The Neural Processes of *Statistical Learning*

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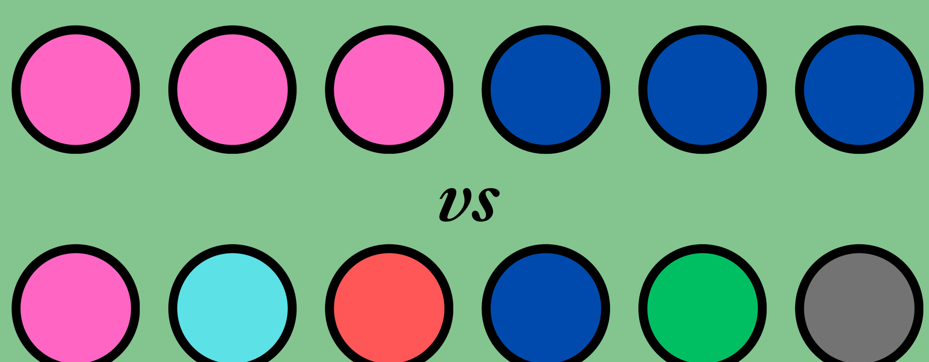
Background

What is *statistical learning*?



- *Statistical learning* is the ability to extract units of information based on patterns of regularities in perceptual input.
- Theory implicates *statistical learning* as a critical mechanism for language acquisition.[11]
- Recent works suggest *statistical learning* is not a unitary process, but occurs along varying spatial and temporal scales in the brain.[5]

Computational formalization

$$P(Y\,|\,X) = \frac{P(X \cap Y)}{P(X)}$$

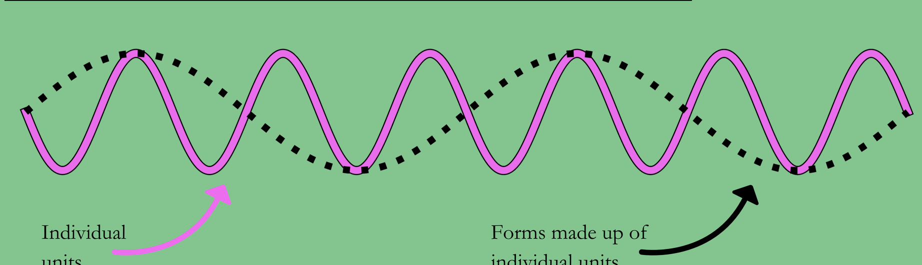
Likelihood stimulus **Y** will co-occur with **X** given the frequency of stimulus **X.**[6]

Linguistic example

Cool dads

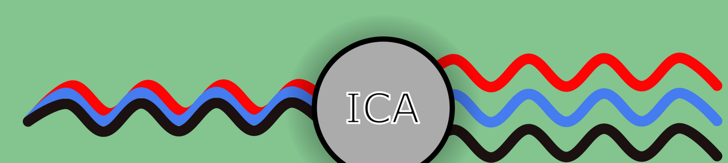
Syllables *within* words have higher transitional probabilities than syllables *across* words.

Neural entrainment

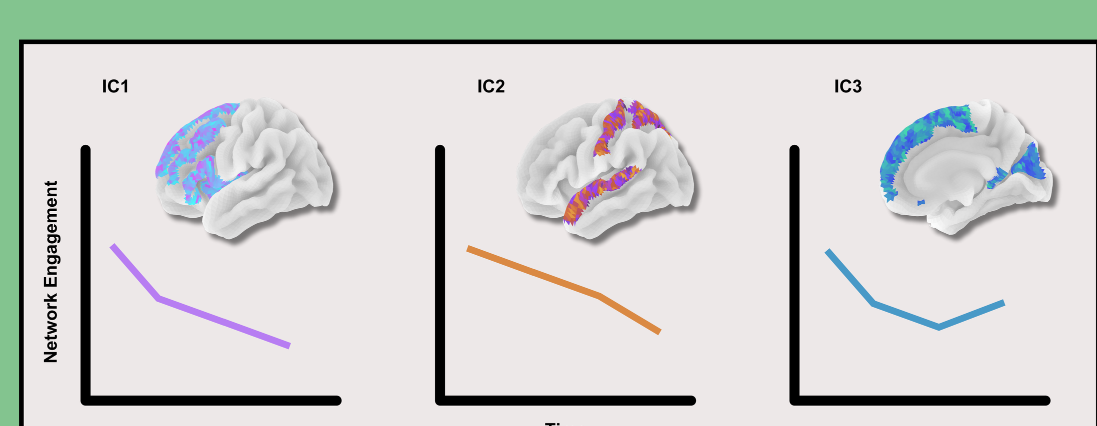


- Brain activity oscillates at the same frequency of rhythmic stimuli as a function of *statistical learning.*[2]
- The methods used to detect neural entrainment (e.g., M/EEG) have low spatial resolution.

