Effects of acute stress on pilots' working memory

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Abstract

Stress has been shown to influence working memory (WM). However, little is known about the effects of acute stress on pilots' WM with varying WM loads. The current study aims to shed more light on this issue. Forty-two pilots were randomly assigned to the stress or the control group. The stress group experienced acute stress induced by the modified Trier Social Stress Test (TSST), and the control group did not receive any stress induction. Then, all participants performed N-back tasks under varying levels of WM load (0-back, 1-back, and 2-back) to examine their WM. We measured their State-Trait Anxiety Inventory scores and salivary cortisol concentrations repeatedly throughout the experiment to determine the effects of induced stress. The results showed that (1) the modified TSST effectively induced acute stress in the stress group; (2) as the WM load level increased, the reaction time increased, and the accuracy decreased; and (3) there were no significant differences in reaction time between the two groups at different WM load conditions. However, there was an interaction effect for accuracy, which showed that the accuracy of the stress group was higher than that of the control group at the medium WM load (1-back). These findings suggest that acute stress improves pilots' WM accuracy during moderately difficult tasks. The results of this study provide a theoretical basis for improving stress management and training pilots' WM abilities.

1 Introduction

Stress is a systemic, nonspecific response to a real or potentially threatening stimulus and can be divided into chronic and acute stress depending on its generation and duration[1]. Acute stress is a short period of psychophysiological and behavioral changes resulting from a sudden, violent stimulus. The hypothalamic-pituitary-adrenal axis (HPAA) is the slow response system in humans, and its activation results in the release of glucocorticoids (primarily cortisol in humans) into the bloodstream. Cognitive function is often impaired during acute stressors, resulting in reduced cognitive flexibility(Shields et al., 2016) and difficulty in memory extraction(Smeets, 2011).

The Trier Social Stress Test (TSST) has been employed to induce stress(Kirschbaum et al., 1993). It consists of a videotaped free speech and a subsequent mental arithmetic task in front of a nonresponsive audience (total duration: 15 min). In the nonstressful control condition, participants were instructed to read magazines and perform simple mental arithmetic tasks for a comparable period of 15 min. The TSST is a well-established laboratory paradigm that reliably elicits an increase in HPAA response(Dickerson and Kemeny, 2004; Kuhlmann et al., 2005).

Working memory (WM) refers to the structures and processes used to temporarily store and manipulate information(Cowan, 2017) that play an essential role in cognitive activity. The N-back task is the classical paradigm for measuring WM(Owen et al., 2010). In the N-back task, a series of stimuli are presented, and participants are asked to judge whether the stimulus presented in the present matches the one presented in N items before. It has been shown that the WM load can be varied by manipulating the value of N; the higher the N value is, the higher the load level. Therefore, changing the N value modulates the task's effectiveness.

Researchers have explored the relationship between acute stress and WM, but it remains controversial. On the one hand, exposure to acute stress impairs WM(Eawa et al., 2019; Jiang and Rau, 2017; Schoofs et al., 2008; Schoofs et al., 2009). On the other hand, some researchers have found that acute stress enhances WM(Cornelisse et al., 2011; Duncko et al., 2009). A recent study showed that this paradoxical effect might be related to the load level of working memory(Yu et al., 2015). Working memory, as a higher-level cognitive ability, is a key executive function for handling flight requirements and acquiring and maintaining situation awareness(Cak et al., 2020).

In aviation activities, the ability of pilots to execute standard operating procedures (SOPs) can be affected by WM. However, when pilots encounter emergencies, such as engine failure, low fuel levels, and bird strikes, acute stress may impair their working memory and lead to human error. For example, the Little Rock air disaster in June 1999 in the U.S. was caused by the impaired WM of pilots under acute stress, which caused pilots to forget SOP procedures and open the spoilers.

