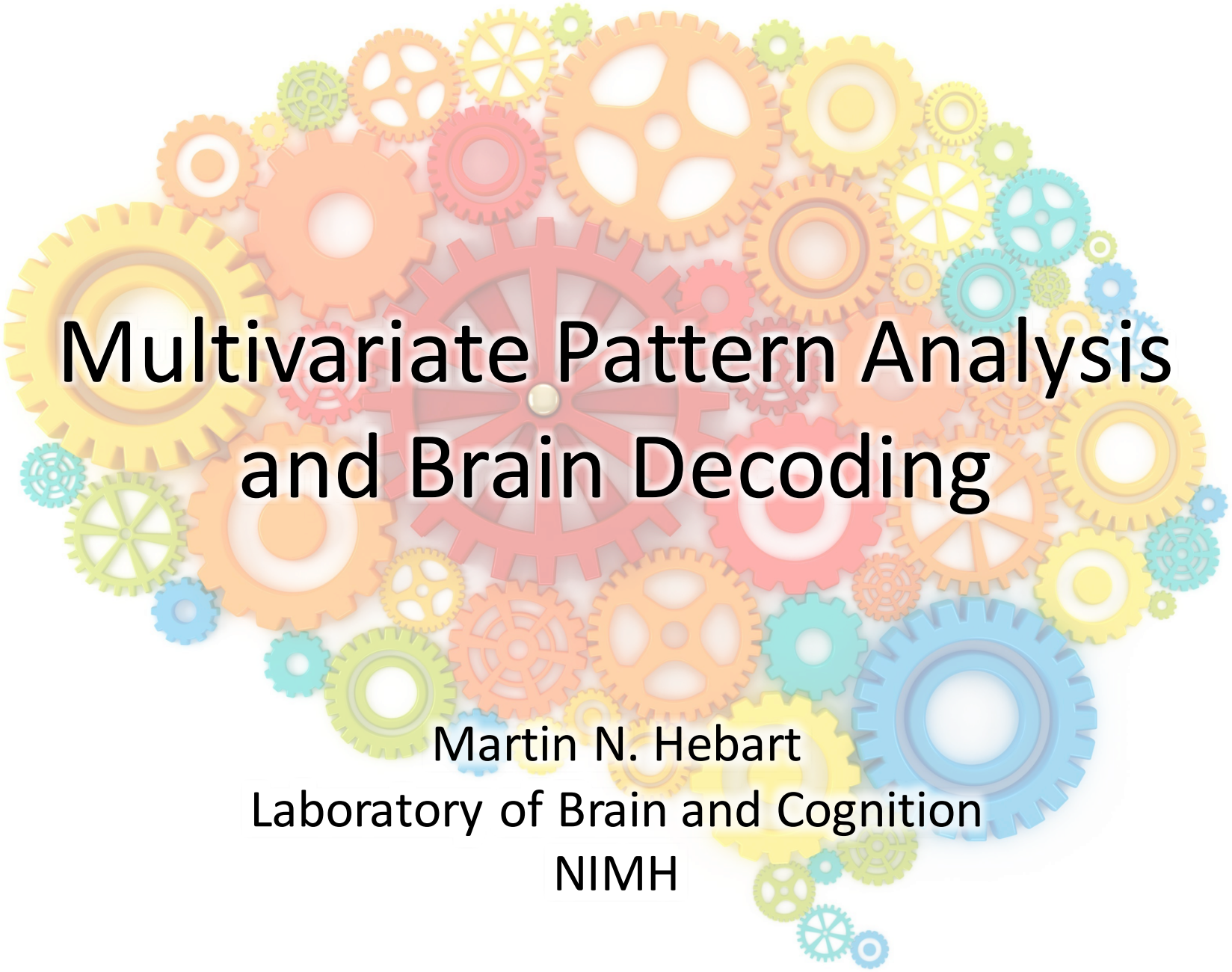


Multivariate Pattern Analysis and Brain Decoding

Martin N. Hebart
Laboratory of Brain and Cognition
NIMH

“Let’s try Cognitive Pattern Recognition”

Movie snippet courtesy: Fox Network

Neural Decoding of Visual Imagery During Sleep

T. Horikawa,[1,2] M. Tamaki,[1*] Y. Miyawaki,[3,1†] Y. Kamitani[1,2‡]

www.sciencemag.org SCIENCE VOL 340 3 MAY 2013

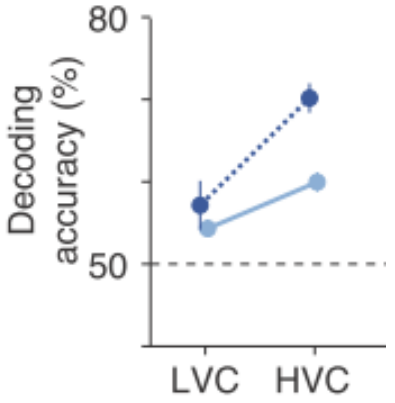
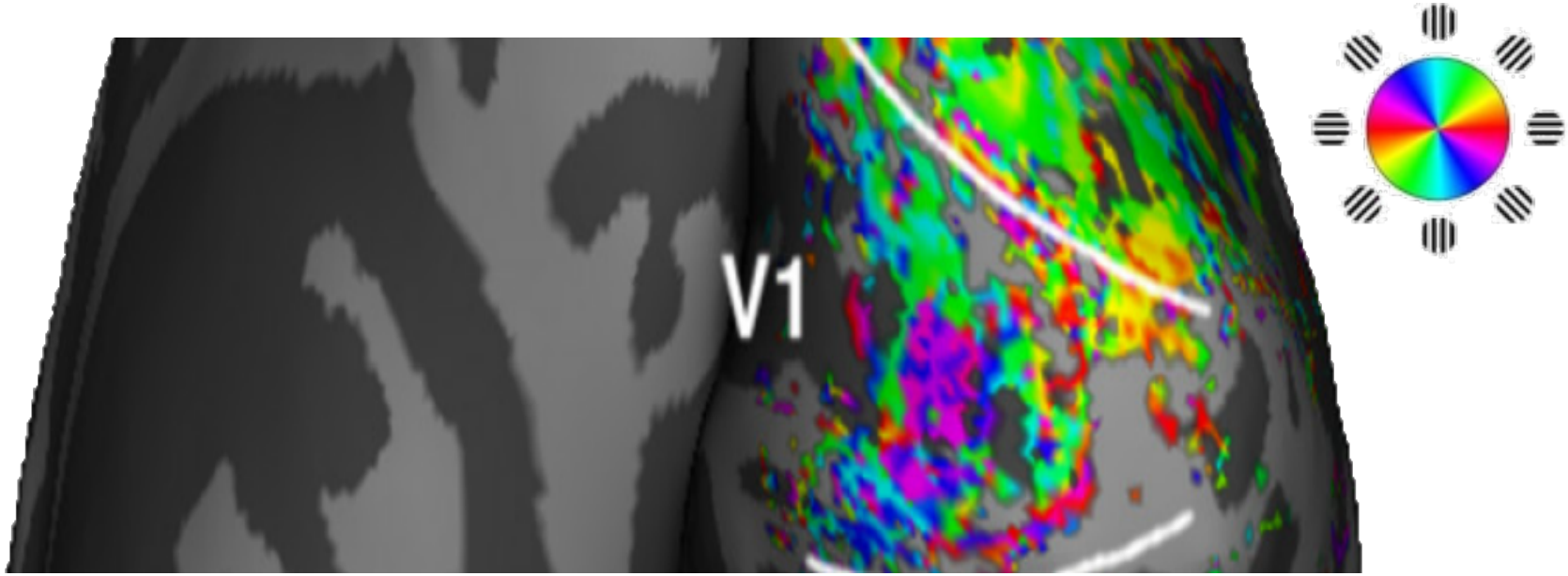


Image courtesy: David Castillo Dominici, http://www.freedigitalphotos.net

What is Multivariate Pattern Analysis?

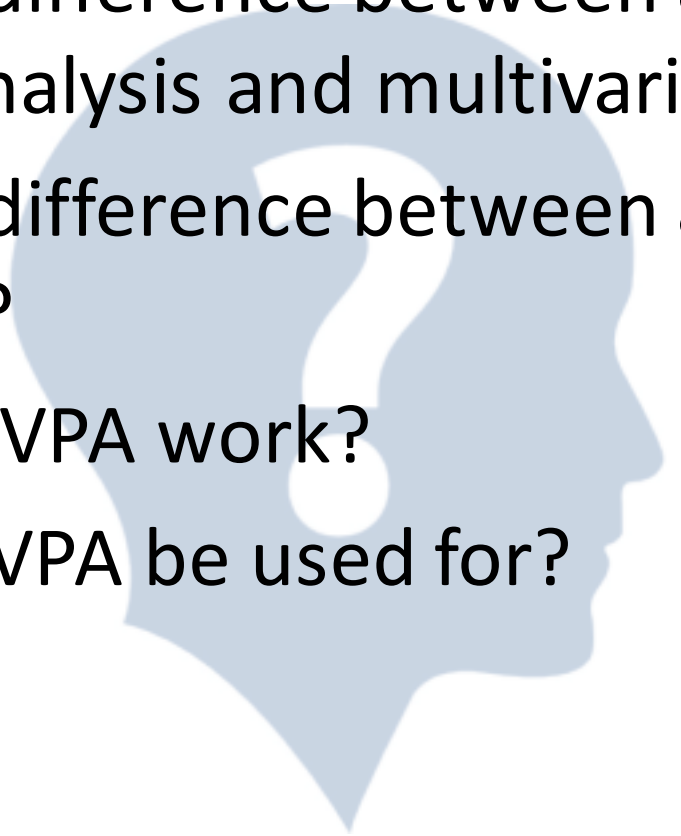
Combined use of multiple variables measuring the brain (e.g. BOLD signal in multiple voxels) to predict or characterize states of the brain



Swisher et al. (2010) – J Neurosci

Central Questions for This Lecture

- What is the difference between a “classical” brain data analysis and multivariate decoding?
- What is the difference between activity and information?
- How does MVPA work?
- What can MVPA be used for?

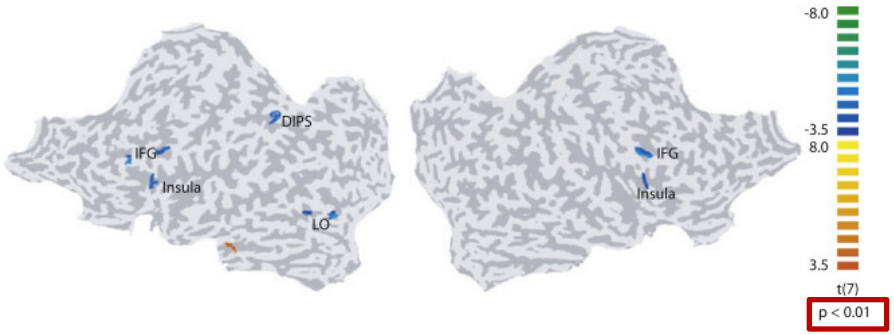


Why Multivariate Pattern Analysis?

