Acute stress impairs target enhancement but not distractor suppression in attention selection: Evidence from the N2pc and Pd

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Abstract: Acute stress has a profound impact on attention selection. However, the cognitive mechanism of acute stress on attention selection for neutral stimuli remains unclear. The current study aimed to investigate how acute stress affects target enhancement and distractor suppression in attention selection using a visual search task while EEG was recorded. The Maastricht Acute Stress Test was successfully induced a stress response in the stress group, as indexed by the higher salivary cortisol, state anxiety, and negative emotion. Crucially, the stress group showed significantly smaller N2pc than the control group in the lateral target/midline and contralateral distractor conditions when the distractor salience was high, whereas no significant differences in the Pd were observed in the lateral distractor/midline target condition. These results suggest that acute stress impairs target enhancement rather than distractor suppression in attention selection. This impairment may be due to the impaired function of the prefrontal cortex under acute stress. The present research provides the first insight into the cognitive mechanism of acute stress on attention selection.

Keywords: acute stress; attention selection; target enhancement; distractor suppression; N2pc

1. Introduction

Acute stress has profound effects on attentional processing through activation of hypothalamus-pituitary-adrenal (HPA) axis and the sympathetic nervous system (SNS) (Arnsten, 2009; Luo et al., 2020). Recent models of visual attention selection implement target enhancement (or target facilitation, directly boosting relevant information) and distractor suppression (suppressing irrelevant information) as independent processes that resolve the competition of simultaneously presented stimuli for attentional resources (Liesefeld & Müller, 2019; Wyble et al., 2020). However, it remains unclear how acute stress affects the target enhancement and distractor suppression in attention selection.

Acute stress is an individual's physiological and psychological response to unpredictable and uncontrollable environmental stressors (Koolhaas et al., 2011). Acute stress activates the sympathetic nervous system (SNS) and the hypothalamus-pituitary-adrenal (HPA) axis, releasing glucocorticoids and catecholamines (Ulrich-Lai & Herman, 2009) , which has profound impacts on the brain regions (e.g., prefrontal cortex, amygdala, hippocampus) associated with attention (Arnsten, 2009; Liston et al., 2009). For example, Liston et al. (2009) found that psychosocial stress decoupled the frontoparietal functional connectivity associated with attentional shifts, thereby impairing selective attentional control.

Attention selection refers to the neural filtering processes that prioritize relevant objects over irrelevant distractors during the processing of visual information through two distinct mechanisms.:One is target enhancement, which refers to how relevant features can be enhanced to facilitate target processing(Desimone & Duncan, 1995) and requires involvement of the frontal-parietal network(Giesbrecht et al., 2003). In the ERP study, target enhancement is related to the N2pc component, which is a

hemisphere-lateralized modulation that indexes the rapid reallocation of attention towards task-relevant information in visual search, when the target attracts more attention, the amplitude of the N2pc would be larger (Eimer, 1996; Hickey et al., 2009; Luck & Hillyard, 1994). The other is distractor suppression, which refers to how irrelevant or potentially distracting visual objects can be suppressed below baseline to reduce distraction(Gaspelin et al., 2015) and requires the involvement of visual cortex regions or/and frontal-parietal network(Adam & Serences, 2021; Geng, 2014; Serences et al., 2004; Won et al., 2022). For example, Serence et al.(2004) found that neural activity in the visual cortex regions increased prior to stimulus onset when the probability of distractors was higher, suggesting that visual cortex is involved in distractor suppression. In the ERP study, distractor suppression is related to the Pd component, which is known to index activity associated with the suppression of irrelevant or distracting information. When the distractor is successfully suppressed, the amplitude of the Pd is higher(Gaspelin & Luck, 2018; Hickey et al., 2009; Sawaki & Luck, 2013).

Previous studies have shown that acute stress impair target processing by reducing the function of the fronto-parietal network(Larra et al., 2022; Sänger et al., 2014). For example, Sänger et al. (2014) found that acute stress impaired target processing, as indicated by a reduced N2pc component. However, the impact of acute stress on distractor suppression is not as clear. On one hand, Some studies suggest acute stress may attenuate distractor suppression if the suppression process involved the fronto-parietal network(Olver et al., 2015; Xu et al., 2017). Xu et al. (2017) found that social stress impaired distractor suppression in a visual search task, as evidenced by a smaller Pd in the stress group compared to the control group.. On the other hand, recent studies has found that the distractor suppression occurs in the

visual cortex(Adam & Serences, 2021; Park & Serences, 2022; Serences et al., 2004; Zhang et al., 2022), and a meta-analysis study revealed that acute stress did not impact neural activity in the visual cortex(Berretz et al., 2021). Therefore, if the suppression process does not involve the fronto-parietal cortex, acute stress may not affect the distractor suppression.

Distractor salience is another factor that influences attention selection. Previous studies have shown that salient stimuli can capture attention in a bottom-up manner(Gaspar & McDonald, 2014; Gaspelin & Luck, 2018).Furthermore, Several studies have demonstrated that stressed individuals are more easily distracted by task-irrelevant threatening (salient) stimulus(Luo et al., 2020; Wirz & Schwabe, 2020). Gaspar & McDonald (2018) found that in the high-anxiety group, the N2pc components appeared earlier compared to the low-anxiety group when a salient distractor appeared, indicating that individuals with high anxiety were less able to suppress distracting information and slower to do so. Xu et al., (2107) included only the highly salient distractor in their study. Although previous studies have examined emotional or high-salience distractors, the interaction between acute stress and the salience of a neutral distractor on attention selection for neutral stimuli remains unknown.

In short, the purpose of this study was to investigate the cognitive mechanism of the acute stress effect on attention selection by examining whether acute stress impairs target enhancement and/or distractor suppression, and whether distractor salience modulates this effect. Participants were required to complete a visual search task, in which target and distractor locations were manipulated to isolate target enhancement and distractor suppression, and N2pc and Pd were measured to reflect these processes.. Based on previous studies, it was hypothesized that acute stress

would impair target enhancement, resulting in a smaller N2pc in stressed participants compared to non-stressed participants. However, it may not be possible to make a clear hypothesis regarding the effect of acute stress on distractor suppression as it involves the visual cortex and/or the fronto-parietal network, and acute stress has different effects in these two regions.

2.Method

2.1 Participants

Participants were recruited through advertisements on university campuses. To minimize the potential influence of sex hormones on cortisol measurements, all female participants were tested during the luteal phase of the menstrual cycle(Duchesne & Pruessner, 2013). Participants were screened for normal color vision using the Ishihara color deficiency test prior to participation. They reported (a) having no history of a diagnosed psychiatric disorder, habitual smoking, fainting, or epileptic seizures; (b) having no current endocrine, autoimmune, cardiovascular, respiratory, or dermatological disorders; (c) not being oversensitive to cutaneous sensation subjectively (to minimize negative reactions to cold water stress); (d) not using medication that could affect cortisol response (e.g., β-blockers); and (e) not suffering from severe sleep disturbance or fatigue. Participants were asked to refrain from vigorous exercise, alcohol, and caffeine for three hours and to abstain from food for one hour before the test. All participants were native speakers of Chinese.

To determine sample size, a priori power analysis(test family: *F* tests, statistical test: ANOVA: fixed effects, special main effects and interactions, numerator df =1, number of groups=4) was performed based on a medium effect size (Effect size f =0.314, see the supplementary materials for details), which indicated that 82 participants were required to detect the hypothesised effect at α=0.05 and power

1-β=0.80(Gaspar et al., 2016; Gaspar & McDonald, 2018; Xu et al., 2017). A total of 87 participants were recruited. Seven participants were excluded from the final analysis due to more than 30 % of trials being rejected in the EEG data. The final sample consisted of 80 right-handed healthy participants (age: 20.95±1.96 years; BMI: 20.97±3.09; 45 female, 35 male).

The study protocol was approved by the Committee on Human Research Protectionat the School of Psychology, Guizhou Normal University (Protocol:20190710) and conducted in accordance with the Declaration of Helsinki. Participants gave written informed consent before the experimentand received 30 CNY per hour as compensation for their participation. The study was not pre-registered.

2.2 Experimental design

A full factorial 2×2 between-subjects design was used, with stress (stress, control) and distractor salience (high, low) as between-subjects factors manipulated in the experiment. Participants were randomly assigned to either the Stress group (n = 41, 23 female) or the Control group (No stress, n = 39, 22 female) . After completing the Maastricht Acute Stress Test (MAST) procedure, participants were randomly assigned to either the high-salience distractor condition (Stress: n =20,12 female; Control: n =17, 11 female) or the low-salience distractor condition (Stress: n =21, 11 female; Control: n =22, 11 female).

2.3 General Procedure

The experiment was conducted between 13:30 and 18:30. Upon arrival, participants were escorted to the behavioral laboratory by an experimenter who was either dressed in a white lab coat and acting in a reserved manner (stress group) or dressed in normal casual clothing and being friendly (control group). Participants

were then asked to rest for 10 minutes, after which they completed two questionnaires, including the Positive and Negative Affect Schedule (PANAS, Watson et al., 1988) and the State-Trait Anxiety Inventory(STAI-T;STAI-S, Spielberger et al., 1970), and the first saliva sample was collected using the Salivette collection tubes (Sarstedt, Germany). Participants were asked to gently chewed the cotton in their mouth to collect enough saliva. They were then seated in a comfortable chair for the preparation of the EEG equipment, which took about 30 minutes, followed by the second questionnaire and saliva sample collection. Then the MAST (a stress or control task) was manipulated for 15 minutes, followed by the third questionnaires and saliva samples.

