Effect of Acute Psychological Stress on Motion-in-Depth Perception: An Event-Related Potential Study

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ABSTRACT

The present study explored the intrinsic event-related potential (ERP) features of the effects of acute psychological stress on the processing of motion-in-depth perception using a dual-task paradigm. After a mental arithmetic task was used to induce acute psychological stress, a collision task was used to evaluate motion-in-depth perception. The error value and average amplitude of late slow waves (SW) were significantly larger for the earlier colliding spheres' than for the later colliding spheres. The P1 peak latency in the left occipital region was significantly shorter than that of the right occipital region in the motion-in-depth perception task. Compared to the control condition, the estimated value of residual time-to-collision and error value were significantly reduced, and the N1 peak amplitude and the SW averaged amplitude were significantly increased in the stress condition. Longer motion-in-depth time improved discrimination accuracy and decreased the investment of cognitive resources. Acute psychological stress increased behavioral performance and enhanced attention resources on the motion-in-depth perception task together with greater investment of cognitive resources.

KEYWORDS

event-related potential
acute psychological stress
motion-in-depth perception
time-to-collision

INTRODUCTION

Motion-in-depth perception is commonly used in daily life, from judging the direction of a flying ball to evaluating the distance of a competitor in a race. In the case of collisions, people need to judge whether the distance between the oncoming object and themselves is safe or not. To do this, they have to accurately estimate whether a collision will occur, and if so, how long it will take before it does (i.e., the time-to-collision or time-to-contact, TTC). Time-to-collision refers to the time interval from perceiving an oncoming object to the moment when the object hits the front surface of the observer (Heuer, 1993). Time-to-collision judgments can be improved through special training (Braly & DeLucia, 2020). Previous studies found that motion-in-depth perception is mainly influenced by factors such as the perceived size and the speed of the oncoming object (Wang & Yao, 2009), the observer's motor expertise (Wei et al., 2017), the observation time, visual field, presence of interference objects, and the observer's emotional state (Brendel, 2019; Brendel et al., 2014). Among these influencing factors, acute psychological stress is important.

Acute psychological stress can be defined a nonspecific physiological response to any uncontrollable or unpredictable threatening stimulus that exceeds the body's endurance in a short period of time (Koolhaas et al., 2011). The acute stress process is characterized by a short duration, lack of physical pain, and high intensity arousal. The re-

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sponse to acute stress includes increases in emotional indicators (such as depression or anxiety) and physiological responses (such as elevated blood pressure and increased breathing rate). Acute stress can increase alertness and sensory information input (Shackman et al., 2011). One study found a shorter reaction time (RT) in biological motion perception tasks in a high mental arousal state (Niederhut, 2009). At the neural level, acute stress influences prefrontal cortex (PFC)-dependent cognition by increasing dopaminergic, noradrenergic, and glucocorticoid mediated signaling (Arnsten et al., 2009; Sänger et al., 2014). Some studies have suggested that stress impairs performance on tasks that require PFC operations, whereas ingrained habits that rely on the basal ganglia circuits are spared or enhanced (Arnsten et al., 2009; Sandi & Pinelo-Nava, 2007). In short, acute stress tends to facilitate cognitive function, particularly in well-rehearsed or simple tasks, or when the cognitive load is not excessive (Qi et al., 2017).

Few studies have addressed the link between acute psychological stress and performance on tests of motion-in-depth perception. In a high mental arousal state, individuals invest more cognitive resources in the early attention stage of pattern recognition, and they show more accurate time estimation (Vagnoni et al., 2015). One study found that individuals in a state of fear made fewer errors when estimating TTC (Brendel et al., 2014). One explanation for the lower number of errors in TTC estimates for threatening pictures is that these pictures destroy the synchronism of the sensory motion area. Although there have been some prior behavioral findings on the effects of acute psychological stress on TTC, there are relatively few studies on the associated brain mechanisms. Therefore, the current study used electroencephalography (EEG) to explore the neurological effect of acute psychological stress on motion-in-depth perception.

The EEG components of motion-in-depth perception have been shown to include P1, N1, EPN, and LPP in the sensory-motor area (Vagnoni et al., 2015), as well as P1, N1, and SW in the occipital region (Wei & Qi, 2019). This evidence is consistent with both the capacity theory (Kahneman & Tversky, 1979) and the dual-competition model (Pessoa, 2009), which assumes that the capacity of cognitive resources is limited. Acute psychological stress is a form of emotional stimulation, while motion-in-depth perception is a form of cognitive processing. These emotional and cognitive demands will compete for limited mental resources when people estimate TTC under stress (Wang & Wang, 2006). Thus, there is both an empirical and a theoretical basis for predicting that acute psychological stress will affect motion-in-depth perception.

Due to the high time resolution of ERP experiments, we selected the mental arithmetic task (modified MIST task, Dedovic et al., 2005) to induce acute psychological stress in the laboratory. The predictive motion task paradigm (Tresilian, 1995) in the collision paradigm was selected as the task for evaluating motion-in-depth perception. The aim of the current study was to explore the neuropsychological mechanisms behind the effect of acute psychological stress on motion-in-depth perception by using event-related potentials (ERPs). This study broadens the research literature on both acute psychological stress and motion-in-depth perception. We hypothesized the following: (a) motion-in-depth perception will be enhanced under stress, (b) the estimated value and the error value of the remaining TTC will be reduced for the stress relative to the control block, (c) a larger frontal N1 component and SW will be found for the stress relative to control block.

