STRESS AND MEMORY RETRIEVAL

DO THE BENEFITS OF RETRIEVAL PRACTICE REMAIN UNDER STRESS?

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A Thesis Submitted to the School of Graduate Studies in Partial Fulfillment of the Requirements

for the Degree Master of Science

McMaster University MASTER OF SCIENCE (2018), Hamilton, Ontario (Psychology, Neuroscience & Behaviour)

TITLE: Do the Benefits of Retrieval Practice Remain Under Stress?

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NUMBER OF PAGES: xI, 45

LAY ABSTRACT

Stress is a ubiquitous experience in the student population. This is concerning, as stress impairs memory functioning. Since memory functioning largely determines academic success, stress prevents students from fulfilling their academic potential. But this impairing effect of stress may not always emerge. Recent research has shown that stress does not impair memory performance if students learn information by practicing retrieval. This has been coined as an inoculation effect. Though surprising, this may simply result from automatizing the retrieval process. This study sought to replicate this finding using ecologically valid materials and test whether the inoculation effect occurred as a byproduct of automatizing the retrieval process. . Altogether, this study adds to a longstanding literature reporting negative effects of stress on cognition and adds to a new literature that investigates ways to nullify the effects of stress on memory performance.

ABSTRACT

Stress is a ubiquitous experience in the student population. This is concerning, as stress impairs memory functioning. Since memory functioning largely determines academic success, stress prevents students from fulfilling their academic potential. But this impairing effect of stress may not always emerge. Recent research has shown that stress does not impair memory performance if students learn information by practicing retrieval. This has been coined as an inoculation effect. Though surprising, this may simply result from automatizing the retrieval process. This study sought to replicate this finding using ecologically valid materials and test whether the inoculation effect occurred with multiple-choice questions (MCQs). Participants learnt a passage by either restudying it or by practicing retrieval. They returned two days later and completed the Trier Social Stress Test or a control version. They then freely recalled the passage and completed the MCQs. Although the results are preliminary, the trends in the data indicate that stress had no effect on free recall performance or MCQ performance when information was learnt by practicing retrieval. This result is discussed along with this study's limitations. Post hoc analyses are also discussed with future research directions. Altogether, this study adds to a longstanding literature reporting negative effects of stress on cognition and adds to a new literature that investigates ways to nullify effects of stress on memory performance.

ACKNOWLEDGEMENTS

I would like to thank Joseph Kim for introducing me to the field of education and cognition and encouraging me to pursue my research interests. I would also like to thank members from the Shore and Milliken labs for giving me great insight and feedback in designing my projects and to my supervisory committee, Scott Watter and Ayesha Khan, for their guidance. I would also like to extend my gratitude to Dr. Meghan McConnell for helping me in the beginning of my graduate education. I would also like to thank members of the Applied Education and Cognition lab who helped me conduct my projects and listen to my long discussions about research. Finally, I would like to thank the Canada Graduate Scholarship Program for allowing me to pursue my research interests and make this thesis possible.

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LISTS OF ABBREVIATIONS AND SYMBOLS

ANS: Autonomic Nervous System

CPT: Cold Pressor Test

f-TSST: friendly Trier Social Stress Test

MR: Mineralcorticoid Receptor

GR: Glucocorticoid Receptor

LTP: Long-Term Potentiation

MCQ: Multiple-Choice Question

SECPT: Socially Evaluated Cold Pressor Test

STICSA: State-Trait Inventory for Cognitive and Somatic Anxiety

TSST: Trier Social Stress Test

DECLARATION OF ACADEMIC ACHIEVEMENT

I, Sebastian Sciarra, declare this thesis to be my own work. I am the sole author of this work. This thesis was completed under the supervision of Dr. Joseph Kim and with the help of my supervisory committee, which included Dr. Scott Watter and Dr. Ayesha Khan. A special thanks is also extended to Dr. Meghan McConnell.

Introduction

Stress permeates nearly every daily task. Employees often rush to work in the morning and rush along the same route after work, while having undoubtedly completed a task in a slapdash manner during the day. When at home, the typical adult then rushes their supper to enjoy their downtime Sand then rushes to sleep. Though this is a caricature of a typical day, it emphasizes how stress has become an all-too familiar experience in contemporary society.

This trend is patent in university students. Several reports have found high levels of stress in university students. A 2011 survey at the University of Alberta found that over half the students felt overwhelmed with anxiety and hopelessness at least once over the past year (Lunau, 2012). A survey at a Turkish university found that 47% of respondents reported moderate-to-severe anxiety and 27% reported moderate-to-severe stress (Bayram & Bilgel, 2007). A recent survey at McMaster University found that almost 90% of students felt overwhelmed and 50% felt overwhelmed with anxiety (Craggs, 2012).

The stress response

Stressful events have three components (Kim & Diamond, 2002): 1) they trigger a heightening in arousal, 2) they are perceived as aversive, and 3) they are perceived as uncontrollable. This is echoed in a meta-analysis of 208 laboratory studies using acute psychosocial stressors, which found stressors elicited the largest cortisol responses when they were uncontrollable, required immediate engagement (i.e., arousal), and evaluated performance such that an important aspect of one's identity could be negatively evaluated (i.e., perceived as aversive; Dickerson & Kemeny, 2004). One stressor that satisfies these

three criteria and elicits the largest cortisol response among the acute stressors is the Trier Social Stress Test (TSST). Participants deliver a 5-minute speech in front of an evaluative triumvirate while being recorded. Delivering a speech triggers arousal. Doing so in front of a triumvirate while being recorded incorporates social-evaluative threat. Finally, ensuring the speech lasts 5 minutes—a nearly impossible task—incorporates an element of uncontrollability.

Situations that satisfy these three components trigger a cascade of events that, in toto, constitute the stress response (for a review, see Joëls & Baram, 2009). This response comprises the activation of two systems: a fast-acting autonomic nervous system (ANS) and a slow-acting hypothalamic-pituitary-adrenal (HPA) axis. The ANS quickly triggers the release of catecholamines such as adrenaline and noradrenaline from the locus coeruleus and adrenal medulla, while the HPA axis triggers the release of glucocorticoids from the adrenal cortex into the bloodstream. Catecholamine levels rise within minutes, whereas glucocorticoid levels peak 20-40 minutes following stressor onset and thus exert delayed effects (Dickerson & Kemeny, 2004). The lipophilicity of glucocorticoids allows them to bypass the blood-brain barrier and bind to two types of receptors in the brain (Reul & de Kloet, 1985): mineralocorticoid (MR) and glucocorticoid (GR) receptors. MRs have far higher affinities than GRs and so MRs are largely satiated by cortisol at baseline levels.

Though the stress response occurs in all individuals, several factors modulate the underlying mechanisms (for a review, see Kudielka, Hellhammer, & Wüst, 2009). Of

these factors, three will be discussed: sex, type of stressor, and trait anxiety. Note that sex and type of stressor are closely linked and so will be discussed together.

Type of stressor and sex. Sex differences follow from the type of stressor used. One study had male and female participants complete either an achievement or social rejection challenge. Participants completing the former challenge had to complete difficult math and verbal tasks under a time pressure and under the assumption that their peers had completed the tasks with ease. Participants in the social rejection condition completed activities with two same-sex confederates while being recorded. The confederates excluded participants from these activities. Men showed larger cortisol responses in the achievement challenge, while women showed larger cortisol responses in the social rejection challenge. No differences in self-reported state affect emerged between the sexes (Stroud, Salovey, & Epel, 2002). From a cognitive perspective, the sex differences in cortisol responses may manifest from differences in self-construals between the sexes; males value independence and performance, whereas females value interpersonal relationships (Cross & Madson, 1997). A situation that threatens these values triggers a stress response. This sex difference in cortisol response has emerged with several other studies employing the TSST—another challenge-oriented stressor (Uhart, Chong, Oswald, Lin, & Wand, 2006; Reschke-Hernández, Okerstrom, Edwards, & Tranel; Bouma, Riese, Ormel, Verhulst, & Oldehinkel, 2009). Though males show a larger cortisol response, some studies have noted larger heart rate responses in females during the TSST (Kudielka, Kuske-Kirschbaum, Hellhammer, & Kirschbaum, 2004; Heponiemi, Keltikangas-Järvinen, Kettunen, Puttonen, & Ravaja, 2004), which has led

some researchers to categorize females as cardiac reactors (Allen, Stoney, Owens, & Matthews, 1993). One notion for this finding is that females have a less effective homeostatic regulation of their heart rate (Collins & Frankenhaeuser, 1978). Since this study employs the TSST and does not measure cortisol but does measure heart rate, females are hypothesized to show greater heart rate responses than males.

