Functional brain activation patterns of creative metacognitive monitoring

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1. Introduction

The neuronal underpinnings of creative ideation have been studied since the early work of Martindale and Hasenfus (1978) and since then, neuroscientific creativity research has been continuously growing (Benedek et al., in press). By now, the vast majority of neuroscience studies on creative ideation has focused on idea generation and investigated basic cognitive functions relevant for creative performance (e.g., originality; Fink and Benedek, 2014; Pidgeon et al., 2016; Stevens and Zabelina, 2019). However, the creative ideation process might be characterized by more than idea generation, as many theoretical models also consider idea evaluation relevant for the production of creative and original ideas (Benedek and Jauk, 2018; Finke et al., 1996; Kleinninz et al., 2019; Lloyd-Cox et al., 2022). Following prominent dual-process models of creative ideation, creative ideas arise from the interplay of generative and evaluative phases which refer to divergent and convergent modes of thinking (Sowden et al., 2015). Although the brain activation patterns during idea evaluation have been investigated before (e.g., Ellamil et al., 2012; Mayseless et al., 2014; Rominger et al., 2020), available work has not yet considered the accuracy of this evaluative process, which may provide crucial insights into the neurophysiological correlates underlying metacognitive performance in creative ideation.

Creative metacognitive monitoring represents the ability to accurately evaluate the quality of own ideas during idea generation. To the best of our knowledge, this study presents the first EEG investigation of creative metacognitive monitoring in the brain, using data, of 100 participants, who generated single, original uses of common objects (alternate uses task). After each response, participants subjectively rated the creative quality of their idea. Additionally, five independent external judges rated the creative quality of all ideas. The correspondence between the subjective and the external performance ratings served as a measure of monitoring accuracy. We applied a generalized linear mixed effects model to investigate effects of creative metacognitive monitoring and creative potential on EEG activity in the alpha band at idea and person level. Participants with both higher monitoring skills and higher creative potential showed stronger alpha power decreases at parietal/occipital sites during creative idea generation and evaluation. Interestingly, only more creative people with lower metacognitive monitoring skills showed the expected alpha power increases at parietal/occipital sites during both phases. Furthermore, metacognitive monitoring skills were associated with lower frontal and temporal/central alpha power during idea evaluation (compared to generation) at the person level. This pattern of findings seems to suggest that less internal attention, less memory load, and increased sensory processing are associated with more effective and accurate monitoring of the creative process. This study sheds first light on the brain mechanisms underlying the interplay of creative metacognitive monitoring skills and creative potential.
convergent mode of thinking that complement more divergent, generative processes. Metacognitive monitoring is relevant for solving creative tasks more effectively by enabling more informed decisions (e.g., whether to report, elaborate or discard candidate ideas), and thus supporting metacognitive control (Finke et al., 1996; Jia et al., 2019; Kaufman et al., 2016; Kaufman and Beghetto, 2013). But how well can people perceive the quality of their own ideas and decide if these ideas are good or bad?

Silvia (2008) reported that people are well able to judge the creative value of their own ideas (see also Benedek et al., 2016; Grohman et al., 2006; Kaufman et al., 2016; Rominger et al., in press; Rominger et al., 2022a). Importantly, the accuracy of creative idea evaluation shows meaningful interindividual (Level 2) and intraindividual (Level 1) variation. Lucas and Nordgren (2020) found that the correspondence between subjective and external originality ratings decreased as participants spent more time on the task. Sidi et al. (2020) found a disassociation between subjective and external originality ratings after false feedbacks. Furthermore, a cluster analysis presented three separate groups in terms of creative metacognitive monitoring: unskilled and unaware, skilled and unaware, and unskilled but aware people (Urban and Urban, 2021). Kravowski et al. (2020) reported that intelligence moderated the relation between self- and experts’ assessment of creative performance. Therefore, in the present study, we differentiated creative metacognitive monitoring skills (Level 2) and performance (Level 1) and hypothesized that creative metacognitive monitoring does not only take place when people explicitly engage in the evaluation process but also during creative idea generation (Guo et al., 2022; Kleinmintz et al., 2019; Sidi et al., 2020). Consequently, variations in creative metacognitive monitoring (at Level 1 and Level 2) should be associated with functional brain activation patterns during both creative idea generation and idea evaluation. Furthermore, creative metacognitive monitoring performance represents a behavioral indicator of the correspondence between the outcomes of the generative and evaluative processes, which are both essential for creative ideation. But which indicator of brain activation should be investigated to study the neurophysiology of creative metacognitive monitoring?