As mentioned above, acute stress impairment and improvement effects on WM have been found. How are pilots' WMs affected by acute stress, and does memory load moderate the relationship between the two? That question still needs to be answered. Therefore, this study used a modified TSST to induce acute stress in pilots and an N-back task to test pilots' WM under different WM load conditions. Additionally, WM was compared with that of control pilots who did not experience acute stress. In this study, it was hypothesized that reaction time would increase and accuracy would decrease as the WM load increased, regardless of whether the pilots were under acute stress; at high levels of working memory load, the control group would react with higher accuracy and shorter reaction time than the stress group. To assess the effects of acute stress induction, State-trait Anxiety Inventory scale (S-AI) scores and salivary cortisol samples were collected at baseline and at various time delays. The aim of this study is to enhance pilots' attention to cognitive abilities under acute stress, strengthen their management of WM under stress, and reduce the hazards associated with acute stressful events during flight missions.

2 Material and methods

2.1 Participants

According to G*power calculations(Faul et al., 2007), a total sample size of at least 28 individuals was required to provide sufficient power to detect a medium size effect ($f = 0.25$) with 80% power and a significance level of $\alpha = 0.05$. We recruited Forty-two healthy male pilots (aged 21–25 years) with normal or corrected-to-normal vision participated in this study. The target population of this study is pilots, who are a special occupational group that often face high-intensity work stress and challenges. Therefore, we mainly selected male participants, as this profession is currently dominated by males. Participants all received commercial aviation licenses from the Civil Aviation Administration of China (CAAC) and logged an average of more than 230 hours of flight in simulators and in real aircraft. The participants were randomly assigned to stress and control groups before the experiment, and both groups were matched on flight hours, age, and education, with 21 participants in each group. They were paid a fee after the experiment. The Ethics Committee of the Civil Aviation Flight University of China approved this study. Written informed consent was given by each participant.

2.2 Experimental design

2.2.1 Procedure

The experiment consisted of two parts: the Trier Social Stress Test (TSST) and the N-back task. First, the stress group participated in a modified TSST, and the procedure for the control group was the same as TSST but without stress induction. The second part was the N-back task, which tested WM.

In this study, State-Anxiety Inventory (S-AI) scores and salivary cortisol concentrations were selected as indicators of acute stress, and accuracy and reaction time were used as indicators of WM. Participants were informed not to exercise strenuously and to abstain from drinking alcohol 24 hours before the experiment and to abstain from eating and smoking 2 hours before the experiment. Three S-AI scores and three saliva samples were collected three times throughout the experiment: 5 min after the participant's meditation (baseline), after the TSST, and after the N-back task. The study was a 2 (group: stress and control groups) $\times$ 3 (WM load: 0-back, 1-back, and 2-back) mixed experimental design, with 'group' as a between-subjects variable and 'load level' as a within-subjects variable.

2.2.2 TSST procedures

The TSST requires participants to complete several tasks, including a short preparation time, a videotaped free speech, and a mental arithmetic task(Kirschbaum C. et al., 1993). In this study, the modified TSST paradigm was appropriately adapted to the pilots' characteristics, including preparation time (2 min), an interview (5 min), and a mental arithmetic task (5 min). During the preparation phase, participants could peruse the interview questions. The questions were selected from the oral proficiency interview of the international civil aviation organization (ICAO) and the oral assessment questions of the practical examination, which experts used to form six questions. In the interview phase, participants were randomly selected to answer the questions in front of the experts. In the mental arithmetic phase, participants were asked to report the results quickly and accurately (e.g., starting from 2031, perform the mental arithmetic task in decreasing order of 18). Before the TSST, the stress group was informed that they would be videotaped and scored. Two experts (a psychologist and flight instructor) were invited to record and evaluate the participant's performance and posture. The experts wear uniforms and work permits, maintain a neutral expression throughout the process, and make specific reactions when necessary. Comparable to the stress group, the pilots of the control group participated in a similarly physically and mentally demanding task. In the preparation phase, participants perused material about civil aviation. In the interview phase, participants read the material at a normal speed. In the mental arithmetic task, participants only had to perform simple addition (e.g., mental arithmetic in successive increments of 5 starting from 3). Throughout the entire process, the experts did not wear formal attire, the tasks were not videotaped, and the pilots were not evaluated. It lacked the stress-inducing components of the TSST.