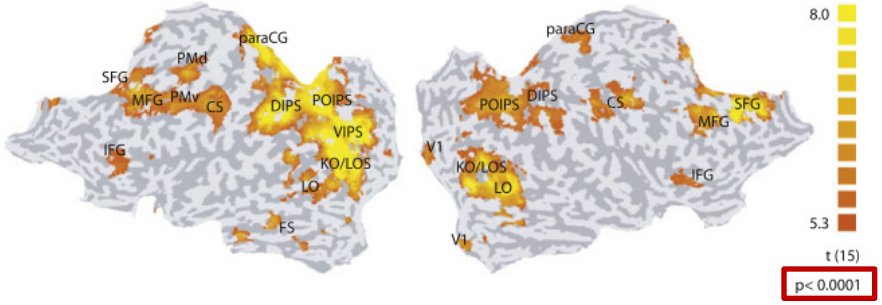
1. Higher sensitivity compared to „normal“ univariate analyses

Example: Representation of perceptual choices

classical univariate



multivariate

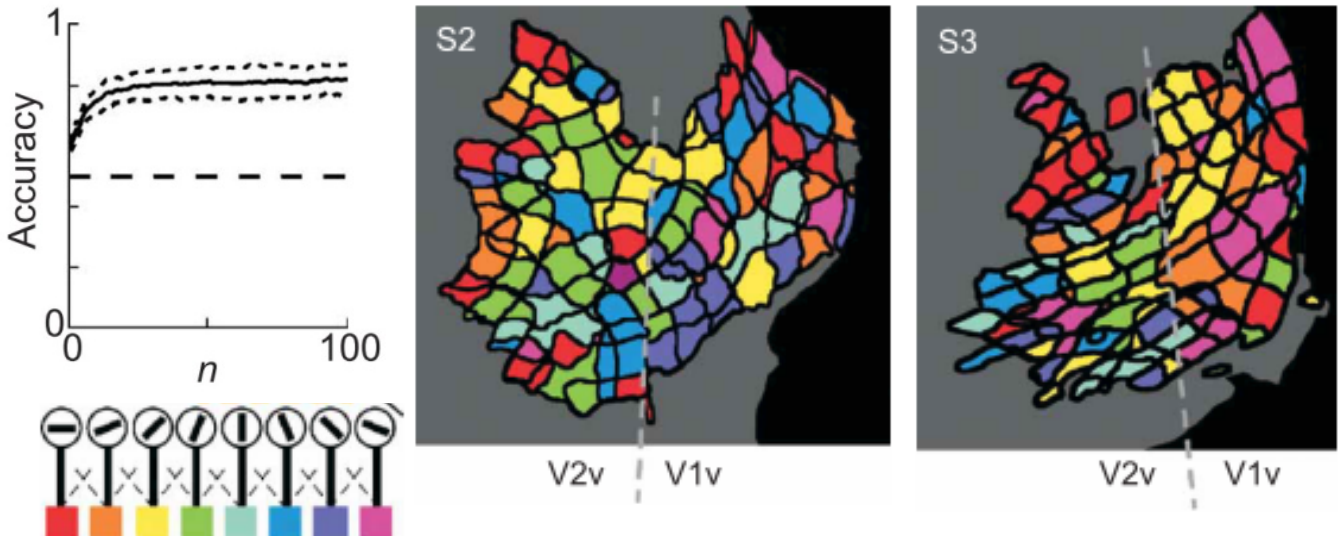


Li et al (2009) - Neuron

Why Multivariate Pattern Analysis?

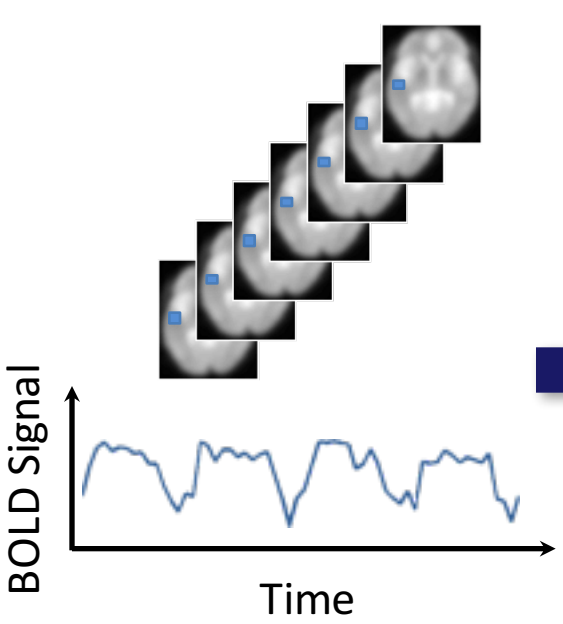
2. Representational content in brain region rather than general activation can be studied

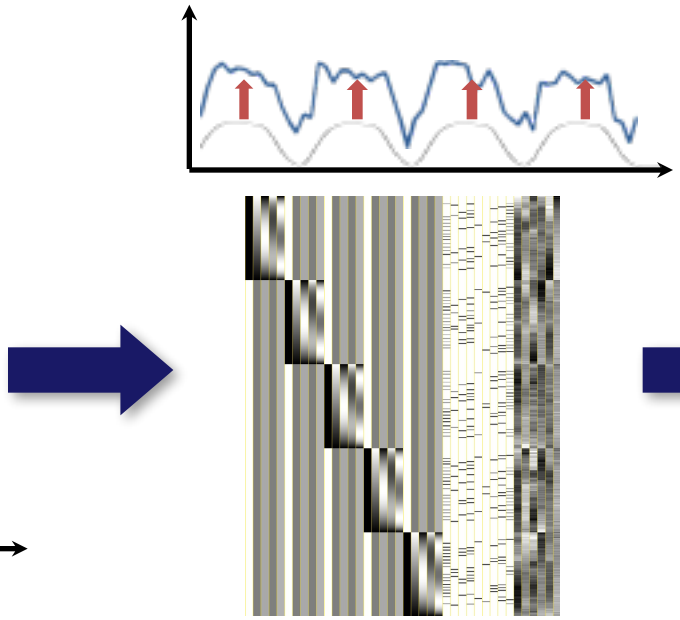
Example: Representation of orientations in visual cortex

