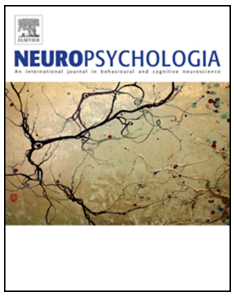

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PII: S0028-3932(23)00048-9

DOI: https://doi.org/10.1016/j.neuropsychologia.2023.108514

Reference: NSY 108514

To appear in: *Neuropsychologia*

Received Date: 26 September 2022

Revised Date: 9 February 2023

Accepted Date: 9 February 2023

Please cite this article as: Gubler, Danièle.Anne., Rominger, C., Jakob, D., Troche, S.J., How does experimentally induced pain affect creative ideation and underlying attention-related psychophysiological mechanisms?, *Neuropsychologia* (2023), doi: https://doi.org/10.1016/j.neuropsychologia.2023.108514.

CRediT author statement

Danièle A. Gubler; Conceptualization, Methodology, Software, Formal analysis, Investigation, Data Curation, Writing – Original Draft, Visualization. Christian Rominger; Methodology, Validation, Writing – Review & Editing. Denise Jakob; Formal analysis, Investigation. Stefan J. Troche; Conceptualization, Resources, Writing – Original Draft, Supervision

How does experimentally induced pain affect creative ideation and underlying attention-related psychophysiological mechanisms?

Original Article

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Conflict of interest statement

The authors have no conflicts of interest to declare.

Abstract

While the adverse effect of chronic pain on attention and more complex cognitive abilities is well documented, the findings for experimentally induced pain are inconsistent. These inconsistencies could be attributable to sufficient attentional resources and/or compensatory mechanisms in individuals with experimentally induced pain that are not observable at the behavioral level but could be revealed by psychophysiological measures such as the electroencephalography (EEG). With the current study, we aimed to investigate whether experimentally induced pain affects creative ideation in an adaptation of the Alternate Uses Task (AUT). Performance in the AUT was compared between 39 females in a pain group and 37 females in a pain-free group. While solving the task, EEG was recorded to measure the degree of internally directed attention assessed by means of task-related power (TRP) changes in the upper alpha-frequency band. The results revealed that the pain group and the pain-free group did not differ in AUT performance at the behavioral level. However, TRP increases in the upper alpha band at right (vs. left) temporal, parietal, and occipital electrode sites were significantly more pronounced in the pain group compared to the pain-free group. These results indicate that individuals in the pain group allocated more attention to internal mental processes during creative ideation than individuals in the pain-free group. The necessary inhibition of pain might have caused this additional activation so that the pain group performed similarly well on the behavioral level as the pain-free group.

Keywords: experimentally induced pain, creative ideation, internal attention, alternate uses task, task-related power changes

Introduction

Pain can be defined as "a distressing experience associated with actual or potential tissue damage with sensory, emotional, cognitive, and social components" (p. 2420; Williams & Craig, 2016). Thus, pain is not only sensory perceived but also cognitively processed and, therefore, requires attention (Eccleston & Crombez, 1999). Given that pain is such a biologically relevant signal, it is not surprising that its onset often overrides other mental demands competing for attention, interrupting current attentional engagement (Vlaeyen et al., 2016). Consistent with this rationale, several studies have observed that different types of attention are adversely affected by both chronic pain (Higgins et al., 2018; Moriarty et al., 2011) and experimentally induced pain (Attridge et al., 2016; Buhle & Wager, 2010; Gong et al., 2019; Moore et al., 2012).

However, the adverse effect of pain on attention-related performances in tests and experimental tasks could not be observed consistently (for reviews, see Gong et al., 2019; Higgins et al., 2018; Moriarty et al., 2011). These inconsistencies have been explained by different factors that can modulate the influence of pain on attention (Eccleston & Crombez, 1999). These include characteristics of pain such as novelty, intensity, predictability, and threat (Eccleston & Crombez, 1999; Moore et al., 2012). Moreover, individual differences, such as pain-related anxiety (Vlaeyen & Linton, 2012), catastrophic thinking about pain experience (Van Damme et al., 2004), emotional arousal (Rhudy & Meagher, 2001; Wiech & Tracey, 2009), or motivation (Van Damme et al., 2010), as well as environmental factors, such as task difficulty, can also moderate the degree of interruption caused by pain. Regarding task difficulty, it has been proposed that differences between individuals with and without pain only become apparent when pain and task demands exceed the limited capacity of the attentional system (Buhle & Wager, 2010). As long as the capacity of the attentional system is not exceeded, behavioral measures such as response latencies or error rates might be unaffected by pain. For this reason, some authors propose to employ electroencephalography (EEG) measures, which are more sensitive to examine the effect of pain on attention and information processing (Houlihan et al., 2004; Troche et al., 2015).

Consistent with this assumption, studies on experimentally induced pain (Troche et al., 2015) and chronic pain (Gubler, Zeiss, et al., 2022) showed that reaction times and error rates in a relatively simple auditory oddball task were unaffected by pain. In contrast, psychophysiological results revealed that both P3a and P3b amplitudes were reduced by experimentally induced and chronic pain, indicating that pain negatively affects both involuntary and voluntary attention, as evidenced by lower P3a and P3b amplitudes,

respectively. This pattern of results provides a more nuanced picture of the idea that in simple tasks, attentional resources, even when reduced by pain as indicated by the lower amplitudes, are still sufficient to complete the task without impairments at the behavioral level (Gubler et al., 2021; Troche et al., 2015).

However, once tasks require more attention than resources are available, chronic pain leads to significant impairments in performance, as has been shown in tasks on abstract thinking (Gunnarsson & Agerström, 2018), daily decision-making (Attridge, Pickering, et al., 2019), and to some extent on logical reasoning (Gunnarsson & Agerström, 2021). Most previously, also creative ideation was reported to be impaired in patients with chronic pain (Gubler, Rominger, et al., 2022). The authors additionally measured EEG activity during creative ideation. An attention-related and creativity-specific EEG pattern was less pronounced in patients with chronic pain compared to a group of healthy controls. This EEG pattern was a task-related power (TRP) increase of the upper alpha band (10-12 Hz) at the right but not at the left parietal hemisphere, and thus a hemispheric asymmetry at parietal electrode sites. Fink and Benedek (2014) as well as Stevens and Zabelina (2019), provided a detailed overview of research showing this TRP pattern is functionally associated with creative ideation. To put it in a nutshell, right posterior alpha power was repeatedly found to increase from a reference phase to a creative ideation phase (Fink et al., 2007; Jaarsveld et al., 2015). This TRP increase was reported to be more pronounced in more creative individuals compared to less creative individuals (Fink et al., 2009; Fink & Neubauer, 2008; Rominger et al., 2019) and more pronounced within individuals when they generated more creative ideas compared to less creative ones (Fink & Neubauer, 2006; Grabner et al., 2007; Rominger et al., 2022; Schwab et al., 2014). Furthermore, this TRP increase was accompanied by a hemispheric asymmetry pattern, with a more pronounced alpha power increase in the right hemisphere than in the left hemisphere (Fink et al., 2009; Rominger et al., 2019; Schwab et al., 2014).