Available EEG research has employed a broad range of creative ideation task adaptations (Benedek et al., 2019; for an update see Benedek et al., in press), which showed a robust association of task related power (TRP; Pfurtscheller, 1999) in the alpha band with the creative ideation process (Fink and Benedek, 2014). First evidence suggests that this relationship also extend to the process of idea evaluation (Rominger et al., 2018). TRP refers to the change of alpha power from a phase of reference to a phase of creative idea generation (or evaluation). The cognitive meaning of TRP in the alpha band depends on the location of the observed power changes (as well as the specific creativity task). (1) Frontal alpha power increases during divergent thinking might argue for increased executive top-down control (Fink et al., 2017). (2) Increases of alpha power at (right) parietal and occipital sites were interpreted as increased internal attention and inhibition of external sensory information (Benedek et al., 2014; Rominger et al., 2019b), for overviews see Benedek, 2018; Fink and Benedek, 2014). (3) Alpha power changes at temporal sites indicate memory and association processes (Luft et al., 2018; Perchtold-Stefan et al., 2020). Taken together, relevant findings point to the involvement of cognitive control, attention, and memory (associative) processes during creative ideation (Benedek and Fink, 2019) and idea evaluation/elaboration (Rominger et al., 2020). Due to the specificity of alpha power changes (Fink and Benedek, 2019), this frequency band seems a promising first target to investigate the neurophysiology for creative metacognitive monitoring. Still, so far it is unknown to what extent alpha power reflects cognitive versus metacognitive processes as they are typically intimately coupled in creative ideation (Kleinmintz et al., 2019; Lloyd-Cox et al., 2022; Rominger et al., 2019b).

Although neuroscientific creativity research has not systematically investigated creative metacognition to date, metacognitive accuracy has been studied in other domains by means of neurophysiological methods. Fleming et al. (2010), for example, showed a significant association between monitoring skills (introspection of self-performance in a visual detection task) and the gray matter in the anterior prefrontal cortex. This association (independent from task performance) indicates the important role of executive control processes for metacognition (Fox and Christoff, 2014; Jia et al., 2019; Rouault et al., 2018).

In order to investigate the neurophysiological basis of creative metacognitive monitoring for the very first time (to the best of our knowledge), we reanalyzed a published data set (Rominger et al., 2019b), which allowed us to quantify participants’ monitoring accuracy of the creative process by calculating the correspondence between subjective and external ratings (Schraw, 2009). In this study, participants produced single, original ideas across multiple alternate uses items. We assessed EEG-brain activation during creative idea generation. After idea generation, participants evaluated the creative quality of the idea (i.e., subjective ratings), which was also recorded by means of EEG. We calculated the (relative) correspondence between subjective ratings and external ratings (assessed via five external raters using consensual originality ratings) by subtracting subjective and external performance ratings for each single creative idea as the measure of participants’ metacognitive monitoring performance. The aggregation across ideas (per person) served as a measure of participants’ metacognitive monitoring skill (e.g., Fleming et al., 2010; Garfininkel et al., 2015; Rouault et al., 2018; Schraw, 2009).

The examination of EEG data on a trial-by-trial basis strongly asks for linear mixed-effects analysis, which allows to analyze within-person effects (Level 1) and between-person effects (Level 2) on the observed brain activation pattern. Based on available study findings, (1) we hypothesized that individual differences in creative metacognitive monitoring (i.e., evaluation skills) might be associated with a specific brain activation pattern in the alpha band reflecting a convergent mode of thinking in the creative ideation process. (2) We further hypothesized that this pattern might be moderated by individual differences in creative ideation performance (i.e., resulting in different brain activation patterns in people who are creative but unaware vs. creative and aware; Urban and Urban, 2021). (3) We expected that the activation pattern should be distinguishable during both creative idea generation (more divergent mode of thinking) and idea evaluation (more convergent mode of thinking). Finally, (4) this specific pattern (idea generation vs. idea evaluation) could be further moderated by individual differences in creative metacognitive monitoring (i.e., evaluation skills).

2. Methods

2.1. Participants

The total sample consisted of 102 participants. Two participants were excluded from the analyses. One participant showed no variance in subjective ratings and the subjective ratings of one participant were lost due to technical problems. The final sample of 100 participants (44 men and 56 women) had an average age of 23.07 (SD = 3.35; min = 18, max = 33). Based on the Monte Carlo Simulation study of Arend and Schafer (2019), who provide information on power analyses of hierarchically structured data, 100 participants should be sufficient to detect medium between-person and cross-level interaction effects. All participants were right-handed (assessed by a standardized hand skill test; Steingruber, 2010), and were requested to refrain from alcohol for 12 h and from coffee and other stimulating beverages for 2 h prior to their lab appointment, and to come to the session well rested. The study was approved by the authorized ethics committee of the university of Graz and written informed consent was obtained from each participant.

2.2. Creative thinking task

In the alternate uses task (AUT; Guilford, 1967) participants had to
generate one use for an everyday object that was as original as possible. We applied a single answer (best idea) and self-paced AUT version, which was followed by an evaluation period asking participants to rate the creative quality of their idea. This single idea approach allows the calculation of a relative agreement between external and subjective ratings for each single idea (i.e., creative monitoring accuracy). The AUT started with a white cross (10 s; reference period) followed by a picture of a common everyday object, which indicated the beginning of the creative ideation period. Participants had to press the idea button (Fink et al., 2007) as soon as they decided on their best possible idea (15 s max. response time). Then, participants evaluated the creative quality of their idea on a six-point Likert scale (max. 4 s response time; from 1 “low quality” to 6 “very high quality”). At the end of each trial, participants briefly vocalized their best idea (10 s), which was recorded and then transcribed for analysis (see Fig. 1). The 16 AUT items (e.g., book, umbrella, brick, key) were presented in randomized order. Since this paradigm did not have a forced answer design, participants generated a total of 1511 ideas (94.4% response rate) and subjectively rated 1421 of their ideas (88.8%). The multi-level approach is well suited to handle this small amount of missing data.

