shorter that is closer to the duration of our time-window

analysis (4 s). Hence, we think that the findings are representative of some key processes taking place during creative problem-solving.

Third, it remained challenging to totally dissociate the specific effect of *semantic remoteness* in associative combination (the SAS) from a mere effect of difficulty or task-related cognitive effort. However, we provided analyses that do not support significant relationships between *semantic remoteness* and difficulty.

Fourth, it may be noted that the individual MRIs of the participants were unavailable. Thus, source reconstruction results must be interpreted cautiously and entail more uncertainty than the effects we characterized at the sensor level. However, the involved regions are broadly consistent with the neuroimaging literature, and our results offer new perspectives on potential networks involved in creative problem-solving.

Fifth, we used the most used and validated approach with self-reports of Eurêka experience to define *insight solving* (Laukkonen & Tangen, 2018). However, the best method to capture the insight phenomenon, which would best reflect specific solving mechanisms, is an open question.

Finally, it may be noted that other—subcortical—brain regions may be important for creative problem-solving, particularly in relation with the dopaminergic system (Faust-Socher et al., 2014; Schuler et al., 2019; Tik et al., 2018). Yet, this was out of scope of the present study, which concentrated on the brain correlates of creative problem-solving at the cortical level.

5 | CONCLUSION

This study explored the EEG correlates of two aspects of RAT problem-solving, *semantic remoteness* in associative combination and *insight solving*. We showed distinct patterns of brain activity in the time-frequency domain for these two aspects. First, *semantic remoteness* was associated with an early alpha and beta activity in latero-temporal regions and a theta activity in frontal areas just before the response. These results suggest that early controlled processes may guide and constrain the search of remote associates, whereas later controlled processes may evaluate, integrate or combine the retrieved information. Second, *insight solving* was associated with alpha then gamma activity in infero-temporal regions and theta activity in frontal areas, which occurred just before the response. These findings indicate that *insight* is supported by specific brain dynamics distributed in space and time that may relate to a sudden restructuration of the problem or its solution. Furthermore, late theta activity might also suggest that solving a problem with *insight* also includes the involvement of control processes, possibly in the selection, evaluation, or monitoring of the Eurêka-mediated solution. Further work is needed to overcome approximates of source reconstructions. Combining neuroimaging approaches or recording intracranial EEG signal can be promising methods for future research to better understand the brain correlates of creative problem-solving.

AUTHOR CONTRIBUTIONS

Conceptualization: Emmanuelle Volle and Théophile Bieth. Method: Théophile Bieth, Marcela Ovando-Tellez, Beatrice Garcin, Laurent Hugueville, Nathalie George, Katia Lehongre, and Richard Levy. Data collection: Théophile Bieth, Marcela Ovando-Tellez, and Beatrice Garcin. Analyses: Théophile Bieth, Alizée Lopez-Persem, Nathalie George, and Katia Lehongre. Supervision: Emmanuelle Volle and Nathalie George. Writing: Théophile Bieth, Emmanuelle Volle, and Nathalie George.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

According to the ethical agreement, the data sets generated and processed in the current study (time frequency matrices per conditions and time window, behavioral scores) will be uploaded after publication on a permanent repository (OSF) and made available on request to the authors. The scripts for EEG analyses used open-access toolboxes, which are cited in the manuscript.

ORCID

Théophile Bieth  <https://orcid.org/0000-0003-2814-4500>

Marcela Ovando-Tellez  <https://orcid.org/0000-0002-9521-4620>

Alizée Lopez-Persem  <https://orcid.org/0000-0002-7566-5715>

Beatrice Garcin  <https://orcid.org/0000-0001-9109-9904>

Laurent Hugueville  <https://orcid.org/0000-0001-6137-6077>

Nathalie George  <https://orcid.org/0000-0002-1556-973X>

Emmanuelle Volle  <https://orcid.org/0000-0001-8420-4155>

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