

Beyond alpha-band: The neural correlate of creative thinking

Original

Beyond alpha-band: The neural correlate of creative thinking / Mazza, Alessandro; Monte, Olga Dal; Schintu, Selene; Colombo, Samuele; Michielli, Nicola; Sarasso, Pietro; Törlind, Peter; Cantamessa, Marco; Montagna, Francesca; Ricci, Raffaella. - In: NEUROPSYCHOLOGIA. - ISSN 0028-3932. - ELETTRONICO. - 179:108446(2023), pp. 1-10. [10.1016/j.neuropsychologia.2022.108446]

Availability:

This version is available at: 11583/2974002 since: 2023-02-14T17:29:41Z

Publisher:

Elsevier

Published

DOI:10.1016/j.neuropsychologia.2022.108446

Terms of use:

This article is made available under terms and conditions as specified in the corresponding bibliographic description in the repository

Publisher copyright

Elsevier postprint/Author's Accepted Manuscript

© 2023. This manuscript version is made available under the CC-BY-NC-ND 4.0 license
<http://creativecommons.org/licenses/by-nc-nd/4.0/>. The final authenticated version is available online at:
<http://dx.doi.org/10.1016/j.neuropsychologia.2022.108446>

(Article begins on next page)

1 Manuscript type
2 Research report

3

4 Title

5 **Beyond alpha-band: The neural correlate of creative thinking**

6

7

8 Authors

9 Alessandro Mazza^a, Olga Dal Monte^{a,b*}, Selene Schintu^{c,d}, Samuele Colombo^e, Nicola Michiellif, Pietro
10 Sarasso^a, Peter Törlind^g, Marco Cantamessa^e, Francesca Montagna^e, Raffaella Ricci^a

11

12 Affiliations

13 ^a Department of Psychology, University of Turin, Torino, 10124, Italy

14 ^b Department of Psychology, Yale University, New Haven, CT, 06520-8205, USA

15 ^c Center for Mind/Brain Sciences-CIMEC, University of Trento, Rovereto, TN, 38068, Italy.

16 ^d Department of Psychology, The George Washington University, Washington DC, DC, 20052, USA

17 ^e Department of Management and Production Engineering (DIGEP), Politecnico di Torino, Turin, 10129, Italy

18 ^f PoliToBIOMed Lab, Biolab, Department of Electronics and Telecommunications, Politecnico di Torino,
19 10129, Turin, Italy

20 ^g Department of Business Administration, Technology and Social Sciences, Luleå University of Technology,
21 Luleå, 97187, Sweden

22

23

24 * Corresponding Author

25 Olga Dal Monte, Ph.D.

26 Via Verdi 10, 10124, Turin, Italy.

27 Email: olga.dalmonete@unito.it

28

29

30

31 **HIGHLIGHTS**

- 32 • Creativity entails Divergent thinking (DT) and Convergent thinking (CT) processes
- 33 • DT is linked to alpha synchronization and beta and gamma desynchronization
- 34 • CT is characterized by alpha desynchronization and beta and gamma synchronization
- 35 • DT is also coupled with leftward gaze shift and greater pupil dilation
- 36 • Different neurophysiological patterns underpin creative idea generation

37

38

39

40 **ABSTRACT**

41 The compound nature of creativity entails the interplay of multiple cognitive processes, making it difficult to
42 attribute creativity to a single neural signature. Divergent thinking paradigms, widely adopted to investigate
43 creative production, have highlighted the key role of specific mental operations subserving creativity, such as
44 inhibition of external stimuli, loose semantic associations, and mental imagery. Neurophysiological studies have
45 typically shown a high alpha rhythm synchronization when individuals are engaged in creative ideation. Also,
46 oculomotor activity and pupil diameter have been proposed as useful indicators of mental operations involved in
47 such a thinking process. The goal of this study was to investigate whether beyond alpha-band activity other higher
48 frequency bands, such as beta and gamma, may subserve *divergent* and *convergent thinking* and whether those
49 could be associated with a different gaze bias and pupil response during ideas generation. Implementing a within-
50 subjects design we collected behavioral measures, neural activity, gaze patterns, and pupil dilation while
51 participants performed a revised version of the Alternative Uses Task, in which *divergent thinking* is contrasted to
52 *convergent thinking*. As expected, participants took longer to generate creative ideas as compared to common
53 ones. Interestingly, during *divergent thinking* participants displayed alpha synchronization along with beta and
54 gamma desynchronization, more pronounced leftward gaze shift, and greater pupil dilation. During *convergent*
55 *thinking*, an opposite pattern was observed: desynchronization in alpha and an increase in beta and gamma rhythm,
56 along with a reduction of leftward gaze shift and greater pupil constriction. The present study uncovered specific
57 neural dynamics and physiological patterns during idea generation, providing novel insight into the complex
58 physiological signature of creative production.

59

60 Keywords

61 Divergent Thinking; Creativity; Alpha band; Beta band; Gamma band; Eye-Tracker.

62

63 **1. INTRODUCTION**

64 It is true that a brainstorming session can help scientists to produce many possible ideas and approaches to a
65 research question but it is also true that following a logical and methodological sequence of steps is necessary to
66 find the best possible answer to the question at hand - scientific research does indeed require a combination of
67 what is called *divergent* and *convergent* thinking.

68 The term *divergent thinking* refers to the ability to generate a variety of solutions, ideally novel and useful,
69 to a problem that is not characterized by a single valid solution. It involves higher-level cognitive processes such
70 as memory retrieval (Madore, Thakral, Beaty, Addis & Schacter, 2019), semantic associations (Fink et al., 2009),
71 and mental imagery (Benedek et al., 2014a; Fink & Benedek, 2014). In contrast, *convergent thinking* refers to the
72 ability to solve a specific problem by allowing only a restricted set of possible correct solutions. It uses stereotyped
73 mental operations (Razoumnikova, 2000) and requires more persistence and focus than *divergent thinking*
74 (Guilford, 1956; Runco, 2010).

75 Many studies investigating the neural correlate of *divergent thinking* consistently reported increased alpha
76 synchronization in different brain regions (e.g., Jauk, Benedek & Neubauer, 2012; Benedek, Schickel, Jauk, &
77 Neubauer, 2014b; Camarda et al., 2018; Agnoli, Zanon, MASTRIA, Avenanti, & Corazza, 2020), especially in
78 primary sensory (occipital lobe; e.g., Fink et al., 2009) and sensory association cortices (parieto-temporal cortices;
79 e.g., Schwab, Benedek, Papousek, Weiss & Fink, 2014; Fink, Grabner, Benedek & Neubauer, 2006; Benedek et
80 al. 2014b). These findings have linked alpha band activity to general top-down attentional control that is thought
81 to be responsible for blocking task-unrelated (distracting) sensory stimuli. Thus, increased alpha power would
82 reflect the re-directing of attention toward the internal world, facilitating high-level mental processes (Benedek,
83 2018; Jensen, Gelfand, Kounios & Lisman, 2002; Fink & Benedek, 2014).

84 While there is general agreement on the involvement of alpha-band activity in *divergent thinking*,
85 inconsistent results have been reported for beta- and gamma-band activity. Greater involvement of beta activity
86 was observed when participants were instructed to generate an idea than when they were asked to generate *original*
87 ideas (Razoumnikova, Volf & Tarasova, 2009), and in the context of problem solving, resting beta activity was
88 found to predict analytic trait-like styles of solution generation as opposed to more insight-based styles (Erickson
89 et al., 2018). However, because beta band activity has been found to either increase (e.g., Razoumnikova, 2000;
90 Stevens & Zabelina, 2020) or decrease (e.g., Sheth, Sandkühler & Bhattacharya, 2009) during creative tasks, a
91 clear interpretation of its involvement in *divergent thinking* has not yet been reached.

92 The literature also reports conflicting results on gamma rhythm. Some studies have excluded the gamma
93 band entirely from the creative process (e.g., Berkovich-Ohana, Glicksohn, Ben-Soussan & Goldstein, 2017) while
94 others have suggested it might have a role in creative thinking (e.g., Danko, Shemyakina, Nagornova &
95 Starchenko, 2009), although the involvement of this band in short-range intra-network communication is at odds
96 with the long-range-driven semantical associations required by *divergent thinking* (Von Stein & Sarnthein, 2000).

97 Other evidence for the possible involvement of gamma band in *divergent thinking* comes from paradigms
98 investigating insight-driven problem-solving, which report an increase in low-gamma activity in right temporal
99 regions during the generation of new solutions (Jung-Beeman et al., 2004; Sandkühler & Bhattacharya, 2008).
100 However, since no studies to date have directly investigated broadband gamma power during *divergent thinking*,
101 the role of this band remains unclear.

102 The heterogeneity of results about the EEG correlates of *creative thinking* can be attributed to (a) the
103 heterogeneity of methods employed and (b) the relatively limited number of studies investigating them. Although
104 methodological incongruencies affect the alpha band as well, this band has been more extensively studied than
105 higher frequency bands, often showing consistent results across studies. In contrast, since a limited number of
106 studies investigated both beta- and gamma-bands, the corpus of findings is markedly reduced and there is no
107 consensus about their role in creativity. Methodological heterogeneity has already been pointed out as one of the
108 main pitfalls of research in this field, as it prevents drawing consistent conclusions about the relationship between
109 the creative process and its neural and cognitive bases (Dietrich & Kanso, 2010). Here, we aimed to exploit one
110 of the most adopted approaches to the study of creativity (i.e., targeting *divergent thinking* via the AUT) to address
111 hypotheses about beta and gamma bands, that are based on either well-established extra-topic knowledge or
112 previous, heterogeneous, findings in the field of creativity. For example, higher-frequencies activity is known to
113 be related to cognitive mechanisms such as externally directed attention (Wróbel, 2000), bottom-up processing,
114 and perceptual binding (Gray & Singer, 1989) as well as unspecific cortical arousal (Pulvermüller et al., 1999);
115 however, it is unknown how such processes relate to *convergent* and *divergent thinking* and whether they should
116 be recruited or suppressed during the creative idea generation process. Answer this question can expand our
117 knowledge of the neurocognitive processes associated with creative idea generation.

