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The Influence of Acute Stress on Brain Dynamics During Task Switching Activities

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ABSTRACT Task switching is a common method to investigate executive functions such as working memory and attention. This paper investigates the effect of acute stress on brain activity using task switching. Surprisingly few studies have been conducted in this area. There is behavioral and physiological evidence to indicate that acute stress makes the participants more tense which results in a better performance. In this current study, under stressful conditions, the participants gave quick responses with high accuracy. However, unexpected results were found in relation to salivary cortisol. Furthermore, the electroencephalogram results showed that acute stress was pronounced at the frontal and parietal midline cortex, especially on the theta, alpha, and gamma bands. One possible explanation for these results may be that the participants changed their strategy in relation to executive functions during stressful conditions by paying more attention which resulted in a higher working memory capacity which enhanced performance during the task switching.

INDEX TERMS Acute stress, alpha power, attention, EEG, executive function, gamma power, theta power, working memory.

I. INTRODUCTION

Under stressful circumstances, higher stress levels may lead to a reduction in job stability, and cause fatigue, and even health problems [1]. Stress can cause illness and lead to increased medical expenses. Furthermore, exposure to chronic or extreme stress may cause mental illness or psychiatric illness such as depression, or to a minor extent, may compromise the person's cognitive abilities such as decision-making and adversely affect their working memory [2], hence they may forget vital information and make incorrect judgments. Executive function is a theoretical construct which captures many crucial aspects of human cognitive functions. Prior studies showed the close relationship between the frontal lobe and executive functions [3]. Executive functioning helps people to achieve a goal-oriented task. It is related to remembering, planning, multitasking, reasoning and so on [4].

Previous studies have shown that theta power significantly increased after a switch cue at the frontal midline during task switching [5]. Evidence supports a relationship between the theta oscillations and working memory tasks at the frontal and parietal regions [6]. Questionnaires are one of the most commonly used methods for assessing subjective stress levels [7]. The assessment of cortisol levels is thought to be an objective method for measuring stress responses [8]. However, several stress-induced tasks failed to produce cortisol secretion as reported in [9]. Heart rate variability (HRV) is usually calculated as the mean or standard deviation of RR intervals for time domain analysis. Heart rate acceleration was noted during periods of intense anxiety [10]. Mental stress increased in low frequency (LF) components in the RR power spectrum [11].

The appearance of frontal midline theta activity (FMθ) was observed in people with low scores on the trait anxiety scale during an arithmetic exam, but FMθ was not found in people who scored highly on the trait anxiety scale [12]. It is well-known that alpha band activity represents the idling state of the human brain [13]. Higher alpha power is found in

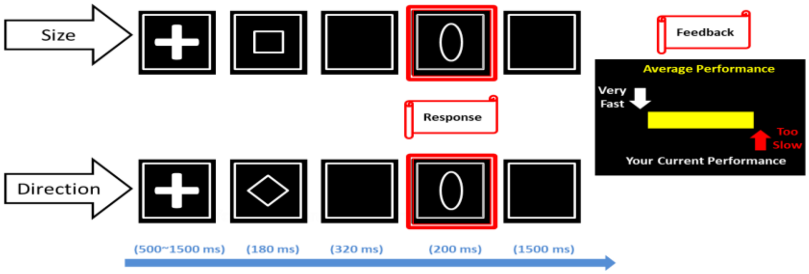

FIGURE 1. Stimulus on size or direction trial.

high-anxiety people throughout baseline and tasks compared to low-anxiety people [14]. Patients with anxiety disorders showed higher gamma activity than the healthy control group in the posterior regions [15]. Contrary to previous research, the gamma (30-50 Hz) band showed relatively more power for negative valence over the left temporal region. Gamma band power increased at the right frontal lobe during emotion processing [16].

The goal of this study is to investigate how acute stress affects the executive functions of task switching in terms of both behavioral performance and corresponding brain dynamics. Furthermore, the influence of acute stress on brain mechanisms during task switching can be inferred from this experiment.