METHODS

Participants

Twenty-five participants were recruited from the local university (13 males, M_{age} = 19.8). All participants were pre-screened with the Beck Depression Inventory (Beck, 1967), the Emotional State Assessment Inventory (Qi et al., 2007), the State-Trait Anxiety Inventory (Spielberger, 1983) and the Mosaic Graphics Test (Deng & Zeng, 2008) to ensure that they were not in a negative emotional state at the beginning of the experiment and had adequate spatial thinking ability. All participants showed nonsignificant levels of depression and anxiety, and all participants had field-independent cognitive styles (i.e., adequate spatial thinking ability). One participant was excluded from the analysis because their RT exceeded the range of *M*±3*SD*, and one participant was excluded due to excessive artifacts (more than 50% of their trials were invalid). Therefore, EEG data from 23 participants was included in the statistical analyses. All participants were right-handed and had a normal or corrected-to-normal vision. They provided written informed consent and received 60 RMB (about 9 USD) after the experiment. The present study was approved by the Institutional Research Ethics Committee of the first author's affiliated university.

Design

The present study employed a 2 (stress level: stress vs. control) × 2 (actual residual TTC: 400 ms vs. 800 ms) within-subject experimental design. Referring to the previous study (Wei & Qi, 2019), the reason for using two TTC conditions is to explore the differences between TTC1 (the actual residual TTC was 400 ms) and TTC2 (the actual residual TTC was 800 ms) conditions under stress, and to minimize the effects of mindset and fatigue in the experiment. The dependent variables were the estimated TTC, the error value of this estimate, the peak amplitude and latency of P1 and N1, and the average amplitude of SW. The estimated TTC refers to the amount of time between when the sphere appears and when the participant pushes the test button to indicate the moment of collision. The error value refers to the difference between the estimated collision moment and the actual collision moment.

Materials

A set of multiplication formulas containing 90 arithmetic expressions (e.g., 4.78 × 2.16) was used to induce acute psychological stress. Participants needed to judge whether the multiplied result was larger than 10 or not. They were instructed to press f on the keyboard if they thought the answer was less than 10, and to press j otherwise.

Drawing on Billington et al.'s (2011) motion-in-depth perception research paradigm, the motion-in-depth simulator was a 3D sphere,

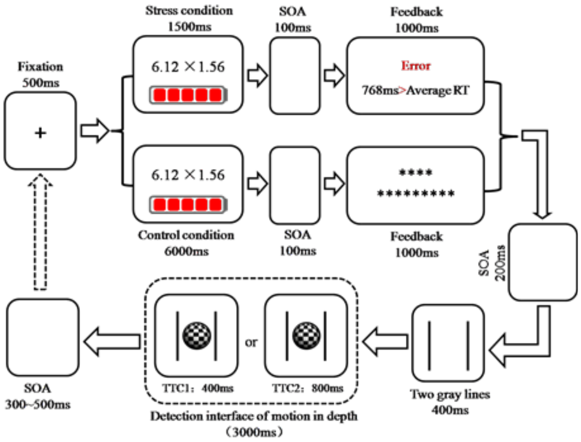

FIGURE 1.

Flow chart of the experimental task to test the effects of acute psychological stress on motion-in-depth perception.

and the collision's reference was a plane composed of two grey parallel vertical lines of equal length on the screen, with the midpoint of the two lines at the center of the screen. These materials were made by Autodesk 3dsMax 2010, and the format was WMV (1440 × 900). All stimuli were displayed at the center of a 19 in. screen using E-Prime 2.0 (Psychology Software Tools, Inc., Sharpsburg, USA). The materials for motion-in-depth perception consisted of two videos, one to help the participants understand collision perception and the other for practice and formal experimentation.

The practice video, which showed real collisions, was divided into a 400 ms video (the TTC1-L condition) and 800 ms video (the TTC2-L condition). The TTC1-L video had the following characteristics. First, two gray lines (presenting a 400 ms TTC) were presented on the screen, 10.4 cm apart and with a visual angle of 8.50 °. The diameter of the sphere was 2 cm, with an initial visual angle of 1.64 °. Then, the sphere flew at a constant speed (6 cm/s) from the inside to the outside in a direction perpendicular to the screen. To create a realistic perception of collision, the sphere expanded at a constant speed and moved down the screen at a constant speed of 0.2 cm/s. When the surface of the sphere touched the plane consisting of two gray lines (taking 1400 ms), the sphere disappeared. The distance travelled by the sphere was 8.4 cm from inside to outside, and the length of the blank interface after the sphere disappeared was 600 ms. Therefore, the total duration of the video was 2400 ms in the TTC1-L condition. The TTC2-L video had the following characteristics. First, two gray lines were presented for 400 ms on the screen, and the distance between the two gray lines was 12.8 cm with a visual angle of 10.44 °. The initial size of the sphere, the direction of flight, the speed of horizontal flight, and the speed of downward flight were consistent with the TTC1-L condition. The distance travelled by the sphere was 10.8 cm from the inside to the outside. The sphere flew for 1800 ms from the appearance to the disappearance, and the length of the blank interface was 600 ms after the sphere disappeared. Therefore, the total video length was 2800 ms in the TTC2-L condition.