118 Interestingly, re-directing attention towards the internal world, which is suggested to occur during
119 *divergent thinking*, has been mapped into gaze patterns (Ceh et al., 2020). Eye movements play an important role
120 in mental manipulation such as retrieving or imaging different objects, and scenes (Walcher, Körner & Benedek,
121 2017) and gaze aversion (i.e., gazing away from the center) allows humans to disengage from external stimuli and
122 re-orient their attention to internally directed cognitive processes (Doherty-Sneddon & Phelps, 2005). Also, pupil
123 dilation has been identified as a potential proxy for creative thinking. For example, during mental imagery pupil
124 diameter varies depending on the imagined scene (Henderson, Bradley & Lang, 2018; Sulutvedt, Mannix, &
125 Laeng, 2018), with a larger pupil size associated with memory retrieval (Kucevicz et al., 2018), mind wandering
126 (Pelagatti, Binda & Vannucci, 2020), internally directed cognition (Walcher, Körner & Benedek, 2017; Benedek,
127 Stoiser, Walcher & Körner, 2017) and *divergent thinking* (Ceh et al., 2020). While several works have investigated
128 gaze directionality during insight-driven problem-solving (Salvi & Bowden, 2016), only one study investigated
129 gaze direction during idea generation and found a better performance when participants were instructed to gaze
130 leftward (Hines & Martindale, 1974). However, the role of spontaneous gaze behavior during *divergent thinking*
131 is still unknown.

132 In the present study, we investigated whether *divergent* and *convergent thinking* are linked only with
133 alpha-band activity or if other, higher frequency bands, such as beta and gamma, might also serve critical functions
134 in creative processes. In addition, we investigated for the first time spontaneous gaze patterns during creative ideas
135 generation as assessed via *divergent thinking*. To this aim, we employed a revised version of the Alternate Uses
136 Task (Guilford, 1967), a well-established paradigm used to investigate *divergent* and *convergent thinking*. Using
137 a within-subjects design, participants were asked to generate either original (*divergent* condition) or common
138 (*convergent* condition) uses for everyday objects while EEG and eye tracker were recorded. We hypothesized an
139 increase in alpha and a decrease in both beta and gamma power during *divergent thinking*. We also expected
140 greater leftward gaze patterns during *divergent thinking* as compared to *convergent thinking* along with an increase
141 in pupil diameter, as a proxy of enhanced arousal and internally directed attention.

142

143 2. MATERIALS AND METHODS

144 2.1. Participants

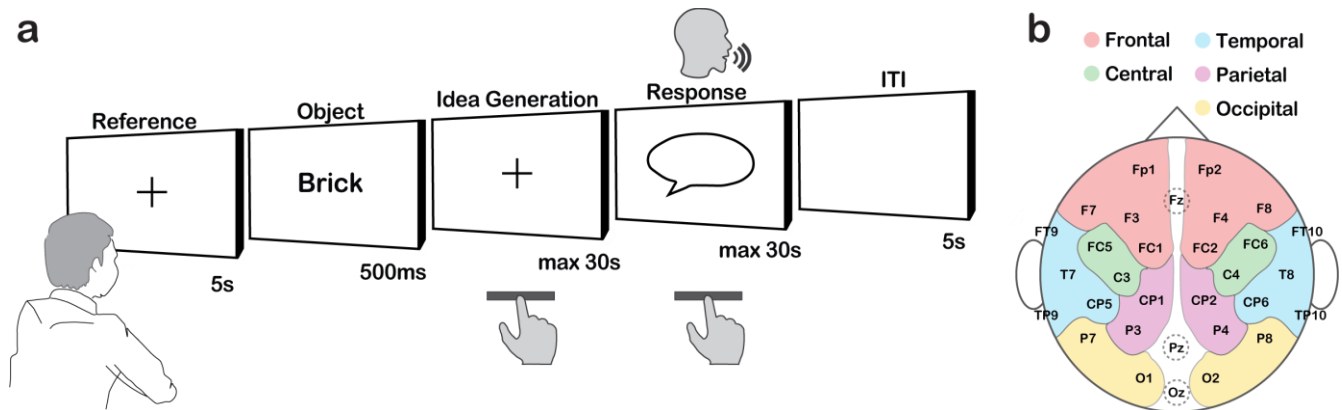
145 Forty healthy participants with normal or corrected-to-normal vision and no history of neurological problems were
146 recruited for this study. All participants gave their written informed consent to participate in this study, which was
147 approved by the ethics committee of the University of Turin. Three participants were excluded because left-handed
148 as assessed by the Edinburgh Handedness Inventory (Oldfield, 1971), and five because either they showed not
149 compliance with task instructions or because of eye-tracker signal loss. A final sample of 32 participants (10
150 females, 22 males; age = 23.91 ± 0.54 SEM) was submitted to statistical analyses.

151

152 2.2. Alternative Uses Task

153 To quantify *divergent* and *convergent thinking*, we employed a revised version of the Alternative Uses Task
154 (Guilford, 1967). The task included two experimental conditions: Common vs. Uncommon, measuring *convergent*
155 and *divergent thinking*, respectively. This revised version of the task allowed us to include the Common condition
156 as an easily comparable control for the condition of interest, the Uncommon condition (Runco & Acar, 2012). For
157 both Common and Uncommon conditions, the stimuli were words depicting different everyday objects. In the
158 Uncommon condition, participants were instructed to think of a highly uncommon/original/creative use for the
159 presented object, whereas in the Common condition, participants had to think about a highly common use for the
160 presented object. For example, for the object “glasses” a common use is “to improve reading” whereas an
161 uncommon one is “to start a fire”. Therefore, in the Uncommon condition participants were explicitly instructed
162 to explore and generate novel ideas, whereas in the Common condition they were instructed to select the most
163 immediate solution, i.e. to channel their thinking towards the answer that is regarded as unique (Guilford, 1956).
164 Forty unique objects were randomly assigned to the Common or Uncommon condition (20 items per condition)
165 for each participant. In a within-subjects design, each participant was presented with one Common block (20
166 consecutive trials) and one Uncommon block (20 consecutive trials). The block order was counterbalanced across
167 participants. The items used were: Axe; Ball; Basket; Bed; Book; Bra; Bread; Can; Coffin; Coin; Colander; Comb;
168 Fork; Guitar; Gun; Hammer; Hanger; Helmet; Lamp; Magnifier; Mirror; Needle; Net; Paperclip; Pillow; Pot; Rag;
169 Ring; Scissors; Shoe; Sock; Sponge; Stick; Tent; Toothpaste; Trousers; Tire; Umbrella; Vase; Window. At the
170 beginning of the experimental session, each participant was presented with task instructions, followed by a short
171 practice in which two trials of the Common and two of the Uncommon condition were presented. At the beginning
172 of each experimental block, participants were presented with a brief reminder of the instructions and then informed
173 about the block condition (Common or Uncommon). As shown in **Figure 1a** each trial started with a fixation cross
174 in the center of the screen (5s, “reference period”). Subsequently, a word depicting an object appeared in the center
175 of the screen for 500ms and was then followed by a fixation cross which stayed on the screen for a maximum of
176 30s or until a response was given (“idea generation period”). During the idea generation period participants were

177 invited to think about the use of that object and instructed to press the spacebar as soon as they felt ready to
 178 verbalize the generated idea. Once the space bar was pressed, or 30s elapsed, a speech balloon appeared on the
 179 screen to indicate that the idea could be verbalized, and it lasted for a maximum of 30s. Once the idea was
 180 verbalized, participants pressed the spacebar to move to the next trial, which was preceded by a 5-second blank
 181 screen, representing the inter-trial interval (ITI). Since participants were from different countries and not all spoke
 182 English as their native language, all the words/stimuli were translated according to the native language of the
 183 participants to avoid linguistic bias within the procedure.



184

185 **Figure 1. Paradigm structure and scalp recording map. (a). The Alternative Uses Task.** Each trial started
 186 with a 5s fixation cross, representing the “reference” period. Then, a word depicting an object (e.g., “Brick”) was
 187 presented for 500ms and then followed by a fixation cross, representing the “idea generation period”. During the
 188 “idea generation” period participants had to think about either a Common or Uncommon use for each given object
 189 and had a maximum of 30s to press the spacebar. After spacebar was pressed (or at the end of the 30s period), a
 190 speech balloon appeared on the screen, indicating that participants had a maximum of 30s to verbalize the
 191 generated idea and press the spacebar. Subsequently, a blank screen appeared for 5s, representing the inter-trial
 192 interval (ITI) before the start of the following trial. **(b). EEG electrode’s locations and subdivision of cortical**
 193 **areas.** Frontal (Left: Fp1, F3, F7, FC1; Right: Fp2, F4, F8, FC2) in red, Central (Left: C3, FC5; Right: C4, FC6)
 194 in green, Temporal (Left: FT9, T7, CP5, TP9; Right: FT10, T8, CP6, TP10) in light blue, Parietal (Left: CP1, P3;
 195 Right: CP2, P4) in purple, and Occipital (Left: P7, O1; Right: P8, O2) in yellow.

196

197 2.3. Behavioral measures

198 For each trial, reaction time (RT) was recorded. The RT consists of the time (in seconds) participants employed to
 199 press the spacebar from the beginning of the idea generation period. In the idea generation period participants had
 200 a maximum of 30s to generate their idea and press the space bar when done. Thus, trials with RTs > 30s or with
 201 no answer were considered invalid trials and were excluded from all analyses (behavioral, neurophysiological,
 202 eye-tracker, and pupil dilation). The originality of each generated idea was subsequently rated by three independent
 203 naïve judges, who were completely blind to the condition in which the answer for each item was given. Judges
 204 assessed originality on a 4-level scale (from 1 [“very common”] to 4 [“very uncommon”]).

