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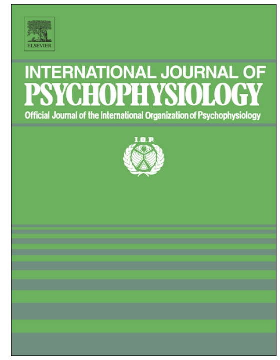

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More creative ideas are associated with increased right posterior power and frontal-parietal/occipital coupling in the upper alpha band: A within-subjects study

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Abstract

The neurophysiological investigation of creative idea generation is a growing research area. EEG studies congruently reported the sensitivity of upper alpha power (10-12Hz) for the creative ideation process and its outcome. However, the majority of studies were between-subject design studies and research directly comparing the neurophysiological activation pattern when generating more and less creative ideas within a person are rare. Therefore, the present study was specifically focused on investigating brain activation patterns associated with the generation of more vs. less creative ideas. We applied an alternate uses task (AU-task; i.e., finding original uses for everyday objects such as a brick) in a sample of 74 participants and recorded the brain activation during the AU-task and reference period. A portable EEG system with 21 dry electrodes arranged in the international 10-20 system and linked ear as reference was used. We found a higher increase of upper alpha power during creative ideation (relative to reference period, i.e., task-related power, TRP) over right posterior sites when people generated more compared to less creative ideas.

This was accompanied by an increase of functional coupling (i.e., task-related coherence increase) between frontal and parietal/occipital sites, which suggests higher internal attention and more control over sensory processes. Taken together, these findings complement the existing creativity research literature and indicate the importance of alpha power for the creative ideation process also within people.

Keywords: creative ideation, portable EEG, upper alpha power, originality

Introduction

Creative ideation is an important human skill essential for arts, science, and sports. Not at least due to the high frequency of occurrence and relevance of creative idea generation (Benedek et al., 2020), the neuronal underpinnings of creative ideation have been extensively studied for many years and still constitute a growing field of scientific research (Benedek et al., in press). In parallel with the increase in published studies and empirical knowledge, scientists have continuously adapted creative ideation tasks and methods to measure the neurophysiology of creative ideation (Benedek et al., 2019). Since the pioneering work of Colin Martindale, EEG studies congruently reported the sensitivity of alpha power for the creative ideation process and its outcome (Martindale & Hasenfus, 1978; Martindale & Hines, 1975; for overviews see Fink & Benedek, 2014; Stevens & Zabelina, 2019).

In more detail, task-related power (TRP) increases in the upper alpha band - that is a power increase from a reference to an active ideation period (Gerloff, 1998; Pfurtscheller, 1999) – were observed for more (vs. less) creative people (between-subjects) and for more (vs. less) creative ideas (within-subjects). However, most evidence came from between-subjects studies investigating the neurophysiological activation associated with the creative potential of participants (Runco & Acar, 2012), and within-subjects studies comparing more and less original ideas are limited (Fink & Benedek, 2014). Following prominent theories on the functional meaning of alpha power (Fries, 2005; Jensen et al., 2002; Klimesch et al.,

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2007), these upper alpha increases were claimed to be more sensitive to specific task requirements (Klimesch, 1999). Depending on the task at hand and the EEG-electrode position of interest, TRP changes should be interpreted differently (Rominger, Papousek, et al., 2020). (1) Frontal alpha power increases might represent increased executive top-down control during the creative ideation process (Fink et al., 2017) and (2) higher TRP at posterior sites (specifically at the right parietal cortex) might represent internally directed attention (i.e., the allocation of attention to internal mental representations and processes; Benedek, Schickel, et al., 2014; Fink & Neubauer, 2006; Jauk et al., 2012). In line with this reasoning, the functional coupling between frontal and parietal/occipital sites in the upper alpha band was interpreted as increased top-down control over sensory information during creative ideation (Rominger et al., 2019; Rominger, Papousek, et al., 2020; Zhou et al., 2018).

Although the TRP approach to study creativity is not without limitations, the largely congruent findings of TRP (and functional coupling; see e.g., Rominger et al., 2019; Zhou et al., 2018) in the alpha band are indicative of some robustness and (internal) validity of findings, especially when focusing on higher-level processes (such as memory and executive functions) by using the alternate uses task (AU-task; Fink & Benedek, 2014; Stevens & Zabelina, 2019). However, since the majority of research firmly focused on between-subjects design, we assessed intraindividual variability of task performance (i.e., originality) and explicitly aimed to examine the neurophysiology of the creative ideation process where it takes place – within people (Hamaker, 2012). This examination is important since between-person findings do not necessarily translate to within-person and vice versa (Hamaker, 2012).

In line with this, the available within-subjects studies comparing more and less original ideas did not indicate a specific alpha power activation pattern as could be deduced from theory. Fink and Neubauer (2006) reported increased alpha power at parietal sites when people generated more creative ideas compared to less creative ideas; however, they did not find a hemispheric effect. Schwab et al. (2014) demonstrated that more original ideas compared to less original ideas go along with a higher upper alpha activation at the right compared to the left hemisphere, which increased with time on the task (see also Grabner et al., 2007 for subjectively rated originality). However, Schwab et al. (2014) did not indicate an interaction with position. When combining these two within-subjects studies, it could be deduced that task-related alpha power increases over right parietal areas might be crucial indicators for more original solutions; however, this has not been shown to date. Furthermore, to the best of our knowledge, no study directly investigated if the coupling between frontal and parietal/occipital sites would impact the subsequent originality of an idea (see e.g., Zhou et al., 2018 for comparing self-rated novel and normal solutions). A stronger coupling between these sites would argue for the importance of increased top-down control over sensory information (e.g., Rominger, Papousek, et al., 2020) and would add to the role of task-related alpha power increases at right parietal areas as an indicator of increased internal attention.

In order to complement the empirical evidence indicating the involvement of specific brain activation patterns to come up with more (vs. less) creative ideas, we applied EEG power and functional coupling measures of brain activation in a comparatively sizeable final sample of 74 participants. Based on the literature, we expected higher TRP in the upper alpha band at (right) parietal sites during the generation of more creative ideas compared to less creative ideas (Benedek, Schickel, et al., 2014; Fink & Neubauer, 2006; Schwab et al., 2014). This should be accompanied by a higher functional coupling between frontal and parietal/occipital sites when generating more creative ideas (Rominger, Papousek, et al., 2020). Furthermore, we additionally investigated the time-course of creative ideation, since research showed a performance relevant brain activation pattern over time (e.g., u-shape of upper alpha power, Agnoli et al., 2020; Jaarsveld et al., 2015; Rominger et al., 2019; Schwab

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et al., 2014; Zhou et al., 2018).