Regarding the psychological meaning of this TRP pattern during creative ideation, it has been proposed that alpha power varies with the degree of internal attentional demands and, thus, can be associated with the extent to which attention is allocated to these internal demands (Benedek, 2018; Benedek et al., 2014). To produce an original idea, access to long-term memory must be enabled and task-irrelevant sensory input should be inhibited. Therefore, simultaneously allocating attention to stored information in memory while suppressing external information may facilitate the retrieval of this information and promote creative ideation (Benedek, 2018; Benedek et al., 2014; Fink & Benedek, 2014). Accordingly,

increased alpha power at the right parietal sites is associated with increased allocation of attention to these internal processes necessary for creative ideation (Benedek, 2018).

Of particular interest for the present purpose, the right posterior alpha power increase and the concurrent asymmetry between the hemispheres were less pronounced in patients with chronic pain than in healthy controls in the study by Gubler et al. (2022). Furthermore, this difference at the psychophysiological level explained a substantial portion of the differences between the two groups in creative ideation at the behavioral level. These findings suggest that the adverse effects of pain on attentional processes partly explain why patients with chronic pain generated less creative ideas compared to healthy controls and therefore performed less well in a more complex cognitive task that relies on a well-functioning attentional system.

However, while patients with chronic pain were found to be impaired in tasks measuring more complex cognitive abilities (Attridge, Pickering, et al., 2019; Gunnarsson & Agerström, 2018, 2021), this could not be confirmed in individuals experiencing experimentally induced pain (Agerström et al., 2017; Attridge, Keogh, et al., 2019). Thus, chronic but not experimentally induced pain seems to harm performance on more complex cognitive ability tests. This challenges the idea that experimentally induced pain represents a model for investigating the cognitive effects of chronic pain (Moore et al., 2019). As a potential explanation, patients with chronic pain often suffer from accompanying comorbidities such as fatigue, anxiety, or depression (Lerman et al., 2015; Van Damme et al., 2018) that additionally impair attention. Furthermore, experimentally induced pain is more controllable than chronic pain as it can be interrupted whenever it is no longer tolerable, making it less threatening (Agerström et al., 2017; Lier et al., 2022). Thus, individuals experiencing experimentally induced pain might be better able to focus their attention on the task at hand and suppress the pain than patients with chronic pain, resulting in fewer cognitive impairments (Attridge, Keogh, et al., 2019).

But even if performance differences cannot be observed at the behavioral level between a group experiencing pain and a group not experiencing pain, the cognitive processing might still be different when the group experiencing pain needs to compensate for the distracting effect of pain by spending more attention on processing the task, more inhibition to suppress the distraction by pain, or using other strategies. Such differences could become evident in different EEG patterns of pain and pain-free groups during the performance on cognitive tests.

Thus, proceeding from the report by Gubler et al. (2022) that chronic pain impairs creative ideation and the accompanying creativity-specific EEG pattern, we investigated in

the present study whether experimentally induced pain affects creative ideation and the accompanying EEG pattern. Given that patients suffering from chronic pain produced less original ideas compared to a pain-free control group (Gubler et al., 2022), a similar result might be expected in the present study, assuming that the attentional resources of individuals suffering from experimentally induced pain are depleted to a similar extent as those of individuals with chronic pain. In this case, less attention can be directed to internal mental processes resulting in impaired performance in a creative ideation task. However, previous studies revealed that experimentally induced pain does not necessarily impair performance on tasks requiring more complex cognitive abilities (Agerström et al., 2017; Attridge, Keogh, et al., 2019). Therefore, it is conceivable that individuals experiencing experimentally induced pain (pain group) do not differ from individuals in a pain-free group in their creative ideation performance at the behavioral level. Such a result is to be expected if the additional processing of experimentally induced pain does not deplete individuals' attentional resources and, consequently, enough attention can be allocated to the task at hand. The present study focuses on EEG activity during creative ideation to investigate this idea. More specifically, we expected that individuals without pain show the well-established pattern of alpha power increase at right posterior electrode sites and a clear asymmetry in TRP changes between the right and the left hemisphere during creative ideation (Fink & Benedek, 2014). For individuals experiencing experimentally induced pain, two patterns are conceivable: On the one hand, the increase of the right posterior alpha power and the hemispheric asymmetry might be less pronounced compared to individuals without pain. The reason for this pattern of results might be that attentional resources are severely reduced or even depleted by processing the induced pain so that less attention can be directed toward internal mental processes. On the other hand, if sufficient resources are available despite the processing of pain, the increase of right posterior alpha power and the hemispheric asymmetry might be more pronounced in individuals experiencing pain than in individuals without pain. This might be caused by the necessary inhibition of pain-related sensory input so that more attention has to be allocated to generate creative ideas.

Method

Participants

A total of 96 right-handed women not older than 34 years participated in the study. Data of 20 participants were excluded from the analyses because of poor EEG signal quality (16), because of misunderstanding the AUT instructions (3), and because of not responding to the pain induction procedure as she did not feel any pain while performing the task (1). The final

sample consisted of 76 women with a mean age of 22.8 (*SD* = 3.2, *Range* = 18-34) years. One of them finished an apprenticeship as the highest education, 52 high school, and 23 higher education. As reimbursement, psychology students could choose between credit points and 30 CHF; the other participants received 30 CHF.

All participants were instructed not to smoke cigarettes or drink caffeinated beverages one hour before the study and not to drink alcohol 24 hours before the study. All participants were informed of the study protocol and signed informed consent prior to their participation. The local ethics committee of the Faculty of Human Sciences at the University of Bern approved the study protocol (Project ID 2021-04-00001).

Instruments

Pain intensity was measured by means of a visual analog scale (VAS; Bijur et al., 2001) as a horizontal line with two endpoints representing the states "no pain" (0) to "worst pain imaginable" (10), on which participants indicated their subjective pain experience.

The Edinburgh Handedness Inventory was used to measure handedness with 11 items (Oldfield, 1971). With this inventory, participants were asked whether they described themselves as right- or left-handed and which hand they preferred for one- and/or two-handed tasks (e.g., writing or throwing). Participants were considered right-handed when they described themselves as right-handed and when they preferred the right hand in more than two-thirds of the tasks.

The mini-q was applied to assess intelligence (Baudson & Preckel, 2015). In this three-minute task, 64 sentences about symbol constellations are to be rated as correct or incorrect. Split-half reliability (r_{tt} = .98) of the mini-q and convergent validity with other measures of intelligence are high (*r* = .37 to .73; Baudson & Preckel, 2015).

Alternate Uses Task

Creative ideation was measured by an adaptation of Guilford's (1967) alternate uses task (AUT) introduced by Schwab et al. (2014). This adaptation has been applied in numerous neuroscience studies to investigate creativity and the role of internal attention as reflected in right parietal and asymmetric TRP changes (Gubler, Rominger, et al., 2022; Rominger et al., 2019, 2022; Schwab et al., 2014). The AUT was programmed with Eprime 2.0, and stimuli were presented on a computer screen (HP EliteBook 840 G2). The task consisted of 20 trials. As depicted in Figure 1, each trial began with the presentation of a white cross for 10 seconds (reference phase), followed by the stimulus presentation phase, in which a word describing an everyday object (e.g., hat, sock, umbrella) was depicted for 4 seconds. In the subsequent creative ideation phase, participants had 10 seconds to generate the most original but, at the

same time, useful idea for the respective everyday object (e.g., hat as a bird's nest, sock as a doll, and umbrella as a walking stick). This phase was symbolized by a white question mark on the computer screen. When the question mark turned from white to green, participants were supposed to express their idea aloud, which was recorded by the test administrator. The instructions explicitly stated that answers must not be given until the green question mark appeared. Before starting the actual task, the entire procedure could be rehearsed during two practice trials, and any ambiguities could be clarified with the test administrator.