Trait anxiety. A profusion of research finds higher baseline levels of cortisol levels in highly anxious (Van den Berg et al., 2008) and neurotic individuals (Portella, Harmer, Flint, Cowen, & Goodwin, 2005; Gerritsen et al., 2009; Laceulle, Nederhof, van Aken, & Ormel, 2014). Additionally, highly anxious individuals show larger cortisol responses to stressors. A study investigating cortisol responses to everyday stressors found individuals high in trait anxiety showed larger cortisol responses than their low-anxiety counterparts (Schlotz, Schulz, Hellhammer, Stone, & Hellhammer, 2006), which presumably occurred because these individuals perceived their environment as a threat. Since an increase in heart rate underlies the stress response, it is hypothesized that trait anxiety will positively correlate with one's heart rate response when under stress.

The stress-induced memory modes

The stress response exerts effects in three overlapping stages (for a review, see Wolf, 2017). The first stage occurs immediately after the stressor whereby catecholamines (mainly noradrenaline and adrenaline) exert effects within 20 minutes. The second stage captures the non-genomic effects of glucocorticoids, which exert effects 20-60 minutes following the stressor's onset. The third stage captures the slower genomic effects of cortisol, which manifest 60-180 minutes following stressor onset. These

genomic actions imply that cortisol levels continue to exert effects even after having returned to baseline levels (e.g., Schwabe & Wolf, 2014). It is important to note that the overlap between the first and second stages occurs from glucocorticoid-noradrenaline interactions in the amygdala that modulate activity in several areas, including the hippocampus and prefrontal cortex (for a review, see Roozendaal, 2000).

These three stages of the stress response induce two general memory modes (for a review, see Schwabe, Joëls, Roozendaal, Wolf, & Oitzl, 2012): a memory formation mode and a memory storage mode. This is the dual process model of stress and memory. Initially, the combined actions of noradrenaline and the non-genomic actions of cortisol induce a memory formation mode, which enhances encoding. Human studies have found enhanced encoding shortly after completing a stressor (e.g., Schwabe, Bohringer, Chatterjee, & Schachinger, 2008). This encoding enhancement presumably occurs because noradrenaline (Huang & Kandel, 1996) and non-genomic actions of cortisol (Wiegert, Joëls, & Krugers, 2006) facilitate induction of long-term potentiation (LTP)—a process central to memory formation. The genomic effects of cortisol induce a memory storage mode where learning is impaired. Human studies that administer stress long before an encoding task find impaired memory for the encoded information (e.g., Zoladz et al., 2013). This impairment presumably occurs because genomic actions of cortisol raise the threshold needed to evoke LTP (Wiegert, Shor, Joëls, & Krugers, 2005).

The effect of stress on memory retrieval

Both modes impair memory retrieval (for a review and meta-analysis, see Shields, Sazma, McCullough, & Yonelinas, 2017). Because both modes function to enhance the

encoding of an event, they suppress retrieval to prevent interfering information from contaminating the encoding of the target event. Schwabe and Wolf (2014) investigated whether both modes impaired retrieval by having participants recall previously learnt information 25 or 90 minutes after completing a stressor. Retrieval impairments emerged at both time delays, which suggests both modes impair memory retrieval. Neuroimaging studies find cortisol decreases hippocampal activity 20 minutes following stressor onset (Lovallo et al., 2010), 1 hour following stressor onset (de Quervain et al., 2003; Oei et al., 2007), and 3 hours following stressor onset (Henckens et al., 2012). Additionally, suppression of prefrontal activity has been found 1 hour (Oei et al., 2007) and 3 hours (Henckens et al., 2012) after cortisol administration. Thus, stress impairs retrieval by suppressing activity in brain regions underlying retrieval: the hippocampus and prefrontal cortex (Simons & Spiers, 2003).

Retrieval impairments from stress have emerged with a variety of stressors. As mentioned above, retrieval impairments have followed from pharmacological applications (De Quervain et al., 2003; 2000;2007), but they have also emerged from the cold pressor test (CPT; Smeets, Otgaar, Candel, & Wolf, 2008), the socially evaluated CPT (SECPT; Schwabe & Wolf, 2014), and the Trier Social Stress Test (TSST; Hidalgo et al., 2015). Thus, the effect is robust (for a review, Gagnon & Wagner, 2016).

For the purpose of providing a more comprehensive overview of the interaction between stress and retrieval, the following section will explicate the relation between sex and trait anxiety with retrieval performance.

Sex. As mentioned before, females show reduced cortisol responses to the TSST. Thus, the lack of a stress-induced retrieval impairment in females would not be anomalous. Indeed, several studies have reported a lack of a retrieval impairment in females (Hidalgo et al., 2015; Smith, Thomas, & Floerke, 2016). Therefore, it is hypothesized that females completing the TSST will exhibit memory performance comparable to that of participants who complete the control version of the TSST.

Trait anxiety. Two factors converge to predict lower memory performance in individuals high in trait anxiety than their low-anxiety counterparts. First, their elevated baseline cortisol levels may exert effects similar to those observed in chronically stressed individuals. Research on chronic stress has found it impairs LTP induction (Pavlides, Nivón, & McEwen, 2002) and causes atrophy and reductions in hippocampal volume (for a review, see Lupien, McEwen, Gunnar, & Heim, 2009). Second, chronically stressed individuals show memory impairments (Lupien et al., 2002) and studies find negative correlations between trait anxiety and academic performance in human studies (Seipp, 1991; Chamorro-Premuzic & Furnham, 2003). Thus, a negative correlation between trait anxiety and initial memory performance is hypothesized.

The testing effect

Cognitive psychology has long known about the testing effect (for a review, see Roediger & Karpicke, 2006a). This is the finding that information is better remembered when it is learnt by retrieval than by restudy. A seminal study by Roediger and Karpicke (2006b) had participants learn prose passages by either restudying them or freely recalling them. All participants then recalled the passage 5 minutes, 2 days, or 1 week later. Recall

for information learnt through retrieval was higher than information learnt through restudy at delays of 2 days and 1 week. Although cognitive researchers have forwarded several explanations for the testing effect (for a review, see Rowland, 2014), all agree that retrieval practice produces a durable memory trace that remains accessible over time. Even recent neurobiological frameworks argue that retrieval promotes rapid consolidation of information and renders later retrieval less dependent on the hippocampus by integrating it with neocortical representations (Antony, Ferreira, Norman, & Wimber, 2017).

Stress and the testing effect

Researchers have recently conducted investigations into interactions between the testing effect and stress. Hinze and Rapp (2014) conducted two experiments investigating whether stress during retrieval practice eliminated the testing effect. They had participants study a set of biology passages and then freely recall them under either a high- or low-pressure setting. Participants then returned one week later to complete a set of multiple-choice questions on each passage. Despite finding no initial impairments in initial recall, the high-pressure condition answered fewer questions than the low-pressure condition. Additionally, the high-pressure condition performed equally well as the restudy condition (who underwent no stress). Though the lack of an initial retrieval impairment from the performance pressure manipulation contradicts the dual-process model of stress and memory, this stress may have interfered with the offline consolidation of the retrieved information.