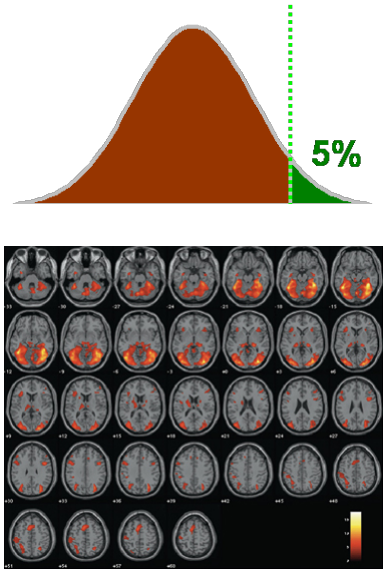


Kamitani & Tong (2005) – Nat Neurosci, Haynes & Rees (2005) – Nat Neurosci

“Classical” Analysis: Mass-Univariate







Functional Brain Scans

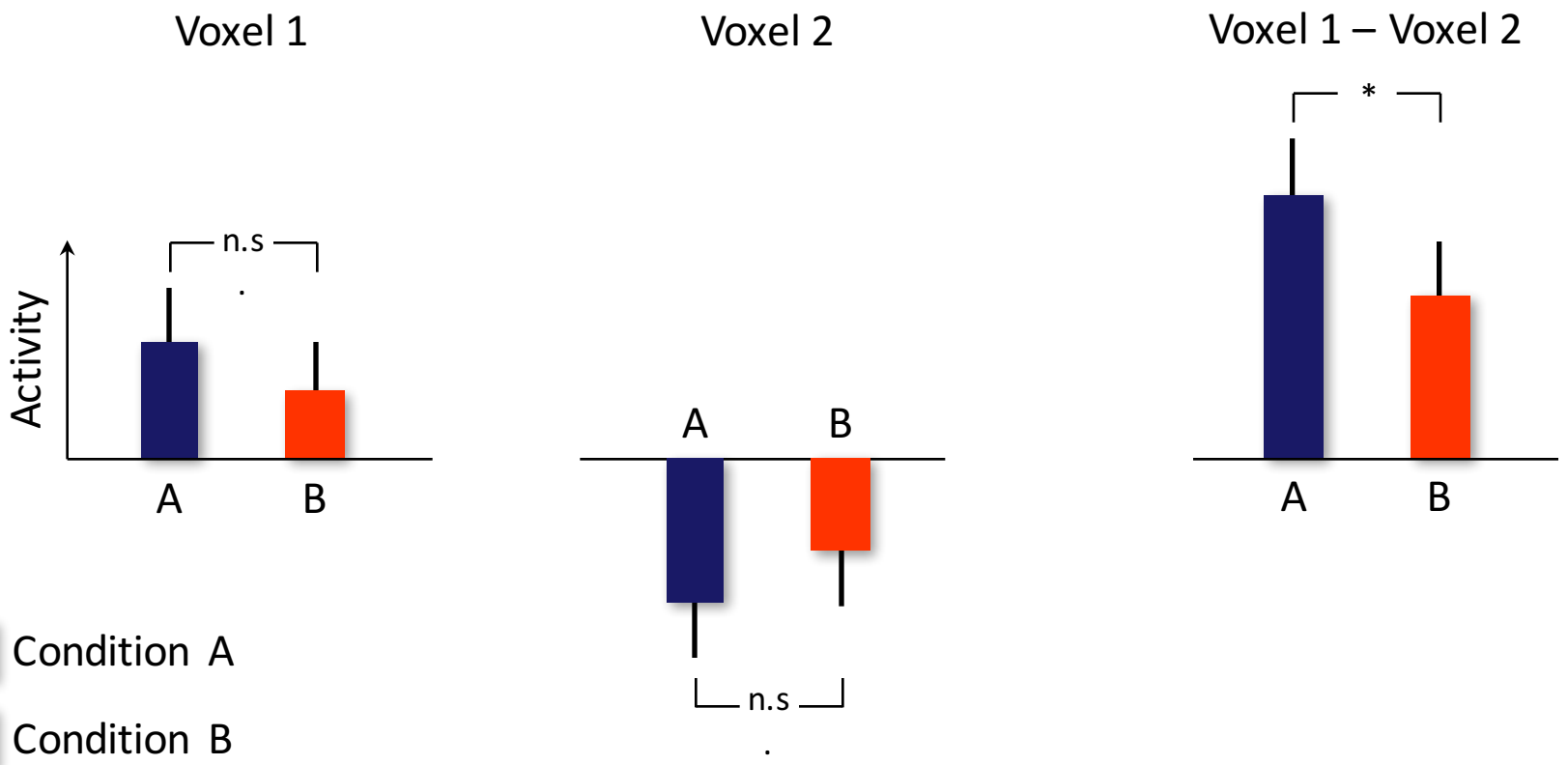
General Linear Model

Statistical Parametric Maps

Each voxel is treated separately, only statistical correction across voxels

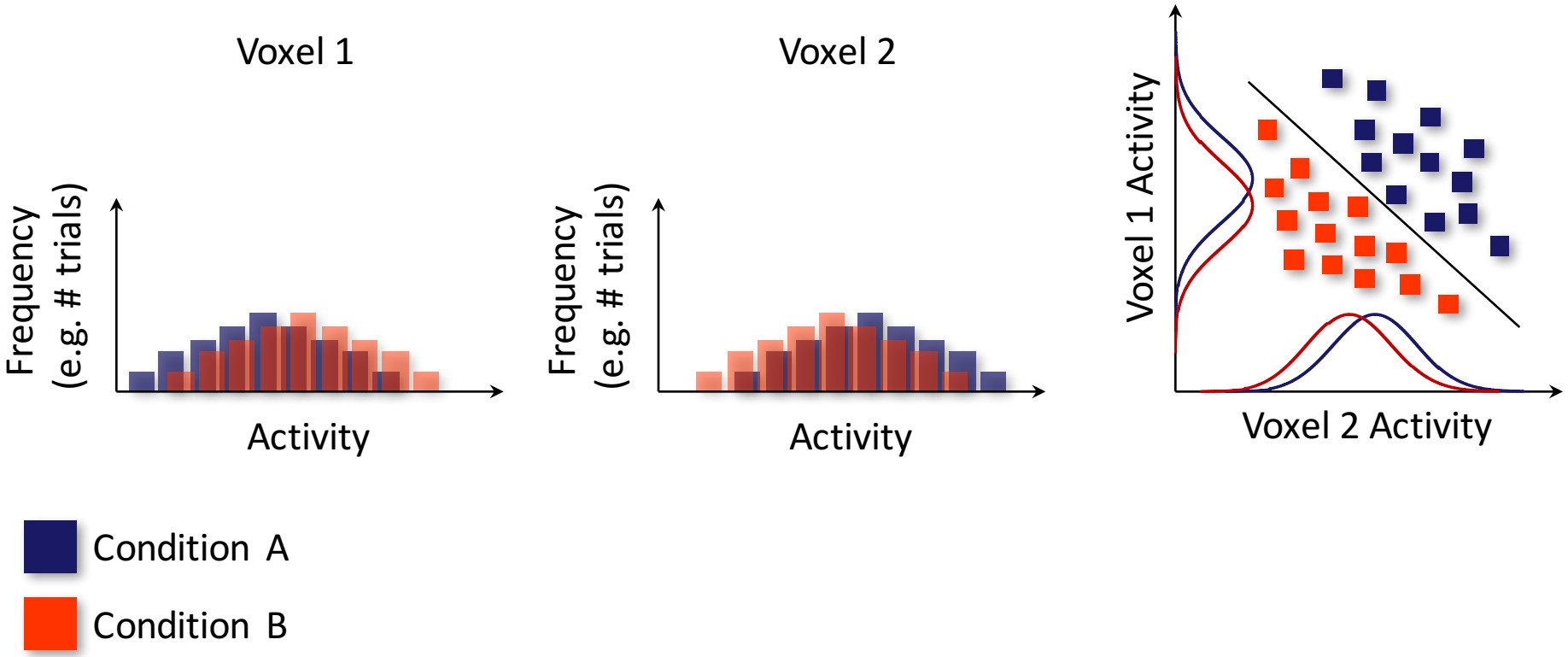
How Does Multivariate Pattern Analysis Work?

1. Information of multiple voxels can be combined



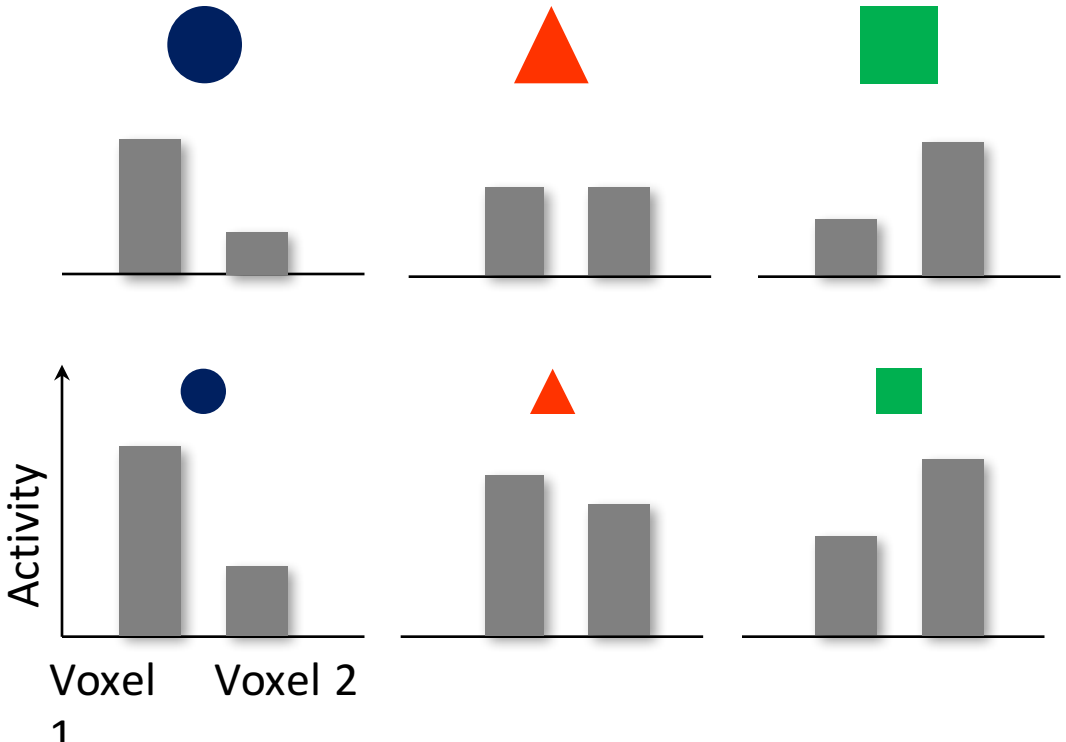
How Does Multivariate Pattern Analysis Work?

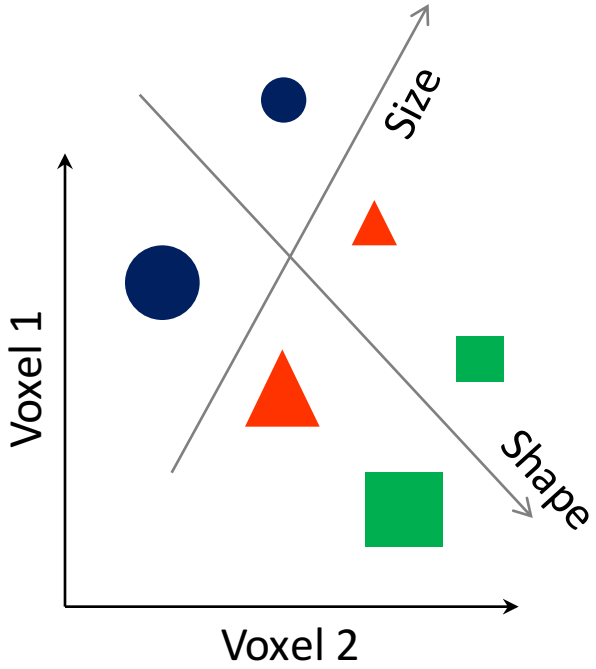
2. Covariation of voxel information can be used



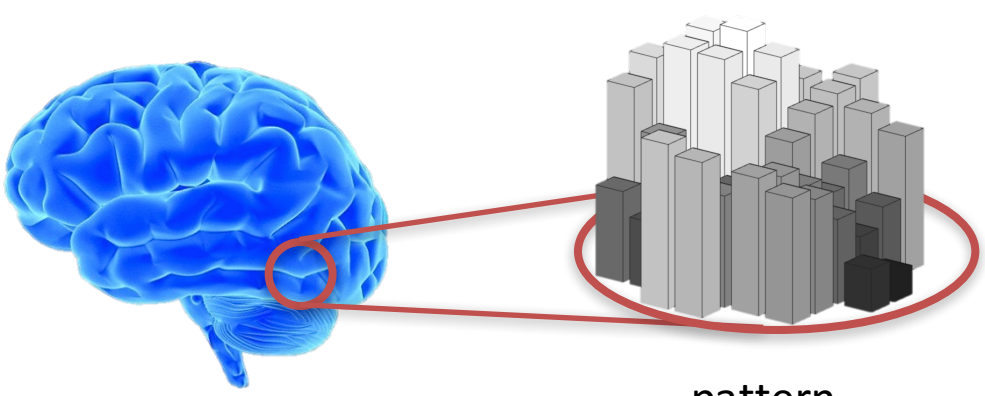
How Does Multivariate Pattern Analysis Work?

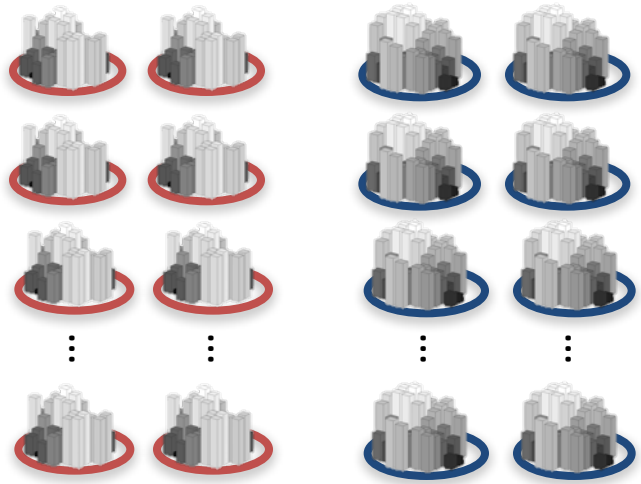
3. Multidimensional representations encoded in distributed patterns of activity can be revealed





