Stress effects on the ability to learn statistical regularities about our world

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Undergraduate Thesis in Neuroscience

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ABSTRACT

Stress, a common feature of everyday life, has been demonstrated in numerous studies to profoundly impact memory function, particularly functions dependent on the hippocampus. The impacts of acute stress on statistical learning are still unknown, as statistical learning has only recently been demonstrated to rely on hippocampal mechanisms. In order to examine the impact of acute stress on statistical learning, as well as investigate individual differences in statistical learning performance, I induced acute stress via shock on healthy young adults during either the encoding or retrieval phase of a previously established statistical learning tasks that is based on implicit learning of temporal community structures. Preliminary results suggest that stress applied during either encoding or retrieval can disrupt statistical learning, though further data collection is needed to generate a more robust model of these effects. A thorough definition of the interactions between stress and statistical learning of temporal relationships has implications for understanding maladaptive effects of stress mechanisms and potential interventions for improving learning and memory – and thus quality of life - for people who suffer from chronic stress disorders, such as generalized anxiety disorder and post-traumatic stress disorder.

INTRODUCTION

The impacts of stress, such as disrupted focus, susceptibility to illness, and diminished quality of life, are well-known. Studies have shown stress can deeply impact memory, in particular disrupting memory retrieval and spatial memory[1,2]. One form of memory that hasn't been investigated under stress is statistical learning - the ability of the brain to learn generalizable rules about how the world works that can be used to guide decisions. Traditional models of memory suggest that statistical learning is supported by slow off-loading to the cortex, while learning of distinct experiences is supported by the hippocampus[3,4]. This theory, though accurately accounting for many phenomena, fails to account for more rapid statistical learning, performed online during encoding before knowledge can be consolidated in the cortex during sleep.

In a potentially fundamental paradigm shift, a group of researchers has proposed that the hippocampus could also support statistical learning by enabling us to learn temporal community structures[5,6]. Temporal community structures are an important mechanism for interpreting co-occurrent stimuli, such as blaring fire alarms and imminent danger or unpleasant smells and unsafe food. An example of such a structure in an experimental context is illustrated in Figure 1(a). Given that we know stress can disrupt hippocampal learning mechanisms[2], a critical question is whether stress alters such statistical learning abilities that are fundamental for survival and our daily lives. A thorough definition of the interactions between stress and statistical learning of temporal relationships has implications for understanding maladaptive effects of stress mechanisms and potential interventions for improving learning and memory – and thus quality of life - for people who suffer from chronic stress disorders, such as generalized anxiety disorder and post-traumatic stress disorder.

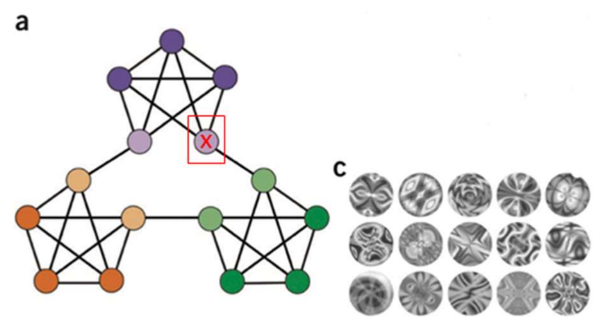

Figure 1. a) Temporal co-occurrence structure, with lines showing which stimuli are likely to follow another. For example, X (red) typically occurs with stimuli in the purple group, but sometimes one from the green. c) Abstract stimuli shown to subjects in the foundational study. Figure taken from[5]

My research had several specific aims. Primarily, I aimed to quantify whether and how acute stress impacts statistical learning, particularly temporal community structure learning. Second, I aimed to quantify the relationship between performance on temporal community structure memory tasks and individual differences, such as sex, free cortisol (stress hormone) levels, and sleep habits. Third, I aimed to evaluate the relationship between conscious awareness of how stimuli are related and demonstrated implicit learning of temporal community structures. Taken together, the goals of this study were to generate fundamental insight into how statistical learning functions in the context of stressors and daily life.

We predicted that statistical learning would increase performance in the encoding stress group and diminish performance in the retrieval stress group, based on previous trends in stress and memory literature. To foreshadow my findings: preliminary results suggest stress decreased performance on statistical learning tasks when induced during encoding and also when induced during retrieval. Performance on statistical learning tasks was not correlated with gender, reported stress levels, or conscious awareness of temporal community structures. Remaining data collection, following the resumption of on-campus research activity, and salivary cortisol results will allow us to generate a more robust model of stress effects and individual differences on statistical learning performance.

LITERATURE REVIEW

Statistical learning is a topic of growing popularity in memory research that integrates long-standing theories and new discoveries of memory processing. Statistical learning is defined as the ability to extract generalizable rules from the environment based on co-occurrence of stimuli. This ability is essential to memory functioning, by reducing a need for storage and effortful processing and inference across repetitive memories, instead helping us generate generalized and/or probabilistic knowledge that facilitates online predictions about events and items. Little is known about how individual differences or stress may affect statistical learning abilities, since statistical learning has traditionally been attributed to different neural mechanisms than episodic memory (which is known to be susceptible to stress). My research focused on filling these gaps in the literature and achieving a better understanding of how statistical learning might function in the context of daily life.

