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Distinct neurodynamics underlie empathy for infant pain: An EEG study of temporal and oscillatory mechanisms

Chunyan Liu [a,b,c], Yi Jiang [a,b,*]

[a] State Key Laboratory of Cognitive Science and Mental Health, Institute of Psychology, Chinese Academy of Sciences, Beijing, China
[b] Department of Psychology, University of Chinese Academy of Sciences, Beijing, China
[c] School of Education and Psychology, University of Jinan, Jinan, China

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ABSTRACT

Protecting infants from harm is widely considered a fundamental evolutionary imperative and a cross-cultural universal. While adults exhibit heightened empathic responses to infant pain, the underlying neurocognitive dynamics remain unclear. Using EEG during a pain empathy paradigm, we identified distinct neural responses to infant pain compared to adult pain. Relative to adult $_{\text{pain-neutral}}$ condition, infant $_{\text{pain-neutral}}$ condition elicited a larger P3 amplitude, suggesting enhanced cognitive empathy. In the oscillatory domain, infant pain (versus infant-neutral) induced enhanced alpha power and greater adaptive modulation of alpha and low beta (15–18 Hz) rhythms. Conversely, adult pain (versus adult-neutral) was associated with stronger suppression of low-alpha (8–10 Hz) activity and reduced adaptive modulation. Furthermore, empathy for infant pain engaged increased posterior-to-anterior information flow, suggesting heightened integration across affective and cognitive networks. These findings collectively suggest that the increased alpha power may reflect rapid threat detection and top-down modulation, while the enhanced adaptive changes signify efficient response optimization during infant pain empathy. Our results are consistent with the model of the parental brain as an evolutionary product that balances conserved subcortical responses with flexible cortical regulation, pointing toward a unique neurophysiological profile supporting the protection of vulnerable offspring.

1. Introduction

Protecting offspring from harm is a fundamental evolutionary imperative across species, shaped by natural selection to ensure species survival. In humans, this protective motivation extends beyond biological necessity to encompass moral and legal obligations, formally enshrined in international declarations (League of Nations, 1924; United Nations, 1959, 1989). Another of our studies (Liu and Jiang, 2026, under review) has demonstrated that non-parental adults exhibit enhanced and automatic empathic responses to infant pain when exposed to threatening contexts. The heightened and involuntary nature of this response strongly suggests its role as an innate releasing mechanism for protective motivation toward vulnerable offspring. However, the neurocognitive mechanisms underlying the empathy for infant pain remain poorly understood.

Previous research on adult responses to infant distress has primarily used infant crying faces (see review: Kuzava et al., 2020) or crying vocalizations (see review: Witteman et al., 2019). While most existing studies have focused on contrasting different emotional expressions in infant faces (e.g., Proverbio et al., 2006; Yrttiaho et al., 2017) or voices (e.g., Dudek et al., 2016), only a limited number have directly compared neural responses to negative facial expressions using infant versus adult stimuli, and these investigations have yielded inconsistent findings. For example, research has shown that sad infant faces elicit significantly larger N170 amplitudes in the right hemisphere compared to sad adult faces (Colasante et al., 2017), as well as greater activation in brain regions including the bilateral fusiform gyrus, posterior cingulate cortex-thalamus, and precuneus when processing uncomfortable infant faces relative to sad adult faces (Li et al., 2016). In contrast, other studies have found no significant differences in neural responses to infant versus adult distress expressions among non-mother participants (no significant difference in N170b amplitude; Rutherford et al., 2017), nor did they observe any interaction between facial expression and age, even when mothers were tested (Peltola et al., 2018).

Beyond these inconsistencies, a key limitation of prior research is its reliance on crying faces or voices as proxies for infant pain. Yet, infant

* Corresponding author at: Institute of Psychology, Chinese Academy of Sciences, Beijing, China.
E-mail address: yijiang@psych.ac.cn (Y. Jiang).

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crying can signal a range of needs and does not always indicate pain or distress. Moreover, due to higher facial fat content and lower muscle tension, infant expressions are more ambiguous and difficult to interpret accurately than adult faces (Kuzava et al., 2020). Therefore, direct evidence for the specific neural mechanisms underlying adult empathy toward infant pain remains limited.

To address these issues, the present study employed a well-established pain empathy paradigm to investigate the mechanisms underlying adults' empathy for infant pain. In this paradigm, participants typically viewed images depicting harmful or neutral tools acting on human faces or limbs (e.g., a needle piercing a hand), and then were asked to evaluate the pain experienced by the person in the image and their own discomfort. This paradigm provides clear and salient cues of harm (Vachon-Presseau et al., 2012), enabling the investigation of adult neural responses when observing infants in threatening or injurious contexts.

Moreover, electroencephalography (EEG) provides a temporally precise method for investigating the dynamics of cognitive processes, including the distinct components involved in pain empathy. Event-related potential (ERP) studies indicate that pain empathy unfolds in two sequential stages: an early affective stage, reflected in components such as N1, P2, and N2, followed by a later cognitive-evaluative stage marked by P3 and late positive components (LPC/LPP) (Li et al., 2019; Meng et al., 2019; Pan et al., 2023; Wu et al., 2024). Research on neural oscillation further indicates that pain empathy involves both the suppression (e.g., Joyal et al., 2018; Motoyama et al., 2017; Pan et al., 2023; Perry et al., 2010; Yang et al., 2009) and enhancement (e.g., Levy et al., 2016; Mu et al., 2008; Zebarjadi et al., 2021; Zhou and Han, 2021) of alpha activity, as well as modulations in beta rhythms (Levy et al., 2018; Riečanský et al., 2015; Zebarjadi et al., 2021). Alpha enhancement is often linked to the inhibition of task-irrelevant regions (Jensen and Mazaheri, 2010), while alpha suppression is thought to reflect cortical disinhibition that facilitates processing (Zebarjadi et al., 2021). Critically, repeated empathic stimulation can lead to neural adaptation (repetition suppression) (Cheng et al., 2007; Grill-Spector et al., 2006; Mu et al., 2008). Notably, under pain (but not neutral) conditions, alpha power decreases from early to late stages (Mu et al., 2008), indicating that adaptation patterns are condition-dependent. However, it remains unclear whether and how these temporal dynamics, neural component specificity, and adaptive changes specifically characterize empathy for infant pain, or whether oscillatory activity (e.g., in the alpha/beta bands) differs from the patterns observed during empathy for adult pain.

This study used EEG to characterize the temporal dynamics and neural signatures underlying empathy for infant pain. We hypothesized that empathy for infant pain, compared to adult pain, would involve distinct neural dynamics, evidenced by differences in ERPs, neural oscillations, and their adaptive changes over time. Additionally, we analyzed functional connectivity to extend the analysis beyond local neural activity.

2. Methods

2.1. Participants

The a priori sample size estimation was performed using G*Power 3.1.9.7 (Faul et al., 2007). Given that previous studies employing the same 2 × 2 within-subject design as ours have reported large effect sizes (e.g., Zhou and Han, 2021), we selected a conservative medium-to-large effect size ($f = 0.3$) for our power calculation. With $\alpha = 0.05$ and power $(1-\beta) = 0.80$, the analysis indicated a minimum of 17 participants. To ensure sufficient statistical power and consistency with previous studies (Pan et al., 2023; Zhou and Han, 2021), the sample size was increased to 22. A total of 23 adults were initially recruited; one participant was excluded from the experiment due to incomplete data caused by equipment failure, leading to a final sample of 22 participants (15 females, mean age = 23.09 ± 2.29 years). All reported no history of biological parenthood, no siblings younger than six years, and no professional experience in infant care (e.g., as nannies). They also had normal or corrected-to-normal vision and no prior neurological or psychiatric diagnoses. The study was approved by the Institutional Review Board of the Institute of Psychology, Chinese Academy of Sciences. Written informed consent was obtained from all participants prior to the experiment, with explicit reminders of their right to withdraw at any time, and they received compensation for participation.

2.2. Stimuli

All facial stimuli were selected from the Same Face with Multi-Expressions' Image Database for Infants and Adults (Jia et al., 2019), including 16 neutral-expression faces each of infants and adults, with balanced gender distribution (8 males and 8 females per group) (Fig. 1a). Tool images were obtained from online repositories or captured in-house (Fig. 1b). Based on our previous research (Liu and Jiang, 2026, under review), scissors were chosen as the pain-related tool and feathers as the neutral control. To ensure consistent contact duration between tools and faces, a standardized image processing protocol was applied. The procedure involved three steps: first, excess black borders were cropped and all face images were resized to 260×300 pixels; second, both tool images were converted to grayscale and adjusted to 263×236 pixels; third, to match physical properties such as luminance, all face and tool images were standardized using SHINEBOX software. The visual angles of the stimuli were $4.96^\circ \times 5.72^\circ$ for faces and $3.65^\circ \times 1.80^\circ$ for tools, with a fixed viewing distance of 60 cm. Stimulus presentation and experimental control were conducted using MATLAB (The MathWorks, Natick, MA) with PsychToolbox extensions (Brainard, 1997).