Multivariate Decoding





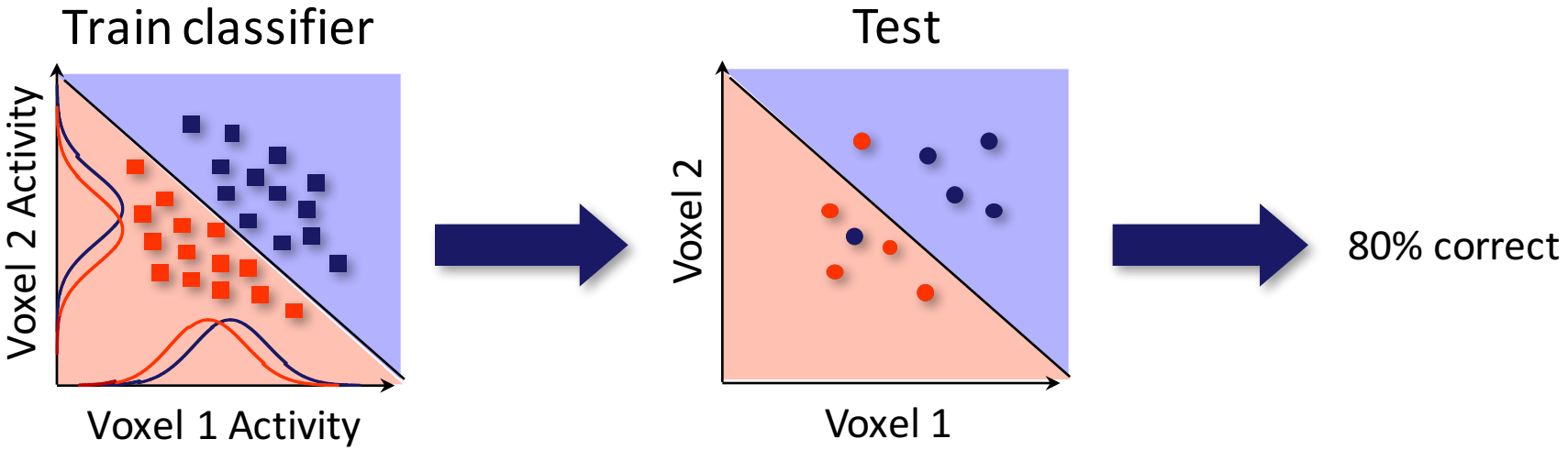


Image courtesy: Simone Brandt/imageBROKER/CORBIS

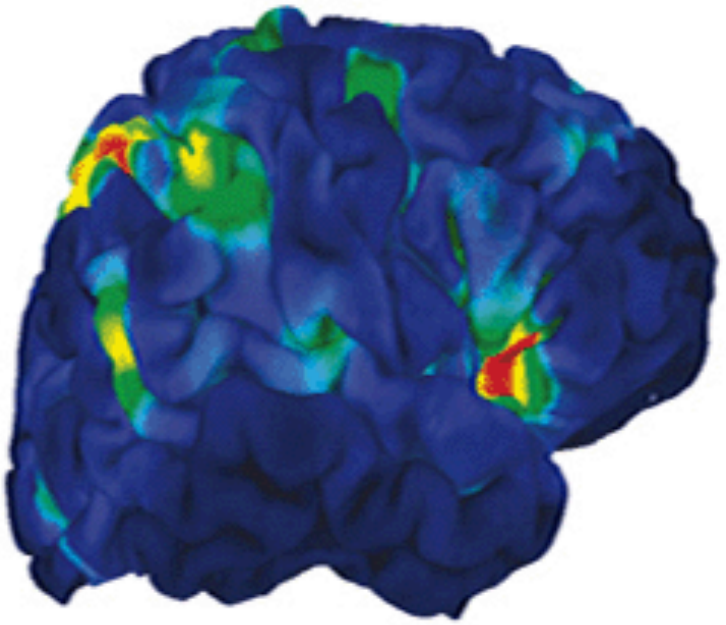
Encoding vs. Decoding

what we normally do
in univariate analyses

Encoding g: X → Y

Cognitive Function

Decoding h: Y → X



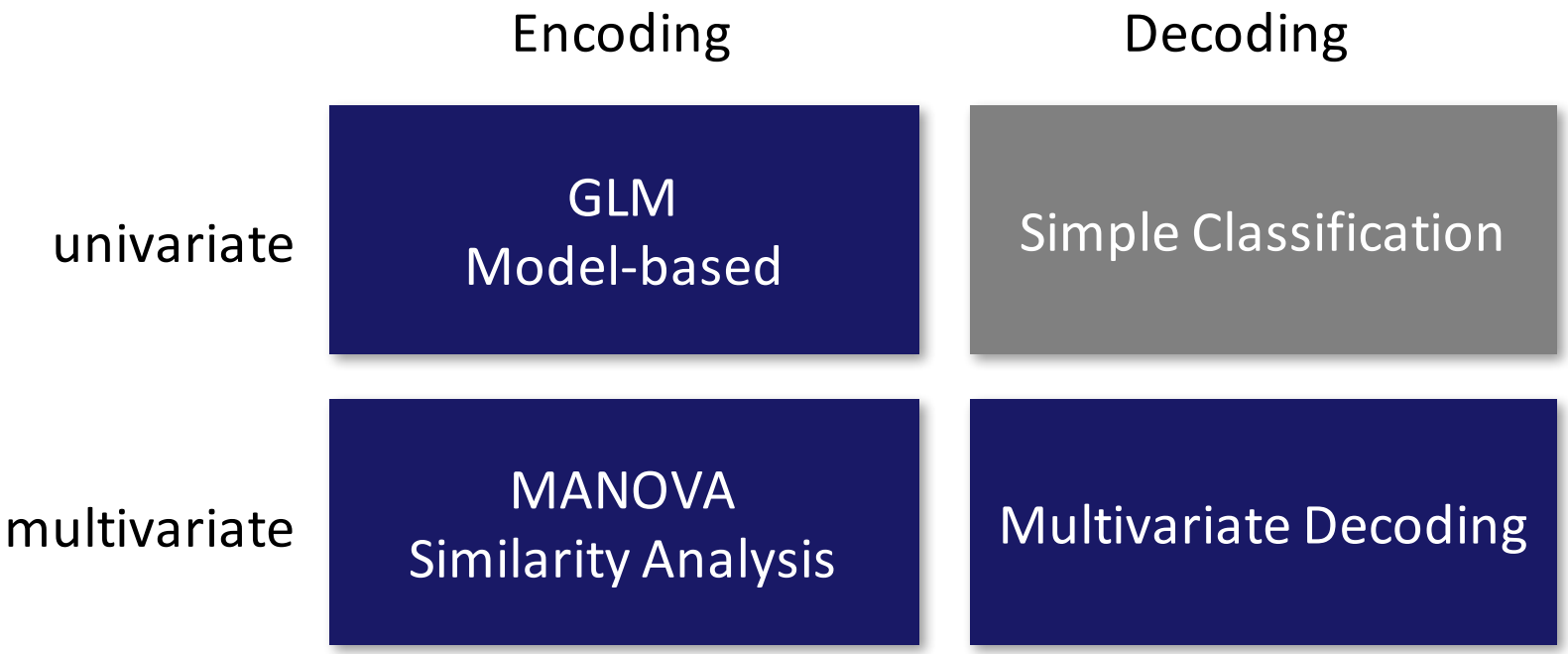
X: Explaining variable

Example: Stimulus, response, cognitive condition

Y: Measured data

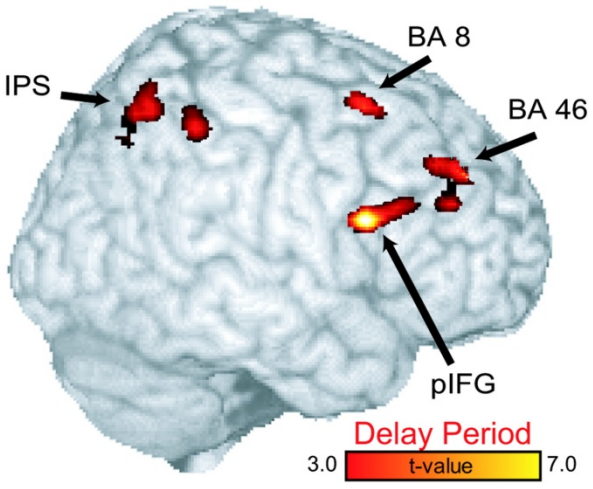
Example: BOLD signal, EEG signal, VBM intensity

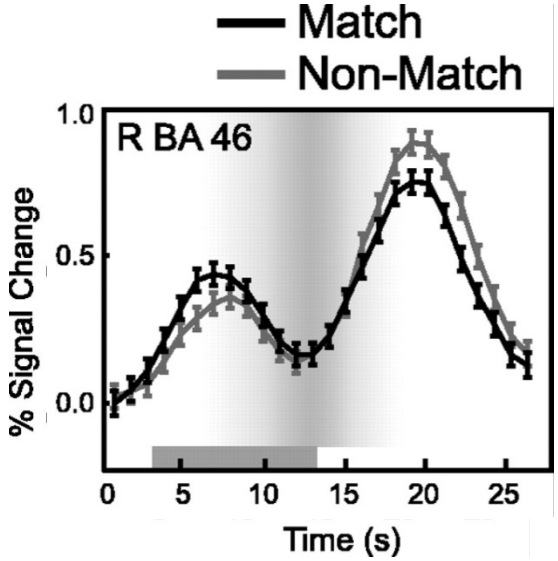
Overview Over Analysis Methods



Activity vs. Information

Activity: Tells us about general involvement in cognitive function (e.g. working memory vs. no working memory)

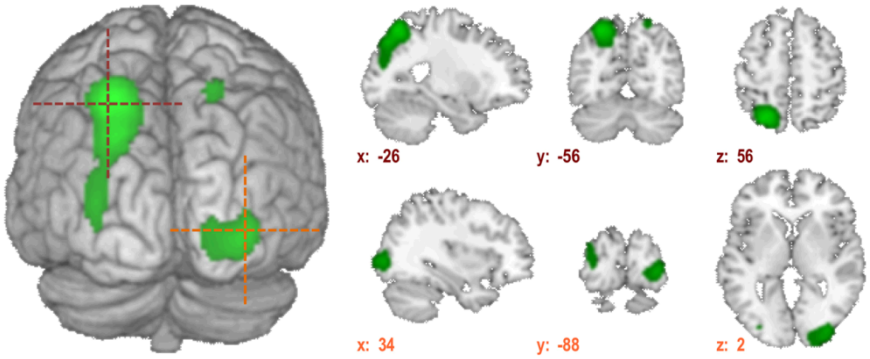


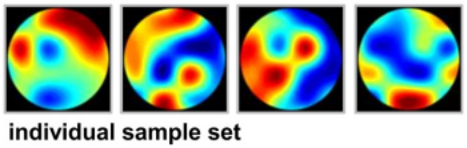


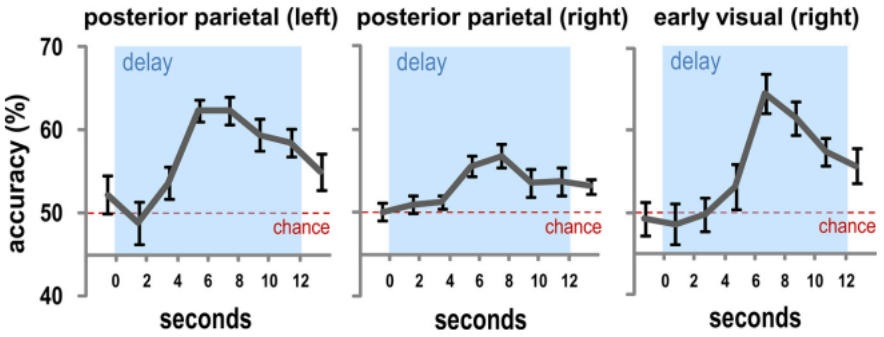
Curtis et al. (2004) – J Neurosci

Activity vs. Information

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







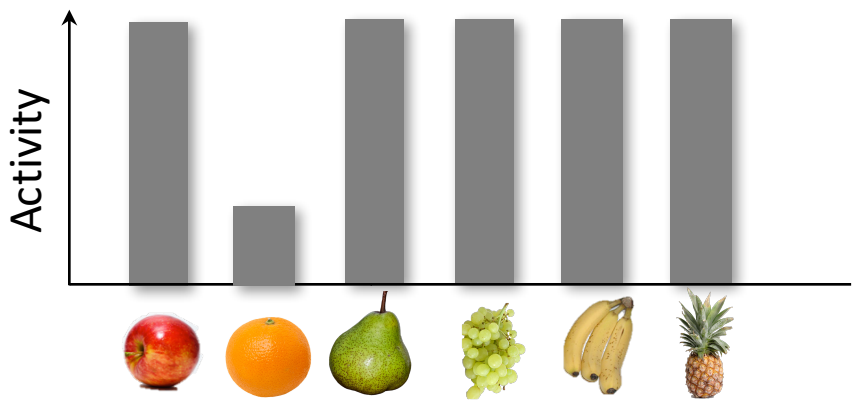
Christophel, Hebart, & Haynes (2012) – J Neurosci, but see Lee, Kravitz, Baker (2013) – Nat Neurosci

Different Methodological Philosophies

Classical approach: More active = more involved

Multivariate decoding: More distinct = more involved

Thought experiment:



Classical approach: Brain region responds to all fruit but oranges

MVPA: Brain region carries information about oranges
(when contrasted with fruit)

