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Temporally differentiated modulation of emotional face processing by attentional resource availability: an event-related potential study

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Abstract

The interplay between top-down attentional control and bottom-up emotional capture remains debated, particularly in the late positive potential (LPP) time window. In the present study, we used mass univariate analysis to examine whether task difficulty itself modulates late-stage emotional processing in an implicit task. In a dual-target rapid serial visual presentation paradigm, perceptual load was manipulated at T1, and at T2, fearful, happy, neutral, or face-absent stimuli were presented in a face-detection task. Emotional differentiation emerged during 148–372 ms and was not influenced by perceptual load, suggesting that emotional features were extracted relatively automatically. During the early LPP (400–600 ms), emotional differentiation was detected under low but not high load, suggesting that inconsistencies in emotion-related LPP effects reported in previous implicit-task studies may stem from differences in task difficulty. During the late LPP (600–800 ms), however, fearful expressions remained distinguishable from neutral expressions even under high load, indicating that resource limitations did not eliminate late emotional differentiation. Together, these findings provide compelling evidence that the availability of attentional resources differentially shapes the processing of emotional information in implicit tasks.

Keywords **attentional control, perceptual load, rapid serial visual presentation, emotional expressions, mass univariate analysis**

Introduction

In daily life, visual attention is shaped by both bottom-up salience and top-down task demands (Bishop 2008). Although attentional control is essential for goal-directed behavior, rapid detection of potential threats such as fearful expressions remains critical for survival (Carlson and Mujica-Parodi 2015, Vormbrock *et al.* 2023, Li *et al.* 2024). ERP studies manipulating task instructions have explored the interplay between attentional control and emotional expression processing, showing that early ERP components generally reflect relatively automatic emotional processing (Schindler *et al.* 2020a). However, whether late-stage emotional processing depends on task demands remains inconsistent across studies (Schindler and Bublatzky 2020).

Specifically, the N170 is considered an index of early configural face processing and typically exhibits larger amplitudes for faces than for objects (Eimer 2011). Emotional expressions relative to neutral ones have also been shown to increase N170 amplitudes (Schindler *et al.* 2023). Notably, previous research has largely reported that N170 emotion effects are unaffected by variations in task demands or attentional allocation, supporting the view that early facial emotion processing is relatively automatic (Rellecke *et al.* 2012, Itier and Neath-Tavares 2017, Schindler *et al.* 2021a, 2021b). Subsequent early posterior negativity (EPN) is typically characterized by enhanced negativity to emotional relative to neutral expressions (Rellecke *et al.* 2012, Calvo and Beltrán 2013) and has been associated with early attentional selection processes (Schupp *et al.* 2004, Gibbons *et al.* 2022). Consistent with this account, ERP studies have

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shown robust EPN enhancement for emotional expressions even in the presence of perceptual distraction (Valdés-Conroy *et al.* 2014, Itier and Neath-Tavares 2017). Nevertheless, recent findings indicate that EPN emotion effects under distraction may depend on temporal interval, suggesting a temporal bottleneck in emotional information processing (Schindler *et al.* 2020b, 2021c).

Finally, late positive potential (LPP) is commonly interpreted to reflect higher-order cognitive operations, including stimulus evaluation and affective categorization (Schupp *et al.* 2006, Schupp and Kirmse 2021), and is sensitive to top-down task demands (Hudson *et al.* 2021). Compared with neutral expressions, both negative and positive facial expressions reliably elicit larger LPP amplitudes (Schupp *et al.* 2004, Schindler and Bublatzky 2020). In explicit emotion tasks, such emotional modulation of the LPP is consistently observed (Rellecke *et al.* 2012, Schindler and Bublatzky 2020, Yang *et al.* 2025). In implicit tasks, however, findings are mixed. Some studies have shown that LPP emotion effects are reduced or absent when attention is directed away from emotional content (Rellecke *et al.* 2012, Müller-Bardorff *et al.* 2016, Schindler and Bublatzky 2020, Li *et al.* 2024), supporting the view that emotional information captures attention primarily when it matches top-down goals (Lavie 2005, Pessoa 2005). Other studies, by contrast, have reported reliable LPP modulation even when emotional content is task-irrelevant (Frühholz *et al.* 2011, Smith *et al.* 2013, Bublatzky *et al.* 2014, Wu *et al.* 2019, Hudson *et al.* 2021), suggesting that emotional information can be processed relatively automatically and may overcome attentional control (Carretié 2014).

It should be noted that emotional information in implicit tasks cannot be assumed to be entirely unattended. According to perceptual load theory (Lavie 2005), the balance between top-down task goals and bottom-up emotional salience likely depends on the availability of attentional resources. Studies reporting absent LPP emotion effects in implicit tasks have typically employed brief face presentations and relatively demanding tasks (Müller-Bardorff *et al.* 2016, Li *et al.* 2024), such as 150 ms displays combined with line-length discrimination. By contrast, longer presentation durations and less demanding tasks may leave more resources available for emotional processing. For example, emotional LPP effects have been observed with 300 ms presentations when participants named colors or made parity judgments about numbers superimposed on faces (Frühholz *et al.* 2011, Wu *et al.* 2019). However, Vormbrock *et al.* (2023) found that presentation duration did not modulate LPP emotion effects in perceptual distraction tasks, suggesting that duration alone cannot explain the inconsistent findings. Taken together, these results indicate that, beyond presentation duration, task difficulty may be a key determinant of attentional resource availability and, in turn, of whether emotional information is suppressed in implicit tasks.

The dual-target rapid serial visual presentation (RSVP) paradigm is widely used to manipulate attentional resources by varying the temporal lag between the first (T1) and second targets (T2) (Pecchinenda *et al.* 2020, Li *et al.* 2023). At short lags (approximately 200–500 ms), recognition of T2 is impaired following correct T1 identification, a phenomenon known as attentional blink (AB) (Raymond *et al.* 1992). Notably, emotional expressions presented as T2 attenuate the AB effect, suggesting prioritized access to post-perceptual processing under limited attentional resources (Maratos *et al.* 2008, Luo *et al.* 2010). This advantage persists even when emotional expressions are task-irrelevant (De Martino *et al.* 2009, Müsch *et al.* 2012, Sun *et al.* 2017). Yang *et al.* (2025) further manipulated perceptual load at T1, providing stricter control over attentional resources than standard RSVP paradigms (Luo *et al.* 2010, Eiserbeck *et al.* 2022, Roth-Paysen *et al.* 2022) or traditional simultaneous target–distractor load manipulations (Müller-Bardorff *et al.* 2018, Schindler *et al.* 2020b, 2021c). They found that higher T1 load reduced resources available for T2 and suppressed post-perceptual emotional processing. However, because T2 required explicit emotion recognition, it remains unclear whether attentional resources similarly influence late-stage processing of emotional faces in implicit tasks.

Building on Yang *et al.* (2025), the present study examined whether emotional processing in an implicit T2 task is modulated by perceptual load at T1. Perceptual load was manipulated with a letter-detection task at T1 (Park *et al.* 2014), whereas T2 consisted of happy, fearful, neutral, or face-absent stimuli and required a face-detection response. Based on prior evidence that early facial-expression processing is relatively insensitive to attentional manipulations (Itier and Neath-Tavares 2017, Schindler and Bublatzky 2020, Schindler *et al.* 2021b), we expected early emotion-related ERP responses to be minimally affected by T1 load. Because early ERP latencies in RSVP paradigms vary and prior findings on the timing of early emotion effects are inconsistent (Luo *et al.* 2010, 2022, Sun *et al.* 2017, Eiserbeck *et al.* 2022, Roth-Paysen *et al.* 2022), these effects were examined using exploratory mass univariate analyses. By contrast, the LPP was analyzed using an a priori hypothesis-driven approach. Given evidence for functional differences between the early (400–600 ms) and late LPP (600–800 ms), these intervals were examined separately (Schindler and Straube 2020). Specifically, the early LPP appears more susceptible to top-down attentional modulation (Pourtois *et al.* 2013, Schindler and Straube 2020), whereas the late LPP is more closely linked to overall attentional capacity (Schupp *et al.* 2006, Olofsson *et al.* 2008, Uusberg *et al.* 2013). Based on evidence that increased task difficulty attenuates emotional LPP effects in implicit tasks (Frühholz *et al.* 2011, Müller-Bardorff *et al.* 2016, Wu *et al.* 2019, Li *et al.* 2024), we predicted that high perceptual load would influence emotional effects, particularly in the early LPP.

