Semantic Variability Predicts Neural Variability of Object Concepts

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CONTEXT-DEPENDENT THEORY OF CONCEPT REPRESENTATION

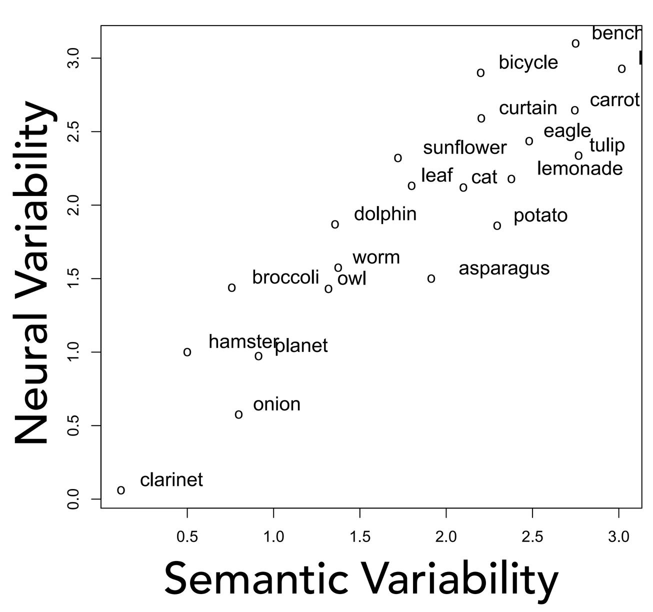
- ✧ Meaning is generated by the dynamic interaction between a concept and the context in which it is accessed.
- ✧ Concepts are not represented as context-invariant, static entities retrieved in isolation.
- ✧ Neuroscientists often treat these representations as fixed.
  - common practices to reduce "noise" in signal: averaging across stimulus presentations; limiting analyses to voxels with the most stable activation profiles

Objective

- ✧ Compare neural patterns elicited by conceptual processing of the same stimulus item as it appears in different contexts
- ✧ Relate within-item, cross-context neural variability to measures of semantic/contextual variability