2.2.1. Quantification of creative performance (Level 1) and creative potential (Level 2)
Five independent judges provided the external ratings for originality of the produced ideas on a four-point Likert scale ranging from “not original” (1) to “very original” (4). This procedure is a common approach in creativity research (cf. Consensual Assessment Technique; Amabile, 1982). The external originality ratings showed good interrater reliability (ICC (2, k) = 0.71). All ratings were averaged across the five raters resulting in one originality score for each single idea of a participant (i.e., creative performance, Level 1). Originality scores were aggregated across trials for each participant for analyses of between-person variance (Level 2) which provides a measure of creative potential.

2.2.2. Quantification of creative metacognitive monitoring performance (Level 1) and monitoring skill (Level 2)
Creative metacognitive monitoring was assessed by the correspondence between subjective and external ratings of originality at item and participant level (Fleming and Lau, 2014; Schraw, 2009). First, all subjective (ci) and external (pi) originality ratings were z-transformed within each participant. Then a modification of the formula of Schraw (2009) was applied to assess the correspondence between subjective and consensus ratings, as a measure of relative correspondence (Accuracy Index = \((zc_i - sp_i)^2^{*}(-1)\)). Higher (less negative) scores indicate higher monitoring accuracy. This approach allows to estimate metacognitive monitoring performance for each single trial (Level 1), as well as metacognitive monitoring skills for each participant (i.e., aggregated over trials; Level 2). The aggregated creative metacognitive skill showed a substantial correlation with the Pearson correlation between external and subjective origination ratings within each single person of \(r = 0.96\) (i.e., correlation with criterion, see e.g., Garfinkel et al., 2015; Guo et al., 2022). This indicates that the result of the applied formula is in high accordance with the correlation approach to assess relative monitoring accuracy (Schraw, 2009; Sidi et al., 2020).

2.3. EEG recordings and analysis
The EEG was recorded in a separate and quiet room via 19 electrodes (10–20 system; 500 Hz sampling rate; Brainvision BrainAmp Research Amplifier, Brain Products™). The ground electrode was located on the forehead, the reference electrode on the nose. Vertical and horizontal electrooculograms were assessed with two bipolar channels for horizontal and vertical eye movements. All electrode impedances were kept below 5 kΩ.

The g.BSanalyzr software (g.tec™, Graz, Austria) was used to preprocess data by removing drifts and low pass filtering of 50 Hz, to manually check the resulting signal for artifacts. Similar to Rominger et al. (2019b), we calculated the band power values (μV²) by squaring the filtered EEG signals (8–12 Hz; FFT-filter (FIR, fft function from MATLAB) with a window size of 100 samples and an overlap of 99 samples). EEG-data containing artifacts such as eye-blinks, eye-movements, or muscle tension were manually skipped from further analyses (in the time domain). Therefore, only band power values from artifact free time-intervals were averaged by means of the median. For the TRP analyses, the 8 s interval from 1 s after onset of the fixation cross until 1 s before its offset served as the reference interval, the period starting 500 ms after stimulus onset until 500 ms before the idea button was pressed served as the activation interval 1, and 250 ms after subjective confidence rating onset and 250 ms before finishing the rating served activation interval 2 (i.e., idea evaluation; Fig. 1). We used 250 ms for subjective ratings due to faster response times for subjective ratings (max. 4 sec) in contrast to the idea button press (max. 15 sec) during creative idea generation. TRP scores for each single trial j were quantified for alpha power for an electrode i by subtracting the log-transformed power of the reference period (\(P_{oi\_reference}\)) from that of the activation period (\(P_{oi\_activation}\); i.e., during creative idea generation and subjective rating of idea quality), according to the formula: TRP = (\(log(P_{oi\_activation})\) – \(log(P_{oi\_reference})\)). Positive values indicate increases of power from the reference to the activation period (Pfurtscheller and Lopes da Silva, 1999).

Then, valid trials were selected based on two requirements. (1)
Sufficient available EEG data per duration was defined with at least 750 ms for the ideation periods, at least 500 ms for the evaluation periods, and a minimum of 1000 ms artifact-free data for the reference periods (2) All behavioral trial data (i.e., external and subjective ratings). were available to calculate metacognitive monitoring performance per trial. Considering both criteria, we obtained $M = 13.04$ (SD = 2.78) valid trials during idea generation creative ideation and $M = 12.82$ (SD = 2.64) during idea evaluation.