Materials and methods

Participants

Twenty-eight right-handed undergraduates from Liaoning Normal University participated in the study (16 females; average age = 21.79 years, $SD = 2.13$). A priori power analysis using G*Power 3.1 indicated that this sample size provided 95% power to detect a medium effect size (Cohen's $f = .25$, $\alpha = .05$). All participants had normal or corrected-to-normal vision and reported no history of neurological or psychiatric disorders. Informed consent was obtained from all participants, and the study was approved by the local ethics committee.

Stimuli

The facial stimuli were identical to those used in our previous study (Yang *et al.* 2025) and were drawn from the young adult subset of the Chinese Facial Affective Picture System (CFAPS; Gong *et al.* 2011). The models were 18–23 years old and were comparable in basic demographic characteristics across emotional conditions. The final stimulus set included 32 oval-cropped facial images (276 × 340 pixels; 16 female): 20 neutral, six happy, and six fearful. Brightness and contrast were normalized using the SHINE toolbox (Willenbockel *et al.* 2010).

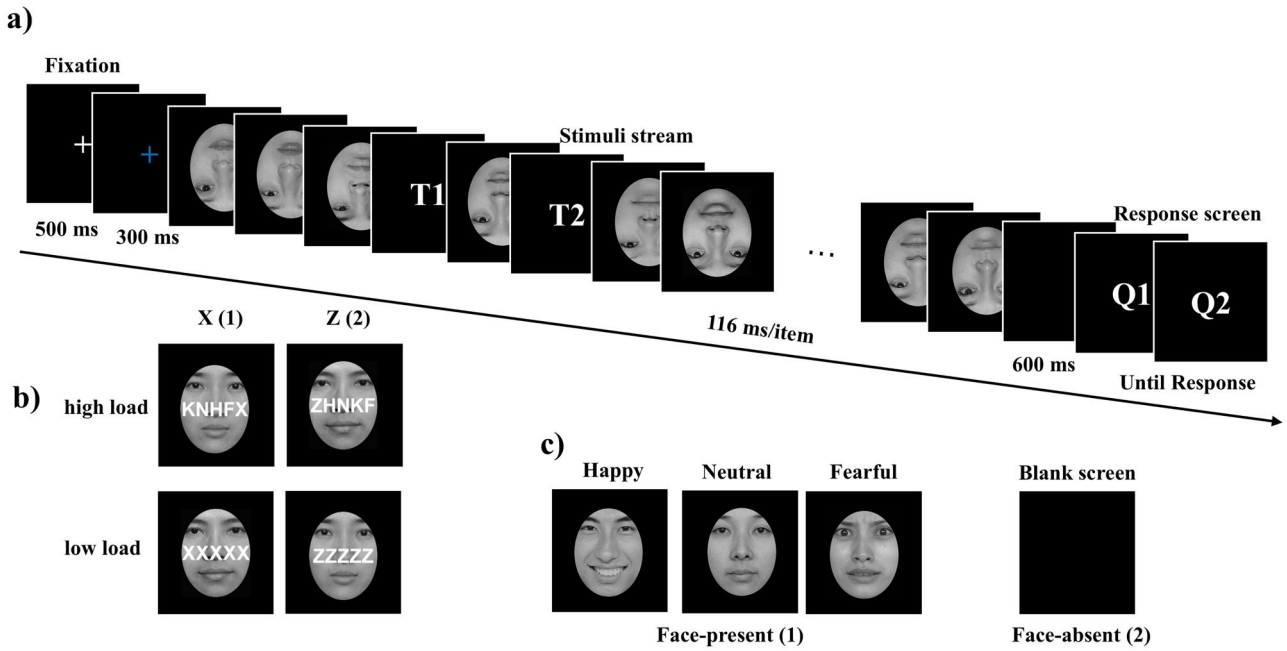


Figure 1 Task procedure and stimulus configuration. (a) Timeline of a representative trial in the dual-target RSVP paradigm. (b) Examples of T1 stimuli used to manipulate perceptual load. (c) Examples of T2 stimuli depicting emotional expressions (happy, neutral, fearful) and the blank screen.

The T2 set comprised 18 upright faces (half female) equally distributed across happy, neutral, and fearful expressions, together with blank screens matched in frequency to each emotional condition (Fig. 1c). Twelve inverted neutral expressions (half female) served as distractors. To manipulate T1 perceptual load, two additional upright neutral faces (half female) were overlaid with a central five-letter string (Park *et al.* 2014). Under the high perceptual load, one target letter (X or Z) appeared among four distractors (N, H, K, F). Under low load, all five letters were identical (all Xs or all Zs; Fig. 1b). Valence and arousal ratings were established using a separate sample (Yang *et al.* 2025, see Supplementary Material).

Procedure

The experiment was conducted in a sound-attenuated, dimly lit room. Participants sat approximately 70 cm from a 19-inch monitor (1440 × 900 resolution, 60 Hz). The task was programmed in E-Prime 2.0 and used a within-participant design with emotional valence (fearful, happy, neutral) and perceptual load (high, low) as factors.

Each trial began with a white fixation cross for 500 ms, followed by a blue fixation cross for 300 ms signaling the upcoming stimulus stream. A centrally presented RSVP stream then appeared, comprising 12 inverted neutral-face distractors and two upright targets (T1 and T2), with each item displayed for 116 ms (Fig. 1a). T1 appeared randomly in the fourth or sixth position to reduce anticipatory effects (Akyürek and Hommel 2006). T2 was presented at lag 2 (stimulus onset asynchrony = 232 ms) to limit attentional resources available for its processing (Pecchinenda *et al.* 2020, Yang *et al.* 2025). After the RSVP sequence, a 600 ms blank interval was shown, followed by two self-paced responses. Participants first indicated whether the central letter string contained an "X" or "Z" by pressing "1" or "2" with the right index or middle finger, respectively. They then reported whether the second upright face was present or absent using the same keys ("1" = present, "2" = absent). No explicit judgment of emotional expression was required, rendering the emotional information task-irrelevant. Responses were self-paced with no time limit. A 600-ms blank screen separated successive trials.

Before the formal experiment, participants completed 16 practice trials. The main task consisted of six blocks (three high-load, three low-load) presented in random order, with emotional valence counterbalanced within each block. In total, the experiment included 576 trials (96 per block) and lasted approximately 60 minutes.

EEG data acquisition and preprocessing

Continuous EEG was recorded with a 64-channel Ag/AgCl cap (Brain Products, Munich, Germany) arranged according to the extended 10–20 system. Data were sampled at 1000 Hz with FCz as the online reference, and electrode impedances were kept below 5 kΩ. A vertical electrooculogram was recorded from an electrode placed approximately 10 mm below the right eye. During acquisition, signals were filtered online from 0.01 to 100 Hz.

Offline preprocessing was conducted in MATLAB R2018b using EEGLAB (v2020.0; Delorme and Makeig 2004) and ERPLAB (v8.01; Lopez-Calderon and Luck 2014). Continuous EEG data were resampled to a sampling rate of 500 Hz and band-pass filtered between 0.01 and 30 Hz (Hamming-windowed finite impulse response, −6 dB cutoff at 0.005 and 33.75 Hz). Persistently noisy channels were reconstructed using EEGLAB's multivariate local weighted regression procedure, after which the data were re-referenced to the average reference. ERP analyses included only trials with correct responses to both T1 and T2. Epochs were extracted from −200 to 800 ms relative to T2 onset and baseline-corrected using the pre-stimulus interval. Artifact correction was further performed using ICA. Thirty components were computed per participant, and components reflecting ocular activity or channel noise were removed ($M = 1.82$, $SD = 1.09$). Remaining contaminated epochs were automatically rejected when peak-to-peak amplitudes exceeded ±80 μV at non-frontal electrodes

(excluding Fpz, Fp1, Fp2, AF3, AF4, AF7, and AF8). Finally, difference waves were calculated by subtracting ERPs in the corresponding face-absent condition from each experimental condition to isolate T2-related neural activity (Zivony and Lamy 2022).

