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Research Article

Investigating the role of rumination on reward and punishment processing in an operant conditioning task using event-related potentials

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ABSTRACT

Pain catastrophizing, and specifically rumination, are key components of the pain experience and a potential predictor of chronic pain. Pain trajectories in chronic pain patients can be influenced by operant conditioning paradigms, with limited knowledge of the mechanisms. Rumination and its impact on event-related potentials (ERPs) in a painful operant conditioning setting, may further elucidate how behavioral and cognitive manipulation can affect somatosensory and nociceptive processing. This study aimed to examine the impact of rumination on ERP responses to auditory feedback cues in a painful operant conditioning paradigm. 29 healthy volunteers initially completed the pain catastrophizing questionnaire followed by a cognitive task. Participants were divided into high- and low-ruminators based on the median split. Negative reinforcement (NR) and positive punishment (PP) were employed as operant conditioning paradigms, using pressure pain as the conditioning stimulus, with correct and incorrect responses resulting in pain relief/no change in pain or no change in pain/increased pain. Electroencephalographic, auditory-feedback ERP P3N3 amplitude and P300 latencies were analyzed.

The group with higher rumination scores exhibited lower P3N3 amplitudes compared to the group with lower rumination scores and in response to the auditory feedback on incorrect compared to correct answers. Delayed P300 latencies were found in feedback to incorrect answers in both conditions, but unrelated to rumination.

These findings suggest that individuals with higher rumination may struggle to process performance outcomes in an operant conditioning paradigm. Future studies may explore if modulation of rumination has an impact on cognitive performance and pain intensity to a painful condition.

Introduction

Pain catastrophizing is considered an integral psychological part of the pain experience, where empirical evidence consistently reports pain catastrophizing as a predictor of chronic pain (Larsen et al., 2021; Lewis et al., 2015). Moreover, pain catastrophizing may interfere with improvements in pain intensity and disability as it has been observed in patients with subacute low-back pain up to six months after graded exposure and/or physical therapy (George et al., 2008). Nonetheless, the concept of pain catastrophizing and its mechanistic underpinnings (including higher-order processing) remain debated which, in turn, may impact the discovery of novel approaches to pain management and effective treatments (Petrini and Arendt-Nielsen, 2020). However, it is generally accepted that pain catastrophizing involves the lack of control over an overwhelming flux of negative thoughts (rumination), the exaggeration on the perceived pain-related threat by envisioning the worst-case scenario (magnification), and the sense of inability to effectively cope with pain (helplessness) (Quartana et al., 2014). This may further manifest in pain-related behaviors such as fear-avoidance that can be targeted through cognitive behavioral therapy (Petrini and Arendt-Nielsen, 2020), utilizing e.g. reinforcement and extinction approaches. Previous research has shown that operant conditioning principles which is rooted in reward and punishment, can decrease disability and pain in chronic low back pain (Bunzli et al., 2011), and decrease experimental pain (Lee et al., 2021). Additionally, operant conditioning may affect pain intensity reporting (Linton and Gotestam, 1985) and influence somatosensory processing in chronic back pain patients (Flor et al., 2002) where the latter focuses on evoked responses. Higher pain

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catastrophizing has been linked with a larger neural activation in areas such as the caudate nucleus in patients living with various persistent pain conditions (Cooke et al., 2023), secondary somatosensory cortex (SII) and anterior cingulate cortex in patients living with fibromyalgia (Gracely et al., 2004) as well as a larger activation of SII in limb amputees when exposed to non-painful electrical stimulation (Vase et al., 2012). These findings may indicate that individuals that have a tendency towards more catastrophizing thoughts also encode sensory stimuli differently, independent of aversiveness. In this sense, rumination has a demonstrated viable predictive ability and discriminative properties where e.g. rumination can predict patient disability severity and pain intensity ratings (Petrini and Arendt-Nielsen, 2020), as well as distinguish chronic pain patients from healthy volunteers (Osman et al., 2000). However, little is known about how the degree of rumination influences ERPs in a reinforcement and punishment setting. The P300, an ERP reflecting context-updating and allocation of cognitive resources in relation to cognitive performance (Dinteren et al., 2014), is sensitive to reinforcement learning, mainly in the context of positive and negative valence (Wischnewski and Schutter, 2018). P300 is reduced in amplitude when comparing individuals living with fibromyalgia or rheumatoid arthritis, with healthy individuals (Cardoso et al., 2021; Tomasevic-Todorovic et al., 2015), which may indicate impairment of both context-updating and cognitive resource allocation. Additionally, delayed P200 (Cardoso et al., 2024) and P300 latencies (Talmi et al., 2013) have been reported in individuals with persistent pain, but conflicting evidence exists (Lenoir et al., 2020) and has never been investigated in the context of rumination. As higher pain rumination consistently has been shown to predict greater pain in both experimental and clinical populations (Van Damme et al., 2002), it could be proposed that delayed P300 latencies are linked to rumination where individuals who tend to ruminate more exhibit a longer delay in P300 ERPs compared to those who ruminate less, due to cognitive interference with context-updating (San Martín, 2012) and error-processing (van Hoogmoed et al., 2012) that can be captured in the P300/N300 (P3N3) complex amplitudes.

To address these unresolved questions, this study investigated the effect of rumination on ERPs evoked by auditory feedback cues in response to an operant conditioning paradigm using pressure pain as the conditioning stimulus. We hypothesized that (1) P3N3 complex amplitudes would be decreased in individuals with high rumination compared to individuals with low rumination and (2) that the latencies of P300 would be delayed in high rumination compared to low rumination, in response to auditory feedback on a cognitive task performance in an operant conditioning paradigm.