Next, participants performed a visual search task while their EEG was being recorded. The visual search task consisted of four blocks. There was a 5-minute break between the second and third blocks. During this break, the fourth questionnaires and saliva sample were collected. The visual search task took approximately 60 minutes to complete. After the EEG recording, the fifth questionnaires and saliva sample were collected immediately, and participants were asked to complete the Beck Depression Inventory (BDI) to assess their current mental health. Salivary cortisol samples were frozen at −20 °C within 1 hour of collection until assayed. Cortisol was assayed by centrifuging at 3,000 rpm for 10 minutes to remove particulate matter. Salivary cortisol concentrations were determined by electrochemiluminescence immunoassay (Cobas e 601, Roche Diagnostics, Numbrecht, Germany), with a lower limit of sensitivity of 1.5 nmol/L. After analysis, the salivary cortisol samples were destroyed as medical waste.

2.4 Stress induction

The Maastricht Acute Stress Test (MAST) was utilized to induce either stress or

a control (non-stress) condition. The MAST is a well-established method for inducing stress, involving asking participants to immerse one hands in ice water and perform mental arithmetic in an environment of unpredictability, uncontrollability, and social evaluation, i.e., negative feedback(Smeets et al., 2012). The participants started with a 5-minutes preparation phase, followed by a 10-minutes acute stress phase. During the preparation phase, the participants were seated in front of a computer and briefed about the upcoming task. In the stress group, the participants were explicitly informed that their facial expressions would be recorded, and they would have to immerse their hand in ice-cold water (2.89 ± 0.32°C, range from 1.9 to 3.4 °C) for a randomly selected period of 60 to 90 seconds several times. Between the hand immersion trials, the participants had to count backwards from 2043 in steps of 17 as quickly and accurately as possible. If they made a mistake, they received negative feedback from the experimenter and had to start again at 2043. The participants were instructed to continue with the mental arithmetic until the computer signaled the start of the next hand immersion trial, which would take at least 45 s. The exact sequence and duration of the hand immersion trials (HIT) and mental arithmetic (MA) backward counting intervals were as follow: HIT-90 s, MA-45 s, HIT-60 s, MA-60 s, HIT-60 s, MA-90 s, HIT-90s, MA-45s, HIT-60 s. In the control condition, the participants immersed their hand in body temperature (i.e. 37.58 ± 0.51°C, range from 36.5 to 38.6 °C) water and counted backwards from 2000 in steps of 10 at a speed of their choice. No feedback was given and no facial expressions were recorded.

2.5 Visual Search Task

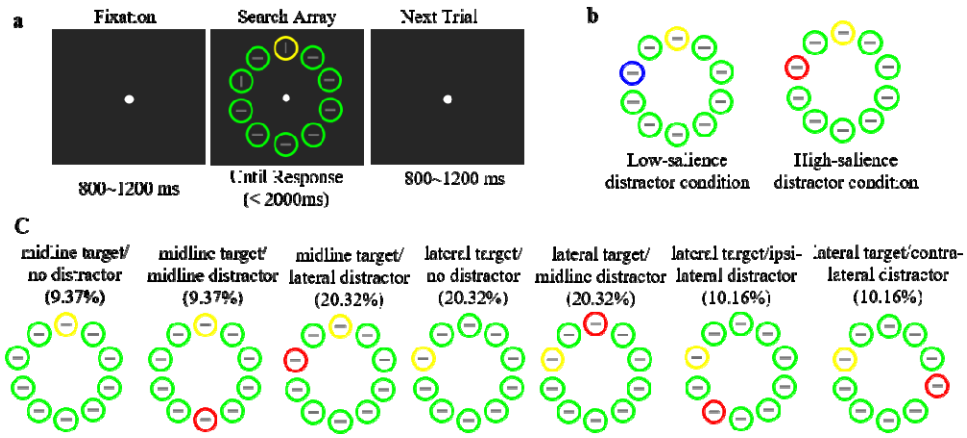
In the visual search task, stimuli were presented using PsychToolbox (http://psychtoolbox.org/) on a 24.5-inch, 144-Hz AOC-AG251FX LCD monitor with a black (RGB: 0, 0, 0) background and was placed at a viewing distance of 57 cm.

As shown in Figure 1, each visual search display contained 10 unfilled circles presented equidistant (9.2°) from a central fixation point. Each circle had a diameter of 3.4° and an outline that was 0.3° thick. There were two types of trials: distractor-present and distractor-absent. In the distractor-present trials, eight of the circles were uniformly colored non-targets, one was a target color singleton, and one was a distractor color singleton. In the distractor-absent trials, nine of the circles were uniformly colored non-targets, and one was a target color singleton. The target was yellow (RGB: 255,255,0), and the non-target circle was either green (RGB: 0,255,0) or orange (RGB: 255,182,75). The distractor was either red (RGB: 255,0,0) or blue (RGB: 0,0,255). Each circle contained a randomly oriented vertical or horizontal gray line (RGB:100,100,100).

On each trial, a fixation period of 800-1,200 ms preceded the presentation of the search display, during which only a central fixation point was visible. When the search display appeared, participants were instructed to maintain fixation on the central point and identify the orientation (vertical or horizontal) of the gray line within the target singleton by pressing one of two response buttons as quickly and accurately as possible within 2,000 ms. The response buttons were counterbalanced across subjects. The next trial began after a response or no response within 2,000 ms (see Figure 1a).

Figure 1

An Overview of the Experimental task



Note. (a) Example trial from the visual search task, (b) example of low-salience distractor and high-salience distractor condition, (c) examples of the seven display configurations used in the present study. In each trial, Participants were instructed identify the orientation of the gray line inside the yellow target singleton. See the online article for the color version of this figure.

The experiment consisted of 4 blocks, with atotal of 1,260 trials per participant. Each experimental block consisted of 315 trials, with a 5-s rest period after every 45 trials. At the end of each block, participants were given a minimum 5-s rest period and could start the next block when ready. At least 36 practice trials were given to each participant before the start of the experiment. During the breaks between blocks, participants received feedback on compliance with the instructions, but no feedback was given on their performance.

To produce the visual search displays, we varied the locations of the target and distractor, resulting in the following display configurations (see Figure 1b) based on previous studies(Gaspar et al., 2016; Gaspar & McDonald, 2014, 2018): lateral target/no distractor (20.32%); midline target/no distractor (9.37%); lateral target/midline distractor (20.32%); lateral target/ipsilateral distractor (10.16%); lateral target/contralateral distractor (10.16%); midline target/lateral distractor (20.32%); midline target/midline distractor (9.37%). These display configurations were randomly intermixed across trials.

In the distractor-present trials, the salience of the distractor was defined in terms of the local contrast between the nontarget color and the distractor or target color singleton, based on previous studies(Gaspar et al., 2016; Gaspar & McDonald, 2014). The high salience distractor condition was defined as having a greater distance in chromatic space between the distractor singleton and the nontargets (i.e., red distractor vs. green nontargets) than the distance between the target singleton color and the nontargets color (i.e., yellow target vs. green nontargets). Conversely, the low salience distractor condition had a smaller distance in chromatic space between the distractor singleton and the nontargets (i.e., blue distractor vs. green nontargets) than the distance between the target singleton color and the nontarget color (i.e., yellow target vs. green nontargets). Note that we manipulated the salience of the distractor as a between-subjects factor to prevent excessive fatigue from interfering with the experiment.

2.6 Electrophysiological Recording and preprocessing

The EEG was recorded using a 64-channel electrode cap (Neuroscan, Herndon, VA, USA) according to the international 10/20 system with Ag/AgCl electrodes. The ground electrode was positioned between FPz and Fz, and the online reference electrode was placed between Cz and CPz. To monitor eye movements and blinks, vertical electrooculograms (EOGs) were recorded supra-orbitally and infra-orbitally relative to the left eye, and the horizontal EOG was recorded as the difference in activity between the right and left orbital rim. The impedance of all electrodes was kept below 5 KΩ. EEG signals were recorded in DC mode using a Neuroscan SynAmps2 amplifier and Curry recording software, amplified with a low-pass filter at 100 Hz, with no high-pass filters applied, and digitized at a sampling rate of 1000 Hz.

All analyses after data acquisition were performed using EEGLAB

Toolbox(Delorme & Makeig, 2004) and ERPLAB Toolbox(Lopez-Calderon & Luck, 2014) . The EEG signals were referenced to the average of the left and right mastoids, and the four EOG signals were referenced using bipolar vertical and horizontal EOG derivations. All the signals were bandpass filtered (noncausal Butterworth impulse response function, half-amplitude cutoffs at 0.1 and 30 Hz, 12 dB/oct roll-off) and resampled at 500 Hz. Portions of the EEG containing large muscle artefacts or extreme voltage offsets (identified by visual inspection) were removed. In addition, segments were excluded from further analysis on an individual-channel basis if the absolute voltage exceeded 100 μV. Independent component analysis (ICA) was then performed on the scalp EEG for each subject to identify and remove components that were associated with blinks (Jung et al., 2000) and eye movements (Drisdelle et al., 2017). The ICA-corrected EEG data were segmented for each trial from −100 to +500 ms relative to the onset of the search array. The baseline correction was based on the prestimulus time interval (−100 to 0 ms).

In order to minimize the impact of residual blinks or saccades on the EEG components in the epoch data, blinks were detected using a moving window peak-to-peak threshold (Test period: 0-400 ms; Moving Windows Full Width: 200 ms; Window step: 100 ms; Voltage Threshold: 80 μV) to identify an absolute amplitude of the vertical EOG exceeding 80 μV. Saccades were defined by using step-like artifacts (Test period: 0-400 ms; Moving Windows Full Width: 200 ms; Window step: 50 ms; Voltage Threshold: 40 μV) to detect a horizontal EOG amplitude difference greater than 40 μV. Trials with incorrect responses or blinks or saccades occurring between 0 ms and 400 ms were excluded from analysis, resulting in the exclusion of an average of 93.58% of trials for RT cutoffs and EEG artifacts. Data from 7 participants who had more than 30% of trials rejected due to artifacts, incorrect responses, or RTs that

were too fast (RT < 300 ms) or too slow (RT > 1,500 ms) were excluded from the analyses.**2.7 Data Analysis**

Data were analyzed using JASP (2022, version 0.16.3.0). JASP is a freely accessible, open-source package for statistical analysis. We report necessary corrections in case of analysis-specific violations of assumptions.