A repeated-measures ANOVA conducted in JASP on the number of retained trials across conditions revealed a significant difference among conditions (see Supplementary Material). Nevertheless, the trial-matched analysis produced a generally comparable pattern of results to the primary analysis.

Data analysis

Behavioral analysis

Behavioral data were analyzed in JASP (Love *et al.* 2019). T1 recognition accuracy was compared between load conditions using paired-sample t-tests to verify the effectiveness of the perceptual load manipulation. The accuracy, sensitivity index (d'), and response criterion (c) were calculated separately in the T2 task. Consistent with previous work noting ambiguity in the source of T2 errors following incorrect T1 responses (Yang *et al.* 2025), T2 analyses included only trials with correct T1 identification. For each participant, trials were classified as face-present (T2 was a neutral, happy, or fearful face) or face-absent (T2 was a blank screen). Hits were defined as correct "face-present" responses on face-present trials, and false alarms as "face-present" responses on face-absent trials. Sensitivity was calculated as: d'=z (hit rate) – z (false alarm rate), and response criterion as: $c = -1/2$ (z (hit rate) + z (false alarm rate)). To avoid infinite values, the Hautus (1995) correction was applied, with hit and false alarm rates computed as (hit + 0.5)/($n_{present}$ + 1) and (false alarm + 0.5)/(n_{absent} + 1), respectively. T2 accuracy, d', and c were analyzed using 3 (emotional valence: fearful, happy, neutral) × 2 (perceptual load: high, low) repeated-measures ANOVAs. Greenhouse–Geisser corrections were applied when the sphericity assumption was violated, and post hoc comparisons used the Bonferroni–Holm correction. Effect sizes were reported as Cohen's d and partial eta squared (η_p^2), with $\alpha = .05$.

Factorial mass univariate analysis

Mass univariate analysis allows statistical testing across all electrodes and time points, increasing sensitivity to effects not specified a priori and reducing the risk of Type II errors (Groppe *et al.* 2011, Fields and Kuperberg 2020). The risk of Type I errors is controlled through multiple-comparison correction procedures (Groppe *et al.* 2011, Luck and Gaspelin 2017, Fields and Kuperberg 2020). For hypothesis-driven tests, mass univariate analyses provide statistical power comparable to, or slightly greater than, traditional ERP approaches, while offering greater sensitivity for exploratory analyses (Groppe *et al.* 2011, Fields and Kuperberg 2020). ERP data were analyzed using the Factorial Mass Univariate Toolbox in the present study (Fields and Kuperberg 2020) with two complementary approaches: an a priori analysis and a whole-scalp exploratory analysis.

For the LPP, a hypothesis-driven a priori analysis was conducted based on prior ERP findings (Schindler and Straube 2020, Yang *et al.* 2025). A centroparietal region of interest was predefined, including electrodes C1/C2, Cz, CP1/CP2, CPz, P1/P2, and Pz, together with two consecutive time windows: an early LPP window (400–600 ms) and a late LPP window (600–800 ms). This confirmatory analysis tested the effects of emotional valence and perceptual load on LPP amplitude.

To examine early ERP effects, an exploratory analysis was performed across the full 0–800 ms epoch and all electrodes. In RSVP paradigms, early ERP components may show delayed latency (Luo *et al.* 2010, 2022), and prior studies have reported inconsistent time windows, providing limited a priori guidance for the present study (Luo *et al.* 2010, Sun *et al.* 2017, Eiserbeck *et al.* 2022, Roth-Paysen *et al.* 2022). A whole-scalp, whole-time-window mass univariate analysis was therefore used to maximize sensitivity to genuine but unanticipated effects (Groppe *et al.* 2011, Luck and Gaspelin 2017, Fields and Kuperberg 2020).

In both analyses, emotional valence (fearful, happy, neutral) and perceptual load (high, low) were entered as within-subject factors in repeated-measures ANOVAs. Multiple-comparison correction was implemented with permutation testing using 10, 000 permutations. Post hoc pairwise comparisons were conducted only when a main effect or interaction survived correction, or when a significant spatio-temporal cluster was identified, to clarify the direction of the effects. Bonferroni-corrected alpha levels were applied where appropriate (e.g., $\alpha = .0167$ for three pairwise comparisons).

The exploratory mass univariate analysis served as the primary inferential framework for early effects, and follow-up pairwise comparisons were used only to decompose significant findings. Global power and global field power are reported in the Supplementary Material for descriptive purposes only and were not treated as independent confirmatory tests (Murray *et al.* 2008, Luck and Gaspelin 2017, Michel and Koenig 2018). To avoid inferential overlap with the a priori LPP analysis, clusters overlapping with the predefined LPP windows were not further decomposed in the exploratory framework; effects in these intervals were interpreted on the basis of the predefined LPP analysis.

Source reconstruction

Based on the global power time course (Figure S3, see online supplementary material for a color version of this figure) and DISS results (Figure S4, see online supplementary material for a color version of this figure), the 150–220 ms, 240–280 ms, and 320–370 ms intervals were considered to represent distinct stages of neural activity. Source localization was therefore performed for these three time windows using a lead-field matrix and the eLORETA regularization approach (Pascual-Marqui 2007). To isolate face-specific neural activity, ERPs elicited in the baseline task were subtracted from face-evoked ERPs to generate difference waves (Luo *et al.* 2010, Yang *et al.* 2025). Source current density was then calculated separately for each

Table 1 Sensitivity index ($M \pm SE$) across the emotional valences and perceptual load levels.

	Neutral	Happy	Fearful
High load	2.80 ± 0.24	3.05 ± 0.19	3.27 ± 0.16
Low load	3.45 ± 0.21	3.85 ± 0.16	3.89 ± 0.15

Table 2 Response criterion ($M \pm SE$) across the emotional valences and perceptual load levels.

	Neutral	Happy	Fearful
High load	−0.23 ± 0.08	−0.35 ± 0.08	−0.46 ± 0.09
Low load	−0.15 ± 0.07	−0.35 ± 0.06	−0.37 ± 0.06

subject and emotional condition (fearful, happy, neutral). For each emotional condition, group-level voxelwise one-sample t-tests were used to assess whether source activity significantly differed from zero. Statistical significance was assessed using nonparametric statistical mapping (SnPM) with 5000 random permutations to correct for multiple comparisons. Effects were considered significant at corrected $p < .01$ with a minimum cluster extent of 50 contiguous voxels. In addition, mean source strength within the fusiform region was quantified across the three time windows for each emotional condition.

Results

Behavioral results

T1 accuracy was significantly higher under low than high perceptual load (99.4% vs 92.1%), $t(27) = 7.73$, $P < .001$, Cohen's $d = 1.46$. T2 accuracy was modulated by both emotional valence [$F(2, 54) = 8.28$, $P = .007$, $\eta_p^2 = .24$], and perceptual load [$F(1, 27) = 61.56$, $P < .001$, $\eta_p^2 = .70$]. Accuracy was higher for fearful (94.2%, $P = .001$) and happy expressions (93.6%, $P = .005$) than for neutral expressions (88.7%), and was overall higher under low (96.9%) than high perceptual load

