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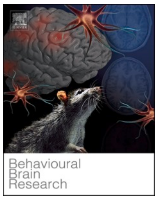

Research article

Neurophysiological correlates of reward and punishment feedback processing in individuals with test anxiety

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ABSTRACT

Understanding how individuals with high test anxiety (HTA) process evaluative feedback is essential to clarifying their responses in evaluative situations. This study examined how individuals with HTA differ from those with low test anxiety (LTA) in processing positive and negative outcomes presented in reward and punishment contexts. Using event-related potentials (ERPs) and a probabilistic learning task, we implemented separate reward and punishment blocks with test-related and test-unrelated images.

Behavioral results indicated that, across reward and punishment blocks, both HTA and LTA individuals responded more quickly and accurately as the task progressed, with no significant performance differences between the groups. ERP findings revealed no deficits in reward processing for individuals with HTA. However, during punishment processing, HTA individuals showed smaller feedback-related negativity (FRN) and larger late positive potential (LPP) amplitudes in response to negative feedback for test-related stimuli. They also exhibited larger FRN amplitudes after positive feedback for test-related stimuli, while no significant group differences were observed in P3 or LPP amplitudes. These findings suggest altered neural responses to evaluative feedback in individuals with HTA, particularly under punitive conditions, which may reflect differences in expectancy and emotional engagement.

1. Introduction

When exams or evaluative situations are perceived as threatening, test anxiety may arise, leading to excessive worry, cognitive disruption, and physiological arousal [56]. Unlike general anxiety, test anxiety is specific to evaluative contexts and can markedly impair academic performance and well-being [50]. From a feedback-based perspective, individuals continuously form and update value predictions about future outcomes based on prior experience and feedback [43]. Those with high test anxiety (HTA) tend to associate evaluative cues with potential failure, resulting in negative value expectations and altered responsiveness to evaluative feedback [47]. Understanding how test anxiety influences evaluative feedback processing is essential for clarifying why anxiety disrupts performance under evaluation.

Test anxiety has been less examined in the context of how individuals process reward- and punishment-related feedback. Feedback-based tasks provide a framework for studying how individuals process relationships between behavior and outcome [6]. Research shows that individuals with high anxiety often overestimate the likelihood of negative outcomes, which intensifies perceived negative consequences [5]. This negative expectation bias is associated with sensitivity to rewards and punishments. Positive expectations are correlated with higher reward sensitivity and lower punishment sensitivity [26,45], whereas negative expectations are associated with greater punishment sensitivity and reduced reward sensitivity [30]. Individuals with high anxiety tend to undervalue rewards and overvalue punishments, leading to low reward sensitivity and high punishment sensitivity [31]. This imbalance has been associated with reduced responsiveness to reward-related feedback [32] and promotes faster avoidance behavior in punishment scenarios [10,34].

It is uncertain whether individuals with HTA display the same patterns of low reward sensitivity and high punishment sensitivity as those with general anxiety, marked by negative expectation bias and heightened sensitivity to negative feedback. A study using the Iowa Gambling Task revealed that HTA individuals tend to choose loss options more frequently [8], indicating a greater inclination toward

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punishment-based feedback. Processing efficiency theory suggests that anxious individuals allocate substantial attentional resources to managing stress, making them more susceptible to distraction from threat-related stimuli, which can disrupt efficient processing of evaluative feedback [2,12]. Additionally, individuals with HTA exhibit an attentional bias toward test-related stimuli [24,57]. Thus, we expected that HTA individuals would exhibit distinct neural responses to evaluative feedback, particularly stronger responses to negative feedback and reduced responsiveness to positive feedback in test-related and punishment contexts.

This study employed a probabilistic learning task [20] in which participants received positive or negative feedback within a limited time or number of trials by repeatedly selecting among different options to optimize decision-making and adjust their behavior to maximize rewards. We used both test-related and test-unrelated images as stimuli in separate reward and punishment blocks.

Feedback-based learning can be understood within the reinforcement learning (RL) framework, in which outcomes are compared with expectations to generate prediction error signals that reflect the comparison between expected and actual outcomes [21,46]. These neural signals are reflected in event-related potential (ERP) components sensitive to outcome valence and motivational salience.

The feedback-related negativity (FRN) is a frontocentral negative deflection peaking around 250–350 ms after feedback and is widely considered an electrophysiological marker of prediction error processing [22,38]. This interpretation is supported by studies employing computational modeling and single-trial EEG analyses [14,9]. The FRN is typically more negative (larger) following unfavorable outcomes and less negative (smaller) following favorable ones. In reinforcement learning theory, this component reflects a reward prediction error—the difference between obtained and expected outcomes—indicating whether feedback is better or worse than expected [21]. The positive-going deflection following rewarding outcomes, often referred to as the reward positivity (RewP), has also been associated with individual differences in reward sensitivity and emotional processing [37]. Other accounts suggest that activity in this time window represents the salience, or absolute magnitude, of prediction errors regardless of valence [11,3].

In this study, separate reward and punishment blocks were used, and the term FRN refers broadly to the neural response in this window, encompassing both the negative-going deflection to unfavorable outcomes and the positive-going deflection to rewards. Importantly, in the present study, it is used solely as an index of outcome evaluation [23,39,51]. Even if individuals with HTA may show heightened punishment sensitivity and reduced reward sensitivity, they also tend to hold more negative expectations. Under such expectations, we suggested that negative outcomes were evaluated as less unexpected, resulting in smaller FRN amplitudes, whereas positive outcomes were evaluated as more unexpected, producing larger FRN amplitudes. Consistent with prior work, individuals with high anxiety often exhibit smaller FRN responses to negative outcomes, which has been attributed to stronger anticipation of negative events rather than to learning-related prediction-error computation [27].

The feedback-related P3 component is a positive deflection peaking between 300–600 ms over centro-parietal sites, reflecting the allocation of attentional resources to motivationally relevant feedback [19,35]. Larger P3 amplitudes are typically observed for unexpected or highly salient feedback, indexing the updating of outcome expectancies [4]. The P3 is also sensitive to the motivational value of feedback, being enhanced for rewards or losses that carry higher affective significance [13]. Previous studies suggest that individuals with high anxiety exhibit reduced P3 amplitudes to positive feedback, indicating diminished motivational engagement or impaired utilization of reward information [33].

The late positive potential (LPP), which activates between 500 and 600 ms, is associated with the sustained emotional and motivational processing of salient feedback. It has been primarily studied in emotion research, showing increased sensitivity to negative stimuli [18]. In feedback processing, the LPP is larger in response to negative feedback than to positive feedback, potentially influencing behavioral adjustments [15,49]. In the present study, we expected that individuals with HTA would exhibit enhanced LPP responses to negative or test-related feedback, reflecting sustained processing of evaluative threat. This expectation was exploratory, as empirical evidence on LPP modulation during feedback processing in anxious individuals remains limited.

Feedback processing in evaluative contexts can be viewed as the integration of motivational salience and affective evaluation [11,1]. Individuals with HTA may exhibit a bias toward test-related cues and a reduced utilization of positive feedback, particularly when feedback is associated with punishment content [54,53]. In contrast, individuals with low test anxiety (LTA) may maintain more balanced feedback processing from both reward and punishment. Examining these processes at the neural level can help to clarify whether anxiety-related differences emerge primarily during early outcome evaluation (FRN), attention allocation (P3), or sustained affective appraisal (LPP).

Therefore, the present study aimed to examine how individuals with HTA process feedback in reward and punishment contexts, and how these patterns are reflected in ERP components during a probabilistic learning task using test-related and test-unrelated stimuli. We expected that HTA individuals would show (a) smaller FRN to negative feedback and larger FRN to positive feedback, particularly under punishment contexts and test-related conditions, as negative outcomes are more consistent with their expectations, whereas positive outcomes are less expected; (b) larger P3 amplitudes to negative feedback, reflecting greater attentional allocation to motivationally significant feedback; and (c) larger LPP amplitudes to test-related negative feedback, reflecting sustained processing of evaluative threat.

2. Methods

2.1. Participants

Participants were recruited online and through flyers, with a total of 347 undergraduate students from Nanjing University assessed using the Chinese version of the Test Anxiety Scale (TAS-C) and the Beck Depression Inventory (BDI-II-C). Inclusion criteria required a TAS score of ≥ 20 or ≤ 12 [52] and a BDI-II-C score of ≤ 13 to exclude depressive symptoms. Participants scoring ≥ 20 on TAS-C were assigned to the HTA group, and those scoring ≤ 12 were assigned to the LTA group [52].

The power analysis was based on detecting a medium effect size (f=0.25) for within-between interactions in the ANOVA design, which was a reasonable expectation given related studies [24,52,57]. Sample size calculations indicated a minimum of 50 participants was needed based on specific parameters (mixed repeated measures ANOVA, α=.05, $1-\beta$=.8, effect size f=.25, groups=2, measurements=4). Ultimately, 61 participants were recruited, with 32 in the HTA group and 29 in the LTA group. However, data from one HTA participant were lost due to a connection issue. Six others were excluded due to excessive movement artifacts in their EEG recordings (resulting in <80 % usable trials even after artifact correction), resulting in a final sample of 54 valid participants: 27 HTA (TAS-C: 24.19 ± 3.41; BDI-II-C: 7.78 ± 2.72) individuals (20.78 ± 2.62 years, 17 females) and 27 LTA (TAS-C: 9.26 ± 2.19; BDI-II-C: 4.67 ± 4.31) individuals (21.92 ± 2.80 years, 16 females).