Methods

Participants

Twenty-nine healthy volunteers were enrolled through local notices and social media. The exclusion criteria included chronic pain, neurological disorders (e.g., diabetes, epilepsy), musculoskeletal issues, mental health conditions (e.g., depression), drug addictions, hearing problems, or pregnancy. All volunteers provided informed consent and received compensation at the end of the experiment (participants were compensated 150 DKK per hour spent in the lab). The study was approved by the local ethics committee (N-20220014), and the study was conducted in accordance with the Declaration of Helsinki.

The hearing-in-noise-task

The Danish Hearing-in-Noise Task (HINT) (Nielsen and Dau, 2011) consists of several sentences that are mixed with noise, where the objective is to listen, memorize, and repeat these sentences. A total of 250 randomized sentences were diotically presented to the participants, in bins of five words.

The signal-to-noise ratio (SNR) was calibrated at the beginning of the experiment to obtain a 50–50 rate between correct and incorrect answers. To obtain a reward, five words had to be repeated correctly, while less than five repeated words was considered as an incorrect answer. Each participant was asked to rate their confidence in whether they had answered correctly or incorrectly on a scale from 0 to 100, where 0 reflects no confidence, and 100 as the highest confidence.

Calibration of the SNR

The SNR psychometric function was estimated and calibrated to 50 % using the Psi-method (Kontsevich and Tyler, 1999), implemented in the Palamedes Toolbox (Prins and Kingdom, 2018). In detail, participants were listening to 20 different HINT sentences with different levels of noise and repeating them. If they were hearing the whole sentence correct or not, the experimenter was selecting ‘yes’ or ‘no’, respectively. This procedure was repeated before every session.

Experimental design

Before starting the experiment, the volunteers completed the Pain Catastrophizing Scale (PCS) questionnaire after which they were randomized to start in one of two conditions: (1) Negative Reinforcement (NR) or (2) Positive Punishment (PP) (Fig. 1; Operant conditioning). The experiment involved three consecutive sessions, separated by 15 mins break in-between. Each session comprised four blocks of 10 trials yielding a total of 120 trials. Four familiarization trials were conducted to ensure that the volunteers understood the methods and ratings with each condition shown twice on a screen. At the start of each block, the participant was shown the condition on-screen. Within each session, blocks were randomized to be either negative reinforcement (NR) or positive punishment (PP), with each condition presented twice. Following the auditory presentation of the sentences, a three-second maintenance interval was provided, after which the participant was asked to recall the sentences. Moreover, the pressure was calibrated to produce a painful stimulation on the visual analogue scale (VAS) 3, 5 (i.e. pain threshold), and 7. Similarly, the noise and sound (sound-to-noise ratio) was calibrated for the Hearing-in-Noise-Task (HINT).

Throughout the experiment, electroencephalographic (EEG) activity was recorded while participants completed the HINT task with concurrent pressure pain stimulation. Performance on these tasks determined the intensity of the next pain stimulus in the following manner: (1) pain intensity was kept constant at VAS 5 during the HINT task but changed according to (2) the consequence of reward (for NR = pain relief and for PP = no change in pressure stimulation) for correct answers, or punishment (for NR = no change in pressure stimulation and for PP = increased pressure stimulation) for incorrect answers (Fig. 1). Between the maintenance phase and the consequence phase, the pressure stimulation was interrupted for a maximum of 10 sec (repeat sentences and feedback). Auditory feedback was given to the participant before the consequence pressure stimulation to inform about correct or incorrect performance (Fig. 2). Reward and punishment stimulation lasted for 15 s.

The pain catastrophizing scale

The pain catastrophizing scale (PCS) is a self-report questionnaire to assess the tendency to magnify or exaggerate the experience of pain (Sullivan et al., 1995b). The PCS is a 13 items instrument divided in three dimensions: rumination, magnification, and helplessness. The rumination subscale (items 8, 9, 10, 11) evaluates the extent to which individuals dwell on and overthink on their pain experiences. The magnification subscale (items 6, 7, 13) captures the degree to which individuals exaggerate the threat posed by their pain. The helplessness subscale (items 1, 2, 3, 4, 5, 12) assesses the perceived lack of control individuals have over their pain. The volunteer will rate the past pain experiences and rate on a 5-point scale where 0 represents “not at all” and 4 is “all the time”. The PCS has been validated on healthy