One of the dominant theories in the psychology and neuroscience of memory is complementary learning systems, which provides a foundation for understanding the significance of recent discoveries from statistical learning research. The theory was first proposed by McClelland et. al in their landmark paper in 1995, bringing together evidence from decades of long-term memory studies to support their argument[3]. This theory postulates that the hippocampus allows for rapid memory storage of specific stimuli/episodes, while the neocortex slowly forms generalized representations of classes of stimuli/event types[3,4]. This explanation of representation formation relies on the slow offloading of memories to the neocortex during sleep, which allows discrete memories to be stored as part of semantic patterns of information over time. Over time, the theory has expanded to juxtapose generalization from learning with putative functions of the dentate gyrus, a specific region of the hippocampus, in pattern separation[4]. Pattern separation allows for incoming memories to be successfully distinguished from existing memories. Knock-out studies of the dentate gyrus in rodents have abolished pattern separation functions, demonstrating evidence for the necessity of the dentate gyrus in this memory process[4]. Although accurately accounting for many phenomena, complementary learning systems theory fails to account for more rapid statistical learning, a specific process whereby generalization from individual experiences extracts mental representations of “likely” co-occurrence of stimuli in space and/or time. The complementary learning systems theory would imply that statistical learning requires memory consolidation and a slower time frame for processing, but recent evidence demonstrates that statistical learning can take place in real time without a sleep cycle.

Generating new evidence in contrast to a complementary learning systems account of statistical learning, researchers at Princeton University recently demonstrated a role for the hippocampus in statistical learning by studying temporal communities[5]. Temporal communities are groups of stimuli or experiences that are related through their co-occurrence in time and consistent statistical relationships. That is, the relationships are not reflected within a distinct, pattern separated episodic memory representation; learning these patterns could thus be considered a form of statistical learning. The researchers showed that people were able to learn complex statistical relationships during a short time period, without a sleep/offline consolidation cycle, and apply this knowledge to mental representations of stimuli[5]. In the studies conducted, implicit learning of the communities was demonstrated when research participants marked event boundaries as occurring between temporal communities[5]. Functional MRI (fMRI) data and simulations suggest that the medial temporal lobe, specifically the monosynaptic pathway of the hippocampus, facilitates the temporal community learning process in real time[6,7]. This series of studies demonstrates a mechanism for hippocampal involvement in statistical learning, that differs markedly from existing theories by allowing the hippocampus to play a role in generalized representation formation. This discovery explains how rapid statistical learning occurs, without the need for sleep, which gives insight into how this ability can be affected by hippocampal damage[7].

The discovery of this new role for the hippocampus in statistical learning mechanisms also introduces the problem of how stress might impact statistical learning. We learn statistical relationships daily under varying emotional states. Critically, many studies have demonstrated that stress impacts a variety of functions of the medial temporal lobe, with effects varying depending on the form of memory, stress type, and individual differences[1,2,8]. For example, stress can impair retrieval by reducing the number of details someone recalls about an event[8]. On the other hand, stress has been shown to enhance memory encoding, specifically for stimuli related to the stressor[8]. Stress effects can be supportive or obstructive to memory processes, depending on the type of memory involved in the specific tasks, which begs the question of how stress could impact the newly reported hippocampal-dependent forms of statistical learning. Stress increases prediction error signaling in a similar task paradigm, which could upregulate encoding when stimulus expectations are violated; however, this was examined specifically in non-hippocampal reward circuitry[9]. This trend suggests that stress manipulations may positively modulate statistical learning abilities, but this requires further study. Knowing that this type of statistical learning relies on the medial temporal lobe suggests that stress could have a pronounced impact on performance.

For my study, acute stress was induced while collecting performance measures, as the method with the most directly controlled stress effects while introducing fewer confounding variables associated with longer-term stress[10,11]. To induce acute stress, a shock protocol as discussed in Kudielka et. al was used, to avoid the other cognitive effects of socially-based stress induction methods[10]. In this field in particular, there is very little data comparing stress effects on memory in human males and females, raising questions about the generalizability of our extant knowledge on this topic[10]. My study aimed to address this gap by performing direct comparisons between each sex's performance, as well as the differences generated by the stress manipulation. Additionally, salivary cortisol levels were collected throughout the study and corrected based on time of day, since cortisol levels are highly impacted by circadian rhythm[12]. Salivary cortisol levels are a measurement of stress hormones, reflecting activation of the HPA axis, which is implicated in stress reactivity[10]. Collecting cortisol data had the potential to provide additional insights into the biological mechanisms of stress effects on this form of memory and information processing.

The current literature on temporal community structure learning also lacks information on individual differences in performance and on how – due to its putatively hippocampal-dependent nature - conscious awareness arises from the learning process. Although studies have convincingly demonstrated the brain's ability to learn temporal community relationships, the data suggest that this learning may reflect only weak associations in some individuals[5]. This possibility presents the potential for significant variations in performance based on individual characteristics, such as sleep, education levels, and emotional state.