A sensitivity analysis was conducted using G*Power 3.1 (mixed repeated-measures ANOVA: within–between interaction, α=.05, power=.8, total sample size = 54, groups=2, measurements=4). With the final sample (N = 54), the design was sensitive to detecting effects of f = 0.24 (partial η^2 =.053).

All participants were right-handed, had normal or corrected vision, and reported no history of mental illness. The two groups did not differ in age, gender, or handedness. Participation was voluntary, with informed consent obtained prior to the experiment, and participants received payment of 90–110 yuan based on their performance. The study was approved by the Ethics Committee of Nanjing University (NJUPSY202304007), and it was performed in accordance with the approved guidelines.

2.2. Materials

All images were selected from the test anxiety picture system [55] and included four low-threat test-related images (T25, T38, T62, T63) and four low-threat test-unrelated images (N17, N42, N70, N75) (see Supplementary). Normative ratings provided by the database for these specific images, including test-relatedness, valence, arousal, and threat, are reproduced in Table 1. According to these norms, the two image categories differ primarily in test-relatedness while both fall within a low-threat range, which aligns with our intention to use test-related but non-intense stimuli.

The database creators standardized luminance and visual complexity across stimuli during construction, although numerical values could not be reported. We selected low-threat images to maintain ecological relevance to evaluative contexts while avoiding strong affective stimuli that might mask group differences in feedback processing.

The "Test-relatedness" column in Table 1 is an index from the Test Anxiety Picture System [55], indicating the degree of test-situation relevance for each image (lower values indicate greater test-relatedness). The test-related pictures depicted mild exam-related scenarios (e.g., students in a classroom or taking a test), designed to represent evaluative situations. The test-unrelated pictures depicted neutral everyday scenes without any test or evaluative elements (e.g., people or objects in non-threatening situations).

Each participant saw a total of 8 images throughout the experiment. Four images (2 test-related and 2 test-unrelated) were used in the reward block, and a different set of four images (2 test-related and 2 test-unrelated) was used in the punishment block. The images were not repeated across the reward and punishment blocks to ensure that learning in the second block was not confounded by familiarity from the first block.

The images were displayed in the center of the screen, one at a time, with key prompts shown at the bottom of the screen. The feedback stimuli used in this experiment were all related to monetary outcomes, including gains for the reward block (+10) and no gain (+0), as well as losses for the punishment block (-10) and no loss (+0).

2.3. Procedure

Before the experiment, participants were informed about the non-invasive nature and principles of the EEG study. After signing the informed consent form, they washed and dried their hair in the preparation area. Participants then entered the soundproof EEG laboratory and sat 60 cm from the computer screen, instructed to focus on the center of the screen and minimize movements. The experimental procedure began with a white fixation point ("+") displayed for 300–500 ms, followed by the presentation of the image stimulus. Participants chose by pressing the "F" or "J" key within 2000 ms. Responses exceeding 2000 ms were recorded as misses and received negative feedback. After the choice, the image stimulus disappeared, and a white fixation point appeared for 800–1200 ms. Feedback stimuli were then displayed for 1000 ms, followed by a blank screen for another 1000 ms (see Fig. 1).

Table 1
The values of various dimensions of the test anxiety images used in this study.

Types	Images	Test-relatedness	Valence	Arousal	Threat
Test-related	T25	1.37	4.42	4.07	3.35
	T38	1.48	4.49	4.58	3.22
	T62	1.47	4.47	4.33	3.36
	T63	1.52	4.05	4.30	3.71
Test-unrelated	N17	2.77	4.42	4.56	3.82
	N42	3.00	4.67	4.00	3.16
	N70	2.82	4.79	4.39	3.27
	N75	2.93	4.07	4.02	3.38

Participants were instructed that they would see four different image cues and that each image was associated with one of two button responses ('F' for a left-hand choice or 'J' for a right-hand choice). Their task was to learn, through trial and error, which button was the "correct" choice for each image to maximize rewards (or minimize losses). They were informed that in the reward block, choosing the correct button for an image would usually lead to a monetary reward (+10 points), whereas choosing incorrectly might yield no reward (+0). Conversely, in the punishment block, choosing the incorrect button would usually result in a monetary loss (−10 points), whereas the correct choice would often avoid a loss (+0). The scores for gains and losses would be accumulated and factored into their final payment. Participants were informed that the feedback outcomes were probabilistic, following certain probability patterns.

The study included blocks of reward and punishment. Each block was subdivided into four sub-blocks of 80 trials each, for a total of 320 trials per block (and 640 trials overall). Within each sub-block, all four images were presented in a random sequence. Each of the four images appeared many times per sub-block (20 trials per image per 80-trial part, counterbalanced). In each block, among the two test-related images, one had a high reward (or loss-avoidance) probability (70 % when the correct key was pressed) and the other had a low probability (30 %), which remained constant throughout the block. The same applied to the two test-unrelated images. The mapping between specific stimuli and feedback contingencies was counterbalanced across participants. The order of reward and punishment blocks was randomized between subjects to avoid systematic sequence effects.

Participants took a 1-minute break between these parts to rest, and then continued with the next sub-block using the same set of images and contingencies. The experiment lasted about 50 min, with a balanced block order. A practice block of 10 trials was conducted prior to the experiment to familiarize participants with the procedure and the feedback symbols.

2.4. ERP recordings and data preprocessing

EEG data were recorded using the ESI-64 EEG system from Neuroscan, Inc. (Scan 4.5, Neurosoft Labs, Inc.) with 64 Ag/AgCl electrodes positioned on an electrode cap according to the 10–20 system. The left mastoid served as the reference, and the forehead was grounded. The bandpass filter was set to 0.05–100 Hz, with a sampling rate of 1000 Hz, and scalp impedance was maintained below 10 kΩ.

Preprocessing was conducted using EEGLAB (Version 13.0.0.0b), an open-source MATLAB toolbox. First, the electrode positions were verified. The average of the left and right mastoids served as the new reference electrode for re-referencing the data, followed by bandpass filtering between 0.01 and 40 Hz. A 50 Hz notch filter was also applied to eliminate line noise. The sampling rate was reduced to 500 Hz/channel. The EEG data were segmented with the presentation of the feedback stimulus as the zero point (200 ms before and 1000 ms after the feedback stimulus), resulting in a total analysis duration of 1200 ms. The data from the 200 ms prior to the feedback stimulus served as the baseline for correction. Independent component analysis (ICA) was used to correct for artifacts from eye movements and muscle activity. Artifacts exceeding ±100 μV were automatically removed.

EEG epochs for each participant were segmented and averaged for each experimental condition, defined by stimulus type (test-related, test-unrelated), feedback (positive, negative), and block (reward, punishment). Data from a participant were included in the analysis only if more than 80 % of trials in each condition were retained after artifact rejection. The mean and median number of valid trials per condition are reported in Supplementary Table S1. The number of retained trials did not differ significantly between groups (all $p > .05$).

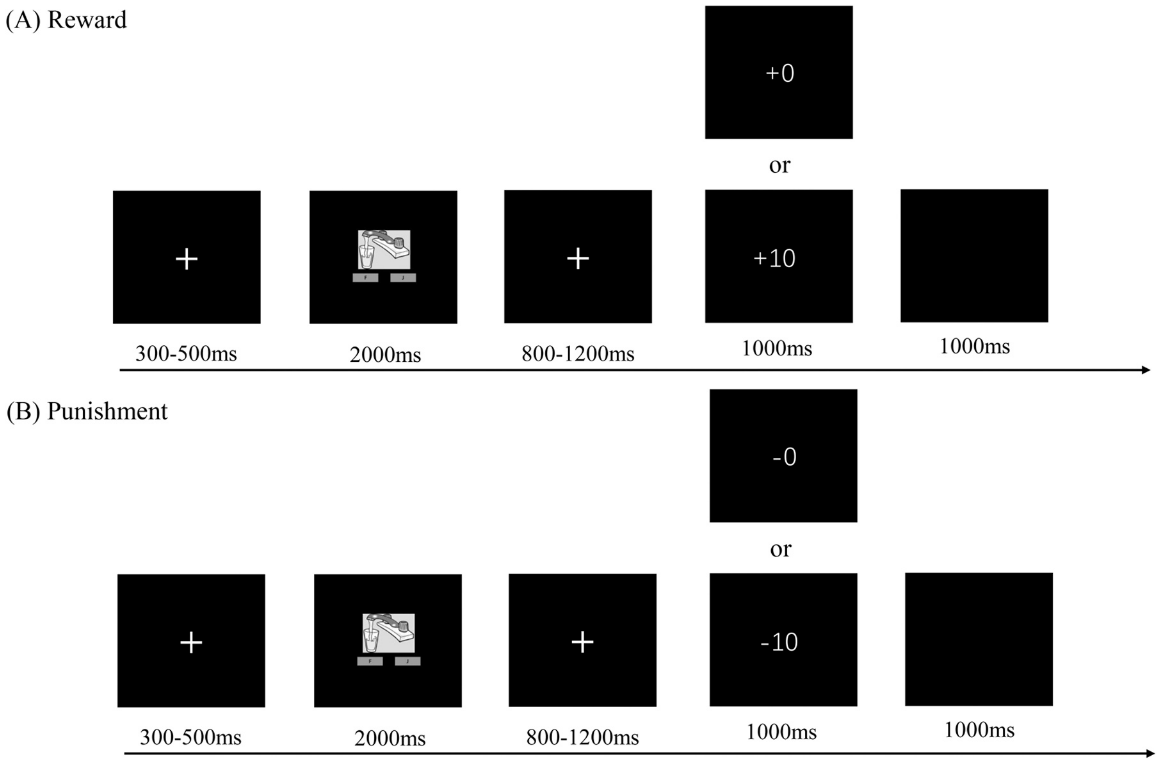

Fig. 1. Scheme of a single trial used in the reward (A) and punishment block (B).