Methods

Participants

A total of 102 participants were recruited through the participant pool of the University and personal contacts. A total of 28 participants (27%) were excluded from further analyses due to low EEG signal quality (e.g., excessive movement artifacts, sweat artifacts, and eye blinks), predominantly because of the use of the EEG system with dry electrodes. The final sample consisted of 74 participants (25 male, 1 other) aged between 19 and 38 years (M = 24.00, SD = 4.39). An a priori power analysis indicated that 68 participants would be sufficient to detect a small to medium sized effect (d = 0.40) with a power of .90 by means of a t test for dependent measures. We strove to sample 75 participants with good EEG-signal quality to be able to compensate for further exclusion (e.g., due to technical problems). Participants were mainly right-handed (88%, 12% left-handed due to self-report) students (90%). The highest education was apprenticeship (11%), high school diploma (80%), and finished master studies (9%). All participants came from Switzerland and did not work on the applied creative ideation task before. Participants were enrolled in the study if they did not have epilepsy or a neurological disorder, had not suffered a concussion, and were not taking medication. All participants were asked not to drink alcohol 12 hours and not to consume caffeinated beverages or smoke cigarettes 1 hour before the study. All participants gave written informed consent to participate in the study. The study was approved by the University's local ethics committee (project ID 2019-09-00007).

Material

Creative ideation task

The alternate uses task (i.e., AU-task) was adapted similar to the study of Schwab et al. (2014), which is a widely-used divergent thinking task to assess creative ideation

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performance. Participants were asked to generate original and useful uses for 20 common everyday objects (i.e., brick, fork, hosepipe, hat, sock, paper bin, umbrella, toothbrush, plaster, key, clothespin, tennis racket, spoon, pen, balloon, screwdriver, mirror, tie, iron, car tire). Twenty items were shown to be sufficient to investigate the within-person variation of creative ideation (Jauk et al., 2012; Schwab et al., 2014). As illustrated in Figure 1, the task started with a fixation cross (10 s), which served as a reference period. The presentation of the item followed the fixation cross for a duration of 4 s. Thereafter a white question mark was presented (10 s), which indicated that the participants had to think creatively about an original use of the given object (i.e., activation period). Finally, the question mark turned green, which signaled that participants had to verbalize their idea within 4 s. All oral responses were transcribed by the experimenter. The presentation of the 20 AU items during EEG recording was realized with the software Eprime 2.0. The creative ideation performance was assessed in a conventional room when the experimenter was present. The experimental setting is illustrated in Figure 1.

Analysis of task performance

Based on the consensual assessment technique (Amabile, 1982), four independent and well-instructed judges (i.e., 3 women and 1 man) evaluated the originality of answers. The judges were asked to rate all responses for one item at a time. All responses per item were sorted in alphabetical order to facilitate the identification of responses that were frequently mentioned. The originality of each response was assessed on a four-point rating scale ranging from 1 (“not original/not useful”) to 4 (“very original”). Interrater reliability of originality ratings was good with ICC (2,k) = .86. For each response, ratings across all four raters were averaged, resulting in 20 originality scores per participant. These 20 scores were further divided into less vs. more original ideas within each participant (by means of a mean-split). The average score of less original answers (M = 1.94, SD = 0.21) was significantly lower

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than the average score of more original answers (*M* = 2.90, *SD* = 0.28; $t(73) = 23.270$, $p <$ .001; for an illustration of means for each participant see supplemental Figure 1). This differentiation between more and less creative ideas and the corresponding EEG signal within each participant was used as a within-subjects factor in all further analyses.

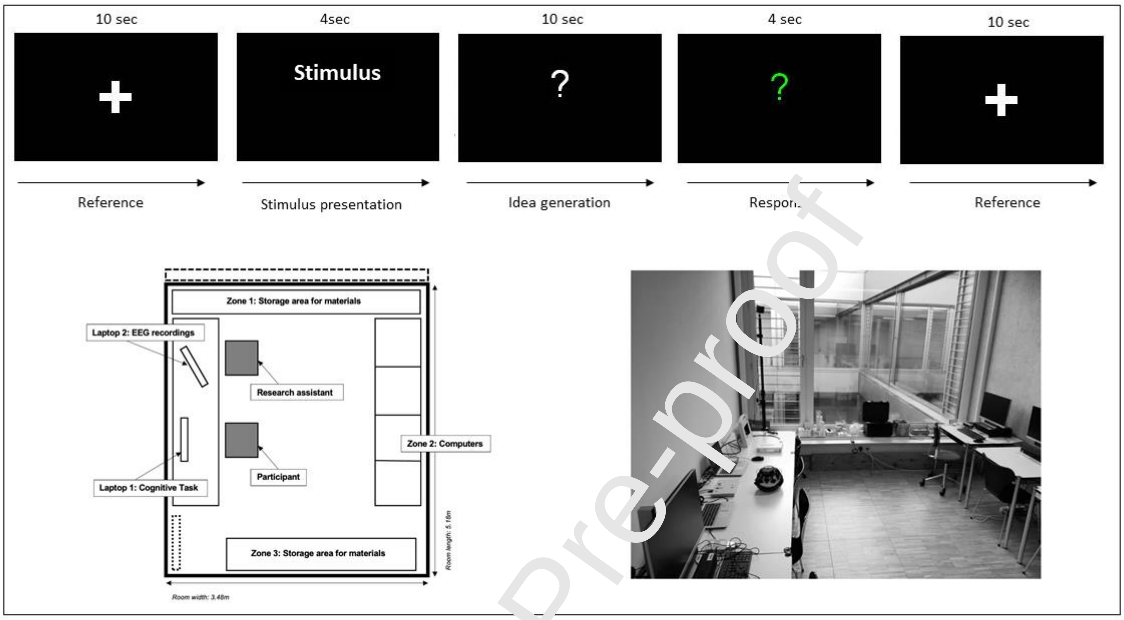

Figure 1. Illustration of the schematic time-course of the adapted AU-task (top) and the experimental setup (bottom).

