

1 Time course of EEG power during creative problem- 2 solving with insight or remote thinking

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25 frequency

29 **Abstract**

30
31 Problem-solving often requires creativity and is critical in everyday life. However, the
32 neurocognitive mechanisms underlying creative problem-solving remain poorly understood.
33 Two mechanisms have been highlighted: forming new connections from and between the
34 problem elements and *insight solving* (with a sudden realization of a solution). We examined
35 EEG activity during an adapted version of a classical insight problem task, the Remote
36 Associates Test, that requires finding a word connecting three words. It allowed us to explore
37 *remoteness in semantic connections* (by varying the remoteness of the solution word across
38 trials) and *insight solving* (identified as a "Eurêka" moment reported by the participants).
39 *Semantic remoteness* was associated with a power increase in alpha band (8-12Hz) in a left
40 parieto-temporal cluster, beta band (13-30Hz) in a right fronto-temporal cluster in the early
41 phase of the task, and theta band (3-7Hz) in frontal cluster before the participants responded.
42 *Insight solving* was associated with power increase preceding the response in alpha and
43 gamma band (31-60Hz) in left temporal clusters and theta band in a frontal cluster. Source
44 reconstructions show the brain regions associated with these clusters. Overall, our findings
45 shed new light on the dynamic of some of the mechanisms involved in creative problem-
46 solving.

47 **Introduction**

48
49 Solving problems can be a societal challenge, an opportunity for progress, or a personal
50 concern. We constantly have to find solutions to new problems and adapt ourselves to new
51 situations, from the everyday life (e.g., how to reorganize my workspace at home), to
52 worldwide concerns (e.g., how to avoid global warming). Problem-solving requires creativity
53 (called here creative problem-solving) when there is no obvious or previously established rule
54 to solve a newly encountered problem or when the heuristics or rules that we spontaneously
55 use are inefficient or lead to an impasse. In creative problem-solving, we need to change our
56 mental representation of the problem by recombining the elements of the problem in new
57 ways or finding new connections between seemingly unrelated elements. In some cases, the
58 solution comes to mind suddenly and spontaneously, with a "Eurêka" phenomenon
59 (Topolinski & Reber, 2010). This problem-solving type is usually considered insight solving
60 (Weisberg, 2013; Kounios & Beeman, 2014). It relates to the illumination phase of the creative
61 process model developed from the reports of eminent scientific discoveries or artistic
62 creations (Wallas, 1926). Combining remote elements and insight solving are considered as
63 central aspects of creative thinking but the underlying neurocognitive mechanisms are still
64 poorly understood. Are these two aspects related? What happens in the brain when solving a
65 problem requires combining remote concepts or elicits a "Eurêka" experience? Here, we
66 explore these questions using EEG during a problem-solving task assessing creative abilities.

67 Combining remote elements is a core component of the associative theory of creativity
68 proposed by Mednick (Mednick, 1962). According to his approach, creativity relies on the
69 ability to form new combinations from unusual associations. Mednick's theory was
70 operationalized in the Remote Associates Test (RAT) that consists in finding a word connecting
71 three given unrelated cue words (Mednick, 1962). The RAT is a creative problem-solving task:
72 it requires forming a new combination of distant elements of knowledge, and it often elicits
73 an experience of insight or "Eurêka" in participants (Bowden et al., 2005; Topolinski & Reber,
74 2010; Kounios & Beeman, 2014). Several versions of the RAT have been developed using
75 lexical (compound words) (Bowden & Jung-Beeman, 2003) or semantic associations between
76 the cue words and the solution (Oltețeanu et al., 2019), or using pictures instead of words
77 (Oltețeanu & Zunjani, 2020; Becker & Cabeza, 2021). Our lab developed a semantic associative
78 version of the task (the Combined Associates Task, CAT) (Bendetowicz et al., 2017, 2018) in
79 which we controlled the semantic association strength (SAS) between the expected solution
80 and the three cue words. The CAT allows us to test Mednick's hypothesis, according to which
81 the more remote the elements to be combined, the more creative the process (Mednick,
82 1962).

83 A previous lesion study identified two distinct brain regions and networks as critical to
84 CAT-solving when remoteness increases (Bendetowicz et al., 2018). First, the medial
85 prefrontal cortex (PFC) as part of the default mode network, a network related to spontaneous
86 cognition and associative thinking (Andrews-Hanna et al., 2010, 2014), was critical for the
87 spontaneous generation of remote associates. Second, the rostro-lateral part of the PFC
88 involved in the executive control network (Yeo et al., 2011; Power & Petersen, 2013) was
89 critical for combining remote associates. These results are consistent with the associative
90 theory of creativity but also emphasizes the importance of controlled processes during CAT-
91 solving (Jones & Estes, 2015). They converge with findings from functional connectivity on
92 divergent thinking in healthy subjects (Beaty et al., 2016), extend them to convergent thinking
93 tasks (CAT), and demonstrate the necessity of both networks. Hence, their findings offer new

94 light on the neural correlates of combining remote associates, while most previous
95 neurocognitive studies that used RAT-like tasks focused on the insight phenomenon (Wu et
96 al., 2020).

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

107 The critical question of the neural underpinnings of insight problem-solving remains
108 unanswered. A few studies explored the brain correlates of insight problem-solving using
109 functional MRI and reported the involvement of frontal regions (anterior and posterior
110 cingulate cortex, inferior frontal gyrus), temporal regions (temporo-polar region, superior and
111 middle temporal gyri, hippocampus) and the insula, during RAT-like tasks (Luo & Niki, 2003;
112 Jung-Beeman et al., 2004; Anderson et al., 2009; Subramaniam et al., 2009; Aberg et al., 2016;
113 Tik et al., 2018; Becker et al., 2020) or other insight tasks (Aziz-Zadeh et al., 2009; Dietrich &
114 Kanso, 2010; Qiu et al., 2010; Shen et al., 2016; Lin et al., 2018). Electrophysiological methods
115 such as EEG provide invaluable information on the time course of information processing and
116 brain dynamics associated with cognitive processes. They thus have the potential to capture
117 the suddenness of Eurêka experience (Jung-Beeman et al., 2004; Sandkühler & Bhattacharya,
118 2008). A pioneering study reported that RAT trials solved with Eurêka (compared to trials
119 without Eurêka) were associated with a power increase in the alpha band in the right parieto-
120 occipital areas around 1.5s before the subject's response, followed by a gamma burst in the
121 right antero-superior temporal lobe 0.3s before the subject's response (Jung-Beeman et al.,
122 2004). Alpha and gamma oscillations have been associated with insight solving in other studies
123 that used the RAT (Sandkühler & Bhattacharya, 2008; Luft et al., 2018) and other paradigms
124 (Sheth et al., 2009; Rosen & Reiner, 2016; Oh et al., 2020). Independently of insight solving,
125 two studies reported a power increase in theta band in prefrontal electrodes and beta band
126 in fronto-temporal electrodes when contrasting RAT-solving with a simple word generation
127 task (Razumnikova, 2007) or a category fluency task (Danko et al., 2009).

128 Overall, the few existing neuroimaging studies of creative problem-solving focused
129 mainly on insight, and none of them explored the effect of the remoteness of the elements to
130 be combined. In addition, most EEG studies restricted their analyses to specific frequency
131 bands or groups of electrodes. Hence, previous studies do not draw homogeneous conclusions
132 on the brain mechanisms involved in creative problem-solving, including in RAT-like tasks.
133 Here, we aim to better understand the neurocognitive mechanisms of creative problem-
134 solving by jointly exploring the EEG correlates of the effects of *associative remoteness* and
135 *insight solving*. For this purpose, we used the CAT (Bendetowicz et al., 2017, 2018), where the
136 *remoteness* of the solution word varies across trials, and *insight* was explored by collecting
137 subjective reports of Eurêka on a trial-by-trial basis. Since EEG data using the RAT are
138 heterogeneous in the literature (Dietrich & Kanso, 2010) and the effect of *semantic*
139 *remoteness* has not been investigated, we used an exploratory approach with no spatial,

140 temporal, or frequency *a priori*. We hypothesized that the effects of *remoteness* and *insight solving* are associated with distinct brain EEG activities in space and time.