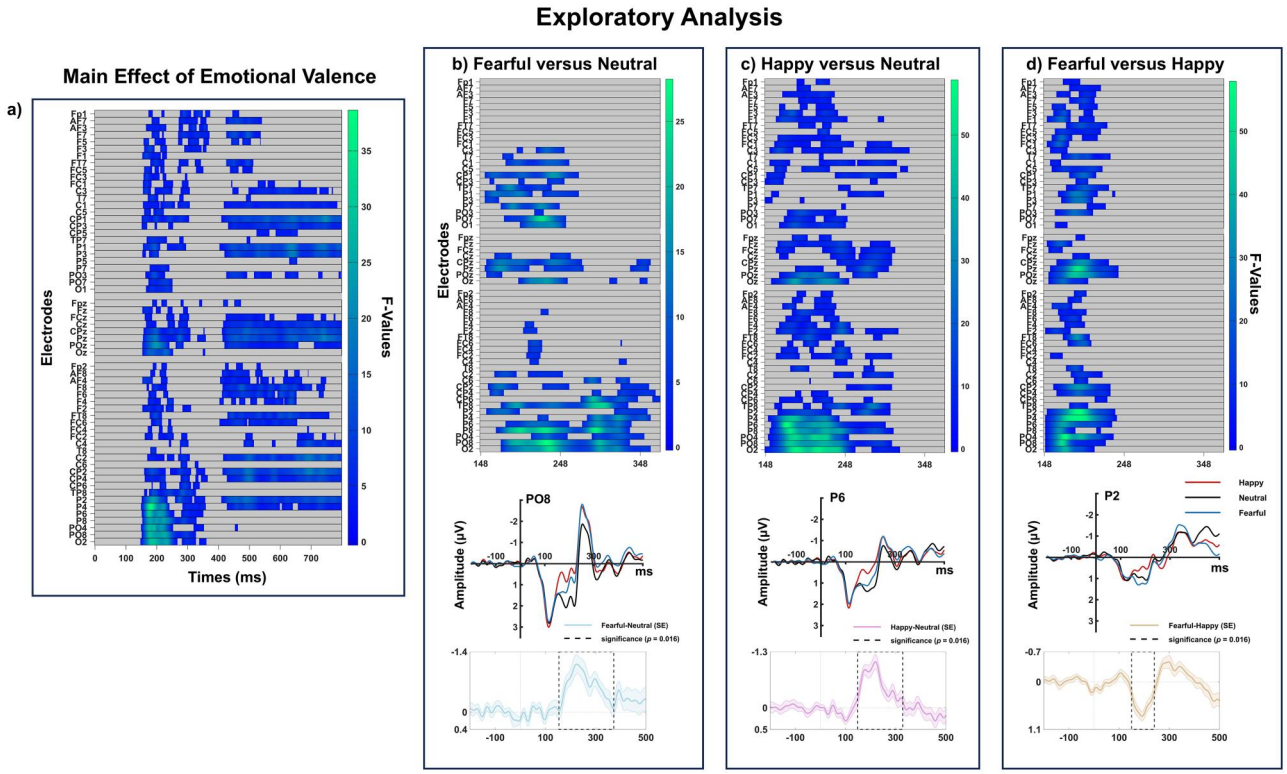


Figure 2 Exploratory findings for all electrodes within 0–800 ms. Panels depict (a) the main effect of emotional valence across electrodes and time points. (b–d) Post hoc pairwise comparisons for the early effect (148–372 ms) identified in the exploratory analysis: fearful versus neutral, happy versus neutral, and fearful versus happy. The ERP waveforms and difference waves shown below each panel were plotted for the peak electrode of the corresponding effect.

Table 3 Significant main effects ($P < .05$) from exploratory analyses, showing time windows, electrodes, and peak *P*- and *F*-values.

Test	Timing	Electrodes	Peak
Emotional valence	148–372 ms	Fp1, Fp2, F3, F4, C3, C4, P3, P4, O1, O2, F7, F8, T7, T8, P7, P8, Fz, Cz, Pz, Oz, FC1, FC2, CP1, CP2, FC5, FC6, CP6, FCz, F1, F2, C1, C2, P1, P2, AF3, AF4, FC3, FC4, CP3, CP4, PO3, PO4, F5, F6, C5, C6, P6, AF7, AF8, FT7, FT8, TP7, TP8, PO7, PO8, Fpz, CPz, POz,	P4 at 182 ms [$F(2, 54) = 38.34$, $P = .0002$]
	404–758 ms	Fp1, Fp2, F4, F7, F8, T7, FC5, FC6, AF4, F5, F6, AF7, AF8, FT7, FT8, TP7, Fpz,	F7 at 496 ms [$F(2, 54) = 14.71$, $P = .01779$]
	404–798 ms	C3, C4, P3, P4, Cz, Pz, FC1, FC2, CP1, CP2, CP5, FCz, C1, C2, P1, P2, FC4, CP3, CP4, PO3, PO4, P5, CPz, POz,	CP1 at 746 ms [$F(2, 54) = 21.05$, $P = .00004$]
Perceptual load	N/A	N/A	N/A
Emotion × load	492–730 ms	C3, C4, P3, P4, Fz, Cz, Pz, FC1, FC2, CP1, CP2, FCz, F1, F2, C1, C2, P1, P2, FC3, CP3, CP4, C5, CPz,	C1 at 572 ms [$F(2, 54) = 13.13$, $P = .01221$]

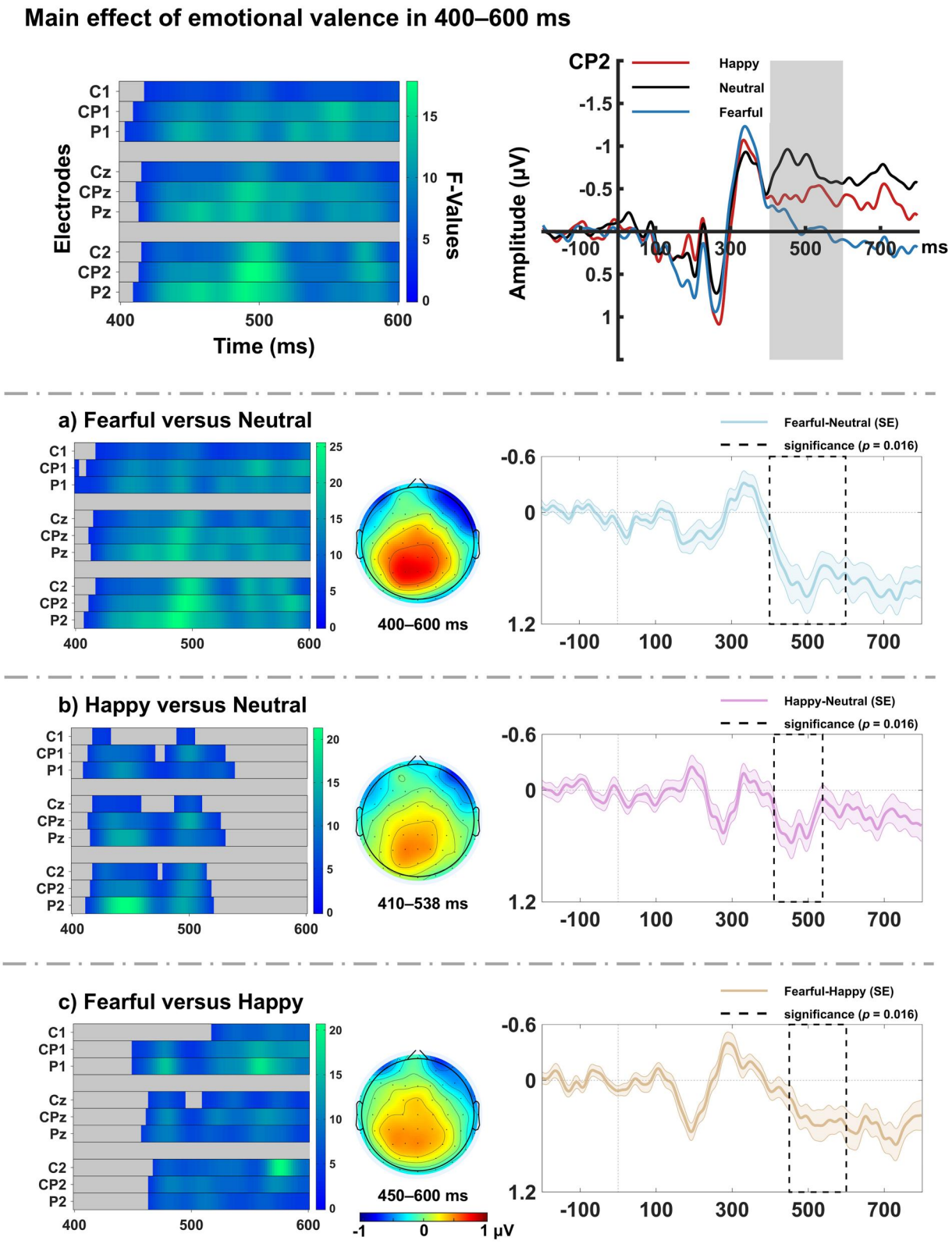


Figure 3 Emotional valence effects within the 400–600 ms interval. Grand-average ERPs at CP2 illustrate responses to fearful, happy, and neutral facial expressions. Pairwise comparisons were conducted between (a) fearful and neutral, (b) happy and neutral, and (c) fearful and happy expressions. The center and right sections present the difference scalp distributions and the difference waveforms at CP2.

