Modeling the Neural Representation of Rapid Visual Sequences in a Statistical Learning Paradigm

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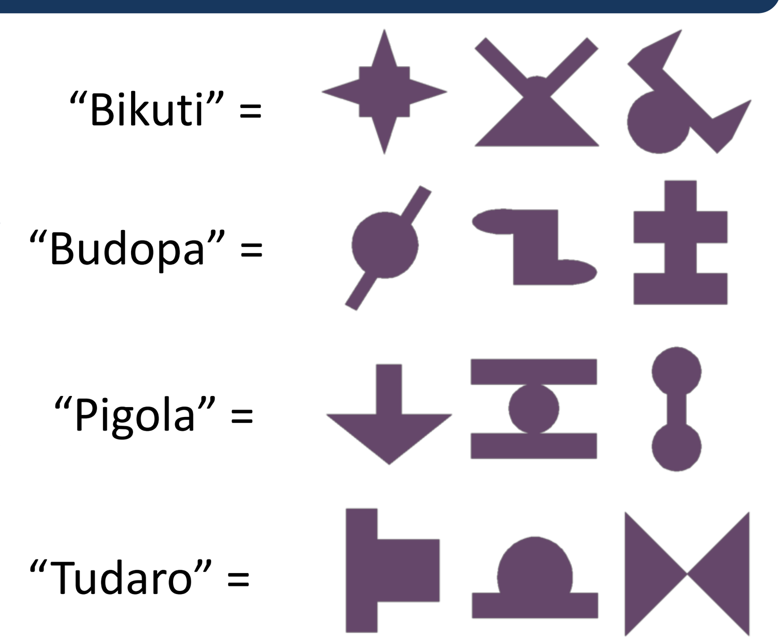
Introduction

- How is sequential structure represented neurally across domains?
- Combine statistical learning paradigm with neuroimaging: greater control than naturalistic video[1] or audio[2]
- In this way, can use finer-grained manipulations to assess cortical encoding of sensory dependencies across time[3]
- Challenge: reconciling slow hemodynamic response with rapid sequential input
- Immediate Goal: to assess whether multivariate analysis of the BOLD response can be used to study fronto-parietal network contributions to sequence processing during rapid stimulus presentation in a statistical learning paradigm.
- Approach: Use pattern similarity analysis[4] to re-analyze pre-existing dataset (Karuza, 2014)

Experimental Design & Methods

- N = 16
- fMRI recorded during exposure to image sequences
- 4 triplets intact images (+ 4 triplets spatially scrambled images, blocked), random order
- 1 s SOA
- 800 ms stimulus duration + 200 ms blank
- Familiarity test for image triplets crossing "word boundaries" vs. not after each run
- Images subtended ~5.5°, purple or green
- 36 images / block, 4 blocks / run, 4 runs

