Sarah To-Do:

* Write up discussion points, including newest data/conclusions
* Find risk aversion/confidence sources relative to stress
* Update other sections of thesis paper to reflect final results
* Reflect on possible long-term stress impacts
* Reflect on how stressful events may stand out more because of lack of statistical learning
  + Include this in introduction
  + How does statistical learning play into real life interactions?

Avery To-Do:

* Analyze cortisol levels (create tertiles) vs performance
* Analyze affective stress rating (create tertiles) vs performance

Discussion:

* The stress manipulation impacted affective stress rating, but not cortisol levels.
  + TBD
* The control group successfully learned the task, while stress participants performed no better than chance. Neither group displayed explicit awareness of statistical relationships between stimuli, indicating that the differences lie on the level of implicit learning.
* Stress increased the likelihood of risk aversion in task response
  + Stress can reduce confidence in quick responses to stimuli
* We’ve demonstrated that acute stress during either phase of statistical learning impacts our ability to learn these relationships. The study was limited in that stress effects were not perfectly constrained to either phase of the learning process, so there may be some differences between stress effects on the two phases in a methodology that separates the two portions of the task further in time.
* Stress effects between the encoding and retrieval phases do not appear to have any meaningful differences in our paradigm
  + ANOVA showed cortisol differences for encoding not retrieval
* Implications of disruption to statistical learning: learning about the environment when young, difficulties compressing experiences (high cognitive load?), struggle to direct attention
  + <https://ntblab.yale.edu/wp-content/uploads/2015/01/Sherman_COBS_2020.pdf>
* If stress impacts our ability to store an event as part of a statistical pattern/compress it, is this why memories of stressful events stand out in our minds?
  + We have shown acute stress to impact our ability to both encode and retrieve statistical relationships. Statistical learning plays a key role in our ability to integrate across experiences and form generalized memories of repetitious events in our lives. If we interrupt the statistical learning process, instead encoding stimuli as individual episodes, those memories will not be represented as part of a repeated related experience. This shift in mechanism, away from learning patterns and predictions, may help explain why stressful events stand out as more distinct in our minds. Stress may shift the pathway our brain takes in interpreting stimuli, from the monosynaptic pathway (which allows more overlap between related experiences) to the trisynaptic pathway which encodes experiences more as unique memory traces. This connection has both positive and negative implications for how our brain functions under stress. On the positive side, this allows us to remember more clearly what may have been causing stress in the first place, thus allowing us to avoid that experience in the future. On the negative side, if we strongly encode specific but irrelevant stimuli under stress, we may unnecessarily view that experience as separate from our other experiences and try to avoid the specific circumstances associated with that stressor.

Follow-Up Questions:

* What drove the differences between our study and the original task?
  + Are our conclusions still valid given that they rely on lag being included as a measure, where the original experiment did not?
* Were cortisol levels associated with performance changes? Is there a correlation between affective stress rating and performance?
* What influences someone to perform the task on a lagged basis?
  + Reflect on the participant’s instructions
  + Uncertainty, evidence accumulation, not sure what their feeling is
* Would longer term stressors impair people’s ability to learn statistical relationships?
* Limitation: Stress was not well-isolated to a specific phase of the task.
* Would changing the salience of stimuli strengthen stress interactions, or cause a distinction between the encoding and retrieval groups?
* Is the difference, though statistically significant-ish, actually big enough to be important, since it seems performance was already pretty low for the control group?
* Do these impacts imply anything further about the brain regions involved?

Discussion:

Our study sought to examine the effects of acute stress on implicit statistical learning, as well as seek predictors of individual differences in performance. The results show an overall pattern of stress obstructing statistical learning performance, agnostic of whether stress is induced during encoding or during retrieval. Individual differences in performance remain largely unexplained, though some interesting differences in subject behavior from prior studies were found. Compared to subjects in the original studies conducted using this statistical learning paradigm5 , 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 21 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 betweencommunity 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 group8 . The unexpected trend observed may be due to the role nonhippocampal 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 22 – neither of which is true in our paradigm13. 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 task14 . 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 23 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 studies10. 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 24 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. 25 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.