Goals of Decoding

Prediction: Goal is to maximize future correct predictions

→ Any information is useful as long as it increases accuracy

http://www.heise.de/tp/artikel/26/26759/26759_2.jpg, http://thinktechuk.files.wordpress.com/2011/10/97877.jpg, http://www.poly.edu/sites/polyproto.poly.edu/files/pressrelease/MRI_Alzheimers_Research.jpg

Lie Detection Companies

Quote (not literal) by one company:

"*Lie detection using traditional polygraphy is unlawful for screening of employees. Our company measures the brain directly and as such is not limited by these regulations.*"

Quote (not literal) by another company:

"*Our technology prevents unlawful infiltration at borders, brings criminals into prison, supports law enforcement and fights terrorism.*"

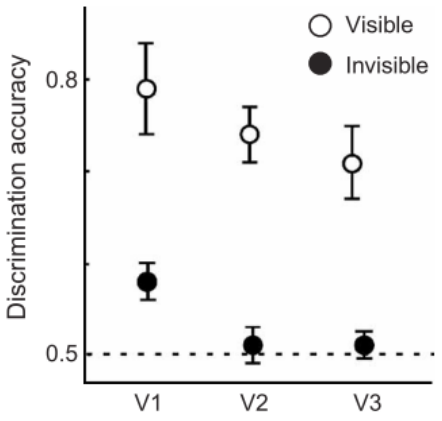
For more information, see: Editorial: Nature Neuroscience 11, 1231 (2008)

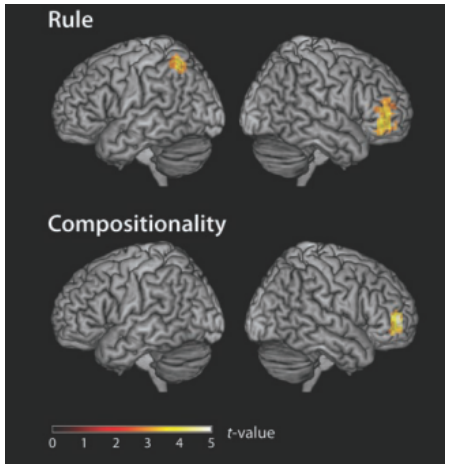
Goals of Decoding

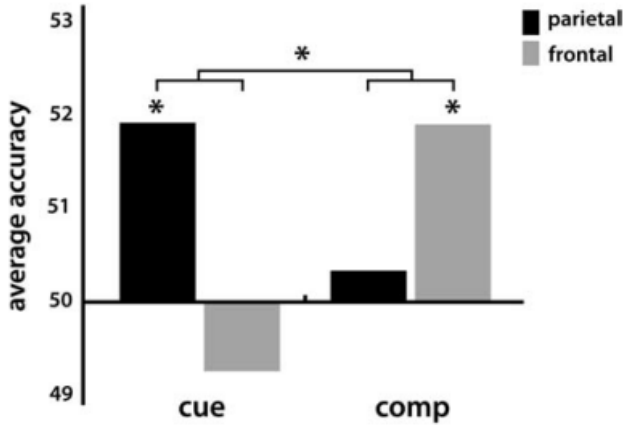
Inference: Is there information about XYZ?

→Sufficient to show above chance accuracy (statistically!)

→Not all information sources ok, need to rule out confounds





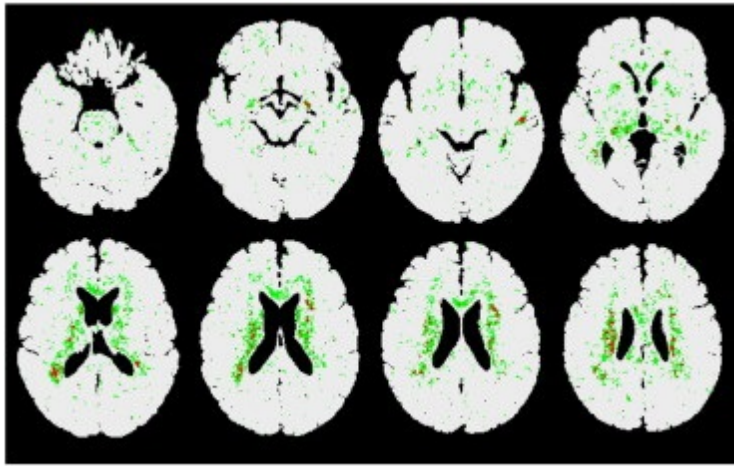


Haynes & Rees (2005) – Nat Neurosci; Reverberi, Görgen, & Haynes (2012) – Cereb Cortex

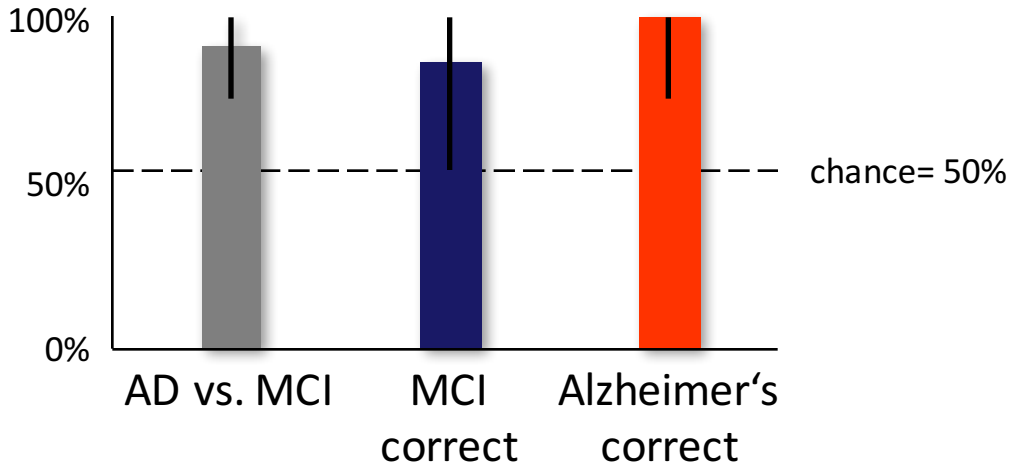
Types of Questions for MVPA

1. Presence of Information

Example: Will a patient with mild cognitive impairment develop Alzheimer's 2 ½ years later?



structural data

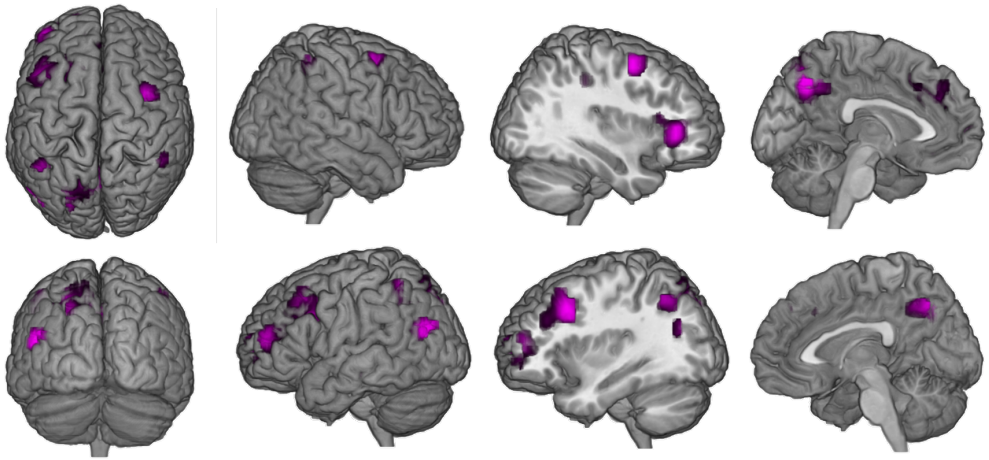


Plant et al. (2010) – Neuroimage

Types of Questions for MVPA

2. Localization of Information

Example: Which brain regions carry information about perceptual decision variables irrespective of the response format?



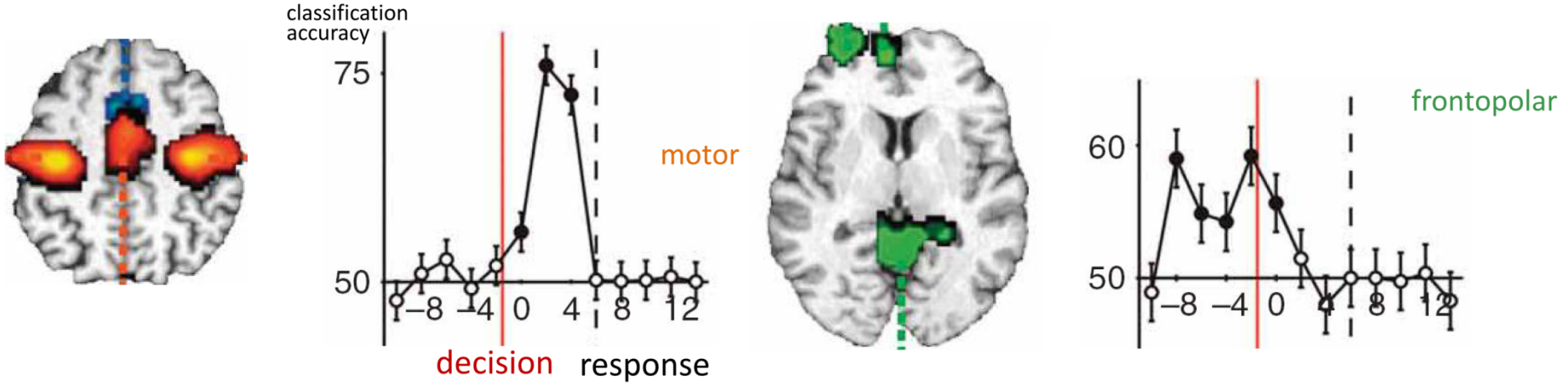
$p < 0.0001$, cluster-corrected FWE $p < 0.05$

Hebart et al. (2010) – Neuroimage, Hebart et al. (2012) – Cereb Cortex

Types of Questions for MVPA

3. Time Course of Information

Example: At what time do you find information about "free" decision of a person?

