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The effect of acute stress on spatial selectivity in dual-stream emotion induced blindness: The role of cortisol and spontaneous frontal EEG theta/beta ratio

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ABSTRACT

The current study explored the effect of acute stress on dual-stream emotion induced blindness (EIB). We focused on spatially localised target processing induced by stress, as well as the role of cortisol and the frontal EEG theta/beta ratio (TBR). Eight-minutes spontaneous EEG data were recorded first. After performing a Trier Social Stress Test (TSST) or a corresponding control task a week apart, the participants completed a dual-stream EIB task. Changes in cortisol levels over time were likewise recorded. We found that stress promoted the target processing in the same stream location as the distractor, eliminating the spatial-localisation effect. Cortisol and frontal TBR positively and negatively, respectively, predicted a reduced spatially localised target detection induced by stress following negative distractors. Overall, acute stress apparently reduced the dual-stream EIB due to the effective allocation of limited resources. Further, the role of cortisol associated with better target detection was more specific to the negative distractor condition and partially disassociated from the general stress response. Cortisol levels and frontal TBR independently predicted the spatially localised processing, suggesting differentiated influence paths of trait and state factors on target detection following emotional distractors.

1. Introduction

Acute stress response activates the sympathetic-adrenal-medullary (SAM) axis and the hypothalamus-pituitary-adrenal (HPA) axis to release catecholamine and cortisol; these can cross the blood-brain barrier and act on the limbic system and prefrontal cortex, which are rich in stress hormone receptors. This broadly affects emotional information processing and attentional resource allocation (Allen et al., 2014). Emotional stimuli that appear as distractors in rapid serial visual presentation paradigms exacerbate the functional blindness caused by insufficient resource allocation, resulting in unconscious ignorance of a target presented shortly afterward. This is known as emotion-induced blindness (EIB) (Most et al., 2005; Wang et al., 2012). EIB occurs in the temporal dimension, but it is also influenced by the spatial stream location. However, research regarding how EIB that involves spatial location changes when under acute stress has not been conducted.

The role of spatial selectivity in EIB can be investigated by using the dual-stream rapid serial visual presentation paradigm. Specifically, the dual-stream EIB consists of two rapid serial visual presentation streams. They allow the emotional distractor and target to appear in either the same or opposite streams. Individuals exhibit more severe EIB when the target appears in the same stream as the distractor (Kennedy et al., 2018; Most and Wang, 2011; Wang and Most, 2017), which is known as the spatial-localisation effect. An early-neural competition model posits that stimuli appeared in the same stream location for a short period of time are required to compete with each other for a shared visual receptive field, which then results in an impaired target detection in the same stream location (Desimone and Duncan, 1995; Keysers and Perrett, 2002). From this perspective, target processing at an opposite stream location will be less affected. Proud et al. (2020) found that the spatial-localisation effect only appears under the negative distractor condition in people with high trait anxiety. The findings further supported the vigilance avoidance account. Specifically, people with high trait anxiety exhibit vigilance avoidance to a negative distractor and can quickly shift

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their attention to a target in the opposite stream; thus, they demonstrate better performance in the opposite-stream condition (Proud et al., 2020).

Existing studies on the effect of acute stress on functional blindness have all focused on attentional blink (Kan et al., 2019; Kan et al., 2021; Momin et al., 2020; Schwabe and Wolf, 2010), which is a blindness phenomenon induced by the trade-off of attentional resources between two targets in single-stream rapid serial visual presentation paradigm (Raymond et al., 1992). Specifically, Schwabe and Wolf (2010) found that stress generally reduced the attentional blink effect, regardless of whether the two targets were neutral or emotionally arousing, nor did the stimulus onset asynchrony between the two targets. Kan et al. (2019) indicated that stress promoted target processing in the context of insufficient attentional resources, which is mainly reflected in the effective allocation of limited resources during cortisol-dominated periods. As in the prior study, this facilitating effect remained unaffected by the emotionality of the target. In a subsequent study, Kan et al. (2021) suggested that stress alleviated the emotional attentional blink effect by enhancing the selective attention process of the target. Momin et al. (2020) also found that acute stress reduced the blindness in a non-emotional letter attentional blink task. Overall, acute stress can reduce the attentional blink, which is less affected by the emotionality of stimuli, and more related to the allocation of attentional resources.

Although previous studies have agreed that stress can reduce attentional blink, there is still a gap regarding the influence of stress on EIB. The emotional stimulus is presented as a distractor in EIB, which represents task-irrelevant information and involves the bottom-up attention process (Corbetta and Shulman, 2002). Based on the perceptual load theory (Lavie, 1995, 2005), acute stress can further consume attentional resources and increase attention focus (Sato et al., 2012; Tiferet-dweck et al., 2016), thereby reducing the allocation of resources to distractors and promoting target processing (Booth, 2019; Chajut and Algom, 2003; Hoskin et al., 2014). However, the emotional stimulus in the emotional attentional blink task is a target to be identified. Participants need to actively motivate endogenous attention, namely the top-down attention process, to perform the task (Knudsen, 2007; Womelsdorf and Everling, 2015). The core reason why individuals with trait anxiety show different attention patterns in emotional attentional blink and EIB is emotional task relevancy, namely whether the emotional information involves the top-down attention process (Chen et al., 2020). Therefore, according to the differences between emotional attentional blink and EIB, the role of attentional control may be important to explore the effect of stress on dual-stream EIB.