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143 Results

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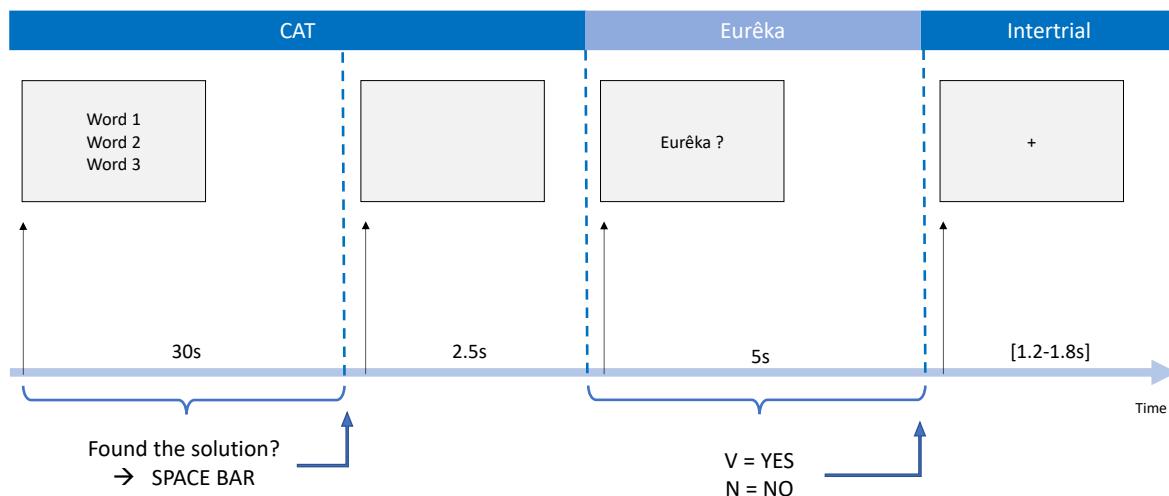
145 Behavioral data

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147 We recorded the EEG activity of 23 participants performing the CAT (100 trials). On each trial, 148 participants had up to 30s to find a word that connects three unrelated words. Then they 149 reported if they solved the trial with a Eurêka (**Figure 1**; see *method*). Each trial was 150 characterized by a semantic association strength (SAS) value (a continuous variable 151 determined by the material and fixed between subjects) and categorized according to how 152 the subject solved it (with or without Eurêka; binary variable that depends on each subject).

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157 **Figure 1. Summary of the CAT procedure.** Experimental design of the CAT. Each trial starts 158 with the presentation of three unrelated words, vertically displayed on a grey screen for up to 159 30s. The participants press the space bar as soon as they think they have the solution, 160 triggering the display of a blank screen during 2.5s. They verbalize their response during this 161 period. Then, the question "Eurêka?" is displayed on the screen, and the participants indicate 162 whether the solution that they just gave came to their mind with a Eurêka, using the keyboard 163 letters "V" (yes) and "N" (no), within a time limit of 5s. Finally, a fixation cross is displayed on 164 the screen for a random time before beginning a new trial (intertrial interval ranges between 165 1.2 and 1.8s).

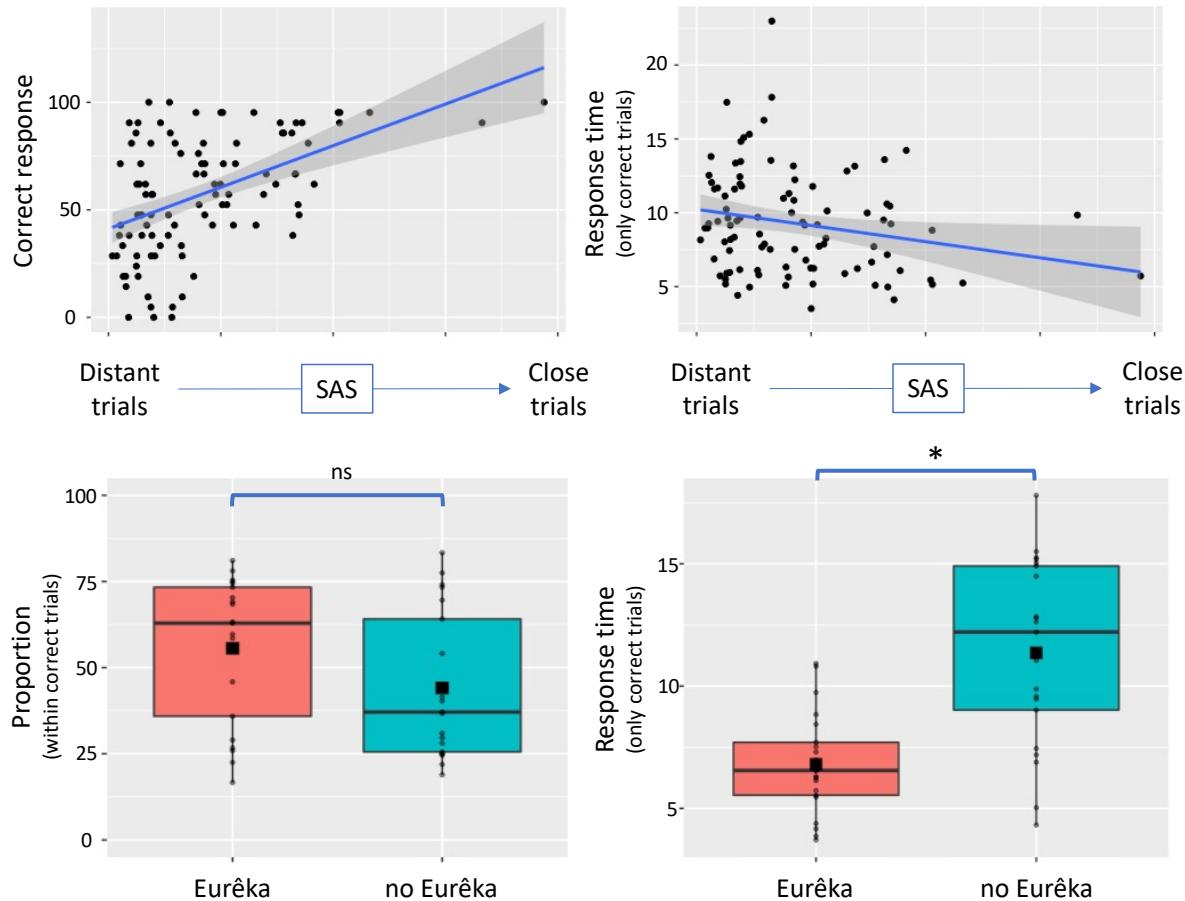
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168 Overall, mean accuracy across individuals was 57.4% (SD=12.0), and mean RT was 8.4s 169 (SD=1.0).

170 Across trials, the percentage of participants who gave a correct response correlated 171 significantly positively with SAS (**Figure 2A**, $\rho=0.48$, $p=3.85 \cdot 10^{-7}$), indicating that the closer 172 the solution was, the more individuals found it. The correlation between the mean RT for 173 correct responses across trial and SAS was negative and marginally significant (**Figure 2B**, $\rho=-0.20$, $p=0.051$).

175 On average, the participants reported a Eurêka in 55.6% ($SD=20$) of correct trials (and
 176 in 22.7% ($SD=16.4$) of incorrect trials), whereas they declared no Eurêka in 44.1% ($SD=21.1$) of
 177 correct trials (and in 49.1% ($SD=20.5$) of incorrect trials). Within correct trials, the percentages
 178 of Eurêka and no Eurêka did not statistically differ ($W=149, p=0.26$; **Figure 2C**). However, mean
 179 RT in trials correctly solved with Eurêka were significantly shorter than mean RT in trials solved
 180 without Eurêka (respectively, 6.8s ($SD=2.1$) and 11.4s ($SD=3.8$), $W=15, p=1.30 \cdot 10^{-3}$, **Figure 2D**).
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 185 **Figure 2. Behavioral results. A.** Percentage of participants with correct responses per trial as
 186 a function of SAS. Each dot represents a trial, and the blue line represents the regression line
 187 between the two variables ($\rho=0.48, p=3.85 \cdot 10^{-7}$). **B.** Averaged RT per trial as a function
 188 of SAS. Each dot represents a trial, and the blue line represents the regression line between the
 189 two variables ($\rho=-0.20, p=0.051$). **C.** Percentage of Eurêka (in red) and no Eurêka (in blue)
 190 within the correct trials. Each dot represents a subject, color boxes represent the upper and
 191 lower quartiles, the black horizontal line within the boxes symbolizes the median, and the
 192 filled square is the mean value across subjects. **D.** Averaged RT of correct trials with Eurêka (in
 193 red) and without Eurêka (in blue). Same legend as in C. ns: non-significant, *: $p<0.05$.
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196 We examined how *semantic remoteness* related to Eurêka reports by computing
 197 logistic regressions at the individual level (see method). The results show no significant effect
 198 of SAS (orthogonalized from RT) on Eurêka reports in any individual (**Figure S1A**). At the group

199 level, the one-sample t-test of the individual regression coefficients was not significant
200 (mean=0.004, SD=0.01, $t(20)<1$, $p=0.70$; **Figure S1B**).

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203 EEG

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

210 The average number of trials included in the EEG analyses (non-artifacted correct trials
211 with $RT>4s$) for the initial and response time windows was, respectively, 32.1 (SD=11.5) and
212 32 trials (SD=11.7) for *semantic remoteness* condition, and 30.3 (SD=12) and 29.4 trials
213 (SD=11) for the in *insight solving* condition. The time-frequency maps of EEG power across all
214 trials are shown in **Figure S2** for each time window of interest, including topographical maps
215 for each frequency band.