205

206 **2.4. Neural activity recording and preprocessing**

207 Brain activity was recorded with a 32-channels BrainVision ActiCHamp EEG (BrainProducts© GmbH, Germany)
208 with 500 Hz sampling rate. Thirty-one electrodes were applied on the scalp according to the International 10-20
209 system, the reference electrode was placed on the tip of the nose, and the ground electrode was on the forehead, in
210 Fpz position. EEG electrode impedance was kept below 5 kΩ. EEG data were processed and analyzed using
211 EEGLAB (v2019; Delorme & Makeig, 2004) implemented in MATLAB© (version R2020a, The Mathworks Inc.).
212 To prevent possible edge artefacts, for each trial, for each electrode, the first and last 500 ms of recording were
213 removed. Direct Current offset was removed, and a 0.5 Hz high-pass FIR filter was applied to continuous data.
214 The 50 Hz line noise was removed via the cleanline EEGLAB toolbox and subsequent 50 Hz notch filter was
215 applied. Bad data segments (i.e., segments presenting large artifacts) were removed via visual inspection of the
216 EEG time course and bad channels (i.e., channels presenting whole-block duration artifacts) were interpolated.
217 Finally, further physiological (e.g., muscular and ocular) and non-physiological artifacts were removed via visual
218 inspection of bad components extracted by independent component analysis (ICA). Frequency bands power was
219 extracted with Welch’s method (Welch, 1967), with 1 second window length and step of 500ms. The frequency
220 spectrum was divided as follows: alpha (7.5 to 12.5 Hz), beta (12.5 to 30 Hz), gamma (30 to 60 Hz). For each trial
221 and electrode, we calculated the Task Related Power (TRP) as the difference between the log-transformed power,
222 in each EEG frequency band, of the “idea generation period” and the corresponding “reference period”, according
223 to the following equation (Jauk, Benedek & Neubauer, 2012):

$$224 \text{TRP} = \log_{10}(\text{Power}_{\text{idea}}) - \log_{10}(\text{Power}_{\text{reference}})$$

226
227 For each hemisphere, electrodes were grouped in five cortical areas (Agnoli et al., 2020) as follows: frontal, central,
228 temporal, parietal, and occipital (**Figure 1b**). The three midline electrodes (Fz, Pz, Oz) were excluded from the
229 analyses to account for any possible hemispheric lateralization. A total of 866 valid trials were included in the
230 analyses.

232 **2.5. Eye gaze and pupil dilation**

233 While participants were performing the Alternative Uses Task and their neural activity was recorded with an EEG
234 device, we also collected their eye gaze as well as their pupil dilation. We employed a Tobii© X2-30 Eye Tracker
235 Compact Edition (Tobii©), with a sampling rate of 30 Hz. The device was installed on the screen’s lower border
236 and required the participant to be at a 60cm optimal distance from the screen. Since we were interested in observing
237 gaze direction during the ideas generation, the 24-inches screen was divided into three vertical regions of interest
238 (ROIs). The central ROI was centered on the fixation cross, and it was 3.6 centimeters large (i.e., 3.44° of visual
239 angle). The two lateral ROIs symmetrically covered the rest of the screen, one on the right and one left, and were

240 24.5 centimeters large (i.e., 23° of visual angle). We calculated the percentage of time participants spent looking
241 at each ROI during the “idea generation” period. As our hypotheses concerned the interaction between the
242 condition and the side of gaze shift, we quantified gaze shift while participants were thinking about the Common
243 or Uncommon use of a given object and we only analyzed data from the two lateral ROIs (i.e., left and right)
244 excluding the central ROI from the analyses. Since we were interested in comparing the time spent in each ROI
245 between the Common and Uncommon conditions, to account for the difference in the trial length across conditions,
246 each trial was normalized by dividing the time spent in each ROI by the sum of the time spent on the right and left
247 ROIs. Data from participants with less than 80% quality (as provided by the software’s output) were excluded
248 from the gaze patterns analyses. A total of 1044 valid trials were analyzed.

249 In addition, we analyzed pupil dilation to investigate participants’ arousal state and internal-directed
250 attention during Common and Uncommon ideas generation. Pupil diameter was calculated for both the “reference”
251 and “idea generation” periods. In this analysis we only included data from the central ROI to exclude possible
252 pupil distortions due to eye movements. Additionally, to account for different trials length we only analyzed the
253 first 3 seconds of both the “reference” and the “idea generation” period. A total of 564 valid trials were analyzed.

254

255 **2.6. Statistical analysis**

256 For each measure (behavioral, neurophysiological, eye-tracker, and pupil dilation) only valid trials (i.e., RT < 30s
257 to generate their idea) were included. For each measure, the statistical analyses were run following a trial-based
258 approach. Therefore, for each measure, the N of the sample size corresponds to the number of valid trials.

259 For the behavioral data analysis, the mean RTs for the Common and Uncommon conditions and the
260 originality scores provided by the external judges in the two experimental conditions were compared via paired-
261 sample t-test.

262 To analyze electrocortical activity characterizing *divergent* (Uncommon condition) and *convergent*
263 (Common condition) *thinking*, the TRP for each frequency band was first analyzed via an omnibus repeated
264 measures ANOVA having Band (alpha, beta, gamma), Condition (Common vs. Uncommon), Hemisphere (right
265 vs left) and Area (frontal, central, temporal, parietal, occipital) as within-subject factors. Then, to follow up the
266 highest-level interaction each frequency band was submitted to independent ANOVAs having Condition
267 (Common vs. Uncommon) and Area (frontal, central, temporal, parietal, occipital) as within-subject factors. Where
268 appropriate, significant effects were corrected by using Bonferroni-corrected pairwise comparisons. Moreover,
269 since we were interested in studying the possible relationship between the behavioral measures and the neural
270 activity, we computed Pearson’s correlations between RT and TRP separately for each frequency band and for the
271 Common and Uncommon conditions.

272 To explore differences in gaze patterns between *divergent* and *convergent thinking*, the proportion of time
273 spent in each ROI was submitted to a repeated measure ANOVA having Condition (Common vs Uncommon) and

274 ROIs (right vs left) as within-subject factors. Where appropriate, significant effects were further evaluated using
275 Bonferroni-corrected pairwise comparisons. We also computed Pearson's correlations between the proportion of
276 time spent gazing in each ROI and the time participant employed to generate their idea (RT), since we were
277 interested in studying the possible relationship between gaze shift and behavioral measures.

278 Finally, to investigate the possible difference in pupil size between the Common and Uncommon
279 conditions, pupil diameter was analyzed via pairwise comparisons for each period of interest: "reference period"
280 and "idea generation period".

281

282 3. RESULTS

283 3.1. Behavioral

284 As expected, in the Uncommon condition participants took longer (mean = 13.77s; SEM = ± 0.27s) to generate an
285 idea as compared to the Common (mean = 3.94s; SEM = ± 0.14s) condition ($t_{561} = -33.891$; $p < 0.001$), indicating
286 that *divergent thinking* is a more effortful and complex process than *convergent thinking*. Also, the originality
287 scores provided by independent naïve judges confirmed that the originality of solutions given by the participants
288 significantly differed between conditions: Uncommon solutions were rated more original (mean = 2.78; SEM = ±
289 0.03) with respect to Common solutions (mean = 21.05; SEM = ± 0.01; $t_{674} = -56.685$; $p < 0.001$) with a high
290 degree of inter-rater consistency in judgements (Cronbach's $\alpha = 0.902$).

292 3.2. Electroencephalography

293 We began by examining whether frequency Band (alpha, beta, and gamma), Condition (Common vs Uncommon),
294 Hemisphere (right vs left) and Area (frontal, central, temporal, parietal, occipital) influenced electrocortical
295 activity during the task. Overall, we found the following significant main effects: Band ($F_{2, 864} = 19.930$, $p < 0.001$;
296 partial $\eta^2 = 0.044$), Condition ($F_{1, 432} = 5.190$, $p = 0.023$; partial $\eta^2 = 0.012$), Area ($F_{4, 1728} = 7.832$, $p < 0.001$; partial
297 $\eta^2 = 0.018$), and Hemisphere ($F_{1, 432} = 29.968$, $p < 0.001$; partial $\eta^2 = 0.065$). Also, we found significant 2-way
298 interactions: Band x Condition ($F_{2, 864} = 56.490$, $p < 0.001$; partial $\eta^2 = 0.116$), Band x Hemisphere ($F_{2, 864} = 13.783$,
299 $p < 0.001$; partial $\eta^2 = 0.031$), Band x Area ($F_{8, 3456} = 20.405$, $p < 0.001$; partial $\eta^2 = 0.045$), Condition x Area ($F_{4,$
300 $1728 = 6.492$, $p < 0.001$; partial $\eta^2 = 0.015$) and Hemisphere x Area ($F_{4, 1728} = 16.069$, $p < 0.001$; partial $\eta^2 = 0.036$).
301 Furthermore, we found the significant 3-way interactions Band x Hemisphere x Area ($F_{8, 3456} = 8.205$, $p < 0.001$;
302 partial $\eta^2 = 0.018$) and, crucially, the Band x Condition x Area ($F_{8, 3456} = 4.103$, $p < 0.001$; partial $\eta^2 = 0.009$). To
303 unpack the last 3-way interaction, each frequency band (alpha, beta and gamma) were separated for further
304 statistical analyses.