The videos used for practice trials and the formal experiment were also divided into a 400 ms video (TTC1) and an 800 ms video (TTC2). The TTC1 video had the following characteristics. First, two gray lines were presented on the screen for 400 ms. The distance between the two gray lines was 10.4 cm with a visual angle of 8.50 °, and the initial size of the sphere was 1.64 °. The horizontal flying speed of the sphere was 6 cm/s, and the downward flying speed was 0.2 cm/s. Then, the sphere disappeared at the 400 ms position before the actual collision, and the actual flight distance of the sphere was 6 cm. The sphere flew for 1000 ms from the appearance to the disappearance, and the blank interface length after the sphere disappeared was 600 ms. Therefore, the total duration of the TTC1 video was 2000 ms. The TTC2 video had the following characteristics. First, two gray lines were presented on the screen for 400 ms. The distance between the two gray lines was 12.8 cm with a visual angle of 10.44 °. The initial size of the sphere, the direction of flight, the speed of horizontal flight, and the speed of the downward flight were consistent with the TTC1 condition. Then, the sphere disappeared at the 800 ms position before the actual collision, and the actual flight distance of the sphere was 6 cm. The sphere flew for 1000 ms from the appearance to the disappearance, and the blank interface length after the sphere disappeared was 600 ms. Therefore, the total length of the TTC2 video was 2400 ms.

Procedure

First, the participants filled out the consent forms and completed the screening measures. Then, the participants were fitted with a 64 channel EEG cap, and then conductive paste was injected onto the electrodes. The impedance of all electrode sites was under 5kΩ. The experimenter asked the participants to sit up straight during the experiment, to keep their eyes at a distance of about 70 cm from the screen, and to try to avoid gross body movements such as swinging their head or legs. To allow heart rate adjustment, the participants observed a relaxing picture on the screen and imagined that they were immersed in it (one minute). The participants completed 10 practice trials. Each trial contained the following elements: fixation (500 ms), collision video (3 s), buffer interval (100 ms), feedback (1500 ms), and blank (300/400/500 ms). At this stage, the participants were asked to press the space bar on the keyboard when the sphere collided with the plane composed of the two gray lines. The feedback included whether the sphere exceeded the plane at the instant the button was pressed, and the length of time when the sphere did not exceed or did exceed the plane. The 10 practice trials with feedback were followed by 160 trials without feedback in the formal experiment (see Figure 1). The participants' emotional states and anxiety levels were then assessed by the Emotional State Assessment Inventory and State-Trait Anxiety Inventory, respectively, immediately after the control and stress blocks.

In order to eliminate the impact of different levels of difficulty across tasks, the same mental arithmetic questions were used in the stress and control conditions. In the stress condition, feedback after the mental arithmetic task was the number of correct trials, the comparison between the participant's score, and the average score of other people (random between 700 ms and 800 ms). In the control condition, feedback was presented as asterisks (see Figure 1). The formal experimental phase consisted of two counterbalanced blocks, one for the stress condition and the other for the control condition (80 trials each). Within each block, there were 40 trials in each of the TTC1 and TTC2 conditions, each of which was randomly presented. The blocks were counterbalanced in order to avoid sequence effects. All participants were required to take a 5-10 minute break by viewing a pleasant picture between the stress and control conditions. In addition, the sphere would disappear at 400 ms or 800 ms before it collided with the plane consisting of two gray lines in the motion-in-depth perception task. The participants were asked to imagine that the sphere continued to fly at the original speed and to estimate the moment when the sphere collided with the plane by pressing the space bar on the keyboard.

Behavioral Data Analysis

All behavioral data analyses were conducted in SPSS 17.0. Paired sample *t*-tests were performed to compare the TTC1 and TTC2 conditions on state anxiety, negative affect, RT, and accuracy in the mental arithmetic task. A two-factor repeated measures analysis of variance (ANOVA) was conducted for RT and the error value separately to determine the effects of stress level (stress vs. control) and actual residual TTC (400 ms, 800 ms).

Electrophysiological Recording and Analysis

Brain electrical activity was recorded at 64 scalp sites using tin electrodes mounted in an elastic cap (Brain Products, Germany). Raw EEG data were recorded by the Recorder software and processed offline by the Analyze 2.0 software. The cap was placed on the scalp according to the 10–20 system positions with the offline reference on the left and right mastoids. The vertical electro-oculography (VEOG) was placed at about 1 cm below the right eye. The horizontal electro-oculography (HEOG) was placed at about 1 cm outside the corner of the left eye. The sampling rate of the signal was 1000 Hz, and the filtering range was 0.01~100 Hz. The IIR filter range of the EEG data was selected to be 0.01 to 35 Hz. Artifacts with amplitudes exceeding ±80 μV were removed, and the ocular correction independent component analysis (ICA) was used to identify and remove artifacts due to eye movement

The baseline of the EEG data was 200 ms before the start of the mental arithmetic task and before the motion-in-depth perception task. According to the experimental conditions of TTC1 and TTC2, the sphere flew for 1s and after it disappeared, it collided with the plane consisting of two gray lines, either 400 ms or 800 ms later. Therefore, in order to explore the participants' ERP characteristics when estimating TTC in different stress conditions, the superimposed time of EEG data was -200~1800 ms. Because ERP experiments are affected by factors such as saccades, muscle artifacts, and reaction errors, the number of superimpositions of the EEG data needed to be higher than 30 trials (Picton et al., 2000). The average number of superimpositions of each experimental condition was 36 in this study.