The originality (creativity) of the ideas was evaluated by four well-instructed raters (two female Ph.D. students and one female and one male research assistant). Raters were instructed to rate creativity based on the usefulness as well as the uniqueness/originality of an idea. The simultaneous satisfaction of both criteria is essential for a creative idea (Diedrich et al., 2015; Runco & Jaeger, 2012). Originality could be rated on a four-point Likert scale ranging from "not creative or not useful" (1), "useful but an ordinary idea/not really creative" (2), "useful and creative" (3), to "useful and very creative/an idea mentioned by only a few participants" (4).

For each item, all answers given were listed in a separate Excel spreadsheet. Answers were then sorted alphabetically to provide a clearer overview of how many participants mentioned the same idea. For each idea, raters first evaluated whether the idea met the criterion of usefulness (if not, it was rated as not creative, regardless of its uniqueness/originality). Second, raters judged the uniqueness/originality of the idea. For example, an answer for the item sock as a piece of cloth was rated with 1 point, as a phone case with 2 points, as a bandage with 3 points, and as a tea strainer with 4 points. Inter-rater reliability for the originality ratings assessed with the intraclass correlation coefficient (ICC) was good, ICC (2,k) = .89. For each item, the scores of the four raters were averaged. A single originality score was then obtained for each participant as an average score across the twenty items. Raters did not know whether participants were in the pain or the pain-free group.

Study and Pain Induction Procedure

After participants completed demographic questions, the Edinburgh Handedness Inventory, and the mini-q, participants were randomly assigned to one of two groups by a dice roll (39 individuals in the pain group vs. 37 individuals in the pain-free group). Thermal heat stimuli were applied by a quantitative sensory testing device (TCS-II, QST Lab, Strasbourg, France, https://www.qst-lab.eu). The stimulation surface of the probe was 4.5cm^2. Pain induction was performed combined with topically applied capsaicin to avoid the risk of thermal damage to the skin by inducing heat stimuli. When applied topically, capsaicin causes

neurogenic inflammation with hyperalgesia. Thus, the pain threshold for heat stimuli is significantly reduced. According to the protocol of Lüke et al. (2020), capsaicin lowers the pain threshold from an average of 45.3 °C down to 37 °C. The capsaicin cream was applied on the left and right forearms about 2 cm above the volar wrist crease of the hand in subjects in the pain group. A wound dressing and gauze bandage were attached to enhance the effect of the cream. The exposure time of the cream was 25 minutes. For the pain-free group, a commercial moisturizer was placed on the skin to maximize the similarity of the experimental procedure in the pain and pain-free conditions.

After the exposure time (25 minutes) of the creams, pain thresholds (at how many degrees Celsius is the stimulus perceived as painful) and tolerance thresholds (at how many degrees Celsius is pain no longer tolerable) were assessed in all subjects. For this purpose, participants placed their left and right forearm on the probe, which was fixed in a holder. The baseline temperature of the probe started at 32 °C and increased at a rate of 1 °C /s. Using a remote control, participants could indicate when pain and tolerance thresholds were perceived. By pressing the remote control, the thermal stimulation was automatically interrupted, and the temperature of the probe returned to the baseline temperature of 32 °C at a speed of 170 °C/s. Pain and tolerance thresholds were measured three times per forearm, and then an average was calculated separately for each forearm. After pain and tolerance thresholds had been measured, the AUT was performed, with heat stimuli induced in the pain group during task processing. Participants were therefore instructed to alternately place their left or right forearm on the probe before each trial. Pain induction occurred throughout the trial from the reference phase to the response phase (28 seconds, see Figure 1). For each subject in the pain group, the temperature was set at 1 °C above the previously determined pain threshold per forearm. We thereby followed the protocol of Lüke et al. (2020). According to the authors, the pain threshold after capsaicin application is, on average, 37 °C and pain induction at an average of 38 °C elicits an average perceived pain intensity of 6.2 (SD = 0.8) on a VAS. As individuals quickly adapted to heat stimuli, the probe temperature increased by 1°C every 10 seconds, resulting in an average of 40 °C after 28 seconds of stimulation (duration of one trial in the AUT). The temperature was set back to the baseline temperature after each trial. As we intended to achieve an approximate pain level between 5-9 on the VAS in the pain group, perceived pain intensities were measured separately for each arm after the first two trials of the AUT and after trials 7,8,13,14,19,20 to adjust the baseline temperature level if necessary. Although the temperature was individually adjusted depending on the previously determined pain thresholds, no temperature level exceeded 45 °C in any

subject. Participants were further given the opportunity to remove their forearm from the probe at any time in case of intolerance and were explicitly instructed to do so. For comparability of the test procedure, the pain-free group was also required to place their left and right forearm on the probe, whereby a pleasant heat stimulus of 34 °C was induced during the entire interval across all trials.

Electroencephalogram Recording and Analysis

For the EEG measurement, a mobile dry-electrode EEG system (DSI 24) was used with 21 electrodes (Fp1, Fp2, Fz, F3, F4, F7, F8, Cz, C3, C4, T7, T8, Pz, P3, P4, P7, P8, O1, O2, A1, A2) arranged in accordance with the international 10-20 system. The EEG activity was recorded at a rate of 300 Hz using the DSI-STREAMER recording software. The reference electrode was Pz, which was re-referenced to earlobes (A1 + A2). The horizontal electrooculogram (EOG) was measured by two electrodes placed to the left and right of the eyes. For the vertical EOG, the electrode Fp2 and one electrode placed on the infraorbital ridge of the right eye were used.

EEG and EOG activities were analyzed using the software BrainVision Analyzer 2.2. First, the EEG signal was resampled to 256 Hz and filtered offline (0.1 to 30 Hz). The data were then corrected using the eye correction procedure of Gratton and Coles (1989) and by visual inspection of motion artifacts, eye blinks, and muscle tension. Due to poor signal quality caused by pulse artifacts or muscle tension, single channels had to be replaced by interpolation with spherical splines in 10 subjects during the recording of the AUT (similar approach see Jia et al., 2021).

Of particular interest for the present purpose was the EEG activity during the reference phase (before a new trial was presented) and the activity during the creative ideation phase. Accordingly, segments of nine seconds duration were extracted from the reference and from the creative ideation phase (0.5 seconds after the onset of the respective phase until 0.5 seconds before the end of the respective phase) for each of the 20 different trials. The 9-second segments were further divided into 17 equal 1-second segments, each with an overlap of 0.5 seconds (50%) with the previous and the following segment. In a final step of data inspection, these 1-second segments were again visually inspected for artifacts to exclude segments with poor data quality. Using a Hanning window for power estimates, all artifact-free segments were subjected to a Fast Fourier Transformation (FFT). An average score for all segments was then computed separately for the reference and creative ideation phase. For each participant, upper alpha power scores (10-12 Hz) for both phases were extracted from the FFT analysis.

Brain activity during creative ideation was determined by means of TRP changes (Pfurtscheller & da Silva, 1999). To extract TRP at an electrode [i], the log-transformed power during the reference phase (Pow_i, reference) was subtracted from the log-transformed power during the creative ideation phase (Pow_i, creative ideation). This resulted in the following formula: TRP = log(Pow_i, creative ideation) – log(Pow_i, reference), which was applied in similar creative ideation research (Fink et al., 2018; Jauk et al., 2012; Schwab et al., 2014). While negative TRP values indicate a decrease in power from the reference to the creative ideation phase, positive values indicate an increase in power from the reference to the creative ideation phase.