2.3. Procedures and EEG data acquisition

The experiment employed a dynamic pain empathy paradigm in which a pain-related or neutral tool image moved toward an infant or adult face and stopped upon partial overlap. Participants then completed two sequential pain empathy rating tasks (Fig. 1c). Each trial began with a central white fixation cross (1000 ms), followed by the simultaneous presentation of a centrally displayed face and a tool positioned 3.25 cm to the left or right. The tool moved centrally at 1.2 pixels per frame for 800 ms, after which a gray screen was presented for 800 ms. Two rating questions were then displayed sequentially at the center of the screen. A prompt appeared: "How much pain do you think the person in the image is experiencing?" Participants rated their perception on a 5-point Likert scale (1 = no pain, 5 = extreme pain), with higher scores indicating greater perceived pain intensity. After responding, they answered: "How unpleasant did you feel while viewing this image?" using a similar 5-point scale. Each condition (face type × tool type) included 128 trials, resulting in a total of 512 trials.

EEG data were recorded using a Neuroscan Curry system with a 64-channel electrode cap. Horizontal electrooculogram (EOG) electrodes were placed at the outer canthi of both eyes, and vertical EOG electrodes were positioned above and below the left eye. Electrode impedances were kept below 5 kΩ throughout the session. Data were sampled at 1000 Hz with a bandpass filter of 0.05–100 Hz.

Following the EEG session, participants completed the Interpersonal Reactivity Index (IRI; Davis, 1983; Rong et al., 2010), a self-report questionnaire assessing trait empathy across four subscales: perspective taking, fantasy, empathic concern, and personal distress.

2.4. Data analyses

2.4.1. Behavioral data analyses

Repeated measures ANOVAs were conducted on the pain empathy rating scores, with face type and tool type as within-subjects factors, using pain intensity ratings and self-unpleasantness ratings as dependent

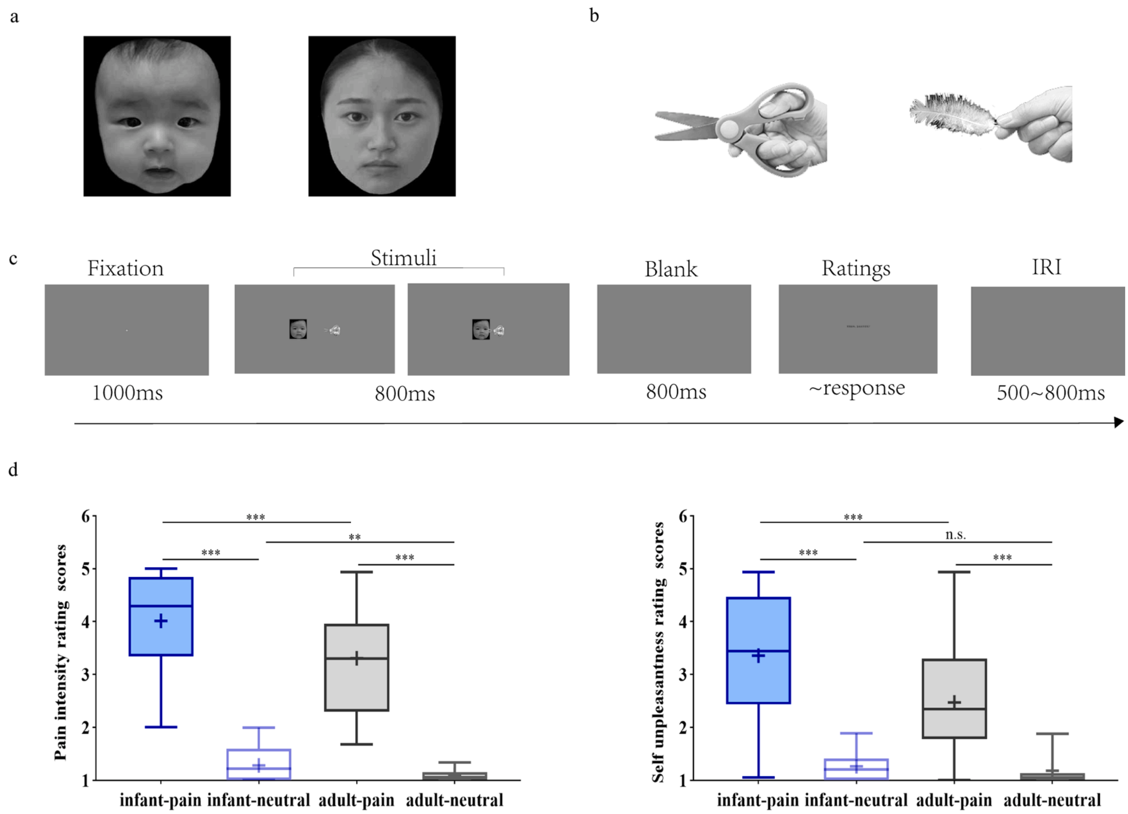

Fig. 1. Stimuli, experimental procedure and behavioral results. a, Examples of infant and adult facial stimuli used in the study. b, Illustrations of the pain-inducing tool (left) and neutral tool (right). c, Illustration of the experimental procedure. d, Behavioral results: left, Pain intensity rating scores; right, Self-unpleasantness rating scores. The plots show the quartiles (boxes), means (cross inside boxes), medians (horizontal lines inside boxes), maximum and minimum (whiskers).

variables in separate analyses.

2.4.2. ERP analyses

The EEG data were preprocessed in MATLAB using the EEGLAB toolbox. First, the data were re-referenced to the bilateral mastoids (M1 and M2). Next, a bandpass filter (0.5–100 Hz) was applied, along with notch filters at 49–51 Hz (to eliminate power line interference) and 59–61 Hz (to suppress screen flicker interference). The data were then segmented into epochs from −1000 ms to 800 ms relative to stimulus onset and baseline-corrected using the EEG signal recorded during the 1000 ms interval preceding cue presentation. To reject artifacts, some epochs were excluded. The number of retained trials did not differ significantly across the four conditions (infant-pain: 124.91 ± 3.38; infant-neutral: 125.55 ± 2.67; adult-pain: 124.64 ± 3.78; adult-neutral: 125.00 ± 3.34; $F(3, 63) = 1.21$, $p = .312$, $\eta_p^2 = 0.055$). Finally, independent component analysis (ICA) was used to remove artifacts. On average, 17.36 ± 4.87 components per participant were excluded, primarily those classified by ICLabel as ocular, muscular, or channel noise. Components labeled as brain were retained.

Subsequently, the experimental data were divided into four conditions: infant-pain, infant-neutral, adult-pain, and adult-neutral. For each condition, the epochs were averaged and baseline-corrected using the 200 ms pre-stimulus interval to obtain ERP waveforms for each participant. Based on prior studies (Coll, 2018) and the grand average waveform, we analyzed N1, N2, P3, and LPP components. Scalp topography showed N1 and N2 were strongest at frontal electrodes, P3 and LPP at central-parietal electrodes. Accordingly, the electrodes of interest (EOIs) were defined as Fz for N1 and N2, and CPz for P3 and LPP. These electrode selections align with prior findings (Coll, 2018; Li et al., 2020). Time windows for analysis were determined based on the grand average waveform: 90–110 ms for N1, 170–230 ms for N2, 450–550 ms for P3, and 550–700 ms for LPP. The average amplitudes and latencies of each component across the four conditions were calculated, and repeated-measures ANOVA was conducted on these measures.

2.4.3. Time frequency analysis

After downsampling of the raw EEG data to 50 Hz (Xie et al., 2022), time-frequency analysis was performed using the Morlet wavelet method (wavelet width = 5) implemented in FieldTrip (Oostenveld et al., 2011). The analysis encompassed the frequency range of 1–30 Hz and the time window from 1000 ms before stimulus onset to 1600 ms after stimulus onset. The time window from −600 ms to −400 ms relative to stimulus onset was selected as the baseline for normalization using the relative change (relchange) method, which expresses post-stimulus power as a percentage change from the baseline period. This baseline window was selected to mitigate temporal smearing effects from Morlet wavelet convolution, which is pronounced at lower frequencies. This window minimizes contamination from post-stimulus activity (near time zero), initial fixation responses (near epoch onset), and edge artifacts, thereby providing a stable pre-stimulus baseline for analysis extending into the theta range.

Then, the adaptive change of neural oscillations was investigated. Following Pan et al. (2023), who showed that 30 trials per condition are sufficient to detect differences in neural oscillations between pain and neutral conditions, the first 30 trials of each condition were designated as the early stage, and the last 30 trials were designated as the late stage. The difference in neural oscillatory activity between these two stages was defined as the index of neural adaptive change. Using neural adaptive change and time-frequency power during the early stage as separate dependent variables, we conducted cluster-based permutation tests (two-tailed, 10,000 permutations, α = 0.025) to compare infant $_{\text{pain-neutral}}$ condition with the adult $_{\text{pain-neutral}}$ condition. The analysis focused on the 0–800 ms post-stimulus time window and 1–30 Hz frequency range across all electrodes, which revealed significant effects in the 8–10 Hz, 11–14 Hz, and 15–18 Hz frequency ranges. Throughout the manuscript, we refer to these as low-alpha (8–10 Hz), high-alpha (11–14 Hz), and low-beta (15–18 Hz) to denote these data-driven narrow bands. Subsequently, a repeated-measures ANOVA was conducted on the average power of the three bands.