2.2.3 N-back tasks

After the TSST (stress induction vs. control situation), the WM performance of the participants was tested with an N-back task. Participants were conducted into a quiet and dimly lit room, approximately 60 cm from the display. The stimuli were presented on a 17-inch display with a resolution of 1024*768 pixels and a refresh rate of 60 Hz using the software E-prime 2.0. The experimental stimuli were all presented on a black background, and the stimulus was a white digit (e.g., 1˜9). The practice block consisted of 3 blocks of 60 stimulus trials with feedback. It was ensured that participants understood the instructions before the formal experiment. The formal experiment consisted of 3 blocks of low (0-back), medium (1-back), and high WM load (2-back), with each block having a total of 180 trials. Of these, 1/3 of the trials were digits that required the participants to perform an "A" key response. The stimulus was presented for 500 ms, followed by a "+" fixation for 1500 ms, for a total response time range of 2000 ms. Participants pressed the "A" and "L" keys with the index finger of their left and right hands, respectively.

In the 0-back condition, participants were asked to determine whether the current stimulus was the same as the first stimulus at the beginning of the experiment and if it was the same, press key A; if not, press key L. In the 1-back condition, participants were asked to determine whether the current stimulus had appeared one position back in the sequence, and if it was the same, press key A, if not, press key L. In the 2-back condition, participants were asked to determine whether the current stimulus was the same as the second stimulus backward in time, and if it was the same, press key A, if not, press key L.

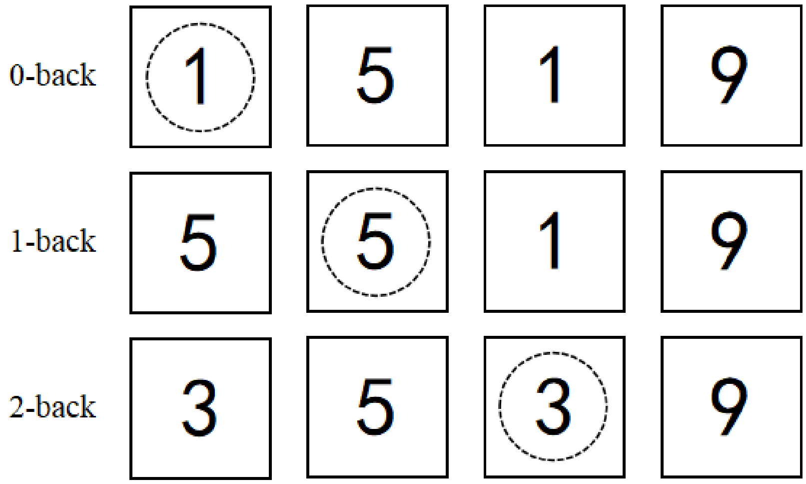

Figure 1 Example of the N-back task with the stimulus material used in the experiments.

2.3 Data analysis

Cortisol concentrations and SA-I scores were used as indicators of stress levels. A 2 (group: stress and control groups) × 3 (measurement time points: baseline, post-TSST, and post-N-back task) repeated-measures ANOVA was performed on the data. To calculate the mean accuracy and reaction time for all participants, a 2 (group: stress and control groups) × 3 (WM load: 0-back, 1-back, and 2-back) repeated-measures ANOVA was performed on the data. Greenhouse–Geisser corrected p values were used when appropriate.