Smith et al. (2016) conducted a slightly different study whereby stress was introduced during final retrieval. Participants here initially studied a collection of words and pictures and then either continued to restudy them or learnt them through retrieval practice. Participants returned one day later to either complete the TSST or a control version and then freely recalled the stimuli from the first day. Participants who restudied the stimuli recalled less information after completing the TSST than participants who completed the control version. In contrast, participants who practiced retrieval incurred no retrieval impairment from stress. That is, learning information through retrieval practice protected later retrieval from the effects of stress. A recent study by Szõllõsi et al. (2017) sought to replicate this inoculation effect. Participants learnt word pairs by completing six cycles of restudy and retrieval practice . Importantly, feedback was provided. Participants then returned 7 days later where they either completed the TSST or a control version. When participants were categorized as cortisol responders and non-responders, responders recalled fewer word pairs than non-responders on the second day, regardless of the initial learning method. Although this means that cortisol responders recalled fewer word pairs than non-responders even when retrieval was used during initial learning, stress may have not necessarily eliminated the inoculation effect. Not only did responders learn fewer word pairs during the first session, participants also learnt word pairs through feedback. Therefore, some word pairs learnt later in the first session may have not benefitted from several cycles of retrieval practice and may have been more vulnerable to stress than word pairs learnt earlier in the first session. Some support for this notion comes from studies reporting stress-induced retrieval impairments after

participants learnt information through one bout of retrieval practice (Wolf et al., 2001; Schwabe & Wolf, 2014).

Smith et al. (2016) attributed the retrieval inoculation effect to retrieval practice creating several routes to access target information (for a review, see Karpicke, Lehman, & Aue, 2014). Although stress may block some retrieval routes, learners can still access the target information through unblocked routes. This fits with the framework put forth by Antony et al. (2017), whereby practicing retrieval integrates new information with pre-existing knowledge in the neocortex. This permits target information to be accessed through hippocampal or neocortical representations. Szõllõsi et al. (2017) mooted another explanation: retrieval practice may protect later retrieval from stress through automatization. When retrieval is practiced over several iterations, the learner automatizes the retrieval process; that is, they organize their retrieval output. In following with this, information learnt through retrieval practice is more quickly retrieved than restudied information at short and long retention intervals (Keresztes, Kaiser, Kovács, & Racsmány, 2013). This process of automatization has been compared to that of learning a skill in that, like a skill, practicing retrieval speeds up the retrieval process following a power function (Racsmàny, Szõllõsi, & Bencze, 2018). Once practiced, skills become resistant to interference (for a review, see Logan, 1988). If stress is conceptualized as a form of interference, then the automatization account predicts the retrieval inoculation effect. Evidence on stress and procedural memory should also be mentioned; stress does not impair procedural memory (Lupien et al., 1994; 1997; Kirschbaum, Wolf, May, Wippich, & Hellhammer, 1996). To the extent that learners automatize their retrieval

output, the process of retrieval comes to resemble a procedure. Lastly, functional imaging studies have found that practicing retrieval places fewer demands on regions in the attentional control network (Keresztes et al., 2013), such as the dorsolateral prefrontal cortex (Wirebring et al., 2015), which contain high concentrations of glucocorticoid receptors. From a neurobiological approach, the automatization hypothesis posits that information learnt by practicing retrieval is not affected by stress, as retrieval can proceed without great reliance on brain regions heavily affected by glucocorticoids.

The current study

In revisiting Smith et al. (2016), participants in the retrieval condition learnt stimuli by completing three cycles of retrieval. If participants automatized the retrieval, then it is possible that the inoculation from stress manifested from this automatization. This study seeks to test this claim by having learners complete multiple-choice questions (MCQ) that require the application of knowledge and cannot be completed by using an automatized retrieval process. Additionally, this study seeks to replicate the findings of Smith et al. (2016) with free recall using ecologically valid materials. The automatization hypothesis predicts that stress will impair memory performance on the MCQs and not on the free recall test. Participants will learn a text passage and then return two days later whereby they will complete a stressor or a control version. Participants will then freely recall information learnt from the first day and then complete MCQs that require them to apply their knowledge.

Methods

Participants

Sixty participants (19 female) were recruited from a pool of introductory psychology course. Participants completed the study in return for course credit. All participants had no history of psychological disorders, no current use of medications, and were not current smokers. Lastly, all participants completed both sessions between 11:30am and 5:30pm to avoid effects from diurnal variations in cortisol.

Materials

Participants learnt a text passage on otters, which was taken from a test-preparation book for the Test of English as a Foreign Language (Rogers, 2001). During session 2, a Polar H10 Chest Heart Rate Sensor was used to monitor heart rate. State and trait anxiety were measured using the State-Trait Inventory for Cognitive and Somatic Anxiety (STICSA; Grös, Antony, Simms, & McCabe, 2007).

Design

This study employed a 2 (Encoding: Restudy, Retrieval) x 2 (Activity: Stress, Control) between-factorial design. Encoding was manipulated during session 1 and Activity was manipulated during session 2.

Procedure

Session 1. All participants were initially instructed to study the text passage for 7 minutes and try to remember it for a later test that may or may not occur at a later time period. Although all participants had to recall the passage in the second session, this uncertainty was introduced to prevent participants from trying to remember the passage

after leaving session 1. Participants then either restudied or freely recalled the passage over three sessions, where each session lasted 5 minutes. Participants completed a 2-minute distractor task (Bejeweled) between each session. After studying the passages, participants completed a trait anxiety measurement (STICSA; Grös, Antony, Simms, & McCabe, 2007). Participants then left the experiment room and returned two days later

Session 2 (Stress and retrieval). After filling out a consent form, all participants completed an initial measurement of state anxiety from the STICSA and then put on a heart rate monitor before either completing the TSST or a friendly TSST (f-TSST).

TSST. The TSST was run in accordance with the procedure of Birkett (2011) with some modifications. Due to time constraints, this study could not give a 45-minute waiting period for participants to adapt to the new environment. This study only used a 5-minute adjustment period where participants sat alone in a room while wearing the heart rate monitor. Following this period, participants had 5 minutes to prepare a 5-minute extemporaneous speech on why they would be an good candidate for their ideal job. The speech was performed in front of a group of three experimenters wearing white lab coats. Moreover, participants were under the impression that a camera was recording their speech so it could be analyzed by speech experts. Following the speech, participants spent 5 minutes completing a difficult math task in front of the experimenters whereby they had to subtract from 1022 in sets of 13.

f-TSST. The f-TSST was run in accordance with the procedure in the control condition followed a procedure similar to that of the friendly-TSST (Wiemers, Schoofs,

& Wolf, 2013). Only one experimenter ran this condition and was not wearing a white lab coat. Additionally, the participant was notified that they would not be recorded. Lastly, the experimenter acted in a friendly manner. Participants in this condition had 5 minutes to think about their ideal job and how they would plan to obtain it. Participants were told that they would be asked questions on how they would intend to obtain their job. After 5 minutes expired, the experimenter began a conversation with the participant by asking several questions (see Appendix A) and ensure no awkward pauses. After answering questions for 5 minutes, participants then performed an easy math task (subtract from 1022 in sets of 6) for 5 more minutes.

Post-stress. All participants then completed a measure of state anxiety from the STICSA and then watched a clip from a nature documentary for the remainder of a 10-minute period (i.e., until 25 minutes had passed since stressor's onset). Participants then freely recalled the passage from session 1 and then completed a short multiple-choice quiz (Appendix 1).

Results

Scoring

Two raters independent scored participants' recall responses. They were instructed to give one point for each correctly recalled idea unit. Both raters scored 50 recall sheets and the Pearson product-moment correlation (r) between the scores returned a value of 0.96. Due to this high level of agreement, one rater scored the remaining recall sheets.

Autonomic measurements

Statistical analyses were done with R (R Development Core Team, 2008). The analyses omitted data from 12 participants due to a dysfunction in the heart rate monitor. Thus, the data analyses for the autonomic measurements come from 48 participants. Figure 1 depicts the heart rate data. The heart rate data was submitted to a 2 (Activity: Control, Stress) x 6 (Time: Baseline, 5min, 10min, 15min, 20min, 25min) split-plot (or mixed-design) ANOVA. Activity was entered as a between-participant factor and Time was entered as a within-participant factor. Within-subject tests of more than one degree-of-freedom were submitted to a Huynh-Feldt estimate of sphericity to adjust p values and F tests (Maxwell & Delaney, 2004). The analysis returned a significant main effect of Activity ($F(1, 46) = 6.71$, $p = 0.012$), a significant main effect of Time ($F(5, 230) = 16.65$, $\tilde{\xi} = 0.83$, $p < 0.001$), and a significant Activity x Time interaction ($F(5, 230) = 5.04$, $\tilde{\xi} = 0.83$, $p < 0.001$). The interaction was further investigated by conducting pairwise comparisons between the Stress and Control conditions at each time point. Each comparison was submitted to a Bonferroni correction. Pairwise comparisons at 5min and 10min were submitted to a Welch correction due to a violation of homogeneity of variance. The Stress condition had a higher heart rate than the control condition at 5 min ($t(36) = 2.91$, $p = 0.036$), 10 min ($t(35) = 2.80$, $p = 0.48$), and 15 min ($t(46) = 3.27$, $p = 0.01$). The means and standard deviations are as follows: 5 min (Stress: $M = 94.2$, $SD = 23.2$; Control: $M=78.4$, $SD = 12.8$), 10 min (Stress: $M = 96.9$, $SD = 23.2$; Control: $M = 81.8$, $SD = 12.2$), and 15 min (Stress: $M = 97.7$, $SD = 17.4$; Control : $M = 14.9$, $SD = 17.4$).