The datasets have been made publicly available via the Science Data Bank (ScienceDB) and can be accessed at: http://cstr.cn/31253.11.sciencedb.02116.

2.7.1 Stress response

Two measures of cortisol output were quantified. First, the area under the cortisol curve with respect to the ground (AUCg) was calculated as the total cortisol concentration over the duration of the experiment. Second, the cortisol concentration specifically related to the increase due to the stress induction (AUCi) was calculated by subtracting the baseline from the AUCg. All calculations followed the trapezoid integration method as recommended in a previous study (Pruessner et al., 2003).

To test for successful stress induction, three separate repeated-measures analysis of variance (ANOVA) were performed on salivary cortisol and subjective affect rating scores, with group(stress, control) as a between-subjects factor and time (T1, T2, T3, T4, T5) as a within-subjects factor. For ANOVAs involving more than two levels of a factor, the Greenhouse–Geisser correction for violation of the assumption of sphericity was applied, and the corrected *p*-values are reported.

2.7.2 Behavioral Performance

Mean RTs were compared between the group and distractor salience using a 2(group: stress, control) ×2 (distractor salience: high, low) analysis of variance (ANOVA) on mean RT in the lateral target/middle distractor, lateral target/contralateral distractor and midline target/ lateral distractor conditions.

2.7.3 ERP amplitude

According to the aim of the present study, only the distractor-present trails were analyzed. The lateralized ERP waveforms were generated for each condition for the following display configurations: lateral target/midline distractor; lateral target/contralateral distractor and midline target/ lateral distractor. ERPs of these search displays were created by collapsing across left and right visual hemifields and left and right electrodes (PO7 and PO8) to produce waveforms recorded ipsilateral and contralateral to the target or distractor stimuli. Lateralized ERP difference waveforms were then derived by subtracting the ipsilateral waveform from the corresponding contralateral waveform. All ERP statistics were calculated using contralateral minus ipsilateral difference values (Hickey et al., 2009).

Pd and N2pc magnitudes were measured using a mean-amplitude approach. By convention, we selected electrodes and time windows based on existing studies that measured mean amplitudes. Both components were measured at lateral occipital electrodes PO7 and PO8, as in most previous publications (Gaspar et al., 2016; Gaspar & McDonald, 2014, 2018; Gaspelin & Luck, 2018; Xu et al., 2017). For the lateral target/middle distractor and lateral target/contralateral distractor trials, the N2pc window was in the time window of 260~310 ms, whereas for the midline target/lateral distractor trial, the Pd window was in the time window of 110~160 ms (Early Pd) and 280~330 ms (Late Pd). N2pc and Pd mean-amplitude was compared between the group and distractor salience by using a 2(group: stress, control) ×2 (distractor salience: high, low) analysis of variance (ANOVA), the corrected *p* values are reported. To further explore the effects of acute stress on target enhancement and distractor suppression, the correlation between AUCg, AUCi of cortisol and mean amplitute of Pd, N2pc was analyzed.

To minimize bias from the choice of measurement window, we also used the signed-area approach(Sawaki et al., 2012): N2pc amplitude was quantified as the negative area between 200~350 ms in the lateral target/middle distractor and lateral target/contralateral distractor trials, and Pd amplitude was quantified as the positive area between 100~200 ms (Early Pd) and 260~360 ms (Late Pd) in the midline target/ lateral distractor trials. Note that in the N2pc component, we measured the negative area over a broad time window, ignoring any periods of positive voltage. In the Pd component, we measured the positive area over a broad time window, ignoring any periods of negative voltage. Because the signed area is naturally biased away from zero, we could not use traditional statistical approaches to determine whether the area was greater than expected by chance (such as a one-sample *t* test comparing the mean to zero). We therefore used the nonparametric permutation approach (Sawaki et al., 2012), which use random permutations of the data are used to estimate the distribution of signed area values that would be expected from noise alone(see the supplementary materials for details).

3.Results

3.1 Stress measurement

Trait Anxiety: No significant difference was observed in trait anxiety scores across the four groups[Stress high-salience distractor: 37.88±8.37 vs. Stress low-salience distractor: 38.96±6.88 vs. Control high-salience distractor: 39.35±7.44 vs. Control low-salience distractor: 36.14±8.59, $F(3,76) = 0.70$, $p = 0.55$]..

Beck Depression Inventory：No significant difference was observed in the Beck Depression Inventory scores across the four groups[Stress high-salience distractor:

5.90±4.73 vs. Stress low-salience distractor: 5.67±3.75 vs. Control high-salience distractor: 6.41±5.91 vs. Control low-salience distractor: 5.05±4.77, $F(3,76) = 0.27$, $p = 0.84$].

Salivary cortisol: As shown in Figure 2a, there was a significant main effect of group[$F(1,78) = 5.74$, $p = 0.02$, $\eta^2p = 0.07$], and a significant main effect of time[$F(4,312) = 4.21$, $p = 0.01$, $\eta^2p = 0.05$]. Crucially, there was a significant interaction between group and time [$F(4,312) = 12.27$, $p < 0.01$, $\eta^2p = 0.14$] . Subsequent comparisons showed that the stress group had significantly higher cortisol levels than the control group at T3[stress: 5.83±4.50 nmol/L vs. control: 2.46±1.48 nmol/L, $t = 4.75$, $p < 0.01$, *Cohen's d* =1.06] and T4[stress: 5.38±4.85 nmol/L vs. control: 2.16±1.57 nmol/L, $t = 4.52$, $p < 0.01$, *Cohen's d* =1.01], no significant difference was observed between the two groups at the rest time points:T1 and T2 (ps > 0.05). Within the stress group, a significantly higher crotisol level was observed at T3 (5.83±4.50 nmol/L) and T4(5.38±4.85 nmol/L) compared to T2(2.94±2.43 nmol/L) and T1(3.59±3.22 nmol/L)[T3 v.s. T1, $t = -4.30$, $p < 0.01$, *Cohen's d* =-0.71; T3 vs. T2, $t = -5.56$, $p < 0.01$, *Cohen's d* =-0.91; T4 vs. T1, $t = -3.42$, $p = 0.02$, *Cohen's d* =-0.56; T4 vs. T2, $t = -4.68$, $p < 0.01$, *Cohen's d* =-0.77].

State Anxiety: The results for state anxiety are shown in Figure 2b. The ANOVA revealed no significant main effect of group[$F(1,78) = 3.05$, $p = 0.09$], a significant main effect of time[$F(4,312) = 30.59$, $p < 0.01$, $\eta^2p = 0.28$], the interaction of group by time was significant[$F(4,312) = 19.87$, $p < 0.01$, $\eta^2p = 0.20$], the post-hoc analysis showed that the stress group had significantly higher state anxiety scores than the control group at T3[stress: 46.51±8.39 vs. control: 35.56±7.16, $t = 6.33$, $p < 0.01$,

Cohen's d =1.42]. No significant difference between the two groups was observed at T1 and T2 (*ps* > 0.05). Within the stress group, a significantly higher state anxiety score was observed at T3 (46.51±8.39) compared to T2(36.12±8.61) and T1 (33.78± 7.11) [T3 vs. T1, t = -12.03, p < 0.01, *Cohen's d* =-1.65; T3 vs. T2, t = -9.81, p < 0.01, *Cohen's d* =-1.34].

Negative Emotion: The results for negative emotion are shown in Figure 2d. The ANOVA revealed a significant main effect of group[$F(1,78) = 6.02$, $p = 0.02$, η^2p= 0.07], and a significant main effect of time[$F(4,312) = 18.88$, $p < 0.01$, $\eta^2p = 0.20$], the interaction of group by time was significant[$F(4,312) = 22.88$, $p < 0.01$, η^2p= 0.23], the post-hoc analysis showed that the stress group had significantly higher negative emotion score than the control group at T3[stress: 21.12±3.61 vs. control: 14.26±3.63, t = 7.44, p < 0.01, *Cohen's d* =1.66]. No significant difference between the two groups was observed at T1 and T2 (*ps* > 0.05). Within the stress group, a significantly higher negative emotion score was observed at T3 (21.11±3.61) comparing to T2(15.98±4.75) and T1 (16.68±3.99) [T3 v.s. T1, t = -7.55, p < 0.01, *Cohen's d* =-1.08; T3 vs. T2, t = -8.75, p < 0.01, *Cohen's d* =-1.25].