Based on previous studies on how stress impacts other forms of memory, I hypothesized that stress would play a supportive role in memory encoding and an obstructive role in retrieval for statistical learning processes[8,9]. Since statistical learning shares many features with prediction error learning, statistical relationships learned under acute stress may form stronger memory traces. If acute stress improves encoding in statistical learning, I predicted increased performance on temporal community learning tasks. If acute stress impairs retrieval in statistical learning, I predicted decreased performance on the same tasks. Finally, I hypothesized that gender differences and conscious awareness of statistical relationships may act as predictors for performance on statistical learning tasks. This prediction was tested through the generation of correlational models for various individual differences and their relationship to statistical learning task performance.

Taken together, the outcomes of my research will help define stress impacts (be they supportive or obstructive) on hippocampal-dependent statistical learning – specifically, the strength of the learned temporal associations between stimuli and whether and how individual characteristics mediate statistical learning. These insights are key to understanding potential negative impacts of stress disorders, such as post-traumatic stress disorder and generalized anxiety disorder, on our ability to cogently form representations of events during rapid processing[11].

METHODS

In order to examine stress effects and individual differences on statistical learning, I utilized the original paradigm that demonstrated human's ability to perform temporal community structure learning[5]. Additional tasks were incorporated to assess conscious temporal pattern awareness, individuals' stress susceptibility, and factors related to the stress response such as sleep quality.

Temporal Community Task

Subjects were exposed to a series of abstract fractal stimuli where repeated image presentations create a temporal co-occurrence structure (as shown in Figure 1, reproduced to the right for clarity). Each line on the structure represents what the possible next shape in the sequence could be,

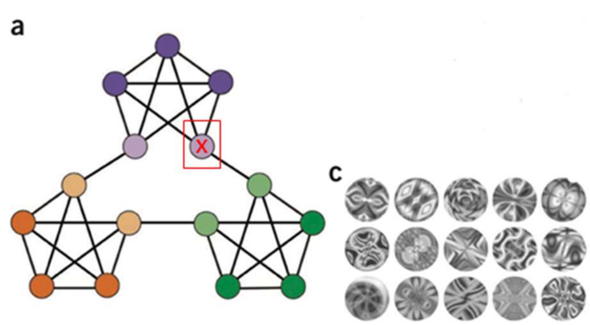

Figure 1. a) Temporal co-occurrence structure, with lines showing which stimuli are likely to follow another. For example, X (red) typically occurs with stimuli in the purple group, but sometimes one from the green. c) Abstract stimuli shown to subjects. Figure taken from[5]

with equal probability weights for each line. Together, these lines create communities where the majority of transitions occur within a community of shapes. Abstract fractals in black-and-white were selected as the visual stimuli to avoid any possible semantic association between shapes. Each fractal's position in the communities was randomized by subject.

The encoding phase consisted of a randomized 1400 fractal sequence based on the community structure, with each fractal displayed for 1.5 seconds. During this phase, subjects performed a masking task to ensure they were attentive to the stimuli. They were asked to press a key if the shape was presented in the correct orientation and another key if they believed the shape was rotated. A low frequency beep was played when the subject failed to respond before the next fractal and a high frequency beep was played when the subject made an incorrect response. Random fractals were rotated 90 degrees from its correct orientation during this task, for 20% of the fractals shown to each subject.

The retrieval phase consisted of a randomized 600 fractal sequence, with each fractal again displayed for 1.5 seconds. During this phase, subjects were asked to mark when they felt a breaking point in the sequence, also known as a parsing task. This task served as an implicit memory test for community structures, without the subjects being made aware of the existence of structures. Following this phase, subjects completed a brief explicit learning worksheet that asks about the strategy they used in the task and tested their knowledge of the community's transition probabilities. This additional worksheet allowed us to test explicit learning of the statistical relationships, which was not examined under the original paradigm. The code for the task was obtained from the researchers at Princeton who developed the paradigm and runs through MATLAB in combination with PsychToolbox.

Stress Induction Procedure

Subjects were randomly divided into three groups for the duration of the study. Acute stress was manipulated in two groups using threat of randomized shocks from a BIOPAC stimulation machine, which has been shown to affect other forms of hippocampal memory[8]. One stress group was shocked during the encoding phase, while the other group was shocked during the retrieval phase. This allowed us to isolate stress effects, if any, for separate encoding and retrieval phases of memory. The third group did not receive any shocks, serving as a no-stress control.

The BIOPAC machine was set up according to manufacturer directions, in combination with a MATLAB program that triggered shocks at randomized intervals during the appropriate test phase. During a set-up phase, subjects worked with a researcher to increase the level of shock until they determine it to be at a pain level of "7/10, or moderately painful, but not unbearable." The shock level never exceeded this setting during the study and did not exceed 30 mA of stimulation. Shocks were delivered randomly between 3 and 5 times in the assigned phase and were unrelated to performance. Subjects developed stress under this protocol primarily due to the anticipation of the shock, rather than the shock itself.

Saliva Collection and Cortisol Measures

Salivary cortisol measurements were taken before the tasks as a baseline, during the encoding phase, and during the retrieval phase. The encoding and retrieval phase samples were both taken about 15 minutes into the phase, as this is approximate delay time in the cortisol response curve from time of stress induction. Obtaining a baseline is essential, as cortisol levels vary highly based on the individual, time of day, and many other factors, so comparison between within-subject measures is a more valid way to test cortisol changes.