When considering the dual-stream EIB under acute stress, the role of attention detection in the spatial dimension should not be ignored. Acute stress-released cortisol has been found to be associated with an increase in negative cognitive bias, which is inseparable from the binding of cortisol to glucocorticoid receptors in the ventral neural network responsible for reorienting attention (Hermans et al., 2011; Kreher et al., 2012; McEwen and Gianaros, 2010). Although acute stress could enhance attentional bias to threatening stimuli (e.g., Macatee et al., 2017; Nelson et al., 2015; Rued et al., 2019), the underlying mechanisms of attentional bias are inconsistent and are unexplored in the rapid serial visual presentation. Proud et al. (2020) explained the spatial-localisation effect in dual-stream EIB by vigilance avoidance, which is a kind of cognitive processing characteristic shown in people with high trait anxiety. Vigilance avoidance involves rapid attentional orientation to threatening stimuli and then rapid avoidance (Mogg et al., 2004). As it regulates arousal, this attentional avoidance mechanism predicts reduced cortisol reactivity in people with high trait anxiety (Applehans and Luecken, 2007). People with high trait anxiety have an impaired attentional control ability, which manifests as enhanced bottom-up and weakened top-down attention (Bishop, 2009; Eysenck and Derakshan, 2011; Eysenck et al., 2007). Attentional control is also a key factor that affects the interference effect of the emotional distractor (Peers and Lawrence, 2009). Specifically, individuals with high trait attention control are able to represent the target more refined, and thus the target processing is less affected by the distractor (Martens et al., 2006). The frontal EEG theta/beta ratio (TBR) is suggested to represent the cortical-subcortical interaction between bottom-up and top-down attention systems and has been considered an objective and reliable index to reflect the trait attentional control, a key function of executive control (e.g., Angelidis et al., 2018; Putman et al., 2010, 2014). Previous studies have confirmed that low frontal TBR is associated with better goal-directed attentional control (Angelidis et al., 2016, 2018; Putman et al., 2014). Therefore, we focused on the frontal TBR and aimed to provide a comprehensive understanding from the perspective of cortisol levels and trait factors.

The present study concentrated on the effect of acute stress on the dual-stream EIB, and further explored whether individuals with differential frontal TBR interact with the changes in cortisol levels to influence the spatial selectivity in dual-stream EIB. We hypothesized that acute stress would reduce the spatial-localisation effect in dual-stream EIB by increasing target processing at the same stream location. The cortisol would be more sensitive to better target detection following negative distractors. The low frontal TBR, representing the high attentional control ability, would be associated with a better dual-stream EIB performance, which may be specific to the negative distractor condition.

2. Method

2.1. Participants and design

The State-Trait Anxiety Inventory (STAI) (Shek, 1993; Spielberger, 1983) and Beck Depression Inventory-II (BDI-II) (Beck et al., 1996) were used to screen participants two weeks before the initial study to exclude the known effects of trait anxiety and depression on cortisol release in acute stress response (Booij et al., 2015; Vreeburg et al., 2010). Specifically, participants with a Trait Anxiety Inventory score from 35 to 50 and with a BDI-II score below 14 were included. Moreover, participants with a body mass index (BMI) between 18 kg/m^2 and 27 kg/m^2, no history of heart disease or hypertension, and no hormonal drug use and who were not in the acute disease stage were further included in the experiment. A total of 119 questionnaires were distributed to students of Shaanxi Normal University through the online platform, and 72 subjects who met the criteria were recruited to participate in the experiment.[1] They also filled out a Perceived Stress Scale (PSS-10, Cohen et al., 1983) to assess their subjective stress experience over the last month. Participants were all right-handed and had normal vision or corrected vision. They were also instructed not to take any medicine during the last week prior to the experiment and not to drink, eat, or engage in strenuous exercise within 3 h of the experiment. Females participants were required to complete the formal experiment during non-menstrual

[1] The selection of sample size was mainly based on the following considerations. We first conducted a priori power analysis for a 2 (condition: acute stress, control) × 2 (distractor emotion type: negative, neutral) × 2 (target stream location: same to the distractor, opposite to the distractor) within-subjects, repeated measures analysis of variance (ANOVA) with a medium expected effect size of 0.25(f) and 95 % statistical power using G*Power 3.1 (Faul et al., 2007), which suggested a minimum sample size of 23 participants. Although regression analysis was the secondary analysis, it is also important to clarify the role of frontal TBR and cortisol in the changes of dual-stream EIB performance induced by stress. Therefore, we also considered the sample size required for regression analysis in the initial recruitment of participants, that is, a minimum sample size of 55 participants was required to achieve a medium effect size ($f^2 = 0.15$) and 80 % statistical power. The large sample size may result in repeated measures ANOVA that, while statistically significant, is of no practical significance. However, the results of repeated measures ANOVA showed that the minimum effect size (η_p^2) of significant conditions was 0.061, thus reaching the level of medium effect size (Cohen, 1988). Therefore, the sample size of this study is reasonable and acceptable.

periods.

The study adopted a within-participant design, and all participants were required to complete two experiments at an interval of one week. They were randomly assigned to experience either acute stress or control manipulation in both experiments. The two parallel versions of the dual-stream EIB task were also balanced between the two experiments, that is, the subjects randomly completed one version of the EIB task in the first experiment and the other version in the second experiment. Data from a total of sixty-six participants were included in the analysis because four participants failed to complete the second experiment on time and two participants had problems with the saliva sample collection. The sample characteristics are depicted in Table 1.

The study conformed to the principles of the Declaration of Helsinki (World Medical Association (WMA), 2013) and was approved by the Academic Committee of the School of Psychology, Shaanxi Normal University in China.

2.2. Acute stress induction and related measurements

The Trier Social Stress Test (TSST) was used to induce an acute stress response (Kirschbaum et al., 1993) and consisted of 5 min each of public speaking and mental arithmetic. Before starting, the experimenter first introduced the rules of public speaking to the participants and let them prepare for 5 min. During the public speaking, participants were required to stand up and speak to two interviewers in white lab coats about their competitive advantage for the job. Then they need to perform a mental arithmetic task quickly and accurately, subtracting 17 from 2023 to zero. If they made a mistake, the interviewer would remind them to start from the beginning. The whole task was recorded by a camera, and the interviewers kept indifferent and did not make any additional verbal and non-verbal evaluation. For the TSST-control task, all the stressors (camera and interviewers) were removed (Kudielka et al., 2007). The participants were asked to spend 5 min speaking about a movie, a novel, or a recent holiday trip. After that, the participants performed a simple addition task, adding up 15 starting at 0 (Het et al., 2009).

We used the Positive and Negative Affect Scale (PANAS) (Watson et al., 1988) to assess the participants' subjective emotional responses to stress. The PANAS contains two ten-item self-report scales, one for negative affect and the other for positive affect. Each item was scored using a five-point scale. Higher scores demonstrated stronger emotional responses. We collected subjective emotional data on PANAS before, and at 15 min and 35 min after TSST/TSST-control task onset.