To rule out the potential impact of our trial selection strategy (i.e., using the first and last 30 trials) on the aforementioned results and to further verify how trial progression modulates neural oscillatory power, we performed the following supplementary analyses. The specific steps were as follows: First, for each trial, neural oscillatory power within each of the three frequency bands was averaged across all electrodes and within specific post-stimulus time windows (0–800 ms for low alpha, 420–660 ms for high alpha, and 480–640 ms for low beta). The data were then downsampled by averaging across every 10 consecutive trials. Trials beyond the 120th trial were excluded. A 2 (face type) × 2 (tool type) repeated-measures ANOVA with trial order as a covariate was conducted. Second, to examine linear trends associated with trial sequence, we performed separate linear mixed-effects models for each frequency band using JASP. The models included oscillatory power in each band as the dependent variable, with face type, tool type, trial order, and their interactions as fixed effects, and participants as a random-effects grouping factor. Third, to assess whether the clusters identified earlier remained stable across all trials, the experimental trials were divided into early and late phases using a 50% cutoff (i.e., the first 50% and the last 50% of trials). Then, the cluster-based permutation test (two-tailed, 10,000 permutations, α = 0.025) comparing the infant $_{\text{pain-neutral}}$ condition with the adult $_{\text{pain-neutral}}$ condition was repeated, following the same procedure described previously.

To further characterize potential baseline differences prior to the emergence of adaptive changes, we conducted an additional exploratory analysis on oscillatory power during the early phase (i.e., the first 30 trials). Cluster-based permutation tests were performed across the 0–800 ms post-stimulus interval and the 1–30 Hz frequency range. Following the identification of significant time windows from these tests, we then performed ANOVAs on the whole-scalp averaged power within those specific intervals to detail the condition effects.

To control the increased Type I error rate from multiple comparisons across frequency bands (low alpha, high alpha, and low beta), we applied false discovery rate (FDR) correction using the Benjamini-Hochberg procedure (Benjamini and Hochberg, 1995) to all primary hypothesis tests. These included: 3 ANOVAs for adaptive change effects, 6 ANOVAs for trial sequence modulation (with trial order as a covariate), 3 linear mixed-effects models for linear trends over time, and 2 ANOVAs for early-stage oscillation power, totaling 14 tests. The FDR method controls the expected proportion of false positives among rejected hypotheses, providing a balance between sensitivity and specificity that is well-suited for correlated neurophysiological data (Genovese et al., 2002; Nichols and Hayasaka, 2003). Statistical significance was defined as a corrected q-value < 0.05.

2.4.4. Functional connectivity analysis

To investigate functional connectivity between brain regions during empathy for infant pain, phase transfer entropy (PTE; Lobier et al., 2014) was calculated using Brainstorm (Tadel et al., 2011) in the theta (5–7 Hz), low alpha (8–10 Hz), high alpha (11–14 Hz), and beta (15–30 Hz) frequency bands during the early stage (first 30 trials) within the 0–800 ms time window. The resulting PTE values were exported and subjected to cluster-based permutation tests using FieldTrip (two-tailed, 10,000 permutations, α = 0.025).

3. Results

3.1. Behavioral results

Pain empathy rating scores during EEG recording are presented in Fig. 1d For pain intensity ratings, a significant interaction between face type and tool type was found (F(1, 21) = 32.9, $p < .001$, $\eta_p^2 = 0.611$). Specifically, pain intensity ratings were significantly higher in the infant-pain condition (4.02 ± 0.90) than in the infant-neutral condition (1.28 ± 0.30) (t(21) = 14.39, $p < .001$, Cohen's $d = 3.068$). Similarly, ratings in the adult-pain condition (3.31 ± 0.97) were significantly higher than those in the adult-neutral condition (1.09 ± 0.09) (t(21) = 10.80, $p < .001$, Cohen's $d = 2.302$). Moreover, the difference in pain intensity ratings (pain minus neutral) for infant faces (2.73 ± 0.89) was significantly greater than that for adult faces (2.21 ± 0.96) (t(21) = 5.74, $p < .001$, Cohen's $d = 1.224$). These results indicate that for the same painful tool, participants attributed higher pain intensity to infants compared to adults.

Self-unpleasantness ratings showed a similar pattern, with a significant interaction between face type and tool type (F (1, 21) = 28.4, $p < .001$, $\eta_p^2 = 0.575$). Self-unpleasantness ratings were significantly higher in the infant-pain condition (3.36 ± 1.20) than in the infant-neutral condition (1.26 ± 0.27) (t (21) = 8.05, $p < .001$, Cohen's $d = 1.715$) and in the adult-pain condition (2.47 ± 1.03) than in the adult-neutral condition (1.18 ± 0.28) (t (21) = 5.70, $p < .001$, Cohen's $d = 1.214$). Furthermore, self-unpleasantness ratings were significantly higher in the infant-pain condition compared to the adult-pain condition (t (21) = 6.48, $p < .001$, Cohen's $d = 1.381$). In contrast, no significant difference was observed between the infant-neutral and adult-neutral conditions (t (21) = 1.52, $p = .144$, Cohen's $d = 0.323$). This pattern suggests that the affective component of pain empathy, the self-unpleasantness, was more strongly engaged when observing infants in pain compared to adults.

In addition, significant correlations were observed between pain empathy ratings and IRI scores. Detailed results are provided in the Supplementary Materials.

3.2. ERP features

The analysis of N1 and N2 components revealed significant main effects of tool type, with reduced absolute amplitudes in pain condition compared to the neutral condition (N1: pain versus neutral condition: −3.36 ± 2.85 vs. −3.76 ± 2.58; F (1,21) = 4.38, $p = .049$, $\eta_p^2 = 0.173$; N2: −3.08 ± 3.80 vs. −3.75 ± 4.18; F (1,21) = 5.45, $p = .030$, $\eta_p^2 = 0.206$). The face main effect of N1 was not significant (F (1, 21) = 3.56, $p = .073$, $\eta_p^2 = 0.145$). The face main effect of N2 was significant (F (1, 21) = 30.12, $p < .001$, $\eta_p^2 = 0.589$), with reduced absolute amplitudes in infant face (−2.64±3.83) compared to adult face condition (−4.18 ±4.15). No significant Face × Tool interaction was observed for either component (N1: F (1,21) = 0.10, $p = .751$, $\eta_p^2 = 0.005$; N2: F (1,21) = 0.02, $p = .897$, $\eta_p^2 = 8.228\times10^{-4}$). These findings indicate that the N1 and N2 components were sensitive to the distinction between infant and adult faces, and between pain-related and neutral tools during early-stage processing, yet did not reveal any significant interaction between face type and tool type.

For the P3 component, a significant Face × Tool interaction was observed (F (1,21) = 4.96, $p = .037$, $\eta_p^2 = 0.191$; Fig. 2), indicating distinct neural sensitivity to infant pain stimuli. Post-hoc comparisons demonstrated significantly enhanced amplitudes for infant-pain versus infant-neutral condition (7.68±4.63 vs. 6.31±4.06; t (21) =3.09, $p = 0.006$, Cohen's $d = 0.658$), whereas adult stimuli elicited no such differentiation (5.50±3.79 vs. 4.86±3.20; t (21) = 1.63, $p = 0.118$, Cohen's $d = 0.347$). This pattern suggests selective potentiation of cognitive empathy specifically during observation of infant pain.

For the LPP, a significant main effect of face type emerged (F (1, 21) = 20.50, $p < .001$, $\eta_p^2 = 0.494$), reflecting larger amplitudes for infant faces (4.98±3.39) relative to adult faces (3.76±2.91). A significant main effect of tool condition was also observed (F (1, 21) = 4.59, $p = .044$, $\eta_p^2 = 0.179$), with greater amplitudes in the pain condition (4.76±3.62) compared to the neutral condition (3.98±2.73). The Face × Tool interaction was not statistically significant (F (1, 21) = 3.37, $p = .081$, $\eta_p^2 = 0.138$).