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

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

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229 *Semantic remoteness in associative combination*

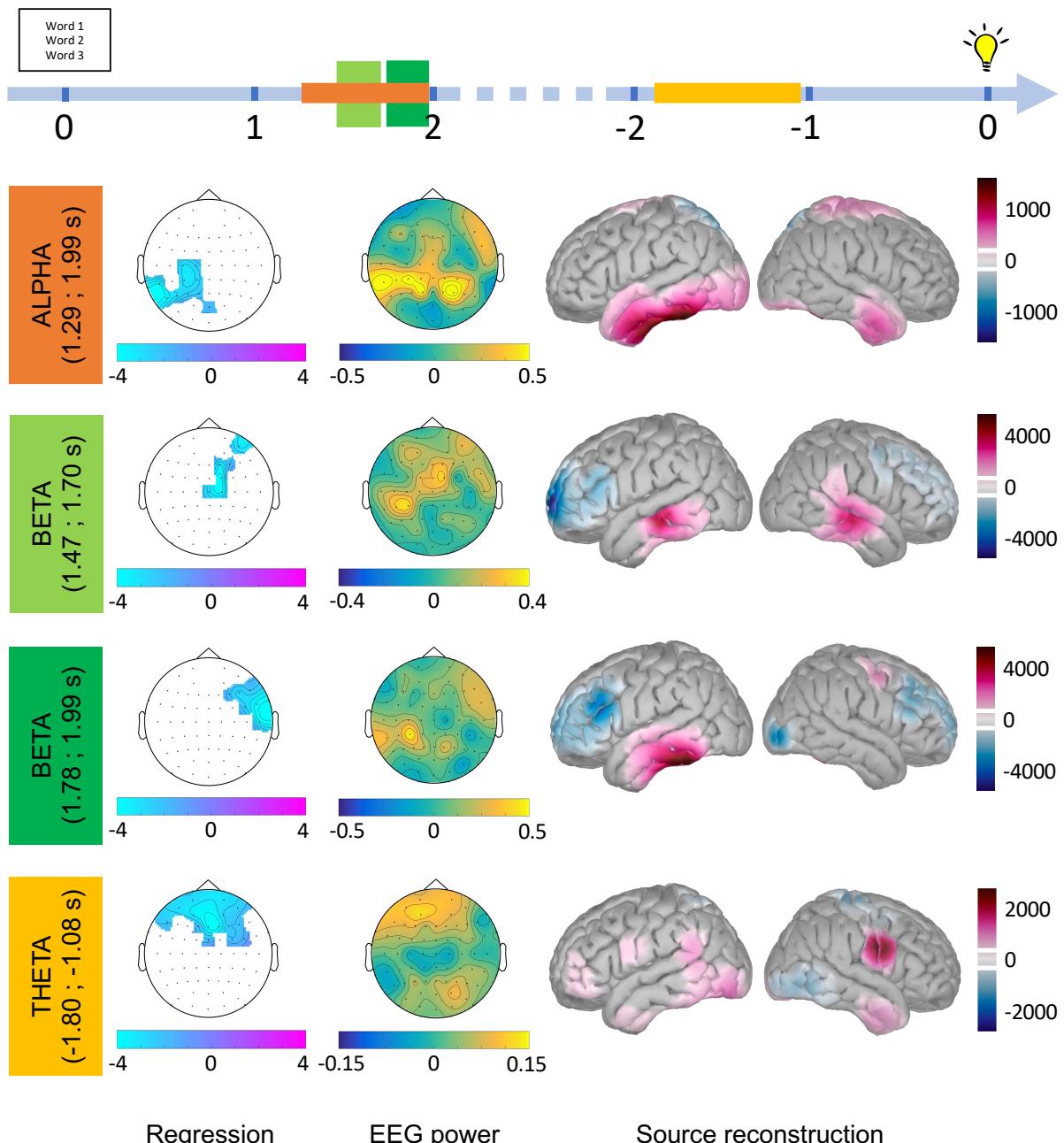
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231 We found three significant negative clusters (i.e., the lower the SAS, i.e., the more remote the
232 solution, the higher the power in the considered frequency band) (**Figure 3**). No positive
233 clusters were found.

234 Two significant clusters were observed during the initial time period. A first negative
235 cluster was observed in the alpha band on left temporal and parietal electrodes, from 1.29 to
236 1.99s after the onset of the cue words (11 electrodes, $sum(t)=-1523$, $p_{corr}=5.99 \cdot 10^{-3}$) (**Figure 3**,
237 "alpha" in orange). We performed a source reconstruction of alpha band activity during the
238 cluster time window and contrasted the cortical source maps between distant and close trials.
239 The largest source differences in alpha band between 1.29 and 1.99s were located in the left
240 inferior temporal gyrus and the left anterior part of the middle temporal gyrus. We also
241 observed source differences in alpha band activity in the right hemisphere in the anterior part
242 of the inferior and middle temporal gyrus and the right pre- and post-central gyrus (**Figure**
243 **S3A**).

245 A second negative cluster was observed in the beta band during the initial time
246 window. It was formed from two subsets of electrodes over time. Beta activity increased with
247 remoteness first on central electrodes from 1.47 to 1.70s after the cue words onset (6
248 electrodes, $\text{sum}(t)=-421$, $p_{\text{corr}}=0.03$) (**Figure 3**, "beta" in light green) and second on temporo-
249 frontal electrodes from 1.78 to 1.99s (7 electrodes, $\text{sum}(t)=-554$, $p_{\text{corr}}=0.02$) (**Figure 3**, "beta"
250 in dark green). We performed source reconstruction in the beta band during these two time
251 periods separately. Between 1.47 and 1.70 s, the distant versus close contrast revealed
252 sources located in bilateral posterior middle temporal gyrus. In addition, there was reduced
253 beta activity for distant than close trials in the left anterior part of the middle frontal gyrus
254 (**Figure S3B**). Between 1.78 and 1.99s, the sources showing differentiated beta band activity
255 for remote versus close trials were located in similar regions (**Figure S3C**): beta power was
256 higher in distant than close trials in a potential source located in the left posterior inferior
257 temporal gyrus and was lower in the left posterior and inferior gyrus encompassing the left
258 inferior frontal sulcus.

259 The third negative cluster was observed in the theta band during the response time
260 window (-1.80 to -1.06s before the response) on prefrontal electrodes (15 electrodes,
261 $\text{sum}(t)=-2574$, $p_{\text{corr}}=2.00 \cdot 10^{-3}$) (**Figure 3**, "theta" in yellow). As for the previous clusters, we
262 reconstructed the sources of theta band activity in the cluster time period. Contrasting distant
263 versus close trials revealed sources located in the right inferior part of pre- and post-central
264 gyrus and in several regions in the left hemisphere, including the lateral part of the orbital
265 gyrus and the anterior part of the inferior frontal gyrus, the inferior pre- and post-central
266 gyrus, the posterior part of the superior temporal gyrus and posterior and anterior temporal
267 areas (**Figure S3D**).



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270 **Figure 3. EEG effects related to the remoteness of semantic associations. Top:** Time course
271 (in second) of the task with the two time windows of interest (initial time window between 0
272 and 2s after the onset of the cue words, and response time window between -2 and 0 s before
273 the response). Colored rectangles symbolize the time period where clusters significantly
274 associated with the remoteness of semantic associations were observed in the alpha band (in
275 orange), beta band (in light and dark green), and theta band (in yellow). For each cluster, the
276 results are further detailed as follows. **First column:** Topographical maps of the clusters. The
277 significant clusters ($p_{\text{corr}} < 0.05$) are represented for each frequency band. The color codes the
278 regression coefficient values in the significant clusters (color bar from negative values in light
279 blue to positive values in purple). **Second column:** Topographical maps of the EEG power in
280 each band contrasted between distant (with low SAS values) minus close (with high SAS) trials,
281 averaged across subjects and in the time-windows of the clusters (as indicated in the colored

282 rectangles on the left). Color bars indicate EEG power (z-score of dB) from negative (in blue,
283 distant<close) to positive (in yellow, distant>close) values. **Third column:** Source
284 reconstruction of EEG activity in each frequency band during the significant cluster time
285 periods. The cortical source maps were contrasted between conditions (distant - close), and
286 we represent the difference in source activity, for each frequency, averaged in the time
287 window of the cluster. The color bar indicates the power (in pA.m) from negative (in blue) to
288 positive (in purple) values. The white lines in the color bars indicate the threshold used to
289 visualize the source on the normalized cortical surface rendering.