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EEG recording and analysis

The DSI 24, a portable EEG system with dry electrodes and the corresponding recording software DSI-STREAMER was used (see e.g., Soufineyestani et al., 2020). The DSI 24 has 21 electrodes (Fp1, Fp2, Fz, F3, F4, F7, F8, Cz, C3, C4, T7, T8, Pz, P3, P4, P7, P8, O1, O2, A1, A2) arranged according to the international 10-20 system. The Pz served as the reference electrode during recording. Simultaneously, an electrooculogram (EOG) was measured with two horizontal electrodes on the left and right side of the eyes (horizontal EOG) as well as Fp2 and an electrode on the infraorbital ridge of the right eye (vertical EOG). EEG and EOG were recorded at a rate of 300 Hz. The EEG signal was re-referenced to linked ear via the DSI-STREAMER software before exporting.

EEG Data were analyzed with the software BrainVision Analyzer 2.2. The signal was resampled with 256 Hz and bandpass filtered (0.1-30 Hz). Eye blinks were corrected using Gratton and Coles' ocular correction procedure (Gratton et al., 1983). Then, remaining artifacts (e.g., uncorrected eye movements, muscle tensions) were excluded from further analysis via visual inspection. When the signal quality of single channels was bad throughout the recoding, we interpolated (mostly) frontal channels for 15 participants by spherical splines implemented in the BrainVision Analyzer 2.2 (M = 0.35, SD = 0.76, min = 0, max = 3; similar approach see Jia et al., 2021). All analyses were focused on the 16 lateralized electrodes (e.g., FP1/2, F3/4, F7/7, etc.).

Data were divided into reference periods (9 s duration, starting 0.5 s after the onset of fixation cross) and activation periods (9 s duration, starting 0.5 s after the onset of the white question mark), respectively. To investigate a potential time-course of the TRP (and functional coupling), the activation period was further divided into three isochronous intervals of 3 s each (Schwab et al., 2014). The first interval (T1) started from 0.5 s after the onset of the white question mark till 3.5 s, the second interval (T2) from 3.5 s till 6.5 s, and the last interval (T3) from 6.5 s till 9.5 s.

Subsequently, the reference period and the three intervals of the activation period (T1, T2, T3) of each trial were segmented into epochs of 1 s with an overlap of 0.5 s each (50%). Artifact-free EEG data segments were submitted to Fast Fourier Transformation (FFT) using a Hanning window for power estimates and no window for EEG coherence analyses. The results were then averaged across all epochs per participant. Power scores (10-12 Hz) were extracted from the resulting FFT analysis (see e.g., Luft et al., 2018; Papousek, Weiss, et al., 2017; Perchtold et al., 2018). EEG coherence between all pairs of electrodes was calculated by the magnitude-squared coherence analysis, based on the magnitude of the cross-spectrum

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and the auto-spectra of the input signals (Zhou et al., 2018).

Brain activity was measured by means of task-related power (TRP) changes (Gerloff, 1998; Pfurtscheller, 1999) and task-related coherence (TRCoh) changes (Gerloff, 1998). In accordance with previous research, TRP at an electrode *i* was obtained by subtracting (log-transformed) power during the reference period from (log-transformed) power during the activation period (Fink, Rominger, et al., 2018; Jauk et al., 2012; Schwab et al., 2014). Negative values represented decreases from the reference to the activation period (i.e., desynchronization), whereas positive values represented increases from the reference to the activation period (synchronization).

Changes in task-related functional coupling were calculated between intra-hemispheric pairs of frontal and parietal-occipital electrodes. After Fisher's z transformation, TRCoh values were calculated by the same formula used to calculate TRP scores (see, e.g., Gerloff, 1998; Rominger et al., 2019). All resulting TRCoh values were averaged per hemisphere to estimate the mean intra-hemispheric task-related changes of frontal-parietal/occipital coupling in a priori defined clusters of electrodes over left and right frontal and posterior association cortex regions (i.e., frontal-parietal/occipital network, 9 pairs per hemisphere; left: FP1–P3, F3–P3, F7–P3, FP1–P7, F3–P7, F7–P7, FP1–O1, F3–O1, F7–O1; right: FP2–P4, F4–P4, F8–P4, FP2–P8, F4–P8, F8–P8, FP2–O2, F4–O2, F8–O2; for illustration see Figure 2). Similar aggregations were used before (Papousek, Ruch, et al., 2017; Reiser et al., 2012; Rominger et al., 2019; Rominger, Papousek, et al., 2020; Terhune et al., 2011), and the involvement of these cortical sites and the increase in their communication/cooperation is well documented during creative ideation (Beaty et al., 2015; Jausovec & Jausovec, 2000; Petsche, 1996; Rominger et al., 2019; Rominger, Memmert, et al., 2020).

Volume conduction leads to the measurement of the same signal at two different electrodes, which would increase the estimated coherence between these sites (e.g., Hardmeier et al., 2014). The applied methods are targeted to mitigate this effect. First, the task-related design reduces potential spurious synchrony in signals because coherence scores of the activation and reference peroid contain a similar amount of spurious/artificial synchronization (Bastos & Schoffelen, 2016; Höller et al., 2017; Keil et al., 2022; Palva et al., 2018). Second, this argumentation is also valid when focusing on the coherence difference between more and less creative ideas within a person. They should show a similar amount of volume conduction inducted coherence between two electrodes while producing more and less creative ideas. Therefore, differences between more and less creative ideas should also mitigate the issue of volume conduction (Keil et al., 2022). Third, lower spurious coherence was reported for electrodes spanning larger distances (Nunez et al., 1997; Srinivasan et al., 2007).