3 Results

3.1 S-AI scores

There was a significant main effect of group (F (1, 40) = 13.40,p = 0.001, $\eta_{\pi}{}^{2} = 0.25$), and the S-AI scores were significantly higher in the stress group than in the control group; the main effect of time was also significant (F (2, 80) = 17.37, $p < 0.001$,$\eta_{\pi}{}^{2} = 0.30$), and the S-AI scores were significantly higher after the TSST (38.36 ± 11.53) than at baseline (31.76 ± 6.68) and after the N-back task (34 ± 9.53). There was a significant interaction between group and time (F (2, 80) = 12.91, $p < 0\ .001$,$\eta_{\pi}{}^{2} = 0.24$). Further analysis revealed that the S-AI of the stress group (45.71 ± 11.30) was significantly higher than that of the control group (31.00 ± 5.57) after the TSST ($p < 0.001$, $d = 0.42$).

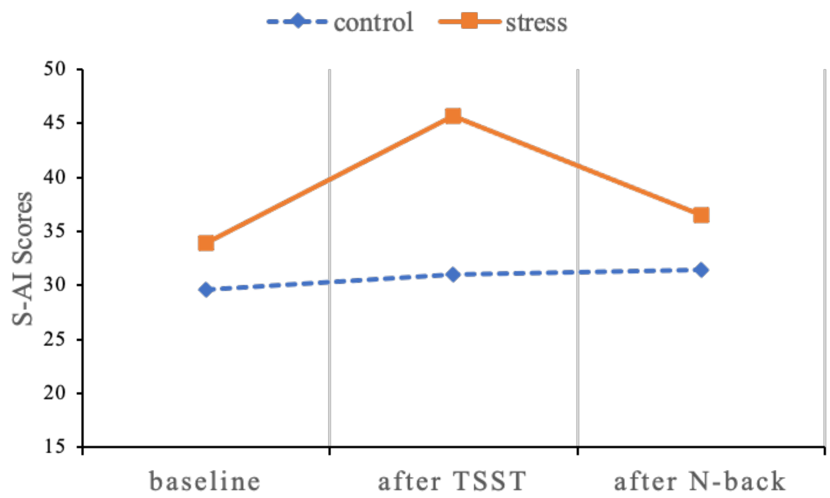

Figure 2 S-AI scores for stress and control pilots at baseline and after the TSST and the N-back task.

3.2 Cortisol concentrations

There was a significant main effect for group (F (1, 40) = 148.54,p < 0.001, η_{π} ^{2}= 0.79). Cortisol was significantly higher in the stress group than in the control group. The main effect of time was significant (F (2, 80) = 28.16, p < 0.001,η_{π} ^{2} = 0.41); cortisol was significantly higher after the TSST (10.68 ± 5.13) than it was at baseline (6.09 ± 4.91) and after N-back tasks (7.4 ± 4.9). The interaction between group and time was also significant (F (2, 80) = 11.2, p < 0.001,η_{π} ^{2} = 0.22). Further analysis revealed that cortisol was significantly higher in the stress group after the TSST than at baseline (p < 0.001), but there were no significant differences between the two time points in the control group (p > 0.05).

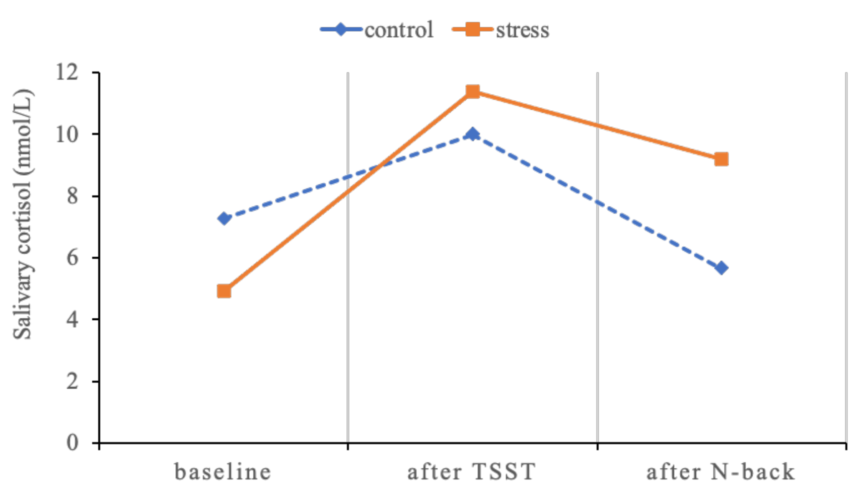

Figure 3 Mean salivary cortisol concentrations (nmol/L) for stress and control pilots at baseline and after the TSST and the N-back task.