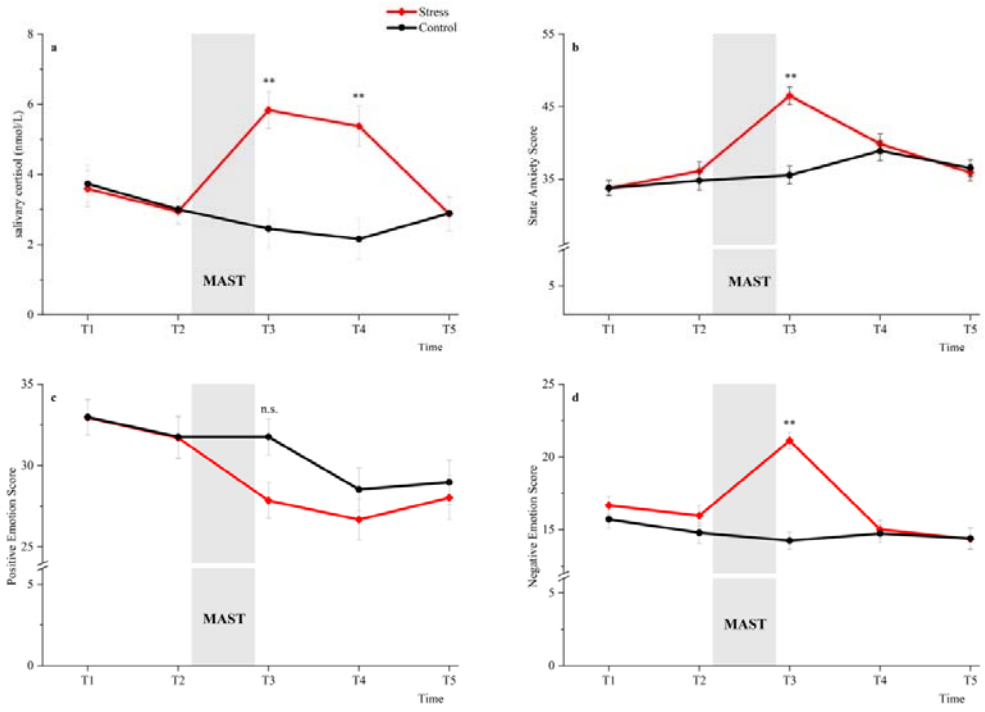
Positive Emotion: As shown in Figure 2c, the results revealed no significant main effect of group[$F(1,78) = 0.73$, $p = 0.40$], a significant main effect of time[$F(4,312) = 34.96$, $p < 0.01$, $\eta^2p = 0.31$]. Crucially, there was a significant interaction between group and time [$F(4,312) = 4.62$, $p = 0.004$, η^2p= 0.06]. However, subsequent comparisons showed no differences between stress and control group at T3[stress: 27.85±6.79 vs. control: 31.77±7.18, t = -2.26, p = 0.08]. Within the stress group, a significantly lower positive emotion score was observed at T3 (27.85±6.79) compared to T2(31.71±8.61) and T1 (32.95±7.41) [T3 vs. T1, t = 6.87, p < 0.01,

Cohen's d =0.66; T3 vs. T2, t = 5.20, p < 0.01, *Cohen's d* =0.50].

These salivary and subjective results suggest that the MAST was successfully used to induce the stress response in the stressed group.

Figure 2

Results of stress response



Note. Means and SEs of salivary cortisol levels(a), state anxiety score(b), positive emotion scores (c), and negative emotion score (d) in the stress and control group during the experiment. Figure 2a shows that the stress group had significantly higher cortisol levels than the control group at T3 and T4, Figure 2b shows that the stress group had significantly higher state anxiety scores than the control group at T3, Figure 2d shows that the stress group had significantly higher negative emotions scores than the control group at T3, *p<0.05, **p<0.01, n.s = $p>0.05$. See the online article for the color version of this figure.

3.2 Behavioral Results

The results for the midline target/lateral distractor condition are shown in Figure 3a. The ANOVA revealed a significant main effect of distractor salience[F(1,76) =

6.02, p = 0.03, η^2p= 0.06], subsequent comparisons showed that the high-salience distractor condition had significantly longer response time than the low-salience distractor condition[high-salience distractor: 823.99±87.53 ms vs. low-salience distractor: 782.36±87.794 ms, t = -2.20, p = 0.03, *Cohen's d* = -0.49]. Neither a significant main effect of group nor an interaction of group by distractor salience was observed ,*ps* > 0.05. The ANOVAs revealed neither a significant main effect of group, distractor salience, nor an interaction of group by distractor salience for the lateral target/midline distractor condition (*ps* > 0.05) and for the lateral target/contralateral distractor condition (*ps* > 0.05).

3.3 Electrophysiological Results: ERP Components

Midline target/lateral distractor

Early Pd: The results for early Pd (110~160 ms) are shown in Figure 3a, there was a significant main effect of distractor salience[F(1,76) = 4.79, p = 0.03, η^2p= 0.06], a larger early Pd amplitude in the high-salience distractor condition than in the low-salience distractor condition[0.48±0.41 μV vs. 0.29±0.38 μV, t = -2.19, p = 0.03, *Cohen's d* = -0.49]. No other significant main effect or interaction of group by distractor salience was observed, *ps* > 0.05.

The non-parametric test showed that there was an early Pd in all conditions in the time window of 100~200 ms, *ps<0.05* (see supplementary materials S.Figure1). However, there were no significant differences across conditions, *ps >0.05* (see supplementary materials S.Figure2).

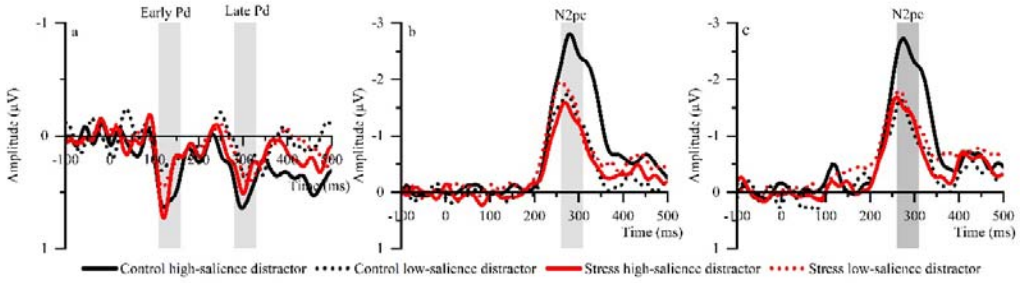
Late Pd: As shown in the Figure 4a, the results for late Pd (280~330ms) showed

neither a significant main effect of group, distractor salience, nor an interaction of group by distractor salience, *ps* > 0.05.

The non-parametric test showed that there was a late Pd in all conditions in the time window of 260~360ms, *ps<0.05* (see supplementary materials S.Figure3). However, there were no significant differences across conditions, *ps >0.05* (see supplementary materials S.Figure4).

Figure 3

The ERP results of three different trials



Note. ERP results of the midline target/lateral distractor trials(a), Lateral target/midline distractor trials (b) and Lateral target, contralateral distractor trials (c). Grand average of difference waveforms obtained by subtracting the ipsilateral waveforms from the contralateral waveforms (averaged over PO7 and PO8). Figure 3a shows that no significant differences in early Pd and late Pd across conditions between stress group and control group; Figure 3b and Figure 3c shows that the N2pc was significantly smaller (more positive) in the stress group than in the control group at the high-salience distractor condition. See the online article for the color version of this figure.

Lateral target/midline distractor

N2pc: As shown in Figure 3b, the results for N2pc (260~310 ms) showed neither significant main effect of group nor distractor salience, *ps*>0.05. Crucially, there was a significant interaction between group and distractor salience[$F(1,76) = 5.47$, $p = 0.02$, $\eta^2p = 0.07$]. The post-hoc analysis showed that the N2pc in the stress group was

significantly smaller (more positive) than in the control group in the high-salience distractor condition[stress: -1.35±0.82 μV vs. control: -2.57±1.68 μV, t = 2.95, p = 0.03, Cohen's d = -0.49]. No significant results were observed in the low-salience condition (ps > 0.05).

The non-parametric test showed that there was a N2pc for all conditions in the time window of 200~350 ms, *ps <0.05* (see supplementary materials S.Figure5). Crucially, the N2pc area was significantly larger in the control group than in the stress group in the high-salience distractor condition, *p <0.05*, which was similar with the results for mean amplitude. No other significant effect was found, *ps >0.05* (see supplementary materials S.Figure6).

Lateral target/contralateral distractor

N2pc: As shown in Figure 4c, the results for N2pc (260~310 ms) showed neither significant main effect of group nor distractor salience, *ps*>0.05. There was a significant interaction between group and distractor salience[F(1,76) = 5.34, p = 0.024, η^2p= 0.066]. The post-hoc analysis showed that the amplitude of N2pc was significantly smaller (more positive) in the stress group than in the control group in the high-salience distractor condition[stress: -1.40±0.86 μV vs. control: -2.50±1.59 μV, t = 2.67 ，p = 0.056 ，*Cohen's d* = 0.88]. In the control group, the amplitude of N2pc was smaller in the low-salience condition than in the high-salience condition [-1.31±1.34 μV vs. -2.50±1.59 μV, t = 2.97, p = 0.024, *Cohen's d* = 0.96].

The non-parametric test showed that there was a N2pc for all conditions in the time window of 200~350 ms, *ps <0.05* (see supplementary materials S.Figure7), the N2pc area was significantly smaller in the stress group than in the control group in the high-salience distractor condition, *p <0.05*, which was similar with the results for

mean amplitude. No other significant effect was found, *ps >0.05* (see supplementary materials S.Figure 8).

3.4 Correlational Results

Spearman's rank order correlations revealed that AUCi of cortisol was negatively correlated with N2pc amplitude at the lateral target/midline distractor condition [*rs* = -0.21, *p* = 0.03] and at the lateral target/contralateral distractor condition[*rs* = -0.19, *p* = 0.04], but not correlated with early Pd [*rs* = -0.06, *p* = 0.29] and late Pd [*rs* = -0.04, *p* = 0.37] amplitude at the midline target/lateral distractor. No other significant correlations were found, *p*s>0.05.