For all statistical analyses, electrodes of relevant cortical sites per hemisphere were averaged. This procedure resulted in three separable cortical sites, which were indicated to be relevant for creative ideation (Agnoli et al., 2020; Rominger et al., 2020). We averaged the frontal areas (left: Fp1, F3, F7; right: Fp2, F4, F8), temporal/central areas (left: C3, T7; right: C4, T8), and parietal/occipital areas (left: F3, P8, O1; right: P4, P8, O2). Since we were interested in lateralized effects, all midline electrodes were excluded from further statistical analyses.

2.4. Statistical analysis

The advantages offered by linear mixed-effects analysis are the possibility to control for the random effects of participants (and random slopes of the trial number) and that it is robust for a varying amount of available data per person. To investigate the behavioral association between subjective and external originality ratings, we calculated a linear mixed-effects model with externally rated originality as dependent variable, subjective ratings at Level 1 (group mean centered) and Level 2 (grand mean centered) as continuous fixed factor, and participant and trial number as random factors. We calculated the group mean centered subjective rating scores by subtracting the average score of each participant from the subjective rating of each single idea and the grand mean centered scores by subtracting the mean of all answers of all participants from each single mean score of a participant (Finch et al., 2019). To evaluate how creative metacognitive monitoring depends on subjective and external ratings of ideas, we calculated a linear mixed-effects model with creative metacognitive monitoring as dependent variable and subjective as well as external originality ratings as fixed effects at Level 1 (group mean centered) and Level 2 (grand mean centered).

For neurophysiological analyses, we calculated one linear mixed-effects model to investigate the impact of creative metacognitive monitoring and originality (at Level 1 and Level 2) on the TRP during creative idea generation and idea evaluation. The TRP changes during creative idea generation and evaluation served as dependent variable and PROCESS (idea generation, idea evaluation), AREA (three regions in each hemisphere; frontal areas served as reference), and HEMISPHERE (left, right) served as factorized variables. The grand mean centered creative metacognitive monitoring skill (Level 2) and the group mean centered monitoring performance (Level 1) as well as the grand mean originality scores (Level 2; creative potential) and the group mean centered creative performance (Level 1) were entered as continuous fixed effects. Participants (and trial number) served as random effects. All possible combinations of these factors were entered as interaction terms into the model. In case of significant interactions, simple slope analyses were conducted. A significance level of $p < .05$ (two-tailed) was used for all analyses, which were calculated with R (version 3.4.2; R Core Team, 2021) by applying the nlme package (Pinheiro et al., 2018) and the reghelper package to calculate simple slopes (Hughes and Beiner, 2021).

Finally, we conducted sensitivity analyses to assess the robustness of the findings, specifically in the alpha band. We calculated the very same linear mixed-effects model for the adjacent frequency bands of theta (4–8 Hz) and beta (12–30 Hz).

3. Results

3.1. Behavioral results

The subjective originality ratings at Level 1 predicted the external originality ratings ($t(1320) = 10.902, p < .001$), indicating that participants were able to judge the creative value of their ideas during each single trial with reasonable accuracy (see Table 1). The subjective ratings at Level 2 did not predict the external originality of ideas ($t(98) = 0.588, p = .558$), suggesting that interindividual differences in the level of subjective ratings of own ideas do not covary with interindividual differences in creative potential – that is more creative people do not generally give higher ratings.

The second behavioral multi-level analysis examined trial- and person-level predictors of metacognitive monitoring (see Table 2). At Level 1, lower externally rated creativity of responses ($t(1319) = −5.236, p < .001$), but not subjective ratings, predicted higher metacognitive monitoring performance. At Level 2, higher subjective ratings ($t(97) = 2.493, p = .014$), but not externally rated creative potential predicted higher metacognitive monitoring skill. This pattern of findings suggests that metacognitive monitoring was higher in less creative trials as well as for people who generally gave higher subjective ratings, which is consistent with the notion that people often underestimate the creativity of responses, but less so for less creative ideas and for people showing a less negative rating bias (Benedek et al., 2016; Ceb et al., 2021).

3.2. EEG results

All EEG results were derived from one comprehensive multi-level model (see Table 3). We start by describing general findings across tasks processes (idea generation and evaluation), before moving on to process-specific analyses. The null model indicated that 28% of total variance in TRP was due to between-person variance (Level 2). This leaves up to 72% of variance in TRP due to within-person.

3.2.1. Brain activation during creative ideation and idea evaluation as a function of position and hemisphere

The TRP was lower at temporal/central ($b = −0.148, t(15,228) = −13.814, p < .001$) and parietal/occipital areas ($b = −0.231, t(15,228) = −21.525, p < .001$) compared to frontal areas. Furthermore, temporal/central sites showed higher TRP compared to parietal/occipital areas ($b = 0.083, t(15,228) = 7.675, p < .001$). There was no significant

| Parameter | Estimatea (SE) | beta | df | t | p |
|-----------|----------------|------|----|---|---|
| Intercept | 2.180 (0.023)  |      | 1320 | 96.785 | .001 |
| LEVEL 2   |                |      |     |   |   |
| Subjective originality rating (grand mean centered) | 0.017 (0.029) | .025 | 98  | 0.588 | .558 |
| LEVEL 1   |                |      |     |   |   |
| Subjective originality rating (grand mean centered) | 0.157 (0.014) | .256 | 1320 | 10.902 | .001 |
| Random effects | Proportion of variance | | | | |
| Participant (intercept) | 0.294% | 0.218 |
| Trial number (slope) | 0.81% | 0.006 |
| Residual | 69.85% | 0.519 |