II. MATERIAL AND METHODS

A. PARTICIPANTS

Seventeen right-handed healthy students aged between 19 and 28 years participated in the study for a small financial compensation. Only one participant was removed from this study due to abnormally large noise recorded in their EEG signal. After the exclusion of this participant, the participants' ages ranged from 19 to 25 years old (mean = 21.6, standard deviation = 1.7). All participants were screened to eliminate those with medical disorders as well as those taking medications or drugs. None of the participants had had brain surgery or had any history of psychiatric problems. The participants were instructed to minimize unnecessary movements during the EEG. When the participants arrived, they were required to complete a questionnaire after which the participant was given an electrode cap to wear for the ECG procedure. For counterbalance, participants were assigned to stress (feedback) experiment before or after the break.

B. EXPERIMENT PARADIGM

Two kinds of trials are used in the present study. One of the trial objectives is to identify the size of the ellipse, and the other is to identify the direction of the ellipse as shown in figure 1. Participants were instructed to respond with answers by pressing one of the two buttons on the keyboard (left arrow or up arrow). A circle appeared in the center of the screen before each session started. The experiment comprised a total of eight sessions. In four of the sessions (stress sessions), the participants were given a bonus payment for good performance in terms of accuracy and response time, however, in the other four sessions (no stress sessions), the participants did not receive a bonus despite the quality of their performance. In the sessions which offered a monetary bonus, feedback was provided on the screen after every eight trials, informing the participant of the accuracy of their response and their response time. There were two single task sessions and two mixed task sessions for both the feedback and non-feedback experiments. To induce acute stress in the feedback experiment, monetary loss is used as a punishment where an incorrect answer and a slower than average response time were punished by the permanent loss of a bonus payment.

The EEG signals were recorded using a sintered *Ag/AgCl* electrode cap with 32 channels (plus two reference channels and ECG channels) in accordance with the modified international 10-20 system with a sampling rate at 1000 Hz. Five different kinds of questionnaires were used in this study to identify different stressors.

(i) Spielberger State-Trait Anxiety Inventory – state version (STAI-S)
(ii) Spielberger State-Trait Anxiety Inventory – trait version (STAI-T)
(iii) Social Interaction Anxiety Scale (SIAS)
(iv) Hassles Scale
(v) Physiological Stress Reaction Inventory (PSRI)

In this study, saliva samples were collected using a dental cotton roll placed in participant's mouth for two minutes. Saliva samples were collected several times throughout the experiments. After the saliva samples were collected, they were immediately stored at -20ř C until assayed.

III. RESULTS AND ANALYSIS

A. BEHAVIOR DATA ANALYSIS

Response time is defined as the time interval from the target's appearance on the screen to the time the response button was pressed. The response time of each session is calculated by averaging the response times of the correct trials only. The EEG trials were excluded from the average calculation. The response time is kept within two standard deviations of the mean values. It is important to note the two cost effects. One is the response time difference between the non-switching trial and the single trial which was defined as mixing cost. The mixing cost can be obtained by calculating the non-switching trials' average response time minus the single trials' average response time. The time difference between the switching trial and the non-switching trial was defined as the switching cost. The switching cost was obtained by the average response time of the switching trials minus the average response time of the non-switching trials.

EEG raw data was down-sampled from 1000 Hz to 250 Hz and filtered with a band-pass filter (0.5∼50 Hz). Each trial epoch is extracted offline for a period from 1 second before the fixation cross-stimuli to 3 seconds after the fixation cross-stimuli. A pre-stimulus period before fixation is defined as a baseline. Channel baseline means were removed from an epoch. Each epoch contains all the events in a trial. After ICA decomposition, frontal and parietal components were selected from the independent component map. Similarly, regional components were clustered for further cross-subject analysis. A new measure of event-related brain dynamics, the event-related spectral perturbation (ERSP), estimates the mean magnitude in the brain dynamics of the EEG frequency spectrum with experimental events. In this study, all events were time warped to average time intervals. The heart rate variability estimation procedure was proposed by prior researchers, and has been modified in the current study [17].