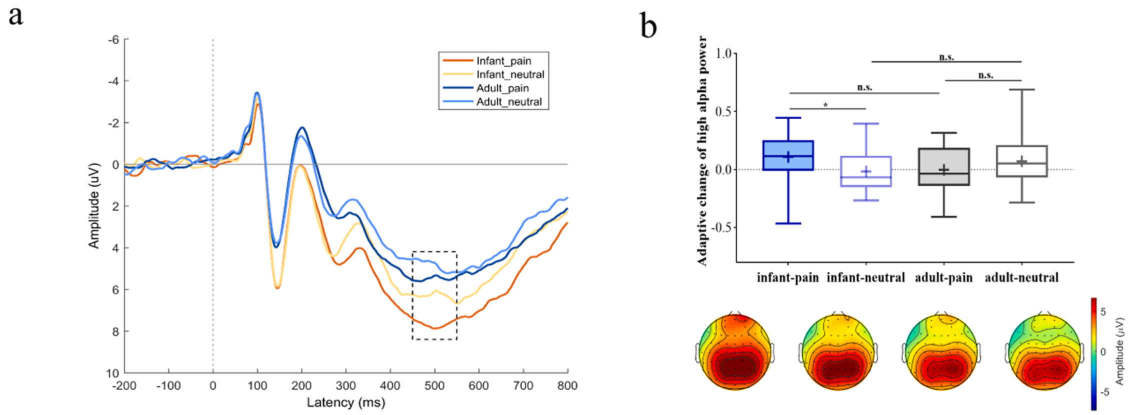

Fig. 2. Results of ERP features. a, ERP responses at CPz electrodes. The dashed boxes show the time windows for the P3 component: 450–550 ms after stimulus onset. b, Amplitude comparisons of the P3 component across conditions.

3.3. Adaptive change of neural oscillations

Using the neural adaptive change as an indicator, we performed a whole-brain cluster-based permutation test (two-tailed, 10,000 permutations, $\alpha = 0.025$) during stimulus presentation (0–800 ms) comparing infant $_{\text{pain-neutral}}$ and adult $_{\text{pain-neutral}}$ condition. Significant positive clusters were observed for frequency between 8 Hz and 18 Hz (cluster-mass value = 4052.45, cluster-level corrected $p = .029$). Given that significant clusters in different frequency bands were localized to distinct brain regions (8–10 Hz in right hemisphere, 11–14 Hz in frontocentral regions, and 15–18 Hz in the right central cortex), we defined three frequency bands: low alpha (8–10 Hz), high alpha (11–14 Hz), and low beta (15–18 Hz). Subsequent frequency band-specific analyses revealed stronger neural adaptive power in infant $_{\text{pain-neutral}}$ condition, evidenced by significant positive clusters in all bands (Fig. 3): low-alpha (240–680 ms, right hemisphere; cluster-mass value = 1771.24, cluster-level corrected $p = .004$), high-alpha (420–660 ms, frontocentral; cluster-mass value = 758.04, cluster-level corrected $p = .011$), and low beta (480–640 ms, right hemisphere; cluster-mass value = 504.96, cluster-level corrected $p = .015$). These results indicate significantly stronger neural adaptive changes in response to infant $_{\text{pain-neutral}}$ compared to adult $_{\text{pain-neutral}}$ across multiple frequency bands.

To further validate the robustness of these effects, we conducted whole-scalp analyses by averaging oscillatory power across all electrodes for each frequency band. For the low-alpha band, a repeated-measures ANOVA on power averaged across all electrodes and the full 0–800 ms post-stimulus interval revealed a significant Face × Tool interaction ($F(1,21) = 5.96$, $p = .024$, $p_{\text{fdr}} = 0.037$, $\eta_p^2 = 0.221$). For the high-alpha and low beta bands, analogous ANOVAs were performed on power averaged across all electrodes within the time windows identified in the whole-brain cluster-based permutation tests (high-alpha: 420–660 ms; low beta: 480–640 ms). Both yielded significant interactions (high alpha: $F(1,21) = 7.34$, $p = .013$, $p_{\text{fdr}} = 0.037$, $\eta_p^2 = 0.259$; low beta band: $F(1,21) = 6.71$, $p = .017$, $p_{\text{fdr}} = 0.037$, $\eta_p^2 = 0.242$). These findings suggest that there are distinct patterns of adaptive change in empathy toward infant and adult pain.

Additionally, neural adaptive changes in the infant-pain condition correlated with empathy ratings. Specifically, the adaptive changes in low beta power (whole-brain mean, 0–800 ms) showed a significant positive correlation with early-stage empathy ratings ($r = 0.487$, $p = .022$, 95% CI = 0.082, 0.754; Fig. 3d, left). This link indicates that greater neural refinement during the task aligns with stronger empathic responses. No significant correlations were found between neural adaptive changes and empathy ratings in the other conditions (all $ps > 0.05$).

Moreover, Cluster-based permutation tests (one-tailed, 10,000 iterations, $\alpha = 0.05$) were conducted to compare neural adaptive changes between the infant-pain and infant-neutral conditions, as well as between the adult-pain and adult-neutral conditions. Significant positive clusters were observed in three frequency bands during the infant-pain vs. infant-neutral comparison: 8–10 Hz (cluster-mass value = 573.85; cluster-corrected $p = .002$), 15–21 Hz (cluster-mass value = 755.82; cluster-corrected $p = .001$, 200–720 ms, central and right hemispheres), and 22–30 Hz (cluster-mass value = 542.48; cluster-corrected $p = .002$, 600–800 ms, central, parietal, and occipital regions). The 8–10 Hz effect first emerged at 120 ms over the occipital lobe, persisted until 800 ms, and gradually expanded spatially to encompass nearly all electrode sites. In contrast, no significant positive or negative clusters were found in the adult-pain vs. adult-neutral comparison (minimum cluster-corrected $p = .089$). These results indicated robust, sustained neural adaptive changes specific to the perception of infant pain, while no such significant response was detected for adult pain.

To address concerns that trial selection might have influenced the aforementioned results, we split all trials into early and late halves and further assessed the stability of the neural adaptive change effect across conditions. Applying the same statistical procedures, we obtained consistent results, thereby confirming the robustness of our findings. See Supplementary Materials for detailed outcomes.

3.4. Modulation of neural oscillatory power by trial sequence

To examine the influence of trial sequence, we analyzed the global mean oscillatory power for each trial (as described in the Methods) during stimulus presentation. For low alpha band, when trial order was not considered, there was no significant Face × Tool interaction ($F(1, 263) = 1.016$, $p = .314$, $\eta_p^2 = 0.004$). However, when trial order was included as a covariate, the Face × Tool interaction became significant ($F(1, 262) = 6.215$, $p = .013$, $p_{\text{fdr}} = 0.037$, $\eta_p^2 = 0.023$), and the three-way interaction of Face × Tool × Trial Order was also significant ($F(1, 262) = 5.212$, $p = .023$, $p_{\text{fdr}} = 0.037$, $\eta_p^2 = 0.020$). For high alpha and low beta power, similar patterns were observed when analyses were restricted to their respective significant time windows (420–660 ms for high alpha, and 480–640 ms for low beta). With trial order as a covariate, the Face × Tool interaction was significant for both high alpha ($F(1, 262) = 6.162$, $p = .014$, $p_{\text{fdr}} = 0.037$, $\eta_p^2 = 0.023$) and low beta power ($F(1, 262) = 6.057$, $p = .014$, $p_{\text{fdr}} = 0.037$, $\eta_p^2 = 0.023$). The three-way interactions were significant at the uncorrected level but became marginally significant following FDR correction (high alpha: $F(1, 262) = 3.964$, $p = .048$, $p_{\text{fdr}} = 0.056$, $\eta_p^2 = 0.015$; low beta: $F(1, 262) = 4.068$, $p = .045$, $p_{\text{fdr}} = 0.056$, $\eta_p^2 = 0.015$). These results indicate that trial order significantly modulated oscillatory responses across conditions.

To further quantify linear trends over time, we conducted linear mixed-effects models. For low alpha power, the Face × Tool × Trial