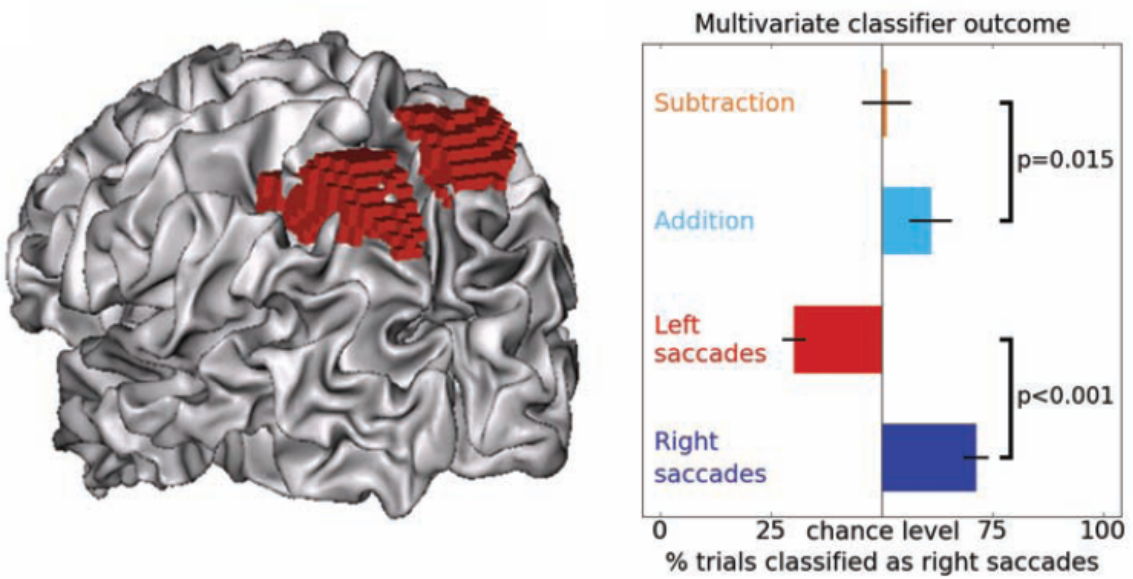


Soon et al. (2008) – Nat Neurosci

Types of Questions for MVPA

4. Association of Cognitive Functions

Example: Generalization of eye movements to calculations

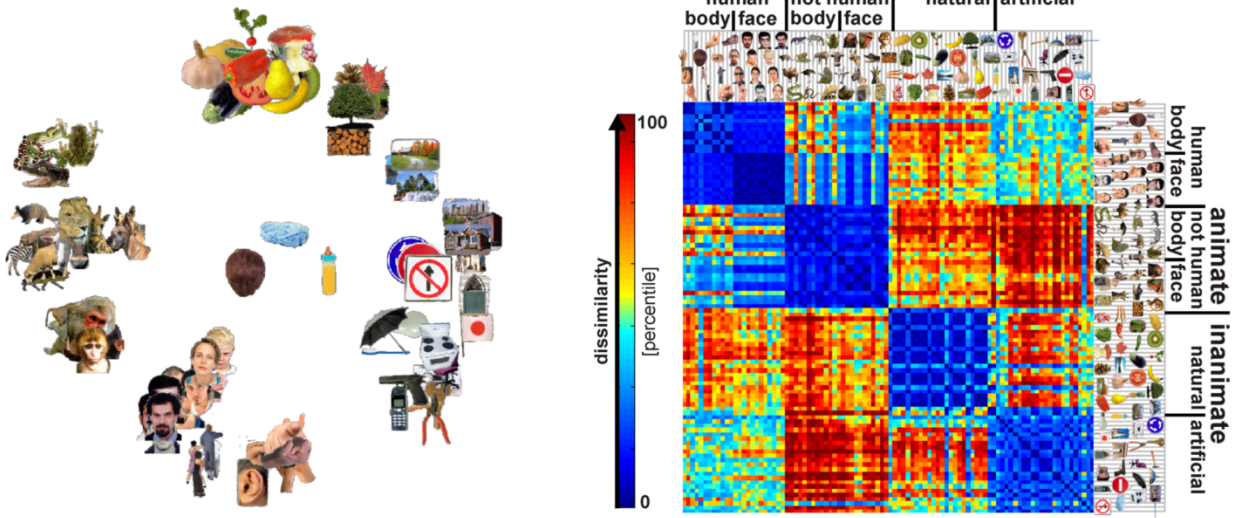


Knops et al. (2009) – Science

Types of Questions for MVPA

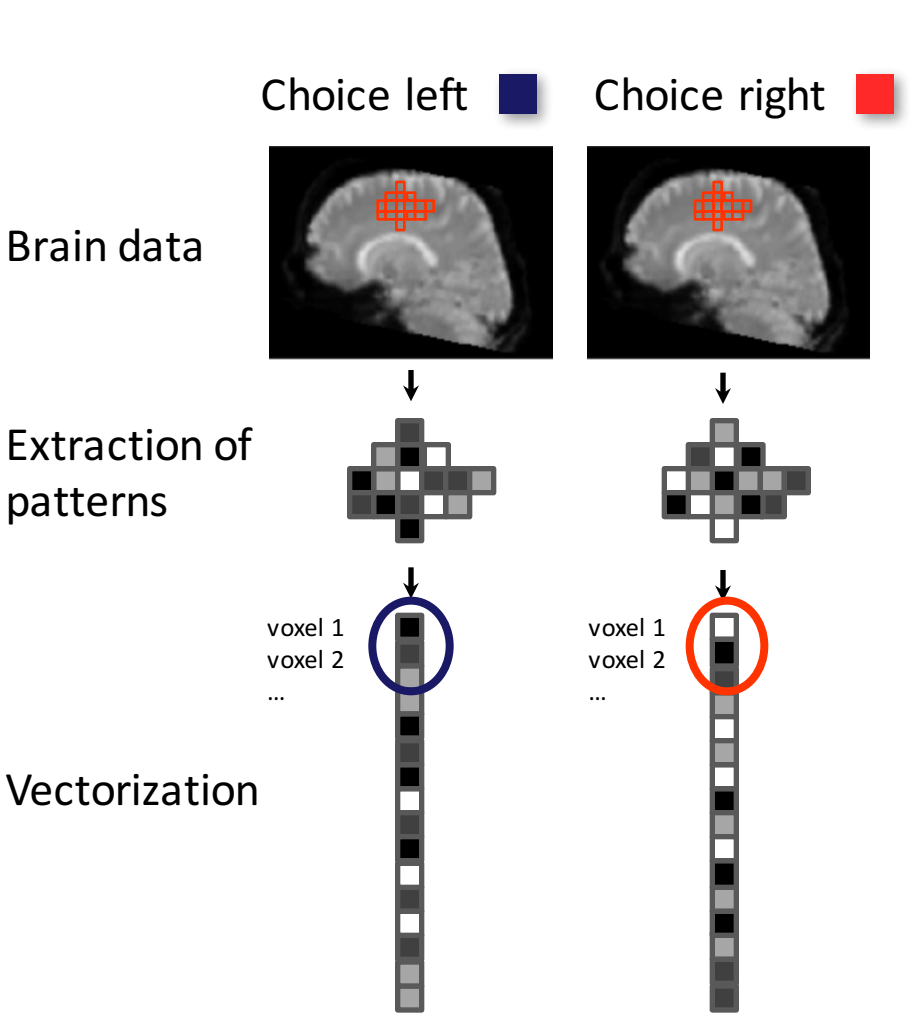
5. Characterization of Activation Patterns

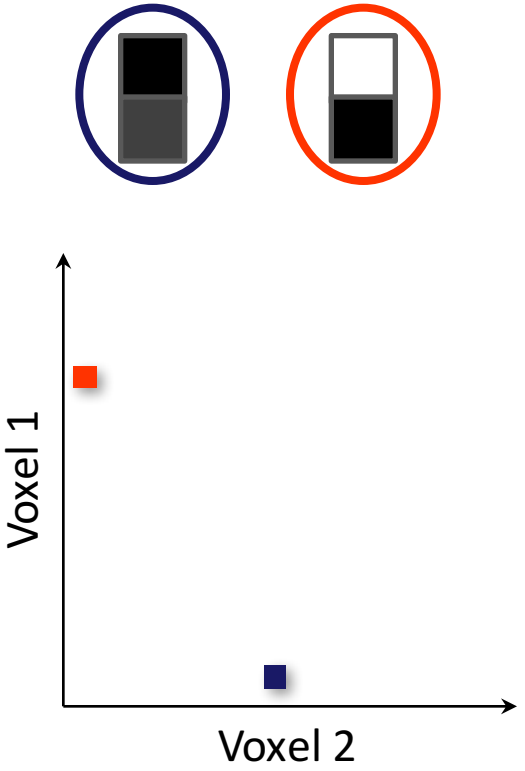
Example: Representational Similarity Analysis



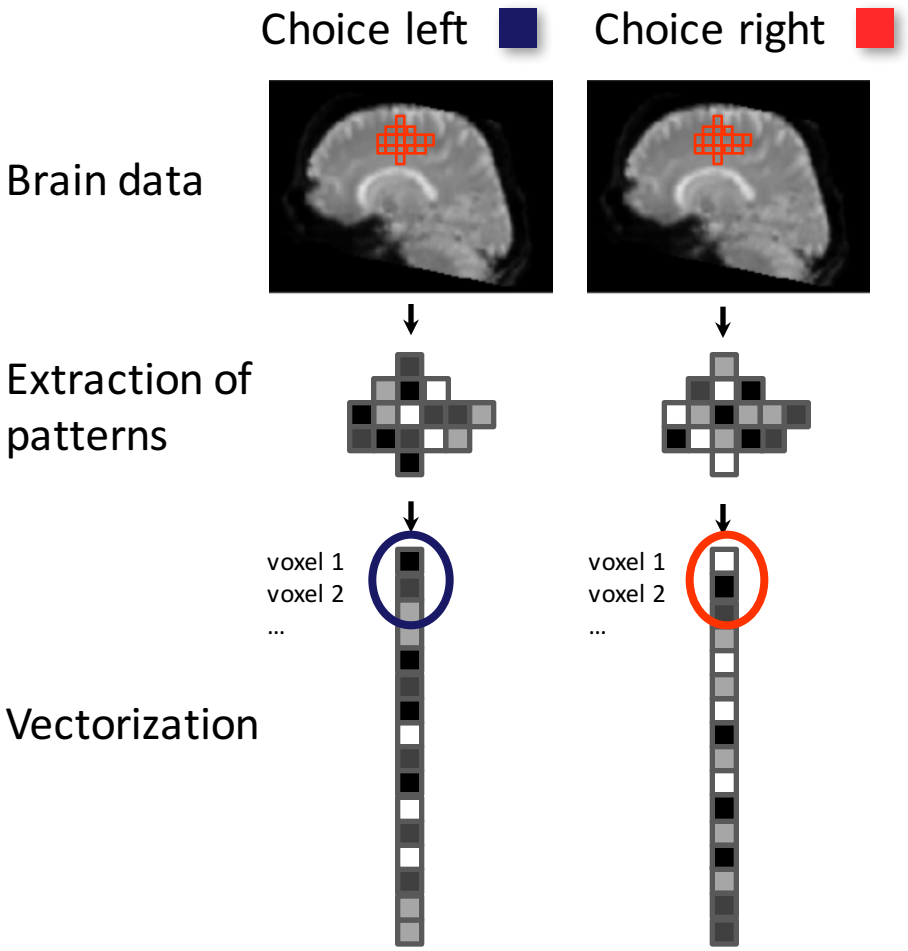
Edelman et al (1998) – Psychobiology; Kriegeskorte et al. (2008) – Neuron; Kriegeskorte & Kievit (2013) – TICS