In the amplitude analysis, the time windows were chosen based on prior literature [15,3] and confirmed by visual inspection of the grand-averaged waveforms and scalp topographies from our data, which showed clear peaks in those intervals. The average amplitude of the FRN was assessed at Fz within a 270–330 ms analysis window [21,27]. Although this window is slightly later than the conventional 200–300 ms range, visual inspection of our grand-average waveforms showed that the negative peak was maximal within this interval, making it the most appropriate latency window for capturing the FRN in the present dataset [16,17]. A supplementary check using the conventional 200–300 ms analysis window is provided in Supplementary Table S2. The average amplitude of the P3 component was examined using the CPz electrode at the centro-parietal midline, with an analysis window of 370–430 ms [13,33]. For the LPP, mean amplitudes were quantified at Pz, where the component exhibited its maximal response in the grand-average waveforms. The analysis window was set to 600–800 ms, consistent with prior work [19,49]. To ensure the robustness of this choice, we also extracted LPP amplitudes from the Pz/P1/P2 cluster, and the results were qualitatively similar (see Supplementary Table S3), supporting the reliability of our findings.

2.5. Statistical analysis

The behavioral data and ERP data obtained from the experiment were analyzed using repeated measures ANOVA with SPSS 20.0.

Greenhouse–Geisser corrections were applied when necessary. To control for multiple comparisons, Bonferroni corrections were applied within narrowly defined comparison families. Specifically, each "family" was defined as a set of related comparisons within a single ERP component (FRN, P3, or LPP) and learning context (reward or punishment block), as well as by test type (main effects, interaction effects, or simple effects). Simple-effect analyses were conducted to examine the effects of significant interactions.

For behavioral measures (reaction time and accuracy), we conducted mixed-model repeated-measures ANOVAs with test anxiety (high, low) as a between-subjects factor and stimulus type (test-related, test-unrelated) and sub-block (1–4) as within-subjects factors, separately for the reward and punishment blocks.

For ERP measures, repeated-measures ANOVAs were conducted for each component and each context. Specifically, for FRN, P3, and LPP, we performed a mixed ANOVA with test anxiety (high, low) as a factor, along with stimulus type (test-related, test-unrelated) and feedback valence (positive, negative), separately for the reward and punishment blocks.

For all major effects and pairwise comparisons, both uncorrected p-values (*p*_unc) and Bonferroni-adjusted p-values (*p*_corr) were provided, along with partial eta squared (η_p^2) and 95 % confidence intervals (CI) to facilitate transparent interpretation. All values are reported as mean ± standard error of the mean (SEM).

3. Results

3.1. Behavioral results

3.1.1. Reaction times (RTs)

Reward Block: The main effect of sub-block was significant, *F*(3156)= 14.740, *p*_unc< .001, *p*_corr< .001, η_p^2= .221, 95 % CI [.122,.301]. Post-hoc comparisons revealed that the RT in sub-block 1 (717.511 ± 24.483) was significantly slower than in sub-block 2 (657.731 ± 25.633, *p*_unc<.001, *p*_corr<.001), sub-block 3 (648.847 ± 22.137, *p*_unc<.001, *p*_corr=.001), and sub-block 4 (615.733 ± 20.091, *p*_unc<.001, *p*_corr<.001). Additionally, the RT in sub-block 3 was significantly slower than in sub-block 4 (*p*_unc=.005, *p*_corr=.030) (see Fig. 2 A). No additional pairwise differences were detected (all *p*_corr>.05).

Punishment Block: The main effect of stimulus type was significant, *F*(1,52)= 20.111, *p*_unc< .001, *p*_corr< .001, η_p^2= .279, 95 % CI [.129,.420], with test-unrelated stimuli (672.207 ± 24.262 ms) eliciting slower RTs than test-related stimuli (642.480 ± 22.302 ms).

The main effect of sub-block was also significant, *F*(3156)= 30.882,

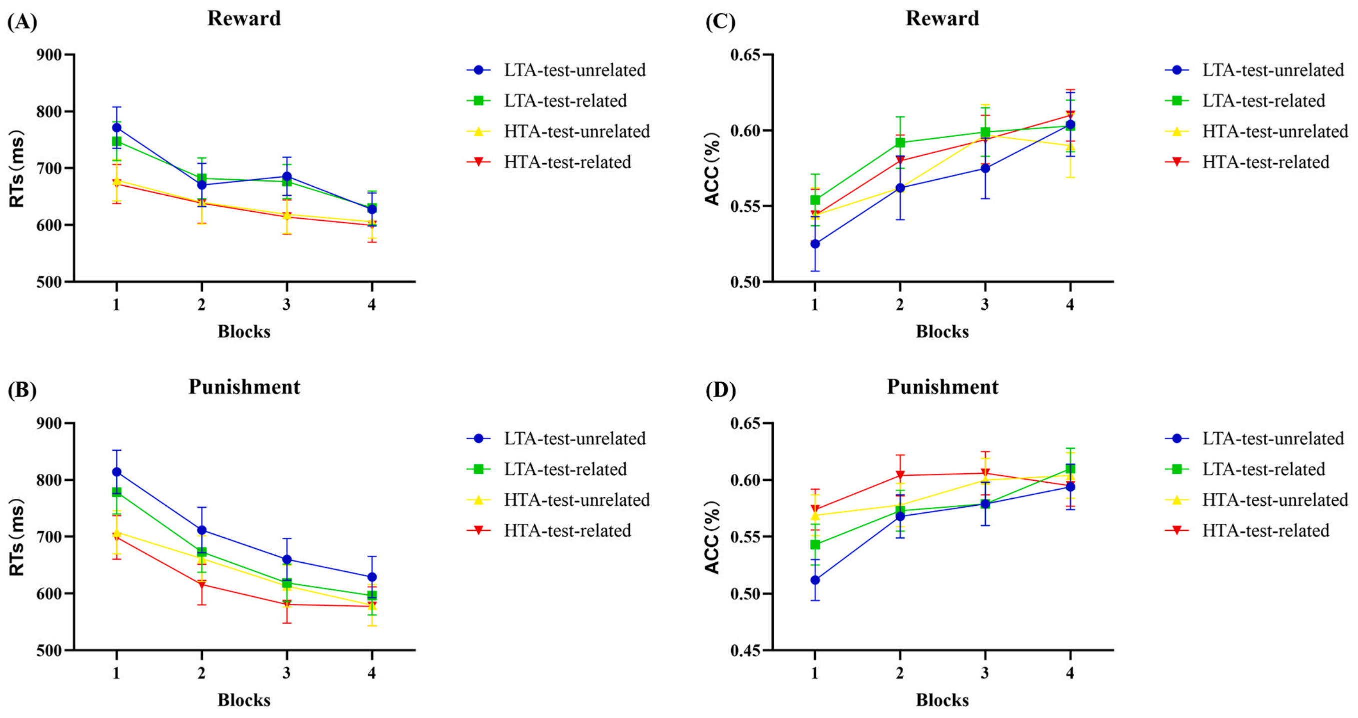

Fig. 2. The mean RTs and mean accuracy across conditions in the reward and punishment blocks (error bars represent ±1 SEM).

*p*_unc < .001, *p*_corr < .001, η_p^2= .373, 95 % CI [.270,.451]. Post-hoc comparisons showed that the RT in sub-block 1 (749.891 ± 26.351) was significantly slower than in sub-block 2 (665.564 ± 26.377, *p*_unc < .001, *p*_corr < .001), sub-block 3 (618.232 ± 24.252, *p*_unc < .001, *p*_corr < .001), and sub-block 4 (595.687 ± 24.534, *p*_unc < .001, *p*_corr < .001). Additionally, the RT in sub-block 2 was significantly slower than in sub-block 3 (*p*_unc=.002, *p*_corr=.011) and sub-block 4 (*p*_unc < .001, *p*_corr < .001) (see Fig. 2B). No additional pairwise differences were detected (all *p*_corr>.05).

No additional main effects or interactions were detected, and the corresponding effects were small with wide confidence intervals.

3.1.2. Accuracy

Reward Block: The main effect of sub-block was significant, *F* (3156)= 13.294, *p*_unc < .001, *p*_corr < .001, η_p^2= .204, 95 % CI [.108,.287]. Post-hoc comparisons indicated that the accuracy for sub-block 1 (.542 ±.010) was significantly lower than that for sub-block 2 (.574 ±.011, *p*_unc=.002, *p*_corr=.011), sub-block 3 (.591 ±.011, *p*_unc < .001, *p*_corr < .001), and sub-block 4 (.602 ±.011, *p*_unc < .001, *p*_corr < .001) (see Fig. 2 C). No additional pairwise differences were detected (all *p*_corr >.05).