Statistical Analysis

All analyses were calculated with the statistical software RStudio version 2022.12.0. First, differences in AUT scores between the pain and pain-free group were analyzed using a one-way analysis of variance (ANOVA) with the between-subjects factor "Group" and the dependent variable AUT scores. Correlation analyses were used to examine whether pain intensity affected AUT scores within the pain group.

Second, differences in TRP values were analyzed by means of a three-way mixed-model ANOVA with one between-subjects factor "Group" (pain vs. pain-free group), one within-subjects factor "Hemisphere" (left vs. right), and one within-subjects factor "Position" (eight electrode positions in each hemisphere). Based on our hypotheses, separate two-way ANOVAs were further calculated, once for the right hemisphere and once for both groups separately, to better understand the three-way interaction. Benjamini-Hochberg procedure was used for post hoc pairwise comparisons (Benjamini & Hochberg, 1995). Finally, to examine the functional relationship between psychophysiological measures and behavioral measures, we averaged TRP values of different electrode sites in which potentially significant differences between the pain and pain-free groups in the right hemisphere and potentially significant asymmetries within the pain and pain-free groups were found. These averaged TRP values were then correlated with AUT values and included as covariates in the ANOVA described above, in which the effect of group on AUT differences was examined to investigate the functional relationship between psychophysiological measures and behavioral measures. Partial η_p^2 was calculated to compare the effect of "Group" between ANOVA and ANCOVA.

Prior to the analyses, several assumptions were tested regarding the absence of outliers, normality, homogeneity of variance, and sphericity (Tabachnik & Fidell, 2019). Outliers were defined as values that were three standard deviations above or below the mean of the

respective sample. Normality was tested by inspecting QQ plots, homogeneity of variance using a Levene test, and sphericity using Mauchly's test. Data and the analysis script are publicly available at the Open Science Framework and can be accessed at https://osf.io/skwz3.

Results

Group characteristics (pain vs. pain-free)

Initially, the pain group (N = 39) and the pain-free group (N = 37) were evaluated according to age, educational level, intelligence scores, and pain scores. Both groups did not differ significantly in age, $t(74) = 0.861$, $p = .392$, Cohen's $d = 0.20$, educational level, $\chi^2(2) = 3.267$, $p = .195$, Cramer's $V = 0.21$, and intelligence scores, $t(74) = -0.782$, $p = .437$, Cohen's $d = -0.18$. Capsaicin successfully reduced pain and tolerance thresholds in the pain group. Pain (left; M = 38.15 °C, SD = 3.43 °C; right; M = 36.42 °C, SD = 2.73 °C) and tolerance (left; M = 43.86 °C, SD = 4.94 °C; right; M = 42.29 °C, SD = 4.74 °C) thresholds in the pain group were significantly lower than pain (left; M = 43.43 °C, SD = 4.04 °C; right; M = 41.62 °C, SD = 3.50 °C) and tolerance (left; M = 48.81°C, SD = 2.99 °C; right; M = 47.36 °C, SD = 2.06 °C) thresholds in the pain-free group (all ts ≥ 5.241, ps < .001, Cohen's ds ≥ 1.21). When averaged across all measures of pain during the AUT, the pain group reported a mean pain level of M = 5.34 on the VAS (SD = 1.45; Min = 2.38; Max = 8.00), which differed significantly from zero, $t(38) = 23.029$, $p < .001$, Cohen's $d = 5.22$. The pain-free group reported not to experience pain during the AUT (M = 0.00, SD = 0.00; Min = 0.00; Max = 0.00).

Behavioral level: Effects of pain on creative ideation performance

Differences in originality between the pain and the pain-free group were compared using a one-way ANOVA with AUT scores as the dependent variable. The main effect "Group" did not yield statistical significance, $F(1,74) = 0.171$, $p = .681$, $\eta_p^2 = 0.002$. AUT scores of the pain group (M = 2.15, SD = 0.22) did not differ from AUT scores of the pain-free group (M = 2.17, SD = 0.19). Although pain scores were negatively correlated to AUT scores within the pain group, this correlation did not reach statistical significance, $r = -.203$, $p = .215$.

Psychophysiological level: Effects of pain on the psychophysiological activation pattern during creative ideation

The mean TRP values (differences in alpha power between the reference phase and the creative ideation phase) at the different electrode sites of the right and the left hemisphere are presented in Panel A of Figure 2, separately for the pain and the pain-free group. As

hypothesized, the three-way interaction "Group" × "Hemisphere" × "Position" of the 2 (Group) × 2 (Hemisphere) × 8 (Position) mixed ANOVA with TRP values as the dependent variable reached statistical significance, $F(4.62,341.61) = 2.306$, $p = .049$, $\eta_p^2 = 0.030$. Furthermore, the ANOVA showed a significant main effect of "Hemisphere", $F(1,74) = 15.669$, $p < .001$, $\eta_p^2 = 0.175$, and "Position", $F(3.11,229.97) = 4.782$, $p = .003$, $\eta_p^2 = 0.061$, and a significant two-way interaction "Hemisphere" × "Position", $F(4.62,341.61) = 5.953$, $p < .001$, $\eta_p^2 = 0.074$. Neither the main effect of "Group", $F(1,74) = 0.126$, $p = .724$, $\eta_p^2 = 0.002$, the two-way interaction "Group" × "Hemisphere", $F(1,74) = 0.869$, $p = .354$, $\eta_p^2 = 0.012$, nor the interaction "Group" × "Position", $F(3.11,229.97) = 0.952$, $p = .419$, $\eta_p^2 = 0.013$, were significant.

To unfold the three-way interaction "Group" × "Hemisphere" × "Position", we investigated this interaction from two perspectives. First, we compared group differences in the right hemisphere to examine whether the expected right-posterior TRP increase during creative ideation significantly differed between the two groups. As depicted in Panels A, B, and C in Figure 2, an alpha power increase was strongly pronounced within the right temporo-parietal sites in the pain group, whereas it was weakly pronounced within the right parietal sites in the pain-free group. However, the 2 (Group) × 8 (Position) mixed ANOVA calculated for the right hemisphere yielded no main effects "Group", $F(1,74) = 0.325$, $p = .570$, $\eta_p^2 = 0.004$, and "Position", $F(3.51,259.58) = 2.175$, $p = .081$, $\eta_p^2 = 0.029$, nor a significant two-way interaction "Group" × "Position", $F(3.51,259.58) = 1.512$, $p = .205$, $\eta_p^2 = 0.020$, indicating that TRP differences in the right hemisphere between the two groups did not differ significantly.

In a second step, we examined for both groups separately whether the expected asymmetry between the left and right hemispheres could be observed. In the pain-free group, the 2 (Hemisphere) × 8 (Position) mixed ANOVA yielded a significant main effect "Hemisphere" $F(1,36) = 5.208$, $p = .028$, $\eta_p^2 = 0.126$. TRP values were significantly higher in the right hemisphere ($M = .005$, $SD = 0.10$) than in the left hemisphere ($M = -.013$, $SD = 0.09$). The main effect "Position", $F(3.08,110.94) = 1.265$, $p = .290$, $\eta_p^2 = 0.034$, and the two-way interaction "Hemisphere" × "Position", $F(4.60,165.63) = 1.684$, $p = .147$, $\eta_p^2 = 0.045$, were not significant, suggesting that the difference between the right and left hemispheres occurred across all electrode sites.