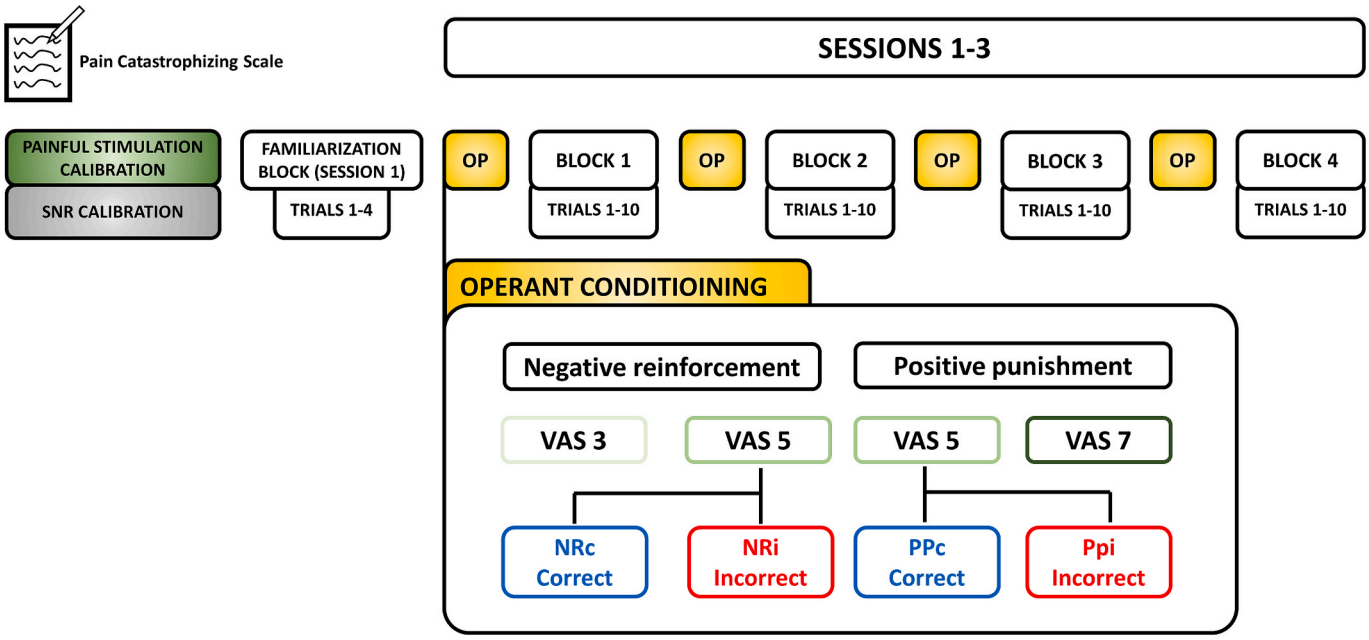

Fig. 1. Experimental design. Prior to the beginning of the experiment, participant completed the pain catastrophizing scale questionnaire. The experiment was made of 120 trials in total, divided into 3 sessions of four blocks containing each 10 trials. Before every session, the SNR (sound-to-noise ratio) and the cuff of pressure for painful stimulation were calibrated. Before every block, the condition (negative reinforcement or positive punishment) was presented to the participant through a screen. During the HINT (hearing-in-noise-test) task, the pressure pain stimulation was kept constant at pain threshold (visual analogue scale = 5), and the consequence was divided into two conditions: (1) the Negative Reinforcement condition, where participants received pain relief as reward or no change in pressure pain stimulation as punishment. (2) The Positive Punishment condition, where participants received no change in pressure pain stimulus as reward and an increased pressure pain stimulus as punishment.

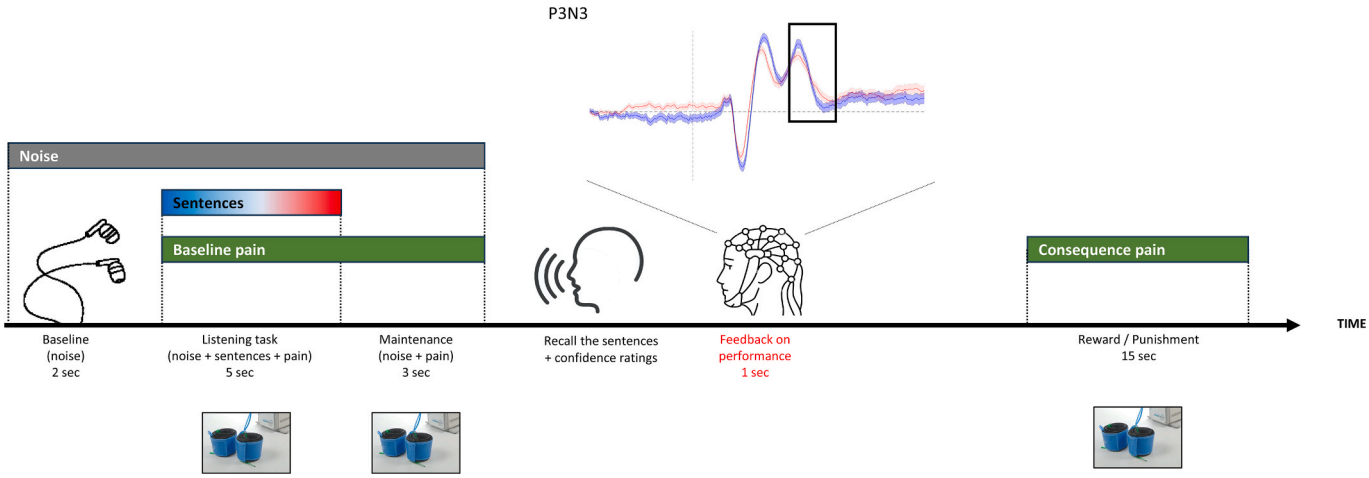

Fig. 2. Overview of the trial flow. Every trial started with a baseline and participants were exposed to noise. Subsequently, the participants performed the listening task with HINT sentences made of 5 words that they had to memorize, during the maintenance phase, and repeat. Feedback in the form of two distinct tones (one for correct answer and one for incorrect answer) was given based on the performance that also determined if participants received reward or punishment. The pressure stimulation was paused during sentences recall and performance feedback.

individuals (Hirsh et al., 2008; Leung, 2012; Sullivan et al., 1995a) and in patients with chronic pain or individuals with acute injuries (Leung, 2012), where higher scores on the overall scale, or each subscale reflect higher tendencies towards catastrophizing. This study focused on the rumination subscale, given the plausible usefulness when investigating e.g. pain intensity reporting (Sullivan et al., 1998).