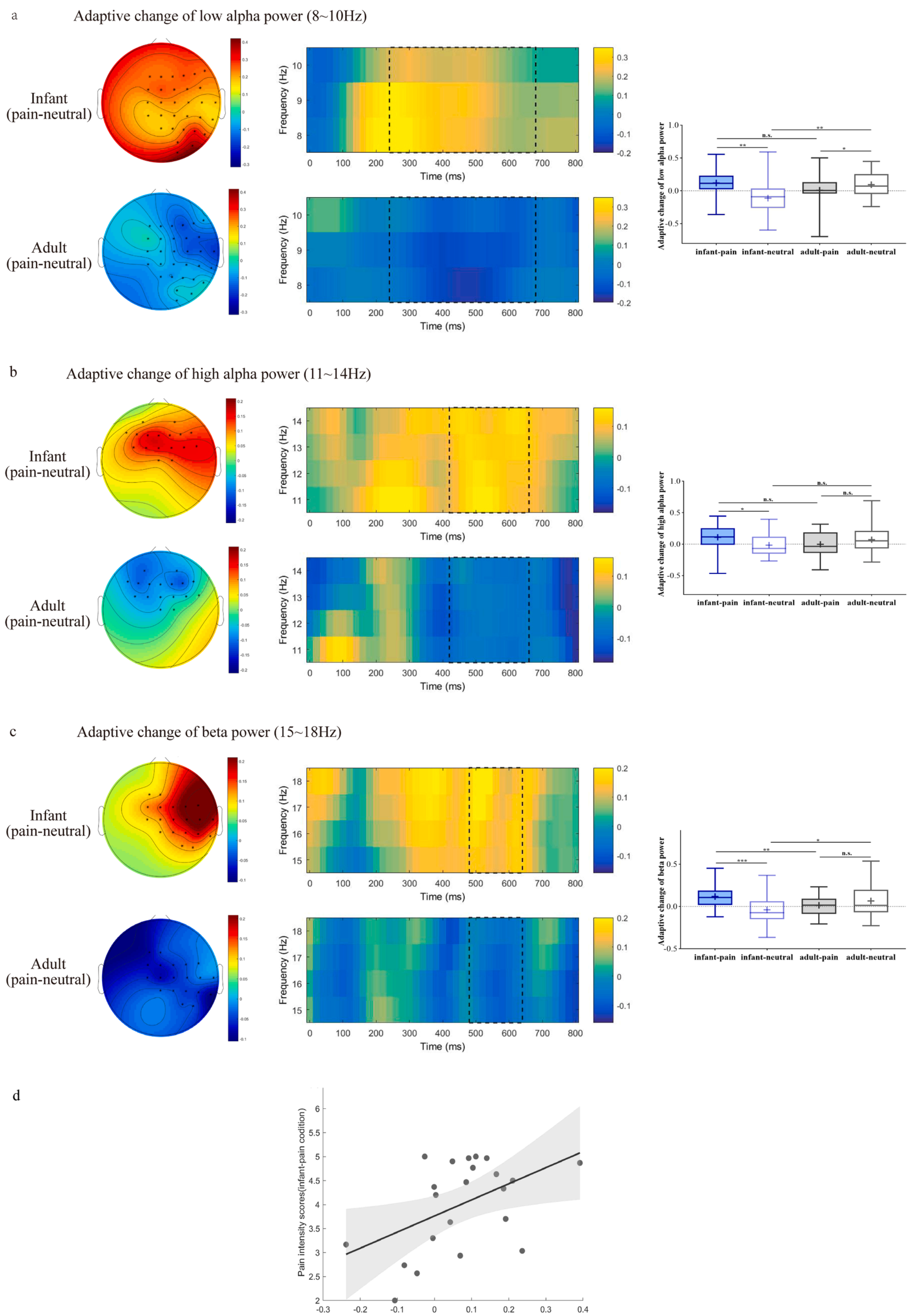

Fig. 3. Results of neural adaptive change in low alpha (a), high alpha (b), and low beta band (c). Left: Scalp topographic maps show the average activity during the significant time windows identified by cluster-based permutation tests (low-alpha: 240–680 ms; high-alpha: 420–660 ms; low-beta: 480–640 ms). Electrodes within significant clusters are marked with black dots. Middle: Time-frequency plots, with significant time-frequency clusters outlined by dashed rectangles. Right: Mean neural adaptation amplitudes within significant clusters for each condition. The plots show the quartiles (boxes), means (cross inside boxes), medians (horizontal lines inside boxes), maximum and minimum (whiskers). d, Correlations between low beta band adaptive change and pain intensity ratings under the infant-pain condition. Scatter points represent the observed data. The black solid line indicates the linear regression fit, and the semi-transparent gray shaded area represents the 95% confidence interval of the predicted values from the linear regression model.

Order interaction was significant (β = –0.013, SE = 0.006, t = –2.192, p = .029, p_{fdr} = 0.041). Slope estimates showed a marginally significant negative trend for the infant-pain condition (slope = –0.027, SE = 0.014, 95%CI= [−0.056, 9.30×10^{-4}], z = –1.895, p = .058) and a significant negative trend for the adult-neutral condition (slope = –0.040, SE = 0.015, 95%CI= [−0.069, −0.011], z = –2.710, p = .007). No significant slopes were found for the other conditions (all $p > .10$). For high alpha and low beta power, the three-way interactions were not significant but showed marginal trends (high alpha: β = –0.007, SE = 0.004, t = –1.787, p = .079, p_{fdr} = 0.084; low beta: β = –0.006, SE = 0.004, t = –1.780, p = .084, p_{fdr} = 0.084). These results provide further evidence that the influence of trial order on neural power was condition-specific.

3.5. Neural oscillation power in early stage

To investigate pain empathy neural mechanisms prior to adaptive change, we analyzed the neural oscillation power of first 30 trials per condition. Cluster-based permutation tests comparing the (pain-neutral) difference waves between infant and adult conditions revealed significant positive clusters in two frequency bands: a right-hemispheric cluster in the low alpha band (8–10 Hz; 320–640 ms; cluster-mass value = 645.75, cluster-corrected p = .005, two-tailed) and a fronto-central cluster in the high alpha band (11–14 Hz; 540–680 ms; cluster-mass value = 368.05, cluster-corrected p = .011, two-tailed) (Fig. 4). This pattern indicates that the infant condition was associated with enhanced alpha-band power compared to the adult condition.

The average power across all channels was analyzed for the two frequency bands using a repeated-measures ANOVA. The results showed a significant Face × Tool interaction in the low alpha band (averaged over 0–800 ms, F(1,21) = 6.14, p = .022, p_{fdr} = 0.037, η_p^2 = 0.226) and in the high alpha band (averaged over 540–680 ms, F(1,21) = 9.07, p = .007, p_{fdr} = 0.037, η_p^2 = 0.302). These findings indicate that neural responses to infant and adult pain stimuli demonstrate distinct patterns of alpha-band power modulation.

Cluster-based permutation tests (one-tailed, 10,000 iterations, α = 0.05) were performed separately for infant-pain versus infant-neutral and adult-pain versus adult-neutral. Results revealed a significant positive cluster in the infant-pain condition compared to the infant-neutral condition within the 8–9 Hz frequency range (cluster-mass value = 226.65, cluster-level corrected p = .006). The significant cluster initially emerged in the occipital lobe around 120 ms after stimulus onset and gradually spread to the parietal and central regions, lasting until the end of stimulus presentation (800 ms). In contrast, no significant clusters were observed between adult-pain and adult-neutral conditions (minimum cluster-level corrected p = .263). These results suggest that infant pain was associated with enhanced alpha power in the early stage, whereas no such association was observed under the adult condition.

3.6. Brain functional connectivity

Cluster-based permutation tests (two-tailed, 10,000 iterations, α = 0.025) showed that theta-band PTE from posterior electrodes (spanning central, parietal, and occipital regions) to anterior electrodes (encompassing prefrontal, frontal-central, and central areas) was significantly