(87.4%, $P < .001$). Importantly, emotional valence and perceptual load interacted significantly, $F(2, 54) = 3.82$, $P = .041$, $\eta_p^2 = .12$. Under high perceptual load, T2 accuracy was higher for fearful (89.9%, $P < .001$) and happy expressions (89.0%, $P = .007$) than for neutral expressions (83.3%), with no difference between fearful and happy expressions ($P = 1.000$). Under low perceptual load, T2 accuracy did not differ across emotional valences (fearful: 98.5%; happy: 98.2%; neutral: 94.1%; Ps > .089).

d' values for each condition are presented in Table 1. Analysis of *d'* revealed significant main effects of emotion, $F(2, 54) = 14.26$, $P < .001$, $\eta_p^2 = .35$, and perceptual load, $F(1, 27) = 50.26$, $P < .001$, $\eta_p^2 = .65$. Pairwise comparisons showed higher *d'* for fearful ($P < .001$) and happy ($P = .001$) than neutral expressions, with no difference between fearful and happy expressions ($P = .491$). The interaction between load and emotion was not significant [$F(2, 54) = 2.28$, $P = .112$, $\eta_p^2 = .08$].

c values for each condition are presented in Table 2. For *c*, the main effect of emotion was significant, $F(2, 54) = 14.26$, $P < .001$, $\eta_p^2 = .35$. Participants showed lower *c* values for fearful ($P < .001$) and happy ($P = .001$) than neutral expressions, with no difference between fearful and happy expressions ($P = .491$). Neither the main effect of perceptual load, $F(1, 27) = 1.24$, $P = .275$, $\eta_p^2 = .04$, nor the interaction between load and emotion, $F(2, 54) = 2.28$, $P = .112$, $\eta_p^2 = .08$, reached significance.

ERP results

Exploratory analysis over all electrodes (0–800 ms)

Across the 0–800 ms interval, mass univariate analyses revealed a main effect of emotional valence in three spatiotemporal clusters (Fig. 2a; Table 3). Follow-up pairwise comparisons were conducted only for the early cluster (148–372 ms) showing a significant emotion effect across a broad set of electrodes (Fp1, Fp2, F3, F4, C3, C4, P3, P4, O1, O2, F7, F8, T7, T8, P7, P8, Fz, Cz, Pz, Oz, FC1, FC2, CP1, CP2, FC5, FC6, CP6, FCz, F1, F2, C1, C2, P1, P2, AF3, AF4, FC3, FC4, CP3, CP4, PO3, PO4, F5, F6, C5, C6, P6, AF7, AF8, FT7, FT8, TP7, TP8, PO7, PO8, Fpz, CPz, POz). This cluster was driven by differences between fearful and neutral expressions from 154–372 ms, peaking at PO8 at 230 ms, $F(1, 27) = 28.03$, $P = .00041$; between happy and neutral expressions from 148–328 ms, peaking at P6 at 176 ms, $F(1, 27) = 58.32$, $P = .00001$; and between fearful and happy expressions from 150–240 ms, peaking at P2 at 190 ms, $F(1, 27) = 57.45$, $P = .00002$. The other two significant clusters related to emotional valence, as well as the significant interaction clusters, were not further decomposed because they occurred temporally close to the a priori defined LPP window. No main effect of perceptual load was observed (*P*s > .1396).

Centroparietal electrodes during the early LPP time window (400–600 ms)

ERP amplitudes showed robust modulation by emotional valence (Fig. 3; Table 4). Relative to neutral expressions, both fearful and happy expressions elicited larger amplitudes, with maximal effects at P2 around 488 ms for fearful faces, $F(1, 27) = 25.37$, $P = .00006$, and 466 ms for happy expressions, $F(1, 27) = 21.16$, $P = .00586$. Fearful expressions also evoked greater amplitudes than happy expressions, with the strongest effect at C2 around 576 ms, $F(1, 27) = 20.54$, $P = .00121$.

This emotional effect was modulated by perceptual load (Fig. 4; Table 4). Under low perceptual load, fearful expressions elicited greater ERP positivity than neutral expressions, with the strongest effect at C2 around 572 ms, $F(1, 27) = 40.63$, $P = .00002$. Happy expressions likewise produced larger amplitudes than neutral expressions, most prominently at P2 around 440 ms, $F(1, 27) = 29.65$, $P = .00256$. Fearful expressions also elicited greater responses than happy expressions, with maximal differentiation at P1 around 526 ms, $F(1, 27) = 16.34$, $P = .00276$. In contrast, emotional differentiation was absent under high perceptual load (*P*s > .04951). The main effect of perceptual load was not significant ($P = .49849$).

Centroparietal electrodes during the late LPP time window (600–800 ms)

ERP responses varied reliably as a function of emotional valence (Fig. 5; Table 4). Fearful expressions elicited larger amplitudes than neutral expressions, with maximal differentiation at Pz around 742 ms, $F(1, 27) = 32.85$, $P = .00001$, and than happy expressions, with

Table 5 Mean fusiform source strength (fusiform mean) across emotional conditions and time windows.

Condition	Time window	Fusiform mean
Fearful	150–220	4.60
	240–280	6.52
	320–370	5.87
Happy	150–220	5.00
	240–280	6.62
	320–370	5.78
Neutral	150–220	5.35
	240–280	5.77
	320–370	5.55

Table 4 Significant main effects ($P < .05$) from prior analyses, showing time windows, electrodes, and peak *P*- and *F*-values.

Priori analyses	Test	Timing	Electrodes	Peak
400–600 ms	Emotion valence	404–600 ms	C1, C2, Cz, CP1, CP2, CPz, P1, Pz, P2,	CP2 at 496 ms [$F(2, 54) = 17.70$, $P = .00001$]
	Perceptual load	N/A	N/A	N/A
	Emotion × load	400–488 ms	C1, C2, Cz, CP1, CP2, CPz, Pz, P2,	CP2 at 464 ms [$F(2, 54) = 8.46$, $P = .02645$]
		498–600 ms	C1, C2, Cz, CP1, CP2, CPz, P1, Pz, P2,	C1 at 572 ms [$F(2, 54) = 13.13$, $P = .01177$]
600–800 ms	Emotion valence	600–798 ms	C1, C2, Cz, CP1, CP2, CPz, P1, Pz, P2,	CP1 at 746 ms [$F(2, 54) = 21.05$, $P = .00001$]
	Perceptual load	N/A	N/A	N/A
	Emotion × load	600–730 ms	C1, C2, Cz, CP1, CP2, P1, Pz,	C1 at 610 ms [$F(2, 54) = 8.57$, $P = .01338$]