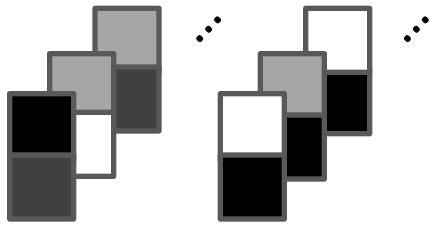
Classification Overview: Example

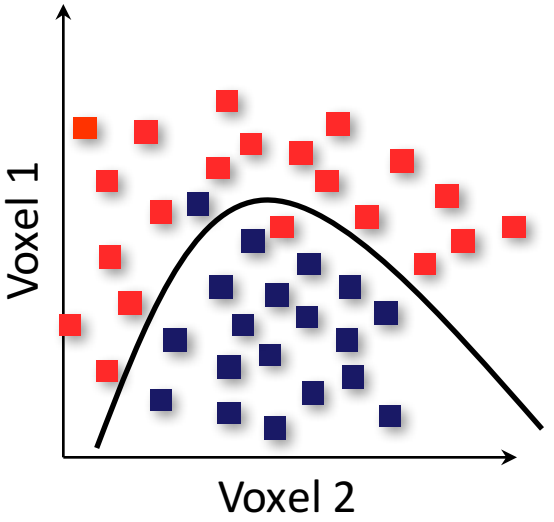




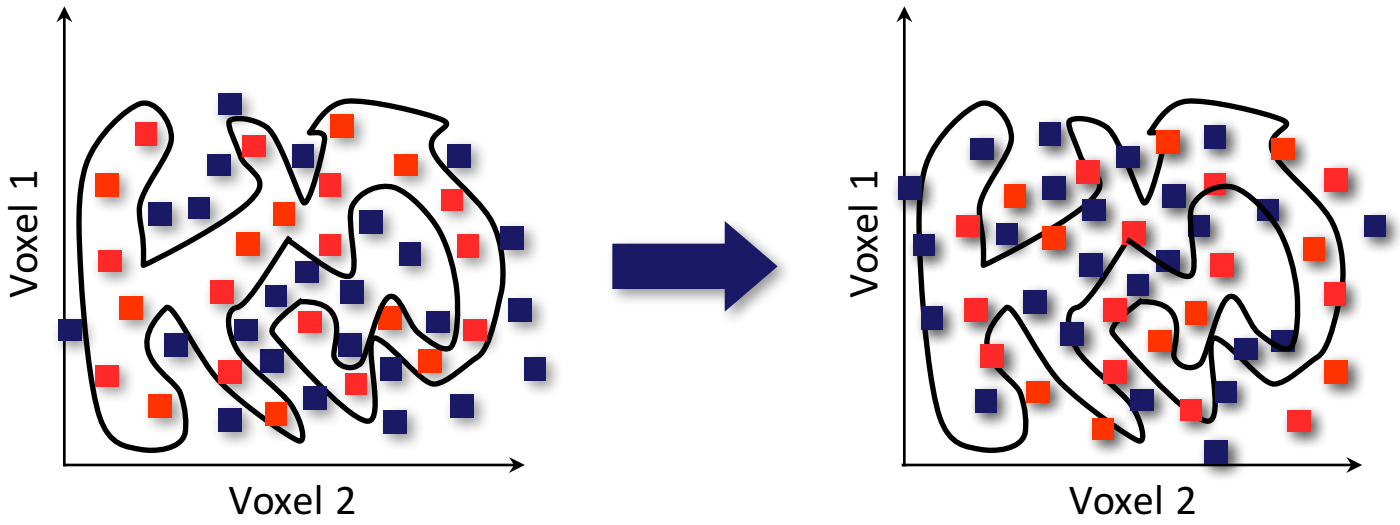
Classification Overview: Example





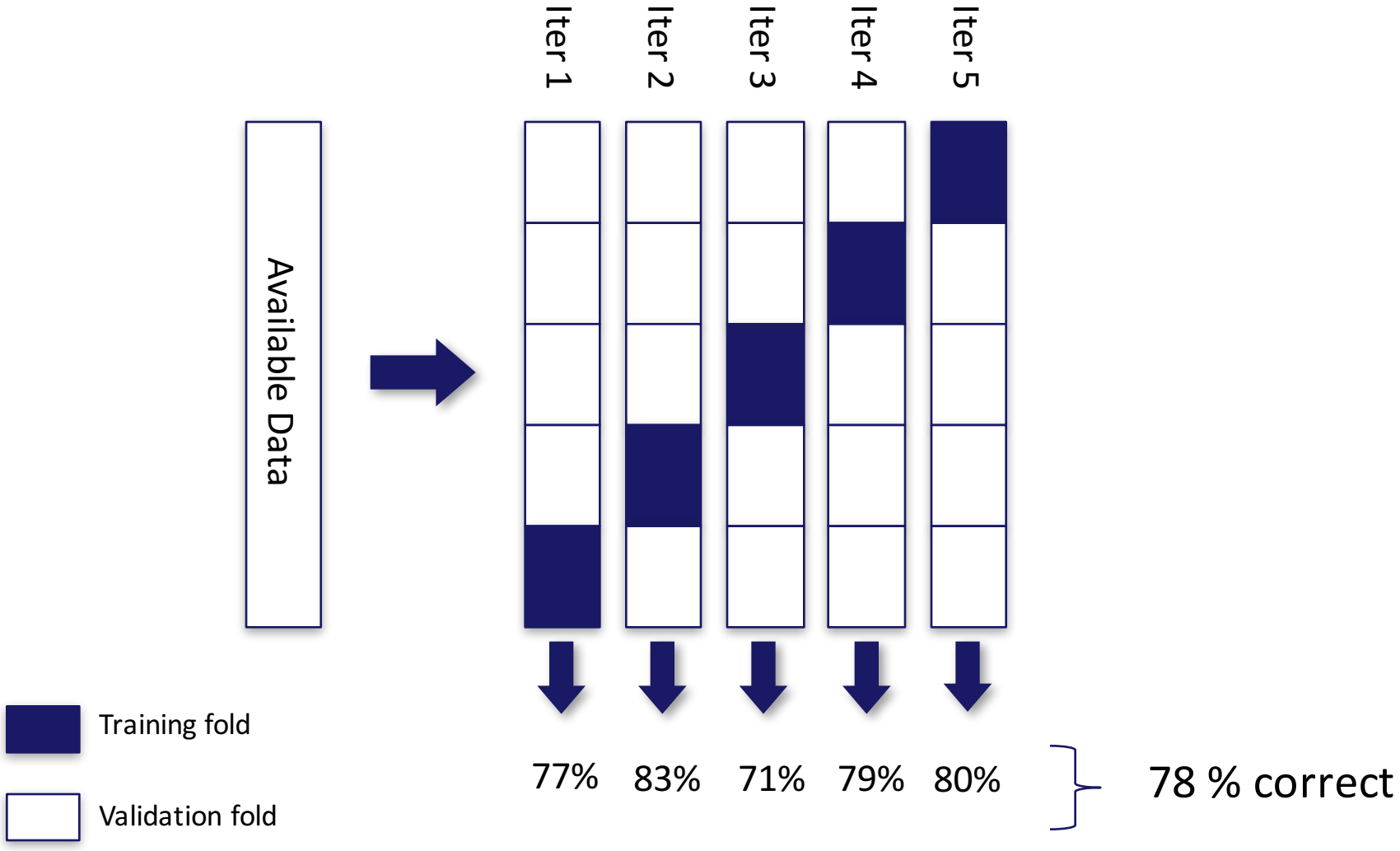


Why Train and Test a Classifier?



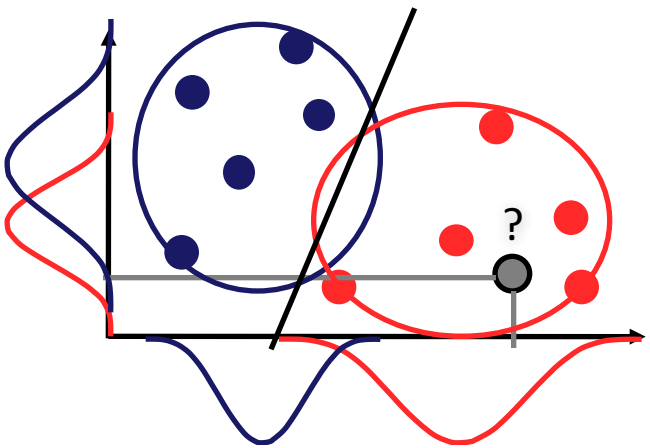
- Goal of classification: Finding a general model beyond noise in the data
- Way of testing generalization: Training and testing classifier

Cross-validation



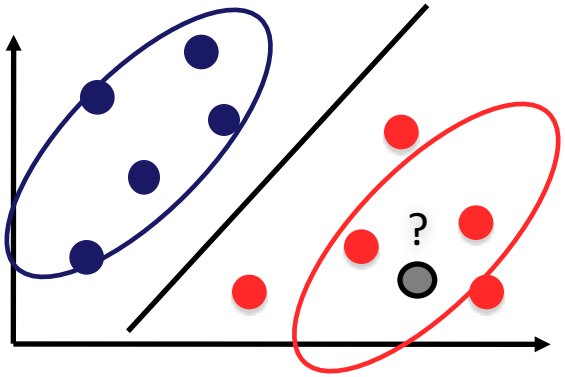
Typical linear classifiers

Gaussian Naïve Bayes



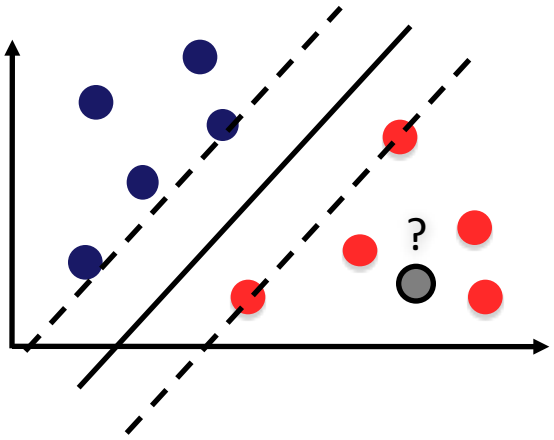
Ignores covariance between voxels

Linear Discriminant Analysis



Considers covariance between voxels

Support Vector Machine

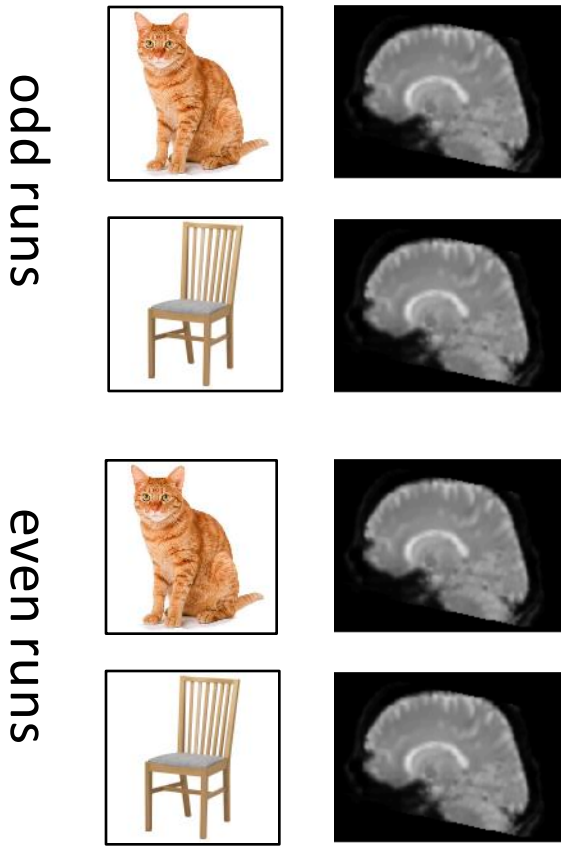


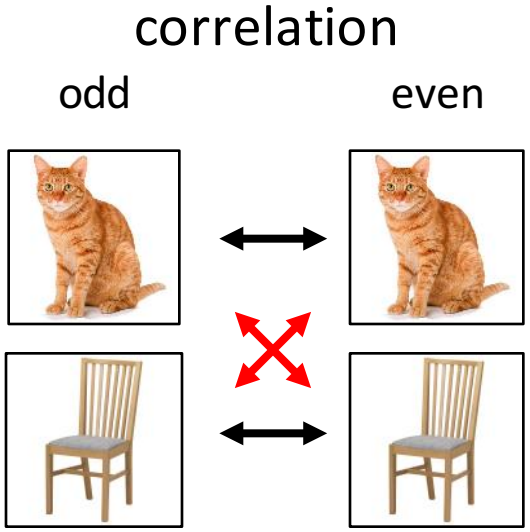
Maximizes margin (distance between closest points of different classes)

- Linear classifiers are the most commonly used classifiers in MVPA
- All share the same formula $y = \Sigma w_i x_i$ but differ in how they find parameters w

Correlation classifier

Very simple classifier: find maximal pattern correlation



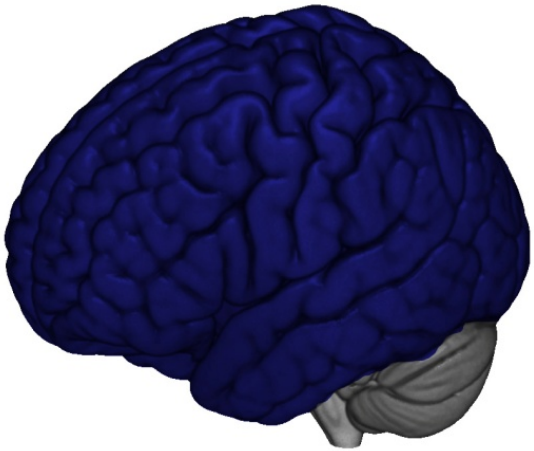


$r_{withincategory} > r_{betweencategory}$?