One-way analysis of variance (ANOVA) is a statistical method for comparing multiple data with only one independent variable. Two-way repeated measures ANOVA examines the influence of two different independent variables. The cross subject ERSP power under the aforementioned four different cases was divided into small portions by events and frequency bands for the ANOVA tests. Both stress and task effects and interactions were examined by two-way repeated measures ANOVA.

B. BEHAVIORAL ASSESSMENT

The state version of the STAI scores significant increased in the feedback (stress) session. The two-way ANOVA yielded a significant main effect of stress [$F = 5.207$, $p < 0.05$], indicating the participants' subjective perceived stress level. The response time significantly decreased in the feedback session. The two-way ANOVA results revealed the significant main effects of stress [$F = 23.504$, $p < 0.001$] and task [$F = 13.052$, $p < 0.01$] as shown in figure 2. The participants responded faster in the stress conditions, and the participants responded more slowly in the mixed task. The response time significantly decreased in the feedback session in both the non-switching and switching trials. The two-way ANOVA results revealed significant main effects of stress [$F = 17.825$, $p < 0.001$] as shown in figure 3.

The response time significant decreased in the feedback session in both the non-switching and switching trials. The two-way repeated measures ANOVA results revealed significant main effects of stress [$F = 22.563$, $p < 0.001$] as shown in figure 4. A significant difference [$F = 8.657$, $p < 0.05$] was found in the mixed effect. These results indicate that the mixed trials resulted in a longer response time. There is sufficient evidence to prove that accuracy significantly decreased in the mixed session. The two-way repeated measures ANOVA evaluated that the main effects of the task reached a significant level [$F = 15.218$, $p < 0.01$], indicating a greater loss of accuracy in the mixed session compared to the single session.

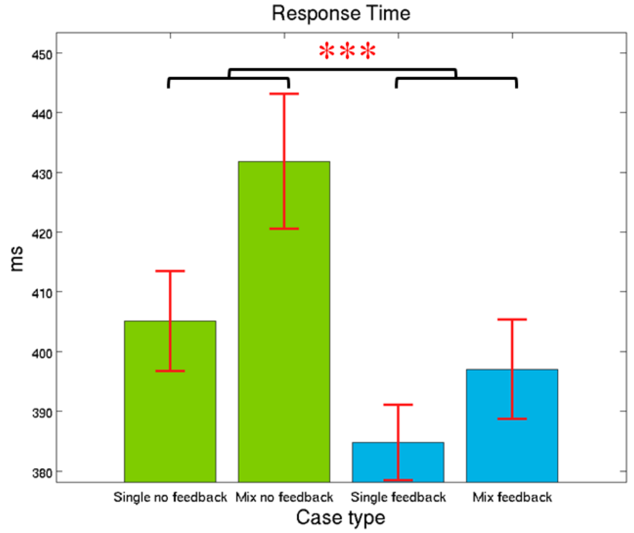

FIGURE 2. Stress Effect of Response Time. The bar chart and red error bars denote the mean and standard error values, respectively. (* p < 0.05; ** p < 0.01; *** p < 0.001).

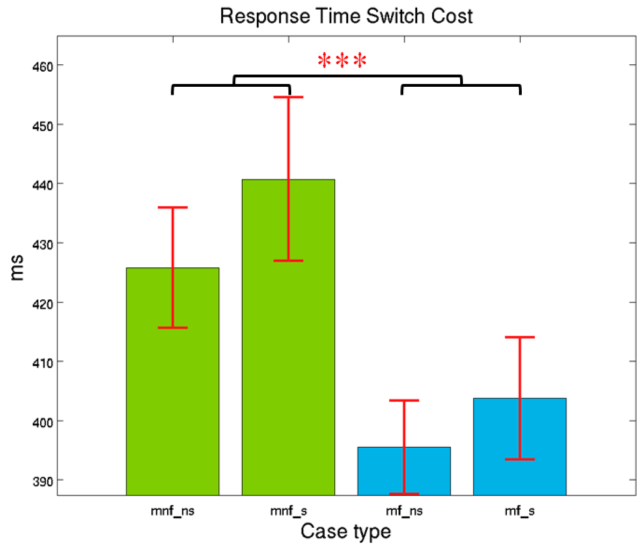

FIGURE 3. Switching Effect of Response Time. The bar chart and red error bars denote the mean and standard error values, respectively. (* p < 0.05; ** p < 0.01; *** p < 0.001) (mnf_ns: mixed no feedback non-switch; mnf_s: mixed no feedback switch; mf_ns: mixed feedback non-switch; mf_s: mixed feedback.