4. Disscussion

The current study aimed to investigate the effect of acute stress on target enhancement and distractor suppression during attention selection for neutral stimuli. The MAST was successfully induced a stress response,as indicated by higher salivary cortisol, state anxiety, and negative emotion in the stress group compared to the control group. In the high-salience distractor condition, the stress group exhibited a smaller N2pc than the control group, while no significant difference was observed for the Pd. These findings suggest that acute stress impairs target enhancement rather than distractor suppression during attention selection. This impairment may be attributed to the negative impact of acute stress on the prefrontal cortex (PFC). These results provide valuable insights into the cognitive mechanism of acute stress on attention selection for neutral stimuli.

Behaviorally, we found no significant effect of acute stress on the reaction times, suggesting that stressed individuals performed as well on the task as their non-stressed counterparts.This results is consistent with a previous study which showed that trait anxiety did not affect behavioral response in a visual search task (Gaspar &

McDonald, 2018), it is possible that behavioral responses are the output of complex multiple processes. Additionally, we found that participants responded more slowly in the high-salience condition than in the low-salience condition, indicating that salience of distractor was successfully manipulated. The results are also in line with previous studies showing that a high-salience distractor would capture attention and lead to a slow response to the target(Gaspar et al., 2016; Gaspar & McDonald, 2014).

Crucially, we found a smaller N2pc in the stress group than in the control group in the high-salience condition, whereas no difference was found for the Pd. These results suggest that acute stress impairs target enhancement rather than distractor suppression, because target enhancement is a PFC-dependent process, whereas distractor suppression may not be (Xie et al., 2020) .For example, sleep deprivation (a type of stress) attenuates attentional direction/orientation processing (Song et al., 2022). The fact that acute stress impairs target enhancement may be due to the detrimental effect of acute stress on the PFC. Previous studies have shown that target enhancement is a PFC-dependent cognitive process(Ort et al., 2019). For example, Ort et al. (2019) found that the fronto-parietal control network was more activated in response to selecting one of two possible targets presented among distractors compared to when only one of the targets was available. It is well known that acute stress down regulates the activity of the PFC and thus impairs related functions (Arnsten, 2009; Larra et al., 2022). This point of view is also supported by the correlation results, which showed that the greater activation of the HPA, the stronger detrimental effect.

Furthermore, we found that target enhancement was impaired only when the distractor was a salient color. This result suggests that acute stress impaired selective attention under high competition condition, which is consistent with previous study

(Sato et al., 2012). This selective impairment effect is most likely due to the fact that the PFC is more involved in the high-salience condition than in the low-salience condition. Existing work indicates that the PFC involvement in top-down attentional control was increased when task-irrelevant(e.g. salience, task relevance, emotionality) information can effectively compete for processing priority(Milham et al., 2003), suggesting that the target processing in the high-salience distractor condition is highly dependent on the PFC and thus more susceptible to stress (Hermans et al., 2014). In contrast, less competition was involved when the distractor was not salient(Kerzel & Huynh Cong, 2022; Wolf et al., 2019). When competition is not strong, less PFC is engaged (Snyder et al., 2014), and target enhancement remains intact in acute stress situations. However, the current study did not directly measure the brain activation, and further research should test this explanation using fMRI.

In contrast, we found no significant effect of acute stress on distractor suppression. The finding is in line with the theory that target facilitation and distractor suppression are controlled by distinct cognitive mechanisms(Noonan et al., 2016). Previous studies have shown that suppression of simple perceptually distracting stimuli(e.g., red circle) may be completed in the visual cortex and does not require the involvement of brain regions (e.g., PFC) with higher cognitive functions (Adam & Serences, 2021; Hopf et al., 2000; Park & Serences, 2022; Zhang et al., 2022).The acute stress effect is mainly due to the activation of the HPA, which targets the prefrontal cortex.A recent meta-analysis study found that the visual cortex is unlikely to be involved in stress processing(Berretz et al., 2021). Therefore, if distractor suppression is completed in the visual cortex, acute stress will not affect distractor suppression, which needs to be confirmed by more relevant research in the future. However, This result is contrary to the existing studies showing that social stress(Xu

et al., 2017) and trait anxiety(Gaspar & McDonald, 2018) impair distractor suppression in a visual search task. One possible reason may be that when individuals are experiencing negative emotions (e.g. social stress), they need to allocate more attention resources to regulate the negative feelings(Chester & DeWall, 2014), resulting in fewer attention resources for distractor suppression. However, the effects of acute stress on cognitive processing are mainly due to the changes neural activity in functional brain areas caused by the hormones released by activation of the SNS axis and the HPA axis under stress (Arnsten, 2009; Liston et al., 2009; Ulrich-Lai & Herman, 2009). Taken together, the lack of stress effect on distractor suppression suggests that acute stress affects cognitive function in a PFC-dependent manner.

There are some potential limitations of the current study that should be noted. Firstly, t although we used a priori analysis to calculate the sample size before the start of the study, the sample size was still relatively small. A larger sample size should be used in future studies. Second, due to the acute stress effect only lasting about 40 minutes (Smeets et al., 2012), distractor salience was manipulated as a between-subjects factor in the current study to shorten the experimental duration. This manipulation was a major shortcoming, as we could not directly compare the low-salience distractor condition with the high-salience distractor condition in the same individual. Therefore, we recommend using distractor salience as a within-subjects factor to test the current findings in future research.

In conclusion, the current study shows that acute stress affects attention selection not because of difficulties in distractor suppression, but because of impairments in goal-directed target enhancement in the presence of a high-salience distractor. This impairment may be caused by the effects of acute stress on the PFC. The current study provides clear evidence for acute stress-induced alterations in attention selection and

reveals the cognitive mechanism of the acute stress effect on attention selection.

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Supplementary Online Materials: Acute stress impairs target enhancement but not distractor suppression in attention selection: Evidence from the N2pc and Pd

Table of Content

Sample Size Considerations

Given that no studies have directly investigated the effects of acute stress on both the target enhancement and distractor suppression of attention selection for neutral stimuli, we used findings from previous studies examining the effects of visual working memory capacity(Gaspar et al., 2016), social exclusion(Xu et al., 2017) and trait anxiety(Gaspar & McDonald, 2018) on selective attention more generally. Xu et al. (2017) reported the effect size(η^2p) of social exclusion on selective attention in ERP components as: NT: η^2p=0.09, Pd: η^2p=0.16, N2pc: η^2p=0.18. In order to avoid false effects, we selected the minimum effect size (η^2p=0.09) reported by Xu et al. (2017) was selected to determine the effect size *f* ,and the conversion between η^2p and effect size *f* was calculated by G*power(Faul et al., 2009). A priori power analysis(Test family: *F* tests, Statistical test: ANOVA: Fixed effects, special main effects and interactions, Numerator *df* = 1, Number of groups = 4) was perfromed based on a medium effect size (Effect size *f* =0.314), indicating that 82 participants were required to detect the hypothesized effect at α = 0.05 and power 1-β = 0.80(Gaspar et al., 2016; Gaspar & McDonald, 2018; Xu et al., 2017).

Permutation Tests results of Pd and N2pc Waveforms (Signed-area approach)

Because signed area is naturally biased away from zero, we could not use traditional statistical approaches to determine whether the area was greater than expected by chance (such as a one-sample *t* test comparing the mean to zero). We therefore used the non-parametric permutation approach (Sawaki et al., 2012), in which random permutations of the data are used to estimate the distribution of signed area values that would be expected by noise alone. We simulated a lack of difference between the contralateral and ipsilateral voltages by randomizing the labels (event codes) indicating which side contained the singleton in the single-trial EEG data. If

there is no real difference between the contralateral and ipsilateral voltages, then it should not matter which side is labeled as containing the singleton. Consequently, we can estimate the positive area that would occur by chance in the absence of a true difference by randomizing the labels, averaging the data, and computing the negative/positive area. If we did this once, the randomization might not produce a representative value, so this procedure is repeated many times to obtain a probability distribution, which reflects the likelihood of obtaining a given negative/positive area if the null hypothesis is true (i.e., if there is no true difference between the contralateral and ipsilateral sites).

Because this is a nonparametric test, it can be performed by measuring the negative/positive area of the N2pc/Pd difference waveform from grand averages across participants (as in the well-validated jack-knife technique, which improves statistical power without inflating Type I error rates;(Miller et al., 1998). We performed 1000 iterations in which we permuted the data and measured the positive area to provide a robust estimate of the distribution of negative/positive area values that would be expected if there was no reliable lateralized activity. We compared the observed positive area measured from the actual grand average ERP waveform to these randomly permuted values. The *p* value can then be estimated with the following equation: p = (number of permuted negative/positive areas $\geq$ observed negative/positive area) /total number of simulated permutations. For example, imagine that our null distribution of 1000 values contains 5 values that were greater than or equal to the observed positive area. The *p* value would be 5/1000 or .005. The observed negative/positive (indicated by red lines in the supplementary materials) were both statistically significant (in the top 5% of values that would be expected from chance: indicated by yellow areas in the supplementary materials). Thus, the

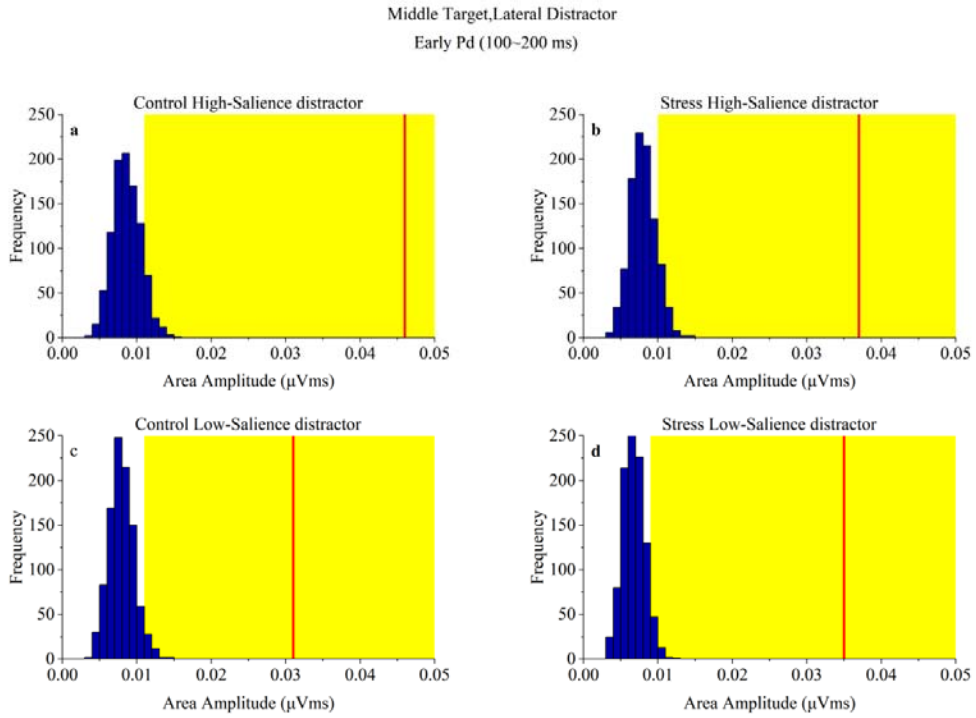
probability that the observed responses were due to random variation was very low, and we can be confident that these effects were real physiological responses.