Swabs from Salimetrics, a saliva testing company, were placed in the subject's mouth for 60 seconds and stored in a freezer before being shipped to Salimetrics for analysis. Cortisol measures for each subject will be obtained from these samples when Salimetrics resumes normal operations.

Subject and Demographic Information

Subjects in this study were young adults ages 18-25, representing both men and women. The total sample size across groups is currently 53 subjects (21 females), with the aim of 75 total subjects at the conclusion of data collection. 30 subjects were assigned to the control condition, 11 to the encoding stress condition, and 12 to the retrieval stress condition. Data collection at this time is halted due to the impact of COVID-19 and will continue in the Fall to reach the full target sample size. Additional information was collected during the study on their overall education, daily life stressors, and sleep habits. This information allowed us to analyze for the effect these individual differences might have on the stress response. Informed consent was obtained from all subjects, and the protocol was reviewed and approved by the Institutional Review Board for Human Subjects at the Georgia Institute of Technology.

Data Analysis

Raw response data was collected via MATLAB code and stored in a text file during each phase of the task. These data were processed to eliminate any double-press responses and the total proportions of between-community (also referred to as node) versus within-community (also referred to as other) selections on the retrieval phase task will be calculated. This proportion reflects what percentage of the time subjects selected "correct" transitions that demonstrate their knowledge of community structures. A correct transition was defined as one where the subject presses the space bar during the presentation of the first shape in a new community. Further analysis was conducted to calculate any latent responses to community transitions, either due to slow response times or additional evidence accumulation strategies. Performance on the task was quantified as the percentage of node selections made from possible nodes minus the percentage of other selections made from possible other selections. This measure controls for lower response rates and prevents undue outlier influence that would appear in other measures, such as a ratio-based measure. In further analyses of selections, a lag response was operationally defined as a selection made on the second shape in a new community. The response window for a lag response was limited as a delay of only one shape, due to the short length of time spent in a community on average (six or seven shapes).

A one-way ANOVA was conducted on performance between stress to determine if each if there is a difference between groups' learning of community structures. Additional linear effects analysis was conducted in R to analyze the impact of several variables on individual performance. As fixed effects, gender, stress group assignment, and gender and stress group interaction were entered into the model. Visual inspection of residual plots did not reveal deviations from homoscedasticity or normality. Correlation tests with performance were conducted for other variables, such as explicit learning performance and reported stress levels. Together these analyses yielded insight into the effects of stress and individual differences on statistical learning abilities.

RESULTS

Our design yielded a rich set of variables to examine as predictors of subject performance on the statistical learning task. Although further data collection will be conducted when research activity on campus resumes, following the COVID-19 closure, sampling in the two experimental stress groups was sufficient to report key outcomes that, in a preliminary form, address my study aims. Before reviewing these outcomes, looking forward: cortisol samples for some subjects have been analyzed by the external Salimetrics lab, but because of the research shutdown most cortisol samples have yet to be analyzed. Consequently, cortisol data will not be discussed here but sample collection and analysis will resume when safe to do so. Additionally, about 25-30 more subjects are planned for the experiment, which will lend additional statistical power and allow us to conduct a robust analysis of the trends we have observed. Note that the use of the word "trend" hereafter refers to the valence or direction of effect and, due to the preliminary nature of the sample, does not signify a range of statistical significance per se.

Performance of control subjects alone was analyzed to assess validity of our implicit learning paradigm. Control subjects demonstrated higher node parse selection than other transitions, suggesting implicit learning of the presented communities (Fig. 2). This response met the criteria for statistical significance in the current sample via a paired t-test, with a p-value of 0.0348.