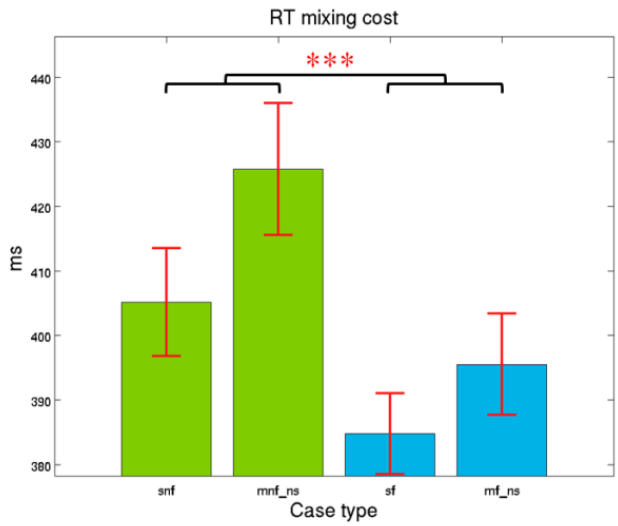

FIGURE 4. **Mixing Effect of Response Time. The bar chart and red error bars denote the mean and standard error values, respectively. (*$p < 0.05$; **$p < 0.01$; ***$p < 0.001$) (snf: single no feedback; mnf_ns: mixed no feedback non-switch; sf: single feedback; mf_ns: mixed feedback non-switch).**

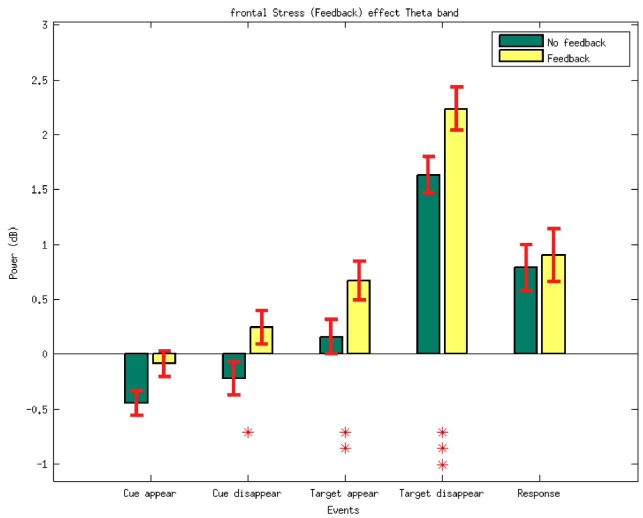

FIGURE 5. **Frontal Stress Effect of Theta Band. The bar chart and red error bars denote the mean and standard error values, respectively. (*$p < 0.05$; **$p < 0.01$; ***$p < 0.001$).**

C. PHYSIOLOGICAL ASSESSMENT

There are three important findings from the physiological assessments. Firstly, the average heart rates increased in the feedback session. The ANOVA results demonstrated the significant main effect of stress [$F = 30.213$, $p < 0.001$], which showed that heart rate accelerated due to acute stress. Secondly, a significant main effect of stress is revealed across all subjects [$F = 4.997$, $p < 0.05$]. The normalized low frequency of heart rate variability was raised by perceived stress in the feedback conditions. Thirdly, cortisol secretion failed to reach any significance levels in the one-way ANOVA test.