Punishment Block: The main effect of sub-block was significant, *F* (3156)= 8.638, *p*_unc < .001, *p*_corr < .001, η_p^2= .142, 95 % CI [.061,.213]. Post-hoc comparisons revealed that the accuracy for sub-block 1 (.550 ±.011) was significantly lower than that for sub-block 2 (.581 ±.011, *p*_unc=.003, *p*_corr=.019), sub-block 3 (.591 ±.012, *p*_unc=.002, *p*_corr=.014), and sub-block 4 (.601 ±.012, *p*_unc < .001, *p*_corr=.001) (see Fig. 2D). No additional pairwise differences were detected (all *p*_corr >.05).

No additional main effects or interactions were detected, and the corresponding effects were small with wide confidence intervals.

3.2. ERP waveform analysis

3.2.1. The FRN

Reward Block: The main effect of feedback was significant, *F* (1,52)= 61.106, *p*_unc < .001, *p*_corr < .001, η_p^2= .540, 95 % CI [.398,.652], with negative feedback (6.638 ±.732μV) eliciting larger FRN amplitudes than positive feedback (10.960 ±.946μV; see Fig. 3).

Punishment Block: The main effect of feedback was significant, *F* (1,52)= 14.982, *p*_unc < .001, *p*_corr < .001, η_p^2= .224, 95 % CI [.079,.365], with negative feedback (7.086 ±.712μV) eliciting larger FRN amplitudes than positive feedback (9.059 ±.806μV).

The interaction between stimulus type and feedback was significant, *F*(1,52)= 6.460, *p*_unc= .047, *p*_corr= .047, η_p^2= .074, 95 % CI [.004,.220]. Simple effects analysis showed that the FRN amplitude elicited by negative feedback following test-unrelated stimuli (6.767 ±.740μV) was significantly larger than that following test-related stimuli (7.404 ±.831μV), *F*(1,52)= 5.688, *p*_unc= .021, *p*_corr= .021, η_p^2= .099, 95 % CI [.011,.241]. Under positive feedback, the FRN amplitudes did not differ significantly between test-unrelated (9.087 ±.823μV) and test-related stimuli (9.032 ±.818μV), *F*(1,52)= .032, *p*_unc= .859, *p*_corr= .859, η_p^2= .001, 95 % CI [.000,.041].

The interaction between test anxiety, stimulus type, and feedback was significant, *F*(1,52)= 5.525, *p*_unc= .023, *p*_corr= .023, η_p^2= .096, 95 % CI [.006,.210]. Accordingly, we ran follow-up 2 × 2 ANOVAs within each group (stimulus: test-related, unrelated; feedback: positive, negative).

In the LTA group, we did not detect a stimulus × feedback interaction, *F*(1,26)= .066, *p*_unc= .800, *p*_corr= .800, η_p^2= .003, 95 % CI [.000,.088].

In the HTA group, the interaction between stimulus and feedback was significant, *F*(1,26)= 7.701, *p*_unc= .010, *p*_corr= .010, η_p^2= .229, 95 % CI [.035,.435]. Simple effects analysis showed that the FRN amplitude elicited by negative feedback following test-unrelated stimuli (5.773 ± 1.144μV) was significantly larger than that following test-related stimuli (6.664 ± 1.081μV), *F*(1,26)= 5.733, *p*_unc= .024, *p*_corr= .024, η_p^2= .181, 95 % CI [.017,.397]. Under positive feedback, there was no significant difference in FRN amplitudes between test-unrelated (7.894 ± 1.164μV) and test-related stimuli (7.295 ± 1.157μV), *F*(1,26)= 1.521, *p*_unc= .228, *p*_corr= .228, η_p^2= .055, 95 % CI [.000,.214].

Comparing the HTA and LTA groups (see Fig. 4), for test-related stimuli, HTA individuals (7.295 ± 1.157μV) showed larger FRN

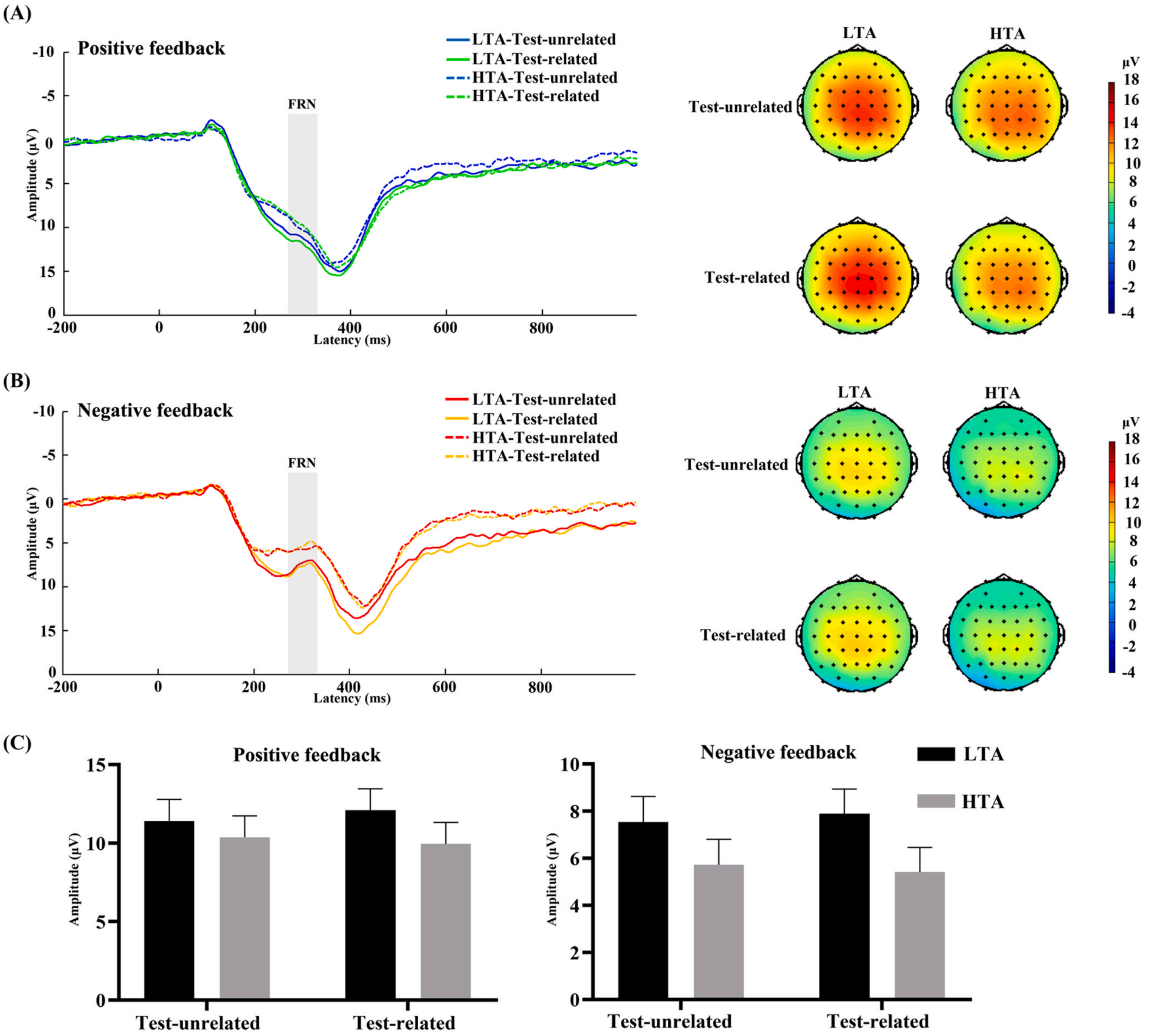

Fig. 3. Average FRN amplitudes at electrode Fz (270–330 ms) in the reward block. (A) Mean FRN amplitudes and scalp topographies for positive feedback in individuals with HTA and LTA; (B) Mean FRN amplitudes and scalp topographies for negative feedback in individuals with HTA and LTA; (C) Bar chart of mean FRN amplitudes across conditions (error bars represent ±1 SEM).

amplitudes than LTA individuals (10.768 ± 1.157μV) under positive feedback, F(1,52)= 4.505, p_unc= .039, p_corr= .039, η_p^2= .080, 95 % CI [.004,.212], whereas no significant group difference (HTA: 6.664 ± 1.001μV, LTA: 8.145 ± 1.001μV) emerged under negative feedback, F(1,52)= 1.093, p_unc= .301, p_corr= .301, η_p^2= .021, 95 % CI [.000,.126]. For test-unrelated stimuli, under positive feedback, FRN amplitudes did not differ significantly between HTA (7.894 ± 1.164μV) and LTA individuals (10.279 ± 1.164μV), F(1,52)= 2.099, p_unc= .153, p_corr= .153, η_p^2= .039, 95 % CI [.000,.162]; and under negative feedback, the two groups also did not differ significantly (HTA: 5.773 ± 1.046μV, LTA: 7.762 ± 1.046μV), F(1,52)= 1.807, p_unc= .185, p_corr= .185, η_p^2= .034, 95 % CI [.000,.152]. No additional main effects or interactions were detected, and the corresponding effects were small with wide confidence intervals.