ICA



- Relevant "components" of brain activity can be extracted using temporal independent component analysis (ICA).[4,9]

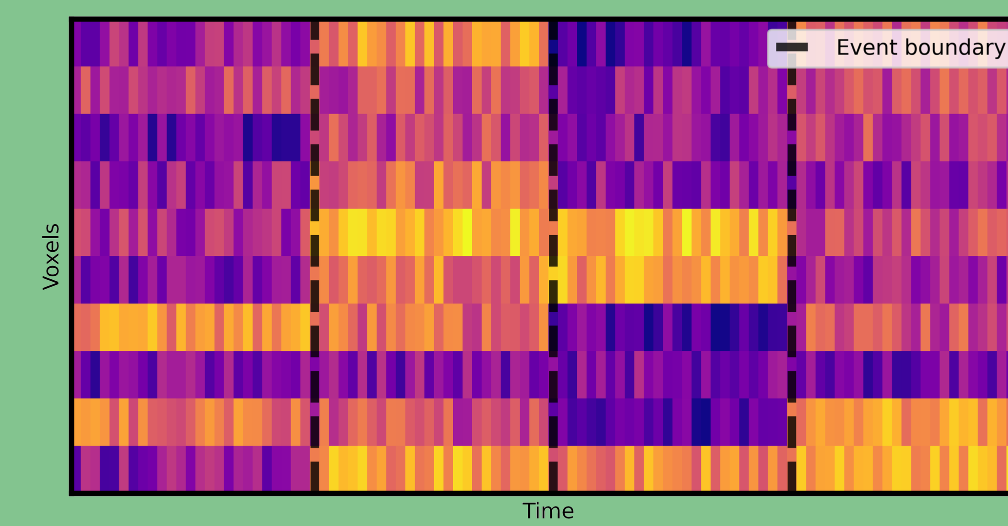


Can we comprehensively characterize *statistical learning* in the brain as it unfolds over space and time with fMRI?