D. FRONTAL COMPONENT

The stress effect of the theta band was significant at baseline [$F = 10.03$, $p < 0.01$], cue disappear [$F = 7.59$, $p < 0.05$], target appear [$F = 10.13$, $p < 0.01$], and target disappear stages [$F = 19.99$, $p < 0.001$], but not on the others as shown in figure 5. The baseline theta power was suppressed in stressful conditions, while theta power constantly increased with time and reached its peak before a response was given by the participant. This clearly indicates the effect of stress. The task main effect of the theta band was significant at baseline [$F = 15.83$, $p < 0.01$], cue disappear [$F = 4.57$, $p < 0.05$], and target disappear stages [$F = 5.43$, $p < 0.05$], but not on the others.

The stress main effect of the alpha band was significant at baseline [$F = 6.03$, $p < 0.05$] and target disappear stages [$F = 5.02$, $p < 0.05$], but not on the others. Alpha power was enhanced at the target disappear stage, indicating that anxiety or stress-related activities resulted in a short period before a response. The task main effect of the alpha band was significant at the baseline [$F = 8.9$, $p < 0.01$] period, but not on the others. Only one significant interaction of the alpha band was observed [$F = 10.5$, $p < 0.01$] at the baseline period. The results from the post hoc analysis indicated that the comparison between the mixed no feedback condition and the mixed feedback condition [$p < 0.01$] was significant. The stress effect of the gamma band was significant at the baseline [$F = 10.33$, $p < 0.01$] and response [$F = 5.05$, $p < 0.05$] stage, but not on the others. Gamma baseline power increased in the feedback sessions, which was associated with negative valence [18].

E. PARIETAL COMPONENT

The task effect of the theta band was significant at baseline [$F = 13.55$, $p < 0.01$], target appear [$F = 6.66$, $p < 0.05$], target disappear [$F = 35.5$, $p < 0.001$] and response [$F = 23.5$, $p < 0.001$] stages, but not on the others. The task effect of the alpha band was significant at baseline [$F = 18.2$, $p < 0.001$], target disappear [$F = 7.69$, $p < 0.05$] and response [$F = 13.74$, $p < 0.01$] stages, but not on the others. There was significant interaction between the alpha band at baseline [$F = 13.43$, $p < 0.01$] and cue disappear [$F = 5.67$, $p < 0.05$] stages. The results from the post-hoc analysis indicate that there is a significant difference between the mixed no feedback condition and the mixed feedback condition [$p < 0.01$]. The stress effect of the gamma band was significant at the baseline [$F = 17.84$, $p < 0.001$] stage.

F. BEHAVIOR AND EEG CORRELATION

It is interesting to note that frontal midline alpha power is positively correlated to STAI-T scores at cue disappear [$r = 0.56$, $p < 0.05$], target appear [$r = 0.499$, $p < 0.05$] and target disappear [$r = 0.534$, $p < 0.05$] stages in the stress session.

IV. DISCUSSION ON BEHAVIORAL AND PHYSIOLOGICAL INDICATORS

The STAI-S scores clearly showed that the participants' stress levels increased. Acute stress improved the response time but there was no significant change to accuracy due to stress. The results show that acute stress enhanced executive function performance. Similar findings of improved performance during a stressful period were observed in [19]. Several studies found that under stressful conditions, heart rate and low frequency heart rate variability increased [10], [11], [20].

Cortisol secretion did not reach a significant level in this study [$p > 0.05$]. Earlier investigations show that cortisol is an indicator of physiological stress [21]. However, other studies found that there was no change to cortisol levels under stress [22]. Neary *et al.* [23] show that there is a high correlation between the cortisol levels in serum, saliva, and urine. One explanation for this is that different kinds of stressors or stressful tasks may affect cortisol secretion [9], [24].