3.2.2. P3

Reward Block: The main effect of feedback was significant, F(1,52)= 10.523, p_unc= .002, p_corr= .002, η_p^2= .168, 95 % CI [.038,.304], with negative feedback (13.169 ± 1.105μV) eliciting lower P3 amplitudes than positive feedback (15.128 ± 1.030μV; see Fig. 5).

Punishment Block: The interaction between stimulus type and feedback was significant, F(1,52)= 6.517, p_unc= .014, p_corr= .014, η_p^2= .111, 95 % CI [.009,.225]. Simple effects analysis indicated that the P3 amplitude elicited by negative feedback following test-unrelated stimuli (12.308 ± 1.040μV) was slightly lower (not reaching significance) than that following test-related stimuli (13.096 ± 1.061μV, F(1,52)= 3.901, p_unc= .054, p_corr= .054, η_p^2= .070, 95 % CI [.000,.197].

Under positive feedback, there was no significant difference in P3 amplitudes between test-unrelated (13.267 ±.936μV) and test-related stimuli (12.801 ±.913μV; see Fig. 6), F(1,52)= 1.527, p_unc= .222, p_corr= .222, η_p^2= .029, 95 % CI [.000,.143]. No additional main effects or interactions were detected, and the corresponding effects were small with wide confidence intervals.

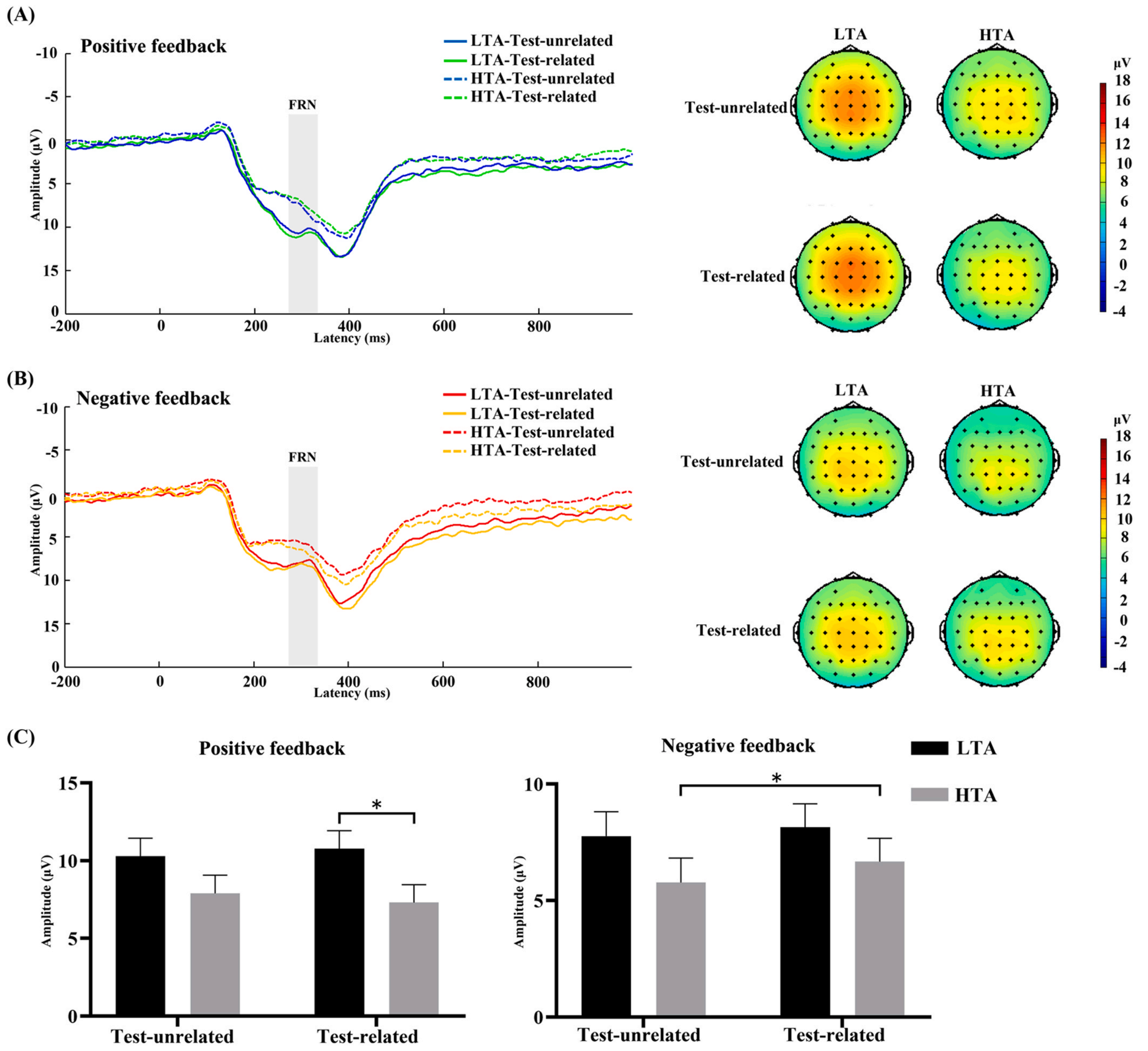

Fig. 4. Average FRN amplitudes at electrode Fz (270–330 ms) in the punishment block. (A) Mean FRN amplitudes and scalp topographies for positive feedback in individuals with HTA and LTA; (B) Mean FRN amplitudes and scalp topographies for negative feedback in individuals with HTA and LTA; (C) Bar chart of mean FRN amplitudes across conditions (error bars represent ±1 SEM). *p_corr < .05.

3.2.3. LPP

Reward Block: The main effect of feedback was significant, $F(1,52)$= 5.179, p_unc= .027, p_corr= .027, η_p^2= .091, 95 % CI [.004,.203], with negative feedback (5.555 ±.768μV) eliciting larger LPP amplitudes than positive feedback (4.652 ±.700μV; see Fig. 7).

Punishment Block: The main effect of feedback was significant, $F(1,52)$= 5.819, p_unc= .019, p_corr= .019, η_p^2= .101, 95 % CI [.006,.215], with negative feedback (5.399 ±.686μV) eliciting slightly larger LPP amplitudes than positive feedback (4.495 ±.645μV).

The interaction between stimulus type and feedback was significant, $F(1,52)$= 4.635, p_unc= .036, p_corr= .036, η_p^2= .082, 95 % CI [.001,.192]. Simple effects analysis revealed that the LPP amplitude elicited by negative feedback after test-unrelated stimuli (4.929 ±.690μV) was significantly lower than that elicited after test-related stimuli (5.870 ±.734μV), $F(1,52)$= 5.908, p_unc= .019, p_corr= .019, η_p^2= .102, 95 % CI [.013,.244]. Under positive feedback, there was no significant difference in LPP amplitudes between test-unrelated (4.464 ±.633μV) and test-related stimuli (4.526 ±.689μV), $F(1,52)$= .043, p_unc= .863, p_corr= .863, η_p^2= .001, 95 % CI [.000,.045].

The interaction among test anxiety, stimulus type, and feedback was significant, $F(1,52)$= 5.156, p_unc= .027, p_corr= .027, η_p^2= .090, 95 % CI [.004,.202]. Accordingly, we ran follow-up 2 × 2 ANOVAs within each group (stimulus: test-related, unrelated; feedback: positive, negative).

In the LTA group, we did not detect a stimulus × feedback interaction, $F(1,26)$= .006, p_unc= .800, p_corr= .800, η_p^2= .000, 95 % CI [.000,.108].

In the HTA group, the interaction between stimulus and feedback was significant, $F(1,26)$= 11.013, p_unc= .003, p_corr= .003, η_p^2= .298, 95 % CI [.082,.493]. Simple effects analysis showed that the LPP amplitude elicited by negative feedback after test-unrelated stimuli (3.833 ±.929μV) was significantly lower than that elicited after test-