N = 100 with 1421 measurements. Note. The model includes a random intercept (trial number within subject). $DF$ = degrees of freedom; $SE$ = standard error. a Estimates are unstandardized partial regression coefficients. b Estimates are standardized partial regression coefficients after z-standardization of all fixed continuous predictors and the criterion (i.e., originality; for a similar procedure, see Benedek et al., 2021).
suggest that creative potential significantly moderated the effects of monitoring skills (b = .076, \( p < .001 \)). Furthermore, an increase in alpha power at parietal/occipital sites in people showing higher creative potential (Level 2) was significant (b = .009, \( p < .001 \)). Follow up simple slope-analyses showed that metacognitive monitoring skills negatively associated with alpha power at parietal/occipital sites in people showing lower creative potential (b = .042, \( p = .669 \); see Fig. 2). Taken together, these results suggest that creative potential significantly moderated the effects of monitoring skills on parietal/occipital TRP changes such that with increasing levels of creativity, TRP became weaker as metacognitive monitoring skills increased.

The interaction between monitoring skills (Level 2) x monitoring performance (Level 1) x creative potential (Level 2) was also significant (b = .174, \( t_{(596)} = 2.354, \ p = .021 \)). Simple slope analyses showed increasing TRP with increasing creative potential in people with lower monitoring skills, especially when showing low metacognitive monitoring performance at Level 1 (b = 0.254, \( t_{(96)} = 2.354, \ p = .021 \)). Finally, TRP decreased with monitoring skills in people with higher

| Parameter                      | Estimatea (SE) | \( \beta \)  | df | t    | p     |
|-------------------------------|----------------|--------------|----|------|-------|
| Intercept                     | -1.346 (0.05)  |              | 1319 | -24.854 | < .001 |
| LEVEL 2                       |                |              |     |      |       |
| Subjective originality rating (grand mean centered) | 0.174 (0.070) | .072         | 97  | 2.493 | .014  |
| Creative potential            |                |              |     |      |       |
| (grand mean centered)         | 0.047 (0.251)  | .006         | 97  | 0.188 | .851  |
| Creative performance          |                |              |     |      |       |
| (group mean centered)         | -0.499 (0.095) | -.137        | 1319 | -5.236 | < .001 |
| Random effects                |                |              |     |      |       |
| Participant (intercept)       | 26.09%         | 0.653        |     |      |       |
| Trial number (slope)          | 2.36%          | 0.059        |     | -.930 |       |
| Residual                      | 71.55%         | 1.791        |     |      |       |

N = 100 with 1421 measurements. Note. The model includes a random intercept (trial number within subject). \( \phi = \text{degrees of freedom}; \ SE = \text{standard error.} \) Estimates are unstandardized partial regression coefficients. b Estimates are standardized partial regression coefficients after z-standardization of all fixed continuous predictors and the criterion (i.e., monitoring performance).

TRP difference between the right and left hemisphere (b = 0.011, \( t_{(15,228)} = 1.019, \ p = .308 \). However, a significant interaction between hemisphere and temporal/central position was observed (b = 0.053, \( t_{(15,228)} = 3.528, \ p < .001 \). Post hoc simple slope-analyses indicated that right hemispheric temporal/central alpha power was higher compared to the TRP in the left hemisphere (b = 0.045, \( t_{(8289)} = 5.148, \ p < .001 \).

3.2.2. Effects of creative metacognitive monitoring and creative potential on TRP during creative idea generation and evaluation

The interaction POSITION with creative metacognitive monitoring at Level 2 showed a significant effect for parietal/occipital sites (b = -0.060, \( t_{(15,228)} = -2.976, \ p = .003 \). Post hoc simple slope-analyses were conducted by changing reference levels for position (frontal vs. parietal/occipital) and monitoring skills at Level 2 (+1 SD). This procedure did not indicate further significant results. Furthermore, the interaction POSITION with monitoring skills (Level 2) and creative potential (Level 2) was significant (b = -0.351, \( t_{(15,228)} = -3.746, \ p < .001 \). Follow up simple slope analyses showed that metacognitive monitoring skills were negatively associated with alpha power at parietal/occipital sites in people showing higher creative potential (b = -0.076, \( t_{(96)} = -2.542, \ p = .013 \; \text{see Fig. 2}). This effect was absent in people with lower creative potential (b = 0.005, \( t_{(96)} = 0.135, \ p = .893 \)). Furthermore, an increase in alpha power at parietal/occipital sites was linked to an increase in creative potential in people with lower levels of monitoring skills (b = 0.367, \( t_{(96)} = 3.387, \ p = .001 \). This finding was absent in people with higher monitoring skills (b = -0.043, \( t_{(96)} = -0.428, \ p = .669 \; \text{see Fig. 2}). Taken together, these results suggest that creative potential significantly moderated the effects of monitoring skills on parietal/occipital TRP changes such that with increasing levels of creativity, TRP became weaker as metacognitive monitoring skills increased.