3.3 Behavioral data

3.3.1 Reaction time (RT)

The main effect of WM load was significant (F (2, 80) = 75.49,p < 0.001, η_{π} ^{2}= 0.6). RT in 1-back tasks (525.67 ± 121.50 ms) was significantly longer than in 0-back tasks (441.64 ± 68.14 ms), and RT in 2-back tasks (645.86 ± 166.36 ms) was significantly longer than 0-back and 1-back tasks. The main effect for group was not significant (F(1, 40) = 0.69,p = 0.41). The interaction of Group and WM load was not significant (F (2, 80) = 1.43, p = 0.26).

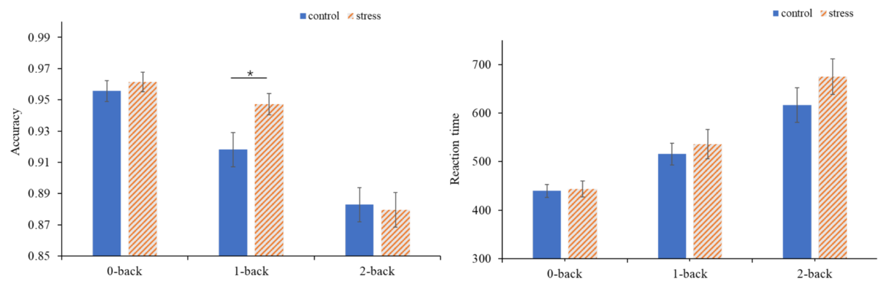

Figure 4 Mean reaction time and accuracy in the 0-back, 1-back, and 2-back conditions.

3.3.2 Accuracy

The main effect of WM load was significant (F (2, 80) = 69.94,p < 0.001, η_{π} ^{2}= 0.64). Accuracy in the 0-back tasks (0.96 ± 0.03) was significantly higher than in the 1-back (0.93 ± 0.04) and 2-back tasks (0.88 ± 0.05), and it was significantly higher in 1-back tasks than in 2-back tasks. The main effect for group was not significant (F (1, 40) = 1.04,p = 0.31). The interaction of group and WM load was significant (F (2, 80) = 3.15, p = 0.048,η_{π} ^{2} = 0.07). Further analysis revealed that the stress group had a significantly higher accuracy (0.95 ± 0.02) than the control group (0.92 ± 0.02) in the 1-back task (p = 0.03, η_{π} ^{2} = 0.11).

4 Discussion

The present study focused on the effects of acute stress on pilots' WM. The results showed that the stress group scored significantly higher on the S-AI after the TSST than the control group; compared to baseline, the stress group had elevated cortisol concentrations after the TSST, with no significant differences observed for the control group. This suggests that the modified version of the TSST paradigm used in this study was effective in inducing stress in pilots. The results of the WM test showed that as the WM load increased, the participants' reaction time increased, and accuracy showed a gradual decrease. This is consistent with the results of most previous studies, where the strain on WM was elevated when the memory load in the N-back task was increased(Itthipuripat et al., 2012). Studies that have used EEG techniques found that the EEG components associated with WM updating were impaired at high-load levels in participants under acute stress(Gärtner et al., 2014), which may help explain the decreased performance on the N-back task.

