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ORIGINAL RESEARCH

Contextual Predictability Modulates Neural Processing of Social Threat Words in High and Low Social Anxiety: Evidence from ERPs and Theta Oscillations

Haichen Wang*, Zhengjun Wang*, Xiuxiu Zhang, Mutian Guo, Yaxi Duan, Qiusha Luo, Zhen Bi, Yue Du, Jianqin Cao

Key Laboratory of Basic Research and Health Management on Chronic Diseases in Heilongjiang Province, Daqing Campus, Harbin Medical University, Daqing, Heilongjiang, 163319, People's Republic of China

*These authors made equal contributions to this work

Correspondence: Jianqin Cao, Daqing Campus, Harbin Medical University, Daqing, Heilongjiang, People's Republic of China, Email cjq338@163.com

Background: Individuals with high social anxiety (HSA) consistently exhibit attentional biases toward social threat. However, most evidence derives from paradigms in which threat and neutral stimuli are unpredictably intermixed, leaving it unclear whether such biases reflect heightened sensitivity to threat content per se or increased sensitivity to contextual unpredictability, where emotional valence changes unpredictably across trials.

Methods: HSA and low social anxiety (LSA) individuals completed an emotional Stroop task comprising a mixed context, in which threat and neutral words were randomly presented, and a threat-only context, in which threat was fully predictable Behavioral responses, event-related potentials (P2, EPN, LPP), and theta-band oscillations were analyzed.

Results: Behaviorally, HSA participants responded more slowly than LSA participants in the mixed context but faster in the threat-only context. At the neural level, early perceptual processing indexed by P2 did not differ reliably across groups. In contrast, EPN amplitudes were selectively enhanced in HSA individuals under predictable threat, whereas LSA individuals showed increased LPP amplitudes reflecting sustained evaluative engagement. Frontal theta power was greater in LSA than HSA individuals in the mixed context.

Conclusion: These findings suggest that threat-related bias in HSA participants is associated with contextual predictability, in addition to threat exposure. HSA is characterized by intact or heightened early sensitivity to threat alongside context-dependent differences in later evaluative and regulatory processes. By highlighting the role of contextual predictability and temporal dynamics, the present study provides a more nuanced understanding of emotional dysregulation in high social anxiety.

Keywords: social anxiety, emotional Stroop task, context predictability, event-related potentials, theta oscillations

Introduction

Social anxiety disorder (SAD) is characterized by a pervasive fear of negative social evaluation, leading affected individuals to experience heightened distress and impaired functioning in social contexts.[1] A central component of this disorder is the biased processing of socially threatening information, which manifests behaviorally as facilitated detection of negative social cues and difficulty disengaging from them.[2–4] Numerous behavioral and electrophysiological studies have shown that individuals high in social anxiety (HSA) exhibit exaggerated vigilance toward social threat stimuli, such as critical words or disapproving expressions, even when such information is task-irrelevant.[5–9] This attentional bias is widely regarded as an important mechanism associated with elevated social anxiety, as early capture of attention by threat interferes with adaptive interpretation and emotional regulation in social interactions.[10,11]

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Although threat-related attentional biases in high social anxiety are well established, an important methodological concern remains unresolved. In most paradigms demonstrating such biases, particularly emotional Stroop tasks, threat and neutral stimuli are presented in a trial-level randomized sequence,[5,12,13] such that emotional valence varies unpredictably from one trial to the next.[5,14] Under these conditions, individuals must continuously adjust attentional sets and prepare for emotional uncertainty, which may induce a generalized state of hypervigilance independent of threat content itself.[15–17] As a result, threat exposure and contextual predictability are typically confounded, making it difficult to determine whether previously observed behavioral and neural effects reflect sensitivity to threatening stimuli per se, sensitivity to unpredictable changes in emotional context, or a combination of both. This methodological confound challenges a core assumption of the literature, namely that observed biases primarily reflect sensitivity to threat itself. Clarifying this distinction is essential, because it bears directly on how threat-related bias in individuals with high social anxiety should be conceptualized.

The concept of contextual predictability can be situated within the broader framework of Predictive Processing, which posits that the brain continuously makes predictions about incoming sensory input based on prior experience and adjusts its predictions when the input is inconsistent with expectations.[18] In the context of social anxiety, individuals may be hypersensitive to discrepancies between predicted and actual emotional stimuli, leading to heightened emotional responses in unpredictable contexts.

This distinction is not trivial. Cognitive[19,20] and cognitive-behavioral models of social anxiety emphasize that unpredictability, uncertainty, and lack of control are themselves highly aversive and can potentiate vigilance, avoidance, and dysregulated emotional responding.[21,22] Given the design of the present study, however, we cannot isolate the effects of contextual predictability from other factors, such as differences in stimulus composition and trial structure, which may also contribute to observed biases. From this perspective, the emotional meaning of a stimulus may be less influential than the predictive structure of the environment in which it appears.[7] If so, then the standard emotional Stroop paradigm, due to its randomized nature, may systematically overestimate the magnitude of threat bias in socially anxious individuals. To date, however, no study has directly tested whether threat-processing biases in HSA individuals persist, diminish, or reverse when threat information is presented without neutral stimuli, in a context where each upcoming stimulus is fully predictable, and the emotional category is consistently known.

Despite extensive study, the field has implicitly assumed that attentional biases in HSA individuals are stimulus-driven and remain stable across task formats.[23–25] However, no existing research has isolated the contribution of contextual predictability from the influence of threat content. Emotional Stroop paradigms that intermingle threat and neutral stimuli inherently conflate threat relevance with uncertainty, preventing clear attribution of observed effects.[26] As a result, it is unknown whether previously documented biases reflect genuine hypersensitivity to social threat or maladaptive responses to unpredictability. The present study directly addresses this limitation by comparing threat-word processing across two task contexts that differ in the predictability of emotional valence. In the mixed-context condition, threat and neutral words were randomly intermixed, so that the emotional category of the upcoming stimulus was uncertain on each trial. In the threat-only condition, all stimuli were threat words, such that the emotional context was fully predictable Importantly, the critical comparison focused on threat trials across these two contexts, allowing us to examine whether the processing of threat words varies as a function of contextual predictability rather than threat content alone.

Emerging evidence suggests that contextual predictability plays a decisive role in determining whether emotional responses escalate or attenuate across time.[27,28] Predictable threat contexts may facilitate rapid early detection while reducing demands on later regulatory mechanisms, given that no updating of expectations is required. In contrast, unpredictable threat contexts can heighten vigilance, elicit excessive monitoring, and impair cognitive flexibility, particularly among individuals with anxiety.[28] These findings raise a fundamental and unresolved question: Does HSA individuals produce a stable, context-invariant threat bias, or does this bias depend on the structure of stimulus presentation? If the latter is true, then prior demonstrations of threat bias may require reinterpretation, not as evidence for enhanced threat perception itself, but as evidence for dysregulated responses to unpredictable emotional environments.

Event-related potential (ERP) components provide a useful temporal decomposition of emotional processing in HSA individuals. Early components such as the P2[29–31] and the early posterior negativity (EPN) have been linked to rapid detection of stimulus salience and the allocation of perceptual resources to emotionally relevant cues.[32–34] Some studies have reported enhanced EPN responses to social threat words in high-anxiety individuals, suggesting facilitated early access to threat-related representations.[3,35] However, EPN modulation by anxiety has not been observed consistently, with other findings reporting attenuated or absent effects depending on task demands, stimulus characteristics, or contextual conditions.[5,36–38] In contrast, the late positive potential (LPP) is widely considered a marker of later evaluative and motivational processes, indexing sustained engagement of cognitive resources during emotional appraisal.[39–42] Prior findings regarding LPP modulation in HSA individuals are likewise mixed: some studies have documented enlarged LPP amplitudes in socially anxious individuals,[40,43,44] whereas others have reported reduced or blunted LPP responses, particularly under conditions involving heightened situational demands or avoidance tendencies.[5,8]

One possible account for the mixed ERP findings in anxiety is that emotional processing is influenced by multiple interacting factors, including task demands,[32] stimulus characteristics,[45] and individual differences.[46,47] Among these factors, the structure of the emotional context, particularly the predictability of emotional information across trials, has received relatively little systematic attention. In most emotional Stroop paradigms, threat and neutral stimuli are randomly intermixed, resulting in trial-by-trial fluctuations in emotional valence. Under such conditions, early ERP components may reflect a combination of stimulus-driven salience detection and heightened sensitivity to contextual uncertainty, whereas later components such as the LPP may vary as a function of how evaluative and regulatory processes are engaged across changing emotional demands. Consequently, some effects attributed to threat processing may be shaped not only by threat content itself but also by properties of the surrounding emotional environment. However, the specific contribution of contextual predictability remains unclear, as few studies have directly manipulated this factor while holding stimulus content constant.