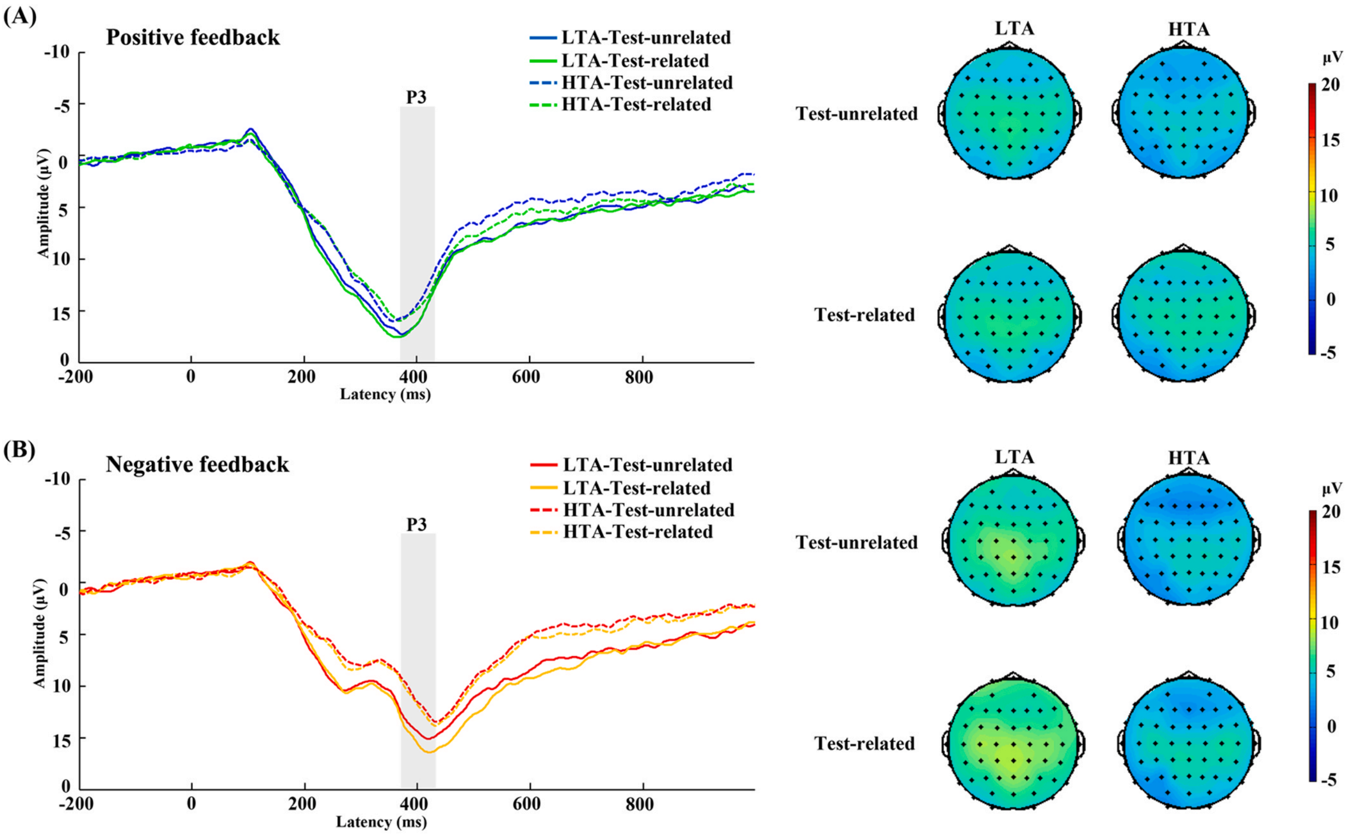

Fig. 5. Average P3 amplitudes at electrode CPz (370–430 ms) in the reward block. (A) Mean P3 amplitudes and scalp topographies for positive feedback in individuals with HTA and LTA; (B) Mean P3 amplitudes and scalp topographies for negative feedback in individuals with HTA and LTA.

related stimuli (5.489 ±.956μV), $F(1,26)= 9.612$, p_unc= .005, p_corr= .005, $\eta_p^2= .270$, 95 % CI [.065,.474]. Under positive feedback, there was no significant difference in LPP amplitudes between test-unrelated (3.828 ±.802μV) and test-related stimuli (3.676 ±.933μV; see Fig. 8), $F(1,26)= .168$, p_unc= .685, p_corr= .685, $\eta_p^2= .006$, 95 % CI [.000,.129].

However, we did not detect reliable differences between the HTA and LTA groups (all p_corr >.05; effects were small with wide CIs). No additional main effects or interactions were detected, and the remaining effects were small with wide confidence intervals.

4. Discussion

This study employed a probabilistic learning task with ERPs to examine how individuals with HTA process outcomes in reward and punishment contexts, using both test-related and test-unrelated stimuli. Consistent with the task design, both HTA and LTA groups improved in speed and accuracy over successive sub-blocks, indicating performance improvement across blocks. Importantly, ERP results revealed no significant group differences in the reward block. In the punishment block, within HTA individuals, negative feedback elicited smaller FRN amplitudes for test-related than for test-unrelated stimuli, suggesting reduced expectancy violation when the feedback aligned with their threat-related expectations. This was accompanied by larger LPP amplitudes, reflecting stronger emotional engagement with negative outcomes. No group differences emerged in P3 amplitudes. In contrast, HTA individuals showed larger FRN responses to positive feedback on test-related stimuli relative to LTA individuals, whereas LPP amplitudes did not differ significantly between the two groups. These ERP differences suggest that individuals with HTA may process evaluative feedback differently under evaluative threat, showing reduced neural responses to expected negative outcomes and increased sensitivity to unexpected positive outcomes. However, as behavioral performance did not differ between groups, these neural patterns should be interpreted as reflecting differences in affective or expectancy processing rather than differences in learning performance or ability.

Notably, we found no significant differences in behavioral performance between HTA and LTA individuals in either reward or punishment blocks. In the reward block, this outcome was contrary to our expectations. Unlike findings in some other anxiety populations, HTA individuals did not show altered behavioral responses during reward processing [32,31]. One possible explanation is that our use of low-threat test-related and unrelated stimuli, along with the low-stakes context, may have reduced the perceived evaluative threat. Under such conditions, rewards may have overshadowed any residual test-related anxiety, allowing HTA participants to allocate sufficient cognitive resources to the task and achieve performance comparable to LTA individuals. This interpretation aligns with prior work suggesting that the impact of test anxiety is highly context-dependent [50] and that performance impairments are more likely when tests are framed as high-stakes or punitive [29]. In the reward context of our study, where evaluative pressure was minimal and positive outcomes were emphasized, HTA individuals may not have experienced a sufficiently strong anxiety response to disrupt their task performance.

In the punishment block, we also did not observe behavioral accuracy or speed differences between the HTA and LTA groups. This suggests that both groups were similarly successful in task performance, despite potential underlying differences in how they processed feedback. ERP data provided further insight: across both groups, negative feedback following test-related stimuli elicited a larger LPP than feedback following unrelated stimuli, reflecting heightened emotional salience under evaluative threat. This pattern suggests that the combination of test-related cues and punitive outcomes was emotionally impactful for all participants, potentially motivating comparable levels of

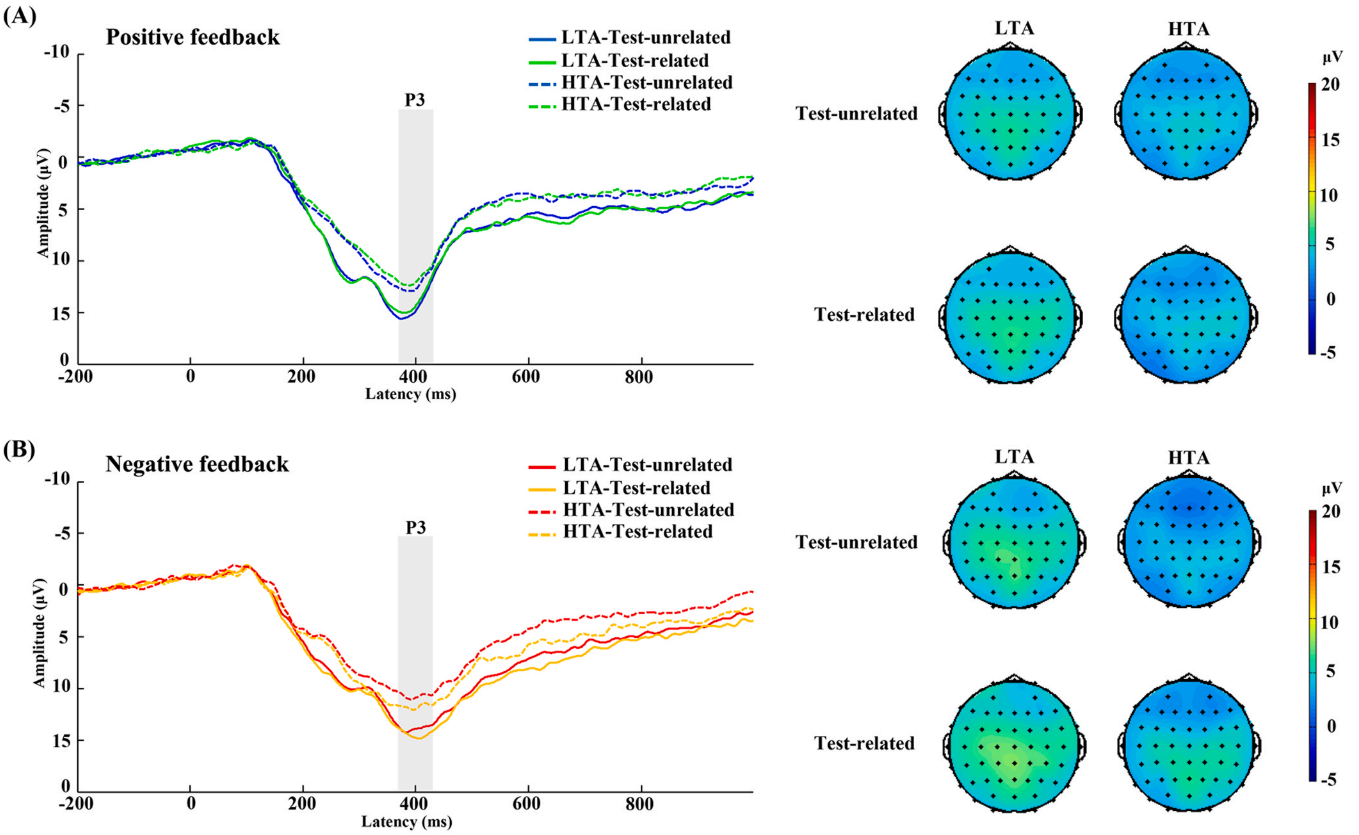

Fig. 6. Average P3 amplitudes at electrode CPz (370–430 ms) in the punishment block. (A) Mean P3 amplitudes and scalp topographies for positive feedback in individuals with HTA and LTA; (B) Mean P3 amplitudes and scalp topographies for negative feedback in individuals with HTA and LTA.

attentional engagement and effort. Neural differences in the absence of behavioral effects emphasize that ERP results reflect variations in affective or cognitive processing, not direct deficits in learning outcomes.