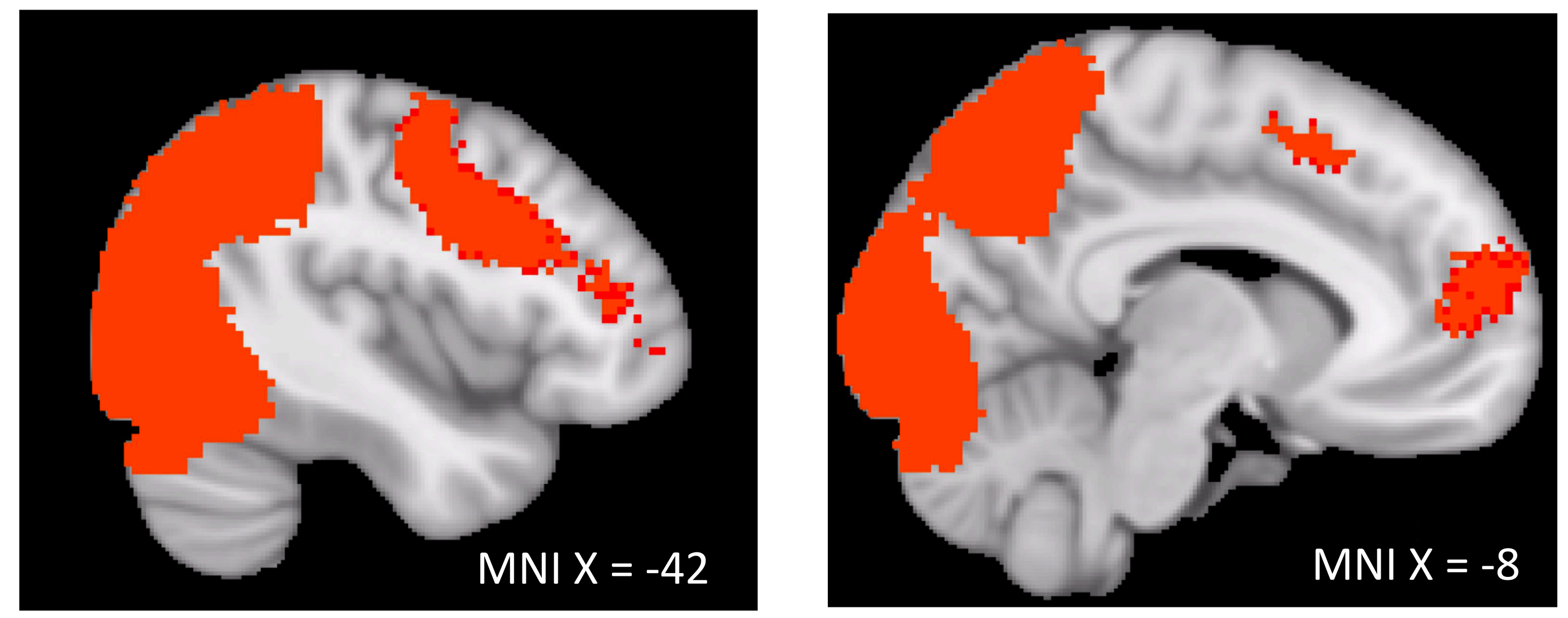


Analysis & Modeling Approach

- Computed V1-like gabor filter features[5] for each image (sensitive to different filter frequencies and orientations)
- Combined features across image triplet by summation, including both intact and scrambled images
- Created dissimilarity matrix among triplets based on triplet features
- Performed GLM on BOLD signal, extracted T-values corresponding to each image triplet (~mean signal over triplet)
- Pattern-similarity analysis conducted using whole-brain searchlight: 100 x 4 mm³ voxels (spherical) in CoSMoMVPA
- Used permutation-based clustering with Threshold-Free Cluster Enhancement to identify significant clusters with above zero pattern similarity to the triplet features, across participants
- Performed across whole session and separately for each run to assess effects of learning / extended exposure to statistical structure

Pattern Similarity Analysis Reveals Cortical Response to Image Sequences

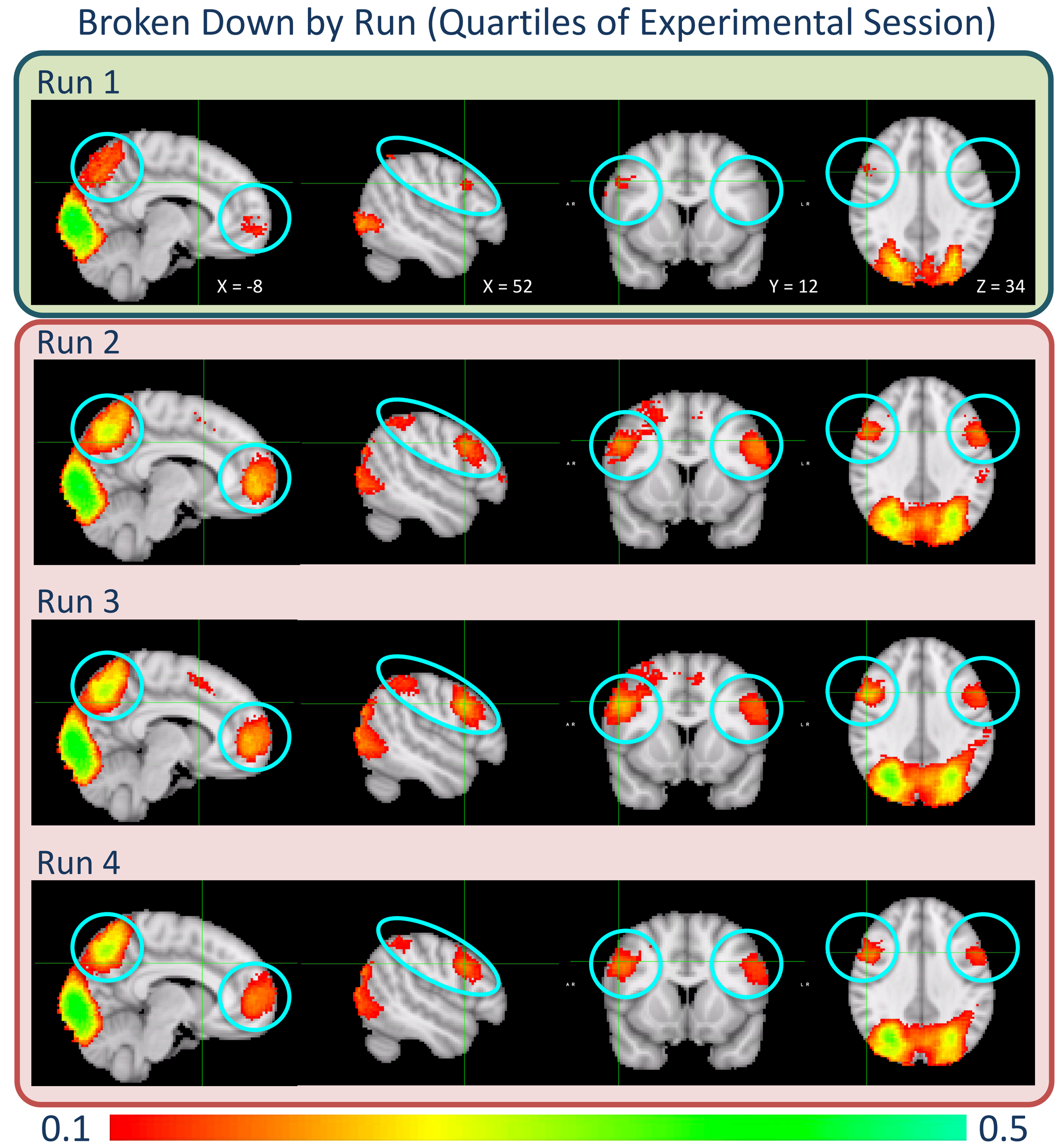
Significant Clusters Showing Pattern Similarity to Visual Features