Electroencephalographic recordings

The electroencephalographic (EEG) signals were acquired by 64 electrodes (gTEC.hiAMP) placed on the scalp according to the 10–20 international system. The reference electrodes were placed on the ear lobes and the ground at AFz. The electrodes impedance was kept under 10 kΩ and the signal was amplified and sampled at 1200 Hz (g.HIamp biosignal amplifier g.Tec medical engineering GmbH, Schiedlberg, Austria). To secure a correct alignment between EEG signal and stimulation, several triggers were utilized, such as onset of the feedback auditory cue, allowing for the extraction of auditory ERPs after the auditory feedback stimuli.

Tonic and conditioning stimulus

Tonic painful stimulation was delivered through a cuff algometer (a silicon high-pressure cuff, Nocitech Aps) placed on the left calf of participants at the level of the gastrocnemius muscle. The cuff was connected to a computer that controlled the inflation rate and level. Volunteers were instructed to continuously rate their pain with a handheld dial, and a button to immediately terminate the inflation of the cuff if the pain became unbearable. The maximum pressure that the cuff could reach was 100 kPa (760 mmHg). Volunteers had to score the perceived stimulation using a visual analogue scale (VAS) where 0 was defined as no sensation, 10 as the worst pain imaginable, and 5 as the pain threshold. A calibration was run prior to the beginning of the experiment. Volunteers had to score the pressure to determine the perception levels of VAS 3, VAS 5, and VAS 7. Initially, the pressure was always kept at VAS 5, and changed according to the condition (NR: Correct answer yielded VAS 3, while incorrect answer kept the pressure at VAS 5; PP: Correct answer kept the pressure at VAS 5 while an incorrect answer yielded an increase in pressure to VAS 7). The pressure never exceeded VAS 7 during the whole experiment.

Calibration of pressure stimulation

The pressure was increased by 1 kPa/s and participants had to continuously score the perception using a digital visual analogue scale (VAS) ranging from 0 (no sensation at all), 5 (pain threshold), 10 (worst pain imaginable) (Graven-Nielsen et al., 2015). This procedure was repeated 3 times before every session and an average between the 3 values of interest were taken: VAS 3 (no pain), VAS 5 (pain threshold), VAS 7 (pain).

Data analyses

EEG data pre-processing

EEG data were pre-processed using EEGlab (Delorme and Makeig, 2004) and Matlab (v.2021b) functions for the analysis and the extraction of the ERPs and EEG features. Data were first resampled at 512 Hz after which powerline noise interference was removed using Cleanline (https://www.nitrc.org/projects/cleanline) and the data were band pass filtered (IIR Butterworth filter, order 8) between 0.1 and 40 Hz. Re-referencing of the data to A1, A2 electrodes was performed. Then the ICA decomposition (Makeig et al., 1995) was performed on the high-pass filtered data at 1 Hz to remove the muscle and eye movement artefacts. Once the composition was finished, the ICA weights were transposed on the signal, filtered at 0.1–40 Hz, and the bad components were removed. EEG data were epoched based on the feedback sound trigger, and the signal was extracted from −500 ms pre-trigger to 1000 ms post-trigger, and baseline corrected. The P3N3 complex was extracted from the Cz electrode (Torta et al., 2019) and categorized on condition and answer outcome (correct/incorrect).

Statistical analyses

Data were tested for normality using the Shapiro-Wilk test for normality. To investigate to which extent pain catastrophizing influenced P3N3 complex amplitudes and P300 latencies, the median split of the rumination subscale was calculated, and the volunteers were divided in two relative groups of rumination: (1) high-ruminators (HR) and (2) low-ruminators (LR). A three-way mixed analysis of variance with the between-subject factor level of rumination (HR/LR) and two within-subject factors answers (correct/incorrect) and condition (NR and PP), was used to analyze the P3N3 complex amplitudes and P300 latencies to test for differences based on the relative level of rumination. Statistical analyses were carried out in Statistical Package for Social Sciences (SPSS v.26, IBM). A p-value <0.05 was considered statistically significant. All simple-simple and simple main effects analyses were Bonferroni-corrected where applicable.

Results

Participants

A total of 29 healthy individuals were enrolled in the current study (mean age 26.25 ± 5.29; 20 women). The final analysis was conducted on 26 subjects due to artifacts in the EEG signal. All subjects had normal hearing.

The effects of rumination on P3N3 amplitudes

When categorizing participants into high rumination (HR, 9.25 ± 2.05) and low rumination (LR, 4.24 ± 1.72), no three-way interaction between condition × answers × rumination ($F_{1, 21} = 2.31$, $p = 0.64$, $\eta = 0.011$) was found. Moreover, no two-way interactions were found between condition × answers ($F_{1, 21} = 0.85$, $p = 0.37$, $\eta = 0.04$), answers × rumination ($F_{1, 21} = 0.083$, $p = 0.78$, $\eta = 0.004$), or condition × rumination ($F_{1, 21} = 0.754$, $p = 0.395$, $\eta = 0.035$). The main effect of answers ($F_{1, 21} = 5.405$, $p < 0.05$, $\eta = 0.205$) was significant, with higher amplitudes for incorrect answers than correct, while condition was not ($F_{1, 21} = 2.496$, $p = 0.13$, $\eta = 0.106$). Volunteers exhibited a larger P3N3 amplitude response when answering incorrectly compared to correctly (mean difference = 1.795 ± 0.77 μV, $p = 0.03$). A significant main effect of rumination was found ($F_{1, 21} = 7.682$, $p = 0.011$, $\eta = 0.27$), with significantly larger P3N3 amplitudes for participants in the LR group compared to the HR group (Fig. 3 and Fig. 4).