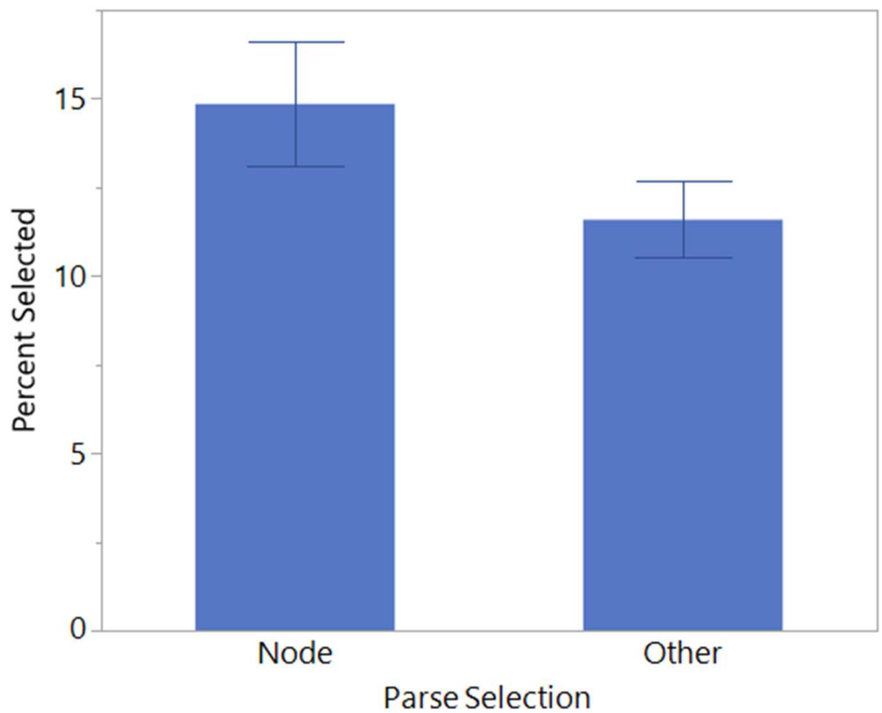

Figure 2. Control subjects demonstrated significantly higher parse selection for nodes than for non-community transitions. Subjects were shown sequences of abstract images that belonged to a temporal structure and were asked to indicate breaking points in the sequence, as a measure of implicit learning. Each error bar is constructed using 1 standard error from the mean.

When comparing subjects from both stress and control groups, control subjects showed a trend of higher performance on the parsing task, indicating more robust implicit learning (Fig. 3). Performance was quantified as the proportion of node selections from possible node selections minus the proportion of other selections from possible other selections. Statistical significance has not been met via one-way ANOVA but may meet significance pending the full sample size. In addition, the overall response rate trended higher for the control group (Fig. 4). The response rate measure represents a combined total of node responses and other transition responses relative to the number of possible responses.

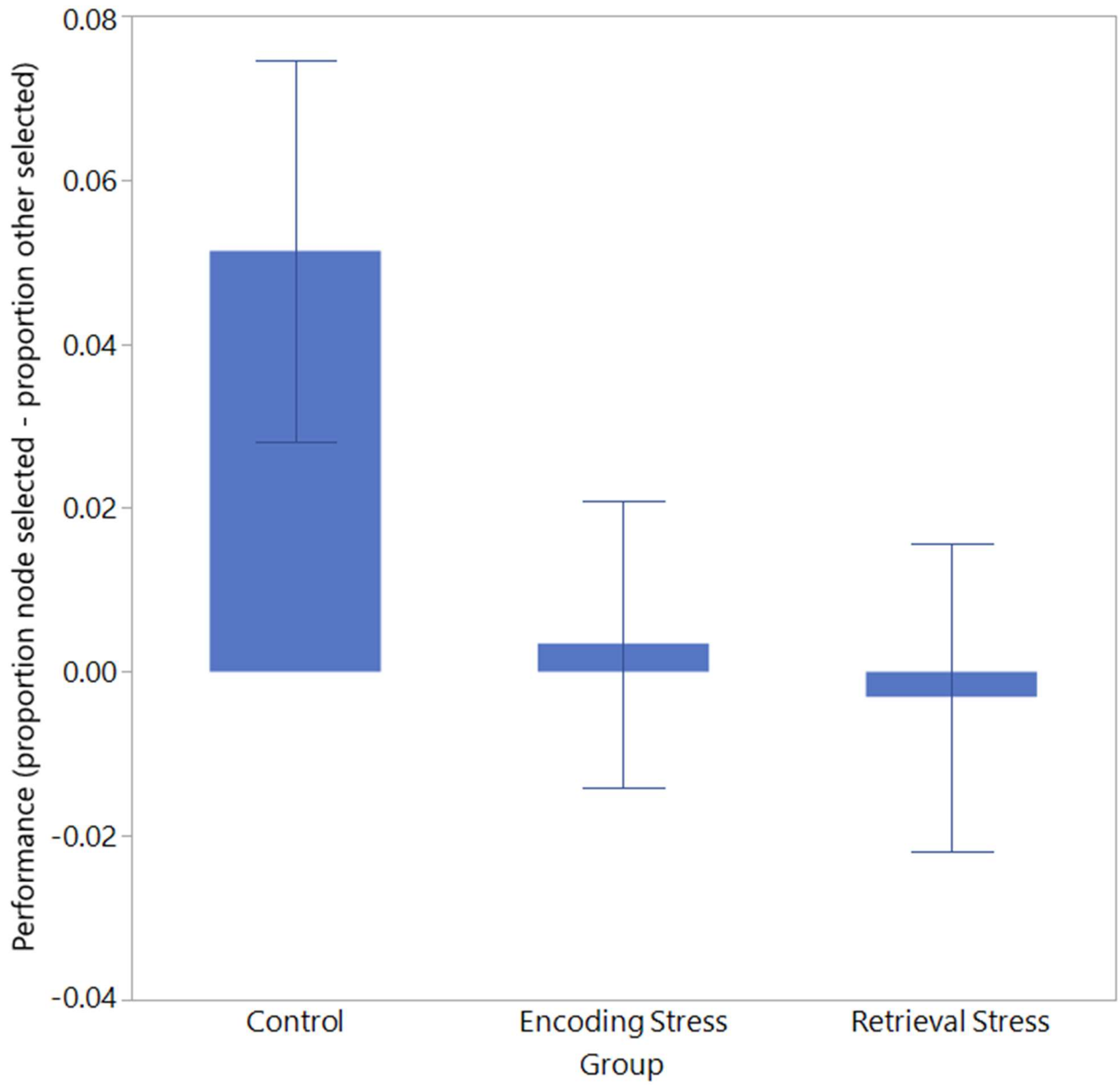

Figure 3. Control subjects show a trend of higher performance on implicit learning in the retrieval task than stress subjects in either condition. Subjects in both control and stress conditions were shown sequences of abstract images that belonged to a temporal structure and were asked to indicate breaking points in the sequence, as a measure of implicit learning. Each error bar is constructed using 1 standard error from the mean.