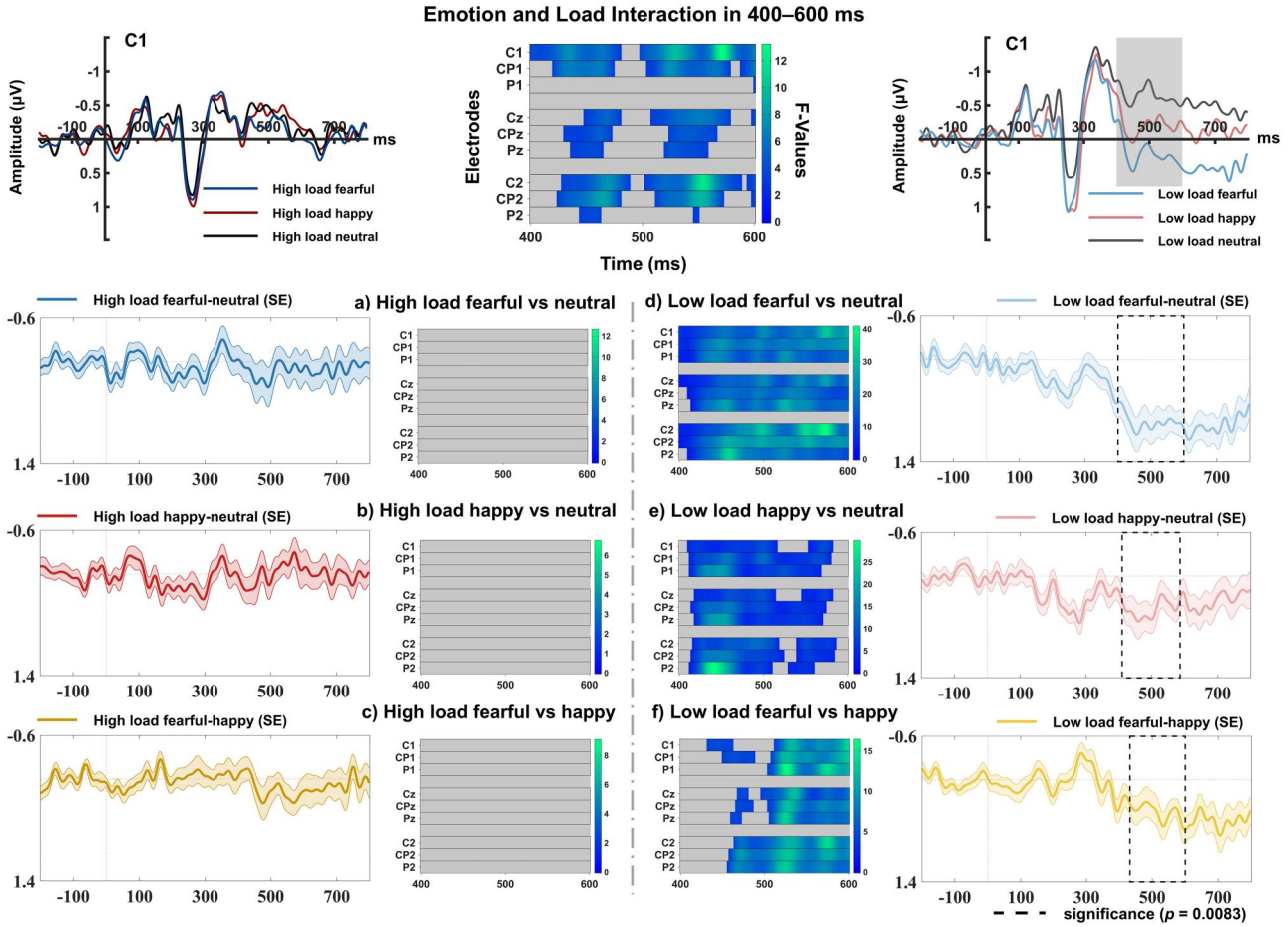


Figure 4 Interaction effects of emotional valence and perceptual load (400–600 ms). (a–c) Pairwise comparisons between emotional expressions under high perceptual load: (a) high load fearful vs neutral, (b) high load happy vs neutral, (c) high load fearful vs happy. (d–f) Pairwise comparisons under low perceptual load: (d) low load fearful vs neutral, (e) low load happy vs neutral, (f) low load fearful vs happy. Grand-average ERP waveforms at C1 and corresponding difference waveforms are shown.

the strongest effect at P1 around 736 ms, $F(1, 27) = 33.78$, $P = .0002$. No reliable difference was observed between happy and neutral expressions ($Ps > .0363$).

This emotional effect was further modulated by perceptual load (Fig. 6; Table 4). Under high perceptual load, fearful expressions elicited greater amplitudes than neutral expressions, with the largest effect at Pz around 770 ms, $F(1, 27) = 20.23$, $P = .00276$. Responses to fearful and happy expressions did not differ significantly ($Ps > .05243$), nor did responses to happy and neutral expressions ($Ps > .04524$). Under low perceptual load, fearful expressions elicited larger amplitudes than neutral expressions, peaking at CP2 around 722 ms, $F(1, 27) = 41.52$, $P = .0001$, and than happy expressions, peaking at P1 around 618 ms, $F(1, 27) = 18.38$, $P = .0001$. Responses to happy and neutral expressions were statistically comparable ($Ps > .03023$). The main effect of perceptual load was not significant ($Ps > .19025$).

Source reconstruction results

Source estimates were descriptively inspected at the peak latency within each time window for each condition (Fig. 7). In the fearful condition, dominant source maxima were primarily located in the cingulate gyrus, fusiform gyrus, and parahippocampal gyrus across the three time windows, respectively. In the happy condition, dominant source maxima were located in the insula across all three time windows. In the neutral condition, dominant source maxima were primarily located in the parahippocampal gyrus, cuneus, and fusiform gyrus across the three time windows, respectively (Table 5). Notably, the relatively stronger fusiform involvement during the 240–280 ms interval is broadly consistent with the view that this stage may reflect a temporally delayed face-sensitive processing phase (Sadeh and Yovel 2010, Dellert *et al.* 2021, Luo *et al.* 2022).

Discussion

The present study examined how attentional resource availability dynamically shapes emotional processing in an implicit task. Emotional modulations were observed at both early (148–372 ms) and late (400–800 ms) processing stages. Early-stage responses were unaffected by perceptual load, supporting relatively automatic extraction of emotional features. By contrast, emotional differentiation during the early LPP was sensitive to perceptual load, whereas fearful expressions remained distinguishable from neutral expressions during the late LPP even under high load. These findings provide new insight into the debate on late-stage emotional attentional capture (Luck *et al.* 2021). Specifically, they suggest that, in an implicit task, emotionally