Methods

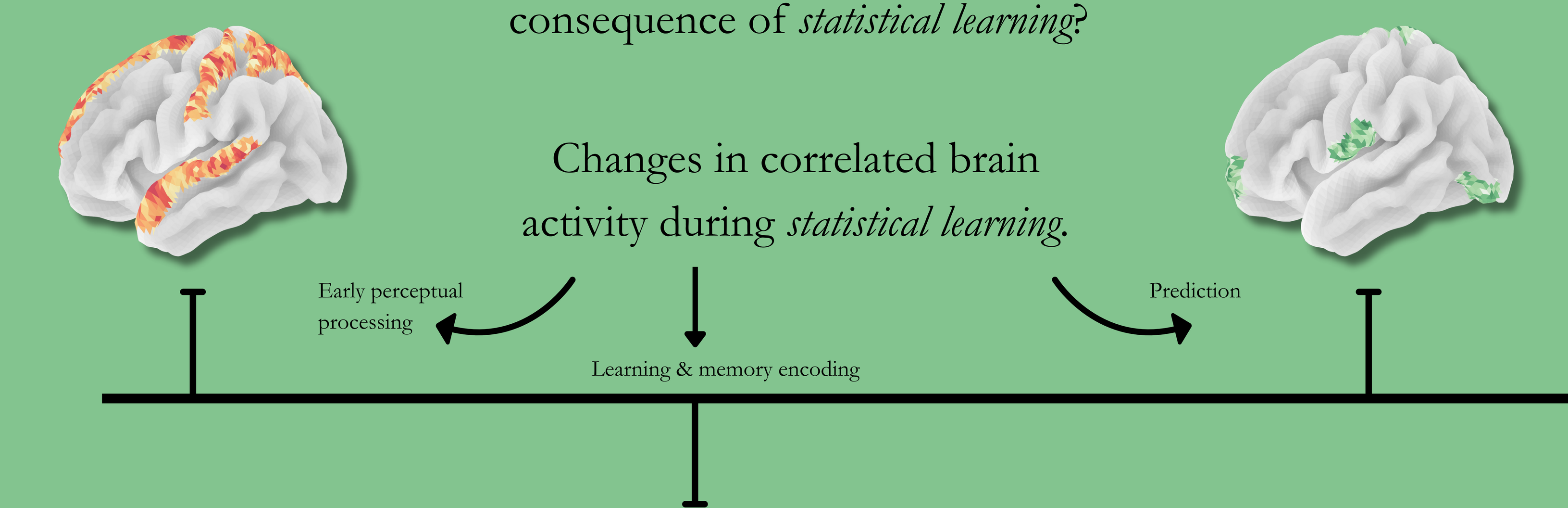
Event Segmentation

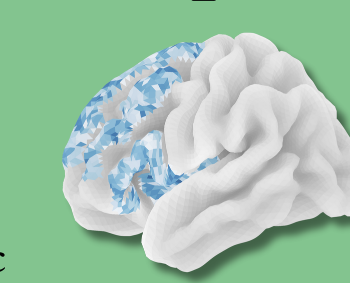
- Brain activity is *not random.* It can exists in various states.[1,14]
- Can we uncover distinct event-states of *statistical learning*?



Dynamic Functional Connectivity

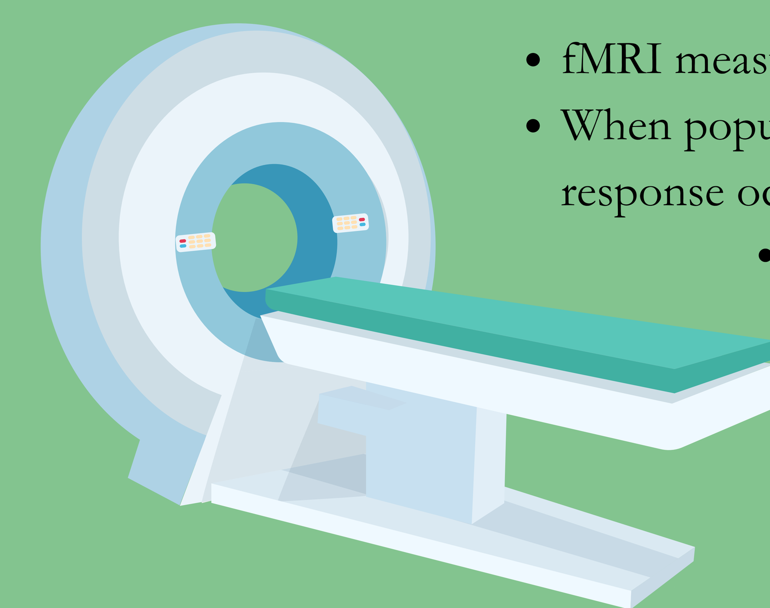
- Brain regions are "functionally" connected; their activity is highly correlated despite being spatially distinct.[3]
- Can we reveal changes in functional connectivity as a consequence of *statistical learning*?





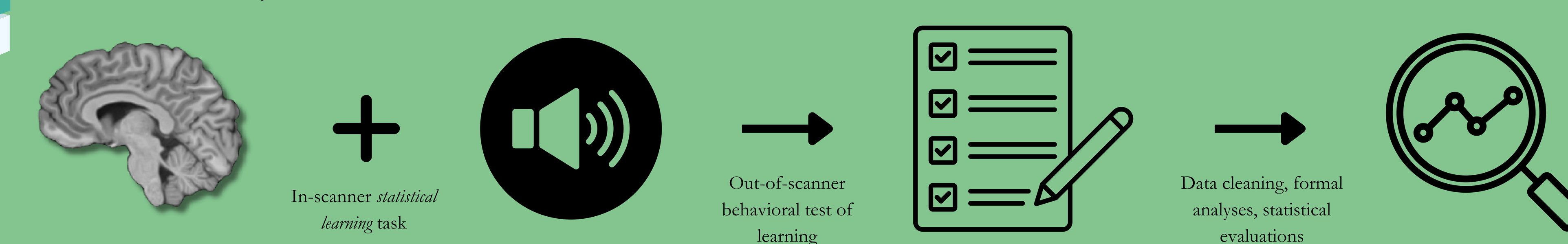
Are their systematic profiles of correlated neural activity at different times during learning?

Functional Magnetic Resonance Imaging



- fMRI measures changes in blood flow inside the brain.
- When populations of neurons are firing, a haemodynamic response occurs, facilitating neural activity.
  - Hemoglobin contains magnetic properties which can be monitored by the fMRI scanner.