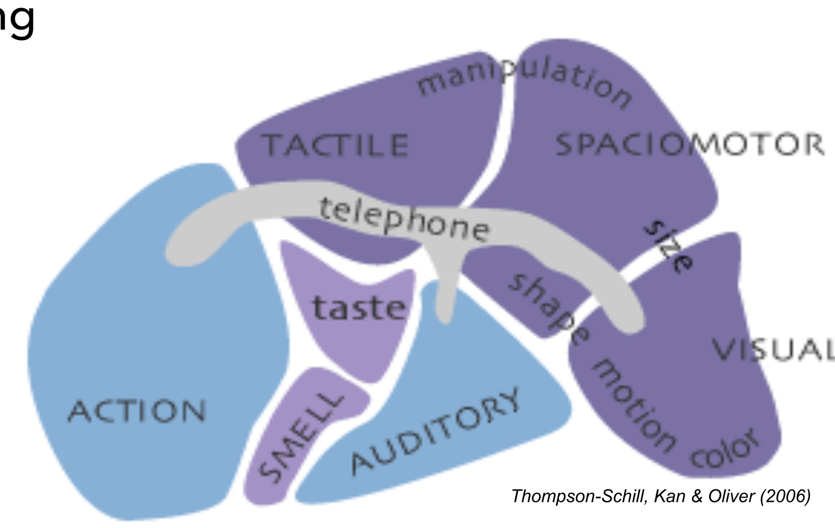
HYPOTHESIS

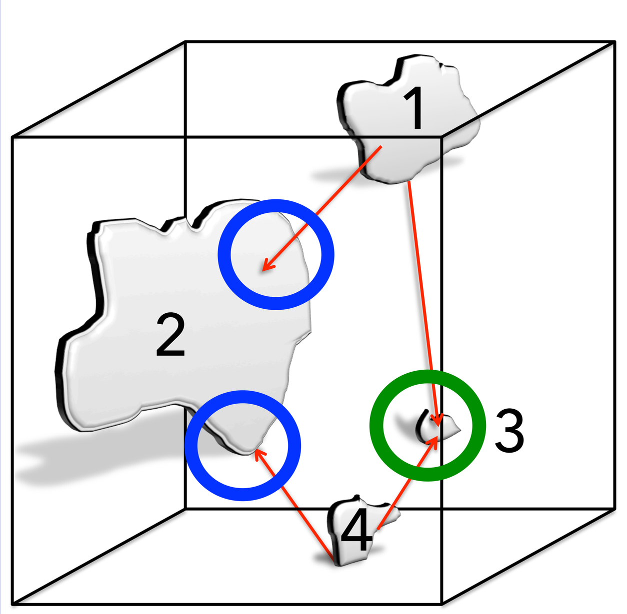
stable meanings
↓
stable neural patterns



variable neural patterns
↑
variable meanings

- ✧ Corresponding neural variability: physical manifestation of concept-context coupling
- ✧ Semantic features are neurally distributed & dynamically activated depending upon current task/context





- ✧ Projected into high-dimensional semantic space: a concept's meanings in its various uses
- ✧ Traverse from one concept to another
- ✧ Concept #2 has more diverse meanings than Concept #3
- ✧ The 2 instantiations of Concept #2 are more variable than the 2 instantiations of Concept #3

QUANTIFYING SEMANTIC VARIABILITY

- ✧ Concept: word appearances in large linguistic corpora
- ✧ Context: paragraph of text in which the word appears
- ✧ How many contexts does each concept appear in, and how similar are these contexts to one another?

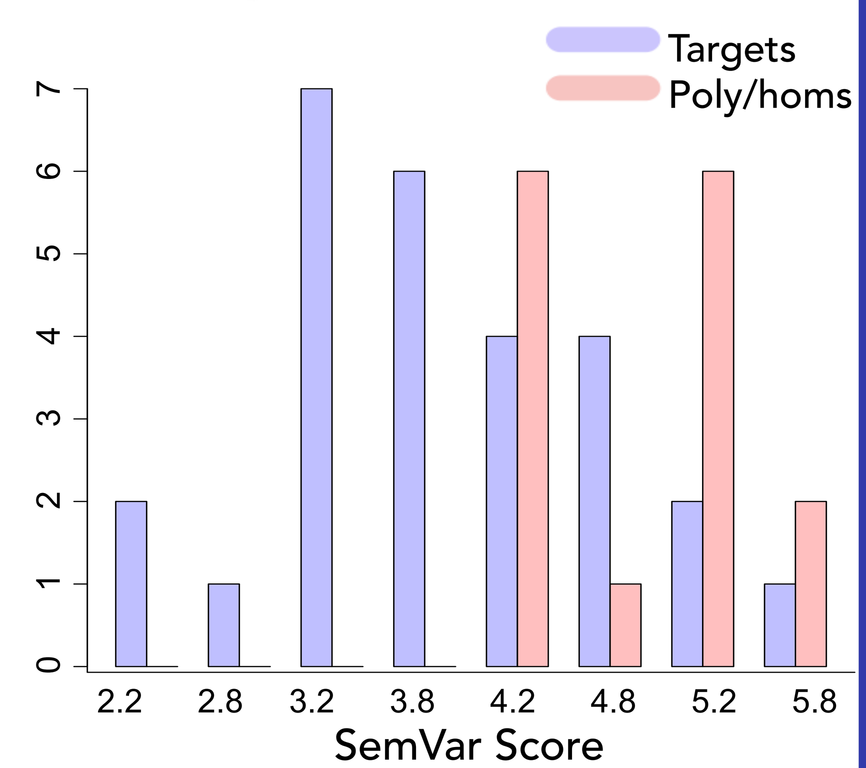
- ✧ SemVar: a composite score for each concept, computed using PCA on results from topic modeling[3], LSA[2], and context frequency counts[1]
- ✧ a measure of diversity amongst a concept's contexts