1.1 Midline target/lateral distractor

Early Pd (100~200 ms):We tested whether the area of the Early Pd component was significantly greater than chance for each trial type by using a permutation test (as described in the above). Permutation tests showed that a significant Pd was present for stress group and control group at high-salience distractor and low-salience distractor(**see S.Figure 1**). However the Early Pd area did not significantly differ between stress group and control group at high-salience distractor and low-salience distractor(**see S.Figure 2**).

S.Figure 1.

Permutation tests of the positive areas from 100 to 200 ms

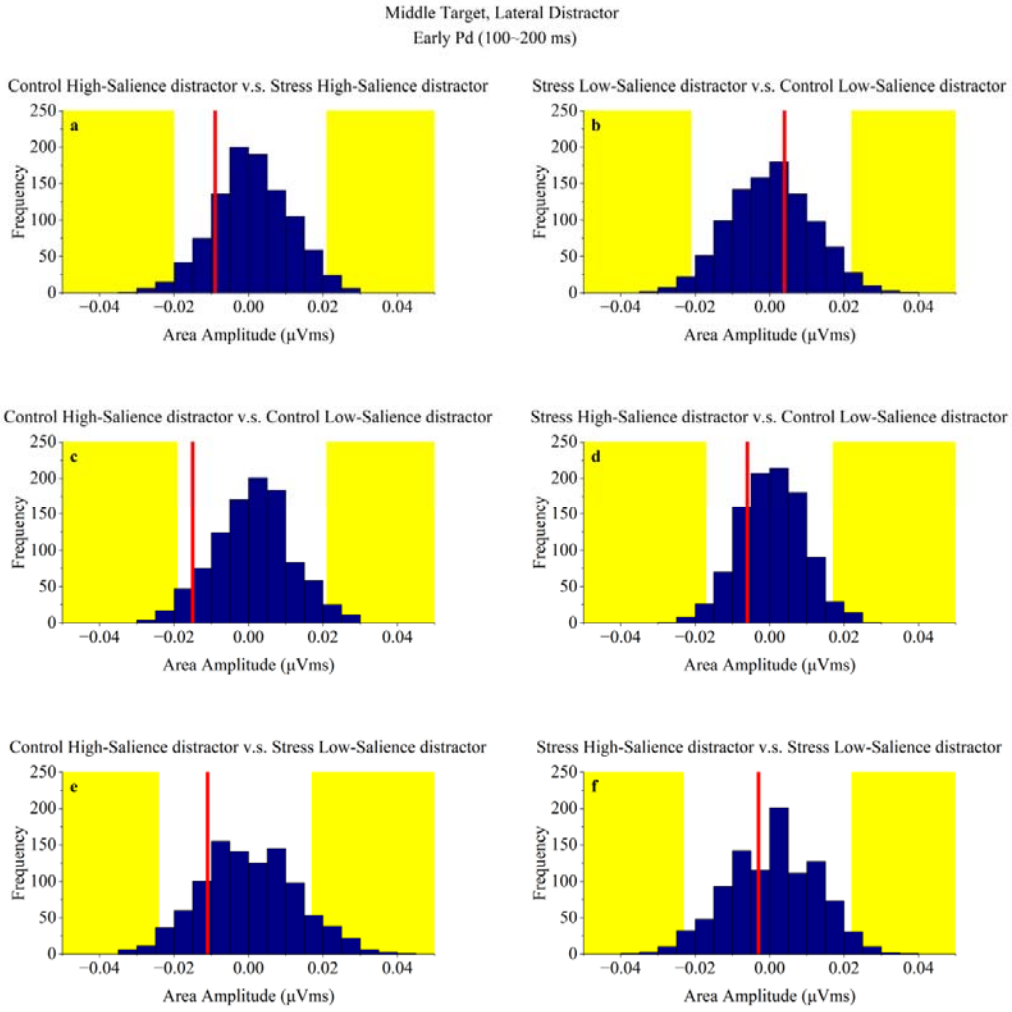


Note. The blue bars indicate the estimated null distribution from 1000 permutations. The red lines represent the observed values of the positive areas (early Pd) from the grand average waveforms. The yellow areas indicate the top 5% of the permutation distribution. Because the red lines fall

within the yellow regions the observed values are significantly greater than would be expected by chance.

S.Figure 2.

Permutation tests of the difference of positive areas from 100 to 200 ms in between stress group and control group at high-salience distractor and low-salience distractor

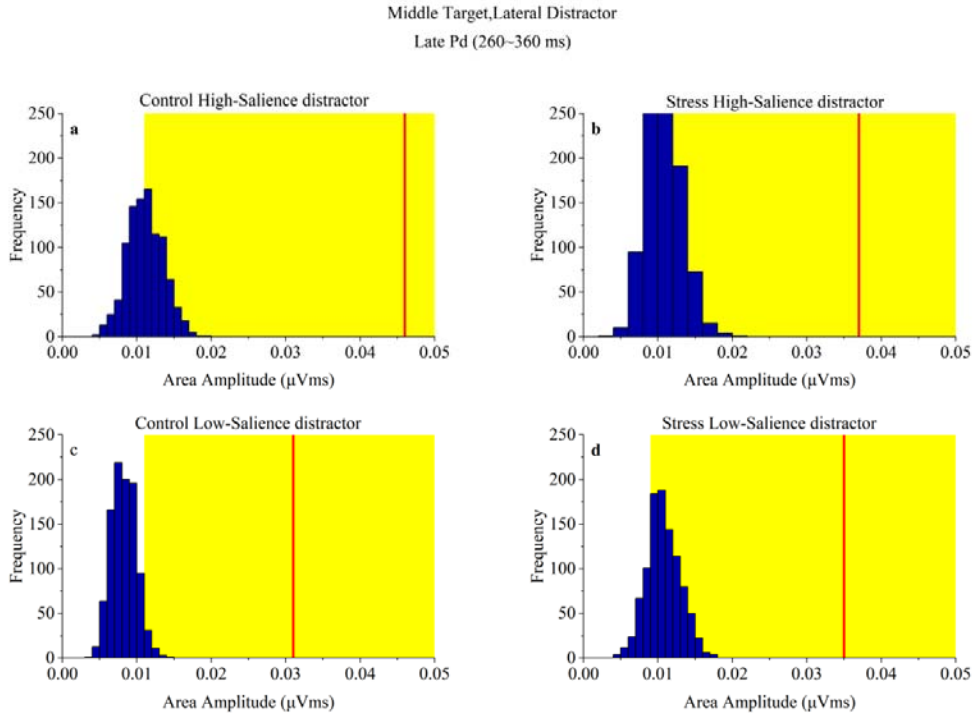


Note. The blue bars indicate the estimated null distribution from 1000 permutations. The red lines represent the observed values of the difference of positive areas (early Pd) from the grand average waveforms. The yellow areas indicate the top 2.5% of the permutation distribution. Because the red lines fall within the yellow regions, the observed values are significantly greater than would be expected by chance.

Late Pd (260~360 ms):We tested whether the area of the late Pd component was significantly greater than chance for each trial type by using a permutation test (as described in the above). Permutation tests showed that a significant Pd was present for stress group and control group at high-salience distractor and low-salience distractor **(see S.Figure 3)**. However the late Pd area did not significantly differ between stress group and control group at high-salience distractor and low-salience distractor (**see S.Figure 4**).