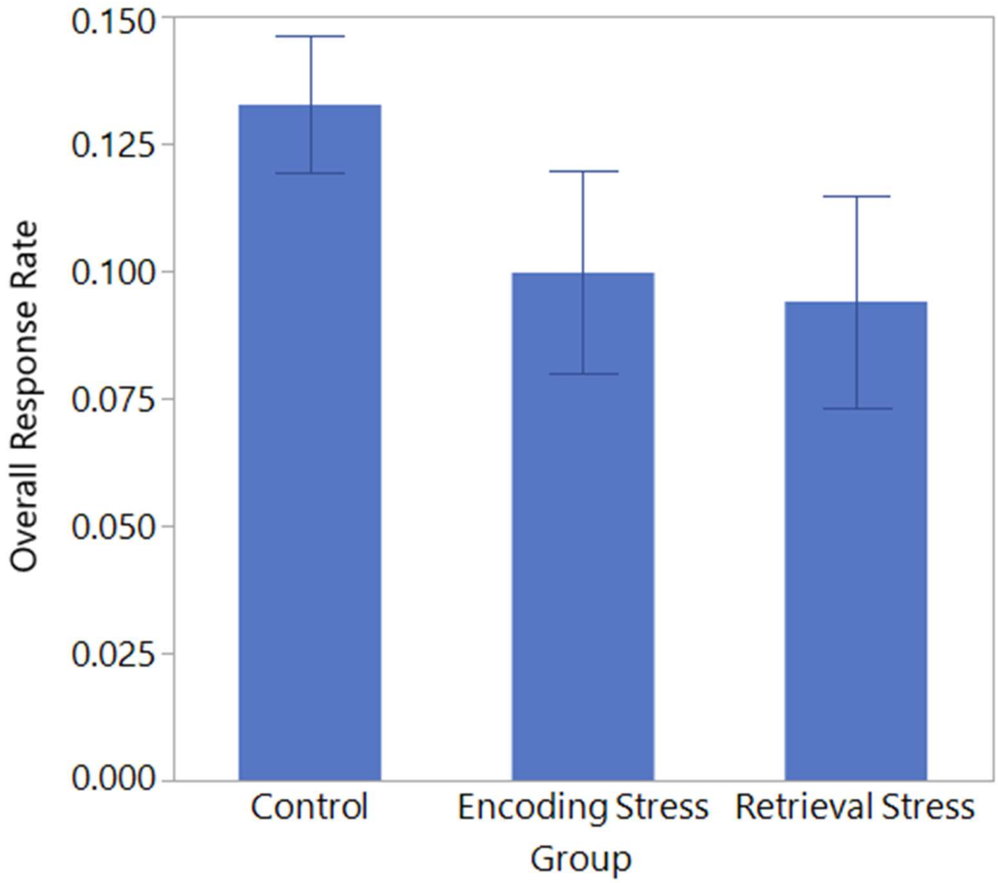

Figure 4. Stress groups show a trend in lower response rates than control subjects during the parsing task. Response rates were calculated as the number of individual presses made during the retrieval portion of a community structure implicit learning task divided by the total possible presses (600).

Importantly, a lag response was also observed in some subjects, who tended to indicate parses reliably (more frequently than at other time points) but did so shortly after transition to a community (on the second shape in a community). Overall, the control group exhibited more lag responses relative to other responses when compared to both the encoding and retrieval stress groups (Fig. 5). The retrieval group showed the lowest ratio of lag responses in comparison to other response compared to the control and encoding stress groups. However, in this preliminary sample these differences did not reach statistical significance in a two-way ANOVA test.