In the pain group, the main effect "Hemisphere", $F(1,38) = 10.814$, $p = .002$, $\eta_p^2 = 0.222$, the main effect "Position, $F(2.94,111.66) = 4.381$, $p = .006$, $\eta_p^2 = 0.103$, as well as the

two-way interaction "Hemisphere" × "Position", $F(3.86,146.56) = 6.016$, $p < .001$, $\eta_p^2 = 0.137$, reached statistical significance. Benjamini-Hochberg corrected post-hoc *t* tests showed that hemisphere mean differences occurred at the temporal T7/T8, parietal P3/P4, P7/P8, and occipital electrode sites O1/O2 (see Figure 3). More specifically, T7 and T8 differed significantly, $t(38) = -3.519$, $p = .001$, Cohen's $d = -0.56$, with an alpha power decrease at T7 but an alpha power increase at T8. A similar pattern was found for P7/P8 with an alpha power decrease at P7 and an alpha power increase at P8, $t(38) = -3.984$, $p < .001$, Cohen's $d = -0.64$. The difference between P3 and P4 was also significant, $t(38) = -2.669$, $p = .011$ Cohen's $d = -0.43$, but an alpha power increase was observed at both electrodes, which was significantly more pronounced at the right P4. Finally, an alpha power decrease was observed at both O1 and O2, $t(38) = -3.317$, $p = .002$, Cohen's $d = -0.53$, which was less pronounced at the right O2 than at the left O1. For all other electrode sites, the differences between the right and the left hemisphere were not significant, all ts ≤ -0.961, ps $\geq .343$, Cohen's ds ≤ -0.15. Taken together, the significant results from the three-way interaction "Group" × "Hemisphere" × "Position" indicated that there was an asymmetry of TRP changes between the left and right hemisphere (i.e. more pronounced TRP increases at right compared to left temporal, parietal and occipital electrode sites), which was more pronounced in the pain compared to the pain-free group.

The functional connection between creative ideation performance and TRP changes in the alpha band

To functionally connect behavioral and psychophysiological results, we investigated how TRP changes were related to AUT scores in a final step. As we observed an asymmetry between the left and right hemispheres in both groups and, in particular, a pronounced asymmetry at the temporal, parietal, and occipital sites in the pain group, we averaged TRP values in the right (T8, P4, P8, O2) and left (T7, P3, P7, O1) electrode sites for further analysis. These averaged TRP values in the right and left hemispheres were both positively related to AUT scores across both groups (see Figure 4). Furthermore, when considered as covariates in an ANCOVA on AUT differences between the pain group and the pain-free group, TRP values were significantly related to AUT scores across all participants, right hemisphere; $F(1,73) = 10.405$, $p = .002$, $\eta_p^2 = 0.125$, left hemisphere; $F(1,73) = 11.163$, $p = .001$, $\eta_p^2 = 0.133$, while the effect of "Group" did not reach statistical significance, right hemisphere; $F(1,73) = 0.530$, $p = .469$, $\eta_p^2 = 0.007$, left hemisphere; $F(1,73) = 0.083$, $p = .774$, $\eta_p^2 = 0.001$. These results indicate that the increase in alpha power across temporal,

parietal, and occipital sites in both hemispheres was positively associated with a participant's originality regardless of whether someone was in pain or not.

Discussion

While studies are accumulating that chronic pain negatively affects more complex cognitive abilities that depend on well-functioning attentional systems (Attridge, Pickering, et al., 2019; Gunnarsson & Agerström, 2018, 2021), recent studies on experimentally induced pain could not show such an adverse effect of pain (Agerström et al., 2017; Attridge, Keogh, et al., 2019). These different outcomes might be attributable to sufficient resources and/or compensatory mechanisms in individuals experiencing experimentally induced pain, which are not observable at the behavioral level but might be revealed by examining the underlying psychophysiological mechanisms. With the present study, we examined whether experimentally induced pain affected performance in a creative ideation task. We further investigated the attention-related psychophysiological mechanisms to obtain a more detailed picture of processes underlying creative ideation. The originality of ideas in the creative ideation task did not differ between individuals experiencing pain and individuals not experiencing pain. However, EEG recordings indicated that the hemispheric asymmetry at temporal, parietal, and occipital electrode sites was more pronounced in individuals with pain than in individuals without pain. This asymmetry was mainly caused by increased TRP changes at the right temporal, parietal, and occipital sites in the pain group compared with the pain-free group. When combining behavioral and psychophysiological data, TRP changes at temporal, parietal, and occipital sites were positively related to originality scores in the AUT across both hemispheres and groups.

In our study, experimentally induced pain did not negatively affect creative ideation performance. This result aligns with previous reports that found no differences in performance on more complex cognitive abilities such as logical reasoning (Attridge, Keogh, et al., 2019) or abstract thinking (Agerström et al., 2017) between a pain-free group and a group experiencing experimentally induced pain. Following the reasoning of Buhle and Wager (2010), this finding may have occurred because the concurrent demands by the AUT and pain did not overstrain the capacity of the attentional system in individuals experiencing experimentally induced pain. Interestingly, however, in the study by Gubler et al. (2022), the same task resulted in decreased creative ideation performance in individuals with chronic pain. Since the actual pain intensity in the group of individuals with chronic pain (M = 4.67, SD = 1.88) was similar to that in the group of the present study (M = 5.34, SD = 1.45), other

qualitative characteristics of the pain or differences in the study samples are likely to account for the different results.

Besides intensity, other pain characteristics, such as novelty, predictability, and threat can also interrupt attention (Eccleston & Crombez, 1999; Gong et al., 2019). For example, compared to chronic, long-lasting pain, the pain stimulus in this study lasted only a short time (approximately 30 seconds) per trial. Participants were further aware that they could withdraw from the pain anytime. These experimental features may have made the pain more predictable and less threatening than chronic pain, reducing attentional demands. The different results for chronic pain and experimentally induced pain may also suggest that the source of cognitive dysfunction in chronic pain is not only the pain (in a narrow sense) but maybe some of the frequently observed comorbidities (Attridge, Keogh, et al., 2019). For example, individuals with chronic pain often suffer from anxiety, depression, and fatigue (Gómez Penedo et al., 2020; Van Damme et al., 2018), which can further place demands on attention.

Along with this, interindividual differences such as such as pain-related anxiety (Vlaeyen & Linton, 2012), catastrophic thinking about pain experience (Van Damme et al., 2004), emotional arousal (Rhudy & Meagher, 2001; Wiech & Tracey, 2009), or motivation to complete a task (Geuter et al., 2016; Van Damme et al., 2010; Verhoeven et al., 2010) could further attenuate the extent to which pain impairs performance. Regarding the latter point, van Damme et al. (2010) suggested that the motivational context in which pain occurs must be considered to understand how pain absorbs attention. When people are highly motivated to complete a task, it is more likely that they ignore or tolerate pain, allowing them to continue with their work. On the contrary, low motivation can intensify the experience of pain and lead to reduced task performance. Consistent with this, it has been demonstrated that task performance under pain was better when motivation was high compared to when it was low(Karsdorp et al., 2010, 2013). A tentative explanation for the lack of differences in AUT performance between the two groups in the present study could be that individuals in the pain group were highly motivated to perform well under these particular conditions, compensating for the pain-related attentional deficits.