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292 *Insight problem-solving*

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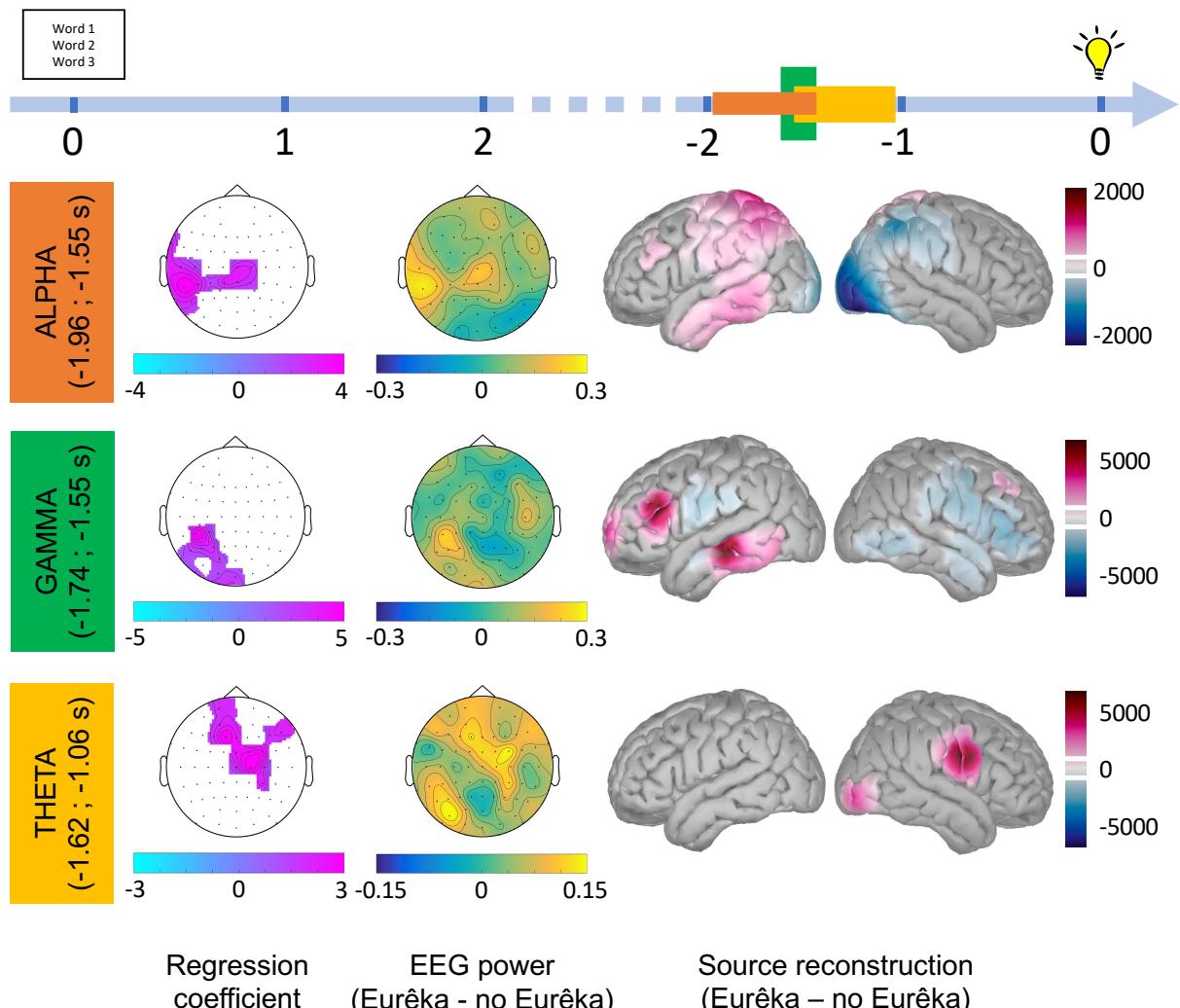
294 We found three significant positive clusters, where trials solved with a Eurêka were associated
295 with significantly higher activity amplitudes than those solved without a Eurêka. All clusters
296 were observed in the response time window (**Figure 4**). No negative clusters were found.

297 The first positive cluster was observed in the alpha band frequency in left central and
298 temporal electrodes, between -1.96 and -1.55s before the response button press (13
299 electrodes, $\text{sum}(t)=1174$, $p_{\text{corr}}=0.01$) (**Figure 4**, "alpha" in orange). The source reconstruction
300 of EEG activity in the alpha band during the time window of this cluster showed increased
301 alpha activity of sources mainly located in the left superior parietal lobule and posterior part
302 of the inferior and middle temporal gyrus. Additionally, sources' alpha activity was reduced in
303 the right occipital polar cortex when participants reported a Eurêka (**Figure S4A**).

304 The second positive cluster overlapped temporally with the end of the first cluster
305 during the response window (-1.74 to -1.55s before the response) and was found in the
306 gamma band in left parieto-temporal electrodes (9 electrodes, $\text{sum}(t)=372$, $p_{\text{corr}}=7.99 \cdot 10^{-3}$)
307 (**Figure 4**, "gamma" in green). The source reconstruction of EEG activity in the gamma band
308 during the time period of this cluster showed increased gamma activity for Eurêka relative to
309 no Eurêka trials in the left anterior superior frontal gyrus, around the inferior frontal sulcus
310 (encompassing posterior part of inferior and middle frontal gyrus) and left middle temporal
311 gyrus (**Figure S4B**).

312 The last positive cluster was observed in the theta band on centro-frontal electrodes
313 from -1.62 to -1.06s before the response (14 electrodes, $\text{sum}(t)=1377$, $p_{\text{corr}}=7.99 \cdot 10^{-3}$) (**Figure**
314 **4**, "theta" in yellow). During the cluster time window, the source reconstruction of EEG activity
315 in the theta band showed greater theta activity in the inferior part of the right pre- and post-
316 central gyrus (**Figure S4C**).

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320 **Figure 4. EEG effects related to *insight solving*.** **Top:** Time course of EEG activity during the
321 two time windows of interest (initial time window between 0 and 2s after the onset of the cue
322 words, and response time window between -2 and 0s before the response). Colored
323 rectangles symbolize the time period where clusters are significantly associated with Eurêka
324 reports in the alpha band (in orange), the gamma band (in green), and the theta band (in
325 yellow). For each cluster, the results are further detailed as follows. **First column:**
326 Topographical maps of the cluster. The significant clusters ($p_{corr} < 0.05$) are represented for
327 each frequency band. The color codes the regression coefficient values in the significant
328 clusters (color bar from negative values in light blue to positive values in purple). **Second**
329 **column:** Topographical maps of EEG power in each band contrasted between trials with
330 Eurêka minus those without Eurêka, averaged across subjects and in the time windows of the
331 clusters (as indicated in the colored rectangles on the left). Color bars indicate EEG power (z-
332 score of dB) from negative (in blue, Eurêka < no Eurêka) to positive (in yellow, Eurêka > no
333 Eurêka) values. **Third column:** Source reconstruction of EEG activity in each frequency band
334 during the time periods of the significant cluster. The cortical source maps were contrasted
335 between conditions (Eurêka – no Eurêka), and we represent the difference in source activity,
336 for each frequency, averaged across the time window of the cluster. The color bar indicates
337 the power (in pA.m) from negative (in blue) to positive (in purple) values. The white lines in

338 the color bars indicate the threshold used to visualize the source on the normalized cortical
339 surface rendering.

340

341

342 **Discussion**

343

344 We explored the neurophysiological correlates of two cognitive components of creative
345 problem-solving. We used an adapted version of Mednick's task (Mednick, 1962; Bendetowicz
346 et al., 2017, 2018) to examine the time course of EEG power related to the *insight solving* and,
347 for the first time, the effect of the *remoteness* of the solution to be found in the context of a
348 semantic associative combination. In contrast with most of the previous EEG studies using a
349 similar task that averaged signal across long time-windows or large set of electrodes, or were
350 restricted to specific electrodes or frequency bands (Jung-Beeman et al., 2004; Razumnikova,
351 2007; Danko et al., 2009; Luft et al., 2018), we employed a data-driven time-frequency
352 approach. We found distinct patterns of activity in several frequency bands associated with
353 *remoteness* and *insight solving*. *Remoteness* was associated with a significant increase in alpha
354 activity in a left temporo-central cluster and beta activity in a right fronto-temporal cluster
355 during the initial phase of the task and a later increase in theta activity in a frontal cluster just
356 before the response. EEG activity changes related to *insight* were observed uniquely in the
357 period just preceding the response. They included an increase in alpha activity in a left
358 temporo-central cluster, followed by a gamma activity increase in a left parietal cluster, and
359 finally an increase in theta band activity in a fronto-central cluster. Overall, these EEG findings
360 provide new insights into the dynamic mechanisms involved in creative problem-solving.

