# Transitional knowledge within counting sequences is processed across multiple levels of cortical hierarchy

*Eli Zaleznik, Joonkoo Park*
Department of Psychological and Brain Sciences, University of Massachusetts Amherst

Cognitive Developmental Neuroscience Lab

## Introduction

- Sequences underlie most complex behavior.
- Counting sequences are critical for learning abstract number processes.[1]
- Despite this, the neural bases of counting have never been directly studied or theorized, and they do not match well existing sequence or number theory.[2]
- Violation of expectation is a useful way to measure sequence processing and has been validated for counting sequences. [2,3]
- Question: What kinds of knowledge are contained in counting sequences?

## Hypotheses

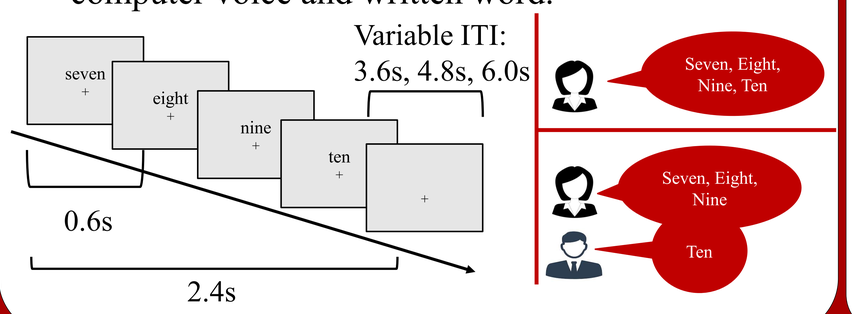
- We predict representation of counting sequences in *sensory*, *motoric, magnitude,* and *linguistic* codes that implicate auditory cortices, motor cortices, parietal cortices and frontal cortices, respectively.

## Participants & Imaging Procedure

- 37 participants (F = 26) in a 3T Siemens MRI.
- 6 runs x 48 trials.
- BOLD T2* parameters: TR = 1.2s, TE = 30ms, Flip interval = 69° FOV = 210mm, no. axial slices = 48, voxel dimensions = 3mm * 3mm * 2.5mm.

## Stimuli

- Numbers 1 through 10 presented in auditory computer voice and written word.




## Methods

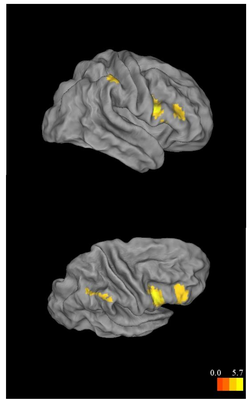
- All trials fell into a 2x2x2 design. Example trials:

| | Orderedness | |
|---|---|---|
| **Consecutiveness** | 3 4 5 6 | 3 5 4 6 |
| | 3 4 5 7 | 3 5 4 7 |

| **Voice Expectation** | Match | Mismatch |
|---|---|---|

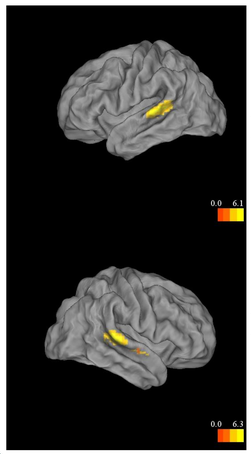
- MVPA on (Ordered – Unordered) by consecutiveness condition, using C=1 approach in libSVM.
- Feature selected top 10% of univariate voxels and created a null distribution through 10,000 permutations of random class labels to calculate p values.

## Univariate Results




Main effect of Orderedness

| Anatomical Region | X Y Z (MNI) | Mean Z-score | $q_{FDR}$ | nVoxels |
|---|---|---|---|---|
| rIFG – Triangularis | 48,11,19 | 5.56 | < .001 | 177 |
| rIFG – Opercularis | 42, 35, 14 | 4.20 | .010 | 92 |
| rIPS | 57, -31, 49 | 4.16 | .022 | 56 |




Main effect of Voice Expectation

| Anatomical Region | X Y Z (MNI) | Mean Z-score | $q_{FDR}$ | nVoxels |
|---|---|---|---|---|
| lSTG | 63, -31, 7 | 6.17 | < .001 | 190 |
| rSTG | -66, -34, 7 | 5.98 | < .001 | 190 |

## MVPA Results

- Tested MVPA on interaction:
  e.g., [3 4 5 6 > 3 5 4 6 ] > [3 5 4 7 > 3 5 4 7]
- Five ROIs identified in whole-brain ANOVA & anatomically-defined SMA.

| ROI | Classification Accuracy | p value |
|---|---|---|
| Oper | 58.45% | <.0001 |
| Tri | 61.67% | <.0001 |
| IPS | 55.32% | .0074 |
| rSTG | 57.77% | <.0001 |
| lSTG | 56.32% | .0004 |
| SMA | 47.56% | .8640 |

## Discussion

- Our hypothesis was supported by MVPA analysis revealing patterns of activation to violated counting sequences in rIPS, rIFG, and bilateral STG.
- Counting sequences engage an auditory code, magnitude representations, and linguistic representations.
- We were surprised by lack of SMA activity, despite its apparent relation to domain-general ordering.
- We suggest that individual elements that contain magnitude are being "bound" together into a sequence in rIFG.

## References

[1] Fuson, K. C. (2012). *Children's Counting and Concepts of Number*. Springer Science & Business Media.
[2] Dehaene, S., Meyniel, F., Wacongne, C., Wang, L., & Pallier, C. (2015). The Neural Representation of Sequences: From Transition Probabilities to Algebraic Patterns and Linguistic Trees. *Neuron*, *88*(1), 2–19.
[3] Lang, S., & Kotchoubey, B. (2002). Brain responses to number sequences with and without active task requirement. *Clinical Neurophysiology*, *113*(11), 1734–1741.