The ERP components of different brain regions reflected different cognitive processes. Stress-induced psychological processing was mainly reflected in the parietal-occipital regions. This corresponds with previous ERP studies on acute stress (Qi et al., 2016, 2017). Based on the topographical maps of the difference waveforms, Pz and POz (80-200 ms) were selected as the electrode sites for analyzing the N1 component, and Fz, FCz, and POz (130-300 ms) were selected as the electrode sites for analyzing the P2 component in the stress induction phase. In the motion-in-depth perception task, the selection of ERP electrodes was mainly based on a previous ERP study (Wei & Qi, 2019). The P7, PO7, P8, and PO8 (80-200 ms) of left and right temporo-occipital regions were selected as the electrode sites for the statistical analyses of the P1 component. The F1, F2, FCz, and Fz (90-200 ms) of forehead-top areas were selected as the electrode sites for the statistical analyses of the N1 component. The Fz, F1, F2, and FCz (400-1300 ms) of forehead-top areas were selected as electrode sites for statistical analyses of SW. The effects on the ERP components produced by the stress-inducing task and the motion-in-depth perception task were analyzed by a repeated-measure ANOVA. All effects with more than one degree of freedom were adjusted for sphericity violations using the Greenhouse-Geisser correction. Significant effects were followed by Bonferroni-corrected pairwise comparisons (Qi et al., 2017; Wei & Qi, 2019).

RESULTS

Behavioral Data

The level of self-reported state anxiety was higher poststress relative to prestress, $t(23) = 2.95$, $p < .01$ (see Figure 2, Panel A). Positive affect was lower poststress versus prestress, $t(23) = 3.32$, $p < .01$ (see Figure 2, Panel B). On the mental arithmetic task, longer RT, $t(23) = 6.88$, $p < .01$, and higher accuracy, $t(23) = 4.01$, $p < .01$, were found for the control condition versus the stress condition, suggesting that this task had a stress-inducing effect.

For the estimated value of TTC in the motion-in-depth perception task, the main effect of stress level was significant, $F(1, 23) = 4.30$, $p < .05$, $\eta_p^2 = .16$. $M_{\text{stress}} = 1620.51$ ms $< M_{\text{control}} = 1695.12$ ms (see Figure 3, Panel A). The main effect of the actual residual TTC was also significant, $F(1, 23) = 209.97$, $p < .01$, $\eta_p^2 = .90$, $\mathrm{M}_{\text{TTC1}} = 1532.15$ ms $< M_{\text{TTC2}} = 1783.48$ ms. However, the interaction between the stress level and actual residual TTC was not significant, $F(1, 23) = 3.63$, $p > .05$, $\eta_p^2 = .14$. For the error value, the main effect of stress level was significant, $F(1, 23) = 4.30$, $p = .05$, $\eta_p^2 = .16$, $M_{\text{stress}} = 20.51 < M_{\text{control}} = 95.05$, and the main effect of the actual residual TTC was also significant, $F(1, 23) = 73.51$, $p < .01$, $\eta_p^2 = .76$, $M_{\text{TTC1}} = 132.1 > M_{\text{TTC2}} = -16.59$ (see Figure 3, Panel B). However, the interaction between stress level and actual residual TTC was not significant, $F(1,23) = 3.59$, $p >.05$, $\eta_p^2 = .14$. These results indicated that the participants performed better on the motion-in-depth perception task in the stress condition.

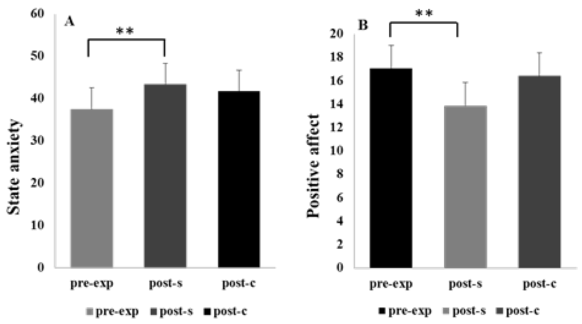

FIGURE 2.

Averaged subjective ratings of state anxiety (Panel A) and positive affect (Panel B) in the stress and control conditions. The error bars indicate the SEM. pre-exp = pre-experiment, post-s = poststress, post-c = postcontrol. $^{**}p < .01$.

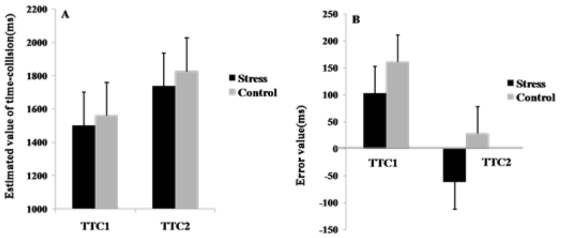

FIGURE 3.

The estimated value of time-to-collision (Panel A) and error value (Panel B) at different stress levels

Electrophysiological Data

STRESS-INDUCTION PHASE

For the P2 peak latency, the main effect of stress level was significant, $F(1, 22) = 18.32$, $p < .01$, $\eta_p^2 = .45$, $M_{\text{stress}} = 206.06$ ms $< M_{\text{control}} = 225.06$ ms. The main effect of electrode site was also significant, $F(1.58, 34.77) = 29.62$, $p < .01$, $\eta_p^2 = .57$, with the P2 peak latency being significantly longer at the POz than at the Fz and FCz ($p < .01$). However, the interaction between stress level and electrode site was not significant, $F(2, 44) = 1.99$, $p > .05$, $\eta_p^2 = .08$.

