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Beyond alpha-band: The neural correlate of creative thinking

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HIGHLIGHTS

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

ABSTRACT

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

Keywords

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

1. INTRODUCTION

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

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

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

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

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

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

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

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

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

2. MATERIALS AND METHODS

2.1. Participants

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

2.2. Alternative Uses Task

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

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

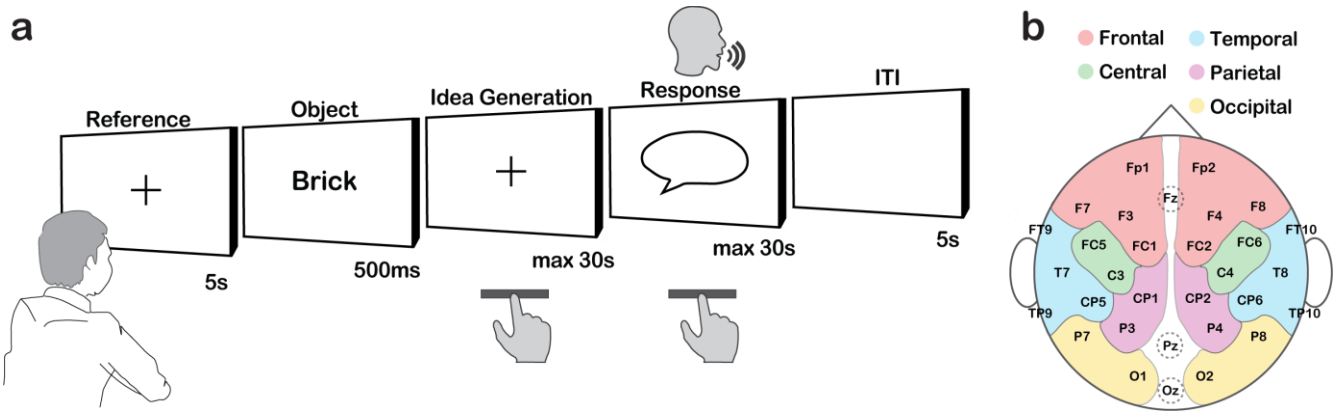


Figure 1. **Paradigm structure and scalp recording map. (a)**. **The Alternative Uses Task**. Each trial started with a 5s fixation cross, representing the "reference" period. Then, a word depicting an object (e.g., "Brick") was presented for 500ms and then followed by a fixation cross, representing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

2.3. Behavioral measures

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

2.4. Neural activity recording and preprocessing

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

$$TRP = \log_{10}(Power_{idea}) - \log_{10}(Power_{reference})$$

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

2.5. Eye gaze and pupil dilation

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

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

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

2.6. Statistical analysis

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

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

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

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

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

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

3. RESULTS

3.1. Behavioral

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

3.2. Electroencephalography

We began by examining whether frequency Band (alpha, beta, and gamma), Condition (Common vs Uncommon), Hemisphere (right vs left) and Area (frontal, central, temporal, parietal, occipital) influenced electrocortical activity during the task. Overall, we found the following significant main effects: Band ($F_{2, 864}$ = 19.930, $p < 0.001$; 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 η^2 = 0. 0.018), and Hemisphere ($F_{1, 432}$ = 29.968, $p < 0.001$; partial $\eta^2 = 0.065$). Also, we found significant 2-way 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, $p < 0.001$; partial $\eta^2 = 0.031$), Band x Area ($F_{8, 3456}$ = 20.405, $p < 0.001$; partial $\eta^2 = 0.045$), Condition x Area ($F_{4, 1728}$ = 6.492, $p < 0.001$; partial $\eta^2 = 0.015$) and Hemisphere x Area ($F_{4, 1728}$ = 16.069, $p < 0.001$; partial $\eta^2 = 0.036$). Furthermore, we found the significant 3-way interactions Band x Hemisphere x Area ($F_{8, 3456}$ = 8.205, $p < 0.001$; 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 unpack the last 3-way interaction, each frequency band (alpha, beta and gamma) were separated for further statistical analyses.