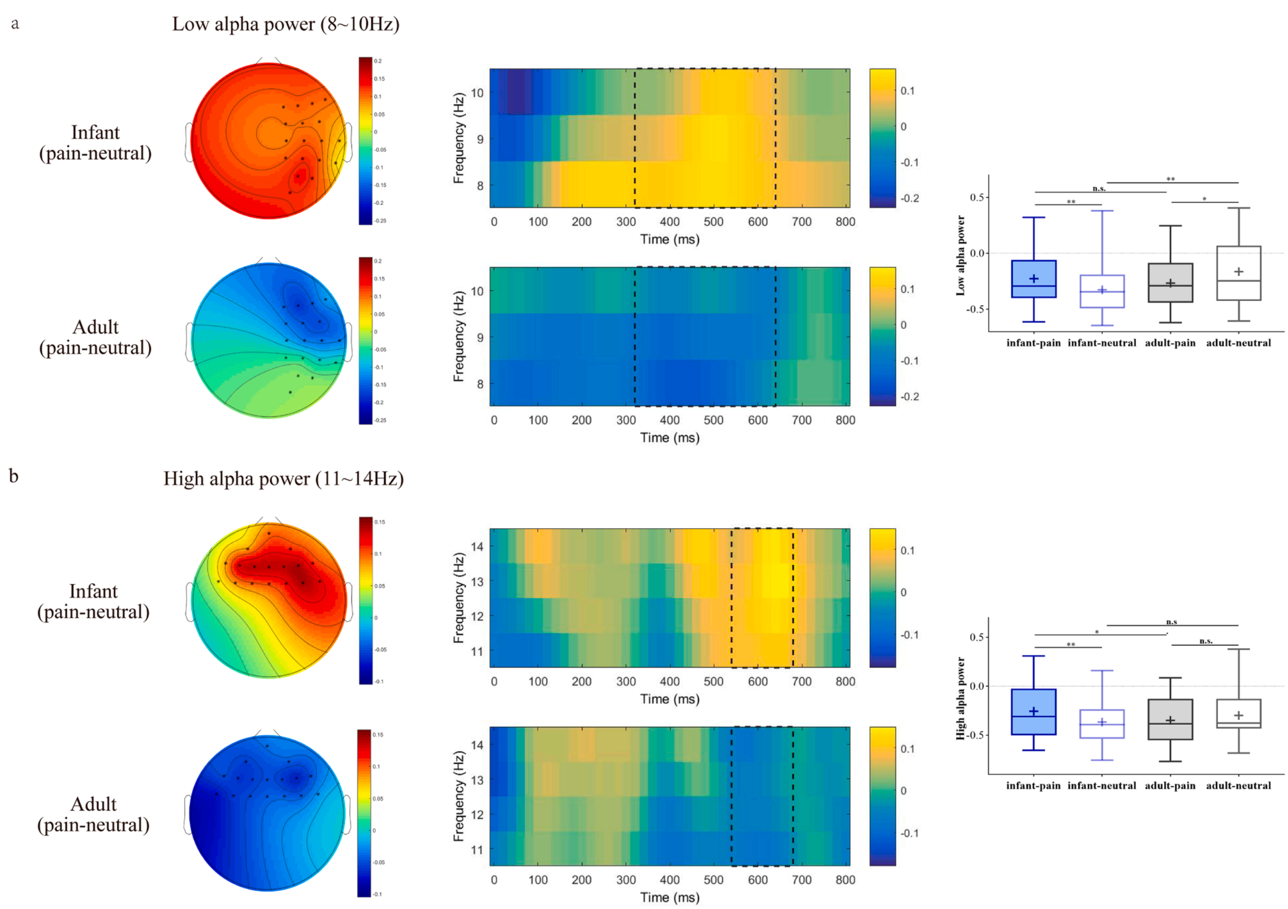

Fig. 4. Results of neural oscillation power in early stage in low alpha (a) and high alpha band (b). Left: Scalp topographic maps show the average activity during the significant time windows identified by cluster-based permutation tests (low-alpha: 320–640 ms; high-alpha: 540–680 ms). Electrodes within significant clusters are marked with black dots. Middle: Time-frequency Time-frequency representations, with significant time-frequency clusters outlined by dashed rectangles. Right: Comparisons of average neural oscillation power within significant clusters across conditions. The plots show the quartiles (boxes), means (cross inside boxes), medians (horizontal lines inside boxes), maximum and minimum (whiskers).

stronger in the infant $_{\text{pain-neutral}}$ condition than in the adult $_{\text{pain-neutral}}$ condition (Fig. 5a). To delve deeper into these patterns, a repeated-measures ANOVA revealed a significant Face × Tool interaction effect on PTE values across these regions (F (1, 21) = 21.18, $p < .001$, $\eta_p^2 = 0.502$; Fig. 5b). Simple effects analysis showed that the PTE value in the infant-pain condition (0.31±0.02) was higher than in the infant-neutral condition (0.30±0.02) (t(21) = 2.01, p = .057, Cohen's d = 0.429), although the difference was not statistically significant. In contrast, the PTE value in the adult-pain condition (0.30±0.02) was significantly lower than in the adult-neutral condition (0.32±0.01) (t(21) = −4.17, $p < .001$, Cohen's d = −.889). This indicates that empathy for infant pain and adult pain exhibits distinct and opposing patterns in brain functional connectivity. Besides, a significant positive correlation was observed between IRI perspective-taking scores and PTE values under the infant $_{\text{pain-neutral}}$ condition (r = 0.504, p = .020, 95% CI = 0.093, 0.769), suggesting that individuals with higher perspective-taking abilities exhibited stronger posterior-to-anterior information flow in this condition.

PTE results for the low alpha, high alpha and beta frequency bands are reported in full in the Supplementary Materials.

4. Discussion

Empathy toward suffering individuals is a well-established driver of prosocial behavior (Decety et al., 2016; Saulin et al., 2024). This empathetic response may be particularly pronounced toward infant pain, potentially as a manifestation of an evolved protective motivation. To investigate this heightened empathy for infant pain, we examined pain empathy in non-parental adults using EEG during a classic pain empathy paradigm. When viewing infant pain stimuli, participants reported higher ratings of pain intensity attributed to the infants and greater self-unpleasantness. These ratings respectively serve as proxies for the cognitive-evaluative and affective-sharing components of pain empathy (Li et al., 2020). These behavioral differences were paralleled by distinct neural responses to infant versus adult pain. Specifically, infant pain elicited significantly larger P3 amplitudes, heightened early-phase alpha power, and more robust neural adaptive changes in the alpha and low beta bands. Spatially, significant neural clusters emerged only in the infant-pain versus infant-neutral contrast, and the infant $_{\text{pain-neutral}}$ condition (compared to the adult $_{\text{pain-neutral}}$ condition) exhibited enhanced posterior to anterior information flow, suggesting a heightened integration across affective and cognitive networks. Collectively, these findings suggest that empathy for infant pain engages distinct neurodynamic processes compared to adult pain empathy. This pattern provides neurophysiological evidence for specialized, yet flexible, neural mechanisms that facilitate adaptive responses to infant distress.

4.1. Enhanced P3 amplitude may reflect heightened cognitive empathy for infant pain

In the present study, both N1 and N2 components showed significant main effects of tool type, with significantly smaller absolute amplitudes in the pain condition compared to the neutral condition, consistent with

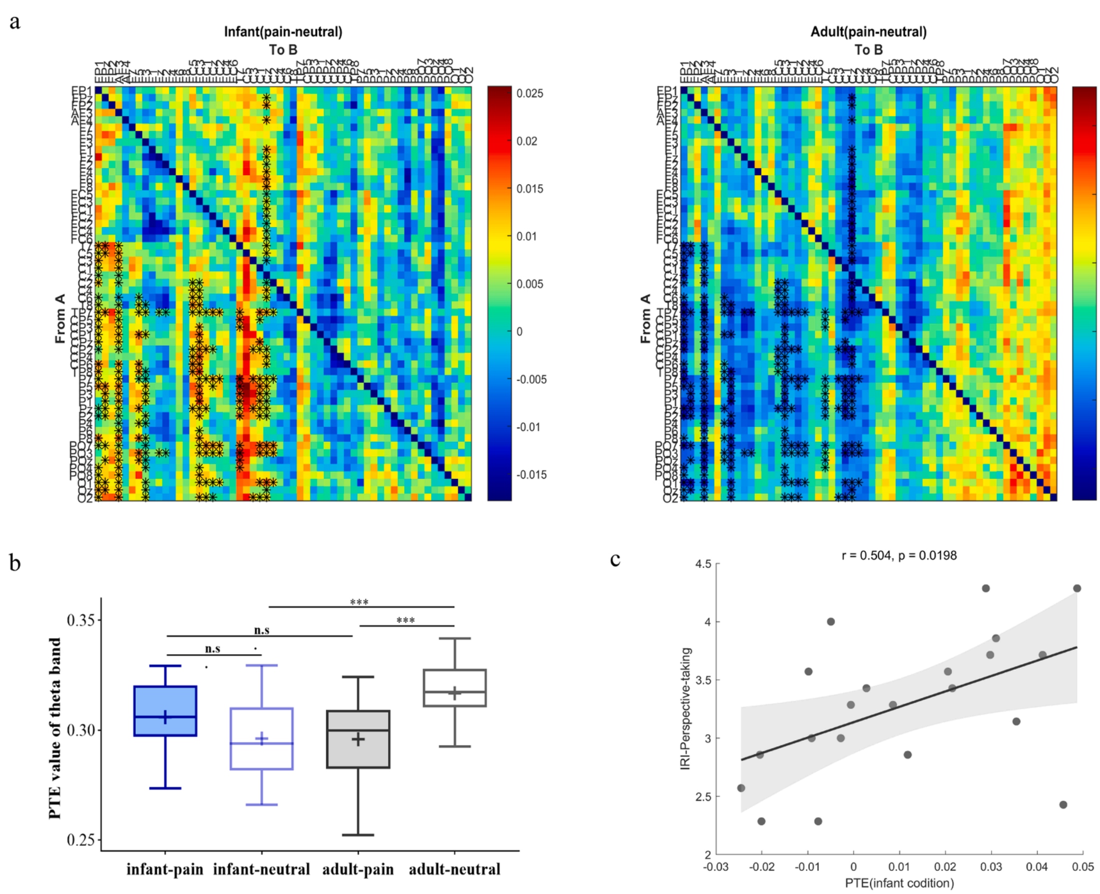

Fig. 5. Results of PTE in the theta band. a, PTE results in the infant condition (left) and adult condition (right). Black asterisks denote clusters where the cluster-based permutation test revealed statistically significant differences between the two conditions (two-tailed test, 10,000 permutations, α = 0.025). b, Comparison of mean PTE values within significant clusters across conditions. The plots show the quartiles (boxes), means (cross inside boxes), medians (horizontal lines inside boxes), maximum and minimum (whiskers). c, Correlation between IRI perspective-taking scores and PTE values under the infant $_{\text{pain-neutral}}$ condition. Scatter points represent the observed data. The black solid line indicates the linear regression fit, and the semi-transparent gray shaded area represents the 95% confidence interval of the predicted values from the linear regression model.

previous findings (Corbera et al., 2014; Cui et al., 2017; Fan and Han, 2008), though increased amplitudes under pain conditions have occasionally been reported (Cheng et al., 2012; Pan et al., 2023; Suzuki et al., 2015). The amplitude modulation of N1 and N2 observed here likely reflects an early stage of perceptual discrimination between painful and neutral stimuli.