S.Figure 3

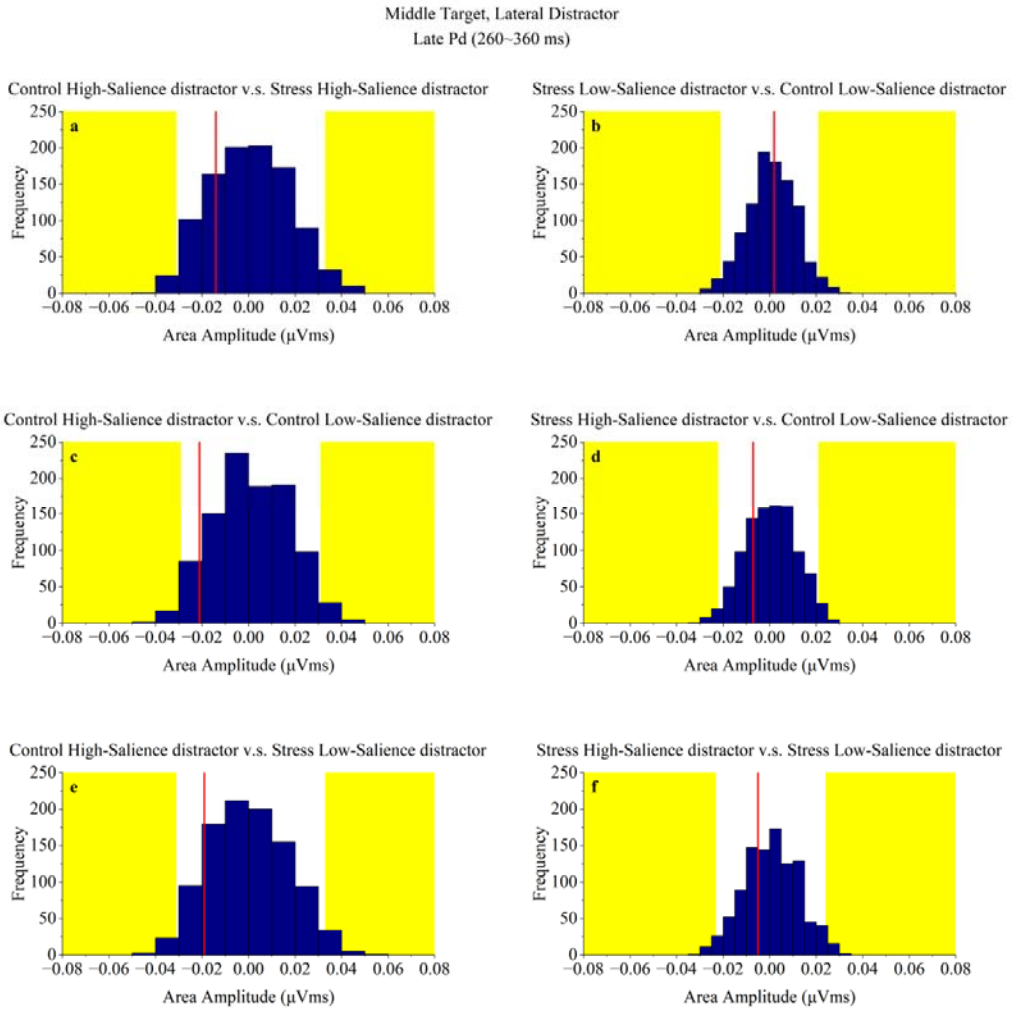
Permutation tests of the positive areas from 260 to 360 ms



Note. The blue bars indicate the estimated null distribution from 1000 permutations. The red lines represent the observed values of the positive areas (late Pd) from the grand average waveforms. The yellow areas indicate the top 5% of the permutation distribution. Because the red lines fall within the yellow regions the observed values are significantly greater than would be expected by chance.

S.Figure 4

Permutation tests of the difference of positive areas from 260 to 360 ms in between stress group and control group at high-salience distractor and low-salience distractor



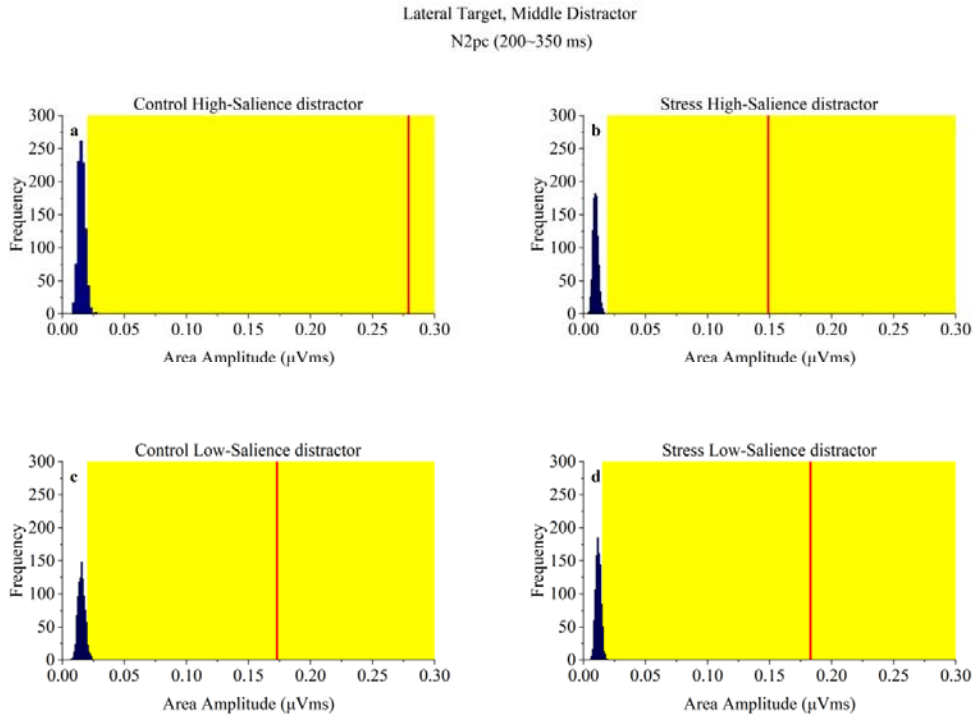
Note. The blue bars indicate the estimated null distribution from 1000 permutations. The red lines represent the observed values of the difference of positive areas (late Pd) from the grand average waveforms. The yellow areas indicate the top 2.5% of the permutation distribution. Because the red lines fall within the yellow regions, the observed values are significantly greater than would be expected by chance.

Lateral target/ middle distractor

N2pc (200~350 ms): We tested whether the area of the N2pc component was significantly greater than chance for each trial type by using a permutation test (as described in the above). Permutation tests showed that a significant N2pc was present for stress group and control group at high-salience distractor and low-salience distractor(**see S.Figure 5**), and N2pc area was significantly larger between stress and control group at high-salience distractor condition. However, the N2pc area did not significantly differ between others condition(**see S.Figure 6**).

S.Figure 5

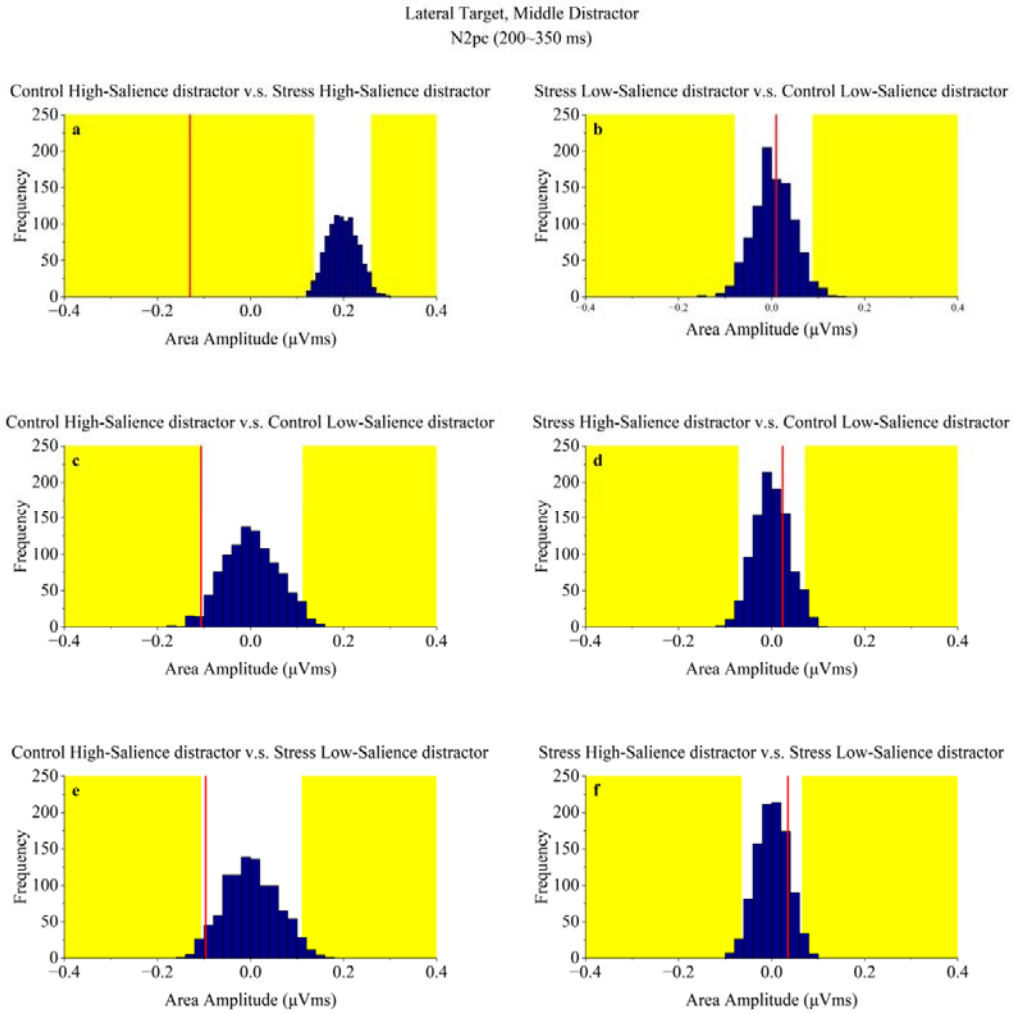
Permutation tests of the negative areas from 200 to 350 ms



Note. The blue bars indicate the estimated null distribution from 100 permutations. The red lines represent the observed values of the negative areas (N2pc) from the grand average waveforms. The yellow areas indicate the top 5% of the permutation distribution. Because the red lines fall within the yellow regions, the observed values are significantly greater than would be expected by chance.