A. STRESS EFFECTS

The bseline power of the frontal midline theta significantly decreased under stressful circumstances. Several existing studies have examined the phenomena of stress-related frontal midline proofread theta. These reports judged the appearance of frontal midline theta with criteria. Nevertheless, about half of participants excluded from this report due to only satisfied the criteria sometimes in the three consecutive days' experiment [12]. It is certain that frontal midline theta power is quite suitable for replacing the criteria. The advantage of estimating frontal midline theta power is that it can be used to assess stress levels. The findings of this research show that alpha power mirrors the trait anxiety of human beings. It is widely accepted that alpha activity reflects brain idling [13], however recently an increasing number of studies has shown that there is a close relationship between alpha activity and anxiety [14], [25].Our results show that alpha power correlates with anxiety and is most pronounced in the frontal lobe. Cooper *et al.* [26] asserted that alpha activity was more likely to represent inhibition and attention, but their results were incongruent with brain idling hypotheses, hence they suggested that alpha power was related with attention. It seems reasonable that one may pay more attention when they are in a stressful state.

Our results show that gamma baseline power significantly increased in stressful conditions across the frontal and parietal regions. There is much evidence to show that negative emotions or anxiety increase gamma baseline power [15], [16], [18]. Muller *et al.* [16] examined gamma (30∼90 Hz) band power and suggested that a gamma band from 30∼50 Hz is suitable for evaluating negative emotions at the right frontal site and is most pronounced at 40 Hz. During the stressful task switching trial period, the frontal midline theta constantly and stably increased from the time the cue disappeared to the time a response was given. It is interesting to note that the frontal midline theta rhythm is associated with focused attention [27]. In line with the existing research, our results show that frontal midline theta power increased, which may indicate more focused attention. The following four findings show how performance improved as a result of stress:

- (i) Working memory capacity affected response time and accuracy [28];
- (ii) Attentional abilities are associated with working memory capacity [29];
- (iii) People pay more attention during stressful conditions which enhances performance [30].
- (iv) Focused attention may result in a faster response time and better performance during stressful periods.

The results of this current work do not indicate any significant impairment to working memory when the participants were exposed to stressful situations. Studies have found that working memory is impaired by stress at high loads, but not at low loads [2]. More noteworthy was the work which proposed the Inverted-U Hypothesis model or Yerkes–Dodson law for stress effects, which describes the relationship between stress-induced arousal levels and the level of performance [31].

B. TASK EFFECTS

In our study, the theta baseline power increased in the mixed session at the frontal and parietal sites, which is in line with the results observed in earlier investigations on task switching [5]. There is further evidence to suggest that working memory involves frontal and posterior cortex synchronization [6]. Alpha suppression was found when the target disappeared at the parietal region in the mixed condition in the current experiment. The same observation was made in previous task-switching experiments [5] and also alpha desynchronization is correlated with task performance [32].

C. INTERACTIONS

The results of our experiment show that alpha power was higher in the mixed no feedback condition compared to the mixed feedback condition at the frontal and parietal sites during the baseline stage. Alpha power synchronization was shown to be linked to cortical inhibition. The most likely explanation for this is that the mixed trial switched between two task-set rules. When switching the task-set rule, one may need to inhibit irrelevant task rules. Acute stress may impair the ability of inhibition. However, no significant impairment to behavioral data was observed in the mixed feedback sessions.

V. CONCLUSION

The aim of this study was to design a task-switching experiment to investigate executive functions during acute stress. Based on the behavioral and physiological data, we can say with reasonable certainty that acute stress was successfully induced in the present study. Mental stress resulted in more focused attention which led to faster response times without sacrificing accuracy. Both heart rate and normalized low frequency of heart rate variability significantly increased in stressful conditions but there was no difference to cortisol secretion.

The EEG results indicate that acute stress had an impact on the frontal and parietal sites, across a wide frequency range, especially in theta, alpha and gamma bands. Executive functions, such as working memory, enable a person to quickly search for information. With a high working memory capacity, one may respond faster and with a high level of accuracy. Based on the Yerkes–Dodson law, our study produced an appropriate level of acute stress which was shown to enhance performance.

It is suggested that chronic stress may have a similar pattern on brain dynamics. To improve healthcare, it is vital to be able to measure stress levels. The phenomena observed in the present study can be used as an indicator to predict chronic stress levels. To avoid conditions caused by stress such as depression, these indicators are useful to identify an unacceptable level of stress.

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