The effects of rumination on P3 latencies

The three-way mixed analysis of variance showed no significant three-way interaction of answers × condition × level of rumination ($F_{1,23} = 0.001$, $p = 0.974$, $\eta < 0.001$) on P300 latencies. No significant two-way interactions answers × level of rumination ($F_{1,23} = 0.048$, $p = 0.828$, $\eta = 0.002$) or conditions × level of rumination ($F_{1,23} = 2.731$, $p = 0.112$, $\eta = 0.106$) on P300 latencies were observed. A significant two-way interaction between answers × conditions ($F_{1,23} = 8.039$, $p = 0.009$, $\eta = 0.259$) was found (Fig. 5). Simple main effects analysis showed that the latencies, in both conditions, were delayed when providing an incorrect answer versus a correct answer (NR: mean difference = 25.52 ± 3.37 ms, $p < 0.001$; PP: mean difference = 11.86 ± 3.79, $p < 0.01$). The latencies were not different between the rumination groups but tended towards significance ($F_{1, 23} = 4.163$, $p = 0.053$, $\eta = 0.153$).

Discussion

This study demonstrated, in agreement with the hypothesis, that volunteers who scored higher on the PCS rumination subscale, also exhibited lower P3N3 complex amplitudes. Not adhering to the original hypothesis, the P300 latency was not influenced by the degree of rumination. However, latencies of P300 were significantly slower when feedback of an incorrect answer was given, and this effect was present in both the NR and PP condition but was most pronounced in the NR condition.

Rumination, painful operant conditioning, and P3N3

Our findings suggest a significant inverse relationship between P3N3 amplitudes and rumination severity. Individuals with higher levels of rumination exhibited overall lower P3N3 amplitudes in response to auditory feedback, compared to those with lower rumination disregarding the operant conditions (NR or PP) or answers (correct or incorrect). This result aligns with previous research where e.g. reduced P300 amplitudes were linked to impaired cognitive control and emotional regulation (Deveney and Pizzagalli, 2008; López Zunini et al., 2016), as the P3N3 is thought to reflect the allocation of attentional

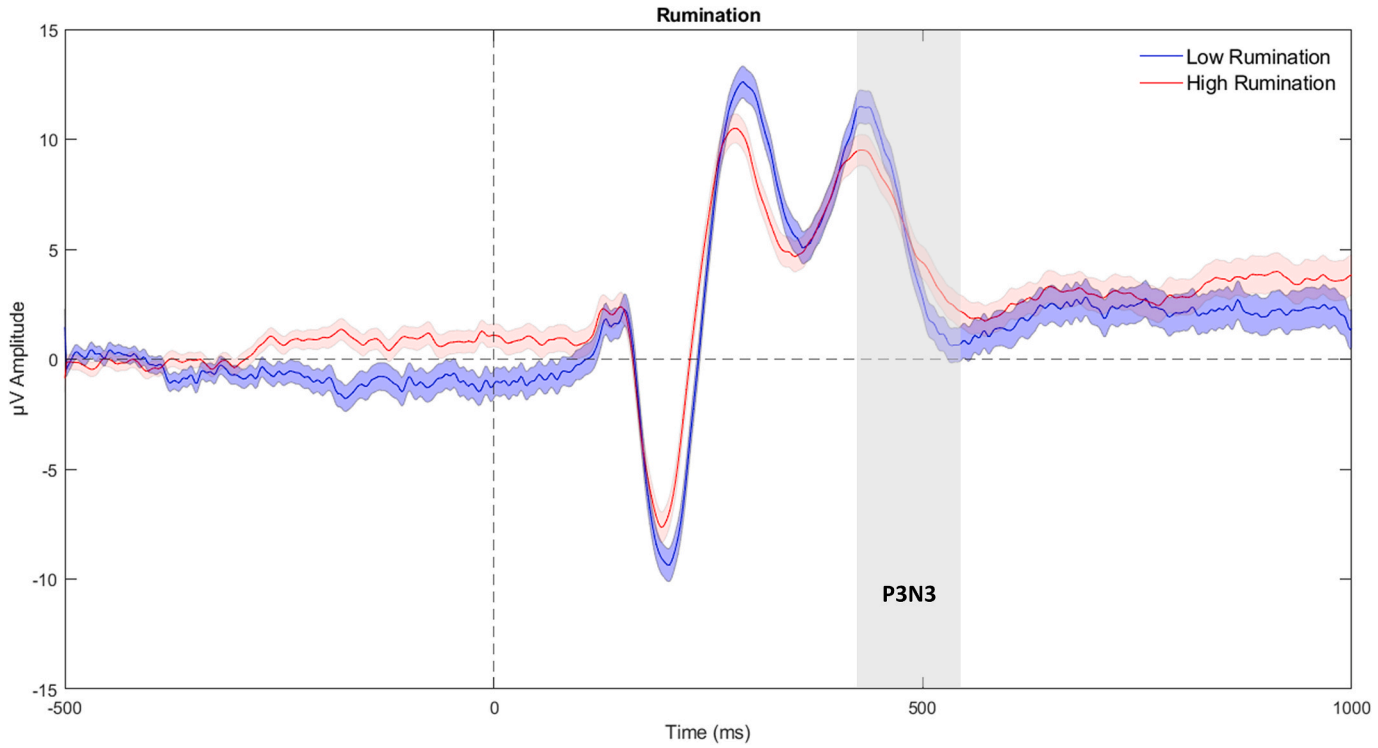

Fig. 3. Raw average traces of P3N3 for high and low rumination subjects. Grand average of all participants divided by the median split of the rumination into two groups (high and low ruminators). Highlighted in grey there is the peak-to-peak complex of interest, P3N3.