Importantly, these inconsistencies raise the possibility that HSA may not be characterized by a uniform amplification of emotional processing, but rather by a dissociation between early attentional engagement and later evaluative or regulatory stages.[8] Such stage-specific effects may remain obscured unless the structure and predictability of the emotional context are explicitly considered. From a theoretical perspective, vigilance-avoidance accounts of anxiety[2] propose that heightened early attentional capture by threat may coexist with reduced sustained engagement at later stages, particularly when prolonged processing incurs emotional or self-referential costs.

Beyond time-locked ERP responses, oscillatory dynamics, particularly frontal theta activity, play a crucial role in emotional processing. Theta oscillations in the 4–8 Hz range have been linked to conflict monitoring, uncertainty signaling, and the mobilization of regulatory resources in response to emotionally salient stimuli.[48–52] In anxiety, elevated theta activity has been interpreted as reflecting heightened efforts to manage intrusive threat representations or to reconcile competing cognitive goals.[53–55] Yet, theta responses appear highly sensitive to task context: predictable emotional environments often elicit reduced theta engagement, whereas unpredictable contexts amplify theta-related regulatory demands.[56–58] These findings position theta oscillations as an ideal candidate marker for distinguishing stimulus-driven effects from responses triggered by contextual uncertainty.

To examine these possibilities, we recorded EEG and extracted event-related potentials (ERPs), including P2, EPN, and LPP, which index early perceptual attention, preferential encoding of emotional salience, and later evaluative processing, respectively. We additionally analyzed theta oscillations, which reflect the temporal dynamics of emotional engagement and regulatory effort during affective processing. Combining these neural markers with behavioral reaction-time data enables a multi-level characterization of how contextual predictability modulates threat processing in HSA and LSA individuals.

Relationship to prior publication: Parts of the stimulus set, and experimental procedures have been reported previously in our published work,[8] which tested the emotion effect by comparing social threat versus neutral words under a fixed neutral-to-threat block order. In the present manuscript, analyses are restricted to social threat trials and the primary contrast is contextual predictability (mixed context vs. threat-only), thereby addressing a distinct research question and using non-overlapping statistical contrasts.

Guided by cognitive models of social anxiety, we expected that contextual predictability would modulate threat processing differently for individuals with high versus low social anxiety. Specifically, we predicted that unpredictable contexts, where threat and neutral stimuli are intermixed, would place greater demands on attentional monitoring systems, thereby amplifying anxiety-related disruptions in behavioral and neural responses. In contrast, when threat cues are presented in a predictable, threat-only context, we expected socially anxious individuals to show relatively more efficient early perceptual engagement with threat cues and reduced reliance on later evaluative processes, given the absence of contextual uncertainty. At the electrophysiological level, we anticipated that these differences would be reflected in distinct patterns of ERP and theta activity across groups and contexts, consistent with models proposing that anxiety biases emerge at early attentional stages and cascade into later regulatory difficulties. Taken together, we hypothesized that threat-related biases in high social anxiety would be associated not only with sensitivity to threatening stimuli but also with the predictability of the emotional context in which those stimuli are embedded, emerging dynamically at different stages of processing.

Method

Participants

A priori sample size estimation was performed using G*Power 3.1. Assuming a medium effect size ($f = 0.25$) based on comparable ERP studies on anxiety-related emotional processing,[5] an α-level of.05, and a desired power of.80, the minimum required sample for detecting a Group × Task Type interaction in a between-subjects ANOVA was N = 128. The final sample of this study (N = 151; 76 HSA, 75 LSA) exceeded this threshold, ensuring adequate statistical power for both behavioral and electrophysiological analyses.

Participants were recruited via an online screening using the Chinese adaptation of the Liebowitz Social Anxiety Scale (LSAS),[59,60] distributed through WeChat Moments. Following established cut-off criteria,[61,62] respondents scoring above 60 were classified as high in social anxiety (HSA), whereas those scoring below 35 were categorized as low in social anxiety (LSA). Based on these criteria, 84 HSA and 82 LSA individuals were invited to the laboratory. All participants reported normal or corrected-to-normal vision.

Data from eight participants were excluded due to excessive EEG artifacts (> 25% of trials), and seven were removed for poor behavioral performance (accuracy < 75% or reaction times exceeding 3 SDs from the mean), resulting in a final sample of 151 participants (120 females, 31 males; $M_{\text{age}} = 21.3$ years, SD = 2.2). LSAS scores differed significantly between groups (HSA: 74.56 ± 14.33; LSA: 21.09 ± 9.52), $t_{(149)} = 27.04$, $p < 0.001$.

All procedures adhered to the Declaration of Helsinki and were approved by the Ethics Committee of Harbin Medical University, Daqing Campus (HMUDQ20251215001). Written informed consent was obtained from all participants prior to the experiment.

Material

The lexical stimuli were identical to those used in our previous work.[5,63] Sixty two-character Chinese words were selected from our laboratory's validated social-threat corpus, including 30 social-threat words and 30 neutral words. The threat words conveyed negative social evaluation or interpersonal rejection (eg, "ungenteel" 不雅; "embarrassment" 尬), whereas the neutral words expressed non-emotional meanings (eg, "coincidental" 凑巧; "elementary" 初步).

Normative ratings of valence, arousal, familiarity, and social relevance were previously obtained from 36 native Chinese speakers using the standardized procedure described in Cao et al (2023). As anticipated, threat words were rated as more negative and socially relevant than neutral words, while the two sets did not differ in familiarity.

Procedure and Design

The emotional Stroop paradigm followed the protocol used in our previous work.[5] Participants were seated approximately 70 cm from the monitor and viewed stimuli subtending roughly 5.2° × 2.3° of visual angle. Each trial consisted of a fixation cross (500–700 ms), a word displayed in one of four colors for 800 ms, and a subsequent blank screen for 700 ms, resulting in an average trial duration of approximately 2 seconds. Participants responded only to the color of the word using pre-assigned keyboard keys while ignoring its semantic content. Additional procedural details are provided in Cao et al (2023), and an overview of the task sequence is shown in Figure 1.

The threat-only condition corresponded to the threat-word block reported in our prior publication.[8] However, that study focused on threat-versus-neutral comparisons within a fixed neutral-to-threat order, whereas the present study focused on threat-word trials only and compared threat processing across two contexts that differed in contextual predictability.

To examine whether the processing of social-threat words varied as a function of contextual structure, two Stroop presentation formats were implemented. In the mixed-context condition, 240 trials were presented in random order, comprising 120 social-threat and 120 neutral words; thus, the probability of encountering a threat word on any given trial was 50%. In the threat-only condition, participants viewed 120 social-threat words consecutively, creating a context in which the emotional valence of the upcoming stimulus was fully predictable (100% threat). Thus, although threat words were present in both conditions, the two task formats differed in whether the emotional category of the upcoming stimulus was uncertain or fully predictable, allowing contextual predictability to be operationalized at the level of the surrounding trial structure. The temporal parameters of individual trials were identical across conditions, reducing the likelihood that any cross-context differences were attributable to variation in trial timing or exposure duration.