The saliva samples were also collected by salivette collection devices (salivette, Sarstedtstr.1 D-51588. Germany) for the cortisol analysis to evaluate the hypothalamus-pituitary-adrenal axis activation. The gathered saliva kept in −20 °C freezer. The centrifugal fluid from saliva samples was used for cortisol data analysis by Enzyme-Linked Immuno Sorbent Assay (Zhuocai, China). Saliva samples were collected before, and at 15 min and 35 min after TSST/TSST-control task onset.

Table 1
Descriptive sample characteristics.

	Complete sample (n = 66)
Age	20.35 (1.73)
Gender	28 / 38
(male/female:n, %)	42.42 % / 57.58 %
BMI	21.53 (2.57)
Trait anxiety scores	42.26 (4.57)
Depression scores	3.29 (3.98)
Frontal TBR	6.94 (3.09)

Note: The table report Mean (SD in parentheses) of age, BMI, trait anxiety score, and depression score for the complete sample, as well as the number and proportion of male and female subjects. BMI = body mass index. Frontal TBR = frontal theta/beta ratio.

2.3. Dual-stream EIB

Two parallel versions of the dual-stream EIB task, with only different image materials, were used in this experiment. The selection of image materials and stimulus parameters refer to the previous studies (Proud et al., 2020; Wang and Most, 2017). The distractor images involve negative and neutral images of people and animals were selected from International Affective Picture System (IAPS) (Lang et al., 2008). The target and filer images were consist of landscape and architecture images, in which the target images were rotated 90° to both the left or the right, and the filer images were presented upright. Due to the large demand for image materials, we also sourced from the internet (e.g., copyright-free website, https://pixabay.com/). This resulted a total of 100 negative distractor images, 100 neutral distractor images, and 150 rotated target images. There were also 800 filer images that are randomly called during programming.

An additional 20 participants (15 females; mean age = 20.68 years, SD = 1.55, range: 18–22) were recruited to re-evaluated the images during rapid serial visual presentation paradigm in 9-point scale. We first rated the pleasure and arousal of negative and neutral images respectively. The independent sample t-test results shown that the pleasure score of negative distractors (M = 3.311, SD = 0.446) was significantly lower than that of neutral distractors (M = 6.356, SD = 0.711), t (198) = −36.100, p < 0.001. The arousal score of negative distractors (M = 8.003, SD = 0.411) was significantly higher than that of neutral distractors (M = 2.734, SD = 0.752), t (198) = 61.157, p < 0.001. The target images were rated for accuracy without the interference of distractors in rapid serial visual presentation to ensure that the impaired target processing was not affected by the judgment of the image itself in the formal experiment. The accuracy between landscape images (M = 0.985, SD = 0.035) and the architectural images (M = 0.988, SD = 0.029) was not significant, t (298) = −0.706, p = 0.480. Participants have no difficulty to determine the orientation of the target.

Participants were seated 70 cm away from a 24-in. monitor with a refresh rate of 100 Hz in an electromagnetically shielded room. The experimental procedure was presented via E-prime 3.0. Each trial starts with a 1000 ms fixation, the two simultaneous streams of images positioned centrally above and below the position of the fixation and separated from each other by 2°. Each stream consists of 14 images, thus 28 images in total, including one distractor, one target and 26 filer images. The distractor randomly appeared at the second, fourth, sixth, eighth position, and the target always appeared in the second position (lag2) after the distractor, because lag2 has been supposed to be a reliable blindness position for EIB (Most et al., 2005). Both the distractor and target appeared equally in either the upper or lower stream location. At the end of each trial, participants were required to judge the orientation of target by pressing the left arrow or the right arrow key on the keyboard. This resulted a total of 240 trials for the experiment. Each block consists of 60 trails. Participants took a fixed rest of 90s between each block in order to ensure the basic consistency of saliva sample collection time points. We also gave a 12-trial practice experiment to familiarize the participants with the task procedure. The illustration of a sample trial is depicted in Fig. 1.

2.4. EEG recording and analysis

EEG was acquired from 64 Ag/AgCl scalp-electrodes base on the international 10–20 system using a SynAmps2 amplifier (Neuroscan, Herndon, VA, USA). Left mastoid served as the online reference and ground electrode was placed on the medial frontal region. Vertical electro-oculograms was positioned on the supra and suborbital ridge of the left eye and horizontal electro-oculograms was positioned on the external canthi of each eye. Scalp EEG electrode impedances were maintained below 5 kΩ in the whole process of the spontaneous EEG activity collection.

Offline signal processing and analysis was done with EEGLAB

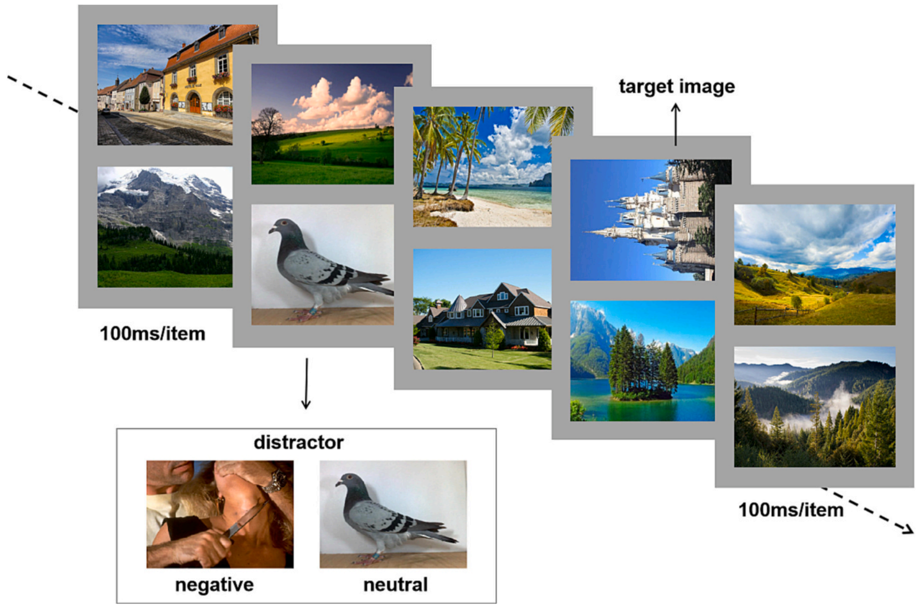

Fig. 1. Illustration of a partial trial in experiment.

toolbox loaded in MATLAB (Delorme and Makeig, 2004). The sampling rate was 1000 Hz, resampled to 500 Hz, and re-referenced offline to the average of the left and right mastoids. Independent component analysis was performed to correct the interference associated with eye movements and eye-blink activity. Scalp signal was filtered with 0.1–100 Hz band-pass. Segments containing residual muscle movements or other forms of artifacts exceeding ±100 μV at any electrode were rejected automatically prior to further analysis.