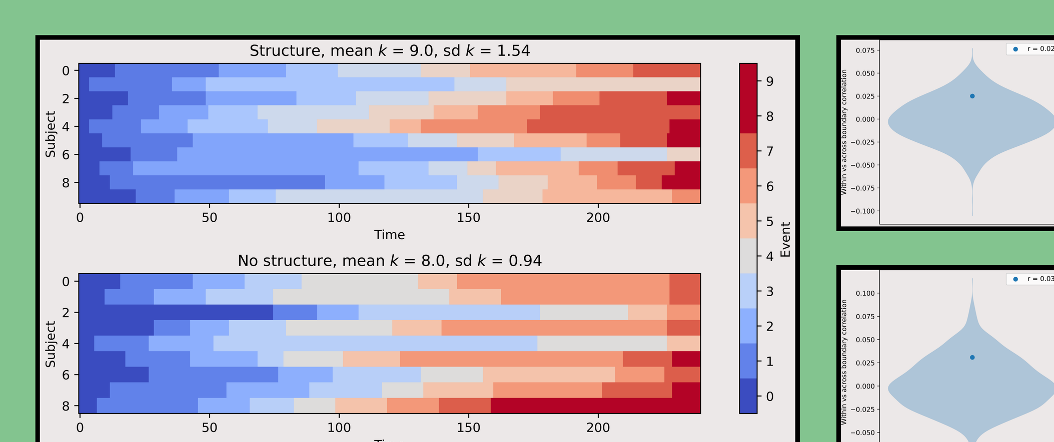
Procedures



Results & Discussion

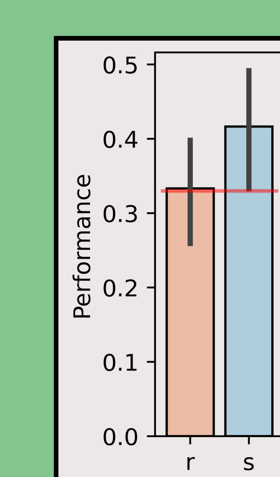
Event Segmentation

- An adapted hidden Markov model (HMM) was used to calculate event structure from the continuous fMRI time series.[1,8]



- Although behavioral results confirmed that learning occurred, subjects' neural data is more variable when learning than when not. This could be due to dimensionality reduction approach. Or....
- These group differences demonstrate the heterogeneity of learning: brain data is more variable when learning compared to not learning.[7,12]

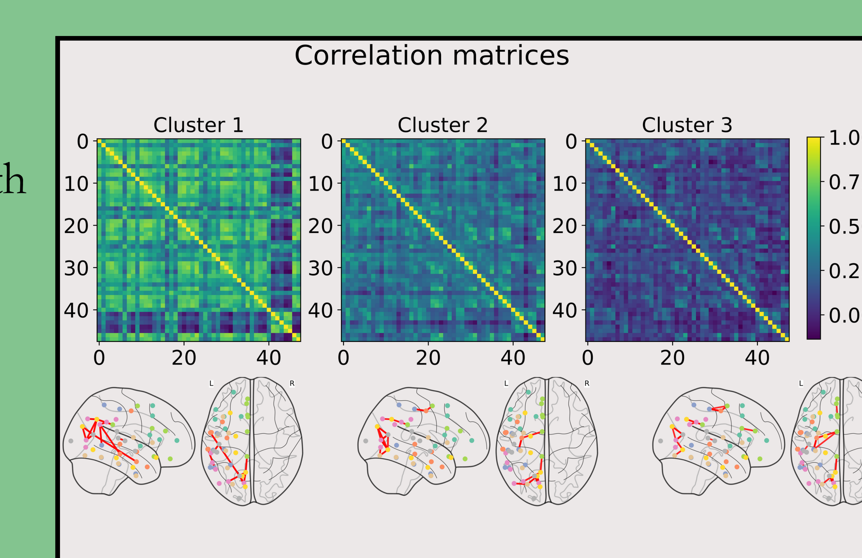
Behavior



- Individuals learned the structure.

Dynamic Functional Connectivity

- Using a sliding window approach, we calculated dynamic functional connectivity for the structured group using Pearson's ***r***.[13]
- Presence of low connectivity "state" inline with previous work.[10]
- Cluster one shows particular emphasis on auditory cortex.