Self-report data

Trait anxiety data from three participants was omitted, as these participants did not answer all the questions in the STICSA. Table 1 shows the trait anxiety data for the different learning conditions. Since the Bartlett test of homogeneity showed a violation of homogeneity of variances ($K^2 = 12.93$, $p < 0.001$), the trait anxiety data from the learning groups were submitted to a one-way ANOVA that did not assume homogeneity of variance. This returned a non-significant value ($F(3, 34) = 0.67$, $p = 0.57$).

In analyzing the state anxiety data, one data point was omitted because the participant neglected to answer 5 of the 21 questions on the STICSA. Table 2 shows the state anxiety data for the Control and Stress conditions. Thus, data from 27 participants constituted the Control condition and data from 32 participants constituted the Stress condition. To test whether participants reported an increase in anxiety, paired-samples t tests were conducted on pre-and post-TSST-STICSA scores. Participants in the Stress condition reported higher anxiety scores relative to their baseline scores ($t(26) = 3.90$, $p < 0.001$, $d = 0.7$), whereas participants in the Control condition reported no such increase $t(31) = -0.209$, $p = 0.8357$, $d=0.03$.

Memory data

Free recall. The free recall data was submitted to a 2(Activity: Control, Stress) x 2 (Learning: Study, Retrieval) factorial ANOVA. Each factor was entered as a between-participant factor. The data is shown in Figure 2. The analysis only yielded a marginally significant main effect of Learning ($F(1, 56) = 2.90$, $p = 0.09$). There was no main effect of Activity ($F(1, 56) = 0.27$, $p = 0.60$) and no significant Activity x Learning interaction

($F(1, 56) = 0.32$, $p = 0.57$). The planned pairwise comparison between the StudyControl ($M = 0.45$, $SD=0.24$) and StudyStress ($M=0.39$, $SD=0.24$) conditions returned non-significant ($t(26) = 0.66$, $p = 0.514$, $d = 0.29$). As expected, no significant difference emerged between the RetrievalControl ($M=0.51$, $SD=0.16$) and RetrievalStress ($M=0.52$, $SD =0.18$) conditions ($t(30) < 0.001$, $p = 0.995$, $d = 0$). It is important to note that 12 participants in this analysis engaged in free recall 40 minutes after stressor onset. An analysis of the free recall data excluding these participants has also been submitted to the same 2 x 2 factorial ANOVA as above. No differences emerged between these results with those above. This analysis returned a non-significant main effect of Activity ($F(1,44) = 0.016$, $p = 0.89$), a non-significant Activity x Learning interaction ($F(1,44) = 0.58$, $p =0.44$), and a significant main effect of learning ($F(1,44) = 0.5.48$, $p =0.023$).

Multiple-choice questions. The multiple-choice data was submitted to a 2 (Activity: control, stress) x 2 (Learning: study, retrieval) factorial ANOVA. Each factor was entered as a between-participant factor. The data is shown in Figure 3. It is important to note that only 48 participants completed the multiple-choice questions. The analysis returned a non-significant main effect of Activity ($F(1, 44) = 1.3$, $p = 0.28$), a non-significant main effect of Learning ($F(1, 44) = 1.58$, $p = 0.214$, $\eta^2_p = 0.012$), and a non-significant Activity x Learning interaction ($F(1, 44) = 1.3$, $p = 0.25$). The planned pairwise comparison between the StudyControl ($M=0.48$, $SD=0.17$) and StudyStress ($M=0.35$, $SD=0.16$) conditions revealed a marginally significant difference ($t(21) = 1.93$, $p = 0.0686$, $d = 0.66$), while the planned pairwise comparison between the

RetrievalControl (M=0.50, SD = 0.21) and RetrievalStress (M=0.50, SD=0.25) conditions revealed no significant difference (t (26) = -0.26, p = 0.79, d < 0.001).

Post hoc analyses

Autonomic measurements. To examine whether females showed a larger heart rate response, a 2 (Activity: Control, Stress) x 6(Time: Baseline, 5 min, 10min, 15min, 20min, 25min) x 2 (Sex: Male, Female) three-way split-plot ANOVA was computed. Only Time was entered as a within-participant factor. Importantly, the difference scores between the baseline heart rate measurements and later measurements were entered into the analysis, as females have higher resting baseline heart rates than males. Figure 4 shows this data. Within-subject tests of more than one degree-of-freedom were submitted to a Huynh-Feldt estimate of sphericity that adjusted *p* values and *F* tests (Maxwell & Delaney, 2004). This revealed a -significant Activity x Sex x Time interaction ($F(5, 220) = 2.98$, $\tilde{\xi} = 0.55$, $p = 0.037$). Further investigation of this significant interaction revealed a significant Activity x Time interaction ($F(5, 220) = 8.89$, $\tilde{\xi} = 0.55$, $p < 0.001$). Investigation of this simple interaction revealed a significant main effect of Time ($F(5, 220) = 16.7$, $\tilde{\xi} = 0.55$, $p < 0.001$) and Activity ($F(1, 44) = 7.45$, $p = 0.009$). No pairwise comparisons between males and females within the Stress condition returned significant following Bonferroni corrections.

Free recall. To test for an interaction with sex, the free recall data was submitted to a 2(Activity: Stress, Control) x 2(Learning: Study, Retrieval) x 2 (Sex: Male, Female) factorial ANOVA. Each factor was entered as a between-participant factor. Figure 5 shows the recall data for males and Figure 6 shows the recall data for females. The

analysis yielded a non-significant Stress x Learning x Sex interaction ($F(1, 52) = 1.243$, $p = 0.26$). Thus, this interaction is not further explored. The one pairwise comparison of interest was between Males (M=0.31, SD = 0.28) and Females (M=0.5, SD = 0.20) in the StudyStress condition. This difference returned non-significant ($t(10) = -1.34$, $p = 0.21$, $d = -0.77$).

Multiple-choice questions. To test for an interaction with sex, the MCQ data was submitted to a 2 (Activity: Stress, Control) x 2(Learning: Study, Retrieval) x 2(Sex: Male, Female) factorial ANOVA. Each factor was entered as a between-participant factor. Figure 7 shows the MCQ data for males and Figure 8 shows the MCQ data for females. The analysis yielded a non-significant Sex x Learning x Activity interaction (($F(1, 40) = 0.019$, $p = 0.891$). Thus, the interaction is not further explored. As with the free recall data, the comparison of interest lied between males and females in the StudyStress condition. Since females were hypothesized to respond less to stress, they were expected to outperform males who restudied the passages. The corresponding pairwise comparison between The StudyStress conditions between males (M = 0.33, SD = 0.16) and females (M=0.36, SD = 0.18) returned a non-significant ($t(8) = 0.3$, $p = 0.77$, $d = 0.19$).

Trait anxiety. To test whether trait anxiety negatively with initial learning, a Pearson product-moment correlation was computed between trait anxiety scores from both retrieval conditions and participants' last practice recall in session 1. The result yielded a non-significant result ($r(29) = 0.05$, $p = 0.77$). To test whether trait anxiety negatively correlated with stress response, trait anxiety scores from participants in the StudyStress and RetrievalStress conditions were correlated with heart rate 15 minutes

following stressor onset. This time point was used because participants, on average, had their highest heart rate response here (see Figure 1). The result revealed a non-significant correlation ($r(22) = -0.03$, $p = 0.88$).