It was also found that there were no significant differences in reaction times between the stress and control groups for the three memory load conditions. In terms of accuracy results, there were no significant differences between the two groups of pilots with the low/high memory load, but there was a significant difference with the medium memory load, with the accuracy being higher in the stress group than in the control group. In other words, when the pilots were under acute stress, their accuracy was significantly enhanced when they completed the medium memory load task. The effect of acute stress on WM is moderated by WM load. This is partially consistent with the results of previous related studies. For example, Cornelisse (2011) et al. found that acute stress could increase WM levels in a group of male participants under moderate memory load conditions. Specifically, male participants had faster reaction times in the moderate memory load condition after completing the TSST. Although there was no significant increase in accuracy, the performance of the stress group was better than that of the control group. Duncko et al. (2009) similarly found that the stress group had significantly faster reaction times in the high cognitive load condition than the control group. When reviewing the controversial results regarding the effects of acute stress on WM under different memory loads, one researcher found that acute stress impaired WM under high memory load conditions(Schoofs et al., 2008). Some researchers have also found that stress impaired cognitive tasks only when memory load was low(Yu et al., 2015). We speculate that three main causes are responsible for this.

First, acute stress is induced in different ways. Previous studies have found that different methods (psychological, physiological, and pharmacological) can lead to different intensities and durations of acute stress(Li and Ku, 2020), which may affect the response time and accuracy of WM. In this study, we used the modified version of the TSST, which is psychological. The induced acute stress levels were considered moderate compared to the potential levels that could be induced by physical and pharmacological interventions. Pessoa et al. (2009) found that a moderate intensity of emotion enhanced cognitive task performance, while a high intensity of emotion impaired task performance(Pessoa, 2009). Therefore, we hypothesized that moderate acute stress might produce similar results. It is worth noting that the relationship between individual stress levels and job performance follows an inverted U-shaped curve and is also influenced by task difficulty(Broadhurst, 1957). In this study, moderate stress levels led to better job performance when performing moderately difficult tasks. Thus, the stress flight group had higher accuracy WM when completing the moderately difficult task (1-back) than the control group.

Second, the participants were different. Some researchers have found that sex, occupation, and mental state also influence the effects of acute stress on WM(Cornelisse et al., 2011; Gärtner et al., 2014). The participants of this study are pilots whose long-term training helped them to have better WM. In addition, the study used a digital N-back task, where pilots are more sensitive to digital information such as radio frequency, altitude, and speed. Therefore, we assume that the pilots in this study had a different difficulty level for the memory load task than other subjects. This may explain the inconsistency with previous studies.

Finally, the present study explored the behavioral results of WM. However, some studies have found that there were no significant differences in behavioral results, but there were significant differences found in neurological results(Han et al., 2013; Yu et al., 2015). For example, in a study by Zhang et al. (2015) examining whether the effects of acute stress on WM were moderated by WM load, no interaction was found between the group and WM load on reaction time. However, EEG results revealed that the P3 component induced in the acute stress group was found to be significantly greater than that of the control group in the low WM load condition. We speculate that the behavioral results may not yet reflect differences in WM because brain neurological techniques such as EEG and MRI were not used in this study.

We acknowledge that our sample selection has some limitations, as it does not represent all pilots or other occupational groups, and lacks diversity in terms of gender, age, education, etc. This may affect the generalizability and universality of our research findings. Future studies can consider increasing the number of female or other background participants to improve the quality and validity of the research.

In summary, we found that acute stress enhances the accuracy of WM for pilots under moderate memory load. According to the Yerkes-Dodson law, the effect of stress on hippocampal and prefrontal cortex-dependent memory follows an inverted U-shaped curve(Broadhurst, 1957). According to the Yerkes-Dodson law, moderate levels of stress promote memory function, while high levels of stress impair memory function(Luethi and Mathias, 2008). After the flight stress group completed the TSST task, moderate stress levels instead promoted them to perform better on moderately difficult WM tasks. The ability of pilots to correctly recall SOPs and operate them accurately after an unexpected event is particularly important for flight safety.

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Declaration of competing interest

The authors have no financial interests or conflicts of interest to disclose.

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