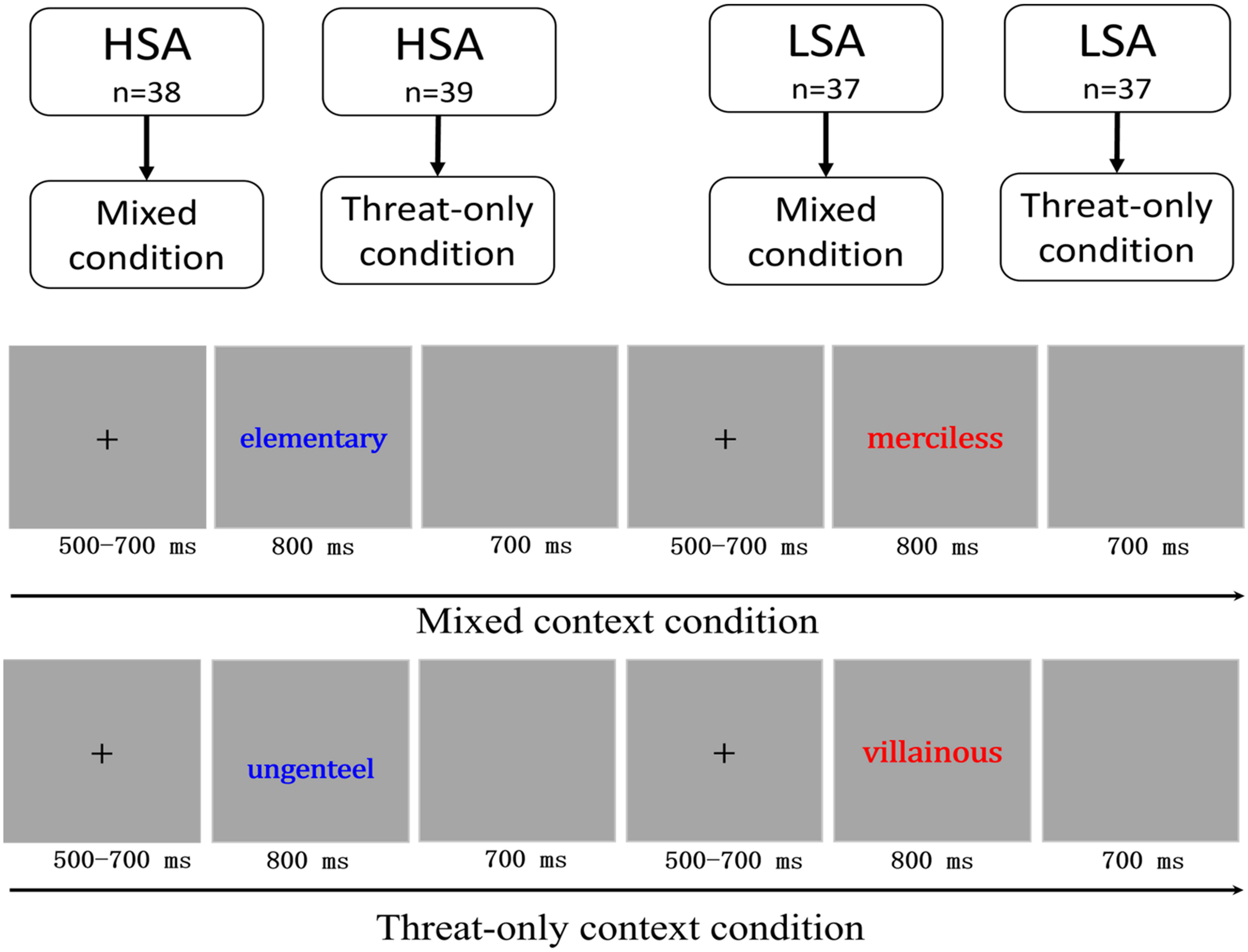

Figure 1 Experimental design and sample trial sequence of the emotional Stroop task. Participants with HSA and LSA were randomly assigned to either a mixed-context condition or a threat-only condition. In the mixed-context condition, social-threat and neutral words were randomly intermixed across trials. In the threat-only condition, only social-threat words were presented consecutively, without any neutral stimuli. Example neutral and social-threat words are shown for illustration. Each trial consisted of a fixation cross followed by a colored word stimulus and a blank interval.

A 2 (Group: HSA vs. LSA) × 2 (Task Type: mixed context vs. threat-only) completely randomized between-subjects design was used, with participants assigned to one of four conditions: HSA-mixed (n = 38), HSA-threat-only (n = 39), LSA-mixed (n = 37), or LSA-threat-only (n = 37). Participants were randomly assigned to one of the four conditions using a random number generator to ensure unbiased allocation (Figure 1). A between-subjects design was adopted to avoid potential contextual carryover effects, because prior exposure to one presentation format could alter expectancy, threat appraisal, or strategic adjustments in the subsequent condition, thereby confounding interpretation of the results.

For the primary cross-context comparisons in the present study, analyses focused on social-threat trials from the mixed-context condition and social-threat trials from the threat-only condition. Neutral-word trials in the mixed-context condition were included to establish the unpredictable emotional context but were not part of the primary cross-context comparisons reported here.

EEG Recording and Preprocessing

Continuous electroencephalogram (EEG) data were acquired using a Neuroscan ESI 64-channel recording system with an Ag/AgCl electrode cap arranged according to the extended international 10–20 system. Signals were recorded with an online bandpass filter of 0.05–100 Hz and a sampling rate of 500 Hz. During acquisition, the left mastoid served as the reference electrode, and the data were subsequently re-referenced offline to the average of the left and right mastoids. Electrooculogram (EOG) activity was monitored using electrodes placed above and below the eyes and at the outer canthi. Electrode impedances were kept below 5 kΩ throughout the experiment. To attenuate high-frequency noise, the raw EEG data were low-pass filtered at 30 Hz using a zero-phase digital Butterworth filter (−6 dB half-amplitude cutoff, 24 dB/octave).

For ERP analysis, continuous EEG was segmented into 1200 ms epochs time-locked to stimulus onset (−200 to 1000 ms), with the −200 to 0 ms interval serving as the baseline. Epochs containing voltage fluctuations exceeding ±75 μV were rejected, which is a commonly used criterion in EEG research for excluding large-amplitude artifacts (eg, eye blinks and muscle activity). Additionally, ocular artifacts were corrected using the linear regression-based procedure proposed by Semlitsch et al,[64] a widely accepted method for eye movement correction in EEG studies. Only correct-response trials were included when computing grand-average waveforms. All ERP preprocessing was performed using Neuroscan Scan 4.5, and statistical analyses were conducted in SPSS 29.0.

For time-frequency analysis, data were segmented into 2000 ms epochs (−500 to 1500 ms) and transformed using a fast Fourier transform (FFT). Power estimates were baseline-normalized to the −500 to 0 ms pre-stimulus period. The same artifact rejection criterion (±75 μV) and ocular correction procedure used for ERP processing were applied. A longer baseline was used for the FFT analysis because reliable estimation of low-frequency power requires a sufficiently extended pre-stimulus interval, whereas ERP analysis captures phase-locked activity and therefore does not require a baseline of equivalent duration.

For ERP analyses, the mean number of retained trials was 114.76 (SD = 8.16) in the HSA-mixed group, 116.11 (SD = 4.77) in the LSA-mixed group, 112.30 (SD = 10.43) in the HSA-threat-only group, and 113.70 (SD = 7.76) in the LSA-threat-only group. For TFR analyses, the corresponding values were the same as those for ERP analyses, because the same trial-selection criteria were applied.

Statistics and Analyses

Behavioral Data Analyses

Reaction times (RTs) for correct responses to threat-word trials were analyzed using linear mixed-effects models in R with the *lme4* and *lmerTest* packages. Trials with incorrect responses or implausible RTs (< 200 ms or > 2000 ms) were excluded prior to analysis. Group (HSA vs. LSA), Task Type (mixed context vs. threat-only), and their interaction were entered as fixed effects, and participant was included as a random intercept: RT ~ Group * Task Type + (1 | Participant). *p*-values for fixed effects were obtained using Satterthwaite's approximation. Post hoc comparisons of estimated marginal means were conducted using the *emmeans* package, with Tukey adjustment for multiple comparisons.