CREATING VARIABLE CONTEXTS

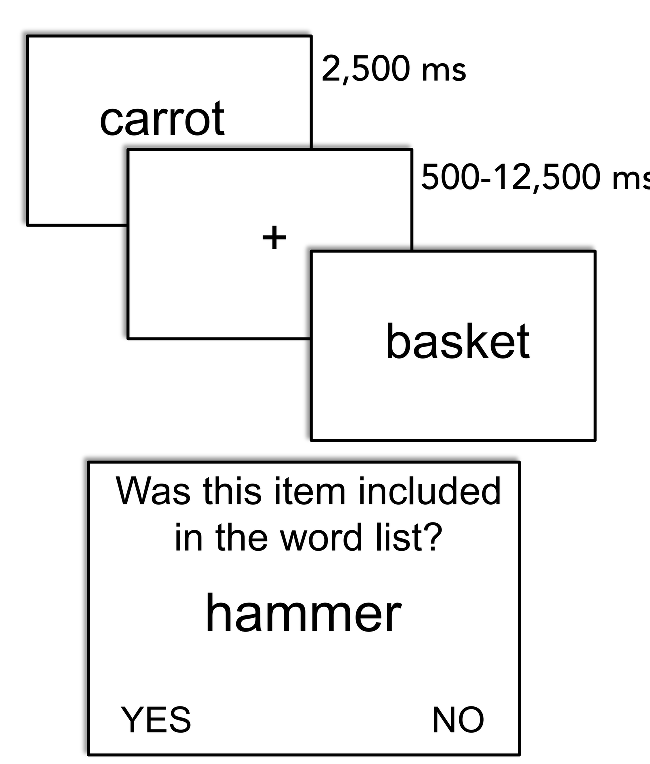
Stimuli

- ✧ 160 single-sense, concrete nouns: 30 "target" & 130 "filler" words
- ✧ 15 polysemous & homonymous words
- ✧ Words assigned to 9 *unique, randomly ordered lists*, each with:
  - 10 targets
  - 15 fillers
  - 5 "poly/homs"
- ✧ Each target & poly/hom word appears in 3 different lists
- ✧ Unique and unrepeated fillers added to lists, to increase list variability

Histogram of SemVar Values



Procedure

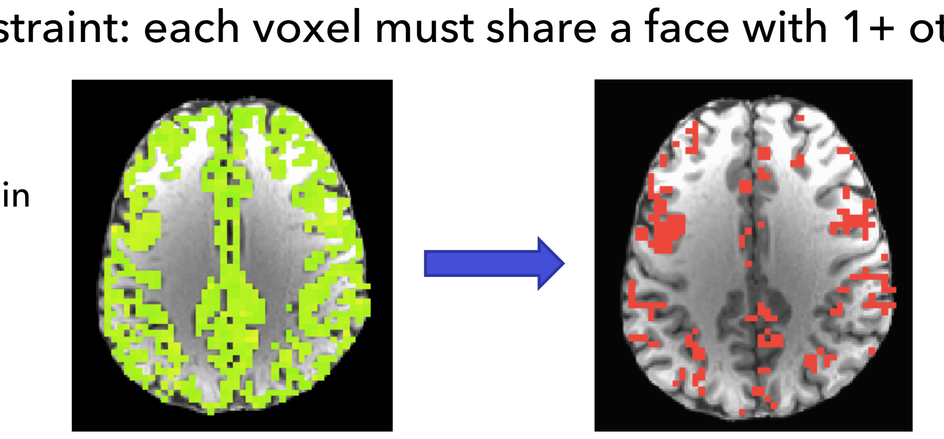


- ✧ Subjects (n=19) completed 9 fMRI scans
  1 scan per list, each 4 minutes long
- ✧ Sequential word presentations
- ✧ Task during scanning: memory encoding
  Purposefully left open-ended, to avoid constraining subjects' semantic interpretations
- ✧ Task after each run: recognition memory tests
  - Probes: 5 foils & 5 fillers
  - Memory for target words never tested between lists