S.Figure 6

Permutation tests of the difference of negative areas from 200 to 350 ms in between stress group and control group at high-salience distractor and low-salience distractor



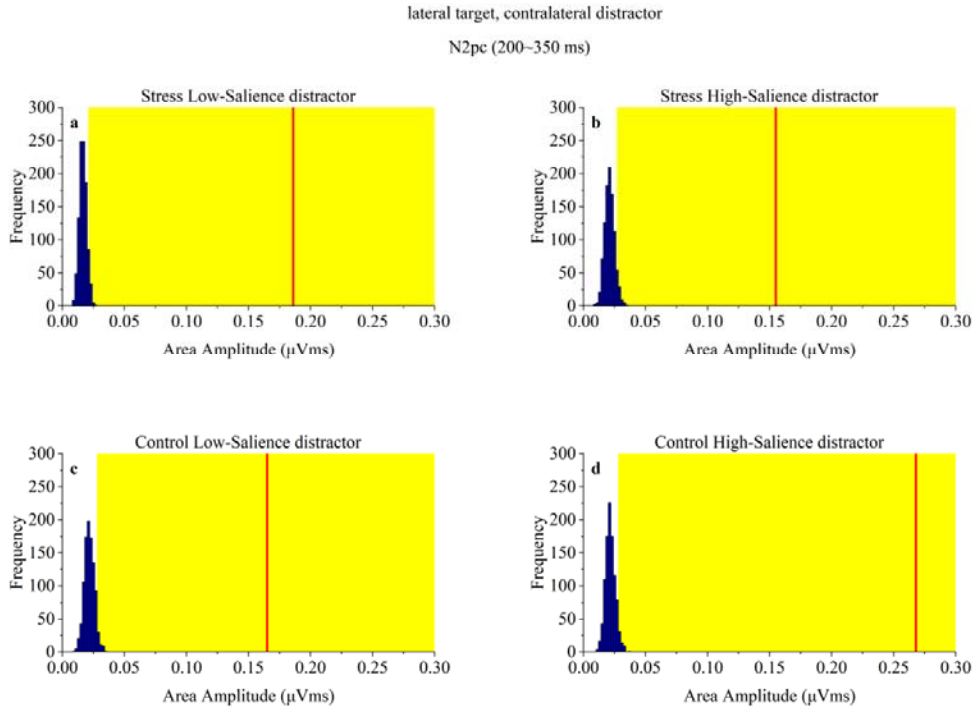
Note. The blue bars indicate the estimated null distribution from 1000 permutations. The red lines represent the observed values of the difference of negative areas (N2pc) from the grand average waveforms. The yellow areas indicate the top 2.5% of the permutation distribution. Because the red lines fall within the yellow regions, the observed values are significantly greater than would be expected by chance.

Lateral target/ contralateral distractor

N2pc (200~350 ms): We tested whether the area of the N2pc component was significantly greater than chance for each trial type by using a permutation test (as described in the above). Permutation tests showed that a significant N2pc was present for stress group and control group at high-salience distractor and low-salience distractor (**see S.Figure 7**), and N2pc area was significantly larger between stress and control group at high-salience distractor condition. However, the N2pc area did not significantly differ between others condition (**see S.Figure 8**).

S.Figure 7

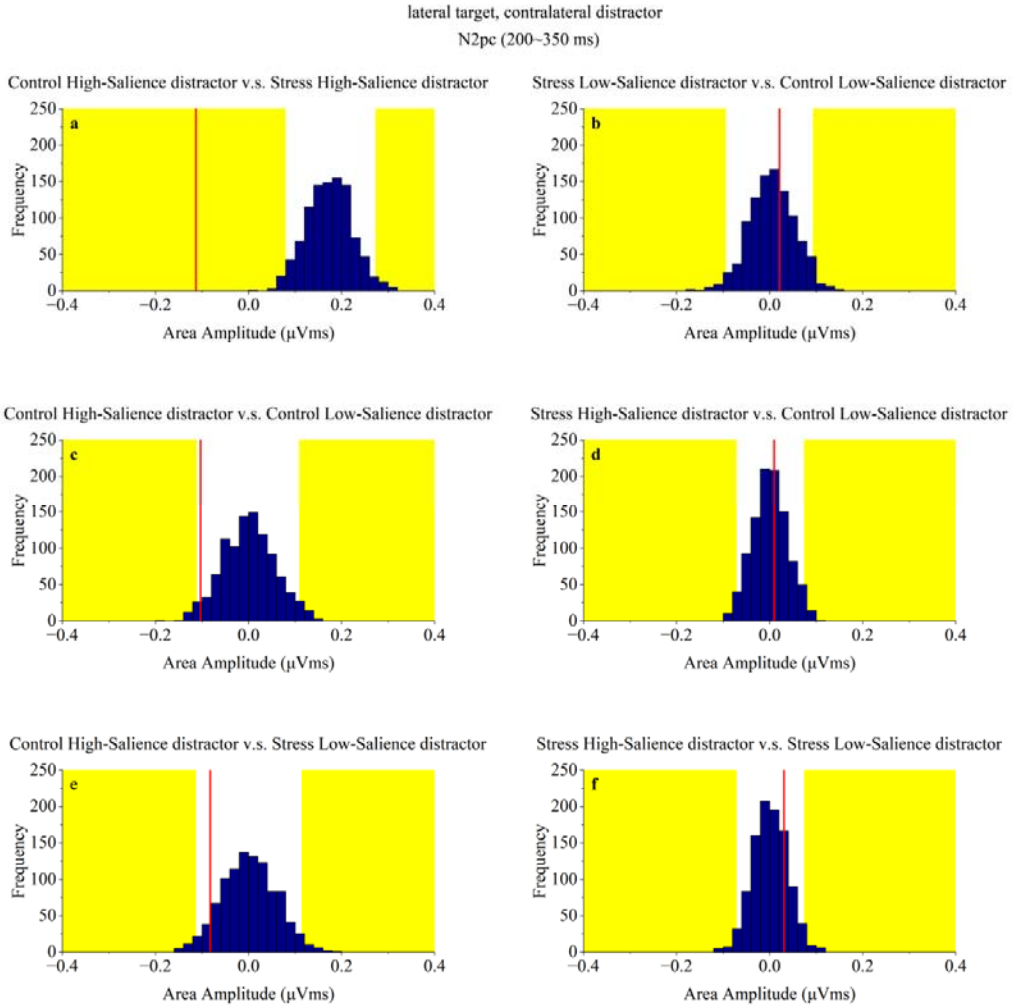
Permutation tests of the negative areas from 200 to 350 ms.



Note. The blue bars indicate the estimated null distribution from 1000 permutations**.** The red lines represent the observed values of the negative and positive areas (N2pc) from the grand average waveforms. The yellow areas indicate the top 5% of the permutation distribution. Because the red lines fall within the yellow regions, the observed values are significantly greater than would be expected by chance.

S.Figure 8

Permutation tests of the difference of negative areas from 200 to 350 ms in between stress group and control group at high-salience distractor and low-salience distractor



Note. The blue bars indicate the estimated null distribution from 1000 permutations. The red lines represent the observed values of the difference of negative areas (N2pc) from the grand average waveforms. The yellow areas indicate the top 2.5% of the permutation distribution. Because the red lines fall within the yellow regions, the observed values are significantly greater than would be expected by chance.

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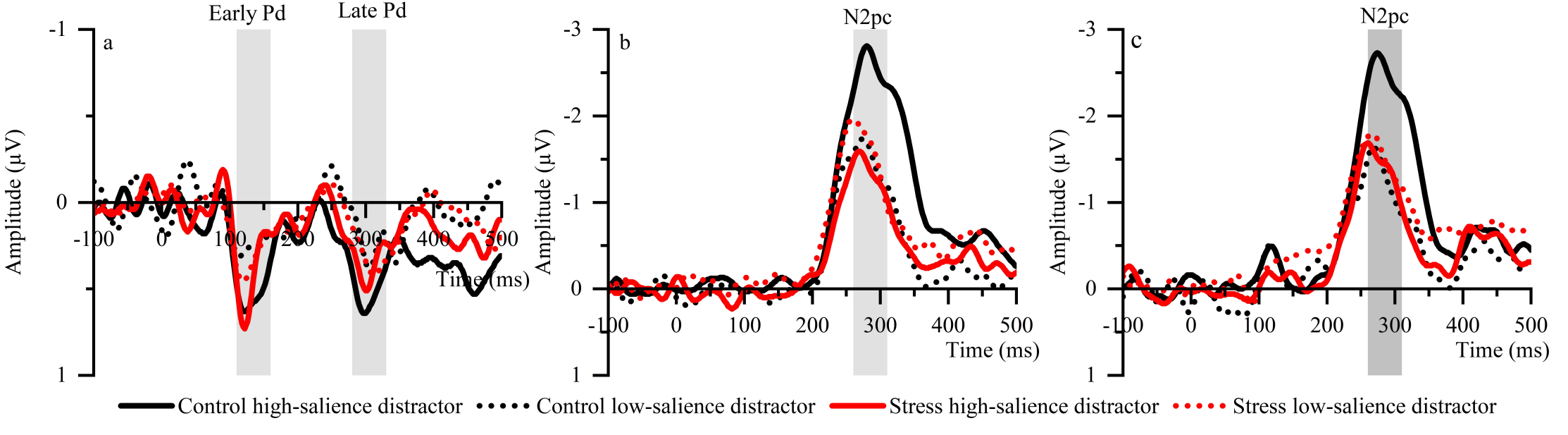
Early Pd
Late Pd
a
b
c
N2pc
N2pc
Amplitude (μV)
Time (ms)
-1
0
1
-3
-2
-100
0
100
200
300
400
500
Control high-salience distractor
Control low-salience distractor
Stress high-salience distractor
Stress low-salience distractor