A total of 8 min of spontaneous EEG were recorded (60 s with eyes opened and 60s with eyes closed alternately) following the same method as Angelidis et al. (2018) and Putman et al. (2010). The periods of eyes opened and eyes closed were superimposed for EEG power analysis. A Welch method fast Fourier transformation (FFT) with 10 % Hamming window length was used to calculate the spectral power density (μV^2/Hz) for the frontal brain region in the theta (4–7 Hz) and beta (13–30 Hz) frequency bands. According to the previous studies, the research questions (attentional control ability) in the present experiment concerned the frontal brain regions (e.g., Angelidis et al., 2016, 2018; Morillas-Romero et al., 2015). The power density of the frontal brain region is obtained through the average of the three frontal electrodes (F3, Fz, F4). Frontal TBR is calculated by dividing the power densities of theta by beta (cf. Angelidis et al., 2016, 2018; Putman et al., 2014). Frontal TBR values were natural log-normalization (Ln) because of the typical skewed distributions.

2.5. General procedure

The participants were asked to complete the two sessions seven days apart. All the experiments were conducted between 14:00 and 18:00 to control the influence of diurnal rhythm of cortisol (Izawa et al., 2010). The participants first read and signed the informed consent, and performed a practice experiment. The experimenter carried out an EEG preparation and then acquired spontaneous EEG data. The spontaneous EEG data were collected only during each participant's first experiment. Participants rested for 10 min, after which their first saliva sample (sC1) and PANAS (P1) were collected. For the first experiment, the participants were randomly assigned to the stress or control condition. In the second experiment, seven days later, they were required to perform another state-intervention task. After the second saliva sample (sC2) and PANAS (P2) were completed, they performed a dual-stream EIB task. The third saliva sample (sC3) and PANAS (P3) were taken and the experiment was concluded. The overall experimental procedure is depicted in Fig. 2.

2.6. Statistical analyses

2.6.1. Repeated measures ANOVA

Statistical analysis was performed in SPSS statistics 21. The repeated measures ANOVA were conducted on salivary cortisol levels, subjective emotional responses, and dual-stream EIB performance, respectively. When the sphericity hypothesis was rejected, Greenhouse-Geisser was applied to correct the degrees of freedom of the *F*-distribution, and Bonferroni was used to correct the pairwise comparisons between conditions in all three repeated-measures ANOVA. The Partial-eta^2 ($\eta 2_p$) was reported as a measure of effect size for F statistics.

2.6.2. Pearson correlation analysis

Pearson correlation analysis was first performed to investigate the relationship of the spatially localised target processing under acute stress with cortisol level, frontal TBR and perceived stress level. We performed FDR correction for *p*-values by running a script in Matlab 2020b to control the false positive rate generated by multiple comparisons of each variable.

The change in cortisol concentration was calculated by the area under the curve with respect to ground (AUCg) under stress and control condition, respectively. The AUC_g was defined below (Pruessner et al., 2003).

$$AUC_g = \sum_{i=1}^{n-1} \frac{\left(m_{(i+1)} + m_i\right) \cdot t_i}{2}$$

In the formula above, m_i represent the salivary cortisol concentration in one measurement, t_i the time distance between measurements, and n the total amount of measures. Stress-induced changes in cortisol reactivity ($\Delta AUC_{g\text{-cortisol}}$) were obtained by subtracting the AUC_g under control condition from the AUC_g under stress condition.

Spatially localised performance changes were calculated first by subtracting the accuracy in the opposite stream from the same stream conditions (same stream minus opposite stream). Then, the role of acute stress, namely the spatially localised performance changes induced by acute stress, was calculated by subtracting the spatially localised performance changes under control condition from that under stress

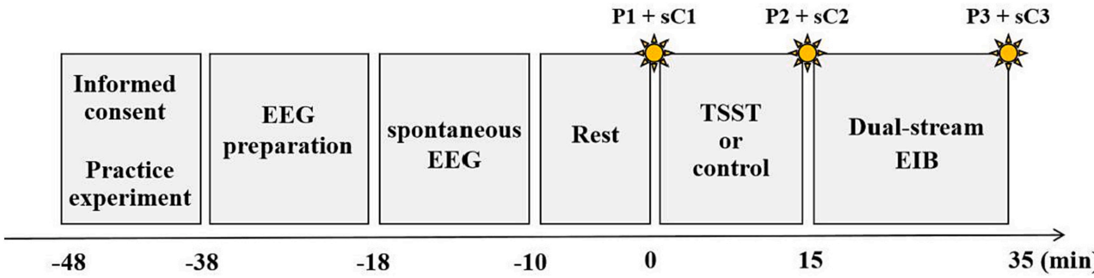

Fig. 2. Schematic illustration of the overall experimental procedure. Spontaneous EEG was collected only when participants came to the laboratory for the first experiment.

condition (stress condition minus control condition). All these above performances were calculated separately for the negative distractor and neutral distractor conditions. Larger values indicate greater accuracy for the same-stream condition and a reduced spatial-localisation effect.

2.6.3. Regression analysis

A regression analysis was also performed to examine the main and interactive effects of $\Delta AUC_{g\text{-}cortisol}$ level and frontal TBR on stress-induced spatially localised performance changes ($\Delta ACC_{negative}$ and $\Delta ACC_{neutral}$) in dual-stream EIB. All of the indicators above were standardized prior to correlation and regression analysis.

3. Results

3.1. Manipulation check

We examined the effectiveness of stress induction from the perspective of physiological and subjective emotional responses. Specifically, a 2 (intervention condition: TSST, control condition) × 3 (time: baseline, 15, 35 min in relation to TSST onset) repeated measures ANOVA was conducted on salivary cortisol, and a 2 (intervention condition: TSST, control) × 3 (time: baseline, 15, 35 min in relation to TSST onset) repeated measures ANOVA was performed on subjective emotional responses measured by PANAS.