3.2.1. Alpha Band

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

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

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

3.2.2. Beta band

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

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

3.2.3. Gamma band

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

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

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

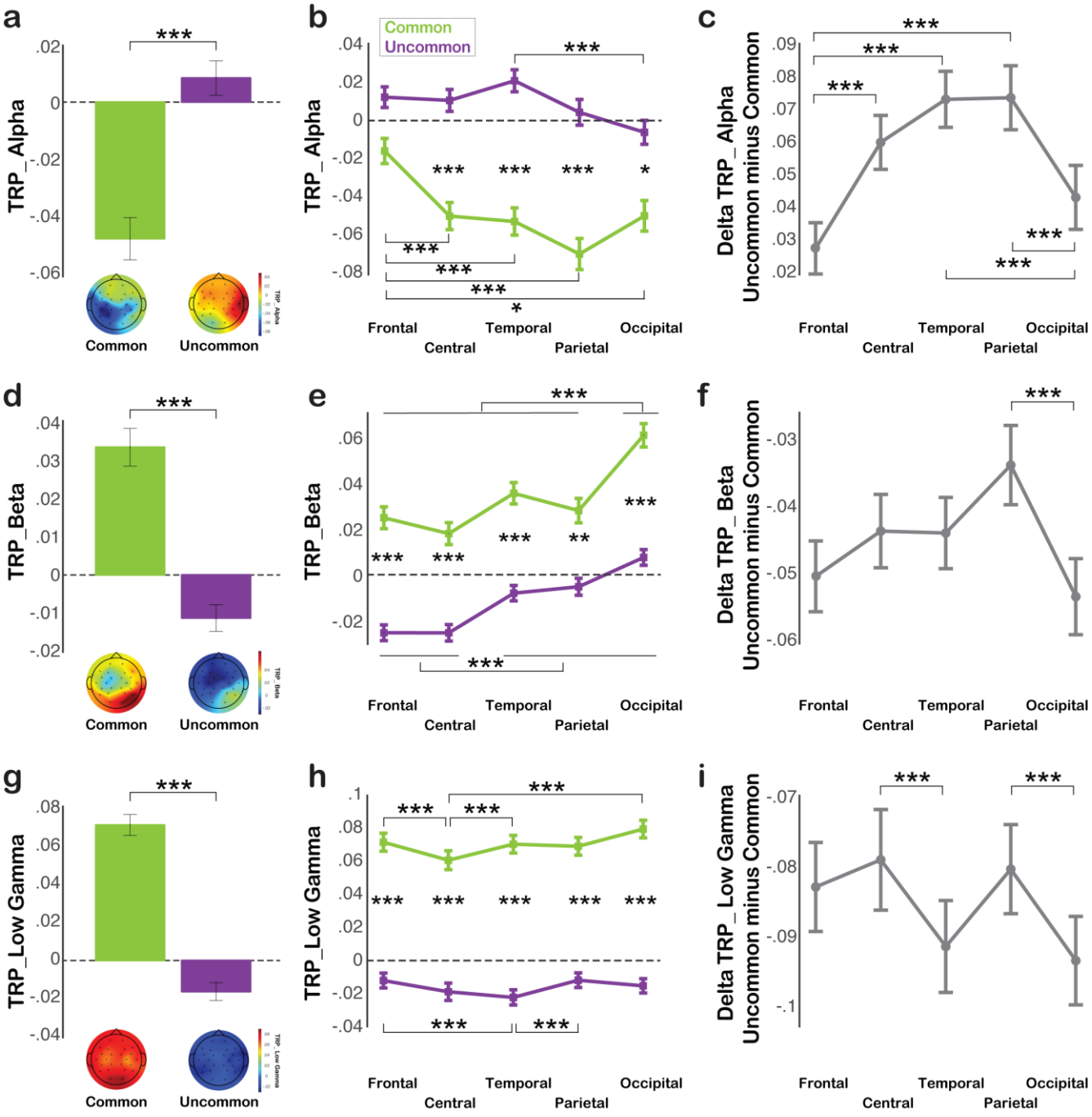


Figure 2. Alpha, Beta, Gamma TRP changes over the entire scalp. (a) Mean alpha TRP changes as a function of the Common (green) and Uncommon (purple) condition. Scalp maps depict the topographical distribution of mean alpha TRP changes for each condition (Common on the left and Uncommon on the right). **(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