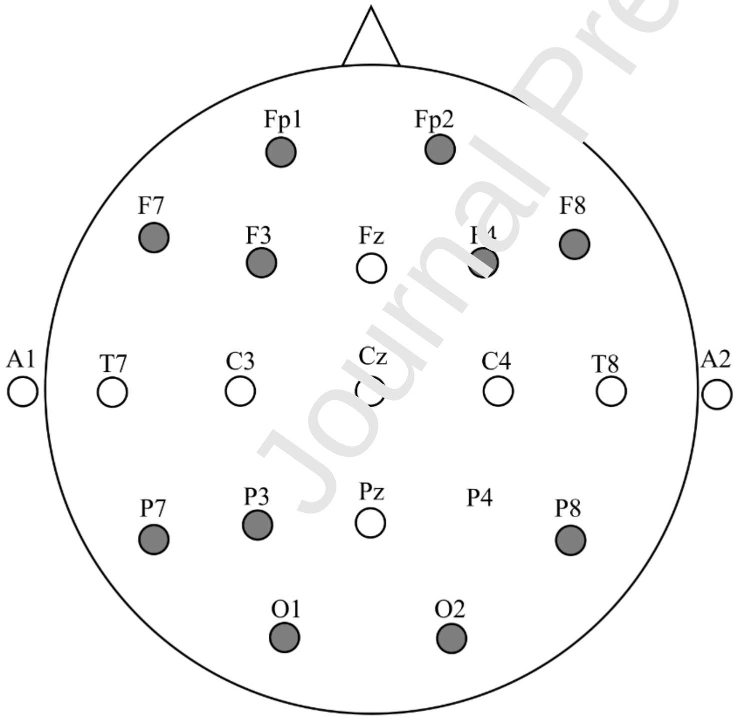

Figure 2. Positions included in the 9 pairs over each hemisphere to quantify task-related frontal-parietal/occipital coherence (gray electrodes; left: FP1–P3, F3–P3, F7–P3, FP1–P7, F3–P7, F7–P7, FP1–O1, F3–O1, F7–O1; right: FP2–P4, F4–P4, F8–P4, FP2–P8, F4–P8, F8–P8, FP2–O2, F4–O2, F8–O2).

In total M = 161.35 (SD = 57.98, min = 61, max = 277) 1 s epochs were available for the reference period and M =172.35 (SD = 47.34, min = 72, max = 270) epochs for activation period during creative idea generation (T1: M =49.64, SD = 19.15, min = 16, max = 93; T2: M =67.64, SD = 17.17, min = 18 max = 92; T3: M = 65.08, SD = 15.94, min = 31, max = 97). Furthermore, M = 94.01 (SD = 33.62, min = 26, max = 174) 1 s epochs were available for less and M =77.39 (SD = 27.63, min = 26, max = 152) for more creative ideas.

Statistical Analysis

TRP scores were analyzed by a 2 x 8 x 2 x 3 analysis of variance (ANOVA) with the within-subjects factors ORIGINALITY (more vs. less creative ideas), AREA (eight electrode positions in each hemisphere), HEMISPHERE (left, right), and TIME on the task (T1 vs. T2 vs. T3). This analysis allows to evaluate (1) the general TRP pattern, (2) the creativity-specific pattern of TRP, and (3) the time course of TRP during creative ideation. In analogy to the TRP analyses, the TRCoh scores were analyzed by a 2 x 2 x 3 ANOVA with the within-subjects factors ORIGINALITY (more vs. less creative ideas), HEMISPHERE (left, right), and TIME on the task (T1 vs. T2 vs. T3). In case of violations of sphericity assumptions, the Greenhouse-Geiser epsilon (ε) correction was used to compensate (Keselman, 1998). Estimates of effect size are reported using partial eta-squared (η_p^2). Simple effects and simple interaction effects were used to explore significant high-order interactions (see e.g., Kayser et al., 2016). Significant main effects with more than two levels (i.e., AREA and TIME) were further examined with follow-up Bonferroni corrected t tests. A significance level of $p < .05$ (two-tailed) was applied for all analyses, which were calculated with SPSS 28. Brain maps were built with the FieldTrip toolbox (Oostenveld et al., 2011).

Results

Task-related alpha power activation during creative ideation

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The 2 x 8 x 2 x 3 analysis of variance revealed a significant main effect AREA (F(7,511) = 3.09, p = .017, ε = .565, η_p^2 = .04), indicating increased alpha power during creative ideation at parietal sites (P3/4) compared to occipital cortical sites (O1/2, Bonferroni adjusted p = .009; see Figure 3, Panel A). For all other electrode sites, there were no significant differences (all Bonferroni adjusted $ps \geq .082$). The main effect HEMISPHERE was not significant (F(1,73) = 3.42, p = .068, η_p^2 = .05). However, there was an interaction AREA x HEMISPHERE (F(7,511) = 7.83, p < .001, ε = .708, η_p^2 = .10). A significant simple HEMISPHERE main effect was observed for dorsolateral prefrontal (F3/4, F(1, 73) = 9.84, p = .002, η_p^2 = .12), temporal (T3/4, F(1, 73) = 6.53, p = .013, η_p^2 = .08), parietal (P7/8, F(1, 73) = 12.91, p = .001, η_p^2 = .15), and occipital sites (O1/2, F(1, 73) = 15.33, p < .001, η_p^2 = .17). While F3/4 showed a higher activation over the left hemisphere, more posterior positions (i.e., T3/4, P7/8, O1/2) showed stronger alpha power increases over the right hemisphere (see Figure 3, Panel A; for single-subject brain maps see supplemental Figure 2-8).

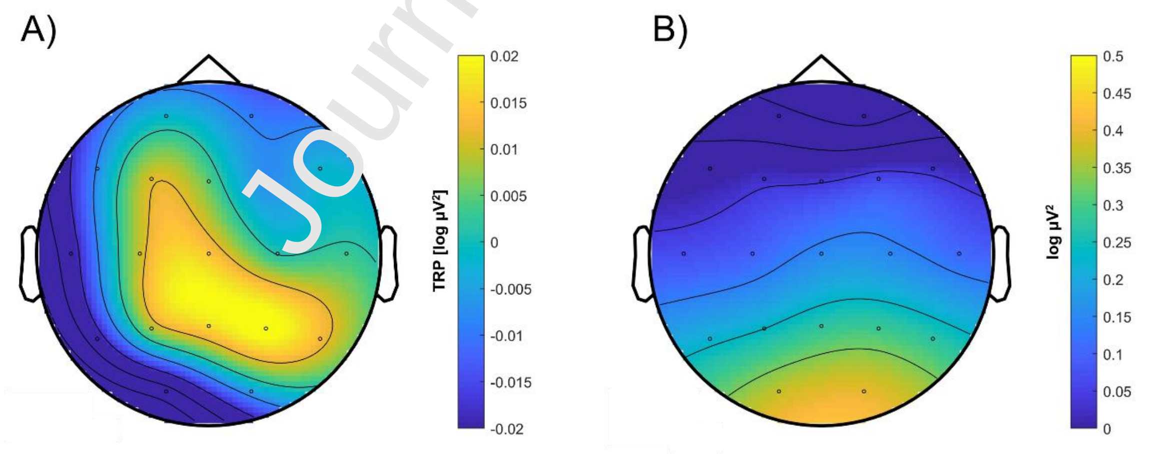

Figure 3. Grand mean of TRP during creative idea generation (Panel A). Panel B illustrates the upper alpha power during the reference period (grand mean).