Crucially, differences related to test anxiety emerged primarily in feedback-locked ERPs, particularly in the FRN component. Within the HTA group, they exhibited a smaller FRN amplitude in response to negative feedback on test-related stimuli compared to unrelated stimuli, a pattern consistent with accounts proposing that expected negative outcomes elicit reduced neural responses [16,17,27]. This may indicate that HTA individuals held more pessimistic expectations for test-related trials, leading to smaller neural responses when those expectations were confirmed. Importantly, in the absence of behavioral-level verification, this neural pattern likely reflects altered evaluative processing rather than impaired learning. In other words, HTA individuals may be more cognitively and emotionally prepared for negative outcomes, leading to altered encoding of failure-related information without observable behavioral differences.

In contrast, HTA individuals exhibited larger FRN amplitudes in response to positive feedback on test-related stimuli compared to LTA individuals. This finding suggests that positive feedback may contradict the negative performance expectations of HTA individuals, eliciting an FRN pattern that aligns with prediction-error accounts. However, prediction errors were not directly assessed in this study. Similar responses have been observed in socially anxious individuals who show heightened neural reactivity to praise that contradicts their negative self-image [7]. However, since HTA participants maintained normal task performance, the enlarged FRN does not necessarily indicate impaired performance. Rather, it may reflect increased cognitive effort to process feedback that is incongruent with internal expectations. This interpretation aligns with prior work showing that anxious individuals may struggle to integrate unexpected positive outcomes, particularly under cognitive load or evaluative stress [52,44]. While our data do not directly assess learning updates on a trial-by-trial basis, the observed FRN patterns suggest a sensitivity to expectancy violation that may contribute to altered feedback processing in test-anxious individuals.

HTA individuals' difficulty in processing positive feedback in evaluative contexts may help explain the persistence of test anxiety. In punishment situations, positive outcomes such as good grades may fail to reduce future anxiety when they conflict with expectations of failure. Educational environments that emphasize negative outcomes while treating success as a baseline may reinforce this discrepancy. Consequently, HTA individuals might perceive success as temporary and focus disproportionately on potential failure. Our ERP findings support this interpretation: HTA individuals showed stronger LPP responses to negative feedback on test-related stimuli, compared to LTA individuals. They also exhibited larger FRN responses to positive feedback on test-related stimuli, relative to LTA individuals, when such positive feedback violated their negative performance expectations. These neural patterns suggest that individuals with HTA process evaluative feedback differently at the cognitive-affective level. Prior studies have similarly shown that anxious individuals exhibit heightened responsiveness to negative feedback [27,28,48], which over time may bias feedback monitoring and sustain anticipatory anxiety in evaluative settings.

The LPP findings provided additional insight into emotional processing during feedback evaluation. Across both reward and punishment contexts, negative feedback elicited larger LPP amplitudes than positive feedback for all participants. This finding is consistent with previous research indicating that the LPP is particularly sensitive to emotionally salient and aversive information [36,49].

Notably, the effect was more pronounced when negative feedback was paired with test-related stimuli, especially during punishment processing, where negative outcomes related to test cues triggered stronger emotional arousal, as reflected by significantly greater LPP amplitudes compared to unrelated stimuli. Although this pattern was

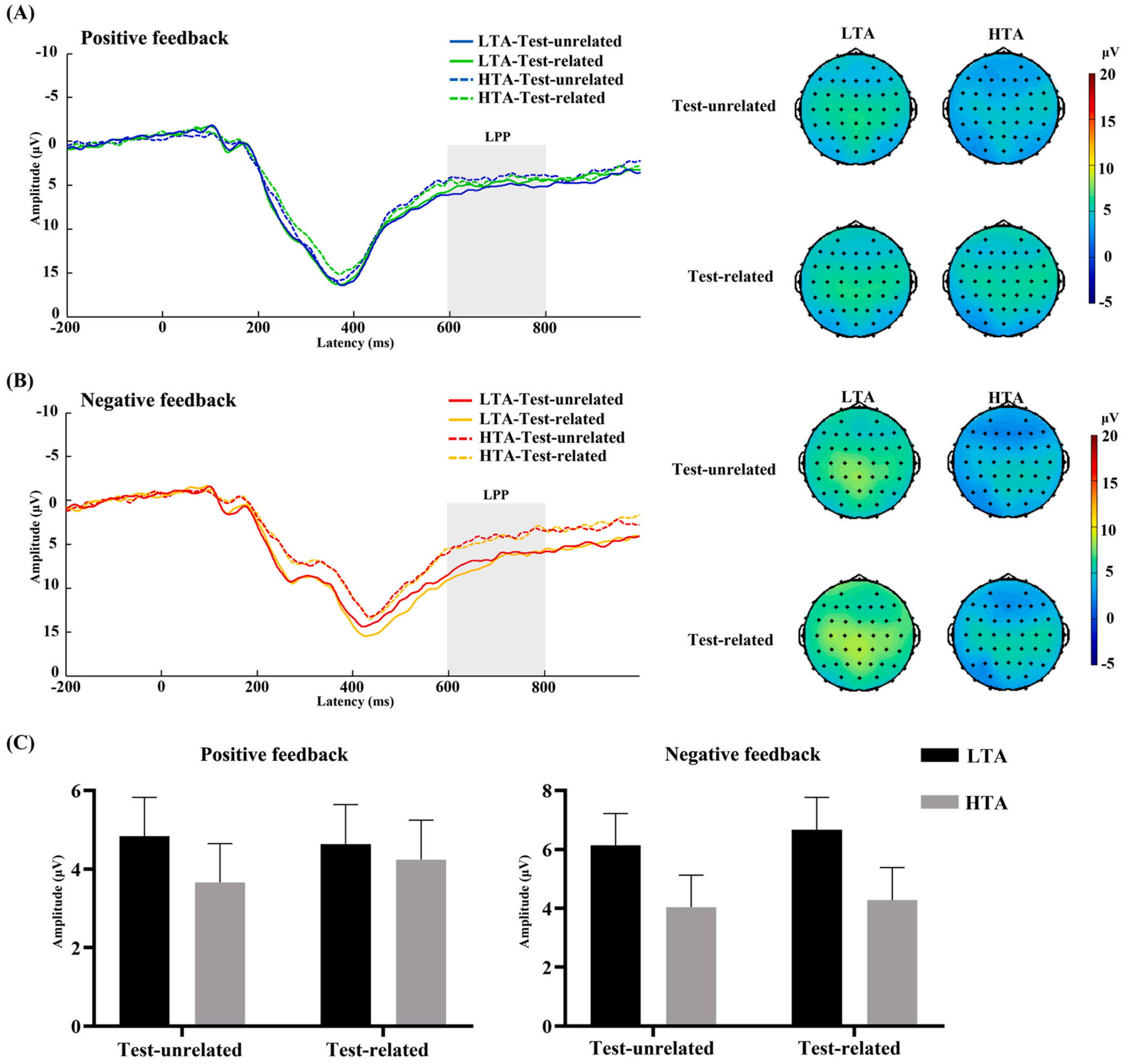

Fig. 7. Average LPP amplitudes at electrode Pz (600–800 ms) in the reward block. (A) Mean LPP amplitudes and scalp topographies for positive feedback in individuals with HTA and LTA; (B) Mean LPP amplitudes and scalp topographies for negative feedback in individuals with HTA and LTA; (C) Bar graph of mean LPP amplitudes (error bars represent ±1 SEM) across all conditions.

present across participants, follow-up analyses revealed that it was primarily driven by individuals with HTA: even when negative outcomes were anticipated, as indicated by the reduced FRN, the LPP results suggest that the emotional impact of evaluative failure remained particularly strong for those with HTA. Thus, the combination of a smaller FRN and a larger LPP in response to test-related negative feedback suggests that such feedback serves more as confirmation of preexisting concerns than as new information. Rewards may mitigate the negative aspects in reward contexts, and the strong emotional reactions to negative feedback in punishment scenarios underscore a deeper distress rather than surprise in response to test-related stimuli. Taken together, the findings suggest that for anxious individuals, test-related negative feedback is not only anticipated but also deeply felt, reinforcing the emotional association between testing situations and distress.

The P3 component did not differ significantly between the HTA and LTA groups, consistent with previous research indicating that anxiety has a minimal effect on P3 amplitude [27]. In our study, P3 responses were shaped more by feedback valence and context than by anxiety level. During reward processing, P3 amplitudes were larger for positive feedback across participants, likely reflecting increased attention to expected gains. This supports the idea that P3 is sensitive to outcome expectancy and motivational significance [13]. In the punishment block, negative feedback to test-related stimuli elicited slightly larger P3 amplitudes than feedback to unrelated stimuli across groups, suggesting that test-related cues drew more attention under threat [33]. However, because these effects did not vary by group, the differences between HTA and LTA individuals likely lie in later evaluative and emotional stages of processing, as captured by the FRN and LPP.