ERP Analyses

Mean amplitudes were extracted for three ERP components, P2 (130–230 ms), EPN (250–320 ms), and LPP (320–650 ms). The time windows and electrode clusters were determined with reference to previous studies on emotional word processing and social anxiety and were further guided by visual inspection of the grand-average waveforms and scalp distributions in the present study (Figures 3–5). P2 amplitudes were quantified at frontal and fronto-central sites (F1, Fz, F2, FC1, FCz, FC2), consistent with prior work implicating these regions in early perceptual processing.[8,65] EPN amplitudes were computed separately for left-hemisphere electrodes (P7, P5, PO7, PO5) and right-hemisphere electrodes (P8, P6, PO8, PO6), in line with evidence for lateralized emotional processing.[66–68] LPP amplitudes were measured over central and centro-parietal sites (C1, Cz, C2, CP1, CPz, CP2, P1, Pz, P2), following established guidelines for analyzing late positive potentials.[69,70]

TFR Analyses

Time-frequency representations (TFRs) of oscillatory activity were computed using a Fast Fourier Transform (FFT) implemented in the FieldTrip toolbox.[71] A single Hanning taper was applied prior to transformation to reduce spectral leakage. Power was estimated using a 500-ms sliding window with 90% overlap, providing a balance between temporal resolution and spectral stability. Baseline correction was performed using the −400 to −100 ms pre-stimulus interval. This interval was selected to minimize contamination from anticipatory activity and slow preparatory shifts observed earlier in the pre-stimulus period, while still providing a relatively stable reference period for spectral normalization. Power estimates from 0 to 1500 ms post-stimulus were converted to decibel units (dB)[72] and were used to construct time-frequency plots.

For the theta band (4–7 Hz), mean power was extracted from frontal and fronto-central electrode sites (F1, Fz, F2, FC1, FCz, FC2), in line with previous research on anxiety-related frontal theta activity.[73] The electrode cluster and time windows were selected with reference to prior literature and were further guided by visual inspection of the grand-average TFR across groups and conditions in the present study (see Supplementary Figure S1). Two-time windows, 130–260 ms and 300–600 ms, were included in the primary analyses. This separation was intended to improve interpretability rather than to imply a strict temporal dissociation between oscillatory and ERP processes. The earlier window was intended to capture rapid perceptual detection and salience appraisal of emotionally negative stimuli, whereas the later window was intended to index more elaborative evaluative and emotion-regulatory processes during stimulus processing.[74,75]

Statistical analyses of ERP and TFR measures were conducted in SPSS 29.0. Greenhouse-Geisser corrections were applied when the assumption of sphericity was violated. The significance threshold was set at $p < 0.05$, and significant interactions were followed by Bonferroni-corrected simple-effects analyses.

Results

Behavioral Data

Reaction times (RTs) were analyzed using a linear mixed-effects model with group (HSA vs. LSA) and task type (mixed vs. threat-only) as fixed factors and random intercepts for subjects.

The model revealed a significant main effect of task type, $F_{(1,\ 4564.1)} = 11.95$, $p < 0.001$, with participants responding more slowly in the mixed condition than in the threat-only condition, but no significant main effect of group, $F_{(1,\ 3226.2)} = 0.01$, $p = 0.91$. Importantly, the Group × Task Type interaction was significant, $F_{(1,\ 1129.9)} = 56.04$, $p < 0.001$, indicating that the influence of task context on threat-word processing differed between the two groups in Figure 2.

Post-hoc comparisons showed that in the mixed condition, HSA participants responded significantly slower than LSA participants ($\Delta RT = 44.9$ ms, $p < 0.001$), whereas in the threat-only condition, this pattern was reversed, with LSA participants exhibiting slower responses than HSA participants ($\Delta RT = 46.0$ ms, $p < 0.001$). Within-group comparisons further revealed that HSA participants responded more slowly in the mixed condition compared with the threat-only condition ($\Delta RT = 31.4$ ms, $p < 0.001$), whereas LSA participants showed the opposite pattern, exhibiting slower performance in the threat-only condition than in the mixed condition ($\Delta RT = 59.4$ ms, $p < 0.001$) in Figure 2.

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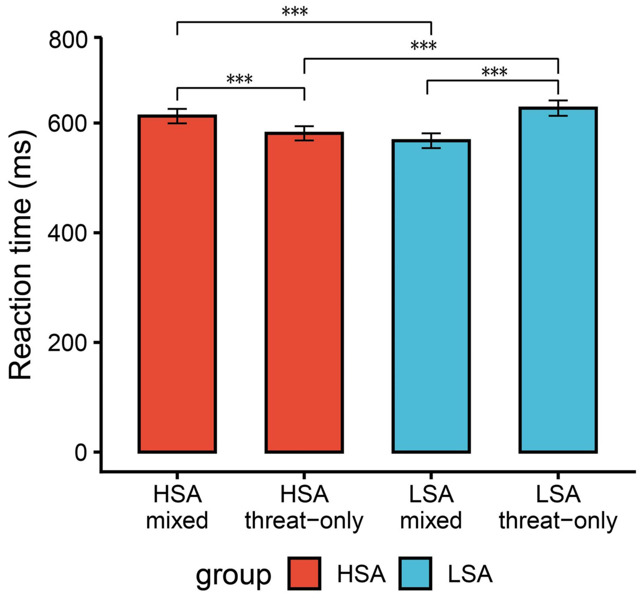

Figure 2 (**A**) Grand-average P2 waveforms under mixed-context and threat-only conditions in the HSA and LSA groups. (**B**) Scalp topographies of mean amplitudes under mixed-context and threat-only conditions, together with difference maps, within the P2 time window (130–230 ms). (**C**) Box plots with jittered individual data points showing extracted mean P2 amplitudes for each group and condition.

ERP Data

P2 (130–230ms)

A 2 (Group: HSA vs. LSA) × 2 (Task Type: mixed context vs. threat-only) × 6 (Electrode: F1, Fz, F2, FC1, FCz, FC2) mixed ANOVA on P2 amplitudes revealed no significant main effects of Group or Task Type, and no significant interactions involving these factors (*Fs* < 2.054, *ps* >0.05). A significant main effect of Electrode was observed, $F_{(5735)} = 30.580$, $p < 0.001$, $\eta_p^2 = 0.172$; however, because spatial distribution was not central to the present hypotheses, this effect is not discussed further. See Figure 3.

EPN (250–320ms)

A 2 (Group: HSA vs. LSA) × 2 (Task Type: mixed context vs. threat-only) × 2 (Hemisphere: left vs. right) × 4 (Electrode) mixed ANOVA on EPN amplitudes revealed a significant Group × Task Type interaction, $F_{(1147)} = 4.752$, $p = 0.031$, $\eta_p^2 = 0.031$. No significant main effects of Hemisphere or Electrode were observed (*ps* >0.05). Simple-effects analyses showed that, within the HSA group, EPN amplitudes were more negative in the threat-only condition than in the mixed-context condition (1.5 vs. 3.0 μV, p =0.046), whereas no significant task-type difference was found in the LSA group (2.2 vs. 3.0 μV, p =0.283). In the threat-only condition, the HSA group showed more negative EPN amplitudes than the LSA group (1.5 vs. 3.0 μV, p =0.039), whereas no significant group difference was observed in the mixed-context condition (3.0 vs. 3.0 μV, p =0.322). This interaction indicated that the effect of task context on EPN amplitude differed between the HSA and LSA groups. See Figure 4.

LPP (320–650ms)

A 2 (Group: HSA vs. LSA) × 2 (Task Type: mixed context vs. threat-only) × 9 (Electrode: C1, Cz, C2, CP1, CPz, CP2, P1, Pz, P2) mixed ANOVA on LPP amplitudes revealed a significant Group × Task Type interaction, $F_{(1147)} = 4.219$, $p = 0.042$, $\eta_p^2 = 0.028$. A significant main effect of Electrode was also observed, $F_{(8,\ 1176)} = 52.636$, p <0.001, η_p^2=0.264. Because spatial distribution was not central to the present hypotheses, this effect is not discussed further. Simple-effects analyses showed that, under the threat-only condition, the LSA group exhibited more positive LPP amplitudes than the HSA group (7.6 vs. 6.0 μV, p =0.040), whereas no significant group difference was observed in the mixed-context condition (6.3 vs. 5.7 μV, p =0.416). In addition, within the LSA group, the threat-only condition elicited more positive LPP amplitudes than the mixed-context condition (7.6 vs. 5.7 μV, p =0.018), whereas no significant task-type difference