3.1.1. Salivary cortisol

The main effect of intervention condition was significant, $F(1, 65) = 129.627$, $p < 0.001$, $\eta_p^2 = 0.666$. Participants who performed the TSST had significantly higher cortisol concentrations than those who performed the control task. The main effect of time was significant, $F(2,130) = 109.225$, $p < 0.001$, $\eta_p^2 = 0.627$. The interaction between intervention condition and time was significant, $F(2, 130) = 64.095$, $p < 0.001$, $\eta_p^2 = 0.496$. The further simple effect analysis showed that the baseline concentrations of cortisol did not differ significantly between the TSST and control condition ($p = 0.831$). For the other time points, the cortisol level induced by the TSST was significantly higher than the cortisol level induced by the TSST-control task ($ps < 0.001$). There were significant differences in cortisol concentration under stress at each time point; however, for the control condition, the changes in cortisol concentration over time were not significant from the baseline to the end of the dual-stream EIB task. The results above demonstrated the effectiveness of acute stress induction. The cortisol levels over time are depicted in Fig. 3.

3.1.2. Subjective emotional response

For the negative affect, there was a significant interaction between intervention condition and time, $F(2, 130) = 23.160$, $p < 0.001$, $\eta_p^2 = 0.263$. Specifically, the negative affect at 15 min after TSST onset was significantly higher than the negative affect after the TSST-control condition ($p < 0.001$), and there were no significant differences at other time points. During the TSST condition, we found that negative affect was significantly higher at 15 min than at baseline and 35 min after TSST onset ($p < 0.001$). During the control condition, there were no significant differences in negative affect at different time points. Furthermore, the main effect of intervention condition was significant, $F(1, 65) = 6.926$, $p = 0.011$, $\eta_p^2 = 0.096$. The negative affect induced by the TSST condition was significantly higher than that induced by the TSST-control condition. The main effect of time was also significant, $F(2, 130) = 18.732$, $p < 0.001$, $\eta_p^2 = 0.224$.

For the positive affect, the interaction between intervention condition and time was significant, $F(2, 130) = 5.168$, $p = 0.007$, $\eta_p^2 = 0.074$. Simple effect analysis showed that positive affect induced by TSST lower than those induced by the TSST-control task ($p < 0.001$, $p = 0.001$), except for the baseline positive affect value ($p = 0.746$). Under the TSST condition, baseline positive affect was significantly higher than the positive affect at 15 min and 35 min after TSST onset (both $ps < 0.001$); however, there were no significant differences between positive affect at 15 min and 35 min after TSST onset ($p = 0.532$). During the control condition, there was no significant difference in positive affect between each time point. The main effect of intervention condition were significant, $F(1, 65) = 14.877$, $p < 0.001$, $\eta_p^2 = 0.200$. The positive affect in the TSST condition was significantly lower than that at the control

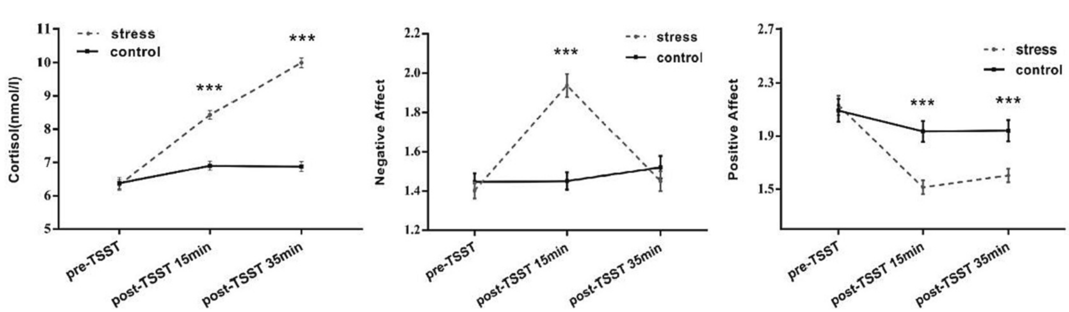

Fig. 3. (1) Left. Cortisol level for the stress and control condition varied with time. (2) Middle and Right. Negative affect and positive affect score for the stress and control condition varied with time. “pre-TSST”, “post-TSST 15 min”, “post-TSST 35 min” stand for baseline, 15, 35 min in relation to TSST onset, respectively. The asterisks represent the difference between the stress and control intervention conditions. Bars represent standard errors of mean.

condition. The main effect of time was also significant, F (2, 130) = 19.793, $p < 0.001$, $\eta_p^2 = 0.233$. Subjective emotional responses over time are depicted in Fig. 3. In general, the TSST results demonstrate a significant increase in negative affect and a significant decrease in positive affect. From the perspective of a subjective emotional response, the acute stress induction in the current experiment is effective.

3.2. Dual-stream EIB performance

A repeated-measures ANOVA was performed on intervention condition (2; TSST, control), distractor emotion type (2; negative, neutral) and target stream location (2; same to the distractor, opposite to the distractor) as within-subjects factors. The main effects of all three variables were significant. Specifically, the main effect of intervention condition was significant, $F(1, 65) = 6.812$, $p = 0.011$, $\eta_p^2 = 0.095$. The target accuracy under TSST was higher than that under control condition. The main effect of distractor emotion type was significant, $F(1, 65) = 26.244$, $p < 0.001$, $\eta_p^2 = 0.288$. The results accord with the classic EIB effect; namely, the target that followed the neutral distractor had significantly higher accuracy than the one that followed the negative distractor. The main effect of target stream location also significant, $F(1, 65) = 11.445$, $p = 0.001$, $\eta_p^2 = 0.150$. The accuracy of the target in the opposite stream was significantly higher than that in the same stream, which supported the obvious spatial-localisation effect.

The interaction between intervention condition and target stream location was significant, F (1, 65) = 4.228, $p = 0.044$, $\eta_p^2 = 0.061$. Further simple effect analysis revealed that acute stress significantly improves the accuracy of targets in the same stream location ($p = 0.01$); this explained the lack of significant differences in target accuracy between the same- and opposite stream was not significant ($p = 0.353$). The significant spatially localised target processing appeared under the control condition ($p = 0.01$). In general, acute stress reduced the spatial-localisation effect by promoting target processing in the same stream location. The descriptive statistics results and the intuitive trends are depicted in Table 2 and Fig. 4.