We also found that infant faces elicited an N2 component that was significantly less negative compared to adult faces. This result initially appears to contrast with prior work reporting enhanced amplitudes for infant faces in the N170 component—a marker associated with structural face encoding (e.g., Colasante et al., 2017; Peltola et al., 2018; Vuoriainen et al., 2022). We attribute this discrepancy to a fundamental difference in task demands. In our paradigm, where faces were presented alongside a tool stimulus and required pain empathy ratings, attention was directed toward the affective evaluation of the overall scene rather than detailed structural encoding of faces. This shift in cognitive focus likely engaged distinct neurocognitive processes, leading to the modulation of the frontocentral N2. Considering that the N2 component we analyzed (170–230 ms at Fz) aligns spatiotemporally with the well-established component for conflict monitoring and expectancy violation (Botvinick et al., 2001; Folstein and Van Petten, 2008), we hypothesize that the observed N2 in our paradigm may primarily reflect a social expectancy conflict, rather than structural face processing. Adults are generally perceived as autonomous and resilient, whereas infants are viewed as vulnerable. The act of evaluating pain in this setting implicitly requires assessing the congruency between the social agent (adult/infant) and the situational context (being touched by a tool). Judging an adult's pain creates a mismatch with the expectation of adult autonomy, heightening cognitive conflict and resulting in a larger N2 amplitude. Conversely, judging an infant's pain aligns with the expectation of vulnerability, leading to reduced conflict and a smaller N2—consistent with findings linking N2 amplitude to conflict strength (Gajewski et al., 2008; Liu et al., 2018). While the aforementioned social conflict hypothesis offers a plausible account for our N2 findings, we acknowledge that the interpretation remains tentative. Future research could employ paradigms that present faces or tools in isolation, or design conditions that explicitly manipulate social expectancy violations. Such approaches would help to disentangle the contributions of configural face processing from the postulated higher-order social conflict.

Beyond the N2 component, the P3 and LPP components revealed a dissociative pattern. A significantly larger P3 amplitude was elicited by the infant-pain condition compared to infant-neutral, whereas no such difference was observed between adult-pain and adult-neutral conditions. This enhancement may reflect a heightened allocation of attention to motivationally salient cues and enhanced cognitive empathy for infant pain (Coll, 2018). The subsequent LPP component, however, displayed a more transient sensitivity to our stimulus paradigm. Our exploratory analysis revealed that the Face × Tool interaction for the LPP was statistically significant only when the time window was restricted to 550–700 ms ($p = .043$), becoming non-significant when extended to 550–800 ms ($p = .081$). This temporal boundary is notable, as it converges with the resolution of significant effects in our time-frequency analyses: the adaptive changes in low-alpha (240–680 ms), high-alpha (420–660 ms), and low-beta power (480–640 ms), along with the early-trial oscillatory power enhancements, all subsided by approximately 700 ms. This synchrony across multiple neural metrics suggests that the attenuation of the infant-pain effect beyond 700 ms is a robust and consistent characteristic of the neural response in our paradigm, rather than a measurement anomaly specific to the LPP. In our paradigm, the tool began to overlap with the face at 510 ms and continued moving for 290 ms, yet no physical deformation of the face was ever depicted. The earlier P3 component (450–550 ms) likely reflects the initial attentional capture and cognitive evaluation triggered by the tool's approaching motion. In contrast, the later LPP window (>550 ms) coincides with a period in which the tool fully overlays the face without causing realistic harm. We hypothesize that as the event unfolded beyond approximately 700 ms, participants explicitly appraised the scenario as a simulated, non-threatening event, thereby curtailing the sustained affective engagement typically indexed by a prolonged LPP.

Importantly, the attenuation of late neural activity does not diminish the salience of cognitive pain evaluation, as evidenced by the robust Face × Tool interaction in explicit pain ratings. This dissociation suggests that while the conscious judgment of pain is preserved, sustained affective arousal—reflected in the LPP—is downregulated once the stimulus is interpreted as a simulation. Future studies employing ecologically valid depictions of physical consequences (e.g., actual tissue deformation) are needed to directly test this hypothesis. Such work could determine whether realistic harmful outcomes elicit a more sustained LPP, thereby clarifying how perceptual realism modulates late affective neural dynamics in empathy.

4.2. *Increased alpha power in response to infant pain may reflect early threat detection and subsequent top-down attentional modulation*

Previous studies have shown that negative affective stimuli can increase alpha power (Uusberg et al., 2013). Similarly, observing painful situations has been linked to decreased alpha desynchronization, indicating elevated alpha power (Mu et al., 2008). Furthermore, empathic responses to ingroup pain have been correlated with enhanced alpha power (Levy et al., 2016; Zhou and Han, 2021). Our findings are consistent with these findings (Levy et al., 2016; Mu et al., 2008; Uusberg et al., 2013; Zhou and Han, 2021), showing that empathy for infant pain is associated with a significant increase in both low and high alpha band power. It is also important to note that a number of studies have found empathy for pain to be correlated with decreased alpha power (i.e., desynchronization) (e.g., Joyal et al., 2018; Perry et al., 2010). This discrepancy underscores the need to understand the cognitive processes underlying these opposing alpha responses. However, contemporary theories of alpha oscillations provide a coherent framework for interpreting our observed alpha enhancement.

Early theories linked alpha enhancement to cortical idling (Pfurtscheller, 1992), but later work redefined it as an active top-down inhibitory process that gates task-irrelevant regions (Jensen and Mazaheri, 2010; Klimesch et al., 2007). Supporting this active view, Petro et al. (2019) showed that heightened pre-target alpha power predicts faster discrimination, suggesting a beneficial preparatory state. Similarly, Stocker et al. (2025) found that high conflict elicited increased alpha power in parieto-occipital regions, indicating a possible role in early threat detection and sensory integration. Our related study using a similar pain empathy paradigm showed that infant-pain stimuli sped up lexical decisions and elicited sustained pupil dilation (Liu and Jiang, 2026, under review). These results are inconsistent with the neural idling account of alpha enhancement but instead support an active role in resource allocation. Accordingly, we propose that empathy for infant pain may involve two distinct processing stages: early threat detection and later attentional modulation.

First, in the infant-pain versus infant-neutral contrast, low-alpha enhancement emerged over occipital regions at ~120 ms, subsequently spreading to most electrodes and lasting until stimulus offset (no such effect was observed in adult contrasts). This early, widespread alpha synchronization is consistent with its proposed role in threat detection (Stocker et al., 2025), suggesting infant faces act as potent cues to rapidly trigger an alert state. This state may function as a beneficial preparatory mechanism, priming the brain for subsequent processing, as supported by findings that heightened pre-target alpha power predicts faster discrimination (Petro et al., 2019).

Second, contrasting infant with adult conditions revealed a later high-alpha enhancement localized to frontal-central regions (540–680 ms in the early experiment phase and 420–660 ms in the neural adaptive change). Given the established role of frontal alpha oscillations in top-down control (Misselhorn et al., 2019), we suggest that high-alpha enhancement may reflect active inhibitory control in preparation for protective action. Effective caregiving toward vulnerable infants requires not only activating care behaviors but also inhibiting rough or impulsive responses that could harm the infant (i.e., suppression of inappropriate motor output) while filtering out irrelevant environmental distractions (i.e., suppression of non-care-related cognitive activity) to focus attention on the infant's needs. This aligns with behavioral studies: viewing infant images enhances attentional control (Karreman and Riem, 2020), and exposure to infant animal images leads participants to exhibit more cautious behavior during fine motor dexterity tasks and a narrowed attentional focus (Nittono et al., 2012). Thus, the "protective motivation" evoked by infant pain may engage a frontal inhibitory system, with high-alpha enhancement serving as its electrophysiological signature, ensuring behavior is both precise and safe.

Previous reports of mu/alpha suppression may primarily reflect sensorimotor resonance or mirror responses to others' pain (Motoyama et al., 2017), which may dominate when observing adult pain. In contrast, responses to infant pain, given infants' vulnerability and the evolutionary basis of caregiving motivation, may additionally engage early stronger threat detection and later top-down inhibitory control, reflected in the distinct alpha enhancement pattern. We acknowledge the speculative nature of our current interpretation, but these findings offer a new perspective on the complexity of human social cognition. Alpha modulation is not a unidimensional process; it encodes the intricate interaction between a stimulus's social meaning, the observer's motivational state, and task demands. Future studies could directly test our two-stage model by manipulating adults' motivational states and measuring caregiving attitudes and behaviors.

4.3. *Enhanced adaptive change to infant pain may reflect rapid response optimization*

It is well established that repeated stimulation leads to a progressive reduction in neural activity, a phenomenon described as adaptation, repetition suppression (Grill-Spector et al., 2006), or habituation (Rankin et al., 2009; Thompson, 2009). Consistent with this principle, our study also revealed adaptive changes in alpha and low beta oscillations over the course of trials. Specifically, compared to the adult $_{\text{pain-neutral}}$ condition, empathy for infant $_{\text{pain-neutral}}$ cues elicited a significantly greater adaptive reduction in oscillatory power across the low alpha, high alpha, and low beta frequency bands. Furthermore, the condition-specific influence of trial order was further quantified: low-alpha power showed a marginally significant negative linear trend for infant-pain (p = .058) but a significant negative trend for adult-neutral (p = .007).