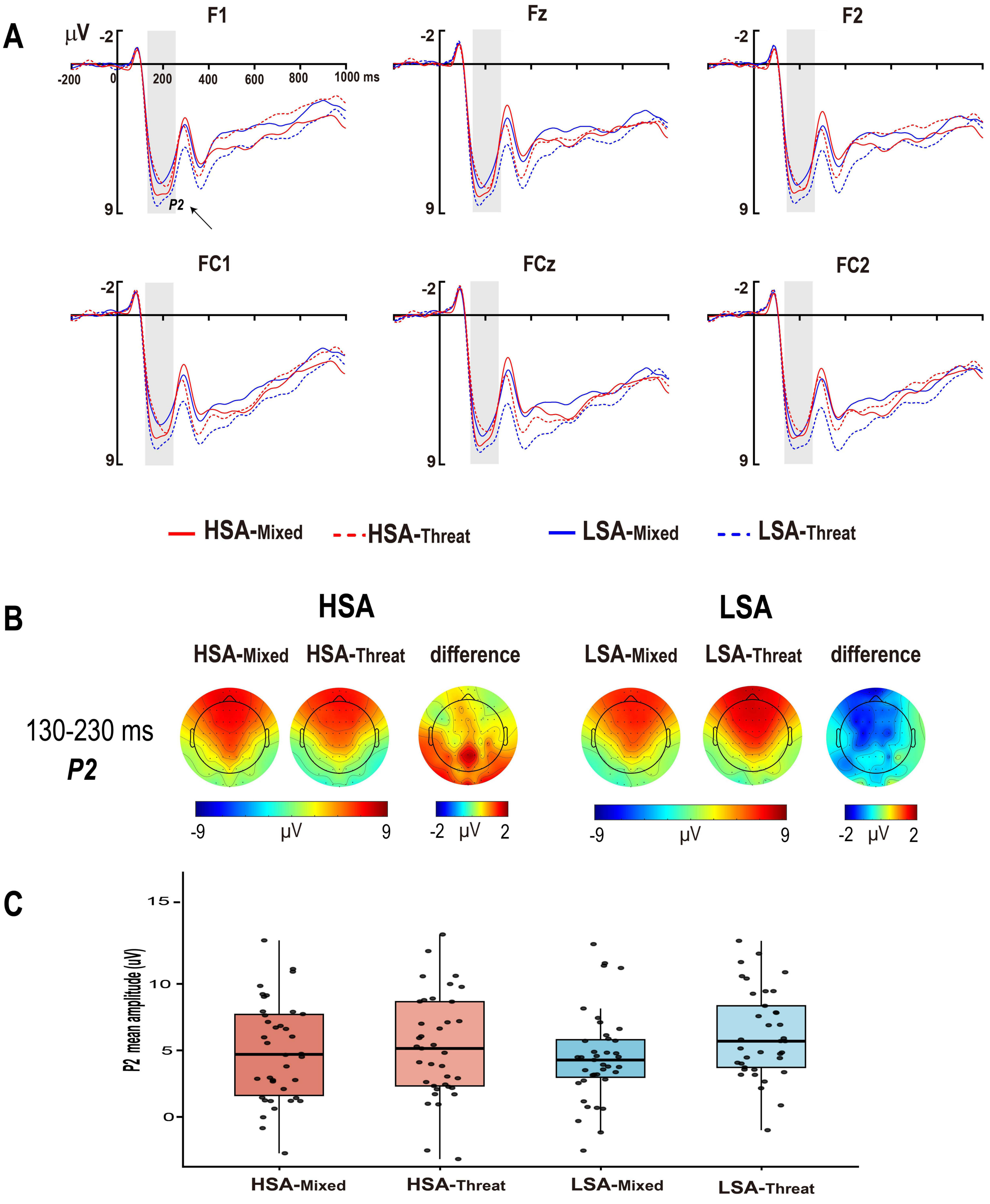

Figure 3 (**A**) Grand-average EPN waveforms under mixed-context and threat-only conditions in the HSA and LSA groups. (**B**) Scalp topographies of mean amplitudes under mixed-context and threat-only conditions, together with difference maps, within the EPN time window (250–320 ms). (**C**) Box plots with jittered individual data points showing extracted mean EPN amplitudes for each group and condition. More negative amplitudes indicate larger EPN responses.

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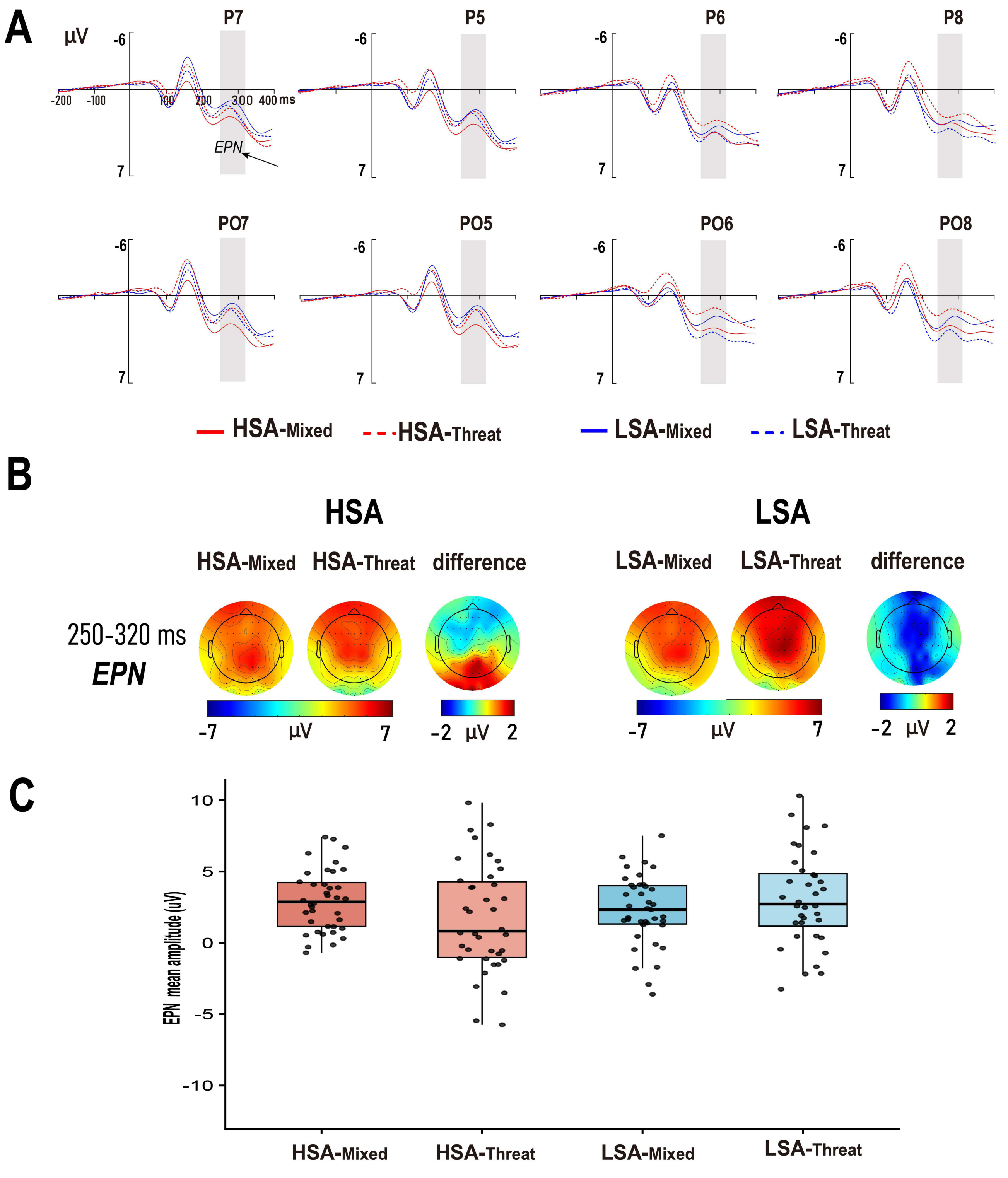

Figure 4 (**A**) Grand-average LPP waveforms under mixed-context and threat-only conditions in the HSA and LSA groups. (**B**) Scalp topographies of mean amplitudes under mixed-context and threat-only conditions, together with difference maps, within the LPP time window (320–650 ms). (**C**) Box plots with jittered individual data points showing extracted mean LPP amplitudes for each group and condition.