Eventually, the different results between experimentally induced and chronic pain may also be attributable to demographic variables. For example, the study by Gubler et al. (2022) included middle-aged individuals of both genders with various educational backgrounds, whereas the study presented here included only young female participants with predominantly higher education. Given that age (Foos & Boone, 2008) and intelligence (Batey et al., 2009) influence performance in creative ideation, these variables may have additionally shaped the

influence of pain on creative ideation. Although both studies accounted for these variables by contrasting groups with and without pain, a direct comparison between the studies is difficult. It remains unclear whether similar results would be found in middle-aged individuals with different levels of education if they were included in the study of experimentally induced pain.

In summary, some or all of these variables may have caused experimentally induced pain to be less demanding on attention than chronic pain. Individuals experiencing experimentally induced pain may have thus been better able to direct their attention away from the pain stimulus and toward the task to maintain performance than patients with chronic pain. The results further imply that there are substantial differences between studies with clinical samples and studies with healthy samples experiencing experimentally induced pain that cannot be readily transferred to each other. The mere experience of pain does not lead to a decrease in performance but still depends on various moderators that can be investigated in more detail in future research.

Our study provides further insights into the cognitive processes underlying creative ideation. Proceeding from previous reports (for reviews, see Fink & Benedek, 2014; Stevens & Zabelina, 2019), we expected to find alpha power increases at the right parietal sites and a hemispheric asymmetry in our sample of pain-free healthy subjects, supporting the idea that creative ideation is related to internal attention reflected by this TRP pattern. However, while a hemispheric asymmetry could be observed across all electrode sites, an alpha power increase was only slightly present at the right parietal electrode sites. At first glance, this result is surprising, as previous studies have found a stable increase in alpha power at the right posterior electrode sites during creative ideation (Fink & Benedek, 2014). This inconsistency might be explained due to the following circumstances: First, we averaged alpha activity across all subjects and across all ideas per group. Thus, more creative and less creative ideas from more and less creative individuals were included in these averages. Therefore, alpha power increases from more creative individuals and more creative ideas may have been leveled out by less creative individuals and less creative ideas, resulting in less pronounced alpha power increases at the right posterior sites. Second, in this adapted version of the AUT, participants were instructed to develop one original idea per object within a few seconds. In other AUT versions, in which subjects are instructed to generate as many ideas as possible for an object, it can be observed that creativity increases over time during a trial. This so-called serial order effect states that ideas generated at the beginning of a creative ideation process are less original than later ideas (Beaty & Silvia, 2012). As there was relatively little time

available per trial in this study, less original ideas may have emerged, which could further explain the smaller increase in alpha power. This explanation would also align with the study of Agnoli et al. (2020), who investigated the psychophysiological underpinnings of the serial order effect during the AUT. The authors found that the first ideas were less original than the later ones and were accompanied by an alpha power decrease. Only the later more creative ideas showed the expected TRP increases. Based on these considerations, it is reasonable to regard the results not as absolute values but relative to a comparison group such as our pain group.

Compared to the pain-free group, a pronounced hemispheric asymmetry in TRP changes at temporal, parietal, and occipital sites could be observed in the pain group. This asymmetry was mainly caused by increased alpha power over the right temporo-parietal electrode sites. As alpha power increases have been associated with the inhibition of task-irrelevant sensory input and the degree of internally allocated attention (Benedek et al., 2011), the TRP pattern in the pain group might reflect the inhibition of experimentally induced pain as an additional sensory input for the pain but not for the pain-free group. Since performance in the creative ideation task did not differ between the pain and the pain-free group, it appears that enough attention could be raised by participants in the pain group to suppress pain-related sensory input and access internal mental representations as well as the pain-free group. In other words, experimentally induced pain increased attentional demands during creative ideation (as reflected by TRP increases), but these demands did not lead to an overload of attentional resources. Consequently, the groups did not differ in the performance on the AUT task but only in the amount of attention required to achieve this performance.

This rationale might also explain the inconsistency between the present results and the results by Gubler et al. (2022), who reported less alpha power increases in patients with chronic pain than in healthy controls. If the concurrent attentional demands by pain and creative ideation exceeded the attentional resources of patients suffering from chronic pain, they might not have been able to increase their alpha power to inhibit the adverse effect of pain. Consequently, their creative ideation performance was worse compared to that of healthy controls.

To functionally connect behavioral and psychophysiological results, we investigated in a last step how TRP values at temporal, parietal, and occipital sites were associated with AUT scores. In both groups and both hemispheres, TRP values were positively related to performance in the AUT (see Figure 4). Furthermore, when considered in the ANCOVA, TRP values significantly explained performance differences in the AUT, whereas the factor

"Group" remained irrelevant. Concerning the right hemisphere, these results are consistent with previous findings as they indicate that alpha power increases at right posterior electrode sites, associated with enhanced internal attention, facilitate the generation of creative ideas (Benedek, 2018; Benedek et al., 2014). Furthermore, this relationship was not moderated by the factor "Group", with the pain group having a higher average alpha power increase, most likely caused by dealing with the additional pain demands. Although both groups showed that alpha power in the right hemisphere was significantly more pronounced than in the left hemisphere during creative ideation, TRP values in the left hemisphere were similarly related to AUT scores as TRP values in the right hemisphere. This positive relationship between TRP values of the left hemisphere and performance on the AUT further indicates that alpha activity in the left hemisphere is associated with creative ideation, similar to alpha activity in the right hemisphere.

As experimentally induced pain can be considered a stressor, the present findings can also be discussed in the broader research context of stress and creativity. Stress is known to impact creative ideation on the behavioral (e.g., Duan et al., 2019; Wang et al., 2019) and the neurophysiological level (Vartanian et al., 2020). A meta-analysis by Bryon et al. (2010) indicated that stress could modulate creativity in both directions. While low-level stressors were found to increase creativity, mainly uncontrollable stressors can decrease creativity (Byron et al., 2010). The present stressor of pain seemed to be in between these two extremes. Furthermore, the neurophysiological findings of increased top-down control over sensory information in the pain group underline the work of Vartanian et al. (2020), who suggested that acute stress might increase the activity of the salience network. The higher network activation might be one reason for the observed alpha power increase at the right posterior sites in the pain group. This is in some contrast to a previous EEG study reporting alpha power decreases after acute stress (vs. before acute stress; Wang et al., 2019). However, the present study was able to investigate creative ideation and the associated EEG activation pattern directly during perceiving stress. The applied experimental procedure allows a deeper look into the cognitive mechanism responsible to maintain creative ideation under the acute stressor of pain.

Overall, the present study provided additional evidence for the notion that experimentally induced pain does not necessarily translate into a broader range of cognitive impairments. However, the simultaneous use of behavioral and psychophysiological measures demonstrated that experimentally induced pain puts additional attentional demands on individuals that can be revealed at the psychophysiological level. Thus, individuals in the pain

group had to pay more attention to internal mental processes during creative ideation than individuals in the pain-free group to perform similarly well on the behavioral level. The results further indicate that the concurrent demands of the creativity task and pain were not high enough to limit subjects' performance at the behavioral level. Therefore, it would be interesting to examine in future studies what other features, such as pain or task characteristics, or individual differences, contribute to excess attentional resources.