- Similarity space based on gabor-like features correlates with cortical activity in significant clusters across much of occipital and parietal cortex, lateral and medial PFC (p < .05 one-tailed cluster corrected)
- Passes first sanity check as viable analysis approach for paradigms involving rapid stimulus exposure + artificial sequence learning
- However, unclear to what extent related to sequential nature of stimuli

Model Fit in Fronto-Parietal Network Improves with Longer Exposure to Novel Statistical Structure

Pattern Similarity to Visual Features: Broken Down by Run (Quartiles of Experimental Session)



Correlation with Visual Feature DSM

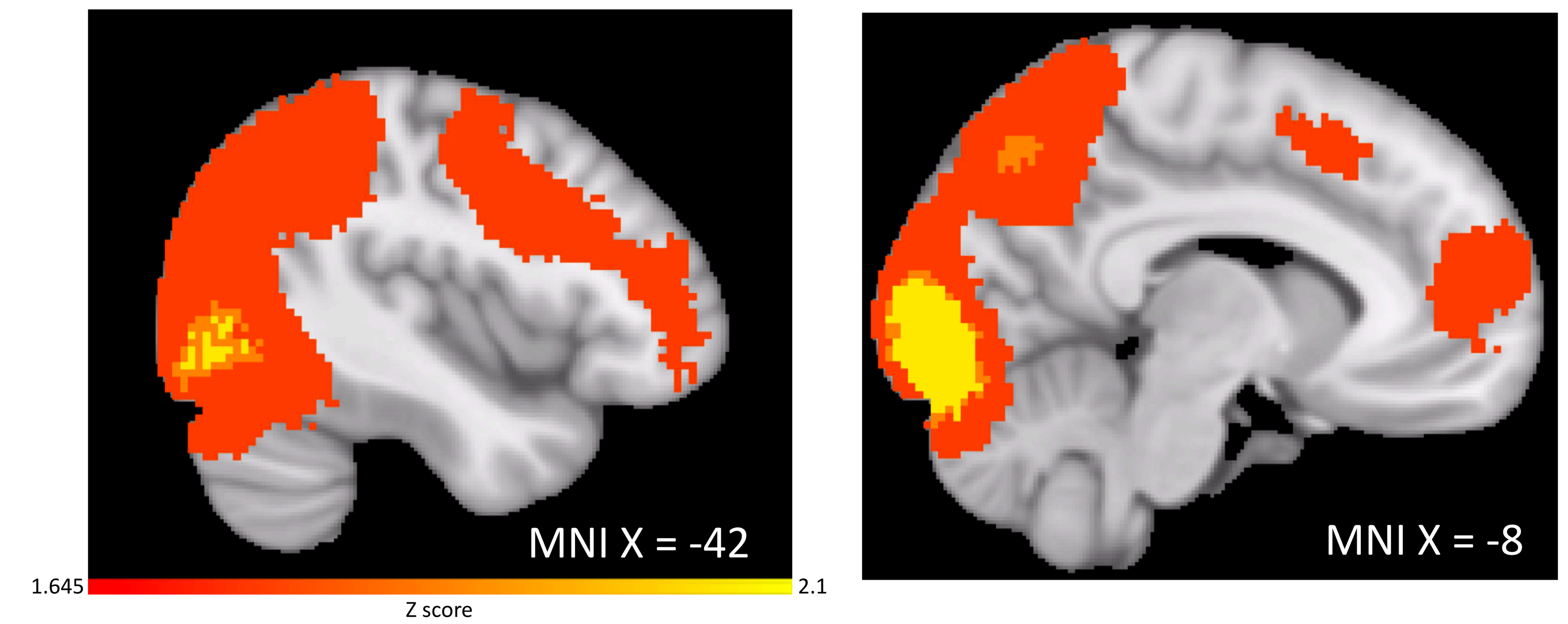
Pattern similarity appears to first emerge or increase in extent in parietal cortex, lateral PFC and and mPFC after first run of experiment.