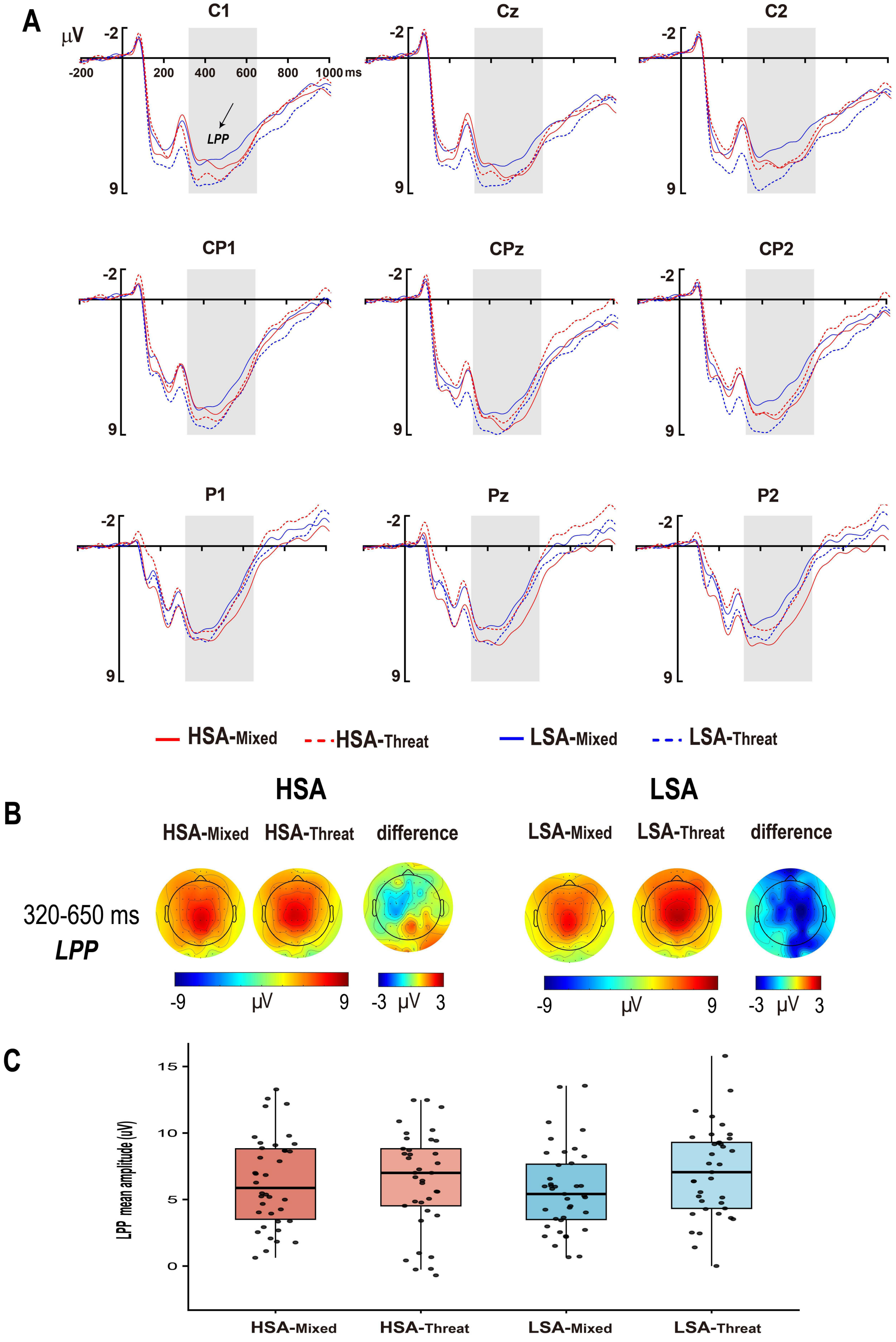

Figure 5 Mean reaction times (RTs) for HSA and LSA groups across task types. Error bars indicate standard errors. (****p* < 0.001).

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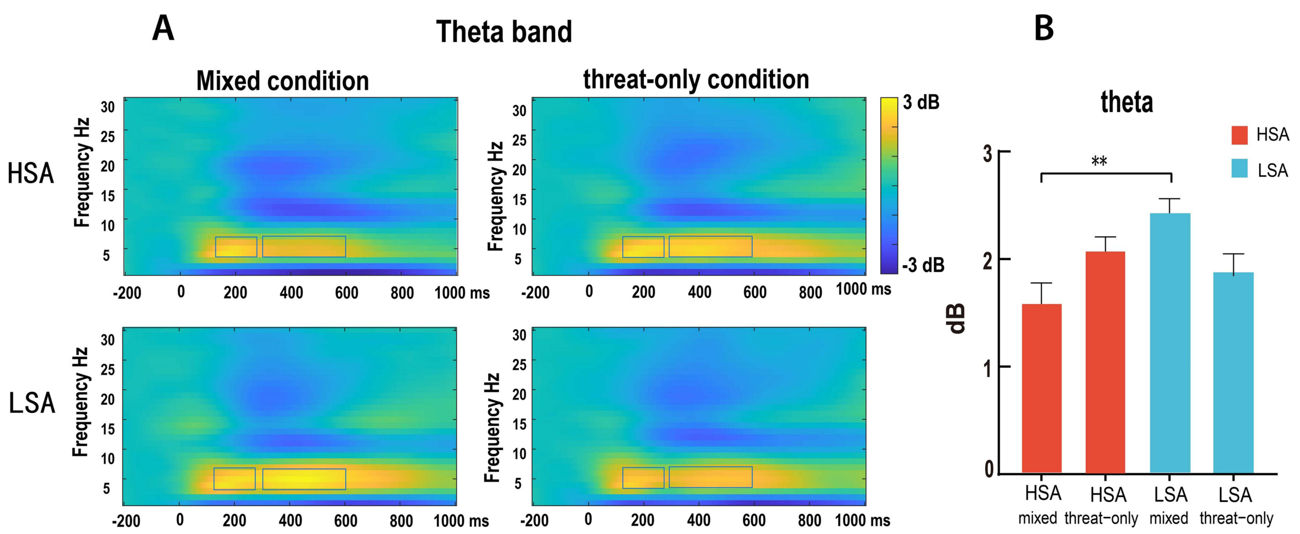

Figure 6 Frontal theta oscillatory activity across conditions and groups. (**A**) Grand-averaged time-frequency plots showing frontal theta oscillatory activity in the mixed-context condition and threat-only condition for the HSA and LSA groups, with separate representations for the 130–260 ms and 300–600 ms time windows. (**B**) Bar graphs depicting the mean theta power (in dB) within the 300–600 ms time window for each condition and group.

was found in the HSA group (6.3 vs. 5.9 µV, p =0.617). This interaction suggested that later evaluative processing was modulated by context in the LSA group, but not in the HSA group. See Figure 5.

TFR Data

Theta-Band (130–260)

A 2 (Group: HSA vs. LSA) × 2 (Task Type: mixed context vs. threat-only) × 6 (Electrode: F1, Fz, F2, FC1, FCz, FC2) mixed ANOVA on theta-band power (130–260 ms) revealed no significant main effects of Group or Task Type, and no significant interactions involving these factors (Fs < 0.423, ps >0.05). A significant main effect of Electrode was observed, $F_{(5,\ 735)} = 3.559$, p =0.014, η_p^2=0.024. Because spatial distribution was not central to the present hypotheses, this effect is not discussed further. See Figure 6.

Theta-Band (300–600)

A 2 (Group: HSA vs. LSA) × 2 (Task Type: mixed context vs. threat-only) × 6 (Electrode: F1, Fz, F2, FC1, FCz, FC2) mixed ANOVA on theta-band power (300–600 ms) revealed a significant Group × Task Type interaction, $F_{(1147)} = 5.412$, p =0.021, η_p^2= 0.036. A significant main effect of Electrode was also observed, $F_{(5,\ 735)} = 16.775$, p <0.001, η_p^2=0.103. Because spatial distribution was not central to the present hypotheses, this effect is not discussed further. Simple-effects analyses showed that, under the mixed-context condition, the LSA group exhibited stronger theta power than the HSA group (2.4 vs. 1.5 dB, p =0.009), whereas no significant group difference was observed in the threat-only condition (1.9 vs. 2.0 dB, p =0.518). This pattern indicated that group differences in frontal theta emerged only when threat was embedded in an unpredictable context. See Figure 6.

Additional exploratory analyses of alpha- and beta-band activity are reported in the Supplementary Materials. These analyses did not reveal significant Group- or Task Type-related effects beyond the primary theta-band findings.

