Session I: Introduction to Multivariate Pattern Analysis (MVPA)

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Neural Decoding of Visual Imagery During Sleep

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Decoding accuracy (%)

80

50

LVC HVC

What is Multivariate Pattern Analysis?

Combined use of multiple variables measuring the brain (e.g. BOLD signal in multiple voxels) to predict or characterize states of the brain

Swisher et al. (2010) – J Neurosci
Overview

Why Multivariate Pattern Analysis?
How Does MVPA work?
Activity vs. Information
Encoding vs. Decoding
Prediction vs. Interpretation
Neural Basis of MVPA
Why Multivariate Pattern Analysis?

1. Often higher sensitivity compared to „normal“ univariate analyses

Example: Representation of perceptual choices

Li et al (2009) - Neuron
2. Representational content in brain region rather than
general activation can be studied

Example: Representation of orientations

How Does Multivariate Pattern Analysis Work?

1. Weak information can be combined across voxels
→ Multivariate analysis enhances signal

<table>
<thead>
<tr>
<th>Activity</th>
<th>Voxel 1</th>
<th>Voxel 2</th>
<th>Voxel 1 – Voxel 2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>A</td>
<td>B</td>
<td></td>
</tr>
<tr>
<td>Condition A</td>
<td><img src="image1" alt="Activity Graph" /></td>
<td><img src="image2" alt="Activity Graph" /></td>
<td><img src="image3" alt="Activity Graph" /></td>
</tr>
<tr>
<td>Condition B</td>
<td><img src="image4" alt="Activity Graph" /></td>
<td><img src="image5" alt="Activity Graph" /></td>
<td><img src="image6" alt="Activity Graph" /></td>
</tr>
</tbody>
</table>

n.s.

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How Does Multivariate Pattern Analysis Work?

2. Covariation of voxel information can be used → Multivariate analysis suppresses noise
How Does Multivariate Pattern Analysis Work?

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How Does Multivariate Pattern Analysis Work?

3. Information becomes accessible that is encoded only in distributed activity patterns
ACTIVITY VS INFORMATION
Activity vs. Information

Activity: Tells us about general involvement in cognitive function (e.g. working memory)

Activity vs. Information

Information: Tells us about representational content (e.g. memory trace of A vs. memory trace of B)

ENCODING VS DECODING
Encoding vs. Decoding

Cognitive Function

Encoding $g$: $X \rightarrow Y$

Decoding $h$: $Y \rightarrow X$

what we normally do in univariate analyses

X: Explaining variable
Example: Stimulus, response, cognitive condition

Y: Measured data
Example: BOLD signal, EEG signal, VBM intensity
Overview Over Analysis Methods

Encoding

- GLM Model-based
- MANOVA Similarity Analysis

Decoding

- Simple Classification
- Multivariate Decoding

univariate

multivariate
Multivariate Decoding Approach (the big picture)

1. Separate data in training and test data
2. “Train” a classifier (i.e. find a good separating line)
3. Apply this classifier (i.e. the line) to test data
4. Result: Accuracy of test data (i.e. % correct prediction)
Why Decoding?

- Decoding sounds cool
- Methods readily available from machine learning
- The principle is relatively easy to understand
- Model-based univariate approaches and RSA are typically limited to condition-rich designs (i.e. few repetitions, many conditions)
- CV-MANOVA has only been developed more recently and is not widely popularized

- Decoding for reverse inference: Poldrack (2011) – Neuron
PREDICTION VS INTERPRETATION
Goals of Decoding: Prediction vs. Interpretation

**prediction**

- **goal**: prediction
- **question**: ?
- **data / method**: multivariate decoding
- **answer**: ✓
- **conclusion**: can be decoded

**interpretation**

- **goal**: interpretation
- **question**: ?
- **data / method**: multivariate decoding
- **answer**: ✓
- **conclusion**: brain region represents objects

*Hebart & Baker (2017) – Neuroimage*
Goals of Decoding: Prediction

Prediction: Goal is to maximize future correct predictions

→ Any information is useful as long as it increases accuracy

Medical Diagnosis

Brain-Computer-Interface

Lie Detection
Goals of Decoding: Prediction

Prediction: Goal is to maximize future correct predictions
→ Any information is useful as long as it increases accuracy
Goals of Decoding: Interpretation