resources and the evaluation of sensory stimuli (Picton, 1992). Therefore, lower P3N3 amplitudes in the high ruminator group may indicate difficulties in focusing attention and effectively processing emotional information, which are core features of rumination (Watkins and Roberts, 2020). Clinically, patients with major depressive disorder and high rumination are more sensitive to punishment than reward, (Whitmer et al., 2012). In general, rumination is considered a maladaptive mechanism that disrupt reinforcement learning (Hitchcock et al., 2022). However, in certain contexts (e.g. a more reflective style of rumination), ruminators may be more attuned to learn from reward outcomes (Whitmer and Gotlib, 2013) and/or more susceptible to punishment (Eshel and Roiser, 2010). Our findings do not align with this, as those with higher rumination exhibited lower P3N3 amplitudes, but independent of condition. One explanation may be that patients with major depressive disorder and high rumination, react differently to punishment than healthy controls, considering that higher rumination is associated with e.g. depression and its symptoms (Nolen-Hoeksema, 2000). Meta-analytic data have shown that high ruminators show more difficulty in performing cognitive tasks such as those that target inhibitory cognitive control or general executive function (Yang et al., 2017). The present results may suggest that anticipating a subsequent painful stimulation (same or more intensity) after an auditory feedback (the operant effector) does not significantly impact the P3N3 amplitudes. Consequently, it may be speculated that high rumination makes individuals more susceptible to poor performance in cognitive tasks due to an overall lower capacity of resource allocation during the performance but is unaffected by saliency and modality of the outcome. Therefore, future studies may investigate the relative impact of rumination on P3N3 during a forced-choice task such as the Go/No-Go task, which may reveal more concrete evidence on the impact of rumination on resource allocation.

P300 latencies, operant conditioning, rumination

Our findings demonstrate a significant delay in P300 latency when participants received auditory feedback on an incorrect answer and thus received punishment (more pain/same pain) in the operant conditioning paradigm. This is consistent with previous research suggesting that the P300 component is sensitive to reinforcement learning and that delayed latencies may indicate difficulties in processing negative feedback (Glazer et al., 2018). For instance, an earlier study demonstrated that patients with major depressive disorder and without dementia showed consistently slower latencies and performance on executive function tasks such as the Stroop and Wisconsin Card Sorting Test (Kindermann et al., 2000). Therefore, the observed delay in P300 latency could reflect increased cognitive effort required to process and respond to punishment (higher or same pain intensity), potentially due to the emotional salience of the aversive stimulus. Additionally, it may indicate difficulties in shifting attention away from the negative outcome. This may be of interest for future studies, as our results suggest a trend of difference between high and low rumination groups in P300 latencies following auditory feedback. Such difficulties in attention shift has been shown in people with mild cognitive impairments where the P300 latency was slower in response to attention- and memory tasks (Demirayak et al., 2023) and delayed P300 latencies have been reported in psychiatric and neurological and neurodegenerative disorders where cognition is affected (Olichney et al., 2022). In healthy participants, an earlier study demonstrated that a ruminative style together with cognitive load predicted poor performance on a continuous performance task (Brinker et al., 2013). In agreement, a study from Procento et al. (2021) reported that participants undergoing acute pain, using ischemic pain, and exhibited high levels of catastrophizing, performed worse in a working memory task performance. Furthermore, it is known that cognition is influenced by pain and that persistent pain increase the risk for cognitive impairments in older adults, specifically pain interference with cognitive abilities but not pain intensity per se (Bell et al., 2022). For instance, individuals living with persistent pain, often present with co-morbid depression, and higher rumination thoughts that influence cognitive processes involved in attention and conflict-handling (Alderman et al., 2020). This was highlighted in fibromyalgia patients