306 3.2.1. Alpha Band

307 This analysis showed a main effect of Condition ($F_{1, 432} = 12.016$, $p < 0.001$; partial $\eta^2 = 0.027$) indicating a larger
308 TRP value in the Uncommon (mean = 0.083; SEM ± 0.012) than in the Common condition (mean = -0.047; SEM
309 ± 0.015) (**Figure 2a**). TRP values in the Uncommon condition positively correlated with RT ($r = 0.102$; $p = 0.047$)
310 indicating that a stronger alpha power was associated with a slower RT when individuals are engaged in creative
311 ideation. We also found a main effect of Area ($F_{4, 1728} = 8.376$, $p < 0.001$; partial $\eta^2 = 0.019$). We also found
312 significant Condition x Area interaction ($F_{4, 1728} = 6.048$, $p = 0.001$; partial $\eta^2 = 0.014$) and post-hoc comparisons
313 within each condition revealed significant differences in the TRP values across Areas: in the Uncommon condition
314 we observed a stronger synchronization over the temporal areas compared to the occipital ones ($p < 0.001$),
315 whereas in the Common condition the frontal areas displayed a weaker amount of desynchronization as compared

316 to all the other four cortical areas (all $ps < 0.05$). Post-hoc comparisons within each area revealed that alpha TRP
317 in the Uncommon condition was significantly larger with respect to alpha TRP in the Common condition over the
318 central, temporal, parietal (all $ps < 0.001$) and occipital ($p = 0.026$) areas but not over the frontal nodes ($p = 0.072$;
319 **Figure 2b**). In fact, the differences between the two conditions were significantly more pronounced over temporal,
320 parietal and central areas than frontal sites, and over temporal and parietal areas than occipital sites (all $ps < 0.001$;
321 **Figure 2c**).

322 Overall, results from alpha band show a synchronization during *divergent thinking* and a
323 desynchronization during *convergent thinking*, with central, temporal, and parietal areas displaying the largest
324 discrepancy between the two conditions.

325

326 3.2.2. Beta band

327 We found a significant main effect of Condition ($F_{1,432} = 17.618$, $p < 0.001$; partial $\eta^2 = 0.039$) indicating an
328 opposite pattern with respect to alpha TRPs: larger beta TRP values in the Common condition (mean = 0.033;
329 SEM \pm 0.010) than in the Uncommon condition (mean = -0.011; SEM \pm 0.007; **Figure 2d**). We also observed a
330 main effect of Area ($F_{4,1728} = 41.344$, $p < 0.001$; partial $\eta^2 = 0.087$) as well as a significant interaction Condition
331 x Area ($F_{4,1728} = 3.184$, $p = 0.012$; partial $\eta^2 = 0.007$). Post-hoc comparisons indicated significant stronger beta
332 synchronization in the Common than in the Uncommon condition over all areas (all $ps < 0.001$ except for Parietal:
333 $p = 0.006$). Furthermore, within each Condition significant differences in TRP values were observed across areas:
334 in the Uncommon condition we observed a stronger desynchronization over the frontal and central areas compared
335 to the temporal ($p < 0.001$) parietal ($p < 0.001$) and occipital ($p < 0.001$) ones, whereas the only area showing a
336 positive TRP value was the occipital compared to all the other cortical areas (all $ps < 0.01$). Interestingly the
337 synchronization in beta band in the Common condition was strongly driven by the occipital areas (all $ps < 0.001$;
338 **Figure 2e**), which displayed the largest discrepancy in TRP values between the Common and Uncommon
339 condition, specifically when compared to the difference occurring over parietal sites ($p < 0.001$; **Figure 2f**).

340 Overall, results from the beta band demonstrated that desynchronization occurred during *divergent*
341 *thinking* and synchronization occurred during *convergent thinking*, with the latter being driven by occipital area.

342

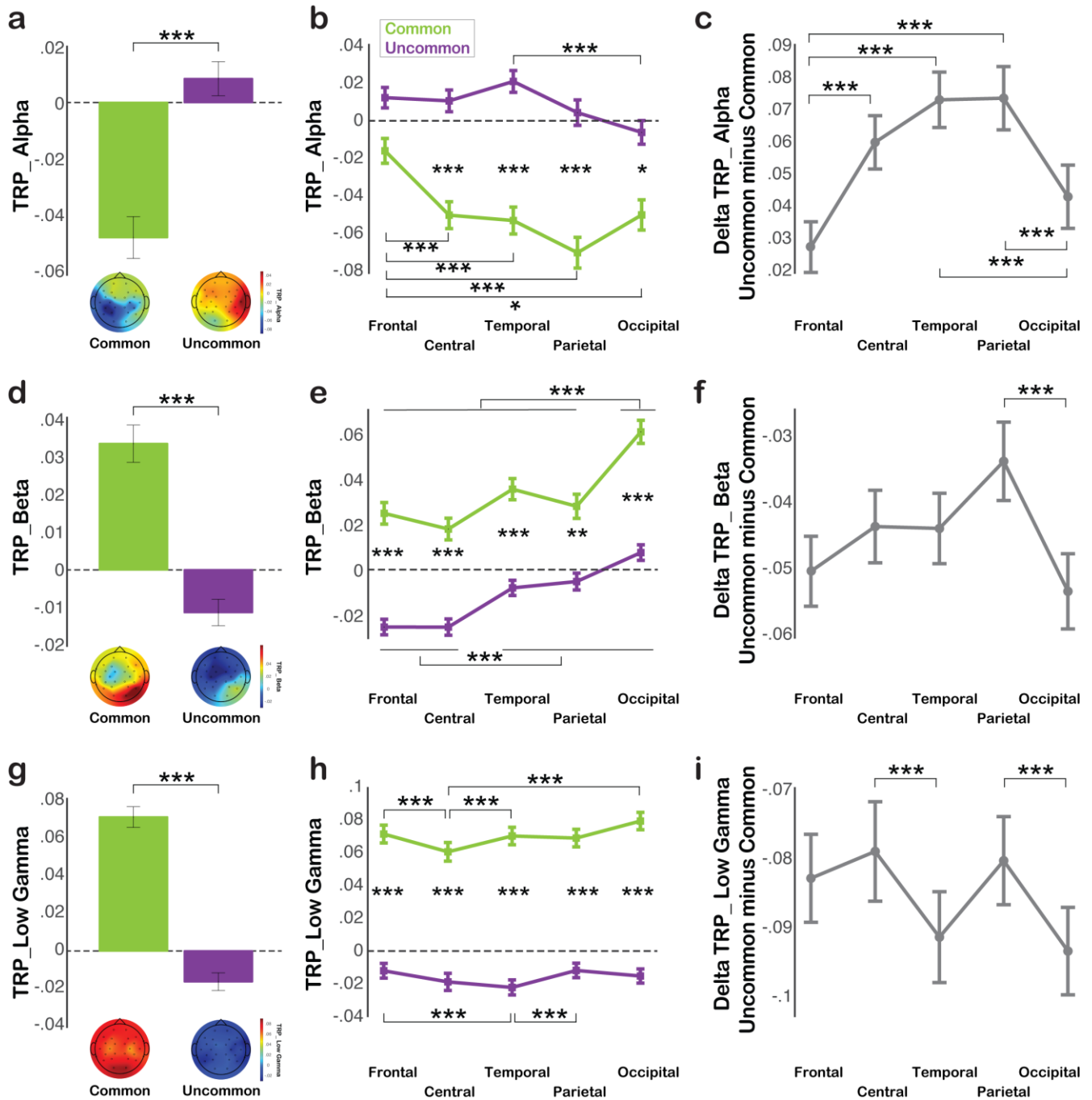
343 3.2.3. Gamma band

344 Consistent with the results in beta, TRPs in gamma revealed a main effect of Condition ($F_{1,432} = 40.854$, $p < 0.001$;
345 partial $\eta^2 = 0.086$) indicating an increase in gamma power in the Common (mean = 0.070; SEM \pm 0.011) and a
346 decrease in the Uncommon condition (mean = -0.016; SEM \pm 0.009; **Figure 2g**). Interestingly, TRP values in the
347 Common condition was negatively correlated with RT ($r = -0.141$; $p = 0.006$) indicating that a stronger power
348 increase in gamma band was accompanied with a faster RT. Also, TRP values in the Uncommon condition
349 negatively correlated with RT ($r = -0.167$; $p = 0.001$). The negative sign of this correlation indicates that a stronger
350 decrease in gamma power was accompanied with a slower RT when individuals are engaged in creative ideation.

351 Additionally, we observed a main effect of Area ($F_{4,1728} = 6.152$, $p < 0.001$; partial $\eta^2 = 0.014$) as well as a
352 significant interaction Condition x Area ($F_{4,1728} = 3.553$, $p = 0.007$; partial $\eta^2 = 0.009$). Post-hoc comparisons
353 showed that all areas exhibited significantly larger TRP values in the Common than in the Uncommon condition
354 (all $ps < 0.001$). Moreover, within each Condition significant differences in the TRP values were observed across
355 areas: in the Uncommon condition we observed a stronger desynchronization over the temporal area, specifically
356 when it was compared with the frontal and parietal ones (all $ps < 0.001$); in the Common condition we observed a
357 weaker synchronization over the central area, specifically when it was compared with the frontal, temporal, and
358 occipital ones (all $ps < 0.001$; **Figure 2h**). Finally, the differences between conditions within each area were
359 significantly larger over central as compared to temporal area ($p < 0.001$), and over parietal as compared to
360 occipital area ($p < 0.001$; **Figure 2i**).

361 Overall, results from the gamma band demonstrated, similarly, to beta band a general synchronization
362 during *convergent thinking* and desynchronization during *divergent thinking*.

363



364

365

366

367

368

369

370

371

372

373

374

375

Figure 2. Alpha, Beta, Gamma TRP changes over the entire scalp. (a) Mean alpha TRP changes as a function of the Common (green) and Uncommon (purple) condition. Scalp maps depict the topographical distribution of mean alpha TRP changes for each condition (Common on the left and Uncommon on the right). (b) Line plot shows mean alpha TRP changes in the five areas (Frontal, Central, Temporal, Parietal, and Occipital) as a function of the of the Common (green) and Uncommon (purple) condition. Positive and negative values represent respectively an increase and a decrease in alpha power compared to the reference period and indicate idea generation-related alpha synchronization and desynchronization, respectively. (c) Mean alpha TRP differences between Uncommon and Common condition in the five cortical areas (Frontal, Central, Temporal, Parietal, and Occipital). (d) Mean beta TRP changes, same format as a. (e) Line plot shows mean beta TRP changes in the five cortical areas, same format as b. (f) Mean beta TRP differences between Uncommon and Common condition same format as c. (g) Mean gamma TRP changes, same format as a. (h) Line plot shows mean gamma TRP changes in

376 the five cortical areas, same format as **b. (i)** Mean gamma TRP differences between Uncommon and Common
377 condition same format as **c.** Values shown are the mean \pm $\frac{1}{2}$ SEM. Significant results are indicated by asterisk *
378 = $p < 0.05$; ** = $p < 0.01$; *** = $p < 0.001$.