Task-related alpha power as a function of originality of ideas

The impact of creative ideation performance on TRP was indicated by the significant interaction effect ORIGINALITY x AREA x HEMISPHERE ($F(7,511) = 2.45$, $p = .036$, $\varepsilon = .685$, $\eta_p^2 = .03$). Follow up 2x2x3 ANOVAs for each AREA indicated that only the position P7/P8 showed a significant interaction ORIGINALITY x HEMISPHERE ($F(1,73) = 6.17$, $p = .015$, $\eta_p^2 = .08$; all other $ps \geq .150$). A significant simple ORIGINALITY main effect was observed for P8 ($F(1,73) = 5.58$, $p = .021$, $\eta_p^2 = .07$) and was absent for P7 ($F(1,73) < 1.0$, n.s.). This indicates that alpha power was higher during producing more creative ideas compared to less creative ideas over P8 but not over P7 (see Figure 4). Furthermore, the simple main effect HEMISPHERE was significant for more creative ideas at P7/8 ($F(1,73) = 18.10$, $p < .001$, $\eta_p^2 = .20$), but did not reach significance for less creative ideas at P7/8 ($F(1,73) = 3.55$, $p = .064$, $\eta_p^2 = .05$; Figure 4).

No further effect including the factor ORIGINALITY was significant (ORIGINALITY: $F(1,73) < 1.0$, n.s.; ORIGINALITY x HEMISPHERE: $F(1,73) < 1.0$, n.s.; ORIGINALITY x AREA: $F(7,511) = 1.30$, $p = .271$, $\varepsilon = .567$, $\eta_p^2 = .02$)

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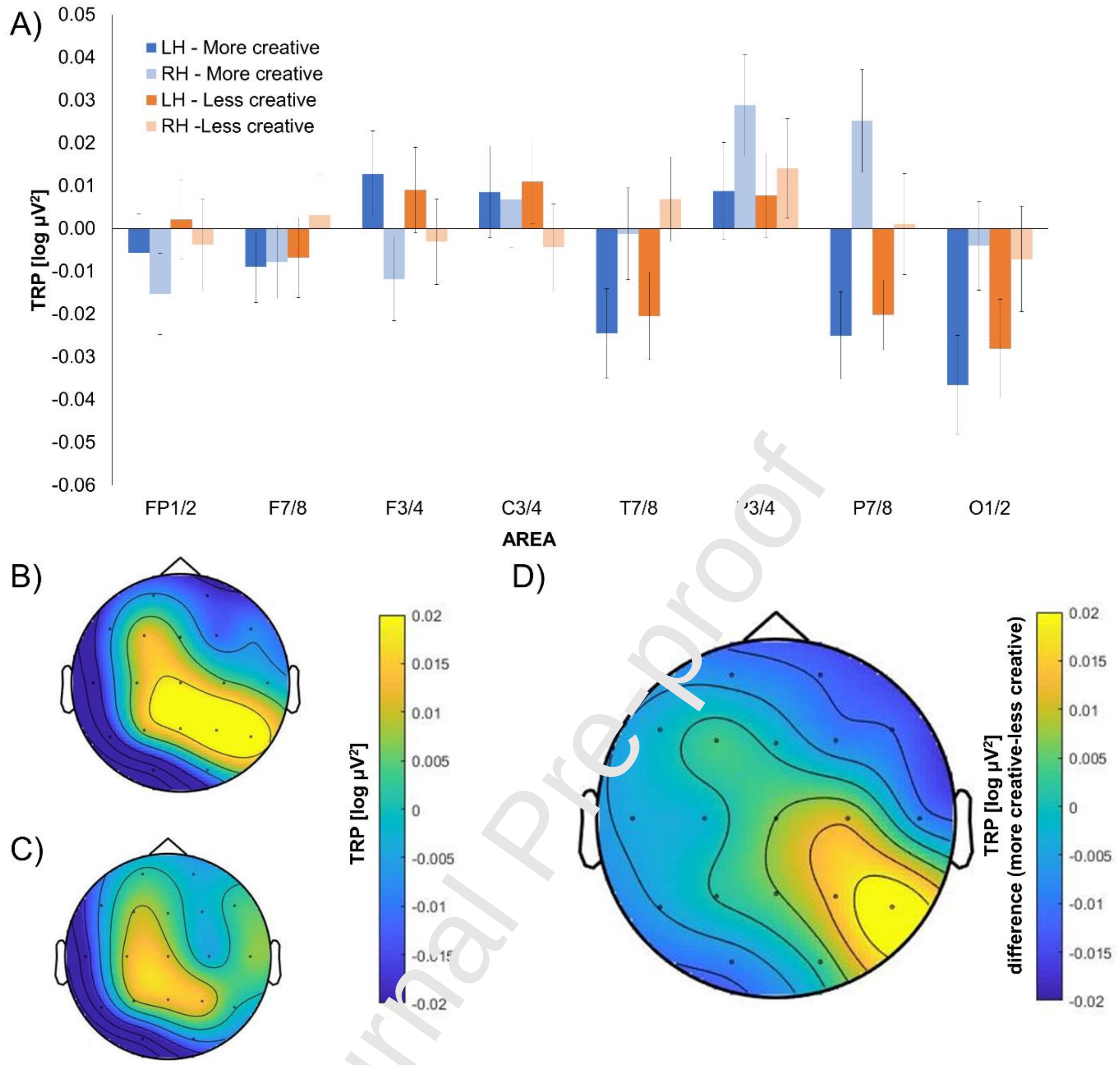

Figure 4. TRP in the upper alpha band as a function of more and less creative ideas (Panel A). Panel B represents the TRP during more creative ideas, panel C during less creative ideas, and panel D illustrates the significant interaction of ORIGINALITY x AREA x HEMISPHERE.