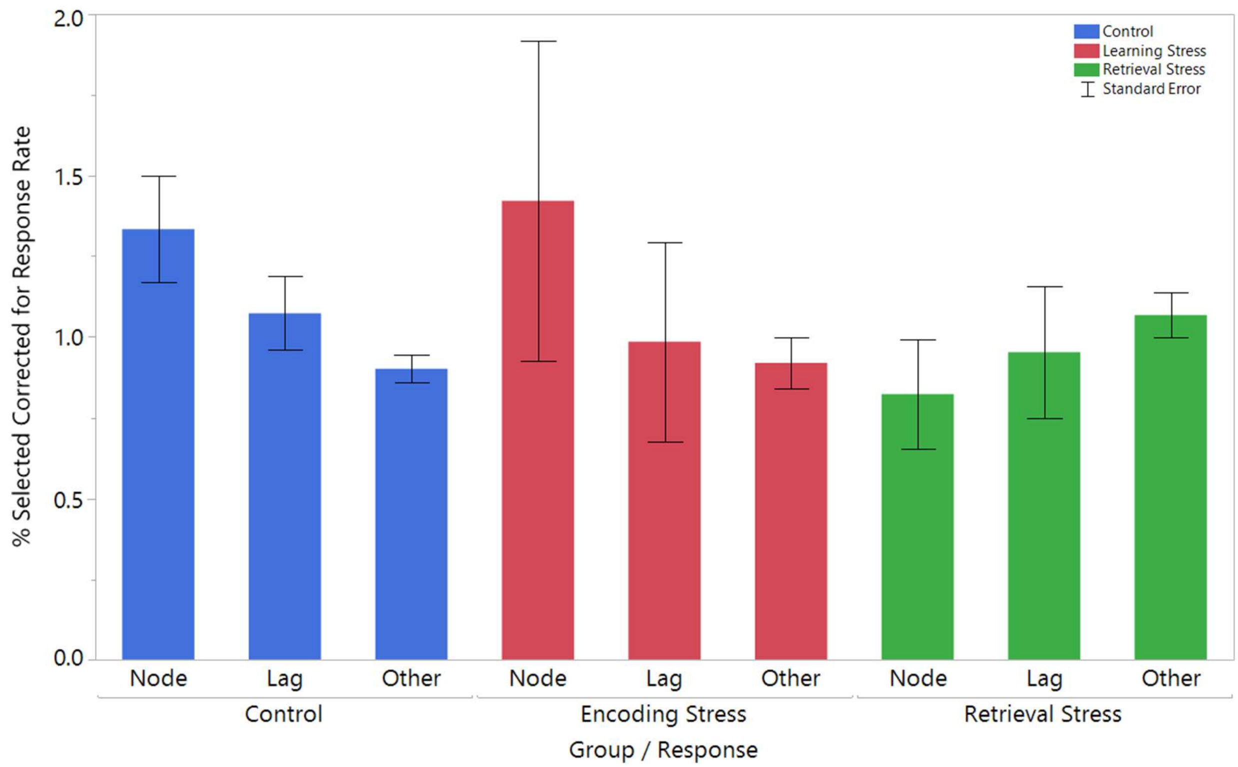

Figure 5. Control groups showed a more robust lag response relative to other selections, when compared to stress groups. Selections were calculated as the percent of possible selections in a category made divided by the individual's overall response rate.

In order to assess the impact of participant-level variables on our data, a variety of correlation tests were conducted for predictors of individual performance. No significant relationship was found between explicit conscious awareness of statistical structures, though explicit learning performance was generally low across the board. No significant relationship with performance was found for accuracy on the initial masking task, gender, or reported stress levels.

Given limited evidence in the current sample for differential effects of the two stress conditions, we constructed a linear model of implicit learning performance as a function of group assignment, where stress groups were collapsed as a single group level. In this simpler model of the variance, the coefficient for group assignment was marginal ($F(1,51) = 3.189$, $p = 0.08008$).

When considered in terms of effect size, the coefficient for stress group membership was -0.05128 ± 0.02872 (standard error), which is a robust effect size relative to the mean performance of 0.029 for all subjects. Taken together, although the present sample size is limited and thus conclusions about statistical significance levels should not be made at this time, the above data indicate that stress at both encoding and retrieval may negatively impact statistical learning performance.

DISCUSSION

My study sought to examine the effects of acute stress on implicit statistical learning, as well as seek predictors of individual differences in performance. The preliminary results show an overall pattern of stress obstructing statistical learning performance, whether stress is induced during encoding or during retrieval. Individual differences in performance remain largely unexplained, though some interesting differences in subject behavior from the prior studies were found. Compared to subjects in the original studies conducted using this statistical learning paradigm[5], subjects in this study generated a much lower overall response rate during the parsing task. There are several possible (not mutually exclusive) explanations of this trend, including whether there were differences in how researchers presented the instructions between studies, fundamental differences in the populations participating in the studies, or differences in parsing counting methods between the studies. Many individual subjects in the present study exhibited similar response levels to the original study, but there were several individuals with extraordinarily low response levels, responding to only 5% of stimuli, rather than the original study's average of around 25%[5]. Interestingly, the trend for lower response rates in our sample was stronger in both stress groups relative to the controls, possibly due to distraction from monitoring for the stressor or lower confidence in responses arising from the stressor impacting memory traces. Although the overall response rate across all groups was lower than expected, general task performance appears consistent for the control group relative to the original study (Fig. 2). Overall, control subjects selected a significantly higher proportion of between-community transitions relative to within-community transitions. First and foremost, this result provides an important replication that this experimental setup can measure implicit statistical learning, as it mirrors the results found in the original studies utilizing this paradigm.

Although further data collection is needed to gain statistical power and the current sample size is lower than projected due to campus closure for COVID-19, stress appears to interfere with implicit statistical learning performance, both when induced during encoding and when induced at retrieval. Based on the results of the linear model and trends observed in performance across groups, both the encoding and retrieval stress groups performed worse than the control group, with the mean performance for the stress groups hovering close to chance performance (Fig. 3). The trends present in the current data partially support our initial hypothesis, given that acute stress seems to impact statistical performance, although interestingly not differentially between encoding and retrieval manipulations.