3.3. Control analysis

Control analysis was performed to exclude the effect of the experimental order and practice effect on the dual-stream EIB.

3.3.1. Order effects

Experimental order (stress-control vs. control-stress) was included in repeated-measures ANOVA as a between-subjects factor. The order in which participants completed the TSST and control task were balanced, that is, half of participants performed the TSST first, and the other half completed the TSST-control task first. Therefore, a total of 33 subjects were included in each experimental order.

The results revealed that the main effect of experimental order was not significant, F (1, 64) = 0.547, $p = 0.462$, $\eta_p^2 = 0.008$. The experimental order has no significant interaction with any other variables, $Fs < 1.923$, $ps > 0.170$, $\eta_p^2 s < 0.029$. These results indicated that the order in which subjects experienced stress and control condition did not affect the task performance.

Table 2
The targets accuracy at each condition (M ± SD).

	Negative distractor		Neutral distractor	
	Same stream location	Opposite stream location	Same stream location	Opposite stream location
Stress	0.750 ± 0.089	0.752 ± 0.081	0.778 ± 0.089	0.791 ± 0.073
Control	0.708 ± 0.081	0.740 ± 0.097	0.742 ± 0.081	0.777 ± 0.089

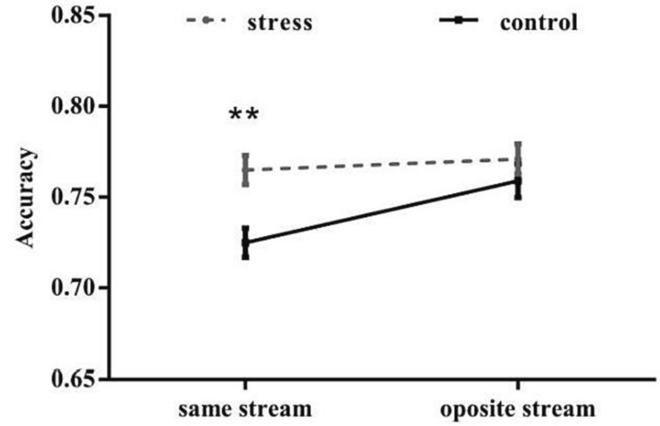

Fig. 4. The accuracy of targets in the same and opposite stream as the distractor under stress and control condition. Bars represent standard errors of mean.

3.3.2. Practice effects

Regardless of the condition, the session (the first dual-stream EIB task vs. the second dual-stream EIB task) was included in the analysis of repeated-measures ANOVA as a within-subjects factor. The results showed that the main effect of session was not significant, F (1, 65) = 0.039, $p = 0.845$, $\eta_p^2 = 0.001$. The session have no significant interaction with any other variables, $Fs < 1.949$, $ps > 0.167$, $\eta_p^2 s < 0.029$. These results rule out the existence of general practice effects between the two dual-stream EIB tasks.

3.4. Stress-induced spatially localised performance: relations with cortisol and frontal TBR

3.4.1. Pearson correlation analysis

We focused on the correlation between the release of cortisol in response to acute stress, frontal TBR, and the spatially localised accuracy changes induced by acute stress under the negative and neutral distractor conditions. Furthermore, perceived stress level was also included to control for potential confusion. Pearson correlations analysis results with 95 % bootstrapped CIs suggested that the changes in cortisol concentration and frontal TBR were positively ($r = 0.311$, 95 % CI [0.118, 0.499], $p = 0.022$) and negatively ($r = -0.264$, 95 % CI [−0.477, −0.041], $p = 0.043$) correlated with spatially localised target accuracy under negative distractor condition, respectively. There was no significant correlation between the perceived stress level and spatially localised performance in dual-stream EIB. The raw frontal TBR values of the three electrodes are depicted in Table 3. The results of the correlation analysis are depicted in Table 4 and Fig. 5.

3.4.2. Hierarchical regression analysis

According to the results of the above correlation analysis, we further explored whether individuals with high and low frontal TBR exhibiting

Table 3
The original mean power spectral density over frontal region when eyes were closed and open for Theta and Beta bands (μV^2/Hz), and frontal TBR (M ± SD).

	F3		Fz		F4	
	EO	EC	EO	EC	EO	EC
Theta	0.430 ± 0.234	0.447 ± 0.184	0.482 ± 0.302	0.509 ± 0.181	0.405 ± 0.206	0.421 ± 0.210
Beta	0.076 ± 0.051	0.071 ± 0.047	0.070 ± 0.028	0.070 ± 0.064	0.0695 ± 0.040	0.067 ± 0.037
Frontal TBR	6.176 ± 3.244	6.990 ± 4.025	7.301 ± 3.984	8.266 ± 3.016	6.465 ± 4.118	6.828 ± 4.374

Note: EO = eyes open; EC = eyes closed; Frontal TBR = frontal theta/beta ratio.

Table 4
Descriptive statistics and correlations of study variables.

Variables	1	2	3	4	5	M (SD)
1. Perceived stress level	1	−0.008	0.024	−0.109	0.001	19.85 (6.53)
2. $\Delta AUC_{g\text{-}cortisol}$		1	−0.055	0.311*	0.152	53.82 (30.52)
3. Frontal TBR			1	−0.264*	0.128	1.83 (0.46)
4. $\Delta ACC_{negative}$				1	0.454**	0.03 (0.13)
5. $\Delta ACC_{neutral}$					1	0.02 (0.12)

Note. *p < 0.05. **p < 0.01. P values were corrected for FDR.

different cortisol responses would predict the stress-induced EIB performance changes. Since perceived stress level had no correlation with dual-stream EIB performance, they were not included as control variables in the regression model. $\Delta AUC_{g\text{-}cortisol}$ level and frontal TBR were entered into the regression equation in the first step. Two-way interactions for $\Delta AUC_{g\text{-}cortisol}$ × frontal TBR were added in the second step. The results revealed that the $\Delta AUC_{g\text{-}cortisol}$ ($p = 0.013$) and frontal TBR ($p = 0.036$) significantly predict the spatially localised performance changes under negative distractors condition. The interactive prediction between $\Delta AUC_{g\text{-}cortisol}$ and frontal TBR ($p = 0.456$) was not significant (see Table 5). The results above suggested a different influence path of state and trait factors on stress-induced spatially localised performance changes.