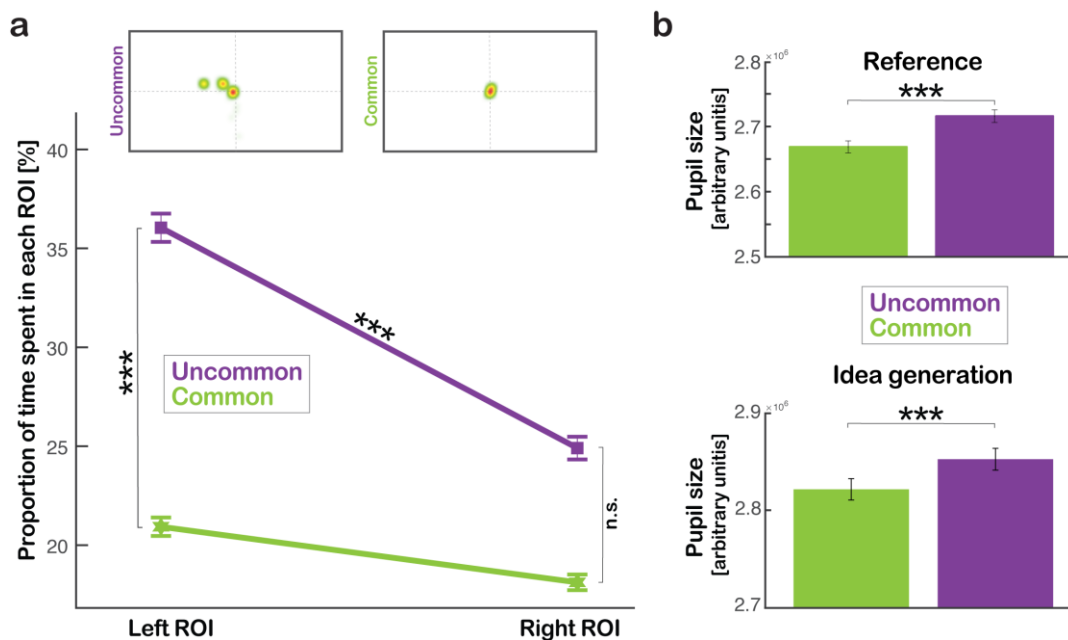
379

380 3.3. Gaze Patterns

381 Visual inspection of the fixation density plots (**Figure 3a**, top panel) for the Common and Uncommon conditions
382 suggested a leftward gaze shift when participants were required to think about an original idea. To characterize
383 this in more detail, we calculated the percentage of the total looking time spent on the right and left ROIs
384 respectively. The repeated-measures ANOVA revealed a main effect of ROI ($F_{1,521} = 28.150$, $p < 0.001$; partial η^2
385 = 0.051), indicating that, while generating their ideas, participants preferentially looked more leftward than
386 rightward, independently of the condition. A significant main effect of Condition was also found ($F_{1,521} = 80.438$,
387 $p < 0.001$; partial $\eta^2 = 0.134$), indicating that participants preferentially averted their gaze from their midline and
388 recruited a stronger oculomotor activity in the Uncommon condition than in the Common condition. Interestingly,
389 we also observed a significant Condition \times ROI interaction ($F_{1,521} = 10.604$, $p = 0.001$; partial $\eta^2 = 0.020$) indicating
390 that participants displayed a significantly stronger gaze shift towards the left side than the right in the Uncommon
391 condition ($t_{521} = 4.876$; $p < 0.001$) while this gaze shift was not present in the Common condition ($t_{521} = 2.290$; p
392 = 0.134 (**Figure 3a**, bottom panel). Crucially the stronger left gaze shift in the Uncommon condition positively
393 correlated with RT ($r = 0.097$; $p = 0.048$). The positive sign of this correlation indicates that a stronger gaze shift
394 towards the left side was accompanied with a slower RT when individuals are engaged in creative ideation.

395 Overall, gaze patterns analyses indicated that *divergent thinking* was supported by a generally stronger
396 oculomotor activity, and that this activity was characterized by a specific leftward shift.

397



398

399 **Figure 3. Changes in gaze patterns and pupil dilation as a function of Common and Uncommon conditions.**
400 **(a) Fixation density plots and normalized proportion of time spent on Left and Right ROIs.** Top panels
401 illustrate an example of a participant's looking behavior superimposed on a computer monitor in an Uncommon
402 (left) and Common (right) trial. At the bottom, the normalized proportion of looking time spent in the left and right
403 ROIs is depicted. Values indicate mean percentage of time participants spent gazing over the left or right ROIs
404 during the generation of Uncommon (purple) and Common (green) ideas. **(b) Changes in pupil dilation.** Mean
405 pupil size during the "reference" (top panel) and the "idea generation" (bottom panel) period for the *Uncommon*
406 (purple) and the Common (green) conditions. Values shown are the mean \pm $\frac{1}{2}$ SEM. Significant results are
407 indicated by asterisk, *** $p < 0.001$. n.s. = not significant.

408
409 **3.4. Pupil Dilation**

410 We also examined changes in pupil size as a metric of general arousal and as an indicator of internally directed
411 cognition. We investigated pupil size during "reference" and "idea generation" period, i.e., while participants were
412 preparing to generate an idea and while they were generating it. On average, participants exhibited greater pupil
413 dilation in the Uncommon compared to the Common condition during the "reference" period ($t_{281} = -5.252$; $p <$
414 0.001 ; **Figure 3b**, top panel), indicating a general arousal difference between the two conditions and suggesting a
415 stronger focus on their internal world when preparing to generate a creative/uncommon idea. Similar results were
416 observed for the "idea generation" analysis ($t_{281} = -3.705$; $p < 0.001$; **Figure 3b**, bottom panel) indicating that pupil
417 size was greater for Uncommon condition. When participants were exposed to an object and they were asked to
418 think about an Uncommon use of it, their pupil size was larger compared to when they were asked to think about
419 a common use, again suggesting a higher arousal and a stronger recruitment of internally-directed cognition during
420 *divergent thinking*.

421

422 4. DISCUSSION

423 The creative processes everyone experiences daily are characterized by a continuous alternation of *convergent* and
424 *divergent thinking* (Liu, Chakrabarti & Bligh, 2003). The goal of this study was to investigate whether beyond
425 alpha-band activity other higher frequency bands, such as beta and gamma, may subserve *divergent* and *convergent*
426 *thinking* and whether those could be associated with a different gaze bias and pupil response during idea
427 generations. In a within-subjects design, we asked participants to generate either original (*divergent thinking*) or
428 common (*convergent thinking*) ideas, while their neural activity, gaze behavior, and pupil dilation were recorded.
429 In agreement with our predictions, the results showed the well-known increase in alpha band power (Agnoli et al.,
430 2020) and a decrease in both beta and gamma power during *divergent thinking*, while, on the contrary, during
431 *convergent thinking* we observed alpha desynchronization and beta and gamma synchronization. As expected, the
432 results also showed a greater leftward bias and an increase in pupil size during *divergent thinking* as compared to
433 *convergent thinking*.

434 Behavioral findings

435 In line with previous research, at the behavioral level, we found that when participants were engaged in *divergent*
436 *thinking* they took longer time to generate novel/uncommon uses for everyday objects (i.e., Uncommon condition)
437 as compared to when they were engaged in *convergent thinking* and thus had to propose a canonical/common use
438 for an everyday object (i.e., Common condition). Longer reaction times in the Uncommon condition indicate that
439 finding unusual solutions requires a stronger mental effort than finding common solutions. Indeed, *divergent*
440 *thinking* is a highly energy-consuming activity, much more than *convergent thinking*, as it recruits several
441 cognitive sub-processes such as memory retrieval, top-down sensory inhibition, internally directed cognition,
442 mental imagery, and loose semantic associations (Benedek, 2018; Madore et al., 2019; Lucchiari, Sala & Vanutelli,
443 2018). Also, as expected, originality scores assigned by external judges (who were blind to the paradigm and
444 objective of the study) were higher for the Uncommon than the Common condition, indicating that the ideas
445 generated when asked to find an unusual use of an object were effectively more creative than the one produced for
446 the canonical use of the object.

447 Neural findings

448 At the neural level, brain power associated with idea generation revealed different patterns of activity in the alpha,
449 beta, and gamma bands. Consistent with previous findings (Agnoli et al., 2020; Ceh et al., 2020; Jauk et al., 2012)
450 the results showed a general increase in alpha power during *divergent thinking*. Specifically, alpha band power
451 was significantly higher in the Uncommon than Common condition in all brain areas except frontal ones, thus
452 indicating greater alpha synchronization in central-posterior cortical areas accompanying creative ideas
453 generation. This result is in line with most findings on *divergent thinking* suggesting that the maintenance of a
454 relatively high alpha activity may be necessary for the generation of creative ideas. Alpha activity has been

455 indicated to reflect cortical inhibition (Klimesch, Sauseng & Hanslmayr, 2007), crucial in gating the mind from
456 the external world, allowing people to re-direct attention towards their internal world (Benedek, 2018; Magosso,
457 Ricci & Ursino, 2021). This link is likely supported by the positive correlation we found between alpha TRPs and
458 reaction times, indicating that a stronger engagement of alpha activity is associated to a longer time spent in
459 generating and exploring divergent solutions. As alpha synchronization helps people to better isolate their mind
460 from the external world and internally re-direct their attention, then it is plausible that a stronger synchronization
461 in alpha is associated with more time in thinking about divergent ideas.