The interaction between monitoring skills (Level 2) x monitoring performance (Level 1) x creative potential (Level 2) was also significant (b = 0.079, \( t_{(596)} = 2.005, \ p = .045 \). Simple slope analyses showed increasing TRP with increasing creative potential in people with lower monitoring skills, especially when showing low metacognitive monitoring performance at Level 1 (b = 0.254, \( t_{(96)} = 2.354, \ p = .021 \)). Finally, TRP decreased with monitoring skills in people with higher

| Parameter                      | Estimatea (SE) | \( \beta \)  | df | t    | p     |
|-------------------------------|----------------|--------------|----|------|-------|
| Intercept                     | 0.108          |              | 15,228 | 6.387   | < .001 |
| LEVEL 2                       |                |              |     |      |       |
| Monitoring skill              |                |              |     |      |       |
| (grand mean centered)         | -0.011         | -.024        | 96  | -0.330 | .742  |
| Creative potential            |                |              |     |      |       |
| (grand mean centered)         | 0.009          | .005         | 96  | 0.114  | .910  |
| Monitoring skill              | 0.002          | .006         | 96  | 0.016  | .987  |
| Creative potential            | (1.418)        |              |     |      |       |

N = 100 with 15,516 measurements. Note. The model includes an autoregressive term (\( \phi = -.11 \) and a random intercept (trial number within subject). \( \phi \) = \text{degrees of freedom}; \ SE = \text{standard error.} a Estimates are unstandardized partial regression coefficients. b Estimates are standardized partial regression coefficients after z-standardization of all fixed continuous predictors and the criterion (i.e., TRP).
creative potential, especially when showing low metacognitive monitoring performance at Level 1 (b = −0.114, t(96) = −2.398, p = .018).

3.2.3. Process-specific effects of creative metacognitive monitoring skills on TRP

The main effect PROCESS failed to be significant (b = −0.021, = −1.927, p = .054). However, the factor PROCESS showed an interaction with POSITION (b = 0.036, t(15,228) = 2.395, p = .017). Post hoc simple slope-analyses were conducted by changing reference levels for position (frontal vs. parietal/occipital). These analyses indicated that lower alpha power during idea evaluation compared to idea generation at temporal/central sites (b = −0.043, t(7653) = −5.752, p < .001) and at frontal sites (b = −0.029, t(7653) = −3.958, p < .001; see Fig. 2-A). The interaction of PROCESS and monitoring skills (Level 2) was significant (b = −0.054, t(15,228) = −2.636, p = .008), which was further moderated by the factor POSITION (PROCESS x POSITION x monitoring skills (Level 2), b = 0.071, t(15,228) = 2.448, p = .014). To better understand this three-way interaction, we conducted post-hoc simple slope-analyses, which indicated decreased TRP at frontal (b = −0.047, t(7648) = −4.231, p < .001) and temporal/central sites (b = −0.055, t(7648) = −4.931, p < .001) during idea evaluation (compared to idea generation) in people with higher monitoring skills (Fig. 3-B). This was also observed for temporal/central sites (b = −0.031, t(7648) = −2.788, p = .005), when monitoring skills were low, but virtually absent for frontal positions (b = −0.006, t(7648) = −0.507, p = .612). Furthermore, metacognitive monitoring skills predicted lower TRP in frontal areas during the idea evaluation process at a potentially meaningful trend level (b = −0.057, t(98) = −1.861, p = .066; see Fig. 3-C). Process-specific brain activation was not further moderated by neither creative potential, creative performance, nor monitoring performance. For all relevant effects in the alpha band, see Table 3.

No further effect involving metacognitive monitoring and creative performance/skill at Level 1 or Level 2 was significant for the alpha band. Higher scores in panel C (yellow) represent higher TRP in the alpha band during idea generation vs. idea evaluation.

3.2.4. Sensitivity analyses in the beta band and theta band

Two analogous analyses with TRP in the theta band (4–8 Hz) and the beta band (12–30 Hz) were conducted to indicate the sensitivity of alpha band findings. We found most significant effects of metacognitive monitoring and creative performance/skill at Level 1 and Level 2 in the alpha band (see Supplemental Table 1 and Table 2). However, the interaction effect PROCESS x monitoring skills (Level 2) was mirrored in the beta band (b = −0.026, t(15,228) = −2.298, p = .022; see Supplemental Table 1).

Furthermore, the additional analyses in the beta and theta band also showed some specific findings. For the beta band, the analysis indicated a significant interaction PROCESS x creative performance (Level 1) and creative potential (Level 2) x creative performance (Level 1; see Supplemental Table 1). For the theta band, the analysis showed a significant interaction PROCESS x creative potential (Level 2) as well as monitoring skills (Level 2) x creative potential (Level 2; see Supplemental Table 2).