Interpretation: Is there information about XYZ?
→ Sufficient to show above chance accuracy (statistically!)
→ Not all information sources ok, need to rule out confounds

Prediction vs. Interpretation

- Machine learning methods have been developed for prediction, but we are using them for the inference that there is information present about XYZ.
- This alternative use of these methods has far reaching consequences that are underappreciated.
- Many misunderstandings in MVPA originate from this, e.g.:
  - Too strong restrictions for interpretation studies (related to non-independence).
  - False sense of certainty when high decoding in study $\rightarrow$ High decoding can arise from confounds and should not be trusted more than activation studies (see Ritchie et al (2017) – bioRxiv).
Milestones of MVPA

- **1998**
  - "first" MVPA study

- **2001**
  - first multivariate decoding study
  - Haxby et al (2001)

- **2005**
  - popularization of multivariate decoding
  - Kamitani & Tong (2005)

- **2005**
  - searchlight approach
  - Haynes & Rees (2005)

- **2005**
  - representational similarity analysis
  - Kriegeskorte et al (2005)

- **2006**
  - model-based encoding methods

- **2008**
  - combination of fMRI and MEG using RSA

- **2011**
  - hyperalignment
  - Haxby et al (2011)

- **2014**
  - use of artificial neural networks as models for cognition
  - Cichy et al (2014)

- **2015/2016**
  - e.g. Di Carlo

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Kay & Gallant (2008)
NEURAL BASIS OF MVPA
Neural Basis of MVPA

Popular Idea: Small random sampling bias in orientation retains orientation information in voxel
Neural Basis of MVPA: Fine-scale patterns?

Does smoothing hurt decoding accuracy?

![Graph showing SVM performance vs. smoothing (FWHM in mm)]

![Graph showing SVM performance vs. smoothing (in voxels)]

Neuroimage: Op de Beeck (2010a,b); Kamitani & Sawahata (2010); Kriegeskorte (2010); Shmuel et al (2010); Chaimow et al (2011)
Dominance of fine scale (evidence for „hyperacuivity“)

Cat: 0.3125 x 0.3125 mm resolution

Neuronal Basis of MVPA

Bias maps instead of columns in V1?

Oblique effect

Radial bias

How does MVPA work – revisited

Radial bias maps, not columns explain „hyperacuity”

How does MVPA work – revisited

The debate continues…

- Chaimow et al (2011) – Neuroimage
- Alink et al (2013) – Front Hum Neurosci
- Carlson (2014) – J Neurosci
- Clifford & Mannion (2015) – Neuroimage
- Carlson & Wardle (2015) – Neuroimage
- Alink et al (2017) – Scientific Reports
Neural Basis of MVPA – Summary

- Both course and fine-grained responses can contribute to decoding results
- Orientation decoding in V1 probably does not work with "hyperacuity"
- This property may also hold for other brain regions where the coarse-scale "maps" are unknown
- **But:** In general decoding based on course-scale signals is fine as long as effects not driven by different feature of the results (e.g. radial bias and not orientation)
Summary

- MVPA is more sensitive than classical univariate approaches and can reveal representational content.
- MVPA works by combining signal across voxels and suppressing correlated noise between voxels.
- Investigating brain activity vs. informational content are two different approaches.
- Encoding methods predict brain data from categories, decoding methods predict categories from brain data.
- Decoding for prediction and decoding for interpretation are very different approaches.
- MVPA likely relies strongly on course-scale signals.
Study Questions

“A colleague comes by to ask for your methodological expertise. She studies action perception with fMRI and got a reviewer comment saying that she should distinguish brain regions that represent perceived actions from brain regions generally involved in perceiving actions.”

Question 1: What does this difference mean?

Question 2: How would you tell her to do the analysis (without details, just in general)?

Question 3 (difficult): Can you think of a way of designing an experiment that addresses this issue without decoding? Can you think of a downside to this approach?