- Left lateralization and general patterns bolster the idea that domain-specific perception *and* higher-order processing scaffold *statistical learning.* This is grounded in theoretical work.[5,7]

Bib

1. Baldassano, C., Chen, J., Zadbood, A., Pillow, J. W., Hasson, U., & Norman, K. A. (2017). Discovering event structure in continuous narrative perception and memory. Neuron, 95(3), 709-721.e5. https://doi.org/10.1016/j.neuron.2017.06.041
2. Batterink, L. J., & Paller, K. A. (2017). Online neural monitoring of statistical learning. Cortex, 90, 31–45. https://doi.org/10.1016/j.cortex.2017.02.004
3. Biswal, B., Yetkin, F. Z., Haughton, V. M., & Hyde, J. S. (1995). Functional connectivity in the motor cortex of resting human brain using echo-planar MRI. Magnetic Resonance in Medicine, 34(4), 537–541. https://doi.org/10.1002/mrm.1910340409
4. Calhoun, V. D., Adali, T., Pearlson, G. D., & Pekar, J. J. (2001). A method for making group inferences from functional MRI data using independent component analysis. Human Brain Mapping, 14(3), 140–151. https://doi.org/10.1002/hbm.1048
5. Conway, C. M. (2020). How does the brain learn environmental structure? Ten core principles for understanding the neurocognitive mechanisms of statistical learning. Neuroscience & Biobehavioral Reviews, 112, 279–299. https://doi.org/10.1016/j.neubiorev.2020.01.032
6. Emerson, S. N., & Conway, C. M. (2023). Chunking Versus Transitional Probabilities: Differentiating Between Theories of Statistical Learning. Cognitive Science, 47(5), e13284. https://doi.org/10.1111/cogs.13284
7. Frost, R., Armstrong, B. C., Siegelman, N., & Christiansen, M. H. (2015). Domain generality versus modality specificity: The paradox of statistical learning. Trends in Cognitive Sciences, 19(3), 117–125. https://doi.org/10.1016/j.tics.2014.12.010
8. Kumar, M., Anderson, M. J., Antony, J. W., Baldassano, C., Brooks, P. P., Cai, M. B., Chen, P.-H. C., Ellis, C. T., Henselman-Petrusek, G., Huberdeau, D., Hutchinson, J. B., Li, Y. P., Lu, Q., Manning, J. R., Mennen, A. C., Nastase, S. A., Richard, H., Schapiro, A. C., Schuck, N. W., … Norman, K. A. (2021). BrainIAK: The Brain Imaging Analysis Kit. Aperture Neuro, 1(4). https://doi.org/10.52294/31bb5b68-2184-411b-8c00-a1dacb61e1da
9. López-Barroso, D., Ripollés, P., Marco-Pallarés, J., Mohammadi, B., Münte, T. F., Bachoud-Lévi, A.-C., Rodriguez-Fornells, A., & De Diego-Balaguer, R. (2015). Multiple brain networks underpinning word learning from fluent speech revealed by independent component analysis. NeuroImage, 110, 182–193. https://doi.org/10.1016/j.neuroimage.2014.12.085
10. Park, J., Janacsek, K., Nemeth, D., & Jeon, H.-A. (2022). Reduced functional connectivity supports statistical learning of temporally distributed regularities. NeuroImage, 260, 119459. https://doi.org/10.1016/j.neuroimage.2022.119459
11. Romberg, A. R., & Saffran, J. R. (2010). Statistical learning and language acquisition. Wiley Interdisciplinary Reviews. Cognitive Science, 1(6), 906–914. https://doi.org/10.1002/wcs.78
12. Schneider, J. M., Scott, T. L., Legault, J., & Qi, Z. (2024). Limited but specific engagement of the mature language network during linguistic statistical learning. Cerebral Cortex, 34(4), bhae123. https://doi.org/10.1093/cercor/bhae123
13. Torabi, M., Mitsis, G. D., & Poline, J.-B. (2023). On the variability of dynamic functional connectivity assessment methods (p. 2023.07.13.548883). bioRxiv. https://doi.org/10.1101/2023.07.13.548883
14. Zacks, J. M., Speer, N. K., Swallow, K. M., Braver, T. S., & Reynolds, J. R. (2007). Event perception: A mind-brain perspective. Psychological Bulletin, 133(2), 273–293. https://doi.org/10.1037/0033-2909.133.2.273

Ack.

Thank you to the **LEND Lab** and **ReLearn Lab** for their continued support.

Some brain plots were generated with my open source Python module, `roipy`. Check it out!

```
$ pip install roipy
```

All code for formal analyses is hosted on GitHub. Scan the QR code.

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