Since the alpha band was of central interest in this study, we did not further elaborate on these additional band-specific effects.

4. Discussion

The creative ideation process is characterized by generative and evaluative processes (Benedek and Jauk, 2018; Finke et al., 1996), and we are only beginning to understand brain activation patterns associated with these stages (Kleinmintz et al., 2019). However, to date the accuracy of the evaluative processes has not been considered when studying evaluative and metacognitive functions involved in the creative ideation process (Kleinmintz et al., 2019). By indexing how well people can evaluate the creative quality of their own ideas we were able to explore brain activation patterns during idea generation and idea evaluation, which were associated with creative metacognitive monitoring at the idea and the person level.

Specifically, participants with a higher creative potential showed stronger alpha TRP decreases at parietal/occipital brain regions (compared to frontal areas) as metacognitive monitoring skills increased. In line with creativity research, creative potential was related to higher TRP in the alpha band, yet only when monitoring skills were low (Fink and Benedek, 2014; Stevens and Zabelina, 2019). Furthermore, participants with higher monitoring skills showed lower TRP at frontal and temporal/central positions during creative idea evaluation compared to idea generation, which argues for reduced cognitive control functions or lower (working) memory load during idea evaluation (vs. generation). This complex pattern of findings was not observed in the beta band nor in the theta band. This indicates some specificity of
TRP changes in the alpha band for the creative ideation and evaluation process and its association with performance measures of creative metacognitive monitoring and creative ideation.

Although most studies reported the importance of alpha power for the creative idea generation process (Fink and Benedek, 2014; Stevens and Zabelina, 2019), even showing good classification performance (Stevens and Zabelina, 2020), to the best of our knowledge no study to date investigated brain functions during creative idea generation and evaluation by taking the accuracy of the evaluative process into account. Both, the process of idea generation and the process of idea evaluation were associated with pronounced parietal/occipital alpha power decreases, arguing for active visual processing, but creative metacognitive monitoring skills and participants’ creative potential moderated this finding. Participants with a higher creative potential and higher
monitoring skills (creative and aware) showed stronger parietal/occipital alpha power decreases compared to people with lower monitoring skills (creative but unaware). Since creative metacognitive monitoring skill was independent from creative potential, this neurophysiological finding suggests that people can achieve higher creative performance by means of largely different neurocognitive strategies, associated with parietal/occipital power decreases as creative metacognitive accuracy increases. In line with previous research, this decrease at parietal/occipital sites with increased monitoring skills might argue for reduced internal attention and increased stimulus-dependent visual processing during idea generation and idea evaluation, which might further indicate that these participants put more effort in the partly visual task (Benedek, 2018). However, when monitoring skills were low, creative potential showed the expected positive association with TRP increases at parietal/occipital sites, which is nicely in accordance with creativity literature arguing for increased internal attention and working memory load during creative ideation in order to enable stimulus-independent, self-generative thought processes supporting imagination (Benedek, 2019). This interpretation is further underlined by the interaction between monitoring skills, creative potential, and metacognitive monitoring performance at Level 1. Alpha power increases were most pronounced in more creative people with lower monitoring skills precisely in those trials in which they demonstrated weak monitoring performances. As first evidenced by brain activation, this points to the intricate interaction between creative performance and metacognitive monitoring at an intra- and interindividual level.

Since these complex interactions seem to hold for idea generation and evaluation (i.e., were not moderated by the ideation stage: generation versus evaluation), it could be inferred that cognitive functions related to metacognition play a role in both generation and explicit evaluation processes (Kleinnitz et al., 2019; Lloyd-Cox et al., 2022; Rominger et al., 2018). These cognitive overlaps might be imagination, visualization, mental simulation, and monitoring of potential solutions (see e.g., Christensen and Ball, 2016, for creative evaluation). However, temporal/central alpha power decreased from idea generation to evaluation, which indicates a reduced involvement of associative and memory processes (Luft et al., 2018). Furthermore, decreased frontal alpha power during idea evaluation compared to idea generation was observed in people with higher metacognitive skills. This can be interpreted as reduced cognitive control and lower working memory load during idea evaluation in people showing better metacognitive monitoring skills (Jensen et al., 2002; Klimesch et al., 1999; Rominger et al., 2019a). Therefore, someone might speculate that people with higher monitoring skills might already inherently evaluate and control their creative ideation processes (i.e., cyclic shifts between generation and evaluation; Kleinnitz et al., 2019), which possibly reduces the need for further evaluation and control during an explicit evaluation process.