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

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368 **Remoteness in associative combination**

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370 The *remoteness* of semantic associations was associated with an increase in activity in the
371 alpha band, about 1.5 seconds after displaying the cue words. Alpha is the most reported EEG
372 correlate in creativity studies using various tasks (Fink et al., 2009; Fink & Benedek, 2014; Fink
373 & Neubauer, 2006; Jauk et al., 2012; Mölle et al., 1996; Shemyakina et al., 2007; Zhou et al.,
374 2018; Mastria et al., 2021), including the RAT (Jung-Beeman et al., 2004; Sandkühler &
375 Bhattacharya, 2008; Luft et al., 2018). Alpha activity increases with the creative requirements
376 of the task (Fink & Benedek, 2014). It has been interpreted as an active inhibition (Klimesch et
377 al., 2007; Klimesch, 2012) of external, non-relevant stimuli, allowing the increase of internal
378 processing (Cooper et al., 2006; Cona et al., 2020) and internally-oriented attention (Fink &
379 Benedek, 2014; Lustenberger et al., 2015). Klimesch (Klimesch, 2012) postulated that alpha-
380 related inhibition is needed to explore and navigate in semantic memory, which is organized
381 as a network. More precisely, access to remote knowledge may require that closely related,
382 but not relevant memory information, is inhibited. Distant CAT trials likely required extended
383 access to the knowledge stored in semantic memory as participants had to find a remote
384 solution and inhibit close but irrelevant associations. The increase in alpha band activity during

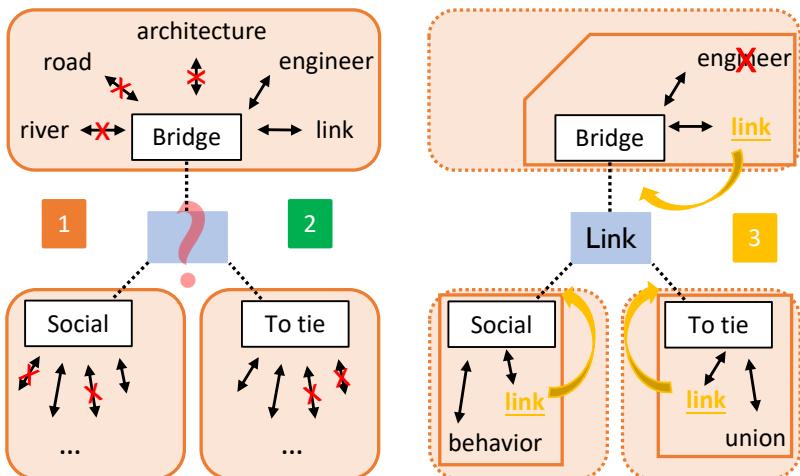
385 the initial time may reflect this process. The source reconstruction suggested that the effect
386 of *remoteness* in the alpha band involved the left (and to a lesser extent to the right) inferior
387 and middle temporal gyrus. Previous studies have identified different temporal regions as key
388 brain areas for semantic processing (Hickok & Poeppel, 2004; Binder et al., 2009; Visser et al.,
389 2012; Ralph et al., 2017) with distinct roles for regions along the rostro-caudal and supero-
390 inferior axes (Ralph et al., 2017). The anterior temporal lobe appears as a transmodal hub in
391 semantic processing in interaction with more posterior temporal areas. The left inferior
392 temporal gyrus plays a role in semantic representation and word meaning (Whitney et al.,
393 2011). The left posterior middle temporal gyrus is involved in a semantic control network
394 (Noonan et al., 2013; Teige et al., 2019; Evans et al., 2020; Vatansever et al., 2021). Semantic
395 control is likely involved in CAT, especially in the distant trials where participants had to
396 retrieve remote associations and combine them. Neuroimaging studies using RAT-like tasks
397 have reported the involvement regions of the semantic control network (Anderson et al.,
398 2009; Gonen-Yaacovi et al., 2013; Jefferies & Wang, 2021). The involvement of semantic
399 control in CAT is also consistent with previous research linking alpha activity with cognitive
400 control (Sadaghiani & Kleinschmidt, 2016). Overall, the initial alpha activity that we found may
401 reflect enhanced controlled access to the knowledge required by distant trials.

402 The *remoteness* of the associative combination was also associated with an early
403 increase in beta power in the right centro-temporal and temporo-frontal electrodes. This beta
404 activity temporally overlapped with the alpha cluster described above. Variation of beta
405 activity during creative thinking or problem-solving is not classically reported. A few studies
406 reported an increase in beta activity in frontal and temporal electrodes associated with the
407 RAT (Razumnikova, 2007) or during other creativity tasks (Rosen & Reiner, 2016; Zioga et al.,
408 2020), but its functional role in the context of creativity is not understood. Beta activity is
409 usually associated with motor preparation, but in different regions and time windows than in
410 our study (da Silva, 2009; Weiss & Mueller, 2012). Hence, the observed higher beta activity
411 for more remote combinations may reflect non-motor cognitive processes. Enhancement of
412 beta-band activity has been related to various aspects of language processing (Weiss &
413 Mueller, 2012), such as the maintenance of a mental state during a cognitive task requiring
414 language (Engel & Fries, 2010) or of visual object representation in short-term memory
415 (Tallon-Baudry et al., 1999). The role of beta activity increase in distant CAT-solving is not
416 obvious. One can speculate that when the cue words to be combined are not quickly
417 converging to a solution, the current mental activity (i.e., active exploration of semantic
418 memory related to the alpha activity) should be maintained, increasing beta activity in the
419 distant condition.

420 Finally, *remoteness* was associated with higher theta activity one second before the
421 subject's response, involving fronto-temporal regions. Theta activity in creative problem-
422 solving has been scarcely reported (Razumnikova, 2007; Sandkühler & Bhattacharya, 2008).
423 The role of theta activity in cognition is debated. Prefrontal theta activity has been associated
424 with several aspects of executive control functions. Cavanagh and colleagues (Cavanagh et al.,
425 2012; Cavanagh & Frank, 2014) proposed that theta rhythm generated by the median PFC
426 region is involved in monitoring novelty, conflict, and surprise. Theta activity increases when
427 information is accumulated (Cavanagh et al., 2012; Cavanagh & Frank, 2014). When controlled
428 processes are engaged during goal-directed behavior, theta band coherence between frontal
429 and other relevant brain regions increases (Zavala et al., 2018). Several studies have also
430 associated theta activity with other controlled processes and functions such as inhibition
431 (Adelhöfer & Beste, 2020), planning (Domic-Siede et al., 2020), prioritizing relevant

432 information in working memory (Riddle et al., 2020), or analytical reasoning (Williams et al.,
433 2019). Importantly, theta activity has been related to memory retrieval and encoding (Düzel
434 et al., 2010) and may reflect integration processes that allow us to build new connections
435 between elements of knowledge in semantic memory (Backus et al., 2016; Nicolás et al.,
436 2021). Hence, theta band activity associated with distant CAT may reflect controlled retrieval
437 and integration in semantic memory. Consistent with this interpretation, the central
438 contribution of executive and memory processes in creativity is now well established (Cassotti
439 et al., 2016; Beaty et al., 2016; Volle, 2017; Benedek & Jauk, 2018; Benedek & Fink, 2019).
440 Recent studies have demonstrated the important role of the executive control network for
441 creative thinking (Beaty et al., 2016, 2017; Bendetowicz et al., 2018). The executive control
442 network supports several control processes involved in creative thinking such as working
443 memory, inhibition, attentional control, planning, flexibility, and control and selection in
444 memory retrieval. The source reconstruction of our theta-related cluster revealed a set of left
445 regions largely coherent with the executive control network, such as the rostro-lateral PFC,
446 parieto-temporal junction, and temporal regions. The rostro-lateral part of the PFC is a node
447 of the executive control network that has been shown critical for solving CAT in frontal
448 patients, especially in distant trials (Bendetowicz et al., 2018). Additionally, the grey matter
449 volume in this region was also correlated with performance at this task (Bendetowicz et al.,
450 2017). The particular role of the left rostro-lateral PFC in the CAT may be to combine the
451 retrieved associates or integrate the result of the search from each cue word, i.e., in the
452 relational integration of distant items (Aichelburg et al., 2016; Green et al., 2016; Urbanski et
453 al., 2016). Thus, observing theta power increase during the response time window is
454 consistent with previous studies using different methods showing the involvement of the left
455 rostro-lateral PFC and executive control network in creativity. The source reconstruction also
456 located theta activity in the right inferior pre- and post-central gyrus, a result that was shared
457 between *remoteness* and *insight* analyses and is discussed below.
458

459 Overall, our results combined with the existing literature suggest that remote
460 associative semantic combination relied on several controlled processes in distinct periods of
461 CAT-solving (**Figure 5**). Hypothetically, in the initial phase of the task, semantic control
462 (supported by alpha activity in the posterior middle temporal gyrus) may enable the
463 exploration of semantic memory in search of remote associates (in relation to alpha activity
464 in infero-temporal regions, including the temporal pole). The semantic search or search space
465 might be reflected in the overlapping beta activity, that is associated with the maintenance of
466 a current mental state or representation. Finally, just before the response, the increased
467 prefrontal theta activity may reflect the involvement of other executive controlled processes,
468 allowing to integrate and combine the search results from each cue word, evaluate the
469 generated candidate solution, and finally select the most appropriate response.
470
471



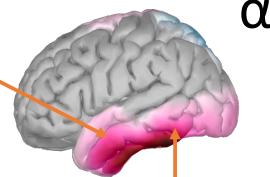
1- Generation of remote associates

Generation of semantic associations (\leftrightarrow):

- Semantic representation
- Word meaning

Semantic control (X):

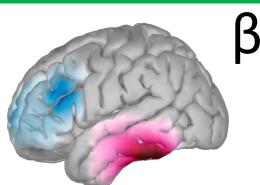
- Active inhibition of non relevant associations
- Increase internal processing
- Create remote associates



2- Maintenance of related cognitive activity

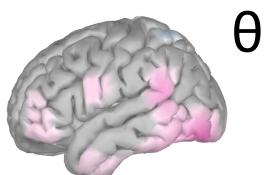
To maintain the active exploration of semantic memory

- To maintain the actual cognitive state
- To maintain the visual representation of words



3- Executive controlled processing

- To integrate and combine the search results from each cue word
- To evaluate the generated candidate solution
- To select the most appropriate response



472

473

474 **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.