Discussion

Although these results are preliminary, the trends replicated the main findings of Smith et al. (2016) with ecologically valid materials. Smith et al. (2016) found that practicing retrieval protected later free recall from the impairing effect of stress. In this study, participants that completed the TSST here incurred no impairment in their free recall performance if they learnt the information by practicing retrieval. But participants who restudied the information in Session 1 recalled less information after completing the TSST than their counterparts who completed the f-TSST. Although no stress-induced retrieval impairment emerged in MCQ performance for participants who practiced retrieval, this data is more equivocal due to the smaller sample size and the novelty of the effect. Thus, the discussion of these results will explore explanations if the data had failed to reject the automatization hypothesis and if the data had rejected it. The autonomic recordings revealed expected patterns; participants who completed the TSST showed greater heart rate responses over time than participants who completed the f-TSST. This was also confirmed by the self-report data provided from the STICSA; participants who completed the TSST reported feeling more anxious than before completing the STICSA, whereas participants who completed the f-TSST reported feeling no increase in anxiety.

The post-hoc analyses showed some interesting trends. First, the TSST evoked a larger heart rate response in females than in males, suggesting that females responded as

cardiac reactors (Allen et al., 1993). Second, trends in free recall data between males and females showed lower recall free performance in males. None of the correlations with trait anxiety returned significant results. This likely occurred because the study's low power to detect any effect. As with the MCQ data, the discussion will explore future research for the effect of sex on free recall performance and discuss situations where females may outperform males and perform equally well as males.

Theoretical implications

As mentioned above, the free recall performance in this study replicates the retrieval inoculation effect discovered by Smith et al. (2016). The automatization hypothesis attributes the inoculation from stress to follow from an automatization of the retrieval process. At a neurobiological level, automatized processes place fewer demands on the prefrontal cortex, which is a major target of glucocorticoids. Additionally, cognitive research finds stress has no effect on tasks of procedural memory. Participants here who learnt the information by practicing retrieval showed no stress-induced performance impairment on the MCQs. Although this result contradicts the automatization hypothesis, an important methodological detail should be noted: participants always completed a free recall test before completing the MCQs. Previous research on stress and retrieval has found that stress does not impair cued-recall performance if participants completed a free recall test shortly beforehand (Kuhlmann, Kirschbaum, & Wolf, 2005; Kuhlmann, Piel, & Wolf, 2005) and studies that have found stress-induced impairments in cued-recall performance placed the cued-recall test as the first memory test (Smeets et al., 2008; Schilling et al., 2013). One potential explanation

for this order effect is that participants may become more relaxed in completing the free recall session. Since concurrent effects of cortisol and noradrenaline underlie retrieval impairments (for a review, see Roozendaal, 2000), a retrieval impairment may not emerge if a decline in noradrenergic activity occurs from participants habituating to the testing situation. Some support comes from Kuhlmann and Wolf (2006), who found cortisol administration did not impair recall if participants had habituated to the testing environment before engaging in recall. Future research should counterbalance the order of these memory tests and monitor HPA activity during retrieval.

If MCQ performance indeed remains unaffected by stress when information is learnt by practicing retrieval, research should address the mechanism that confers this benefit. Studies here could investigate the extent to which forming an elaborate memory trace protects later retrieval from stress. This could be done in several ways. For instance, studies could investigate the extent to which relational processing and/or item-specific processing (e.g., Hunt & Einstein, 1981) negate the effects of stress on later retrieval. Other studies could investigate how the inoculation effect generalizes to study methods other than retrieval that strengthen memory. For instance, future studies could explore whether learning through pretests (e.g., Richland, Kornell, & Kao, 2009) or concept mapping (e.g., Karpicke, 2014) protects later retrieval from stress.

If MCQ performance is indeed impaired by stress even when participants learn by practicing retrieval, then simply automatizing the retrieval process is limited in its effectiveness. In this case, the literature may benefit from studies that investigate whether the stress-induced impairment in MCQ performance disappears with a more rigorous

study strategy. For instance, studies could adopt the procedure of Szõllõsi et al. (2017) whereby participants restudy the information after practicing retrieval.

Lastly, the free recall findings did not change when the data was restricted to participants who completed free recall 25 minutes following the TSST's onset. This is predicted by the dual process model of stress and memory: both memory modes impair memory retrieval.

Two data trends from the post hoc analyses should be mentioned. First, females showed numerically greater heart rate responses than males. Although the precise explanation remains unknown, some researchers posit that females have a less effective dampening response of their heart rate following an increase (Collins & Frankenhaueser, 1978). Other research shows men have more adrenergic receptors than women (Freedman, Sabharwal, & Desai, 2001). More research is clearly needed on how the stress response between the sexes interacts with the type of stressor. Second, the trend in the free recall data appeared to show a lack of a retrieval impairment in females, which may have followed from a less intense cortisol response in females after completion of the TSST. More research on this issue is also needed and this will be discussed in greater detail later in this section.

Practical implications

The trend of stress to impair recall performance in participants who restudied information falls in line with calls for the use low-stakes quizzes in the classroom (McDaniel, Agarwal, Huelser, McDermott, & Roediger, 2011; Khanna, 2015). For instance, Khanna (2015) reported increased final exam performance in students who

completed ungraded pop quizzes throughout the term than students who completed graded pop quizzes. Moreover, students who completed the graded quizzes reported greater anxiety than students completing the ungraded quizzes. Research from the stress literature supports the notion that the anxiety experienced by students completing the graded pop quizzes hampered their learning. First, these students likely experienced more anticipatory stress, which, as expected, hampers learning (Preston, Buchanan, Stansfield, & Bechara, 2007). Second, their reports of greater anxiety suggests they experienced more stress while completing the pop quizzes. Hinze and Rapp (2014) found that introducing stress during initial retrieval largely eliminates the testing effect. Thus, although these students engage in retrieval, they may not receive the full memory benefits of retrieval. It is important to note that other factors can explain this finding by Khanna (2015). For example, students completing the graded pop quizzes may have lost motivation as a result of experiencing more stress and thus exerted less effort.

Limitations and future directions

The current study is limited in several ways. First, the study only recruited half the required number participants (60 of 120) required by the power analysis. Thus, all results are preliminary and should not be used to make inferences. Second, the current study did not measure cortisol levels in participants, which decreased the power of the analyses, as the analyses did not separate stress responders from non-responders. This likely masked the effects of stress, as some participants do not respond to the TSST. Moreover, some participants in the f-TSST may show a cortisol response (e.g., Szõllõsi et al., 2017). Thus, the categorization of participants into the stress and control condition is imperfect. Third,

the lack of a strong testing effect in both the control and stress conditions likely followed from underperformance in the retrieval conditions. Although this study adopted the methodology by Roediger and Karpicke (2006b), the retrieval condition had lower memory performance than that in Roediger and Karpicke (2006b). The retrieval condition here recalled just over 50% of the passage, whereas the retrieval condition in Roediger and Karpicke (2006b) recalled nearly 70% of the passage. This difference in recall between the studies may have occurred because this study gave participants only 5 minutes to practice retrieval during session 1, whereas Roediger and Karpicke (2006b) gave 7 minutes. Therefore, it is possible that participants in this study would have recalled more information in session 1 had they received additional time. Fourth, participants here had high baseline heart rates. The control condition had a baseline heart rate of 82.9 beats per minute (BPM) and the stress condition had a baseline heart rate of 84.5 BPM. Although the precise reason is uncertain, this result likely follows from the lack of a prolonged period of time for participants to habituate to the testing environment and to the heart rate monitor. For practical reasons, this study could only allocate a 5-minute habituation period, which falls short of the 45-minute recommendation from Birkett (2011). With such high baseline heart rates, there is some concern that the control condition may have experienced a stress response. Two pieces of evidence argue against this concern: 1) the StudyControl condition likely incurred no retrieval impairment seeing as they performed similarly to the study condition from Roediger and Karpicke (2006) and 2) the control condition reported feeling no more anxious after completing their task than before completing it. Thus, the effects of the slightly elevated heart rate can be

inferred to be minimal and, at worst, may have slightly decreased free recall performance in the StudyControl condition.

Future research should correct for the above limitations and should also investigate the effects of stress within several other memory-related domains.