462 Specifically, our finding indicates that the largest differences in alpha power between Uncommon and
463 Common conditions occurred over central, temporal, and parietal areas, as well as over occipital sites. Notably,
464 these areas encompass low-level striate and extrastriate visual cortices as well as higher-level sensory association
465 cortices. Thus, a greater amount of alpha power over these regions during the generation of uncommon ideas might
466 reflect a weaker processing of external cues and a more robust recruitment of internal cognition. Also, the temporal
467 and parietal areas include the temporo-parietal junction (TPJ), which is a highly associative region and has been
468 linked to top-down regulation of visual information processing during high internally-directed cognition
469 demanding tasks (Benedek et al., 2016). TPJ is a key hub of the ventral attentional network, which is responsible
470 for bottom-up re-orienting of attention towards salient external stimuli (Corbetta & Shulman, 2002; Ricci et al.,
471 2012; Salatino et al., 2021), and the inhibition of the ventral attentional network can prevent other networks'
472 activity (e.g., the dorsal attentional network, responsible for top-down processing) from being disrupted by
473 external sensory stimuli (Solís-Vivanco, Jensen & Bonnefond, 2020). Since alpha synchronization indicates
474 cortical inhibition (Klimesch et al., 2007), these results might suggest a functional deactivation of such network
475 during the generation of *divergent thinking*, allowing to re-direct mental resources to other networks and thus a
476 deeper focus on internal states. In line with our findings, central and posterior alpha band activity has also been
477 found to increase with the cognitive load of a task (Fink & Benedek, 2013); this physiological activity has been
478 explained as reflecting a top-down control over cognition, necessary for internally redirecting the focus of attention
479 during goal-directed idea generation (Benedek, 2018; Magosso et al., 2021). External stimuli inhibition, re-
480 directing attention towards the internal world, memory retrieval, and mental imagery are core features of creative
481 cognition (Benedek et al., 2014b) and, not surprisingly, have been repeatedly associated with alpha
482 synchronization.

483 While we found alpha synchronization, the present findings reveal the opposite patterns of activity for
484 beta and gamma power that showed a general decrease during *divergent thinking*. Beta activity is normally
485 associated with wakefulness, active cognitive processing, and maintenance of the “status quo” (Ray & Cole, 1985;
486 Engel & Fries, 2010). As an indicator of cortical activation, the beta band can be thought of as the counterpart of
487 the alpha band, which indicates cortical idling instead (Klimesch et al., 2007). This is consistent with our findings
488 showing a double dissociation between states. While during the generation of common ideas the co-occurrence
489 of alpha desynchronization and beta synchronization was observed, an alpha synchronization and beta

490 desynchronization pattern characterized the generation of uncommon ideas. Regarding *divergent* versus
491 *convergent thinking*, while alpha synchronization is associated with redirection of attention towards the internal
492 world (Benedek, 2018), beta band might instead play a specific role in thinking about an association with an
493 external stimulus, which necessarily requires a re-orientation of attention towards the external world. Indeed, beta
494 activity has previously been associated with externally directed attention (Wróbel, 2000), and an increase in beta
495 power during *convergent thinking* might suggest that associating an object with its common use requires
496 redirecting attention to the external stimulus and maintaining the focus on the concrete representation of the object
497 itself, such as its common use. Interestingly, studies on resting beta activity found that increased resting beta
498 power might be a neurophysiological marker of preferentially analytic problem solving as compared to an insight-
499 based one (Erickson et al., 2018). Importantly, while an insight (another process linked to creative production) is
500 associated with internally directed attention (Kounios & Beeman, 2014), analytical thinking has been found to be
501 triggered by a concrete problem that needs to be addressed (Förster et al., 2004). These observations also support
502 the idea of a specific role of beta activity in maintaining the focus on external cues during *convergent thinking*.

503 Similar results have been found for gamma power; our analyses showed desynchronization in *divergent*
504 *thinking* and synchronization in *convergent thinking*. Gamma activity is thought to be responsible for the
505 perceptual binding of sensory information (Gray & Singer, 1989; Lustenberger, Boyle, Foulser, Mellin &
506 Fröhlich, 2016) and to represent the oscillatory signature of short-range intra-network connectivity (Von Stein &
507 Sarnthein, 2000). Similarly to the beta band, these neurophysiological mechanisms likely contrast with the alpha-
508 driven top-down sensory inhibition and its role in long-range connectivity subserving loose semantic associations.
509 Also, these mechanisms are more often selectively involved in *convergent thinking* than in *divergent thinking*,
510 that is, when the goal is to find the most immediate association between the stimulus in front of us and its closer
511 semantical representation. In fact, gamma has also been associated with the maintenance of alertness and attention
512 towards external cues (Horan, 2009), and our observation of an increase in power is consistent with the idea that
513 gamma synchronization subserves direct, bottom-up driven idea generation. Accordingly, in the Uncommon
514 condition we observed a negative correlation between reaction times and gamma TRPs, in contrast to the positive
515 correlation we observed with alpha TRPs. This result supports the idea that gamma-band plays an antagonist role
516 with respect to alpha-band during uncommon idea generation: it is likely that gamma power contrasts the function
517 of alpha-band in prolonging mind-gating from external stimuli and internal redirection of attention required during
518 *divergent thinking*. In line with this, we also observed that gamma TRPs negatively correlated with reaction times
519 in the Common condition. This suggests that gamma-band activity not only contrasts alpha-band-related
520 mechanisms, but also facilitates convergent associations by slowing down the time people employ to find a
521 common solution to a problem. These two putative roles do not exclude one-another: in fact, they both suggest
522 that gamma-band promotes the selection of an idea. This likely represents an advantage during *convergent*
523 *thinking*, as it allows reaching the correct solution more rapidly; however, it could represent a disadvantage during
524 *divergent thinking*, as it prevents a deeper exploration and generation of alternatives.

525 The role of gamma band in creativity has been poorly investigated. While some studies have linked
526 gamma activity with creativity by reporting a sudden burst in gamma during insight-driven problem-solving
527 (Jung-Beeman et al., 2004) others have excluded the involvement of gamma during creative ideation (e.g.,
528 Berkovich-Ohana, Glicksohn, Ben-Soussan & Goldstein, 2017). These inconsistent results together with
529 methodological differences in creativity literature, may explain why the association of gamma activity with
530 creativity is ambiguous and inconsistent. Here, we provided a direct comparison of gamma band activity in
531 *convergent* versus *divergent thinking*. Our results suggest that gamma has similar patterns as those observed in
532 beta band and that an increase in gamma power is likely to reflect and promote bottom-up driven associative
533 processes.

534 These contrasting neurophysiological activations may suggest a coherent neural dynamic by which
535 *divergent* and *convergent thinking* can selectively tune cortical states on different frequencies depending on
536 contingent demands by recruiting different cognitive mechanisms based on top-down or bottom-up processing.

537 Gaze pattern and pupil dilation findings

538 At the gaze behavior and pupil response level, we observed different patterns associated with generating either
539 original or common ideas. Results showed a higher gaze shift away from the center when participants were
540 engaged in elaborating on the original use of a common object. Gaze aversion has been indicated as an oculomotor
541 mechanism that facilitates those different cognitive sub-processes necessary for creative ideation, i.e., external
542 stimuli inhibition, internally-directed attention, mnemonic recall, and mental manipulation (Glenberg, 1997; Salvi &
543 Bowden, 2016). It has been indeed proposed that when people recall, mentally re-explore, and manipulate
544 experienced scenarios they tend to produce eye movements that are coordinated with the generated mental image
545 (Walcher, Körner & Benedek, 2017). Our results on the directionality of gaze behavior showed that when engaged
546 in *divergent thinking*, and thus while generating uncommon ideas, participants preferentially looked leftward.
547 Leftward-gaze bias during creativity tasks had first been investigated by Hines and Martindale (1974), who found
548 that when participants were forced to look leftward during a creativity task showed a higher performance than
549 when forced to gaze rightward. Moreover, Salvi and Bowden (2016) reported that priming the left visual field is
550 linked to insight-driven problem solving, while this is not true when priming the right visual field. Other findings
551 revealed that when people look towards their left during problem-solving tasks, they show clearer mental imagery
552 and perform better in *divergent thinking* tasks while spending time looking rightward helps verbal and arithmetical
553 problem solving (Salvi & Bowden, 2016). These studies support the idea that leftward gazing is associated with
554 idea generation and, specifically, with creative thinking, and are in line with our results which showed a stronger
555 spontaneous leftward gaze specifically occurring during *divergent thinking*. Also, in the Uncommon condition our
556 results showed a positive correlation between leftward gaze shift and reaction times. This suggests that when
557 people spend longer time in gazing leftward they also spend longer time in generating and exploring novel
558 solutions. Similar results have been found for cortical activity in the alpha-band, therefore suggesting that the

559 neural and oculomotor mechanisms underlying creative idea generation showed similar patterns in facilitating
560 specific cognitive mechanisms recruited during *divergent thinking*.

561 Concerning pupil response during the generation of Common versus Uncommon ideas, we found a
562 specific increase in pupil size in the Uncommon condition during both the “reference period” (i.e., when
563 participants were waiting for the object to appear on the screen) and “idea generation period” (i.e., when the
564 participants were actively involved in generating an original idea). Since increases in pupil size represent a
565 physiological marker of increased arousal (Mathôt, 2018), which in turn plays a role in driving cortical activity
566 (Sara & Bouret, 2012), this result indicates that the increased pupil dilation observed for the Uncommon condition,
567 and thus an enhanced arousal state, does not depend on the appearance of the stimulus per se but rather reflects a
568 state of general arousal.

569 The increase in pupil size supports the idea of a general higher arousal during creative processing (Ceh et
570 al., 2020) and together with the leftward gaze bias finding suggests that such spontaneous gaze behavior may
571 reflect the shielding of the mind from external distracting events in favor of a more internal focus necessary to
572 produce *divergent thinking* (Walcher et al., 2017).