For the P2 peak amplitude, the main effect of stress level was significant, $F(1, 22) = 8.33$, $p < .01$, $\eta_p^2 = .28$, $M_{\text{stress}} = 8.13\ \mu\text{V} < M_{\text{control}} = 9.38\ \mu\text{V}$, with shorter peak latency and lower peak amplitude of P2 in the stress condition versus the control condition (see Figure 4). The interaction between stress level and electrode site was not significant, $F(1.40, 30.75) = 1.22$, $p > .05$, $\eta_p^2 = .05$

MOTION-IN-DEPTH PERCEPTION TASK

For the P1 peak latency, there was a significant main effect of electrode site, $F(1.66, 36.56) = 6.20$, $p < .01$, $\eta_p^2 = .22$. Post hoc testing found that the P1 peak latency was significantly shorter at the P7 than at the PO8 ($p < .05$), and the difference between the other two electrodes was not significant ($p > .05$). The interaction between the electrode site and the actual residual TTC was also significant, $F(1.68, 36.97) = 4.37$, $p = .03$, $\eta_p^2 = .17$. A simple effects analysis showed that in the TTC2 condition, the P1 peak latency at the P7 was significantly shorter than that of the P8 ($p < .05$) and PO8 ($p < .01$), and the P1 peak latency at the PO7 was significantly shorter than that of the PO8 ($p < .01$). The three-way interaction among electrode site, stress level, and actual residual TTC was significant, $F(1.65, 36.23) = 5.12$, $p < .05$, $\eta_p^2 = .19$. A simple effects analysis showed that the P1 peak latency was significantly shorter at the P7 than at the P8 in the stress and TTC1 conditions ($p < .05$); the P1 peak latency was significantly longer in the stress condition than in the control condition at the P8 in the TTC1 condition ($p < .01$). The P1 peak latency in the TTC1 condition was significantly shorter than that in the TTC2 condition at the PO8 in the control condition ($p < .01$); and the P1 peak latency of TTC1 condition was significantly shorter than TTC2 in P8 and control condition ($p < .05$, see Figure 5). For the P1 peak amplitude, the main effect of electrode site was significant, $F(3, 66) = 25.15$, $p < .01$, $\eta_p^2 = .53$, and post hoc testing found that the P1 peak amplitude was significantly lower at the P7 than at the PO7 and PO8 ($p < .01$), at the P8 than at the PO7 ($p < .05$), and at the P8 than the PO8 ($p < .01$). The main effect of stress level was not significant, $F(1, 22) = 1.63$, $p > .05$, $\eta_p^2 = .07$, $M_{\text{stress}} = 5.15\ \mu\text{V}$, $M_{\text{control}} = 4.91\ \mu\text{V}$. The main effect of the actual residual TTC was not significant, $F(1, 22) = 1.40$, $p > .05$, $\eta_p^2 = 0.06$, $M_{\text{TTC1}} = 4.88\mu\text{V}$, $M_{\text{TTC2}} = 5.18\mu\text{V}$. There was no significant interaction between stress level and actual residual TTC ($p > .05$).

For the N1 peak latency, the main effect of the electrode site was significant, $F(3, 66) = 3.97$, $p < .05$, $\eta_p^2 = .15$, $M_{\text{Fz}} = 151.21$ ms, $M_{\text{F1}} = 152.70$ ms, $M_{\text{F2}} = 154.50$ ms, $M_{\text{FCz}} = 154.14$ ms. Post hoc testing showed that although no pairwise comparisons were significant, N1 peak latency was slightly longer at the F2 and FCz than at the Fz and F1. The main effect of stress level was not significant, $F(1 ,22) = 1.01$, $p > .05$, $\eta_p^2 = .04$, $M_{\text{stress}} = 155.59$ ms, $M_{\text{control}} = 150.68$ ms. The main effect of the actual residual time-to- collision was not significant, $F(1, 22) = 0.002$, $p > .05$, $\eta_p^2 < .01$, $M_{\text{TTC1}} = 153.19$ ms, $M_{\text{TTC2}} = 153.09$ ms. For the N1 peak amplitude, the main effect of stress level was significant, $F(1, 22) = 16.68$, $p < .01$, $\eta_p^2 = 0.43$, $M_{\text{stress}} = -6.85\ \mu\text{V}$, $M_{\text{control}} = -5.40\ \mu\text{V}$, with the N1 peak amplitude being significantly larger in the stress condition than in the control condition, as shown in Figure 6. The main effect of electrode site was not significant, $F(1.35, 29.60) = 1.81$, $p > .05$, $\eta_p^2 = .08$. The main effect of the actual residual time-to-collision was not significant, $F(1, 22) = 0.19$, $p > .05$, $\eta_p^2 = .01$, $M_{\text{TTC1}} = -6.20\ \mu\text{V}$, $M_{\text{TTC2}} = -6.04\ \mu\text{V}$. There was no significant interaction between the actual residual TTC and stress level for the N1 peak latency or amplitude ($p > .05$).

For the SW average amplitude, the main effect of stress level was significant, $F(1, 22) = 4.91$, $p < .05$, $\eta_p^2 = .18$, $M_{\text{stress}} = -11.06\ \mu\text{V} > M_{\text{control}} = -9.68\ \mu\text{V}$ (see Figure 7, Panel A). The main effect of the actual residual time-to-collision was significant, $F(1, 22) = 15.80$, $p < .01$, $\eta_p^2 = .42$, $M_{\text{TTC1}} = -11.22\mu\text{V} > M_{\text{TTC2}} = -9.53\ \mu\text{V}$ (see Figure 7B). The main effect of electrode site was also significant, $F(2.04, 44.79) = 13.65$, $p < .01$, $\eta_p^2 = .38$. The $M \pm SD$ of each electrode site was Fz: $-10.11 \pm 0.77\ \mu\text{V}$; F1: $-9.10 \pm 0.87\ \mu\text{V}$; F2: $-9.67 \pm 0.93\ \mu\text{V}$; FCz: $-12.61 \pm 0.97\ \mu\text{V}$. Post hoc testing found that there was a significant difference between FCz and Fz, and between F1 and F2 ($p < .01$). There was no significant interaction between stress level and actual residual time-to-collision ($p > .05$).