Other benefits of retrieval practice. In addition to strengthening memory, retrieval practice confers a handful of other benefits that render learning more productive (for a review, see Roediger, Putnam, & Smith, 2011). For instance, retrieval helps learners identify gaps in their knowledge such that they spend more time studying non-retrieved items during a subsequent restudy session (Soderstrom & Bjork, 2014). In sensitizing learners to unlearnt information, retrieval decreases their confidence in their knowledge of the material such that they become less overconfident in their knowledge (Finn & Metcalfe, 2007). In other words, learners that restudy information become overconfident in their ability to remember the information at a later time point. To the extent that stress impairs retrieval, it may also impair the ability to identify non-retrieved information. If learners show fewer metacognitive benefits, learners may still be overconfident in their knowledge. On the other hand, stress may render learners even more aware to gaps in their knowledge, as they recall less information than non-stressed learners. Research here could certainly clarify this problem. Some research has already investigated how stress affects benefits conferred by retrieval. For instance, one study found stress eliminates retrieval-induced forgetting (Koessler, Engler, Riether, & Kissler, 2009)—when retrieval of target information impairs retrieval of related but non-retrieved information.

Stages of the stress response. Although stress has only been mentioned to impair retrieval, some evidence shows engaging in retrieval at the beginning of the stress response enhances retrieval performance. Schönfeld, Ackmermann, & Schwabe (2014) had participants study nouns and pictures and then return one day later to either complete the TSST or a control version. The TSST here differed from the traditional procedure in that participants began the stressor by recalling information from the first session in front of a panel. Participants who showed autonomic arousal (i.e., increase in blood pressure) recalled more information in front of this panel than participants who showed no autonomic arousal. This retrieval enhancement is attributed to the effects of noradrenaline (for a review, see Sara, 2007). Future studies should investigate the effects of autonomic arousal on retrieval performance, as students may have a short window of opportunity for practicing retrieval performance shortly after experiencing stress.

Stages of memory. Stress affects all stages of memory (for a review, see Vogel & Schwabe, 2016). One stage not yet mentioned is that of reconsolidation. Whenever a memory is retrieved, it is brought into a labile state and must be reconsolidated. Stress can either strengthen or weaken a memory in its reconsolidation. The precise reason for this paradox remains unknown, but factors such as stressor type, material type, and type of test have been mooted (for a review, see Akirav & Maroun, 2013). One study investigating the effect of stress on reconsolidation had participants complete a three-day experiment (Hupbach & Fieman, 2012). On day 1, participants studied a textbook passage and then retrieved it once. On day 2, they completed the cold pressor test (CPT) or a control version and then recalled the information they learnt on day 1. On day 3,

participants returned to recall the information again. Participants who completed the CPT recalled more information than their counterparts in the control condition. Surprisingly, this retention enhancement carried over to recall performance on day 3. These participants still recalled more information than their counterparts who completed the control version of the CPT on the second day. Similar results have occurred with cue-target pairings of nonsense syllables (Coccoz, Maldonado, & Delorenz , 2011; Coccoz, Sandoval, Stehberg, & Delorenzi, 2013) and word lists (Bos, Schuijer, Lodestijn, Beckers, & Kindt, 2014). But some studies have found no impairments in reconsolidation from stress (e.g., Schwabe & Wolf, 2010). Thus, more research is needed to identity variables that mediate these effects of stress on reconsolidation.

Sex & menstrual cycle. Although this study analyzed for sex differences in stress response and memory performance, this was not the focal purpose of the study. Although effects of stress were mentioned in the introduction, two additional modulating variables are mentioned here: menstrual cycle and oral contraceptives. Several studies have noted heightened stress responses during the luteal phase than in the follicular phase (Kirschbaum et al., 1999). This is thought to occur because negative feedback regulation of the HPA axis is reduced during the luteal phase (Altemus et al., 1997). Contraceptives exert an opposing effect on stress responses within females; they curtail the stress response (Kirschbaum et al., 1995a; 1999; Kumsta et al., 2007) by presumably increasing the level of cortisol-binding globulin (CBG)—a protein that inactivates cortisol. Therefore, stress may impair retrieval in females not using oral contraceptives, but only when in in the luteal phase. Future studies should address these variables, as this will give

insight into the underlying mechanisms that produce sex differences in memory performance.

Type of stressor. As discussed in the introduction, males seem to react more strongly to challenge-oriented stressors and females react more to social-rejection stressors (Stroud et al., 2002). Therefore, future studies should investigate how these different stressors affect memory performance between the sexes. One potential avenue would be to test whether the introduction of a social rejection component into the TSST would trigger a stress response in females and a corresponding retrieval impairment.

Stress and study habits. Recent research in rats and humans has shown that stress promotes habitual responding (for a review, see Wirz, Bogdanov, & Schwabe, 2018). For instance, Schwabe and Wolf (2009) had participants complete the SECPT or a control version. They then completed an instrumental learning task where they learnt associations between cues and food rewards. After this learning session, participants consumed one of the food rewards (chocolate or orange) until satiation and then resumed the task. Unknown to participants, the food reward they consumed no longer appeared when participants responded to its corresponding cue. Participants who completed the SECPT continued to select for the devalued cue, whereas participants in the control condition stopped selecting for this cue. Thus, stress in this context desensitized participants to the loss in the cue's value, leading participants to continue responding to that cue. Since many students (about 84%) reread information to learn it (Karpicke, Butler, & Roediger, 2009), rereading can be argued to becomes a habit. Given that students experience high amounts of stress (see Introduction), it is possible that stress

triggers students to reread information. This also follows from findings that rereading renders learners more confident in their memory (Roediger & Karpicke, 2006b), which likely alleviates feelings of stress.

Conclusion

Although incomplete, this study revealed several expected trends. First, stress impaired retrieval performance in participants who learnt the passages through restudy, but not in participants who learnt the passage through retrieval. Trends from post hoc analyses of the free recall data indicated this retrieval impairment to be more prominent in males than in females. Future studies should investigate this sex difference in memory performance by measuring menstrual cycle and use of oral contraceptives. The autonomic data also revealed a trend for a sex difference; females showed larger heart rate responses than males. Lastly, the trend in the MCQ contradicted the prediction from the automatization hypothesis that stress would impair performance regardless of the initial learning method. Although a methodological factor may explain this finding, future studies should investigate how stress affects the ability to generalize information.