573 Finally, some limitations of our study should also be considered. First, although there is weak evidence of
574 gender differences in creativity research (e.g., Razumnikova, 2004), due to the unbalanced composition of our
575 sample, we cannot rule out or demonstrate possible gender effects. Also, the task procedure used resulted in
576 different EEG and Eye-Tracking recording times for the Common and Uncommon conditions, which prevented
577 the comparison of time-varying EEG and Eye-Tracking measures (e.g., time-frequency EEG changes and
578 oculomotor time-variant patterns). While in our case different EEG recordings times do not represent a hard
579 limitation since we ran time-independent analyses, they however prevented a deeper investigation of the
580 neurocognitive flows characterizing both *divergent thinking* and *convergent thinking*. These different EEG
581 recordings times also prevented us from splitting both *divergent thinking* and *convergent thinking* in different
582 temporal windows, and thus from investigating possible different mechanisms occurring in a serial fashion.
583 Therefore, future studies could consider these limitations to better exploit these neurophysiological tools and
584 investigate novel aspects related to *convergent thinking* and *divergent thinking*.

585 In conclusion, the present study is among the first that have attempted a comprehensive investigation of
586 the different neurophysiological measures underpinning creative thinking. Our findings provide relevant
587 information on patterns of physiological proxies for mental activity during *divergent thinking* and set the base for
588 future studies to investigate more in detail the temporal dynamic of such proxies, since here more temporally
589 sensitive analyses were not possible due to the intrinsic limitation of the technology employed. By showing that
590 during creative thinking alpha power is synchronized in central and posterior areas of the brain, beta and gamma
591 bands are instead desynchronized, along with pupil dilation and leftward gaze we suggest coherent
592 neurophysiological patterns underpinning creative ideas. By combining behavioral, electrophysiological, and

593 oculomotor activity along with pupillometry, this study offers the base for a comprehensive neurophysiological
594 framework. The several behavioral and neurophysiological aspects of *convergent* and *divergent thinking* have
595 usually been explored independently. Electroencephalographic studies have usually reported results related to
596 narrowband analyses, while oculomotor and pupillometric findings are still lacking. Nonetheless, such
597 independent results have pointed to similar conclusions regarding both the cognitive mechanisms underlying
598 creative production and their neural substrates, thus giving promising hints for a more comprehensive investigation
599 of creativity. Being able to collect multimodal data in a unified paradigm would help to overcome some
600 methodological issues and to build a deeper and unified knowledge about creative thinking.

601

602 **Declaration of competing interest**

603 The authors have no conflicts of interest or competing interests to declare.

CRedit statements

Alessandro Mazza: Term, Conceptualization, Methodology, Formal Analysis, Investigation, Data Curation, Writing – Original Draft, Visualization, Project Administration. **Olga Dal Monte:** Formal Analysis, Data Curation, Writing – Original Draft, Visualization. **Selene Schintu:** Formal Analysis, Writing – Original Draft. **Samuele Colombo:** Term, Conceptualization, Methodology, Investigation, Writing – Original Draft, Project Administration. **Nicola Michielli:** Formal Analysis, Writing – Review & Editing. **Pietro Sarasso:** Formal Analysis, Writing – Review & Editing. **Marco Cantamessa:** Term, Conceptualization, Writing – Review & Editing, Supervision. **Francesca Montagna:** Term, Conceptualization, Resources, Writing – Review & Editing, Supervision, Project Administration. **Peter Törlind:** Term, Conceptualization, Writing – Review & Editing, Supervision, Project Administration. **Raffaella Ricci:** Term, Conceptualization, Writing – Review & Editing, Supervision, Project Administration.

REFERENCES

- Agnoli, S., Zanon, M., Mastria, S., Avenanti, A., & Corazza, G. E. (2020). Predicting response originality through brain activity: An analysis of changes in EEG alpha power during the generation of alternative ideas. *NeuroImage*, *207*, 116385. <https://doi.org/10.1016/j.neuroimage.2019.116385>
- Benedek, M., Jauk, E., Fink, A., Koschutnig, K., Reishofer, G., Ebner, G., & Neubauer, A. (2014a). To create or to recall? Neural mechanisms underlying the generation of creative new ideas. *NeuroImage*, *88*, 125–133. <https://doi.org/10.1016/j.neuroimage.2013.11.021>
- Benedek, M., Schickel, R. J., Jauk, E., Fink, A., & Neubauer, A. C. (2014b). Alpha power increases in right parietal cortex reflects focused internal attention. *Neuropsychologia*, *56*, 393–400. <https://doi.org/10.1016/j.neuropsychologia.2014.02.010>
- Benedek, M., Stoiser, R., Walcher, S., & Körner, C. (2017). Eye Behavior Associated with Internally versus Externally Directed Cognition. *Frontiers in Psychology*, *8*. <https://doi.org/10.3389/fpsyg.2017.01092>
- Benedek, M. (2018). Internally Directed Attention in Creative Cognition. In R. Jung & O. Vartanian (Eds.), *The Cambridge Handbook of the Neuroscience of Creativity* (Cambridge Handbooks in Psychology, pp. 180-194). Cambridge: Cambridge University Press. doi:10.1017/9781316556238.011
- Berkovich-Ohana, A., Glicksohn, J., Ben-Soussan, T.D. & Goldstein, A. (2017). Creativity Is Enhanced by Long-Term Mindfulness Training and Is Negatively Correlated with Trait Default-Mode-Related Low-Gamma Inter-Hemispheric Connectivity. *Mindfulness* *8*, 717–727. <https://doi.org/10.1007/s12671-016-0649-y>
- Camarda, A., Salvia, É., Vidal, J., Weil, B., Poirel, N., Houdé, O., Borst, G., & Cassotti, M. (2018). Neural basis of functional fixedness during creative idea generation: An EEG study. *Neuropsychologia*, *118*, 4–12. <https://doi.org/10.1016/j.neuropsychologia.2018.03.009>
- Ceh, S. M., Annerer-Walcher, S., Körner, C., Rominger, C., Kober, S. E., Fink, A., & Benedek, M. (2020). Neurophysiological indicators of internal attention: An electroencephalography–eye-tracking coregistration study. *Brain and Behavior*, *10*(10), 1. <https://doi.org/10.1002/brb3.1790>
- Danko, S. G., Shemyakina, N. V., Nagornova, Z. V., & Starchenko, M. G. (2009). Comparison of the effects of the subjective complexity and verbal creativity on EEG spectral power parameters. *Human Physiology*, *35*(3), 381–383. <https://doi.org/10.1134/s0362119709030153>
- Delorme, A., & Makeig, S. (2004). EEGLAB: an open source toolbox for analysis of single-trial EEG dynamics including independent component analysis. *Journal of Neuroscience Methods*, *134*(1), 9–21. <https://doi.org/10.1016/j.jneumeth.2003.10.009>
- Dietrich, A., & Kanso, R. (2010). A review of EEG, ERP, and neuroimaging studies of creativity and insight. *Psychological Bulletin*, *136*(5), 822–848. <https://psycnet.apa.org/doi/10.1037/a0019749>
- Doherty-Sneddon, G., & Phelps, F. G. (2005). Gaze aversion: A response to cognitive or social difficulty? *Memory & Cognition*, *33*(4), 727–733. <https://doi.org/10.3758/bf03195338>
- Engel, A. K., & Fries, P. (2010). Beta-band oscillations—signalling the status quo? *Current Opinion in Neurobiology*, *20*(2), 156–165. <https://doi.org/10.1016/j.conb.2010.02.015>
- Erickson, B., Truelove-Hill, M., Oh, Y., Anderson, J., Zhang, F. Z., & Kounios, J. (2018). Resting-state brain oscillations predict trait-like cognitive styles. *Neuropsychologia*, *120*, 1–8. <https://doi.org/10.1016/j.neuropsychologia.2018.09.014>

- Fink, A., Grabner, R. H., Benedek, M., & Neubauer, A. C. (2006). Divergent thinking training is related to frontal electroencephalogram alpha synchronization. *European Journal of Neuroscience*, *23*(8), 2241–2246. <https://doi.org/10.1111/j.1460-9568.2006.04751.x>
- Fink, A., Grabner, R. H., Benedek, M., Reishofer, G., Hauswirth, V., Fally, M., Neuper, C., Ebner, F., & Neubauer, A. C. (2009). The creative brain: Investigation of brain activity during creative problem solving by means of EEG and fMRI. *Human Brain Mapping*, *30*(3), 734–748. <https://doi.org/10.1002/hbm.20538>
- Fink, A., & Benedek, M. (2013). The Creative Brain: Brain Correlates Underlying the Generation of Original Ideas. *Neuroscience of Creativity*, 207–232. <https://doi.org/10.7551/mitpress/9780262019583.003.0010>
- Fink, A., & Benedek, M. (2014). EEG alpha power and creative ideation. *Neuroscience & Biobehavioral Reviews*, *44*, 111–123. <https://doi.org/10.1016/j.neubiorev.2012.12.002>
- Förster J, Friedman RS, & Liberman N. (2004). Temporal construal effects on abstract and concrete thinking: consequences for insight and creative cognition. *Journal of Personality and Social Psychology*. *87*(2), 177-89. <https://psycnet.apa.org/doi/10.1037/0022-3514.87.2.177>
- Glenberg, A. M. (1997). What memory is for. *Behavioral and Brain Sciences*, *20*(1), 1–19. <https://doi.org/10.1017/s0140525x97000010>
- Gray, C. M., & Singer, W. (1989). Stimulus-specific neuronal oscillations in orientation columns of cat visual cortex. *Proceedings of the National Academy of Sciences*, *86*(5), 1698–1702. <https://doi.org/10.1073/pnas.86.5.1698>
- Guilford, J. P. (1956). The structure of intellect. *Psychological Bulletin*, *53*(4), 267–293. <https://doi.org/10.1037/h0040755>
- Guilford, J. P. (1967). Creativity: Yesterday, Today and Tomorrow. *The Journal of Creative Behavior*, *1*(1), 3–14. <https://doi.org/10.1002/j.2162-6057.1967.tb00002.x>
- Henderson, R. R., Bradley, M. M., & Lang, P. J. (2017). Emotional imagery and pupil diameter. *Psychophysiology*, *55*(6), Article e13050. <https://doi.org/10.1111/psyp.13050>
- Hines, D., & Martindale, C. (1974). Induced Lateral Eye-Movements and Creative and Intellectual Performance. *Perceptual and Motor Skills*, *39*(1), 153–154. <https://doi.org/10.2466/pms.1974.39.1.153>
- Horan, R (2009). The neuropsychological connection between creativity and meditation. *Creativity Research Journal*. *21*, 199–222. <https://doi.org/10.1080/10400410902858691>
- Jauk, E., Benedek, M., & Neubauer, A. C. (2012). Tackling creativity at its roots: Evidence for different patterns of EEG alpha activity related to convergent and divergent modes of task processing. *International Journal of Psychophysiology*, *84*(2), 219–225. <https://doi.org/10.1016/j.ijpsycho.2012.02.012>
- Jensen, O., Gelfand J., Kounios J., Lisman JE. (2002). Oscillations in the Alpha Band (9–12 Hz) Increase with Memory Load during Retention in a Short-term Memory Task. *Cerebral Cortex*, *12*(8), 877–882. <https://doi.org/10.1093/cercor/12.8.877>
- Jung-Beeman, M., Bowden, E. M., Haberman, J., Frymiare, J. L., Arambel-Liu, S., Greenblatt, R., Reber, P.J., & Kounios, J. (2004). Neural Activity When People Solve Verbal Problems with Insight. *PLoS Biology*, *2*(4), Article e97. <https://doi.org/10.1371/journal.pbio.0020097>
- Klimesch, W., Sauseng, P., & Hanslmayr, S. (2007). EEG alpha oscillations: The inhibition–timing hypothesis. *Brain Research Reviews*, *53*(1), 63–88. <https://doi.org/10.1016/j.brainresrev.2006.06.003>