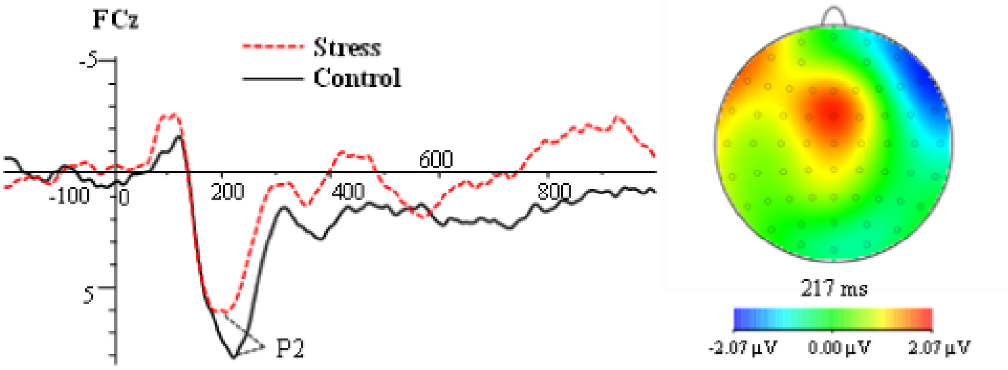

FIGURE 4.

The grand average waveform of P2 at different stress levels (left). The topographic map indicated the difference between the control and stress conditions (right).

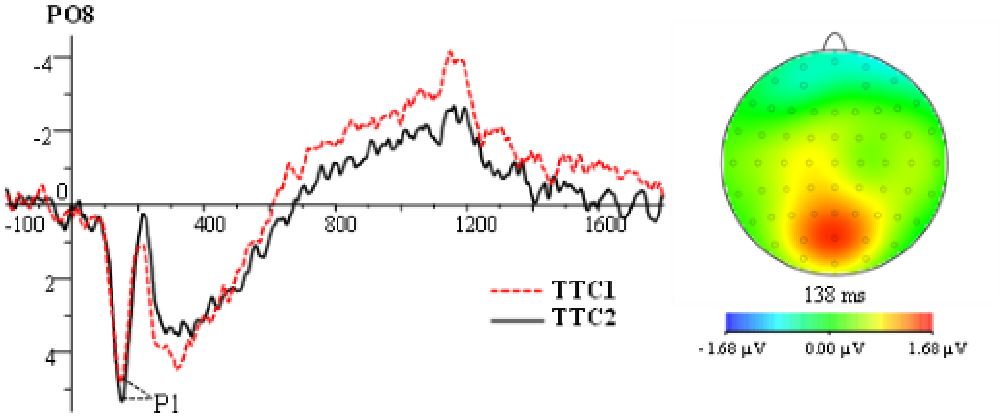

FIGURE 5.

The grand average waveform of P1 in different TTC conditions (left). The topographic map indicated the difference between TTC2 and TTC1 (right).

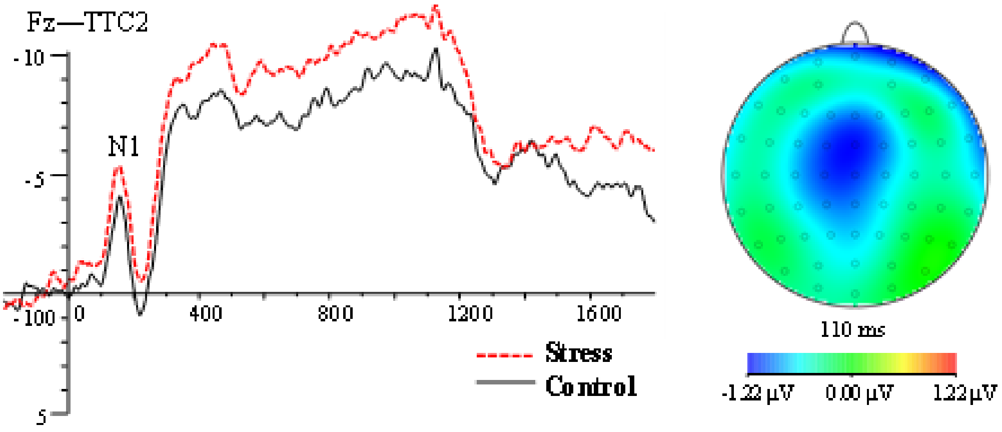

FIGURE 6.

The grand average waveform of N1 (TTC2) in different stress levels (left). The topographic map (TTC2) indicated the difference between stress and control (right).