In line with Silvia (2008), we found that people are able to rate the creative value of their ideas (Benedek et al., 2016; Rominger et al., in press; Rominger et al., 2022a). As expected, participants showed good discrimination between more and less creative ideas (Sidi et al., 2020). However, in some contrast to literature, we did not find an association between the creative metacognitive monitoring skills and the creative potential (Guo et al., 2022). This null finding indicates that although creative monitoring shows a specific brain activation pattern during creative ideation, it is not strongly associated with the creative potential of a person. However, it should also be noted that the effect sizes for this association between originality and creative metacognitive accuracy are lower for alternate uses tasks compared to other divergent thinking tasks (Guo et al., 2022). Furthermore, our null finding is in some agreement with the study of Urban and Urban (2021), who showed that high creative potential can be observed with and without high creative metacognitive skills. The authors identified three separable groups: One group with high creative potential but no awareness of their potential, a group of participants who were unskilled and unaware, and a group with low creative skills and high awareness. These behavioral findings are in line with the neurocognitive findings of the present study.

In our study, those people who showed high creative potential but less metacognitive monitoring skills, exhibited stronger alpha power increases indicating internal attention, higher working memory load, and spontaneous modes of thinking in order to come up with original ideas. Those people, however, who showed better monitoring skills and higher creative potential exhibited parietal/occipital alpha power decreases, indicating stimulus dependent sensory processing and the use of more convergent modes of thinking associated with their monitoring accuracy.

This moderating effect of metacognition on brain activation associated with creative potential might suggest at least two routes to creative ideas. This is in accordance with the idea of dual process models of creative thinking (Benedek and Jauk, 2018; Kleinnitz et al., 2019). In these models, both the divergent and convergent modes of thinking are important to finally arrive at a creative and original solution (Benedek and Jauk, 2018). This assumption is further in line with the dual pathway model of creativity assuming the generation of creative output via flexibility and persistence (Oreu et al., 2008; Nijstad et al., 2010). By taking the evaluative accuracy of people into account, this study was able to investigate idea generation and idea evaluation as intimately coupled processes in creative ideation (Fox and Christoff, 2014; Kleinnitz et al., 2019). Participants’ monitoring and evaluative skills might decide which neurocognitive route is chosen (more dominantly) to come up with a creative output. However, further research is needed to replicate these findings and to investigate if contextual variables such as affect can modulate them (Kauffman and Vosburg, 2002; Mastria et al., 2019; Mueller et al., 2012; Rominger et al., 2022c).

In line with Benedek et al. (2016), we observed higher monitoring skills when subjective ratings (at Level 2) were also high (Ceb et al., 2021). This indicates that people tend to underestimate their creativity (Urban and Urban, 2021), but less so when they show less negative bias and thus give higher ratings (Benedek et al., 2016). The negative association between creative performance and monitoring performance at Level 1 seems to mirror this finding. Given that people systematically underestimate their creative output, it fits that metacognitive accuracy is lower in trials with more original ideas. Nevertheless, further research is needed to determine if and when an association between both performance measures can be observed.

4.1. Limitations

First, the idea generation and idea evaluation phases have a different time duration, which might have weakened the comparability of both phases. Furthermore, both phases included the presentation of visual stimuli, which might have affected the observed brain activation. Therefore, future studies should investigate the stability of the present findings by further parallelizing the assessment of creative idea generation and evaluation as well as by changing the visual information presented during the task.

Second, this study specifically focused on the EEG alpha band. Although this constitutes a very first step into the neuroscience of creative metacognitive monitoring, following previous work on creative ideation (Pink and Benedek, 2014; Stevens and Zabelina, 2019), future research should investigate additional sub bands such as beta and theta and their interactions with alpha in more detail. In line with this, we found performance relevant brain activation patterns in the adjacent bands of beta and theta in this study (see Supplemental Tables 1 and 2). This hints at the relevance of episodic memory processes (i.e., theta band synchronization; Klimesch, 1999) as well as top-down processes (i.e., beta synchronization; Fries, 2015) for creative metacognition. Although the applied sensitivity analyses are explorative in nature, and replications are highly warranted to arrive at stronger conclusions, the findings are in accordance with former creativity research indicating a broader range of frequency bands associated with the creative ideation process (see e.g., Agnoli et al., 2018; Bhattacharya and Petsche, 2005; Boot et al., 2018; Rominger et al., 2022a).
4.2. Conclusion

To conclude, the findings of this study provide first insights into the neuroscience of creative metacognitive monitoring, as reflected in the accuracy of evaluative processes in the creative ideation process. In accordance with our assumptions, the alpha band is sensitive for not only creative potential, but also creative monitoring accuracy. The observed interaction effect of creative potential and creative monitoring skills on the observed brain activation pattern is in accordance with the assumption that different people might use different neurocognitive routes to come up with original ideas, depending on their creative monitoring skills. Creative people, which are aware (i.e., higher monitoring skills) showed alpha power decreases at occipital areas, while creative people which are not aware of their creative potential (i.e., lower monitoring skills) showed the expected alpha power increases at these areas. This pattern suggests that metacognitive skills of a person moderate the extent of convergent and divergent thinking processes in creative ideation, consistent with assumptions of dual process models of creative cognition as well as the dual pathway model of creativity. To the best of our knowledge, this study presents first neurophysiological evidence for the involvement of metacognitive processes in creative ideation.

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Credit author statement

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.neuropsychologia.2022.108416.

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