In summary, individuals with HTA showed a distinct pattern of neural responses to feedback. While their behavioral performance did

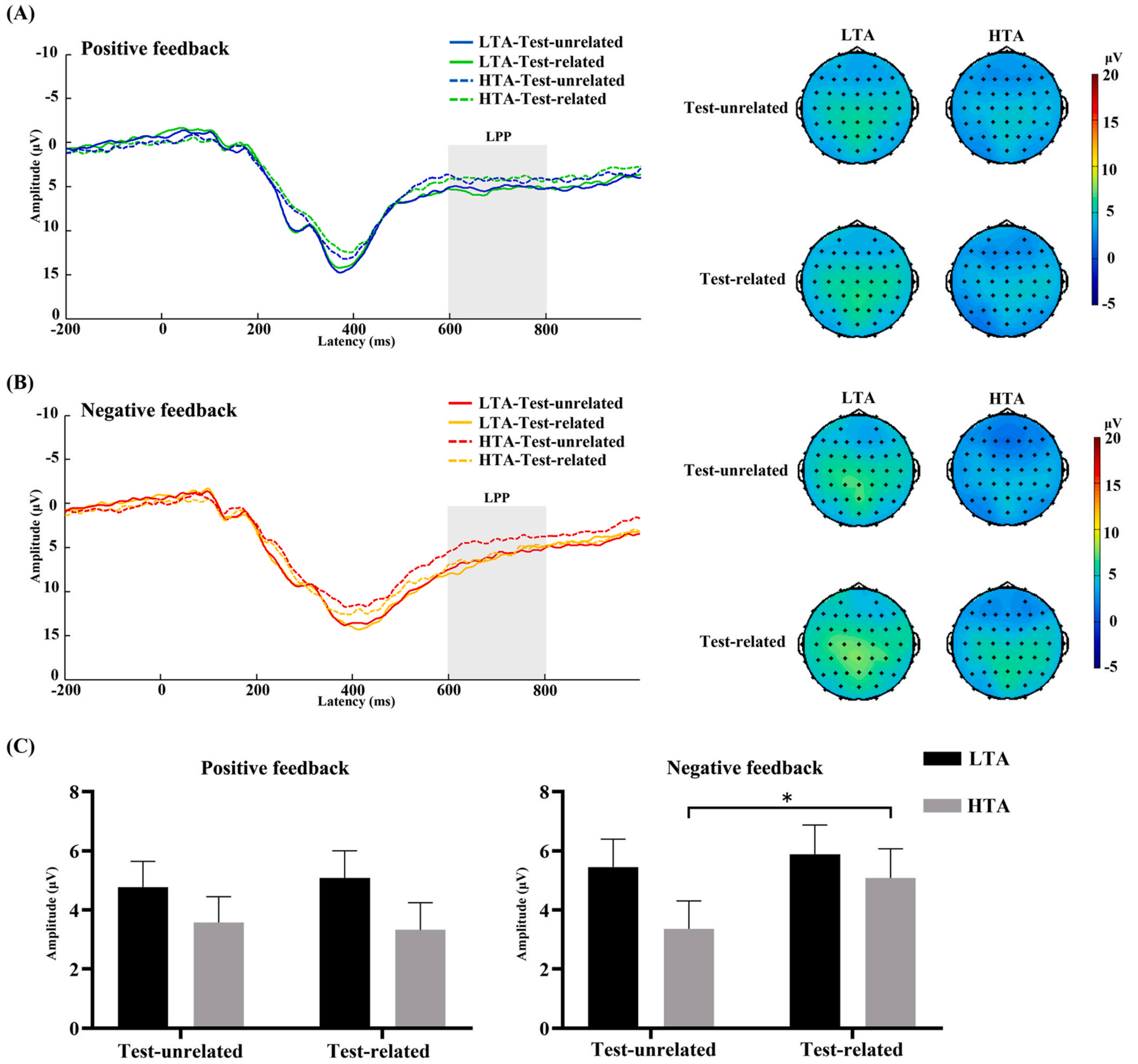

Fig. 8. Average LPP amplitudes at electrode Pz (600–800 ms) in the punishment block. (A) Mean LPP amplitudes and scalp topographies for positive feedback in individuals with HTA and LTA; (B) Mean LPP amplitudes and scalp topographies for negative feedback in individuals with HTA and LTA; (C) Bar graph of mean LPP amplitudes (error bars represent ±1 SEM) across all conditions. *$p\_corr < .05$.

not differ from LTA individuals, they exhibited smaller FRN amplitudes to test-related negative feedback and larger FRN responses to positive feedback in evaluative, punishment-based contexts. These patterns indicate that negative outcomes were expected, whereas positive outcomes were more unexpected for HTA individuals, reflecting a bias in evaluative processing that could shape their interpretation of feedback. Heightened LPP amplitudes to test-related negative feedback further suggest elevated emotional engagement, even when outcomes are predictable. Together, these findings suggest that individuals with HTA may process negative feedback in a manner that reinforces their pre-existing fears and expectations, whereas positive outcomes are less readily integrated. These biases in evaluative and emotional processing may not directly impair task performance in low-stakes settings but could contribute to long-term maintenance of test anxiety.

From a neurocognitive standpoint, the anterior cingulate cortex (ACC) may play a role in the feedback processing patterns observed in individuals with HTA. The ACC is thought to be a key generator of the FRN and plays a central role in performance monitoring and adaptive control based on feedback. Prior research has linked anxiety-related differences in feedback processing to altered ACC functioning. For example, Santesso et al. [40] reported amplified responses to negative feedback in individuals with high negative affect, while Aarts and Pourtois [1] found that anxiety can affect evaluative monitoring in a Go/NoGo task. Although we did not localize neural generators, our findings of altered FRN responses in HTA individuals are consistent with the idea that the ACC is involved in processing unexpected outcomes, especially when such outcomes contradict internal predictions.

The expected value of control theory provides a useful lens for interpreting our findings [42]. It suggests that the ACC allocates control based on the expected value of outcomes. For HTA individuals, negative expectations in test contexts may lower the perceived value of effort [41,43]. When they receive expected negative feedback, the ACC registers a small prediction error, supporting continued vigilance. In contrast, unexpected positive feedback generates a larger prediction error and a stronger FRN, but does not substantially increase perceived task value. This may explain why individuals with HTA show increased neural effort when integrating positive feedback, rather than internalizing it readily. Supporting this view, prior imaging research suggests that individuals with HTA exhibit reduced functional connectivity between the ACC and other prefrontal areas [25], which may limit their capacity to flexibly integrate unexpected feedback and adjust control strategies.

This study has several limitations. First, we used low-threat cartoon test stimuli rather than ecologically intense evaluative cues. It may have reduced participants' perceived evaluative stress. As a result, the absence of behavioral differences between HTA and LTA individuals may not generalize to more stressful, high-stakes testing situations. Future studies should consider using more realistic and high-pressure test scenarios to better capture anxiety-related performance differences. Second, our main findings were based on ERP differences, whereas behavioral measures, such as accuracy and response time, showed no group differences. Although ERPs provide important insights into cognitive and emotional processes, future research should include trial-level behavioral analyses such as win-stay or lose-shift patterns and apply reinforcement learning models to more directly examine learning mechanisms. These methods were not applied in the current study. Third, depressive symptoms were screened but not analyzed dimensionally. Including BDI scores as a covariate in future analyses would help clarify whether the observed effects are specific to test anxiety. Fourth, the limited number of standardized stimuli hindered the comparison of different types of test-related content. Although the images were preprocessed for consistency, dimensions such as luminance and complexity were not available, which may limit interpretation. Additionally, because the affective properties of the images were not rated by participants in this study, we cannot fully exclude the possibility that subtle differences in valence, arousal, or threat influenced neural responses, despite the use of standardized low-threat materials with published normative ratings.

In conclusion, this study offers new insights into the neural processing of evaluative feedback in individuals with HTA. While behavioral performance was comparable between groups, ERP results revealed altered feedback-related brain responses in evaluative, punishment-based contexts, especially for test-related stimuli. These patterns included smaller FRN amplitudes in response to test-related negative feedback and enhanced LPP amplitudes in response to test-related negative feedback within the HTA group, as well as larger FRN responses to test-related positive feedback in the HTA compared with the LTA individuals. Together, these effects reflect differences in expectancy and emotional engagement, rather than deficits in behavioral learning, and no conclusions regarding learning mechanisms should be drawn in the absence of trial-wise behavioral coupling. From a theoretical standpoint, these findings contribute to a more nuanced understanding of how test anxiety influences feedback processing, even in the absence of observable behavioral impairments. Interventions targeting feedback interpretation and emotional responses—such as cognitive-behavioral strategies or feedback-based training—may help individuals with HTA better utilize positive feedback and reduce maladaptive anticipation of failure in evaluative settings.

Ethics approval

Approval was obtained from the ethics committee of Nanjing University (NJUPSY202304007). The procedures used in this study adhere to the tenets of the Declaration of Helsinki.

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Disclosure statement

The authors report there are no competing interests to declare.

CRediT authorship contribution statement

Yuhong Ou: Writing – review & editing, Writing – original draft, Validation, Formal analysis, Data curation, Conceptualization. **Renlai Zhou:** Writing – review & editing, Writing – original draft, Supervision, Project administration, Investigation, Funding acquisition, Conceptualization.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.bbr.2025.115991.

Data availability statement

The datasets generated for this research are available on request to the corresponding author.

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