482

483

484 Insight solving

485

486 The second aspect of the CAT that we analyzed, the effect of *insight solving*, was associated
 487 with distinct EEG correlates than remote associative combinations. Eurêka-related EEG
 488 differences were observed only during the response time window, suggesting that the early
 489 stages of problem-solving were similar for trials with or without Eurêka. It might be explained
 490 by the fact that the two solving modes (with and without Eurêka) are not exclusive and may
 491 co-occur within a trial. It is possible that people initially used analytical thinking until they
 492 reach an impasse and finally solved the problem with insight. Cognitive theories link insight
 493 with the need to experience a mental impasse and to restructure the problem representation
 494 before solving it with insight (Ohlsson, 1992; Sandkühler & Bhattacharya, 2008). It may thus
 495 be not surprising that insight and non-insight trials only differ in the period just preceding the
 496 response. Nevertheless, we examined only the first and last two seconds of problem-solving.
 497 We cannot exclude that differences between trials with Eurêka and without Eurêka occurred
 498 in between these time windows.

499 Just before the response, we observed successive modulation of alpha- and gamma-
 500 band activities for trials with Eurêka (compared to those without Eurêka), which is consistent
 501 with previous EEG studies (Jung-Beeman et al., 2004; Sandkühler & Bhattacharya, 2008; Sheth
 502 et al., 2009; Oh et al., 2020). The source reconstruction suggested that alpha activity related
 503 to Eurêka involved the left posterior inferior and middle temporal gyrus and the parietal
 504 region. Although the alpha activity associated with the *remoteness* and *insight solving* effects
 505 showed some similarities, they occurred at different time periods (initial vs. response time
 506 windows), suggesting that they reflected distinct mechanisms. Given the role of alpha in
 507 inhibition processes and the involvement of the left inferior and middle temporal gyrus in
 508 semantic processing discussed above, the Eurêka-related alpha increase may reflect the
 509 inhibition of non-relevant information to overcome the mental impasse and restructure the
 510 problem (Sandkühler & Bhattacharya, 2008). The source reconstruction also suggested that
 511 the superior parietal lobule, a region often showing alpha activity in relation to creativity (Fink
 512 & Benedek, 2014), played a role in *insight solving*. Given the classical role attributed to alpha
 513 activity in parietal areas in creativity research, this cluster might alternatively or additionally
 514 reflect in increased state of internally oriented attention during trials with *insight solving* (Fink
 515 & Benedek, 2014).

516 Succeeding to alpha, we observed a gamma activity increase in left parietal electrodes,
 517 which involved the left anterior superior frontal gyrus, left posterior inferior, and middle
 518 frontal gyrus and left middle temporal gyrus. An increase in gamma activity is often reported
 519 by studies exploring insight problem-solving (Jung-Beeman et al., 2004; Sandkühler &
 520 Bhattacharya, 2008; Sheth et al., 2009; Rosen & Reiner, 2016; Oh et al., 2020) and was related
 521 to the suddenness of the solution (Sandkühler & Bhattacharya, 2008). Gamma burst has been
 522 associated with the sudden awareness of a mental representation from memory (Tallon-
 523 Baudry et al., 1999; Engel et al., 2001; Engel & Singer, 2001). Hence, the gamma activity
 524 observed during the CAT-solving with *insight* may reflect the awareness of a solution that
 525 popped up suddenly in mind, yielding the subjective Eurêka experience.

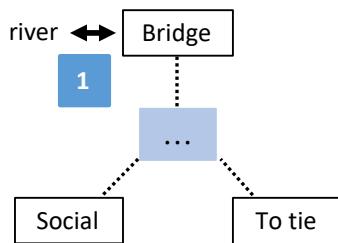
526 The similar alpha followed by gamma synchronization associated with insight reported
 527 by previous studies involved distinct electrodes that we observed, especially in the right
 528 hemisphere (Jung-Beeman et al., 2004; Sandkühler & Bhattacharya, 2008; Sheth et al., 2009).
 529 The reasons for this left-right difference with our results are unclear. They might relate to the
 530 use of different paradigms. Previous studies mostly used the compound remote associate
 531 task, requiring finding a word that forms a compound word with each cue. Instead, we use a

532 version where the solution is associatively related to the cue words. Thus, our task may rely
533 more on semantic processing than the compound remote associate task, thus recruiting more
534 left-brain areas (Hickok & Poeppel, 2004; Gonzalez Alam et al., 2019). Another methodological
535 difference is that previous EEG studies on insight focused on specific scalp regions or
536 frequency bands based on a priori hypotheses. In contrast, we used a data-driven approach
537 considering all the electrodes and frequencies in our analyses while controlling for multiple
538 comparisons. It potentially revealed new brain correlates of insight problem-solving. In
539 addition, as in other EEG studies based on the RAT (Sandkühler & Bhattacharya, 2008; Oh et
540 al., 2020), we observed alpha and gamma effects earlier than in Jung Beeman and al study
541 (Jung-Beeman et al., 2004). This difference may relate to the instructions given to our
542 participants of pressing the space bar when they thought the solution they had in mind was
543 correct. It may have encouraged the participants to evaluate their solution more carefully and
544 added a delay between the insight moment and button press.

545 Finally, as for remote trials, insight trials were associated with higher theta activity in
546 frontal electrodes. This theta activity may reflect conflict monitoring because when the
547 solution arises suddenly in consciousness, a conflict (or surprise) with the ongoing mental
548 representations or ideas can arise, signaling a need for monitoring and selection. The source
549 reconstruction located a potential source in the right inferior part of the pre- and post-central
550 gyri. Although sensorimotor regions in creativity has already been described (Matheson &
551 Kenett, 2020), its role remains challenging to interpret. Interestingly, this region was also a
552 candidate source for the theta activity associated with *remoteness* during the same time
553 window. *Remoteness* in associative combination and *insight solving* are often confused in
554 previous studies (Dietrich & Kanso, 2010), leading to an unclear link between them. According
555 to some theory, they are both resulting in overcoming a mental impasse suggesting that they
556 might share similar thread in the time course of EEG power. In our study, we explored both
557 components with the same task. Overall, our results did not suggest a link between *insight*
558 solving and *remoteness* (no significant interaction at the behavioral level, distinct brain cluster
559 at the sensor level). The shared sources in the theta band frequency cannot be explained by
560 an imbalance in the distribution of trials between the two conditions (for instance, more
561 Eurêka reports in distant trials) as the average number of trials included in the EEG analyses
562 did not significantly differ between conditions (see *Supplementary Data*). Even if our source
563 reconstruction is not specific to the cluster found at the sensor level (but rather to a frequency
564 band during a specific time window), we cannot exclude that *remoteness* and *insight* effects
565 shared some similar brain event occurring just before the response. Further study will be
566 needed to clarify this question.

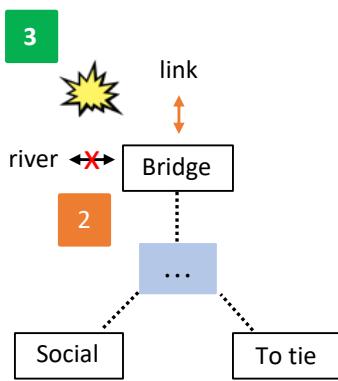
567
568 To summarize (**Figure 6**), we show that *insight solving* is associated with successively
569 increased alpha, gamma, and theta power during the last seconds of a CAT-solving. Alpha
570 activity could help to overcome strong but obvious associations of ideas. The solution could
571 hence suddenly emerge in the individual's mental representation, and lead to a gamma
572 activity. Then, a conflict might occur between the Eureka-mediated solution and the
573 previously ongoing mental thinking. This conflict needs to be monitored and controlled, which
574 may be reflected by the increase in theta activity.