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Time-course of alpha power during creative ideation

The main effect TIME was significant (F(2,146) = 7.308, p = .001, ε = .920, η_p^2 = .09). During T3 the TRP decrease in the upper alpha band (M = -0.020, SE = 0.06) was significantly lower compared to T1 (M = 0.009, SE = 0.009, Bonferroni adjusted p = .006) and to T2 (*M* = 0.003, *SE* = 0.007, Bonferroni adjusted $p = .008$), which showed power increases (see Figure 5). TRP during T1 and T2 showed no significant difference (Bonferroni adjusted $p > .999$). No further effect including the factor TIME was significant (all $ps \geq .100$) and more and less creative ideas did not show a different TRP time course (ORIGINALITY x TIME: $F(2,146) < 1.0$, n.s.; ORIGINALITY x HEMISPHERE x TIME: $F(2,146) < 1.0$, n.s.; ORIGINALITY x AREA x TIME: $F(14,1022) < 1.0$, $\varepsilon = .596$, n.s.; ORIGINALITY x AREA x HEMISPHERE x TIME: $F(14,1022) < 1.0$, $\varepsilon = .663$, n.s.).

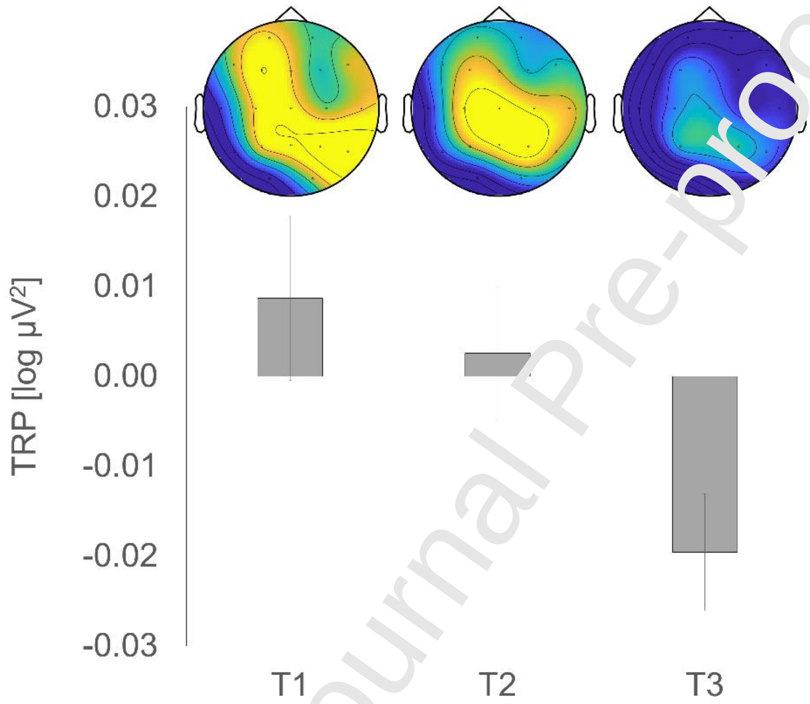

Figure 5. Time-course of the TRP in the upper alpha band. The creative ideation process was divided into three isochronous intervals with a length of 3 s each (T1, T2, T3).

Task-related coherence (functional coupling) in the upper alpha band during creative ideation

The 2 x 2 x 3 analysis of variance revealed a significant main effect ORIGINALITY ($F(1,73) = 7.182$, $p = .009$, $\eta_p^2 = .09$), which indicated increased functional coupling during producing more creative ideas (*M* = 0.052, *SE* = 0.05) compared to less creative ideas (*M* =

0.040, *SE* = 0.05; see Figure 6). The significant main effect TIME (F(2,146) = 14.82, p < .001, η_p^2 = .17) indicated higher coupling during T1 (*M* = 0.060, *SE* = 0.06) than during T2 (*M* = 0.043, *SE* = 0.05; Bonferroni adjusted p = .001) and T3 (*M* = 0.035, *SE* = 0.05, Bonferroni adjusted p = .001; T2 and T3 were not significantly different, Bonferroni adjusted p = .257; see Figure 6). No further effect reached significance (HEMISPHERE: F(1,73) < 1.0, n.s.; TIME x HEMISPHERE: F(2,146) < 1.0, n.s.; ORIGINALITY x TIME: F(2,146) = 1.257, p = .285, ε = .882, η_p^2 = .02; ORIGINALITY x HEMISPHERE: F(1,73) < 1.0, n.s.; ORIGINALITY x TIME x HEMISPHERE: F(2,146) < 1.0, n.s.)