CRediT author statement

Danièle A. Gubler; Conceptualization, Methodology, Software, Formal analysis, Investigation, Data Curation, Writing – Original Draft, Visualization. Christian Rominger; Methodology, Validation, Writing – Review & Editing. Denise Jakob; Formal analysis, Investigation. Stefan J. Troche; Conceptualization, Resources, Writing – Original Draft, Supervision

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Figure 1

The procedure of the Alternate Uses Task (AUT). Every trial started with a fixation cross (10 seconds), followed by an everyday object (4 seconds) for which participants were instructed to generate one original solution. Participants could think of possible creative ideas during the creative ideation phase (10s). During the response phase (4 seconds), participants were instructed to express their most original idea aloud (procedure and figure adapted from Schwab et al. 2014). Throughout all trials, subjects in the pain group were applied heat stimuli with an average temperature of 38 °C, and subjects in the pain-free group were applied pleasant thermal stimuli with a temperature of 34 °C.

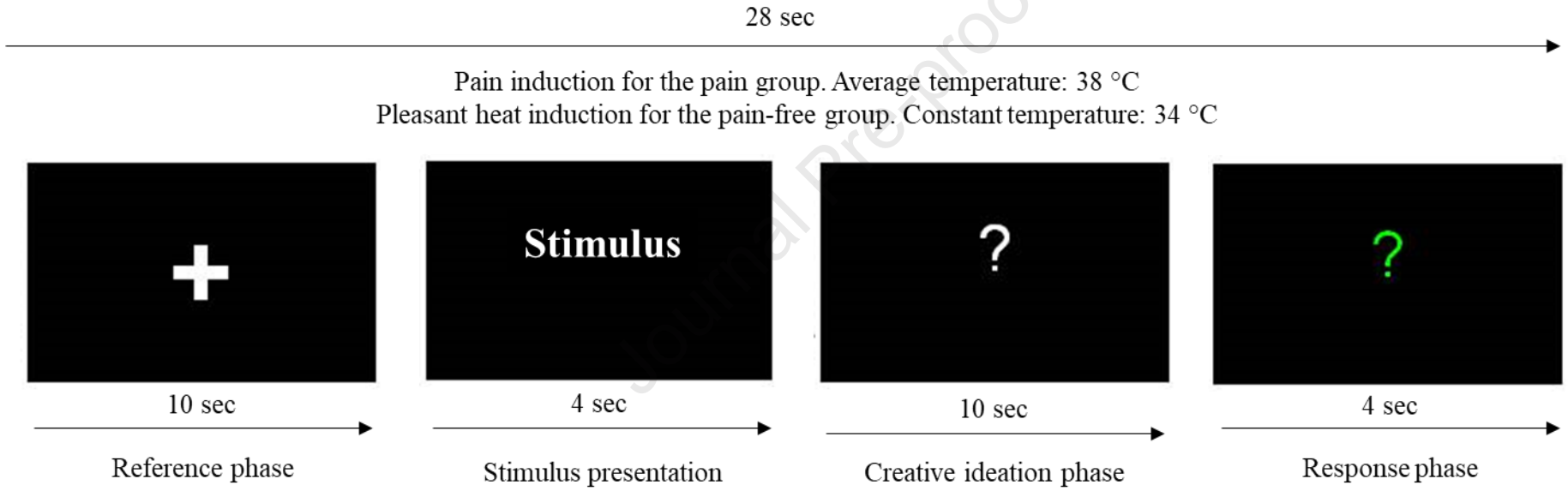

Figure 2

Means and standard errors of TRP changes (10-12 Hz) during creative ideation between the pain-free and the pain group for eight cortical electrode sites of the right vs. the left hemisphere (A). TRP changes in the pain-free group (B), TRP changes in the pain group (C), and TRP differences between the pain group and the pain-free group (D).

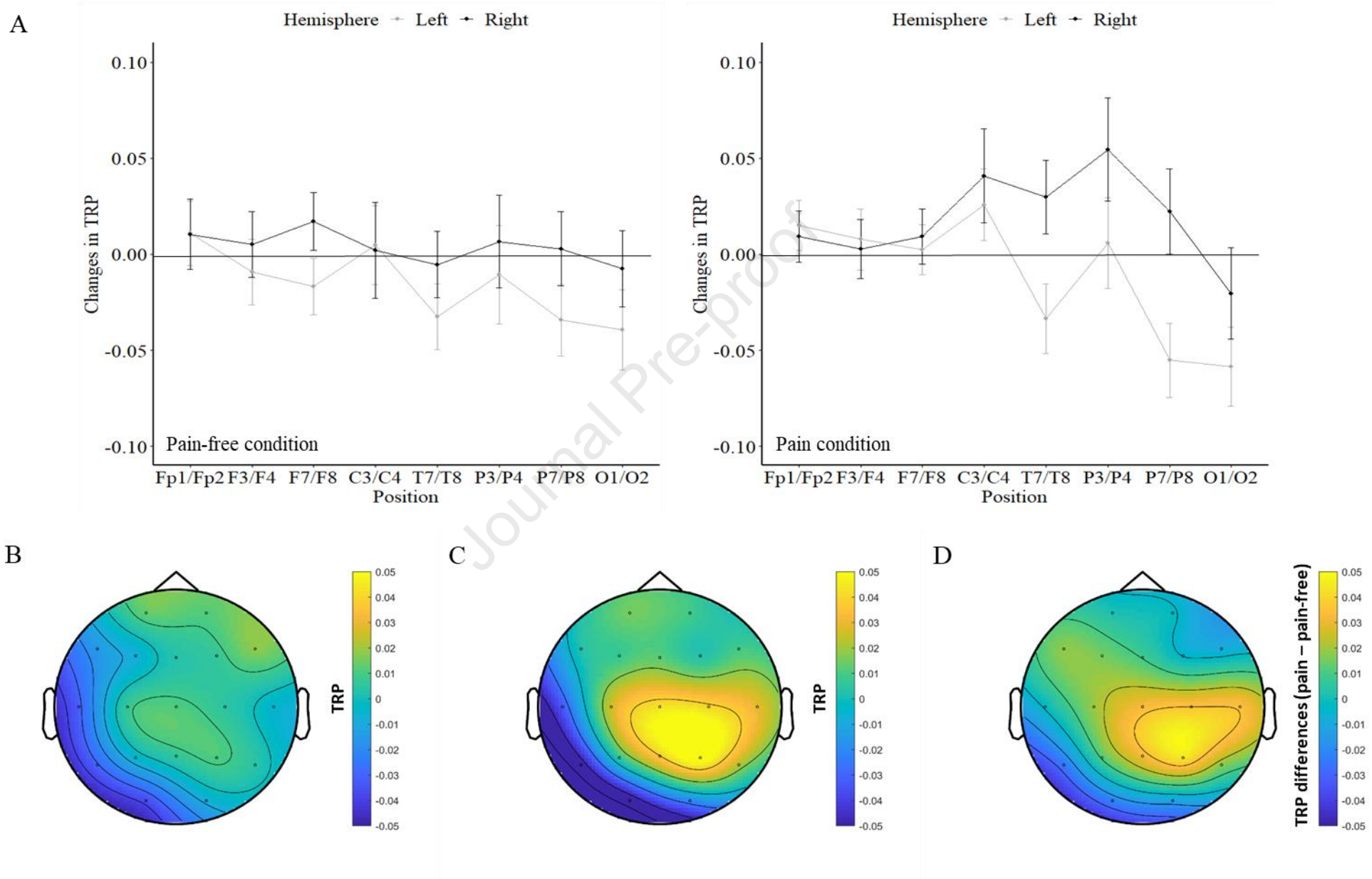

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Figure 3

Means and standard errors of TRP changes (10-12 Hz) during creative ideation in the pain group for the left and right hemispheres.