- Kounios, J., & Beeman, M. (2014). The Cognitive Neuroscience of Insight. *Annual Review of Psychology*, 65(1), 71–93. <https://doi.org/10.1146/annurev-psych-010213-115154>
- Liu, Y.-C., Chakrabarti, A., & Bligh, T. (2003). Towards an ‘ideal’ approach for concept generation. *Design Studies*, 24(4), 341-355. [https://doi.org/10.1016/S0142-694X\(03\)00003-6](https://doi.org/10.1016/S0142-694X(03)00003-6).
- Lucchiari, C., Sala, P. M., & Vanutelli, M. E. (2018). Promoting Creativity Through Transcranial Direct Current Stimulation (tDCS). A Critical Review. *Frontiers in Behavioral Neuroscience*, 12. Published. <https://doi.org/10.3389/fnbeh.2018.00167>
- Lustenberger, C., Boyle, M. R., Foulser, A. A., Mellin, J. M., & Fröhlich, F. (2015). Functional role of frontal alpha oscillations in creativity. *Cortex*, 67, 74–82. <https://doi.org/10.1016/j.cortex.2015.03.012>
- Madore K.P., Thakral P.P., Beaty R.E., Addis D.R., Schacter D.L. (2019). Neural Mechanisms of Episodic Retrieval Support Divergent Creative Thinking. *Cerebral Cortex*. 29(1), 150-166. <https://doi.org/10.1093/cercor/bhx312>.
- Magosso, E., Ricci, G., & Ursino, M. (2021). Alpha and theta mechanisms operating in internal-external attention competition. *Journal of Integrative Neuroscience*, 20(1), 1. <https://doi.org/10.31083/j.jin.2021.01.422>
- Mathôt, S. (2018). Pupillometry: Psychology, Physiology, and Function. *Journal of Cognition*, 1(1). <https://doi.org/10.5334/joc.18>
- Oldfield, R. (1971). The assessment and analysis of handedness: The Edinburgh inventory. *Neuropsychologia*, 9(1), 97–113. [https://doi.org/10.1016/0028-3932\(71\)90067-4](https://doi.org/10.1016/0028-3932(71)90067-4)
- Pelagatti, C., Binda, P., & Vannucci, M. (2020). A closer look at the timecourse of mind wandering: Pupillary responses and behaviour. *PLoS ONE*, 15(4), Article e0226792. <https://doi.org/10.1371/journal.pone.0226792>
- Pulvermüller F, Keil A, & Elbert T. (1999). High-frequency brain activity: perception or active memory? *Trends in Cognitive Sciences*, (7), 250-252. [https://doi.org/10.1016/S1364-6613\(99\)01344-3](https://doi.org/10.1016/S1364-6613(99)01344-3)
- Ray, W., & Cole, H. (1985). EEG alpha activity reflects attentional demands, and beta activity reflects emotional and cognitive processes. *Science*, 228(4700), 750–752. <https://doi.org/10.1126/science.3992243>
- Razoumnikova, O. M. (2000). Functional organization of different brain areas during convergent and divergent thinking: an EEG investigation. *Cognitive brain research*, 10(1-2), 11-18.
- Razumnikova OM. (2004). Gender differences in hemispheric organization during divergent thinking: an EEG investigation in human subjects. *Neuroscience Letters*. 362(3), 193-5. <https://doi.org/10.1016/j.neulet.2004.02.066>
- Ricci, R., Salatino, A., Li, X., Funk, A.P., Logan, S.L., Mu, Q., Johnson, K.A., Bohning, D.E., George, M.S. (2012). Imaging the neural mechanisms of TMS neglect-like bias in healthy volunteers with the interleaved TMS/fMRI technique: preliminary evidence. *Frontiers in Human Neuroscience*, 6:326. <https://doi.org/10.3389/fnhum.2012.00326>.
- Rominger, C., Papousek, I., Perchtold, C. M., Benedek, M., Weiss, E. M., Schwerdtfeger, A., & Fink, A. (2019). Creativity is associated with a characteristic U-shaped function of alpha power changes accompanied by an early increase in functional coupling. *Cognitive, Affective, & Behavioral Neuroscience*, 19(4), 1012–1021. <https://doi.org/10.3758/s13415-019-00699-y>
- Runco, M. A., & Acar, S. (2012). Divergent Thinking as an Indicator of Creative Potential. *Creativity Research Journal*, 24(1), 66–75. <https://doi.org/10.1080/10400419.2012.652929>

- Salatino, A., Iacono, C., Gamberi, R., Chiadò, S. T., Lambert, J., Sulcova, D., Mouraux, A., George, M. S., Roberts, D. R., Berti, A., & Ricci, R. (2021). Zero gravity induced by parabolic flight enhances automatic capture and weakens voluntary maintenance of visuospatial attention. *Npj Microgravity*, 7(1). <https://doi.org/10.1038/s41526-021-00159-3>
- Salvi, C., & Bowden, E. M. (2016). Looking for Creativity: Where Do We Look When We Look for New Ideas? *Frontiers in Psychology*, 7, 1. <https://doi.org/10.3389/fpsyg.2016.00161>
- Sandkühler, S., & Bhattacharya, J. (2008). Deconstructing Insight: EEG Correlates of Insightful Problem Solving. *PLoS ONE*, 3(1), Article e1459. <https://doi.org/10.1371/journal.pone.0001459>
- Sara, S., & Bouret, S. (2012). Orienting and Reorienting: The Locus Coeruleus Mediates Cognition through Arousal. *Neuron*, 76(1), 130–141. <https://doi.org/10.1016/j.neuron.2012.09.011>
- Schwab, D., Benedek, M., Papousek, I., Weiss, E. M., & Fink, A. (2014). The time-course of EEG alpha power changes in creative ideation. *Frontiers in Human Neuroscience*, 8, 310. <https://doi.org/10.3389/fnhum.2014.00310>
- Sheth, B. R., Sandkühler, S., & Bhattacharya, J. (2009). Posterior Beta and Anterior Gamma Oscillations Predict Cognitive Insight. *Journal of Cognitive Neuroscience*, 21(7), 1269–1279. <https://doi.org/10.1162/jocn.2009.21069>
- Solís-Vivanco, R., Jensen, O., & Bonnefond, M. (2020). New insights on the ventral attention network: Active suppression and involuntary recruitment during a bimodal task. *Human Brain Mapping*, 42(6), 1699–1713. <https://doi.org/10.1002/hbm.25322>
- Stevens, C. E., & Zabelina, D. L. (2020). Classifying creativity: Applying machine learning techniques to divergent thinking EEG data. *NeuroImage*, 219, 116990. <https://doi.org/10.1016/j.neuroimage.2020.116990>
- Sulutvedt, U., Mannix, T. K., & Laeng, B. (2018). Gaze and the Eye Pupil Adjust to Imagined Size and Distance. *Cognitive Science*, 42(8), 3159–3176. <https://doi.org/10.1111/cogs.12684>
- Von Stein, A., & Sarnthein, J. (2000). Different frequencies for different scales of cortical integration: from local gamma to long range alpha/theta synchronization. *International Journal of Psychophysiology*, 38(3), 301–313. [https://doi.org/10.1016/s0167-8760\(00\)00172-0](https://doi.org/10.1016/s0167-8760(00)00172-0)
- Walcher, S., Kömer, C., & Benedek, M. (2017). Looking for ideas: Eye behavior during goal-directed internally focused cognition. *Consciousness and Cognition*, 53, 165–175. <https://doi.org/10.1016/j.concog.2017.06.009>
- Welch, P. (1967). The use of fast Fourier transform for the estimation of power spectra: A method based on time averaging over short, modified periodograms. *IEEE Transactions on Audio and Electroacoustics*, 15(2), 70–73. <https://doi.org/10.1109/tau.1967.1161901>
- Wróbel, A. (2000). Beta activity: A carrier for visual attention. *Acta Neurobiologiae Experimentalis* 60(2), 247–260.