Acute stress has often been shown to have a supportive effect on the encoding process through effects on the hippocampus, so the encoding stress group was predicted to have higher performance than the control group[8]. The unexpected trend observed may be due to the role non-hippocampal structures play in the statistical learning process, the non-emotional nature of the task, or differences in the nature of statistical learning from other memory tasks, which require further investigation. One important consideration is that stress has typically been shown to support encoding when the stimuli to be encoded are related to the stressor or emotionally salient

– neither of which is true in our paradigm[13]. It is also possible that our encoding condition outcome reflects a retrieval-phase stress effect, if participants in the encoding stress group remained stressed for the remainder of the study during the retrieval phase (despite there being no threat of shock in their retrieval phase). Once cortisol results and a larger stress group sample size are available, clearer separation between stress groups may be possible based on observing participant's changes from baseline cortisol.

One extension of the original paradigm that was introduced this thesis was assessment of responses outside of the between-community transition period. In this more detailed analysis, our study revealed that some subjects exhibited a lagging response, where they reliably indicated a parse one shape after the original transition, more often than for shapes later after the transition that are solidly within-community (Fig. 5). These subjects may be relying on greater evidence accumulation, requiring more certainty to make a decision about a true community transition. The lag response was only reliably more common than other responses in the control group, suggesting the stress groups may have either a) higher decision confidence (despite trending worse performance) or b) lower overall implicit knowledge of community transitions such that correct lag responses rarely manifest. Previous studies have found increased decision confidence in decisions made under stress where there is uncertainty around outcomes, as is inherent in the implicit instruction format of our task[14]. This trend may also be a result of weaker learning of community structures, as the node responses that don't rely on evidence accumulation are also lower relative to other responses in the stress groups than the control group.

Another extension of the original paradigm introduced here is assessment of explicit awareness of statistical relationships that may form despite the implicit nature of the task. Overall performance on explicit learning task was low across groups and was not correlated with performance on the implicit learning task. This supports the argument that memory retrieval performance for the community structures in this design may be supported largely by “gists” gained from an implicit mechanism - and indeed, this may be ecologically valid given that statistical learning is frequently not explicitly expressed in day-to-day life. From our results, it seems that strength of conscious awareness does not impact a subject’s ability to perform well on the implicit task, and in fact some subjects claimed high awareness despite their inability to correctly report the communities in the explicit test. Future studies could examine this further by developing a recognition-based explicit learning task, rather than the difficult multiple-selection task utilized in our study, to obtain a more sensitive measure of explicit learning.

With regards to individual differences, no significant difference has been found in overall performance between sexes, masking task accuracy, reported stress levels, or sleep quality. Our model, with the current (small) sample, was unable to predict performance on the implicit learning task based on these factors, which indicates that there may be highly complex interactions determining individual performance not measured by our current study paradigm. Insights into individual differences were limited in the study by current sample size, but could also be made more robust in future studies by further collection of demographic information and an expanded sample to include subjects with varying ages and education levels. In particular, no relationship was found in the current sample between sex and performance on the task, despite frequently reported differences in acute stress’s impact on performance in males and females in other studies[10]. Differences in response to stressors by sex remain understudied in the field of neuroscience, as many studies only examine male subjects due to the complex effect of hormones on cortisol measures in females. At this stage in data collection, stress seems to impact males and females equally in our study, although stress group sample sizes do not currently allow us the statistical power to analyze males and females separately by group, with only 8 females currently represented across both stress conditions. It will be of great value to follow this outcome as the sample size continues to grow, because it speaks to the generalizability of our results and addresses a broader lack of data in the field on stress effects on learning in both genders.

One major limitation of this paradigm is the low level of attention demanded of participants during the retrieval task, as participants are not required to make a minimum number of responses or accuracy. This raises the possibility that the stress effects observed may be driven more strongly by attentional disruption by the stressor than by glucocorticoid impacts on the hippocampal memory mechanisms this paradigm is known to target. Self-reported distraction levels were not significantly different between the control and stress groups in this sample, but no other attentional measure was collected. Future studies utilizing this paradigm may include an additional task that requires participants to make a yes or no response for every stimulus presented rather than a yes only when they decide to indicate a breaking point between communities. This adjustment or another measure of attention would help diminish the possibility of distraction impacting performance results.

The generalizability of this study is also limited in that our results target the impacts of acute stressors on learning emotionally neutral stimuli, which has been shown in the past to differ from stress impacts on more salient stimuli.[13] In order to apply the insights of the study to long-term chronic stress disorders, further study is needed that examines general stress levels and stress resiliency of the subjects enrolled in the study. Though acute stress seems to negatively impact encoding and retrieval processes in statistical learning, more research is needed to determine whether this trend holds for stimuli that carry emotional valence.

In conclusion, this thesis has provided preliminary evidence that both stress at the time of encoding and the time of retrieval can disrupt the formation of statistical learning memory traces. Defining the interplay of stress and statistical learning, and with respect to individual differences, could have profound impact on our understanding of statistical learning as it plays out in the complex world outside the laboratory. Learning relationships between neutral stimuli based on temporal (or other) statistical features, such as understanding spoken language and interpreting music, could be negatively impacted by acute stress during both encoding and retrieval processes, as suggested by the trends found in this study. Further data collection will allow us to refine our models and better understand the specific relationship between stress and statistical learning performance. Though work remains to shed light on individual differences in this process, our preliminary results suggest that stress may play a powerful role in dismantling statistical learning abilities, regardless of the timing of stress induction.

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