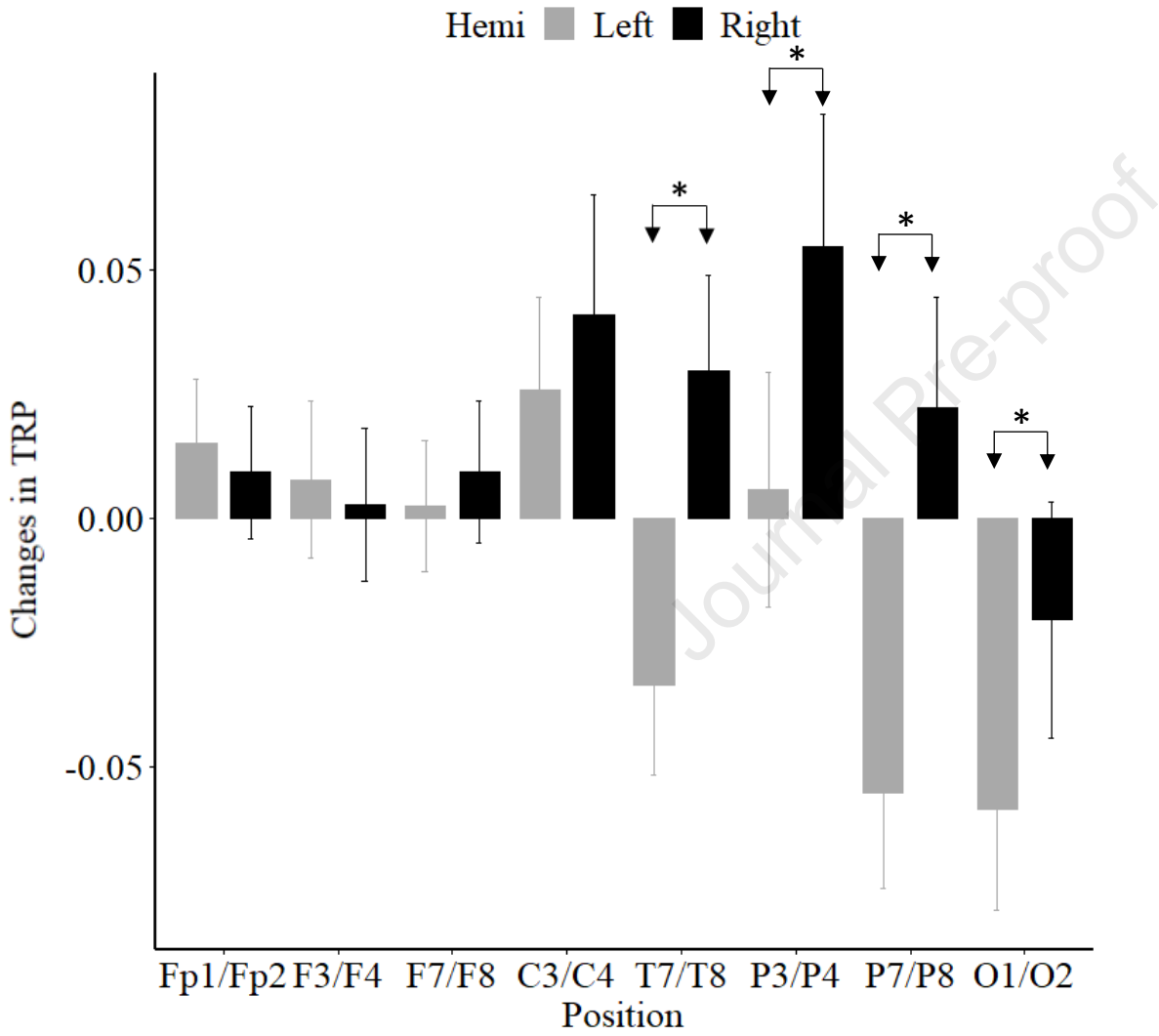
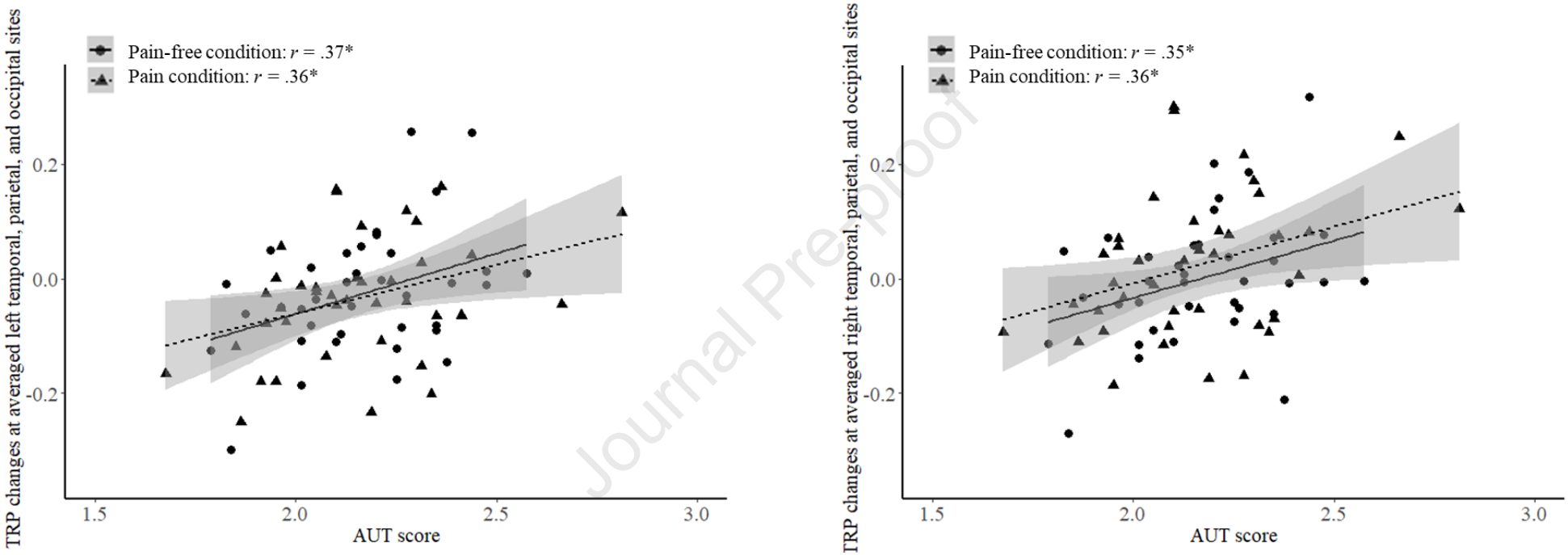


Figure 4

Correlation plot between AUT scores and averaged TRP changes at left (T7, P3, P7, O1) and right (T8, P4, P8, O2) temporal, parietal, and occipital electrode sites in the pain group and the pain-free group, respectively.



Highlights

- Experimentally induced pain does not impair creative ideation performance
- Experimentally induced pain increases hemispheric alpha asymmetry in the EEG
- Enhanced alpha asymmetry is associated with increased internal attentional demands
- Enhanced alpha asymmetry may reflect increased attentional demands due to pain