4. Discussion

To the best of our knowledge, this study is the first to explore the influence of acute stress on spatial selectivity in dual-stream EIB. Cortisol levels and the frontal TBR were also analyzed to understand the underlying cognitive mechanisms. We found that acute stress eliminated the spatial-localisation effect in dual-stream EIB by promoting target detection in the same stream, regardless of the emotionality of the distractor. Cortisol and frontal TBR have a more targeted effect in stress-reduced dual-stream EIB, and they were able to positively and negatively, respectively, predict the spatially localised performance changes under the negative condition. Cortisol response and frontal TBR provide a more comprehensive interpretation of the effect of stress on dual-stream EIB.

4.1. The validity of stress induction

The subjective emotional responses and concentrations of cortisol under the stress conditions were significantly higher than those under the control conditions, indicating the validity of stress induction. There was a dissociation between cortisol level and negative affect at 35 min after TSST onset, which was associated with the neuroendocrine response to stress. Specifically, the acute stress response comprises an initial quick response form the SAM axis and a somewhat slower activation of the HPA axis (de Kloet et al., 2005). Individual negative affect reflects the activation of the SAM axis, which always quickly drops back to the baseline level as the stressor withdraws. In contrast, cortisol, which is represented on the HPA axis, exhibits hysteresis and remains high after the end of the whole experiment (Chrousos, 2009).

4.2. The dual-stream EIB effect

This study found that individuals exhibit greater attentional blindness following negative distractors, which is consistent with the classic EIB effect (e.g., Guilbert et al., 2020; Haddara et al., 2019; Macleod et al., 2017). The EIB indicated a more severely impaired visual awareness in the case of high attentional-priority given to a negative distractor (Most et al., 2007; Ohman et al., 2001). The negative distractor could further access the highly limited stage and affect the working memory consolidation of the target (Baker et al., 2021; Hoffman et al., 2020). The spatial selectivity in dual-stream EIB indicated an

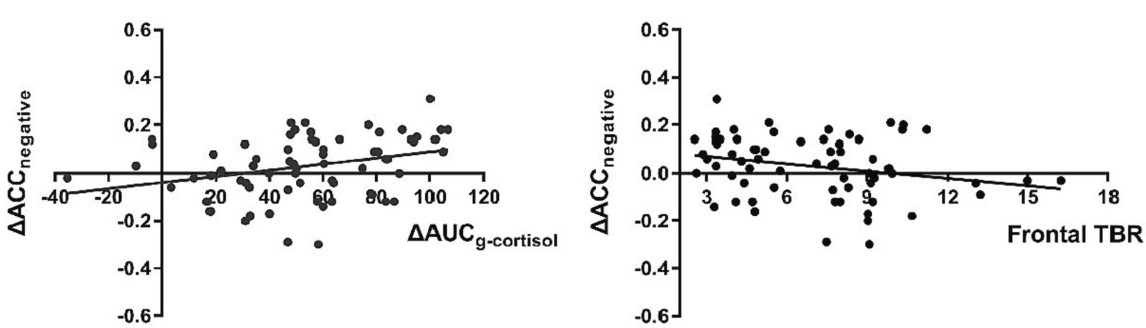

Fig. 5. Scatter plots for correlation analysis. (1) Left. Significant positive correlation between $\Delta AUC_{g\text{-}cortisol}$ and the changes in spatially localised target accuracy induced by acute stress under the negative distractors condition. (2) Right. Significant negative correlation between frontal TBR and the changes in spatially localised target accuracy induced by acute stress under the negative distractors condition.

Table 5
Hierarchical regression for stress-induced changes in spatially localised performance under negative distractors condition: The predicting effects of $\Delta AUC_{g\text{-}cortisol}$ and frontal TBR.

Independent variable	Dependent variable: $\Delta ACC_{negative}$					
	b	SE	95 % CI	β	*t*	ΔR^2
Step 1						0.158
$\Delta AUC_{g\text{-}cortisol}$	0.298	0.116	[0.066, 0.530]	0.297	2.563*	
Frontal TBR	−0.565	0.264	[−1.043, −0.44]	−0.248	−2.140*	
	Total adjusted $R^2 = 0.131$, $F(2, 63) = 5.895$*					
Step 2						0.008
$\Delta AUC_{g\text{-}cortisol}$×frontal TBR	−0.207	0.276	[−0.759, 0.345]	−0.386	−0.750	
	Total adjusted $R^2 = 0.125$, $F(1, 62) = 0.563$					

Note. *p < 0.05.

obvious spatial-localisation effect: the target accuracy in the opposite stream was significantly higher than that in the same stream, which aligned with previous findings (Kennedy et al., 2018; Most and Wang, 2011; Wang et al., 2012; Wang and Most, 2017). Moreover, the spatially localised target processing was not affected by distractor emotionality, which supported the early neural competition model (Desimone and Duncan, 1995; Keysers and Perrett, 2002); that is, distractor and target appeared in a shared visual receptive field compete to drive neuronal responses, resulting in impaired target detection at the same stream location (Most and Wang, 2011; Wang et al., 2012).

4.3. The effect of stress on dual-stream EIB

4.3.1. Stress eliminates the spatial-localisation effect

Stress alleviated dual-stream EIB mainly by promoting target detection in the same stream location, thus showing the insignificant differences in accuracy between targets appearing in the same and opposite stream locations. Stress also has an generally promoting effect on dual-stream EIB, according to the main effect of the intervention condition. These results revealed that elimination of stress on the spatial-localisation effect was a matter of degrees; that is, stress promotes target processing in the same location more than in the opposite location. The current results regarding reduced blindness were consistent with previous conclusions concerning the emotional attentional blink in single-stream rapid serial visual presentation under stress from the perspective of temporal attentional processing (Kan et al., 2019; Kan et al., 2021; Schwabe and Wolf, 2010), and also with prior studies on the reduced interference of distractors under stress (Booth, 2019; Hoskin et al., 2014). These results indicate that acute stress has an obvious advantage in processing targets under high temporal pressure, as well as when attentional resources were insufficient, irrespective of single- or dual-stream rapid serial visual presentation. It is reasonable to understand this promoting effect from the perspective of attentional resource allocation, as the processing advantage was not affected by the emotionality of the distractor. Specifically, stress could further consume attentional resources and make the remaining limited resources more concentrated on the current task (Booth, 2019; Sato et al., 2012; Tiferet-dweck et al., 2016). Target that appeared in the same location with distractors need to compete with it to be represented in the visual receptive field (Desimone and Duncan, 1995; Keysers and Perrett, 2002), thus resulting in fewer resources allocated to the target, which further improves the concentration of attention.