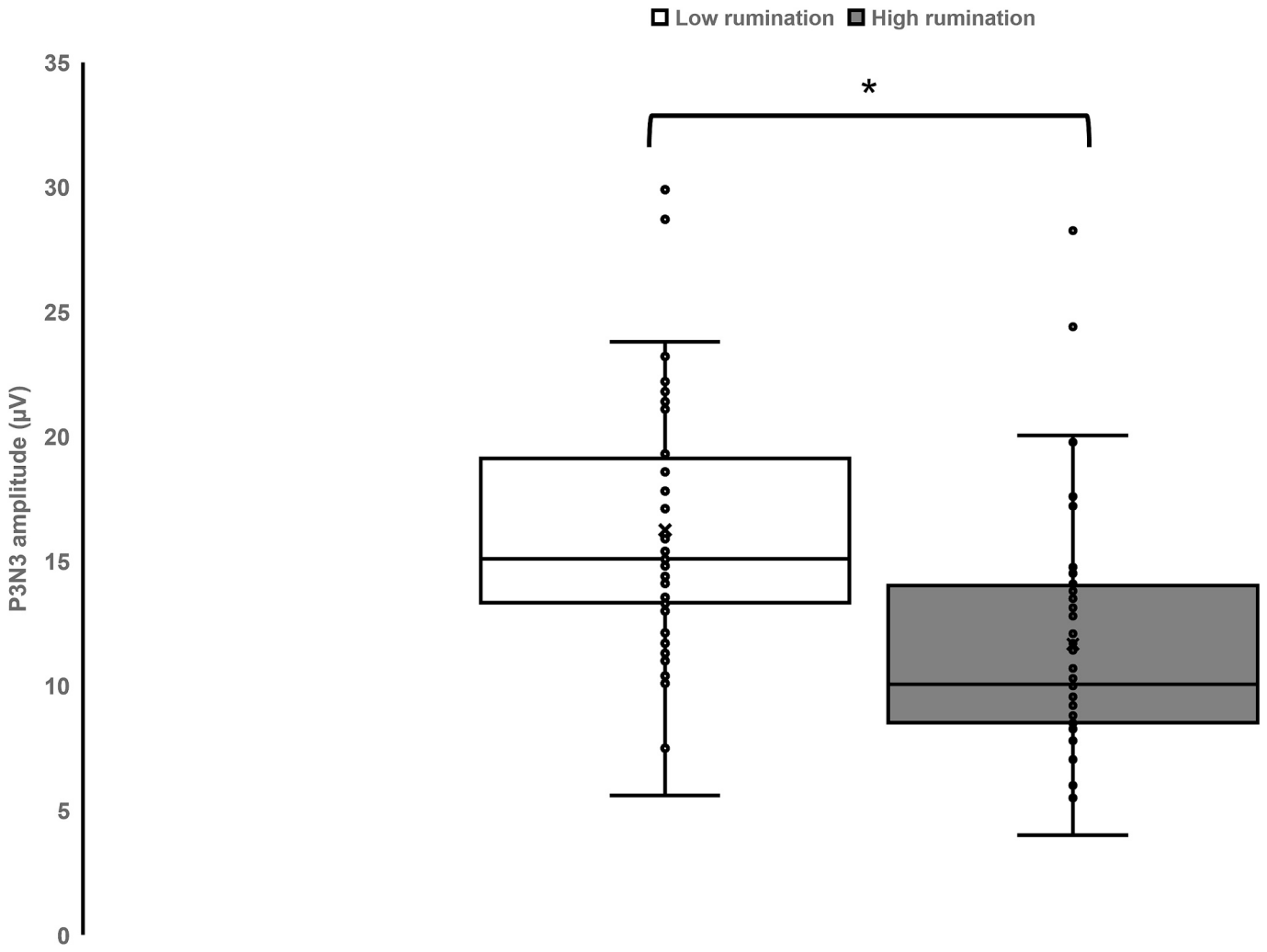

Fig. 4. Boxplot with individual data of P3N3 amplitudes in the groups divided by the median split of the Rumination scores. A significantly lower P3N3 amplitude was found for subjects with high rumination thoughts. *: $p < 0.05$. The boxplot depicts median, interquartile ranges (25 % and 75 %), and the high and low extremes.

where those with high levels of pain catastrophizing, also performed the worst in a trail making test (Galvez-sánchez et al., 2018). Investigating how a delay in P300 latencies reflects worse cognitive processing may be of interest in future studies, using operant conditioning paradigms that link pain relief or worsening to cognitive performance.

Limitations

Despite the novel method of investigating cognitive- and error-related processing as reflected by the P3N3 complex, using pain as reinforcement or punishment in an operant conditioning paradigm, some limitations should be taken into account when interpreting the results. As it is known, peak latency measures are sensitive to many factors like e.g. noise and individual variability but remains a good measure of the timing of an ERP component, and, together with peak-to-peak amplitude, provide more information on sensory processing (Clayson et al., 2013; Luck, 2005). To overcome the problem of the noise, data were low pass filtered at 40 Hz to remove the high frequency components that could disrupt the signal. Usually, cortical reward and punishment responses have been examined using peak ERP values, which provide insights into the specific neural processes involved in the cognitive, sensory, and emotional aspects of information processing (Meyer et al., 2021). However, peak amplitudes come with methodological drawbacks such as the background noise that can affect the EEG signal to a very high degree (Clayson et al., 2013; Luck, 2005) and the baseline stability due to the subtraction of the baseline or zero point of the EEG signal from the voltage value of the peak. Therefore, the current study compromised comparability by using peak-to-peak amplitudes to accommodate limitations of using peak ERP values. The generalizability of the present findings is limited by the characteristics of the sample, which was composed predominantly of healthy, relatively young, and female participants. Therefore, it remains unclear whether the observed effects would extend to more diverse populations, including males, older adults, or individuals with medical or psychiatric conditions. Future research should examine whether these results replicate across broader demographic and clinical groups to better establish their external validity. Moreover, the term of pain catastrophizing has been widely employed in pain research, yet its terminology has been criticized. A study highlights that the term carries stigmatizing connotations, often perceived by patients as invalidating or blaming, which may influence clinical interactions and undermine trust (Connoy and Webster, 2024). Similarly, Crombez et al. (2024) argue that the term lacks conceptual precision, with existing measures capturing broader constructs such as pain-related worry or distress rather than catastrophizing per se. This has little impact on the current findings but should be considered in future research.