Tables and figures

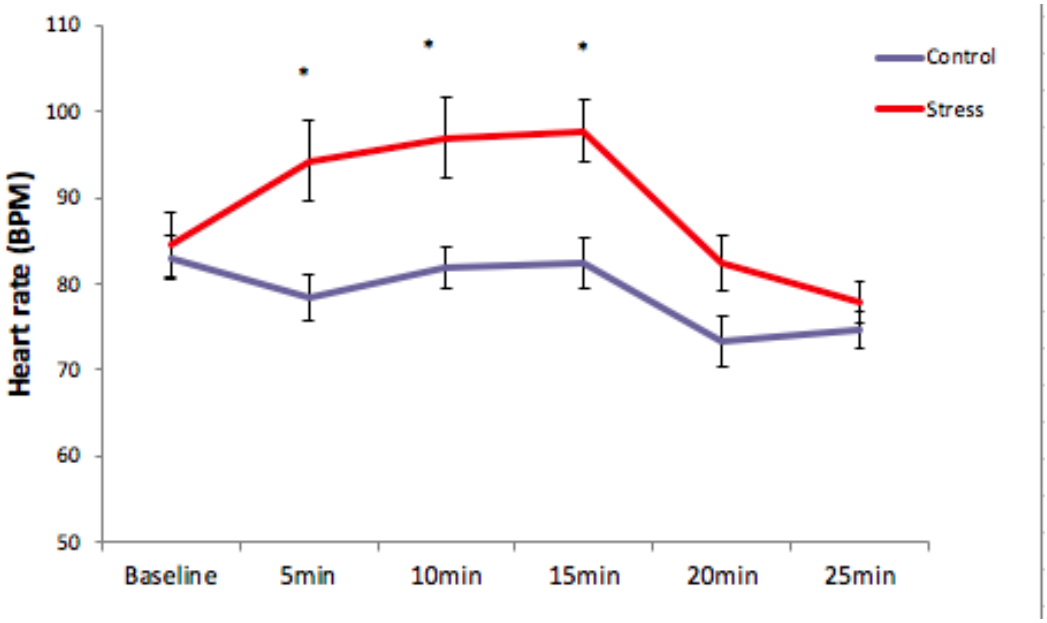

Figure 2. Heart rate measurements with standard errors. * indicates $p < 0.05$

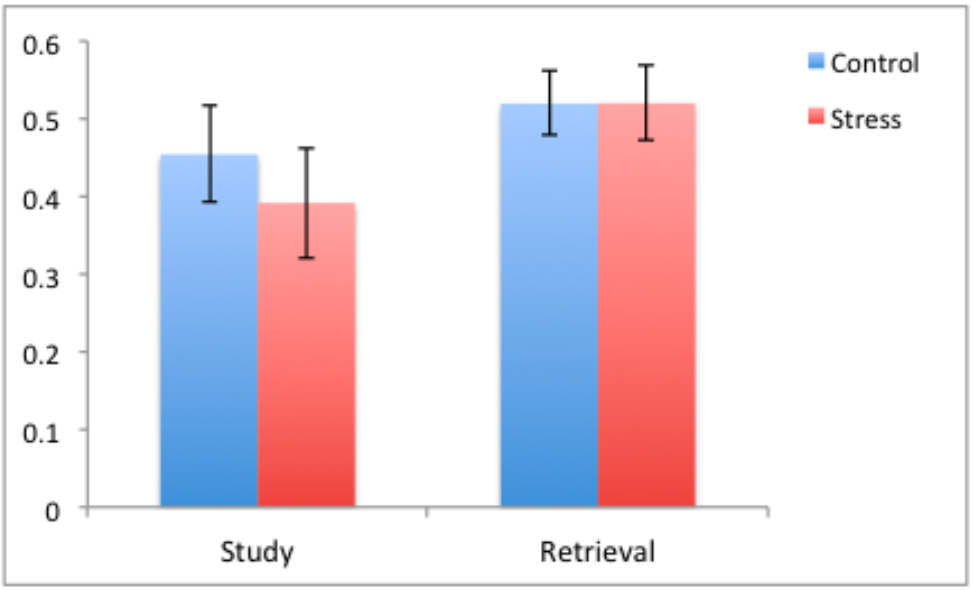

Figure 2. Free recall performance in Session 2. Errors bars represent standard errors of the mean.

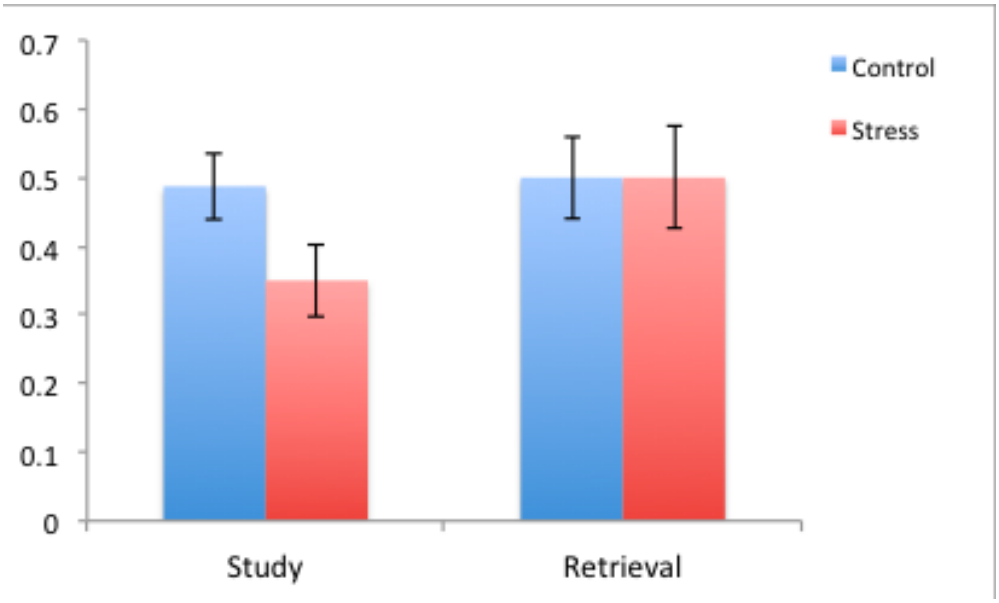

Figure 3: Multiple-choice question performance in Session 2. Error bars represent standard errors of the mean

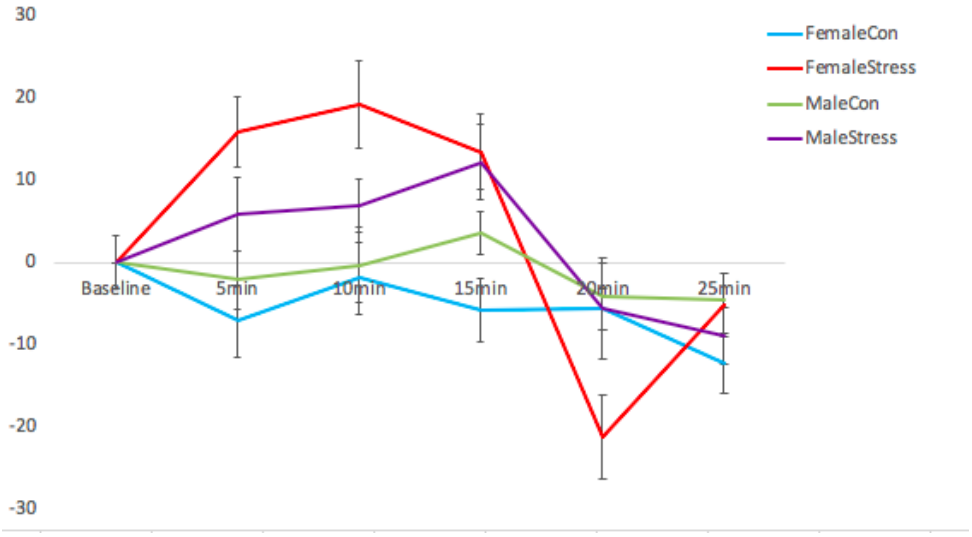

Figure 4: Heart rate data categorized by sex and activity and shown as difference scores with the baseline measurements. Error bars represent standard errors of the mean.

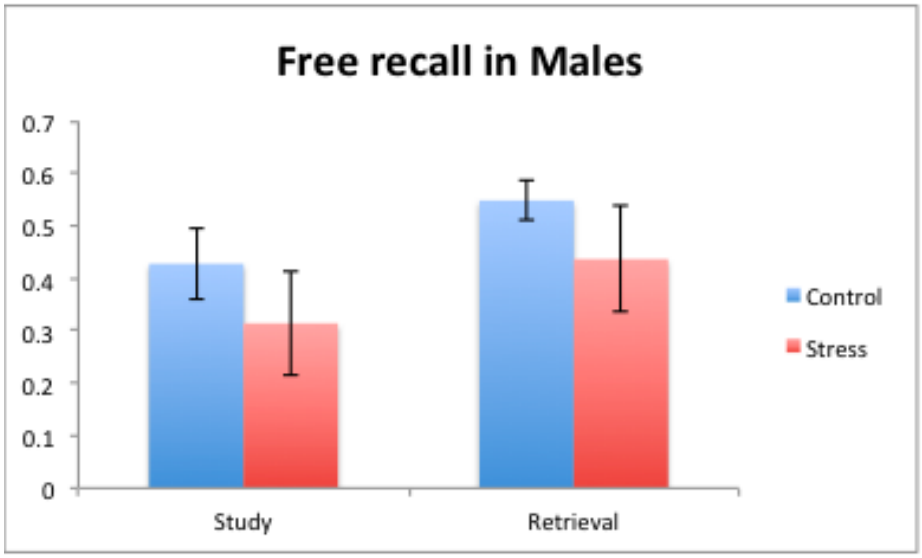

Figure 5: Free recall performance during Session 2 in males. Error bars represent standard errors of the mean.