4.3.2. Stress-reduced spatial-localisation effect: relations with cortisol

The present study demonstrated that cortisol was more sensitive to stress-induced spatially localised performance changes under the negative distractors condition, and its role was disassociated with the general stress response. Specifically, a higher cortisol level could positively predict a higher accuracy of the target appearing in the same location, which reflects the weakening of the spatial-localisation effect induced by stress. Prior studies found that cortisol was associated with the reduced single-stream emotional attentional blink, regardless of the emotionality of the stimulus (Kan et al., 2019; Schwabe and Wolf, 2010); thus, in a sense, the current results seem to be inconsistent. However, previous studies only verified the role of cortisol based on the known influence of stress on attentional blink, and also did not comprehensively investigate the effect of cortisol levels on task performance. Specifically, Schwabe and Wolf (2010) divided participants into high and low cortisol response groups, based on the median of peak cortisol concentrations generated by a stress-induced task, and found that the high-response group had better attentional blink performance. Kan et al. (2019) further validated the predictive role of cortisol by finding that stress reduced the attentional blink effect when attentional resources were insufficient. Furthermore, the impaired attentional disengagement mechanism reflected by the role of cortisol in the current study may be more sensitive to attentional shifts involving spatial position changes. Actually, the endogenous cortisol induced by acute stress binds to glucocorticoid receptors in the amygdala and promotes the bottom-up attention process (Karst et al., 2010; Kavushansky and Richter-Levin, 2006), thus enhancing the attentional bias towards negative stimuli (Roelofs et al., 2007; Ursache and Blair, 2015). The underlying mechanism of cortisol-induced attentional bias is related to impaired attentional disengagement (Kimura et al., 2016; Roelofs et al., 2007), meaning that individuals have difficulty in redirecting attention from a threatening distractor to an alternative location. Therefore, a target that appears in the same stream location was perceived more accurately, and the cortisol level positively predicted the reduced spatial-localisation effect.

4.3.3. Stress-reduced spatial-localisation effect: Relations with frontal TBR

The current results revealed that low frontal TBR is associated with increased target processing under the negative distractor condition. Frontal TBR was associated with cognitive-emotional processes (Angelidis et al., 2018; Angelidis et al., 2016; Putman et al., 2010, 2014), and positively correlated with the attentional bias to threat stimulus in the dot-probe task (Angelidis et al., 2018). Individuals with low frontal TBR with high trait attentional control abilities can better inhibit the distraction of a task-irrelevant emotional stimulus, especially in the late stage (Putman et al., 2010; van Son et al., 2018). In the EIB task, negative distractors access the late stage of the elaborate processing after the initial sensory process, and can powerfully interfere with target detection (Baker et al., 2021; Hoffman et al., 2020). Individuals with low frontal TBR had high attentional control abilities that could effectively disregard the emotional distractor and also had more refined target processing, which was associated with better target detection performance. Conversely, those with high frontal TBR had a low attentional control ability, which was associated with reduced accuracy following emotional distractors (rather than neutral distractors). The early neural competition model further supports these findings (Desimone and Duncan, 1995; Keysers and Perrett, 2002). Impaired target detection was more serious in the same stream location due to the competition for target representation; individuals with low frontal TBR had a high trait attentional control ability that more evidently alleviate the competition caused by emotional distractors at the same location. In general, individuals with low frontal TBR further enhanced the stress-reduced spatial-localisation effect by fundamentally inhibiting the interference of emotional distractors on targets in the same location.

In this study, frontal TBR negatively predicted the difference in accuracy between the same and opposite stream location caused by stress. Moreover, frontal TBR did not interact with cortisol to influence EIB, and both cortisol and frontal TBR levels were independently related to the spatially localised processing. In fact, previous studies have indicated that frontal TBR affects attentional bias to emotional distraction, regardless of the level of state anxiety level (van Son et al., 2018). This aspect may be explained by brain region differences. Specifically, frontal TBR is mediated by dorsolateral frontal cortical activity, while emotional responses, such as state anxiety, are associated with the activation of the amygdala, during emotional distraction (Bishop, 2007; van Son et al., 2018). Cortisol also acts on the amygdala and promotes the bottom-up emotional attentional capture (Karst et al., 2010; Kavushansky and Richter-Levin, 2006). This evidence suggests that the influence paths of trait and state factors on attention processing may differ under emotional distractors.

5. Limitations and future directions

The current study examined the effect of acute stress on dual-stream EIB. There are some limitations that need to be noted. First, regarding the relationship between frontal TBR and dual-stream EIB, this study is a preliminary and completely new attempt. The correlation coefficients are indeed a little low. Further research can be conducted on the basis of this study. Furthermore, to focus more on the spatially localised characteristics of target processing, we calculated the spatially localised index under different emotional distractor conditions, referring to Proud et al. (2020). Consequently, we may have ignored some information, such as the correlation between the frontal TBR and target detection accuracy in the same and opposite stream location, respectively. Although we have made some reasonable speculation based on the results that stress promoted the target accuracy, especially in the same stream location, and that larger values for the spatially localised index indicated greater accuracy for the same-stream condition, more precise studies need to be conducted in the future to further explore potential processing characteristics. In addition, we only chose college students to carry out the experiment because of the convenience of sampling; this limits the generalizability of the study. Future research could extend these findings to other populations. Finally, as the dual-stream EIB involves target processing in a millisecond time frame, the event-related potential measures have high temporal resolution, which can effectively investigate the time course of the effect of acute stress on dual-stream EIB and further clarify the formation mechanism of the spatially-localisation effect at the electrophysiological level.

Open practices statements

None of the data or materials for the experiments reported here is available, and none of the experiments was preregistered.

Declaration of competing interest

No financial interest or benefit has arisen to the authors from the direct application of the research described in this report.

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