Conclusion

This study demonstrated that individuals with higher rumination

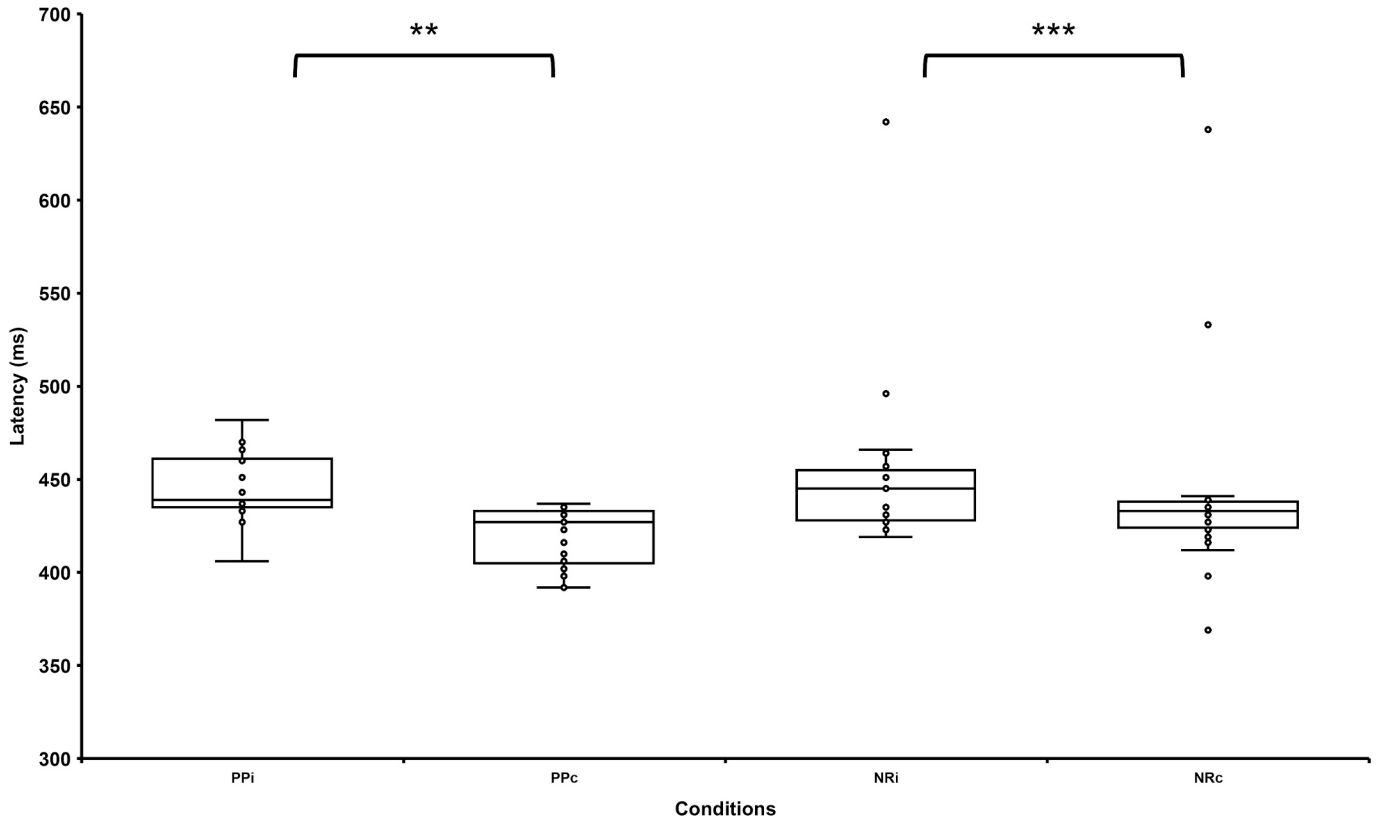

Fig. 5. Box plot of P300 latencies value. Latencies are measured in milliseconds on the y-axis and on the x-axis are represented the data divided per condition (Positive Punishment (PP) and Negative Reinforcement (NR)) and correct/incorrect answer. **: $p < 0.01$; ***: $p < 0.001$. The boxplot depicts median, interquartile ranges (25 % and 75 %), and the high and low extremes.

scores have lower P3N3 peak-to-peak amplitudes compared to those with lower rumination scores. Moreover, The P300 latencies were delayed after an incorrect answer, irrespective of condition and degree of rumination. These findings may indicate that individuals who ruminate to a greater extent, also exhibit more difficulties in painful operantly conditioned reward and punishment processing. This may have important implications for research on painful cognitive processing, particularly in context of reinforcement learning, as the latency of P300 is primarily affected by the known consequence of an incorrect answer. This suggests that error processing slows in response to an anticipated aversive outcome.

CRediT authorship contribution statement

Carolina Ceruti: Writing – original draft, Visualization, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Dennis Boye Larsen:** Writing – review & editing, Writing – original draft, Supervision, Formal analysis. **Giulia Erica Aliotta:** Writing – review & editing, Formal analysis. **Elia Valentini:** Writing – review & editing, Formal analysis. **Kristian Hennings:** Writing – review & editing, Methodology. **Carina Graversen:** Writing – review & editing, Conceptualization. **Carsten Dahl Mørch:** Writing – review & editing, Supervision, Formal analysis, Conceptualization. **Laura Petrini:** Writing – review & editing, Supervision, Formal analysis, Conceptualization.

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Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Kristian Hennings works for LabBench ApS, and kindly supported the study in the form of equipment and working hours in the lab. All other authors have no conflict of interest to declare.

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