575
576



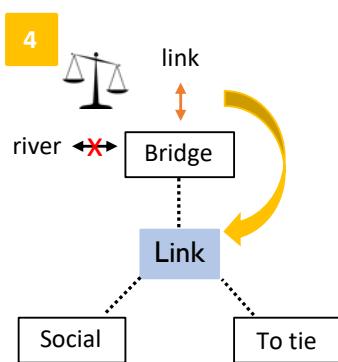
1- Impasse mentale

- Result from initial solving phase (Figure 6) that failed
- Strong association (\leftrightarrow) or no more new associates



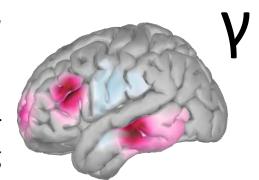
2- Restructuration

- To overcome the mental impasse
- Inhibition of strong association (\times)



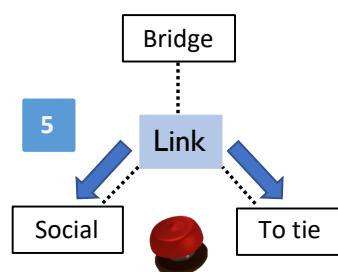
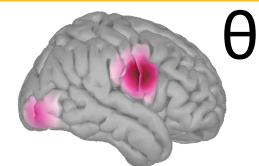
3- Eureka moment

- Sudden awareness of a new mental representation from memory (\star)
- Lead to a conflict or surprise with the ongoing mental representations or ideas



4- Control processes

- To monitor and control conflict and surprise ($\frac{\Delta}{\Delta}$)
- To select solution



5- Verification

- To evaluate the selected response
- Delay between the Eureka moment and the press button (red button)

577
578

579 **Figure 6. Hypothetical model of *insight solving* related results.** After reaching a mental
580 impasse (in blue), restructuration is needed to break out it. Inhibition of stong associations
581 can be supported by alpha activity in temporal areas (in orange). When a new association
582 suddenly arises in consciousness, a realization of the solution occurs (supported by gamma
583 activity, in green). It ensures a conflict or surprise that needs to be monitored to select the
584 appropriate association (supported by theta activity, in yellow), verified before answering (in
585 blue).
586
587

588 **Limitations**

589

590 This study is not without limitations. First, the CAT is a difficult task with a low correct response
591 rate, often around 60%. Added to the constraints related to EEG artefact cleaning, we included
592 in our analyses much fewer trials than expected. We chose not to analyze incorrect trials since
593 the cognitive involvement of the participants in incorrect trials is uncontrolled. Second, the
594 usually long response time in such a task led us to analyze fixed time windows at the beginning
595 and end of each trial without considering the time in between. We thus do not provide the
596 whole picture of the processes happening during our task. Finally, it may be noted that the
597 individual MRIs of the participants were not available. Thus, source reconstruction results
598 must be interpreted cautiously and entail more uncertainty than the effects we characterized
599 at the sensor level. However, the involved regions are broadly consistent with the
600 neuroimaging literature, and our results offer new perspectives on potential networks
601 involved in creative problem-solving. Finally, we used the most used and validated approach
602 with self-reports of Eureka experience to define *insight solving* (Laukkonen & Tangen, 2018).
603 However, the best method to capture the insight phenomenon that would best reflect specific
604 solving mechanisms is an open question.

605

606

607 **Conclusion**

608

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

625

626

627 **Method**

628

629 **Participants**

630

631 Twenty-three right-handed native French speakers aged from 21 to 25 years old (mean
632 age=23.04; standard deviation, SD=1.15; 13 women) were included in the study. All
633 participants were healthy adults with MMSE \geq 28 (Folstein et al., 1975), no history of
634 neurological and/or psychiatric illness, no psychoactive substance abuse, nor consumption
635 less than 24 hours before the experiment. Two participants were excluded because of

636 technical problems during the experiment. The analyzed sample thus consisted of 21 healthy
637 adults (mean age=22.95, SD=1.15 years old, 12 women). A national ethical committee
638 approved the study. All the participants gave their written informed consent and received
639 financial compensation.

640

641 Experimental task

642

643 EEG was recorded during the performance of the CAT (Bendetowicz et al., 2017, 2018), which
644 is an adapted version of the RAT (Mednick, 1962). In such a task, subjects are asked to provide
645 a word that connects three unrelated cue words. Our adapted version varied the semantic
646 strength association (SAS) between the cue words and the expected solution, based on French
647 associative norms (Debrenne, 2011; Bendetowicz et al., 2017, 2018). We considered the
648 average SAS between the expected solution and each of the three cue words within each trial.
649 Hence, every trial was characterized by a SAS value: the lower the SAS value, the more remote
650 the solution was from the cue words (an example trial with a low SAS value - hence distant
651 solution - is Bridge-Social-To tie, where the solution is Link; an example trial with a high SAS
652 value – hence close solution – is Street-Countryside-Centre, where the solution is Town).
653 Previous studies using the CAT (Bendetowicz et al., 2017, 2018) have shown that the
654 performance in this task, especially for distant trials, correlated with other creative
655 assessments suggesting its external validity. Following the same principles as in the original
656 CAT, we built 28 additional trials for the current study in order to anticipate the loss of
657 analyzable trials due to EEG experimental constraints and artifacts. In total, each participant
658 performed 100 trials (median SAS value 6.5, range from 0.3 to 38.8).

659 During the experiment, the participants were seated comfortably in front of a
660 computer screen. Before starting the task, the examiner explained the general design and
661 instructions with written support. Explanations on Eurêka were particularly detailed. It was
662 described as "the subjective experience you can have when you solve a problem, and the
663 solution comes to mind suddenly, it is not the result of cognitive efforts, and you are not able
664 to report the mental steps leading to this solution". It was opposed to analytic solving in which
665 "you have a strategy and the feeling of gradually getting closer to the solution". We clarified
666 that these two solving methods were not incompatible or exclusive and instructed the
667 participants to consider only a few seconds before their response. To ensure the participants
668 understood the instructions correctly, they completed ten practice trials, and the instructions
669 were repeated when needed. After instructions and training, the participants performed 100
670 trials in random order while EEG was recorded. Breaks were proposed to the participants
671 every 25 trials to limit fatigue.

672 The CAT was computerized and programmed using the Psychtoolbox (version 3.0.11)
673 running in MATLAB (MATLAB version 9.0 (R2016a), Natick, Massachusetts: The MathWorks
674 Inc.) (**Figure 1**). For each trial, the three cue words were displayed on the center of the screen,
675 one above the other to limit eye movements as much as possible. The participants were asked
676 to give a unique word related to all three cue words and had up to 30s to respond. They were
677 aware that the response could be a noun, a verb, or an adjective but not a proper noun or a
678 compound word. As soon as they thought they had found the correct answer, they pressed
679 the space button of the keyboard. This made the three words disappear, and the participants
680 had then a fixed time of 2.5s to tell their response verbally. The screen remained blank during
681 this period. The examiner wrote down the participant's response. In addition, as classically
682 performed in previous studies using similar tasks, we collected the self-report "Eurêka"

683 experience on a trial-by-trial basis (Kounios & Beeman, 2014). Thus, after the 2.5s response
684 period, the question "Eurêka?" was displayed on the screen. The participants had to indicate
685 whether the solution they gave came to their mind with a Eurêka by pressing the keyboard
686 letters "V" (Eurêka) or "N" (no Eurêka) within a time limit of 5s. A central fixation cross was
687 displayed during the intertrial interval followed by a jittered duration (mean=1.5s, range
688 between 1.2s and 1.8s).

689

690

691 Behavioral measures and analyses

692

693 Accuracy (correct or incorrect) was determined based on the French associative norm
694 (Debrenne, 2011; Bendetowicz et al., 2017). Responses were also considered valid if they were
695 lexically similar or synonyms to the one defined by the French associative norm. Finally, few
696 additional answers were accepted if they provided semantic similarities with the cue words
697 but were not in the French associative norm. In this case, only responses selected by a panel
698 of five external judges were considered correct. We defined response time (RT) as the time
699 between the onset of the display of the cue words and the space bar press.

700 Each trial is characterized by a *SAS* value (a continuous variable determined by the
701 material and fixed between subjects) and can be categorized according to how the subject
702 solved it (with or without Eurêka; binary variable that depends on each subject). To estimate
703 the effect of *remoteness* (*SAS*) on performance, we computed the percentage of individuals
704 with correct responses (i.e., number of individuals who gave a correct response divided by the
705 total number of participants) and the mean RT for correct responses on a trial-by-trial basis.
706 We explored the relation of accuracy and RT with the corresponding *SAS* value using Spearman
707 correlations.

708 We also explored how many trials were solved (or not) with a Eurêka and without a
709 Eurêka. To examine whether trials solved with a Eurêka differed from those without a Eurêka,
710 we compared the averaged percentage of Eurêka and no Eurêka, and the averaged RT of trials
711 with and without Eurêka across individuals. We focused on correct trials as incorrect ones
712 were excluded from the EEG analysis. Statistical comparisons were performed using non-
713 parametric paired Wilcoxon tests.