Consistent with emergence of behavioral indicators of sensitivity to sequential structure (familiarity test)

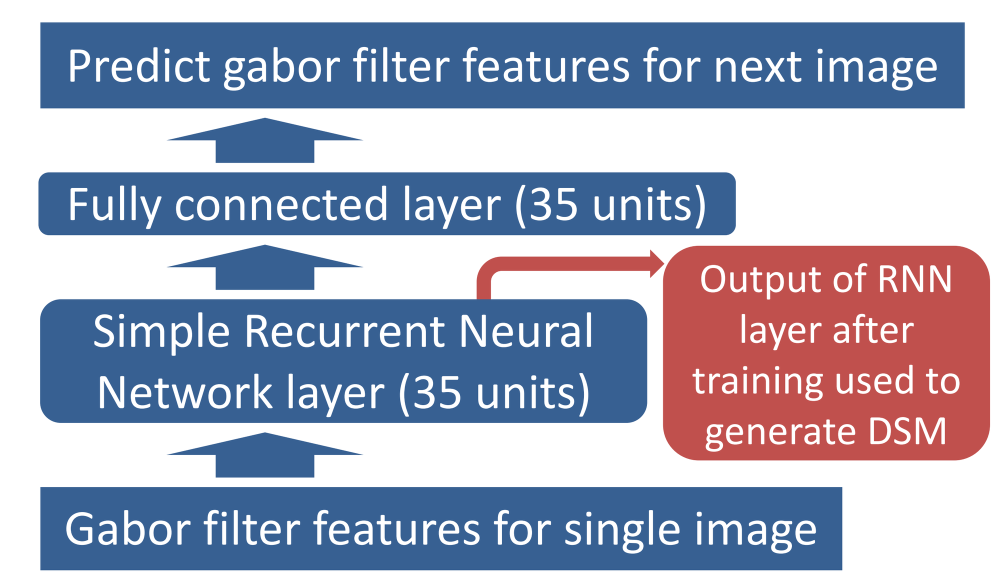
Caveat: need to rule out alternative explanations for decreased power in run 1 (e.g. increased movement)

Modeling Sequential Structure with Recurrent Neural Networks

Significant Clusters Showing Pattern Similarity to RNN Features



Recurrent Neural Network Architecture



- Using internal state of RNN designed to predict upcoming input features yielded improved pattern similarity match across multiple cortical regions:
  - higher correlations
  - larger cluster size
- Both fronto-parietal and occipital cortex

Summary and Conclusions

- Pattern similarity analysis of the BOLD response can be used to identify cortical regions sensitive to short sequences of images, including within the fronto-parietal network
- Several lines of evidence are consistent with sensitivity to sequential order, including sensitivity to duration of exposure to statistical structure, and improved model fit using a recurrent neural net.
- **Future directions:**
  - Comparison with auditory sequence data
  - Collection of new fMRI + EEG data: manipulation of hierarchical sequential structure.

References

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