Introduction

- Neuroimaging studies of semantic memory often suggest localization of conceptual domains in cortex.
- Connectionist models of semantic memory propose:
  - A voxel can encode information about >1 domain.
  - Adjacent voxels may encode different information.
  - Distal regions can contribute to one representation.
  - Experience determines what a given voxel encodes.
- We argue that univariate analyses are ill suited to detect such radically distributed signals should they exist in fMRI datasets. [1]
- We use sparse logistic regression (LASSO) to test the localist and distributed hypotheses with less bias.

Sparse Logistic Regression

Given T samples \((x_1, y_1), \ldots, (x_T, y_T)\) the conditional log-likelihood is:

\[
\ell(\beta) = -\sum_{t=1}^{T} y_t \log p_t + (1 - y_t) \log (1 - p_t)
\]

In this case, \(\beta^T x\) is a vector and \(\beta^T x\) shows the influence of voxel i on the solution. When voxel \(|\beta_i| = 0\), it does not contribute at all.

Least Absolute Shrinkage and Selection Operator (LASSO) is used to find a sparse solution.

\[
\arg\min_{\beta} \ell(\beta) + \lambda \|\beta\|_1
\]

SUMMARY: LASSO satisfies two conditions, which can be parametrically prioritized; (1) minimize prediction error (2) while keeping the sum of the absolute values of \(\beta\) low. For large enough \(\lambda\) many \(|\beta_i|\) are zero—the solution is sparse.

Simulation: Methods

Created 1-0 brains with 128 voxels for 30 “subjects”, with three structures:

- Subj 1
  - Modular
  - Distributed
  - Diff. Distrib.

- Subj 30
  - Modular
  - Distributed
  - Diff. Distrib.

- Noise added to each voxel \(N(0, \sigma = 1)\).
- Signal strength = 2.
- When applying a blur, FWHM = 4 voxels.
- Analyzed either by univariate method (t-test) or LASSO.

Simulation: Results

- Modular:
  - Distributed:
  - Diff. Distributed:

- d-prime:
  - Raw
  - Smooth

- Hit Rate
  - Univariate
  - LASSO

fMRI Dataset:

Participants: 34 right handed subjects; scanned at the Medical College of Wisconsin. Stimuli: 1200 letter strings (900 words, 300 nonwords obeying English phonology). 600 words were concrete, 300 abstract. Of the concrete nouns: 94 animals 145 artifacts.

Task: Respond to the question “Is it something physical you can experience with your senses?” by button-press every 100 ms.

Procedure: Letter strings presented one at a time at jittered intervals in random order over the course of 10 scanner runs with no repetitions in a rapid event-related design. Imaging and Preprocessing: Participants were scanned in a GE 3T scanner with a 2-second TR. The first 6 TRs from each run were discarded. Functional data was time-shifted, registered to the anatomy and scaled prior to deconvolution. Cerebral Masts: Surface reconstructions for each subject’s anatomy were created and used to select only cortical voxels (i.e. space between pial and white matter ribbons) from the volumes of beta coefficients for each word and subject (Freesurfer[3]).

Univariate: Methods

Spatial smoothing: 4mm fwhm gaussian kernel applied prior to deconvolution.

Deconvolution: Multiple linear regression with gamma variate HRF [LASSO(2)]

ROI Selection: Limited analysis to cortical mask derived from T, N27 atlas.

Contrasts:
- Animal - Artifact
- Animal - Nonword
- Artifact - Nonword

GLM analysis included a regressor for artifacts, other words, and non-words.

Correction for Multiple Comparisons: Cluster thresholding (p < .05, k > 20) based on simulating 10,000 datasets of the same size/smoothness as our own filled with noise (afni 3dClustSim[3]).

Multivariate: Methods

Deconvolution: Multiple linear regression with gamma variate HRF. GLM analysis included a regressor for each word and nonword stimulus, resulting in 1200 volumes with beta coefficients at each voxel for each subject.

Classification Tasks: In separate tasks, LASSO[4] is used to discover a sparse solution given \(\lambda\) to classify 900 words as animal/non-animal or artifact/non-artifact.

Pre-selection: Applied cortical mask to the beta-volumes for each participant.

Cross Validation: The words were separated into 10 blocks, each balanced for number of animals, artifacts, and abstract words.

Cross validation was performed at two levels: one to pick a good value of \(\lambda\) from 10 pre-specified choices without peeking, and another to evaluate the chosen \(\lambda\) for all train-test combinations of the 10 blocks of words.

Univariate: Results

- Animals - Nonwords
- Animals - Artifacts
- Artifacts - Nonwords

Multivariate: Results

Above Chance Accuracy
- Animal Classifier: 0.53±0.03, t=16, p<0.001
- Artifact Classifier: 0.53±0.06, t=14, p=0.003

Discussion and Future Directions

- LASSO provides evidence of radically distributed and overlapping code in areas implicated by disorder.[1]
- Each solution is likely a subset of the full system.
- Elastic nets blend LASSO and ridge regression, sparsity and inclusiveness.
- Constraining regression in different ways changes the preferred solution; different brain regions may encode semantics in different ways.
- Tuning elastic nets to prefer solutions of different types should identify regions thought to represent semantics in a corresponding way.

References

[6] Our results, including variable in solution of >3 participants

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