Discussion

The present study investigated whether threat-processing biases in high social anxiety vary across contexts that differ in the predictability of the emotional environment. By contrasting a mixed context, in which threat and neutral words were unpredictably intermixed, with a threat-only context in which emotional valence was fully predictable, we sought to examine whether sensitivity to threat content and sensitivity to contextual structure could be partially distinguished under the present task design. Across behavioral, ERP, and time-frequency measures, the results suggest that threat-related biases in HSA participants are associated with contextual features rather than being entirely fixed across task conditions. HSA individuals showed distinct patterns of early and later-stage processing across contexts.

The behavioral findings suggest that performance differences in high social anxiety are associated not only with exposure to threatening stimuli but also with the predictability of the emotional context in which threat occurs. HSA individuals responded significantly more slowly than LSA individuals when threat and neutral stimuli were unpredictably intermixed, whereas this pattern reversed in the threat-only condition, with HSA participants responding faster than LSA participants. This crossover interaction suggests that high social anxiety may be associated with altered sensitivity to contextual structure rather than with a uniform performance cost in the presence of threat.[15,16] In the mixed context, threat exposure was embedded within trial-by-trial uncertainty regarding emotional valence. Under these conditions, HSA participants exhibited disproportionate response slowing, which is unlikely to be explained by threat exposure alone, given that an equivalent number of threat trials were included across contexts. Instead, this behavioral inefficiency is consistent with theoretical accounts that identify heightened sensitivity to uncertainty as a core feature of anxiety.[76,77] According to attentional control models, unpredictable environments impose additional demands on monitoring and control processes, thereby reducing processing efficiency even when task requirements remain unchanged.[78,79] Converging behavioral evidence from other domains further supports this interpretation. For instance, studies on selective information exposure have demonstrated that perceived threat can bias behavioral choices and reduce openness to competing information, even when alternative options are simultaneously available.[80] These findings suggest that threat-related behavioral effects may arise from situational demands and contextual instability rather than from stimulus content alone, although the present design does not fully isolate contextual predictability from other task features. By contrast, when threat cues were presented in a fully predictable context, HSA participants responded faster than LSA participants. This pattern aligns with evidence suggesting that predictable threat contexts reduce uncertainty-related costs and allow anxious individuals to rely on stable, overlearned processing strategies.[76] Taken together, the present behavioral results suggest that interference effects commonly observed in emotional Stroop tasks may partially reflect sensitivity to unpredictable emotional environments, rather than solely an invariant behavioral bias toward threat content itself.[5,26]

The P2 component has been widely associated with early perceptual processing and the rapid detection of stimulus salience, reflecting the initial allocation of attentional resources toward potentially relevant information.[29,31] In the context of emotional stimuli processing, enhanced P2 amplitudes are often interpreted as indexing early sensitivity to emotionally salient cues before more elaborate semantic or evaluative processing unfolds.[8,30] In the present study, P2 amplitudes did not show robust group differences across contextual conditions, suggesting that early perceptual registration of threat-related information may be relatively preserved in both HSA and LSA individuals. This finding aligns with prior work indicating that P2 is not consistently modulated by anxiety level per se, but may instead reflect a general mechanism of early salience detection that operates independently of individual differences in emotional vulnerability.[29,31] Of note, the absence of marked P2 differences across contexts suggests that contextual predictability may not strongly influence the earliest stage of perceptual processing indexed by this component under the present task design. Rather than reflecting anxiety-specific hypervigilance, P2 activity may instead represent a broadly intact, pre-attentive or minimally attentive capacity to register emotionally salient stimuli. This interpretation aligns with models proposing that anxiety-related biases emerge not during initial stimulus detection, but at subsequent stages involving selective attention, evaluation, and regulation.[77,78] These findings suggest that early perceptual encoding of social threat is neither selectively amplified in high social anxiety nor strongly influenced by contextual predictability under the present task design. Conversely, anxiety-related differences are more likely to arise during later processing stages, where contextual demands and regulatory requirements become more prominent. This pattern establishes an important boundary condition for interpreting threat-related attentional biases, suggesting that early salience detection alone cannot account for the behavioral and neural differences observed across contexts.

Contrary to the P2, the EPN findings point to a more selective and context-dependent modulation of early attentional processing. The EPN has been consistently linked to the preferential encoding of emotionally salient information during early stages of stimulus categorization and selective attention allocation.[32,81,82] In anxiety research, enhanced EPN responses to threat-related stimuli have often been interpreted as evidence for facilitated early access to threat representations.[3,8,35] However, growing evidence indicates that EPN modulation is not uniform but varies as a function of task demands, attentional focus, and contextual structure.[83,84] Importantly, this pattern aligns with theoretical accounts emphasizing the flexibility of early emotional processing rather than its automaticity. For example, Schindler and Kissler (2016) proposed that early threat-related neural responses are dynamically shaped by task context and attentional goals, rather than being obligatorily triggered by emotional content alone.[68] From this perspective, inconsistent EPN findings in social anxiety may reflect differences in contextual structure and predictability across paradigms, rather than true contradictions in early threat sensitivity. Against this background, the present findings show that EPN amplitudes in HSA individuals were selectively enhanced in the threat-only condition, whereas no reliable group differences emerged in the mixed context. When threat information was fully predictable, HSA participants exhibited stronger EPN responses, consistent with heightened sensitivity to threat salience under conditions of reduced contextual uncertainty. By contrast, when threat and neutral stimuli were unpredictably intermixed, EPN responses did not differ between groups, despite equivalent exposure to threat stimuli. Similar context-sensitive modulation of early emotional ERP components has been reported in prior work demonstrating that uncertainty or competing attentional demands can attenuate or redistribute early affective responses.[85] One plausible account is that unpredictable contexts bias early attentional resources toward monitoring environmental changes rather than amplifying responses to individual threat cues. Taken together, these findings indicate that EPN modulation in high social anxiety reflects a flexible, context-sensitive early attentional mechanism rather than a fixed marker of threat hypersensitivity. This pattern may help explain previously mixed EPN findings, although the contrast also involves broader task differences beyond predictability alone.

Following the context-sensitive modulation observed at the EPN stage, later-stage processing indexed by the LPP revealed a qualitatively different pattern. The LPP has been robustly linked to sustained evaluative, motivational, and regulatory processes during emotional stimulus processing, reflecting prolonged allocation of cognitive resources to emotionally salient information.[42,69,86] Larger LPP amplitudes are generally interpreted as indicating deeper appraisal and continued engagement with emotional meaning, whereas attenuated LPP responses have been associated with disengagement, avoidance, or reduced elaborative processing.[42] In the present study, only LSA individuals exhibited enhanced LPP amplitudes in the threat-only condition, whereas HSA individuals did not show a corresponding increase. This dissociation suggests that, despite showing preserved or even heightened early sensitivity to threat under predictable conditions, individuals with high social anxiety may show reduced later-stage evaluative processing of threat cues. Such a pattern aligns with prior findings reporting blunted or reduced LPP responses in anxious individuals, particularly in contexts that elicit avoidance tendencies or increased emotional load.[5,8,87]

Notably, the LPP literature in social anxiety has yielded mixed results, with some studies documenting enhanced LPP amplitudes to social threat, interpreted as prolonged threat engagement or difficulty disengaging,[40,43,44] and others reporting attenuated responses suggestive of strategic or automatic disengagement.[5,8] The present findings help reconcile these inconsistencies by highlighting the role of contextual predictability. When threat cues were fully predictable, LSA individuals showed sustained evaluative engagement, as reflected in larger LPP amplitudes, whereas HSA individuals did not. This divergence suggests that individuals with high social anxiety may show reduced later-stage processing even in predictable threat contexts, possibly reflecting a tendency to limit sustained emotional engagement. Importantly, the absence of LPP enhancement in HSA participants cannot be readily attributed to reduced threat exposure or diminished early processing, given the concurrent EPN enhancement observed in the same condition. Instead, the dissociation between early (EPN) and late (LPP) stages is broadly consistent with vigilance–avoidance models, which propose heightened early attention to threat followed by reduced sustained engagement.[2,88] Within this framework, early threat detection serves an adaptive warning function, whereas prolonged engagement may be downregulated to prevent further emotional escalation. Crucially, the present findings extend this account by suggesting that vigilance–avoidance dynamics may not be fixed characteristics of high social anxiety, but may vary as a function of contextual predictability. HSA individuals showed preserved or enhanced early sensitivity to threat under predictable conditions, yet reduced later-stage evaluative and regulatory engagement when contextual demands increased. This pattern suggests that avoidance may emerge not as a generalized response to threat, but as a context-sensitive strategy triggered by emotional instability.