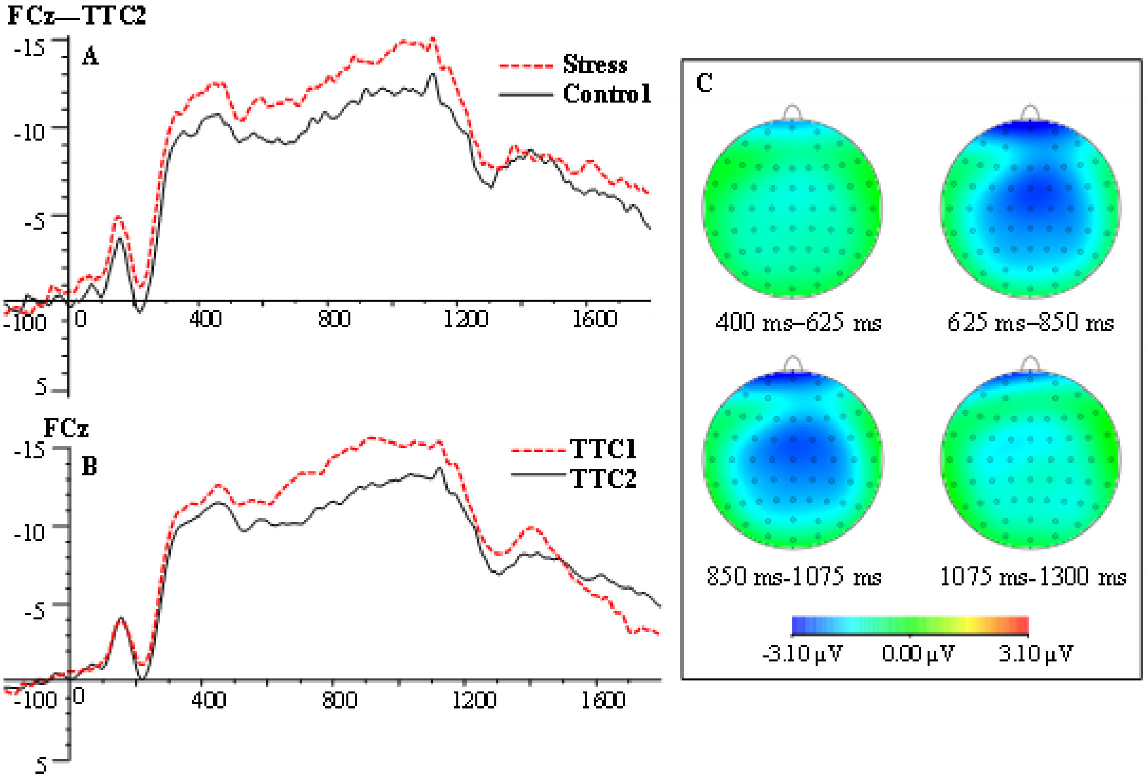

FIGURE 7.

The grand average waveform of SW in different stress (Panel A) and TTC (Panel B) conditions. The topographic maps indicated the difference between TTC1 and TTC2 (Panel C).

DISCUSSION

The current study used behavioral measures and EEG to explore the effect of acute psychological stress on motion-in-depth perception. In a dual-task paradigm, a mental arithmetic task was used as the primary task to induce acute psychological stress in all participants, and the depth-collision task was used as the secondary task to assess motion-in-depth perception. In the stress condition, the participants performed better at the behavioral level of the motion-in-depth perception task and increased the investment of attention and cognitive resources. These results contribute to the literature by revealing the inherent features between acute psychological stress and motion-in-depth perception from behavior to brain mechanism.

The stress-induced effects were evident in higher state anxiety, lower positive affect, lower RT, and lower accuracy in the stress versus control condition. These results indicated that the mental arithmetic task successfully induced psychological stress, in line with the findings of previous studies in which psychological stress was induced by computerized mental arithmetic with built-in social evaluation (Yang et al., 2012; Qi et al., 2016). Qi et al. also found that compared with participants in the control condition, participants in the stress condition had a shorter RT and lower accuracy, which was consistent with the results of the current study. These results may indicate that participants used two different strategies in the stress and control conditions. Specifically, participants appeared to adopt the speed-priority strategy in the stress condition and the accuracy-first strategy in the control condition. The EEG data showed that the P2 latency was shorter and the amplitude induced by mental arithmetic tasks was lower in the stress condition than in the control condition. Some studies have found that P2 represents the early processing of attention, and the magnitude of the P2 peak amplitude reflects the allocation of attention resources in the visual perception task. That is, the lower the P2 amplitude, the less attention resource allocation in the perceptual process (Lenartowicz et al., 2014; Löw et al., 2015). In the stress condition, participants had higher alertness (Shackman et al., 2011), which led to an increase in their RT. The increased attention further caused an earlier P2, which was consistent with the results of Yang et al. (2012). Participants needed more attention resources to cope with the increased alertness, and the allocation of attention resources for the mental arithmetic task was reduced in the stress condition, which induced a smaller P2.

In the stress condition, the behavioral performance on the motion-in-depth perception task was better. The behavioral data showed that the estimated TTC and error value were significantly lower in the stress condition than in the control condition. Previous studies reported that emotional processing had a certain degree of regulation on cognitive processes, such as visual processing, executive function, and working memory (Luo et al., 2006; Huang et al., 2013). Bertsch et al. (2011) found that participants had a faster perceptual processing speed and lower accuracy in the stress condition, as compared with the control condition. In another study, individuals' breadth of attention was reduced under time pressure, which hindered perceptual processing and led to a decrease in perceived processing efficiency, a shorter RT, and lower accuracy (Dambacher & Hübner, 2014). Brendel et al. (2012) found that threatening emotional stimuli induced more psychological arousal and a shorter estimated residual of TTC. Together, the results of these studies suggest that because participants had higher alertness and a stronger sense of self-protection under the stress condition, they had a faster RT and a more accurate estimated residual of TTC. In addition, the current study found that the error value of the TTC1 condition was significantly larger than that of the TTC2 condition, indicating that the participants had enough time to estimate the instantaneous scene of the sphere collision in the actual residual TTC of 800 ms.