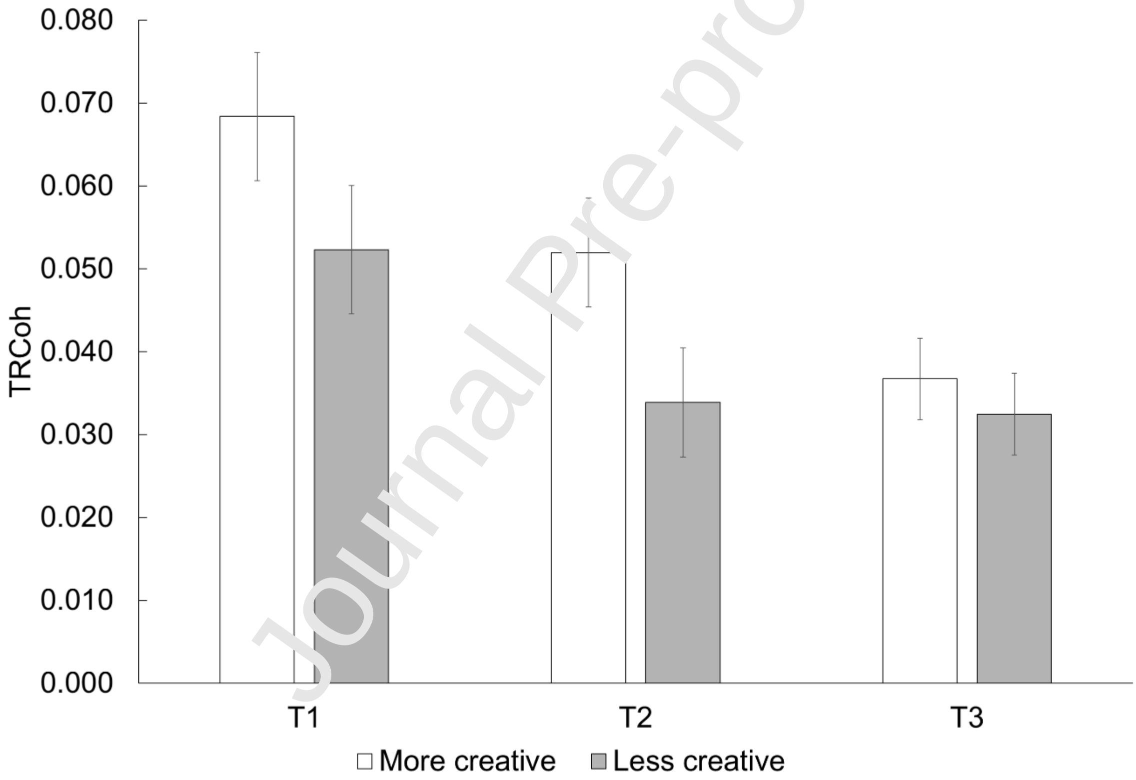

Figure 6. TRCoh in the upper alpha band as a function of more and less creative ideas and the time-course of creative idea generation (T1, T2, T3).

Additional analyses to investigate if creative ideation effects expand to the adjacent frequency bands of upper alpha

Additional analyses applying the same ANOVA, however, with the TRP for the lower

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alpha band (8-10 Hz) and the lower beta band (12-14 Hz) indicated that the observed interaction ORIGINALITY x AREA x HEMISPHERE was specifically observed in the upper alpha band and did not expand to the adjacent frequency bands of lower alpha (F(7,511) < 1.0, ε = .762, n.s.) and lower beta (F(7,511) < 1.0, ε = .733, n.s.). The TRCoh scores, however, showed similar effect sizes of ORIGINALITY in the lower alpha band (F(1,73) = 6.551, p = .013, η_p^2 = .08) and the lower beta band (F(1,73) = 6.459, p = .013, η_p^2 = .08).

Discussion

The aim of this study was to investigate the specific brain activation pattern relevant for producing more (vs. less) creative ideas. In general, we found higher upper alpha power at the right parietal, right temporal, and right occipital sites (compared to the left sites), when generating creative ideas. This was accompanied by increased left dorsolateral prefrontal power (i.e., F3; compared to F4) and an increase in functional coupling between frontal and parietal/occipital sites, which argues for increased sensory top-down control over external stimuli during creative idea generation (Benedek, Schickel, et al., 2014; Rominger et al., 2019; Schwab et al., 2014). This neuronal pattern of creative idea generation is in accordance with the findings of between-subjects studies (Benedek, 2018; Fink & Benedek, 2014; Rominger, Papousek, et al., 2020) and underlines the replicability of the neuroscience of creativity.

The most prominent finding of the present study is the upper alpha power increase at right parietal sites when more creative ideas compared to less creative ideas were produced (Benedek, Schickel, et al., 2014). The involvement of right parietal areas as a central hub for internal attention during creative ideation was often suggested (Fink & Benedek, 2014; Jauk et al., 2012; for an overview, see Benedek, 2018). However, to the best of our knowledge, it has not been shown that the alpha activation of right parietal areas can differentiate between more and less creative ideas (but see Stevens & Zabelina, 2020 for common/uncommon ideas). Therefore, the present study nicely adds a new and more specific finding to the literature, which is in accordance with available studies reporting higher posterior, but not right hemispheric (Fink & Neubauer, 2006) and higher right hemispheric, but not posterior (Schwab et al., 2014) alpha power increases associated with more original ideas (see Grabner et al., 2007 for self-rated originality; overview see Benedek, 2018; Fink & Benedek, 2014). Furthermore, studies experimentally asking participants to produce uncommon or common solutions reported higher alpha power increases at (right) posterior sites during solving the uncommon trials (Fink, Rominger, et al., 2018; Jauk et al., 2012; Stevens & Zabelina, 2020). The study results are also in accordance with Jung-Beeman et al. (2004), who reported higher alpha increases at right parietal-occipital areas when experiencing insights during creative problem solving (as opposed to experiencing no insights), which could be interpreted as inward focused attention (Benedek, 2018).

Additionally, this study showed increased coupling between frontal and posterior/occipital sites when producing more (vs. less) creative ideas, which argues for top-down control over sensory information (e.g., Rominger et al., 2019). Although the TRCoh result is less specific with respect to the upper alpha band compared to the TRP findings, it is in accordance with previous research showing increased functional coupling during creative idea generation in the verbal (Rominger et al., 2019; Zhou et al., 2018) and the figural domain (Rominger, Papousek, et al., 2020). Increased functional coupling of brain networks during creative ideation was also described by means of fMRI (e.g., Beaty et al., 2015). In addition to previous research, the present study indicated for the very first time that functional coupling might not only take place due to general characteristics of the creative ideation process (e.g., involvement of executive functions during idea elaboration; Rominger, Papousek, et al., 2020), the creative potential of participants (Rominger et al., 2019), or characteristics of participants (Rominger, Memmert, et al., 2020), but also because of the

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quality of ideas within people. This study adds the observation to the literature that more creative ideas are associated with increased functional coupling, which might signal increased control over sensory information. This interpretation is in accordance with the alpha power increase over the right parietal area (i.e., P8) when producing more creative ideas (vs. less creative ideas).

However, contrary to previous research, we did not find a general pattern of strong frontal alpha power increases during the generation of original ideas (Fink et al., 2017; Fink & Benedek, 2014; Fink & Neubauer, 2006; Fink, Rominger, et al., 2018; Rominger et al., 2019; Rominger, Memmert, et al., 2020). The absence of an alpha power re-increase over time, which was interpreted as increased executive top-down control during later stages of the creative ideation process (Rominger et al., 2019; Schwab et al., 2014), might explain lower TRP at frontal sites in this study (for a similar continuous decrease of alpha power during the creative ideation process see e.g., Zhou et al., 2018). However, further research is needed to investigate which parameters are important to evoke general frontal alpha power increases during creative idea generation and which parameters could shape the alpha power time course of creative ideation (see Yu et al., 2022 for problem solving with insights).