WHOLE-BRAIN VOXEL SELECTION

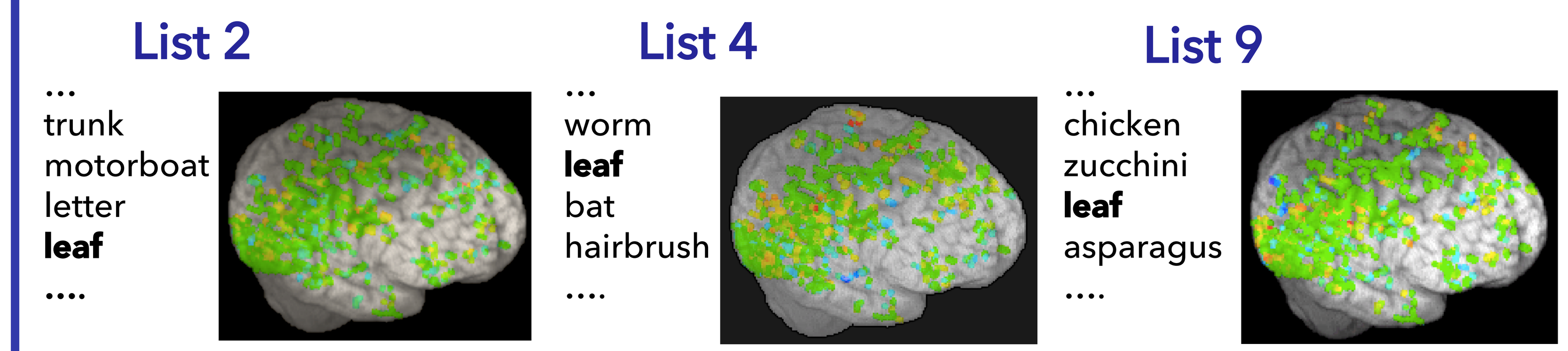
- ✧ Gray matter voxels ranked by test statistic, those most responsive to both: (1) words vs. fixation and (2) differences across word presentations
- ✧ Measured neural patterns in 12 voxel sets of varying sizes: top 25-10,000 voxels
- ✧ Contiguity constraint: each voxel must share a face with 1+ other included voxels

Voxel test statistics in gray matter voxels



Mask of voxels with top 2,000 test statistics

MEASURING NEURAL VARIABILITY



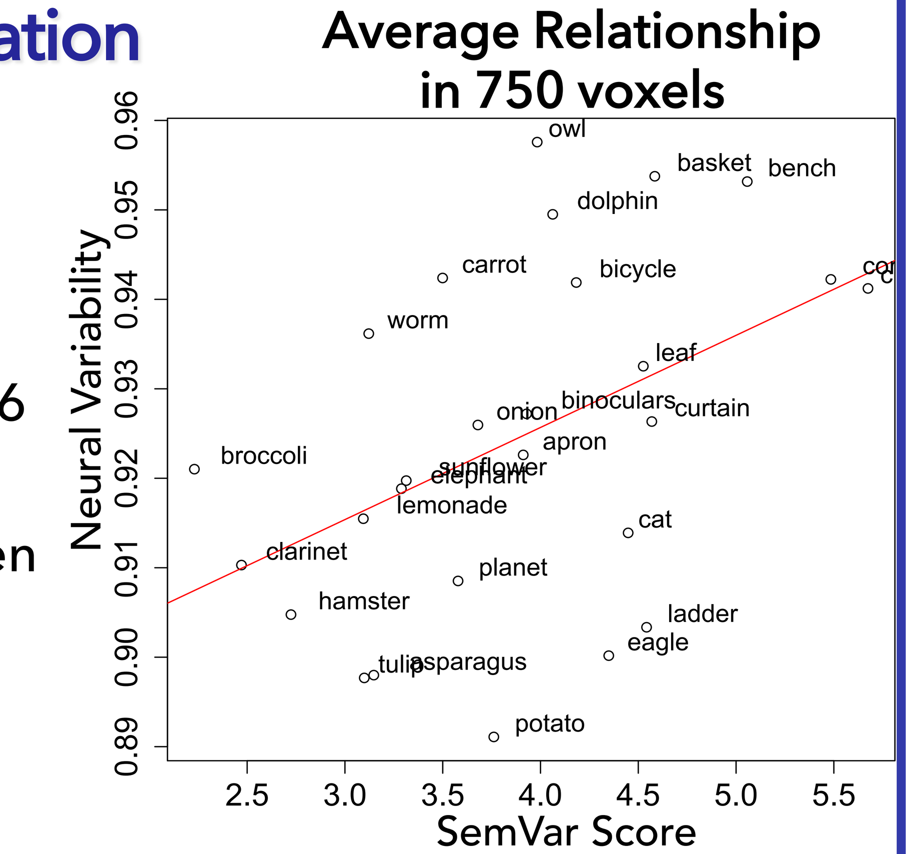
- ✧ Across spatially distributed voxels: measured average dissimilarity between neural patterns evoked by each concept in its three different contexts (1 - Pearson correlation coefficient)