In this study, attention resources were enhanced in the stress condition. The P1 peak latency induced by the motion-in-depth perception task in the stress and TTC1 conditions was significantly larger than that in the control condition. P1 has been shown to be the main component of the early processing of visual information, which mainly reflects the encoding of the initial features (such as shape, size, color, and contrast) of the visual information stimuli (Luck & Kappenman, 2011). Hillyard et al. (1998) found that P1 reflected changes in the parameters of external stimuli and was sensitive to the direction of spatial attention to stimulus information. This suggests that P1 is related to visual attention. An important element of motion-in-depth is the interaction of initial features and visual attention. So, although the paradigm used in the present study was different from the paradigm adopted by Vagnoni et al. (2015), that P1 induced in the occipital region can be the indicator of judgment process of TTC was affected by psychological arousal.

Since psychological stress increases the level of arousal and alertness (Wang et al., 2005), the participants needed to pay more attention in order to deal with higher alertness in the stress condition, and the attention resources involved in the TTC task were reduced accordingly. Because the call speed of attention resources was slowed down by the higher psychological arousal level and the shorter reservation time of the actual collision, the P1 component appeared later in the stress condition. Therefore, the current results with respect to later P1 were different from the previous results. The current study also found that the P1 component in the left occipital-temporal region appeared earlier than in the right occipital-temporal region during the motion-in-depth perception task, which was consistent with the results of a previous study (Wei & Qi, 2019). That is, the left parietal-occipital region took the lead in paying attention to the deep-moving sphere, and then the right brain region was also involved in the task.

The N1 peak amplitude induced by the motion-in-depth perception task in stress condition was larger than that in the control condition, suggesting that attention to stimuli was enhanced in the stress condition. Lamberty et al. (2008) found that a negative component appeared about 150 ms after the P1 component, and it was related to the process of visual attention. It was similar to the classical N1 component, and so was also named N1. The N1 component is related to the orientation of spatial attention and the attention process in identification tasks (Hopf et al., 2002). Hillyard et al. (1998) also found that the N1 peak amplitude was related to the position of attention, that is, an increased N1 peak amplitude indicated that attention to stimuli was enhanced, and target detection was better. Shackman et al. (2011) found that N1 was related to the perceptual process, which indicated that the level of alertness and sensory input were significantly increased under the threatening condition. Qi and Gao (2020) found that acute psychological stress increased general alertness and promoted attentional control in selective attention processes. In the stress condition in the current study, the participants had to use cognitive resources to deal with the stress process of alertness, and at the same time, use attention resources to participate in the motion-in-depth perception task. Therefore, the attention resources invested in the motion-in-depth perception task were increased significantly, with the phenomenon of attention enhancement being seen in the stress condition.

The investment of cognitive resources was increased in the stress and TTC1 conditions. The averaged amplitude of SW induced by the motion-in-depth perception task in the stress condition was larger than that in the control condition, and the mean amplitude of TTC1 was significantly larger than that of TTC2. Earlier research showed that SW was related to memory coding, and the brain region distribution of SW changed with the change of sensory input channel and stimulation type (Ruchkin et al., 1995). The long-lasting negative slow wave appears to be a late ERP component that reflects the coding of visual space and working memory (Barceló et al., 1997). In the present study, the participants needed to remember the position of the sphere and estimate the moment when the sphere collided with the plane. Thus, the allocation of cognitive resources may have continued into the early stages of working memory.

Mecklinger and Pfeifer (1996) used EEG to research the mechanism of the effect of memory load on the coding process of visual spatial information. They found that SW amplitudes were disrupted by memory load. That is, the larger the memory load, the higher the SW amplitude. These results showed that SW was closely related to the consumption of cognitive resources: The larger the SW amplitude, the more cognitive resources were consumed. Given that the mental state of higher arousal and alertness are induced by psychological stress (Wang et al., 2005), the participants in the stress condition of the current study needed to use more cognitive resources to internally adjust the higher arousal and to process the motion-in-depth perception. Therefore, the participants needed to consume more cognitive resources to accurately estimate the residual TTC of the sphere in the stress condition.

In short, as compared to the control condition, better behavioral performance for the motion-in-depth perception task was found under the stress condition, which can be reflected by a lower error value. Meanwhile, the peak amplitude of N1 (time-locked to the onset of the motion-in-depth perception task) was larger in the stress condition than the control condition, which suggests that the attention to stimuli was enhanced under stress. Moreover, we also found the mean amplitude of the SW (400-1300 ms time-locked to the onset of the motion-in-depth perception task) was larger in the stress condition than the control condition, which indicates that the investment of cognitive resources was increased. Taking the behavioral and neurophysiological results together, we may infer that the enhanced performances are highly associated with the increased N1 and SW activities. This is basically consistent with previous research (Hillyard et al., 1998; Shackman et al., 2011). So, when the attention is focused, or the investment of cognitive resources is increased, the discrimination accuracy is higher in the motion-in-depth perception task.

CONCLUSIONS

The present study drew the following conclusions: Longer motion-in-depth time improved discrimination accuracy and decreased the investment of cognitive resources. Acute psychological stress increased behavioral performance and enhanced attention resources on the motion-in-depth perception task together with greater investment of cognitive resources.

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