However, we found higher left dorsolateral prefrontal alpha power increases (compared to the right) when generating creative ideas (Zhou et al., 2018). This finding argues for the relevance of executive top-down control processes to reach creative performance outcomes (Gonen-Yaacovi et al., 2013; for behavioral results, see Edl et al., 2014; Rominger et al., 2017; Rominger, Papousek, Weiss, et al., 2018; Zabelina et al., 2012). Furthermore, the complex activation pattern also indicated higher right-hemispheric alpha power activation at temporal, parietal, and occipital sites (compared to the left hemisphere). This lateralization effect was more pronounced during the production of more creative ideas. This observation is in some accordance with neurophysiological creativity research investigating the serial order effect during creative ideation, which describes a decrease of the number of generated ideas, while the mean originality of ideas increases (e.g., Beaty & Silvia, 2012). These EEG studies indicated the involvement of frontal and parietal alpha power (Agnoli et al., 2020; Wang et al., 2017). Interestingly, Agnoli et al. (2020) reported that right parietal alpha power increased with the number of responses and (frontal) left-hemispheric alpha power could predict response originality. However, at a closer look at the neuronal activation pattern during the generation of one single idea, as we did in this study, especially the right parietal areas seem important for increased idea quality.

However, this research is not without limitations. First, we only applied the AU-task to study the neurophysiology of creative idea generation. Therefore, the within-person findings should be replicated with additional creativity tasks attempting to assess more real-world creative behavior such as creative ideation in soccer (Fink et al., 2019), in the affective context (Fink et al., 2017, for overviews see Fink, Perchtold, & Rominger, 2018; Perchtold-Stefan et al., in press), in humor (Perchtold-Stefan et al., 2020), in musical improvisation (Lopata et al., 2017), in drawing (Rominger, Papousek, Perchtold, et al., 2018), and in designing (Jia et al., 2021; Jia & Zeng, 2021). Nevertheless, the AU-task is often used in creativity research and therefore constitutes a promising task to investigate intra-individual brain activation patterns associated with creative idea generation in more detail. Second, although much theoretical and empirical effort was put into the role of higher order cognitive functioning during creative idea generation (e.g., memory and executive control; Benedek & Fink, 2019) much less attention was spent to investigate lower-level processes that might also contribute to complex creative processes (e.g., feelings of insight; Yu et al., 2022). For example, Rominger et al. (2021) indicated that the integration of perceptual information is important for creative task performance (e.g., in soccer decision-making situations; see also Fink et al., 2019). Third, some participants might have solved items of the AU-task via the recall of original solutions (Benedek, Jauk, et al., 2014). Although, memory processes are important ingredients of creative ideation (Gilhooly et al., 2007), simply recalling original solutions should not have strongly influenced the present study results since participants did not work on the AU-task before.

Fourth, the applied coherence measure did not control for zero-lag phase-relations such as the phase locking index (PLI) and the weighted phase locking index (wdPLI; Hardmeier et al., 2014). Nevertheless, the task-related design as well as the within-subjects design should attenuate the effects of spurious volume condition on the reported interaction effects since volume conduction during the reference period and activation period, as well as during producing more vs. less creative ideas should be similar (Höller et al., 2017). This is even more compelling since the number of available epochs as well as the alpha frequency are both associated with a reliable connectivity estimate (Haartsen et al., 2020; Hardmeier et al., 2014; Höller et al., 2017). Fifth, it should be noted that the direct link between an electrode and a brain region is tenuous, and references to specific brain regions should be taken with caution till a replication with higher-density and source localization. Finally, the analysis did not include the midline electrodes, which should be considered in future replication studies.

Nevertheless, the present study was able to indicate that the technological development might allow to assess creative ideation and the associated brain activation in more naturalistic situations (see, e.g., De Vos et al., 2014; Gramann et al., 2014; Wascher et al., 2014 for the assessment of more general cognitions). Therefore, modern creativity research can target a mobile assessment of brain activation during creative idea generation to increase ecological validity and generalizability of findings (Kranczioch et al., 2014; see e.g., Jia & Zeng, 2021). Future studies might combine portable (smartphone) EEG systems (see e.g., Stopczynski et al., 2014; Williams et al., 2019) with smartphone apps, which are developed to randomly prompt participants to find creative uses of everyday objects (Rominger, Fink, et al., in

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press). This might allow to study contextual factors of the creative process leading to more vs. less creative ideas, which constitutes an often neglected but important target of creativity research (Rominger, Schwerdtfeger, et al., in press).

In this study, we used a portable EEG device with dry electrodes to go one little step into this direction (i.e., DSI-24, Wearable Sensing; see Soufineyestani et al., 2020). Although the application of a mobile EEG system with dry electrodes was associated with low-quality EEG signals within a considerable number of participants, we were able to show that the neurophysiological activation during creative ideation could be studied in less controlled settings (for mobile EEG in clinical settings see, Lau-Zhu et al., 2019; Williams et al., 2019). At the current stage of development, the portable EEG approach could be used to assess the complex pattern of neurophysiological activation during creative ideation, such as executive functioning and internal attention demands (Benedek & Fink, 2019), in samples, which would not (easily) visit our laboratories such as clinically relevant samples (e.g., suffering from chronic pain; see e.g., Gubler et al., 2022), people at work, or students at school. The observation that the mean of high creative ideas of most people was higher than the mean of less creative ideas of most other people (see supplemental Figure 1) further underlines the feasibility of this within-subjects approach and indicates that originality differences between people might not strongly affect the study results.

Conclusion

To sum up, this study indicated a specific brain activation pattern associated with more creative ideas, arguing for increased internal attention and sensory top-down control. This complements the available evidence of neuroscience of creativity from predominately between-subjects design studies with findings from a within-subjects study. In line with the literature, we showed that specifically more creative ideas go along with (1) increased right parietal alpha power and (2) increased frontal-parietal/occipital coupling. This specific pattern of brain activation is consistent with the assumption that executive top-down control processes and internal attention are important ingredients to come up with more original ideas (Benedek & Fink, 2019).

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Highlights

Task related power (TRP) is the power-change from reference to activation interval.

More creative ideas show higher right parietal upper alpha TRP compared to left.

Greater frontal-posterior coupling was linked to more than less creative ideas.

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