the five cortical areas, same format as **b. (i)** Mean gamma TRP differences between Uncommon and Common condition same format as **c.** Values shown are the mean ± ½ SEM. Significant results are indicated by asterisk * = $p < 0.05$; ** = $p < 0.01$; *** = $p < 0.001$.

3.3. Gaze Patterns

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

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

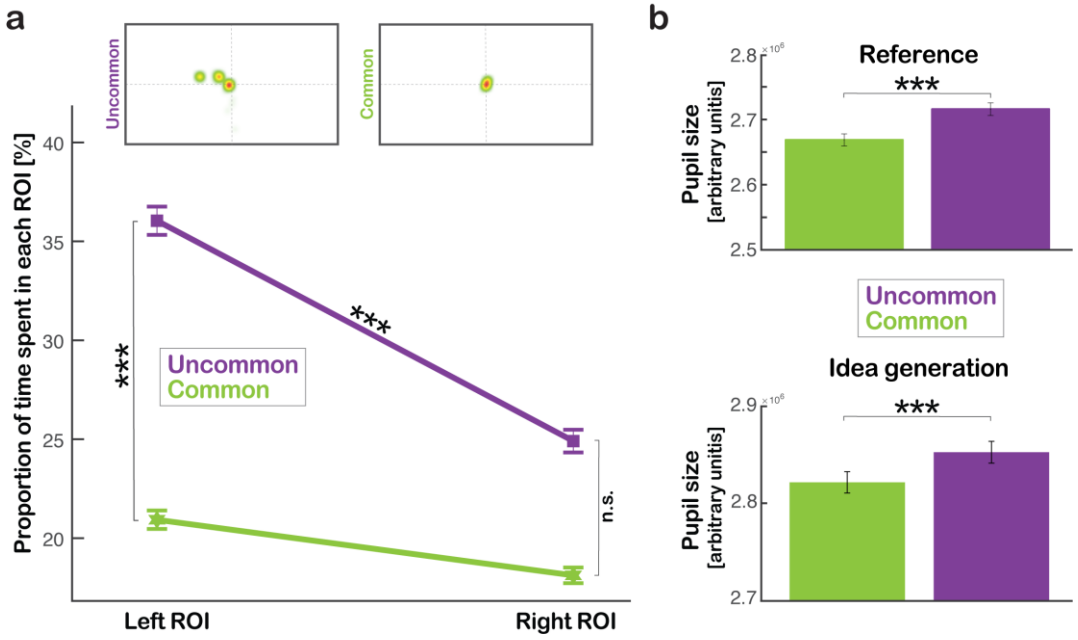


Figure 3. Changes in gaze patters and pupil dilation as a function of Common and Uncommon conditions. (a) Fixation density plots and normalized proportion of time spent on Left and Right ROIs. Top panels illustrate an example of a participant's looking behavior superimposed on a computer monitor in an Uncommon (left) and Common (right) trial. At the bottom, the normalized proportion of looking time spent in the left and right ROIs is depicted. Values indicate mean percentage of time participants spent gazing over the left or right ROIs during the generation of Uncommon (purple) and Common (green) ideas. **(b) Changes in pupil dilation.** Mean pupil size during the "reference" (top panel) and the "idea generation" (bottom panel) period for the *Uncommon* (purple) and the Common (green) conditions. Values shown are the mean ± ½ SEM. Significant results are indicated by asterisk, *** $p < 0.001$. n.s. = not significant.

3.4. Pupil Dilation

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

4. DISCUSSION

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

Behavioral findings

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

Neural findings

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

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

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

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

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

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

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

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

Gaze pattern and pupil dilation findings

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

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

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

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

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

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

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

Declaration of competing interest

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.

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