714 Finally, we explored the link between the effect of *SAS* and Eurêka using a two-level
715 modeling approach. First, we ran a Global Linear Model (GLM; using the *glmfit* function in
716 MATLAB) at the individual level using only correct trials. Taking advantage of the *SAS* value of
717 each trial, we used logistic regression to explore whether the *SAS* predicted a Eurêka. As we
718 expected the *SAS* to be correlated with RT, we removed the variance explained by RT from the
719 *SAS* variable. We then computed a logistic regression exploring the relationship between the
720 corrected *SAS* and Eurêka. Then, for the second-level analysis, we computed a one-sample
721 two-tailed t-test (against zero) on the subject's regression coefficients resulting from the GLM.
722 This allowed us to analyze the relation between Eurêka reports and *SAS* at the group level.

723

724

725 EEG

726

727 *EEG recording*: EEG data were recorded using BRAINAMP DC system (Brain Products GmbH,
728 München, Germany) with 64-active electrodes mounted in an elastic cap (actiCAP) according to
729 the extended International 10–20 system and including a row of low fronto-temporo-occipital

730 electrodes (PO9/10, TP9/10, FP9/10). Two additional electrodes were used as reference (FCz
731 electrode) and ground (AFz electrode). Disposable electrodes placed above and below the
732 right or left eye and lateral to the outer canthus of both eyes recorded vertical and horizontal
733 EOG, respectively. Electrode impedances were at or below ten kOhm. The EEG data were
734 recorded at 1 kHz with an online 0.016-250 Hz bandpass filter.

735

736 *EEG preprocessing:* All EEG preprocessing and analyses were performed using the FieldTrip
737 toolbox (Oostenveld et al., 2011), completed by homemade scripts, and brainstorm (version
738 09-Sep-2020) (Tadel et al., 2011) running under MATLAB (MATLAB version 9.0 (R2016a),
739 Natick, Massachusetts: The MathWorks Inc.).

740 EEG signal was downsampled offline to 128 Hz, and filtered with zero phase, third
741 order high pass, and low pass Butterworth filters (set at 0.5 and 63 Hz, respectively).
742 Independent component analysis (ICA) was used to detect and remove artefacts caused by
743 eye blinks. On average, two independent components (IC) were removed after the visual
744 inspection of the time series and topographies of the IC. Then, the EEG signal was visually
745 inspected to exclude artifacts related to muscles or movements. Next, noisy channels were
746 interpolated using the averaged signal of adjacent channels. A mean of 7 electrodes (SD=2.1)
747 was interpolated across participants. Trials containing more than 10% of bad channels were
748 removed (11 trials per individual on average, SD=6.5). Finally, the signal was re-referenced to
749 the average of all electrodes (recovering the FCz channel).

750 We segmented the EEG signal for each trial in two time windows of interest. First, the
751 "initial time window" corresponded to the 2s period following the onset of the cue word
752 display on the screen. Second, the "response time window" corresponded to the 2s period
753 preceding the space bar press (i.e., the subject's response). We considered only correct trials
754 for EEG data analysis. We excluded the trials with an RT shorter than 4s to avoid overlapping
755 our two time windows (14 trials excluded on average per individual, SD=9.5).

756 Averaged numbers of analyzed trials across individuals are presented in **Table S1**. In
757 addition, supplementary analyses are provided to ensure there was no unbalance between
758 the number of trials analyzed across conditions (i.e., *semantic remoteness* and *insight solving*;
759 see supplementary material).

760

761 *Time-frequency computation:* Time-frequency maps were computed for each electrode, trial,
762 and time window (initial and response) in a frequency range between 3 and 60 Hz. We used a
763 multitaper time-frequency transform (Slepian tapers, lower frequency range: 3-32 Hz, six
764 cycles, and three tapers per window; higher frequency range: 32-60 Hz, fixed time-windows
765 of 240ms, 4-31 tapers per window). This approach allows better control of time and frequency
766 smoothing. It uses a constant number of cycles across frequencies up to 32 Hz (hence a time
767 window with a duration that decreases when frequency increases) and a fixed time window
768 with an increasing number of tapers above 32 Hz in order to obtain more precise power
769 estimates by adaptively increasing smoothing at high frequencies. Hence, the resulting EEG
770 power represents the signal amplitude in a given frequency after its spectral decomposition.
771 Time courses were aligned to the onset of the cue word display for the initial time window
772 (corresponding to time 0 for the initial time window epochs) and the space bar press for the
773 response time window (corresponding to time 0 for these latter epochs). We performed a z-
774 score baseline correction of time-frequency maps using the time-frequency maps computed
775 from the EEG signal recorded -1.2 s to -0.1 before the onset of the display of the cue words on
776 each trial. Finally, time-frequency maps were averaged along the frequency dimension

777 according to the four frequency bands: theta 3-7 Hz, alpha 8-12 Hz, beta 13-30 Hz, and gamma
778 31-60 Hz.

779

780 *Task-based analysis:* As for the behavioral analysis, we used a two-level statistical analysis
781 approach at the sensor level. First, we used individual linear regressions to explore the relation
782 between EEG power and behavior. To explore EEG correlates of *semantic remoteness*, we used
783 EEG power as the dependent variable and SAS as the independent variable. To explore *insight*
784 *solving*, EEG power was the dependent variable, and the Eurêka report was the independent
785 variable. These two analyses were performed independently at the individual level for each
786 point in time, in each frequency band (theta, alpha, beta, gamma), and for each time window
787 (initial and response time window). This first level of analysis allowed us to obtain regression
788 coefficients at the individual level. Then, at the second (group) level, the resulting individual
789 regression coefficients were analyzed at the between-subject level with a one-sample two-
790 tailed t-test against zero. According to the following procedure, we corrected our results for
791 multiple comparisons using a cluster-based correction for the time and space (electrode)
792 dimensions. For each frequency band and time window of interest, the results from the one-
793 sample t-tests performed at each time point and on each electrode were clustered based on
794 spatio-temporal and statistical criteria. The cluster spatial extent was defined as at least one
795 neighboring electrode in either time or space based on the template "easycapM1" provided
796 by the Fieldtrip toolbox and matched our electrode cap. The clusters formation considered
797 only the (time, electrode) points where the one-sample t-tests were significant with a *p-value*
798 lower than 0.0125. We selected this statistical threshold because we computed a cluster-
799 based analysis for each of the four frequency bands of interest (0.05/4=0.0125). Then, we
800 computed the sum of the t-test statistics within each obtained cluster (sum(t)). In order to
801 obtain the distribution of this cluster statistics under the null hypothesis while correcting for
802 multiple comparisons, we repeated this analysis on 1000 Monte Carlo randomizations,
803 retaining only the maximum value of the sum of t-test across clusters on each randomization.
804 The clusters obtained from the original data were finally considered significant if their *p-value*
805 (p_{corr}) was lower than 0.05 across the 1000 randomizations.

806

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

812 For each individual, first, a head model was computed using the symmetric boundary
813 element method (BEM) method from OpenMEEG open-source software (Gramfort et al.,
814 2010), based on the template MRI normalized in the Montreal Neurological Institute (MNI)
815 system, available in Brainstorm software (MNI/Colin27), and coregistered with the 65
816 electrodes considering standard 10-10 electrode coordinates. Next, the noise covariance
817 matrix was computed on the time window of interest of all trials with a baseline corresponding
818 to the time period preceding the onset of the word triplet (-1.2s to -0.1s). Sources were then
819 computed at the trial level using preprocessed EEG signal (that is, 128-Hz, ICA-corrected,
820 average-referenced EEG signal). Next, we applied a weighted minimum norm imaging (wMNE)
821 method with current density map measures computed for 15000 trihedral dipoles – total of
822 45000 elementary dipoles, equivalent to sources unconstrained in their orientation –
823 distributed over the cortical mantle of the brain model obtained from the standard MNI/Colin

824 27 brain template. Then, we computed the power within the considered frequency band using
825 a Hilbert transformation at the source level for each cluster identified at the sensor level (i.e.,
826 in each time window and frequency band of interest). Since we used unconstrained
827 orientations for the sources, we computed the time-frequency decompositions for all 45000
828 elementary dipoles and summed the power for the three orientations at each source location
829 (or vertex) as recommended. Finally, power was averaged within the time window of the
830 cluster and then averaged across trials separately for each studied experimental condition.
831 This procedure was repeated for each participant, and the obtained cortical current power
832 maps were averaged across participants in each condition. Then, we contrasted the maps
833 between conditions (Distant minus Close conditions or Eurêka minus no Eurêka conditions)
834 according to the considered cluster. We did not run further statistical analysis at the source
835 level to avoid double-dipping. The cortical current power maps were thresholded to visualize
836 only sources with activity higher and lower than 10% of the absolute maximal source.
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838

Conflict of interest

841 The authors declare no conflict of interest.
842
843

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853

Authors'contribution

854
855
856 Conceptualization: EV and TB; Methodology: TB, MOT, BG, LH, NG, KL and RL; Data
857 acquirement: TB, MOT and BG; Analyses: TB, ALP, NG and KL; Supervision: EV and NG; Writing:
858 TB, EV and NG.
859
860

Data availability

861
862
863 The material and the data sets generated during and/or analyzed during the current study are
864 available from the corresponding author (TB) on reasonable request.
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