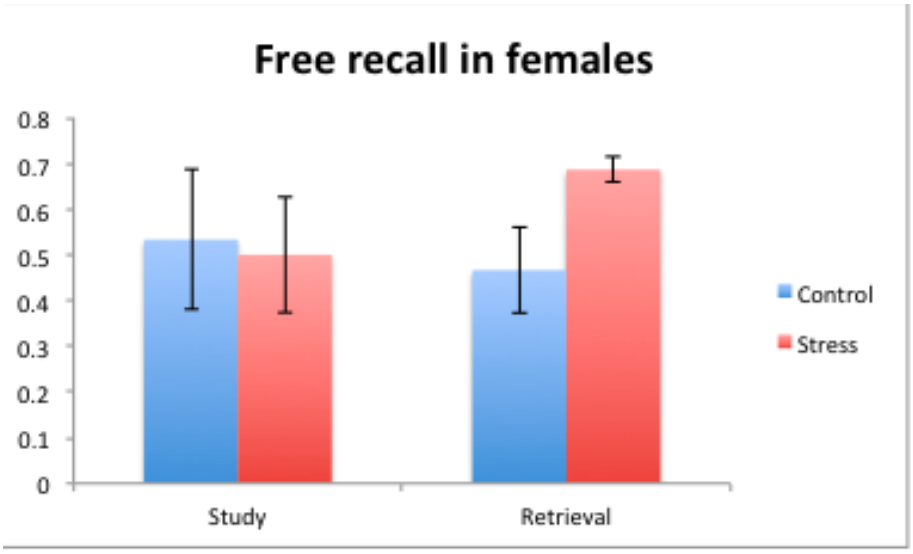

Figure 6: Free recall performance during Session 2 in females. Standard error represent standard errors of the mean.

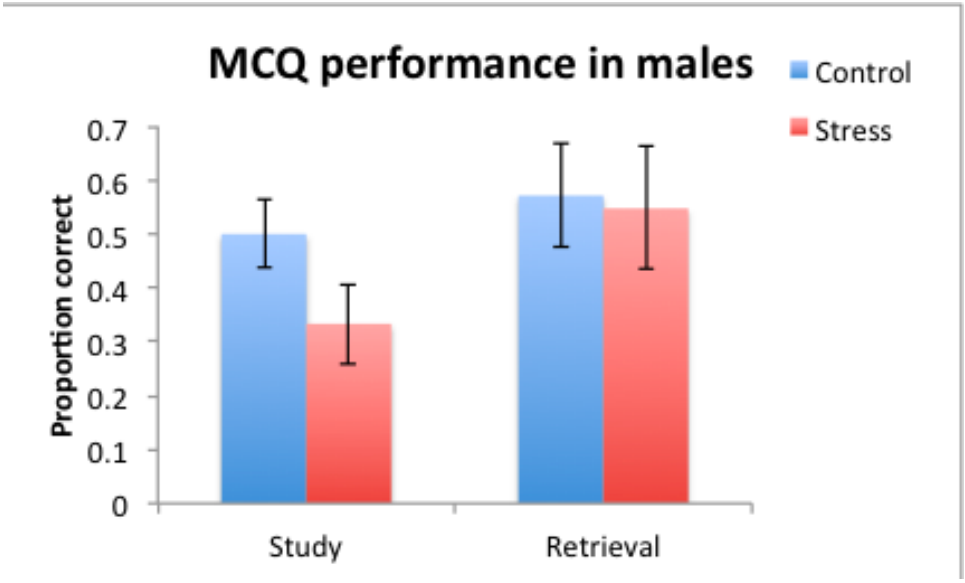

Figure 7: MCQ performance by males in Session 2. Errors bars represent SEMs.

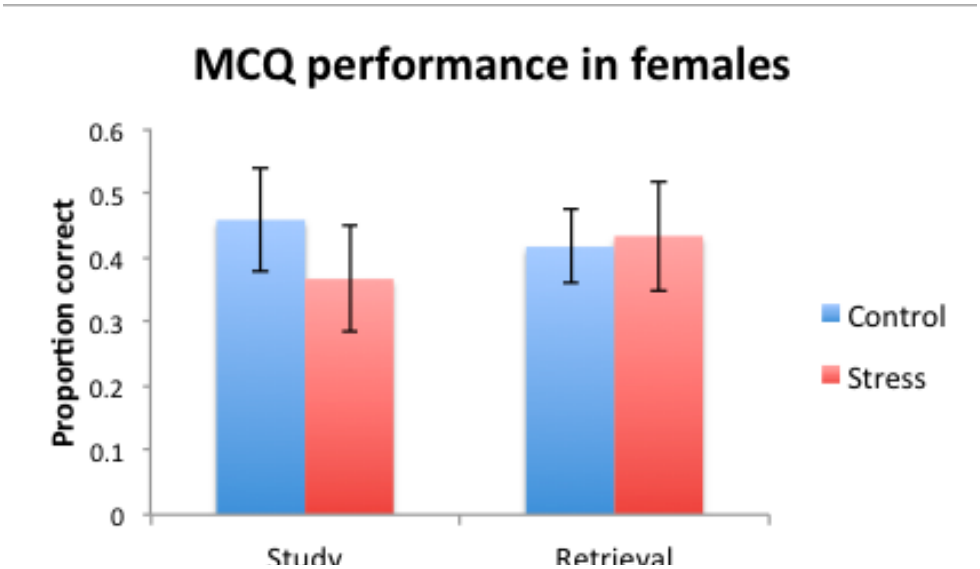

Figure 8: MCQ performance by females in Session 2. Error bars represent SEMs.

	StudyCon	StudyStress	RetCon	RetStress
Trait anxiety score	35.6 (1.62)	39.27 (3.42)	34.41 (1.55)	38.07 (3.68)

Table 1: Trait anxiety scores from learning groups. Means and standard errors provided in parentheses.

	State Before	State After
Control	32.65 (5.76)	32.87 (5.81)
Stress	35.22 (6.77)	42.96 (8.26)

Table 2: State anxiety scores before and after the activity. Means and standard errors are provided in parentheses.

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Appendix 1: Multiple-Choice Questions

1. A new species of sea otters has a layer of blubber. What is *most likely* to occur in an environment containing this new species?

a. There will be more invertebrates (like sea urchins and abalones) and less kelp.

b. There will be fewer invertebrates (like sea urchins and abalones) and more kelp.

c. There will be too many food sources.

d. There will be fewer invertebrates (like sea urchins and abalones) and the population of kelp will remain unchanged.

2. A new predator has been introduced into the environment that has been ravaging the population of clams, crabs, and squids. What may happen to the population of sea otters?

a. The sea otters will lose their layer of blubber due to a lack of food resources.

b. The sea otters will begin to feel the cold in the Pacific Ocean.

c. The sea otters will deplete the population of sea urchins and abalones.

d. The sea otters will lose their outer layer of fur.

3. Which of the following species descriptions most closely resembles characteristics found in sea otters?

a. A new species of insects that lacks an exoskeleton only comes out to eat during midday when it is warm.

b. A certain tiger species has voraciously decimated the population of elephants.

c. A certain shark frog species floats on water lilies, leaving it vulnerable to aerial predators.

d. A certain rat species has thick and insulating skin and preys on a species that destroys sources of shelter.

4. Which of the following new regulations most effectively guards the sea otter population from dangerous threats?

a. A new regulation prevents humans from extracting oil in the North Pacific.

b. A new regulation prevents humans from hunting clam, crab, fish, octopus, and squid in the North Pacific.

c. A new regulation requires that the North Pacific be provided with a chemical that eliminates the luxuriant underfur of the sea otters, which will detract hunters.

d. A new regulation only allows otters above 70 pounds to be hunted.

5. Which of the following situations presents the greatest threat to the sea otter population?

a. A new predator has ravaged the population of clams, crabs, fish, octopus, and squids leaving only sea urchins and abalones.

b. There has been an enormous oil spill in the Pacific Ocean.

c. The sea otters have migrated to the Arctic Ocean.

d. There are rare instances of sea otter poaching.

6. Researchers have discovered a new species in the mustletid family and are trying to determine whether it is a species of sea otter. From what is known, members of this species consume squids, clams, and crabs, have two layers of fur, and often come on shore. Based on the passage, should the researchers categorize this mustletid member as a sea otter species?

a. Yes; the new species shares the same characteristics as sea otters.

b. No; sea otters almost never come onto shore.

c. No; the new species lacks a layer of blubber.

d. Yes; simply because this new species frequently comes to shore.