An additional point worth noting is that the behavioral and ERP findings were not fully isomorphic. Behavioral slowing in the mixed-context condition likely reflects the integrated outcome of multiple processing stages, including uncertainty monitoring, response selection, and control demands accumulated across the trial. By contrast, ERP components index temporally specific subprocesses that may be selectively modulated at different stages. Accordingly, the absence of parallel effects across behavioral and ERP measures should not necessarily be viewed as inconsistent, but rather as suggesting that contextual uncertainty exerts dissociable influences on early perceptual, intermediate attentional, and later response-related processes.

Beyond time-locked ERP components, theta-band oscillatory activity provides complementary insight into the dynamic regulation of emotional processing. Frontal and fronto-central theta activity has been widely implicated in processes related to emotional regulation, conflict monitoring, uncertainty processing, and the coordination of cognitive control in the presence of salient or challenging information.[74,89,90] In affective contexts, increased theta power is often interpreted as reflecting the recruitment of regulatory resources required to manage emotional responses, particularly under conditions of ambiguity or heightened demand. In the present study, theta power in the 300–600 ms time window was greater in LSA individuals than in HSA in the mixed context, whereas no group differences emerged in the threat-only condition. This pattern suggests that theta-related regulatory processes may be more strongly recruited when emotional information is unpredictable and demands continuous adjustment. It should also be noted that the selected theta windows left a 40 ms gap between 260 and 300 ms, which falls close to the EPN time range. This separation was intended to reduce analytic overlap between the early theta window and later stimulus-related processing, although oscillatory and ERP measures are not assumed to reflect fully independent processes.

Building on this, the absence of theta difference in the threat-only context indicates that predictable threat does not uniformly elicit heightened regulatory demands, consistent with evidence that predictable emotional environments reduce the need for sustained control and monitoring processes.[28,76] The reduced theta engagement observed in HSA individuals under mixed-context conditions may reflect less efficient recruitment of regulatory resources in response to contextual uncertainty. However, an alternative possibility is that reduced theta reflects lower sustained engagement with the emotional context, rather than impaired regulation per se. This interpretation aligns with models of anxiety emphasizing impaired adaptation to uncertainty and reduced efficiency of control processes in dynamically changing environments.[77,79] This interpretation should also be considered in light of prior studies reporting enhanced theta in anxious individuals, often interpreted as compensatory hyper-monitoring or increased control effort. One possible reason for the discrepancy is that theta increases in those studies may reflect active recruitment of control resources under tasks that strongly elicit monitoring demands, whereas the reduced theta observed here may indicate less efficient or less sustained engagement under prolonged contextual instability. Thus, anxiety-related theta responses may not be uniformly increased, but may vary depending on task structure, uncertainty demands, and the degree to which participants remain engaged over time.

Strikingly, theta modulation in the present study parallels the dissociation observed between early and late ERP components. While early threat detection indexed by the EPN was preserved or enhanced under predictable conditions, later-stage engagement reflected by the LPP and theta activity was selectively reduced in HSA individuals. This pattern may be consistent with reduced regulatory engagement, although alternative interpretations, such as reduced elaborative processing or lower sustained task engagement, cannot be ruled out under the present design. Collectively, these findings suggest that high social anxiety may be associated not with a generalized amplification of emotional responding, but with altered coordination between detection, evaluation, and regulation processes across time. For individuals with HSA, reduced theta engagement in the mixed condition could lead to behavioral slowing by limiting their ability to resolve competing emotional demands or stabilize processing under uncertainty. In contrast, greater theta recruitment in LSA may support more adaptive responding under fluctuating emotional input. Thus, these theta results highlight how contextual predictability may influence emotion-regulation dynamics under the present task design. However, because the task formats also differed in stimulus composition and overall structure, these findings should be interpreted as context-related rather than as a fully isolated test of predictability. They further suggest that threat-related differences in high social anxiety extend beyond early attentional biases to include later-stage regulatory or engagement-related processes, which may be particularly sensitive to emotional unpredictability. This oscillatory perspective extends ERP findings and supports integrating time-frequency analyses to better capture the temporal complexity of emotional processing in social anxiety.

Across behavioral, ERP, and oscillatory measures, the present findings suggest that threat-related processing in high social anxiety is associated with the predictability of the emotional context, in addition to threat exposure. Early perceptual processing indexed by the P2 component was largely preserved across groups, whereas early selective attention indexed by the EPN was enhanced in HSA individuals only when threat cues were presented in a predictable context. At later stages, LSA individuals showed sustained evaluative engagement with predictable threat, as reflected by increased LPP amplitudes, whereas HSA individuals did not. Frontal theta activity further revealed reduced engagement of control-related processes in HSA individuals under unpredictable conditions, suggesting less efficient adaptation to contextual instability. Together, these results suggest a dissociation between relatively intact early threat sensitivity and context-dependent differences in later evaluative and regulatory processing in high social anxiety.

Theoretical Implications

The present findings contribute to cognitive-behavioral models of high social anxiety by suggesting that threat-related biases may not be fully context-invariant but may vary as a function of the predictability of the emotional environment. While existing models emphasize heightened sensitivity to social threat, the current results suggest that such sensitivity unfolds dynamically across processing stages rather than as a uniform amplification of threat processing. Specifically, high social anxiety appears to involve intact or heightened early detection of threat cues, alongside context-dependent differences in later evaluative and regulatory processes, particularly under conditions of emotional unpredictability. Rather than revising current models, these findings suggest that contextual predictability may represent an important boundary condition influencing when and how threat-related biases emerge, underscoring the relevance of temporal dynamics and environmental structure in accounts of emotional dysregulation in high social anxiety.

Limitations and Future Directions

Several limitations of the present study should be acknowledged. First, although the between-subjects design reduced potential carryover effects between task contexts, it did not fully isolate contextual predictability from other design features. In particular, the mixed-context and threat-only conditions differed not only in the predictability of emotional valence, but also in stimulus composition and overall trial structure. Accordingly, the present findings should be interpreted as showing associations with contextual predictability under the current task design, rather than as providing a fully isolated test of predictability alone. Future studies could address this issue by more closely matching stimulus composition and trial number across contexts. Second, the threat-only condition involved 120 consecutive threat words, which may have introduced emotional fatigue or habituation over time. Such repeated exposure could have contributed to reduced later-stage engagement, including the attenuated LPP response, and therefore represents an alternative explanation beyond predictability alone. Future studies should further disentangle contextual predictability from repeated-exposure or habituation effects. Third, the present findings were based on word stimuli presented in a laboratory Stroop task and on a sample consisting primarily of young adults. These features may limit generalizability to more complex and dynamic social situations, other age groups, or clinical populations with diagnosed social anxiety disorder. Extending this paradigm to richer or more ecologically valid stimuli, and testing more diverse samples, would help clarify the broader applicability of the observed effects. Finally, longitudinal or intervention-based studies could examine whether sensitivity to contextual unpredictability represents a modifiable mechanism underlying high social anxiety.

Conclusion

The present study suggests that threat-related processing in high social anxiety is associated not only with exposure to threatening stimuli but also with the predictability of the emotional context under the present task design. Across behavioral, ERP, and oscillatory measures, high social anxiety was associated with preserved or selectively heightened early threat sensitivity alongside context-dependent differences in later evaluative and regulatory processes, particularly under conditions of emotional unpredictability. However, these findings should be interpreted cautiously, because the mixed-context and threat-only conditions differed not only in contextual predictability but also in stimulus composition and overall trial structure. Within these constraints, the present results provide a more nuanced account of emotional processing in high social anxiety and may help reconcile previously inconsistent findings in the literature. These findings may also inform future work examining whether context-sensitive threat processing has implications for assessment or intervention in individuals with elevated social anxiety.

Data Sharing Statement

The datasets generated and analyzed during the current study are available from the corresponding author upon reasonable request.

Ethical Approval and Consent to Participate

The studies involving human participants were reviewed and approved by the Ethics Committee of Daqing Campus of Harbin Medical University (No.: HMUDQ20251215001) following the Declaration of Helsinki; all participants signed informed consent forms in this study.

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Disclosure

The authors declare no conflicts of interest.

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