RESULTS

Semantic-Neural Correlation

- ✧ Positive correlation between target words' SemVar score and corresponding neural variability, $t(18)= 3.1$, $p= .006$
- ✧ Correlations significantly positive across subjects, when patterns measured in sets of 250-2,000 voxels.

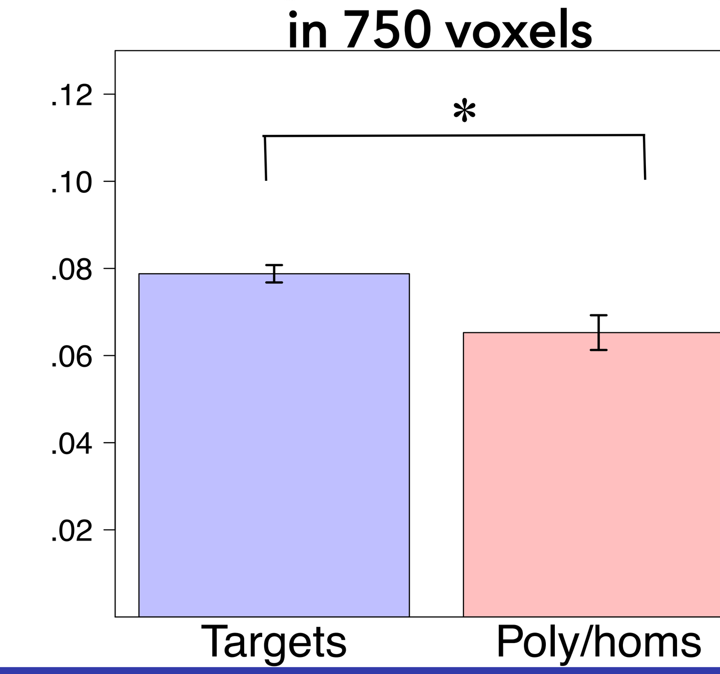
Average Relationship in 750 voxels



Effects of Lexical-Semantic Ambiguity

- ✧ Polysemous and homonymous words: 2+ different meanings or senses share the name same (e.g., chicken $_{meat}$ & chicken $_{bird}$)
- ✧ these words should exhibit especially variable patterns, since they denote multiple concrete meanings.
- ✧ Polyhoms elicit less neural similarity than target words: $t(19)= -2.2$, $p= .04$
- ✧ Robust at voxel set sizes: 25-750

Average Pattern Similarity in 750 voxels



DISCUSSION

- ✧ Neural activity varied across repeated stimulus presentations, and this variation was reliably predicted by measures of semantic variability.
- ✧ Supports a flexible, distributed theory of semantic memory organization, in which a concept's meaning varies continuously as a function of its context.
- ✧ Within-stimulus "noise" can reflect context-modulated variation in a concept's semantic representation

REFERENCES

1. Brysbaert, M., & New, B. (2009). Moving beyond Kučera and Francis: A critical evaluation of current word frequency norms and the introduction of a new and improved word frequency measure for American English. *Behavior Research Methods*, *41*, 977–990.
2. Hoffman, P., Lambon Ralph, M. A., & Rogers, T. T. (2012). Semantic diversity: A measure of semantic ambiguity based on variability in the contextual usage of words. *Behavior Research Methods*, *45*, 718-730.
3. Pereira, F., Botvinick, M., & Detre, G. (2013). Using Wikipedia to learn semantic feature representations of concrete concepts in neuroimaging experiments. *Artificial Intelligence*, *194*, 240–252.