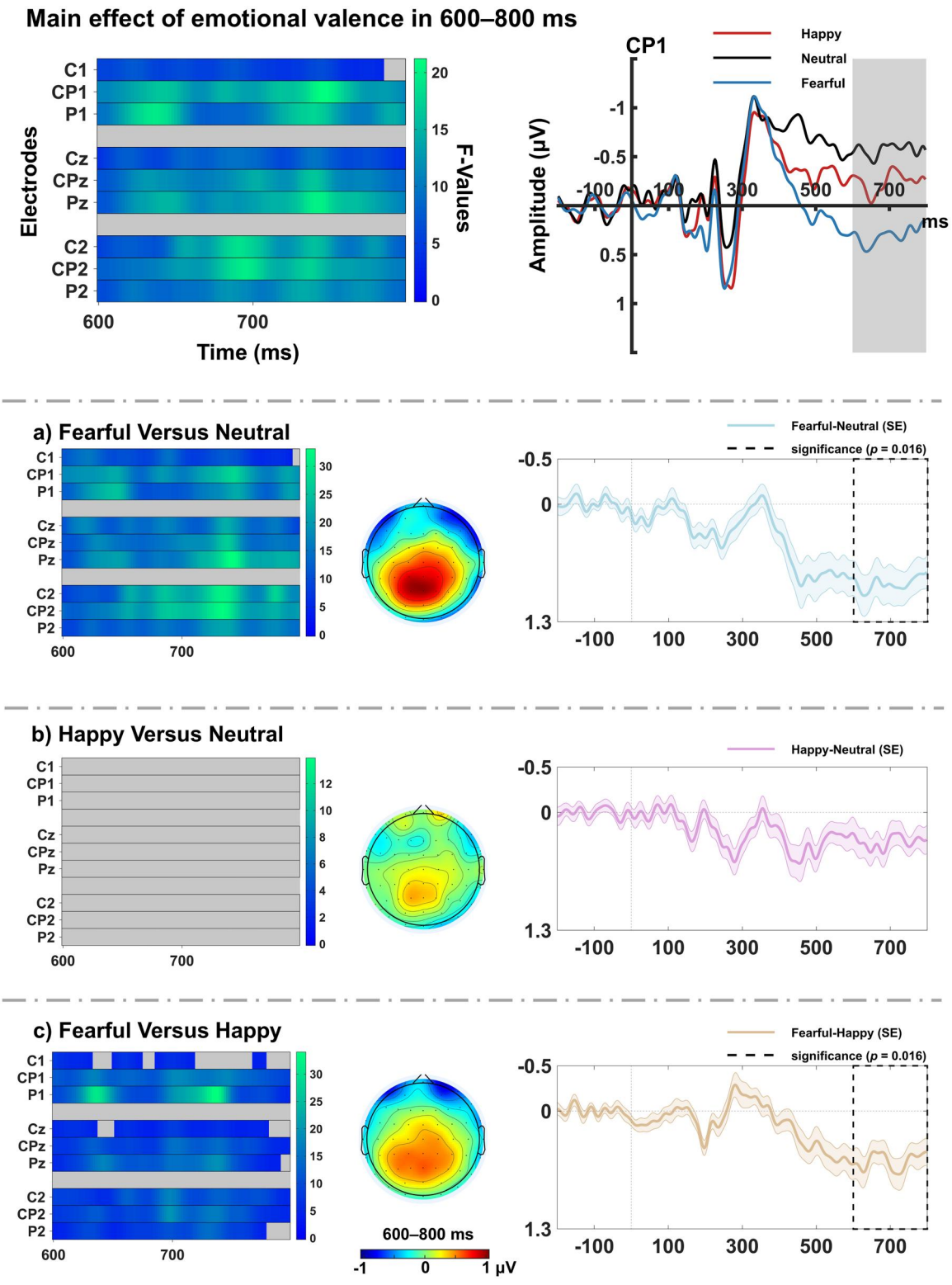


Figure 5 Emotional valence effects within the 600–800 ms interval. Grand-average ERPs at CP1 illustrate responses to fearful, happy, and neutral facial expressions. Pairwise comparisons were conducted between (a) fearful and neutral, (b) happy and neutral, and (c) fearful and happy expressions. The center and right sections present the difference scalp distributions and the difference waveforms at CP1.

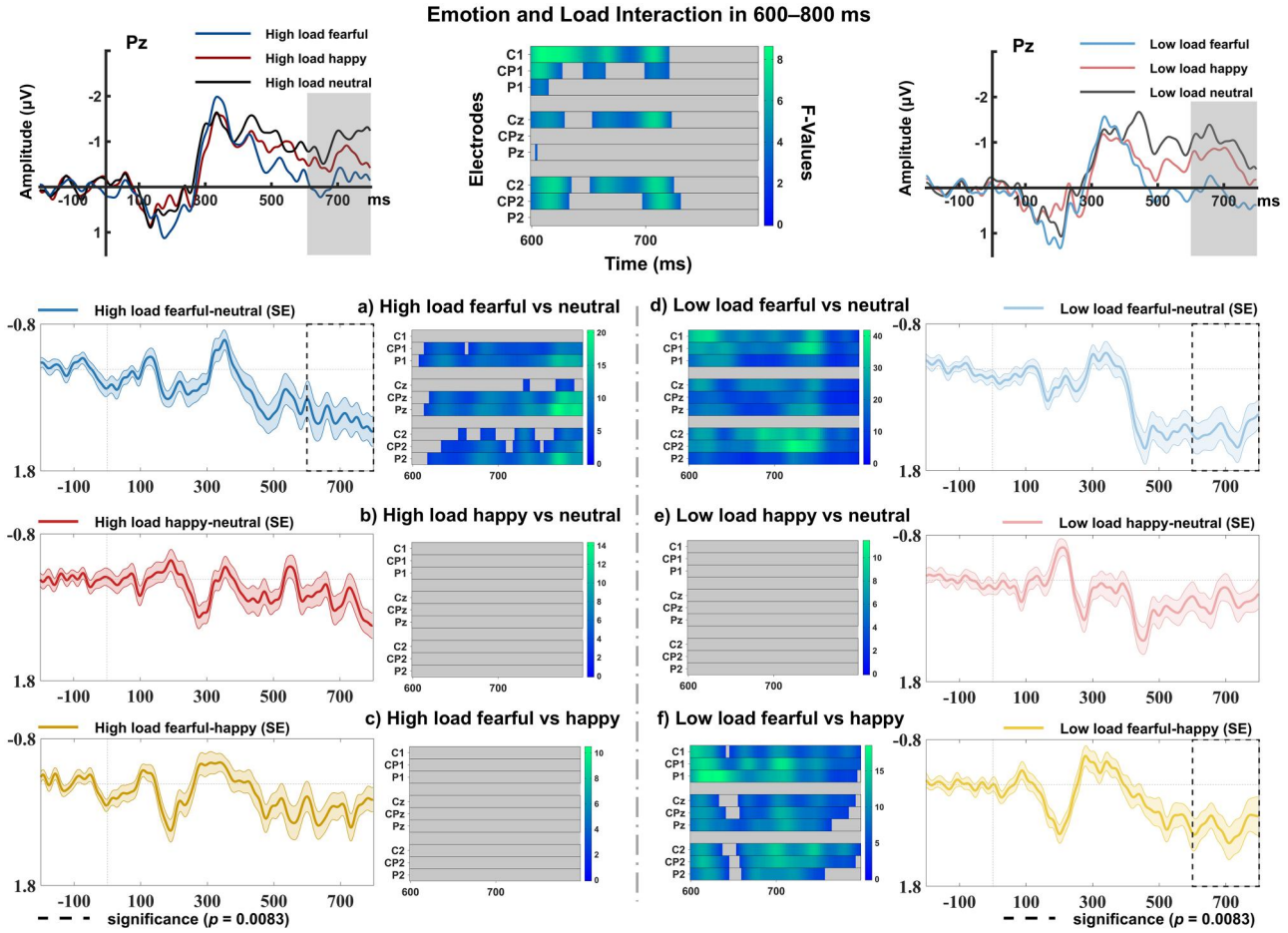


Figure 6 Interaction effects of emotional valence and perceptual load (600–800 ms). (a–c) Pairwise comparisons between emotional expressions under high perceptual load: (a) high load fearful vs neutral, (b) high load happy vs neutral, (c) high load fearful vs happy. (d–f) Pairwise comparisons under low perceptual load: (d) low load fearful vs neutral, (e) low load happy vs neutral, (f) low load fearful vs happy. Grand-average ERP waveforms at Pz and corresponding difference waveforms are shown.

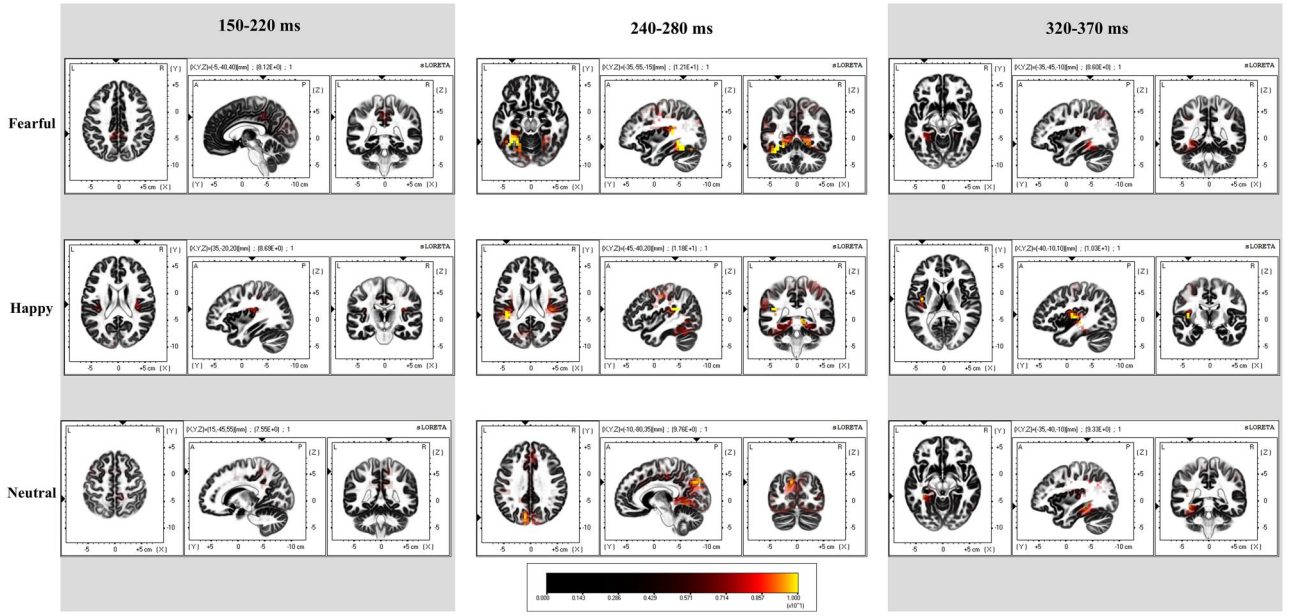


Figure 7 Group-level sLORETA source localization results for different emotional conditions across three-time windows. Columns represent the three-time windows (150–220, 240–280, and 320–370 ms), and rows represent the fearful, happy, and neutral conditions. Each panel shows the source distribution at the peak latency within the corresponding time window for each condition, displayed in axial, sagittal, and coronal slices. All panels were rendered using a common color scale. The color scale indicates values of source current density (A/m^2).

salient stimuli are neither obligatorily strong enough to override top-down control nor fully suppressed by it (Rellecke *et al.* 2012, Müller-Bardorff *et al.* 2016, Schindler and Bublatzky 2020, Li *et al.* 2024). Rather, their processing is dynamically modulated by resource availability without being completely eliminated.