We propose that this pattern of habituation can be interpreted within the specific experimental context. The trial-by-trial attenuation in neural oscillation power may reflect two distinct neurocognitive processes, operating under different combinations of evolutionary salience and threat value.

First, the enhanced adaptive change to infant pain may reflect rapid response optimization. Although the stimuli conveyed threat-related connotations by superimposing tools on faces, they depicted no actual harm (e.g., no physical contact, skin deformation, or distress vocalizations). A healthy neural system thus rapidly learns these cues are benign, despite their appearance, leading to an adaptive response reduction to conserve resources (Rankin et al., 2009; Thompson, 2009). An evolutionarily efficient protective system should avoid sustaining high arousal in the absence of genuine threat, as it is metabolically costly and disruptive. Instead, it must rapidly engage when threat is probable and disengage promptly when it is not. Consistent with this, we observed significantly stronger oscillation power to infant $_{\text{pain-neutral}}$ cues than to adult $_{\text{pain-neutral}}$ cues in the early experiment stages, indicating an initial heightened sensitivity to infant threat. As participants learned that these scenarios were benign, they optimized resource allocation more efficiently. According to predictive coding theory, greater repetition suppression reflects a quicker minimization of prediction error (Auksztulewicz and Friston, 2016; Feldman and Friston, 2010; Friston, 2005). Thus, the stronger neural adaptation to infant pain does not indicate a diminished protective motivation. Rather, it suggests that the caregiving system responded more vigorously to initial infant threat cues and subsequently regulated its response more efficiently upon safety confirmation. This context-sensitive flexibility is precisely the hallmark of an evolutionarily optimized protective mechanism.

Second, the adaptive change in the adult-neutral condition may represent the clearest case of domain-general repetition suppression—a basic cortical mechanism that dampens responses to repeated, motivationally irrelevant stimuli to improve processing efficiency (Grill-Spector et al., 2006). Because this stimulus carries neither evolutionary significance nor threat, neural resources can be disengaged rapidly and cleanly, yielding the most clear-cut linear decline. The presence of significant attenuation in this condition—unlike the neutral condition reported in Mu et al. (2008)—may stem from the fact that our "adult-neutral" stimuli, while non-threatening, still possess basic social meaning (adult faces) that makes them initially detectable, after which they are rapidly deprioritized as truly irrelevant.

Furthermore, in the infant-neutral condition, the stimulus is salient but non-threatening. The system maintains a baseline vigilance, preventing the rapid disengagement seen in the adult-neutral condition, and thus no significant attenuation is observed. For the adult-pain condition, the low-salience threat cue fails to trigger sustained safety learning; while conflict may be registered, it does not produce systematic adaptive change.

We emphasize that this framework is exploratory. Future studies should employ causal methods—such as TMS, targeted learning paradigms, or computational modeling—to empirically dissect the contributions of fatigue versus safety learning across salience-threat combinations.

4.4. *Distinct neural connectivity patterns may reflect neural information integration in response to infant pain*

Using the PTE index, this study revealed enhanced directed information flow from posterior to anterior electrodes during the infant $_{\text{pain-neutral}}$ condition compared to the adult $_{\text{pain-neutral}}$ condition. This finding converges with our observation that occipital clusters differentiated infant-pain from infant-neutral conditions as early as 120 ms post-stimulus. Together, these results suggest a neural mechanism that prioritizes rapid transmission of visual input from occipital to prefrontal areas for further processing. This posterior-to-anterior information flow may reflect a specialized neural integration process, consistent with the frontal lobe's role in processing pain empathy and infant-specific stimuli. Specifically, the medial prefrontal cortex (mPFC) is associated with mentalizing during cognitive empathy, while the anterior cingulate cortex (ACC) contributes to empathic concern in emotional empathy (Marsh, 2018). The orbitofrontal cortex (OFC) is critical for detecting infant faces (Kringelbach et al., 2008; Parsons et al., 2013) and cries (Young et al., 2017), and the inferior frontal gyrus (IFG) also participates in processing infant cries (De Carli et al., 2019; Riem et al., 2011, 2014; Witteman et al., 2019). Thus, the enhanced connectivity likely facilitates integrating early visual signals with these prefrontal regions responsible for executive-emotional processing.

Furthermore, a significant positive correlation was observed between IRI perspective-taking scores and PTE values in the infant $_{\text{pain-neutral}}$ condition. This correlation suggests that individuals with higher perspective-taking ability may exhibit enhanced neural information transfer during the empathy for infant pain. Specifically, heightened perspective-taking may serve to catalyze this evolutionarily conserved pathway, thereby potentiating its input to prefrontal cortical regions involved in mentalizing and contextual appraisal.

It is important to note, however, that our functional connectivity analysis was conducted at the sensor level. EEG signals are susceptible to volume conduction, which can inflate spurious correlations and complicate the interpretation of connectivity estimates (Sanchez-Bornot et al., 2024; Vink et al., 2020). In addition, the observed increase in PTE values reflects a relative enhancement in the infant $_{\text{pain-neutral}}$ condition compared to the adult $_{\text{pain-neutral}}$ condition, rather than an absolute strengthening under the infant condition alone. Consequently, these results should be interpreted with caution. Future studies employing neuroimaging techniques with superior spatial resolution, such as fMRI or MEG, are needed to delineate the precise neural sources underlying this posterior-anterior information flow.

4.5. Limitations

To our knowledge, this study provides the first evidence on the neural dynamics of empathy for infant pain in non-parental adults. Several limitations should be considered. First, although the 2 × 2 experimental design and image processing were implemented to control for low-level physical differences, the inherent salience of infant faces and pain-inducing tools may have contributed to the observed effects. Future studies incorporating control conditions that present faces or tools in isolation would help to disentangle their respective neural contributions. Second, to equate low-level visual properties, all face stimuli were scaled to the same pixel dimensions. While this controlled for extraneous visual variables, it enlarged infant faces beyond their natural proportions, potentially altering perceptually relevant cues of the baby schema. This reflects a necessary trade-off between experimental control and ecological validity. Future studies could use naturally proportioned stimuli or immersive paradigms like virtual reality to better understand how baby schema modulates empathic neural responses. Third, tool-face contact was depicted via superimposition without dynamic deformation; more realistic dynamic stimuli would enhance ecological validity. Fourth, the current study utilized a sample of moderate size with an uneven gender distribution, which may affect the generalizability of our findings. In addition, behavioral empathy ratings for infant pain exhibited a potential ceiling effect, as a subset of participants consistently selected the highest score. The resulting restricted range in responses posed challenges for detecting consistent correlations between behavioral and neural measures. Future studies employing larger, more gender-balanced samples, as well as behavioral tasks capable of eliciting a wider distribution of responses, will help to validate the present results. Finally, all participants were non-parental adults from China. Although empathy for infant pain is likely a universal capacity present across cultures and caregiving experiences, the extent to which these neural responses generalize to parents and individuals from other cultural backgrounds remains an open question. Further research in these populations would be valuable. Our conclusions are also based on responses to painful events depicted on faces, which are ecologically salient but do not capture the full range of infant pain cues. Future work using bodily or vocal expressions of infant pain would help determine whether the observed neurodynamic patterns extend to other modalities and contexts.

4.6. Conclusions

In summary, this study shows that empathy for infant pain in non-parental adults is characterized by a distinct neurophysiological profile. This profile encompasses both rapid, early differentiation (~120 ms) and enhanced late-stage cognitive evaluation (as indexed by P3), alongside increased neural adaptability in alpha and low beta rhythms. These findings suggest that the human brain possesses evolutionarily conserved mechanisms for detecting infant vulnerability that operate independently of parenthood, forming a foundational neural substrate for alloparenting.

Our results align with the model of the parental brain as an evolutionary product balancing conserved, rapid responses with flexible, cortical modulation (Feldman, 2015). The early neural differentiation observed here, akin to rapid OFC activation (Parsons et al., 2017), may represent a core, conserved caregiving component. In contrast, the later cognitive and adaptive oscillatory dynamics underscore the role of higher-order, potentially experience-sharpened processes. This duality—where humans share core neuroendocrine mechanisms with other mammals yet recruit extensive cortical networks for regulation and adaptation (Rilling and Young, 2014)—may be the key neural innovation supporting humans' highly socialized, collective child-rearing practices. The robust empathic responses in non-parental adults confirm that this capacity is deeply embedded in the human brain, extending beyond the mechanisms primarily gated by reproductive hormones, and is readily available to support alloparenting.

Author contributions

Chunyan Liu played a lead role in data curation, formal analysis, investigation, visualization, and writing–original draft and an equal role in methodology and writing–review and editing. Yi Jiang played a lead role in conceptualization, project administration, funding acquisition, and supervision, and an equal role in methodology, writing–review and editing.

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Data and code availability

The raw data, processed data, and analysis code are available at Science Data Bank (ScienceDB) at https://cstr.cn/31253.11.sciencedb.34071.

Ethics statement

This study has been approved by the Institutional Review Board of the Institute of Psychology, Chinese Academy of Sciences. The ethics approval code is H21058.

Declaration of competing interest

All authors have no competing interests to declare.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.neuroimage.2026.121928.

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