A significant main effect of emotional expression on ERP activity emerged between 148 and 372 ms and was not significantly modulated by perceptual load. Previous studies have reported reliable emotional effects on the N170 across different task demands (Itier and Neath-Tavares 2017, Schindler *et al.* 2020a, Hudson *et al.* 2021), suggesting that feature-based attention does not modulate early processing of emotional expressions. By manipulating attentional resources in an implicit task, the present findings further support the view that early extraction of emotional facial information is unaffected by resource availability (Hinojosa *et al.* 2015, Schindler *et al.* 2023). Importantly, the broad 148–372 ms cluster is unlikely to reflect a unitary ERP component. Rather, convergent evidence from GFP, DISS, topographic maps, and source estimation suggests that it comprises multiple temporally contiguous and partially overlapping processing stages. In RSVP paradigms, early ERP components may be delayed relative to conventional presentation formats (Luo *et al.* 2010, 2022). The 240–280 ms interval was characterized by stable occipitotemporal negativity and a GFP peak. Source estimation suggested relatively stronger fusiform involvement during this interval, suggesting a later-emerging face-sensitive stage (Sadeh and Yovel 2010, Dellert *et al.* 2021). Correspondingly, the 150–240 ms interval may reflect overlapping delayed early visual processing and the rising phase of face-sensitive activity (Luck 2014, Hinojosa *et al.* 2015). Finally, fearful relative to neutral faces elicited enhanced negativity between 300 and 372 ms (Fig. 2b), primarily over right occipitotemporal sites (Figure S2, see online supplementary material for a color version of this figure), which may reflect sustained posterior selective processing of threat-related facial information (Rellecke *et al.* 2012, Calvo and Beltrán 2013).

The present study suggests that attentional resource availability exerts a temporally differentiated influence on the processing of emotional expressions in an implicit task. Previous research has shown that the LPP is sensitive to the task relevance of facial stimuli (Shafto and Pitts 2015, Dellert *et al.* 2021). In RSVP paradigms, the LPP is also modulated by the task relevance of T2 stimuli in general (Dellert *et al.* 2022) and of emotional T2 stimuli in particular (Sun *et al.* 2023). When emotional features are task-irrelevant, LPP emotional effects are often absent under high task difficulty (Müller-Bardorff *et al.* 2016, Li *et al.* 2024), but are more consistently observed under lower task difficulty (Frühholz *et al.* 2011, Wu *et al.* 2019). Consistent with this literature and our hypothesis, emotional differentiation in the early LPP window was observed only under low perceptual load when emotional content was task-irrelevant. The early LPP has been suggested to reflect the interaction between emotional salience and top-down attentional modulation (Bishop 2008, Pourtois *et al.* 2013, Schindler and Straube 2020). Accordingly, the present pattern is consistent with the view that, during the early LPP window, limited attentional resources render emotional processing more strongly constrained by task demands, thereby reducing the differentiation of task-irrelevant emotional facial information.

Finally, fearful facial expressions showed a distinct pattern of late-stage processing. Under low perceptual load, fearful expressions were differentiated from both happy and neutral expressions during the early and late LPP windows, whereas happy expressions differed from neutral expressions only during the early LPP. This pattern suggests that fearful expressions may receive more sustained processing because they signal potential threat (Suess *et al.* 2015, Li *et al.* 2024) and are associated with enhanced attentional orienting and delayed disengagement (Fox *et al.* 2002, Carlson and Reinke 2014, Carlson and Mujica-Parodi 2015, Carlson *et al.* 2016). Under high load, the fearful-versus-neutral distinction was absent at the early LPP but re-emerged at the late LPP. This temporal pattern may indicate that fear-related processing is initially constrained when attentional resources are prioritized for task-relevant information. However, as task-related processing demands decrease over time, relatively greater availability of attentional resources may permit the recovery of emotional differentiation for fearful expressions (Lavie 2005, Uusberg *et al.* 2013, Schindler and Straube 2020). Previous studies have shown that higher task difficulty often results in reduced P3 and LPP amplitudes (O'connell *et al.* 2012, Twomey *et al.* 2015, Schindler *et al.* 2021a). In the present study, emotional-face and blank-screen trials occurred with equal probability, which may have reduced face-detection difficulty and consequently weakened the allocation of attentional resources. This may help explain why the main effect of perceptual load on the LPP was not significant. Accordingly, the present findings suggest that fearful expressions may be more resistant to reduced attentional availability than other emotional expressions, rather than providing direct evidence for their automatic processing at the late LPP time window (Schupp *et al.* 2004, Schindler *et al.* 2020b, Li *et al.* 2024).

A potential limitation of the present study should be noted. To create face-present and face-absent trials and to isolate T2-evoked ERP activity by subtracting blank-screen trials (Luo *et al.* 2010, Yang *et al.* 2025), each emotional condition and the blank screen were presented with equal probability. Although this design was necessary for the planned ERP contrasts, it may have reduced the overall difficulty of the face-detection task. As a result, attentional resource engagement may have been attenuated, potentially weakening the influence of attentional resources on late-stage emotional processing.

Conclusion

This study aimed to resolve inconsistencies regarding emotional modulation of the LPP in implicit tasks. Emotional effects were observed across multiple processing stages, but their sensitivity to perceptual load varied over time. Early emotional effects (148–372 ms) were not modulated by perceptual load, suggesting that the initial extraction of emotional information is relatively robust under limited attentional resources. By contrast, emotional differentiation during the early LPP window (400–600 ms) was reduced under high perceptual load, indicating that attentional resource availability plays a critical role in shaping implicit emotional processing. However, fearful expressions remained distinguishable from neutral expressions during the late LPP window (600–800 ms) even under high load, suggesting that threat-related stimuli may retain prioritized access to later stages of emotional processing. Together, these findings indicate that attentional resource availability influences emotional modulation of the LPP in a temporally dissociable manner. They further challenge the assumption that, in implicit tasks, attention is allocated exclusively to non-emotional features.

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Author contributions

Lan Yang (Conceptualization [lead], Data curation [lead], Formal analysis [lead], Investigation [lead], Methodology [lead], Software [lead], Visualization [lead], Writing—original draft [lead], Writing—review & editing [lead]), Junyu Liang (Formal analysis [equal], Writing—review & editing [equal]), Yongjian Li (Visualization [equal], Writing—review & editing [equal]), Shuaixia Li (Data curation [equal], Writing—review & editing [equal]), Yuchen Li (Software [equal], Writing—review & editing [equal]), Xing Fang (Writing—review & editing [equal]), Jun Chen (Conceptualization [equal], Funding acquisition [equal], Supervision [equal]), and Wenbo Luo (Conceptualization [lead], Funding acquisition [lead], Project administration [lead], Supervision [lead])

Supplementary material

Supplementary material is available at *SCAN* online.

Conflicts of interest

None declared.

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Data availability

The available data and code can be found at https://osf.io/tzyue/.

Ethics statement

This work was approved by the Ethics Committee of Liaoning Normal University (LL2022015) in accordance with the Declaration of Helsinki (1991). Informed consent was obtained from all subjects involved in the study.

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