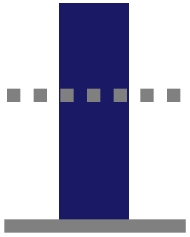
Geometric interpretation: smallest angular distance from centroid

Levels of MVPA Analyses

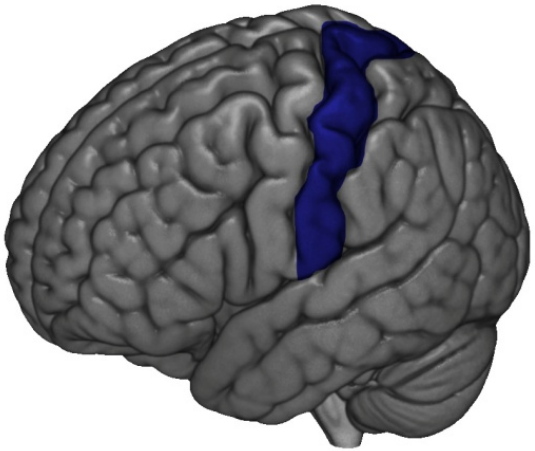
Wholebrain



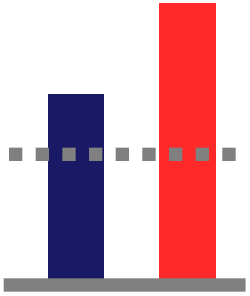
One value per brain



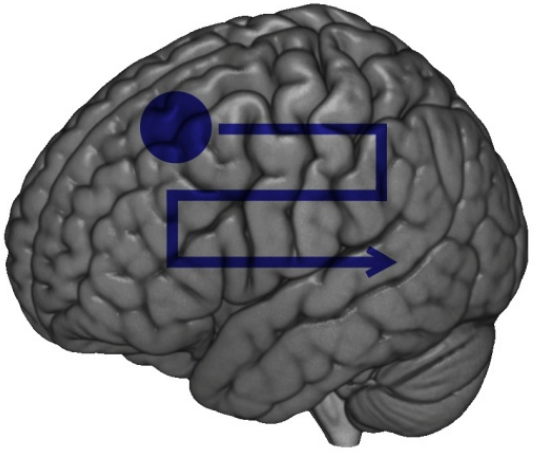
Region of Interest



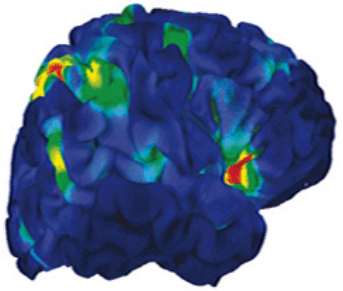
One value per ROI



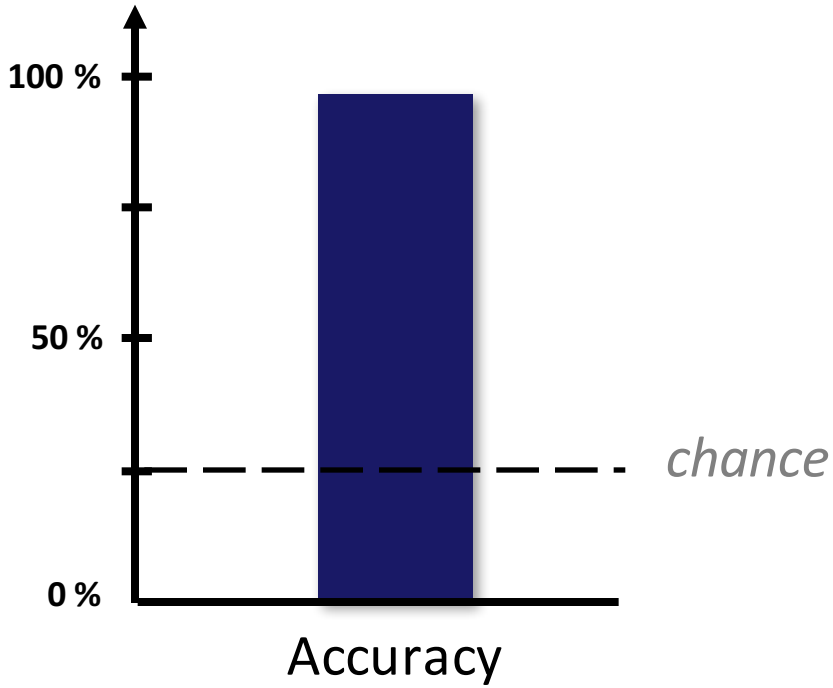
Searchlight



A value per searchlight,
i.e. a map of values



Great Finding?



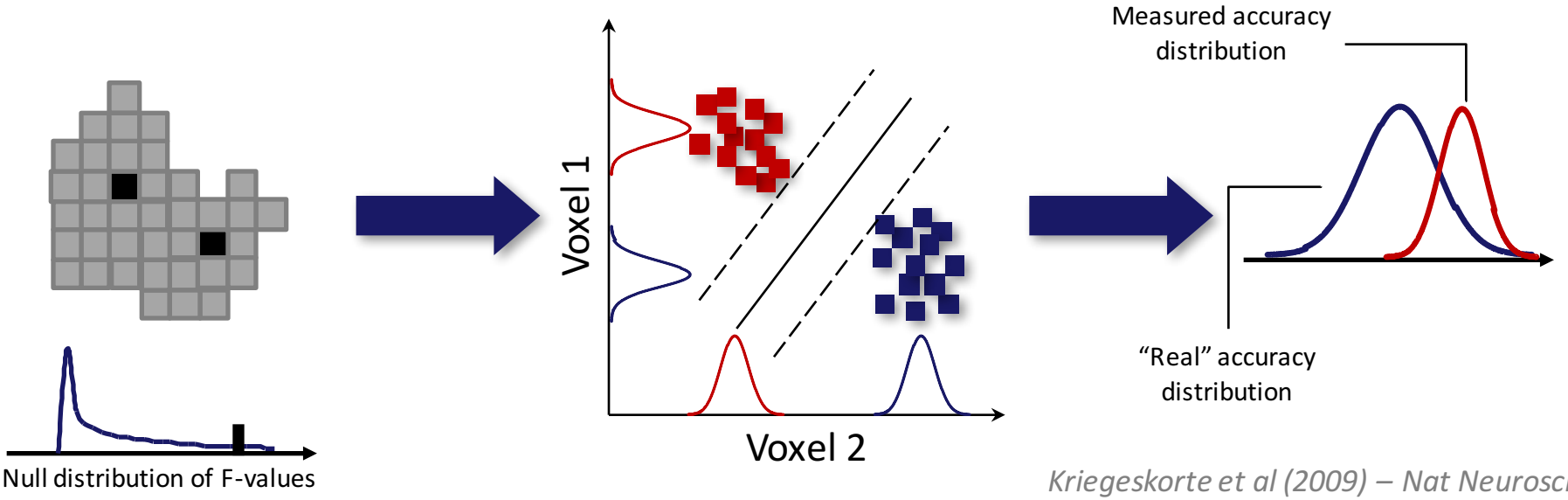
http://www.smallbiztechnology.com/wp-content/uploads/2012/12/success.jpg

Non-independence and Double Dipping

For classification: Information about class membership leaks from training set to test set

Example: Voxel selection prior to classification that is

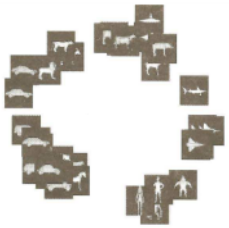
(1) based on label (red vs. blue) and (2) uses **all data**



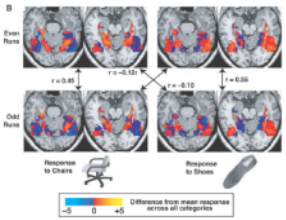
Kriegeskorte et al (2009) – Nat Neurosci

Milestones of MVPA

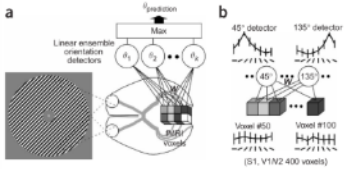
Edelman et al (1998)



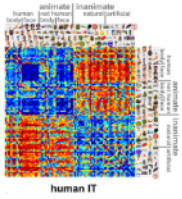
Haxby et al (2001)



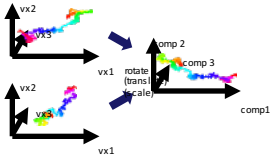
Kamitani & Tong (2005)
Haynes & Rees (2005)



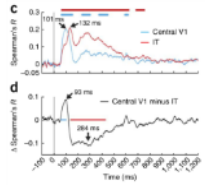
Kriegeskorte et al (2008)



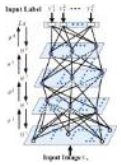
Haxby et al (2011)



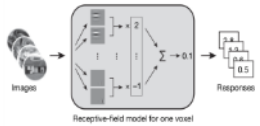
Cichy et al (2014)



e.g. Di Carlo



Kay & Gallant (2008)



Kriegeskorte et al (2006)

1998 2001 2005 2006 2008 2011 2014 2015/2016

"first" MVPA study

first multivariate decoding study

popularization of multivariate decoding

searchlight approach

representational similarity analysis

model-based encoding methods

hyperalignment

combination of fMRI and MEG using RSA

Demonstration of homologies in feed-forward architecture btw artificial neural networks and visual cortex

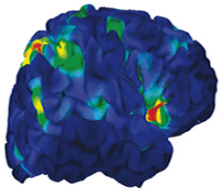
More Recent Developments

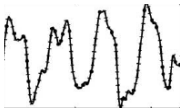
Idea of a representational geometry

Human fMRI

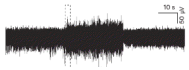
Monkey recordings

Measurement level





seconds

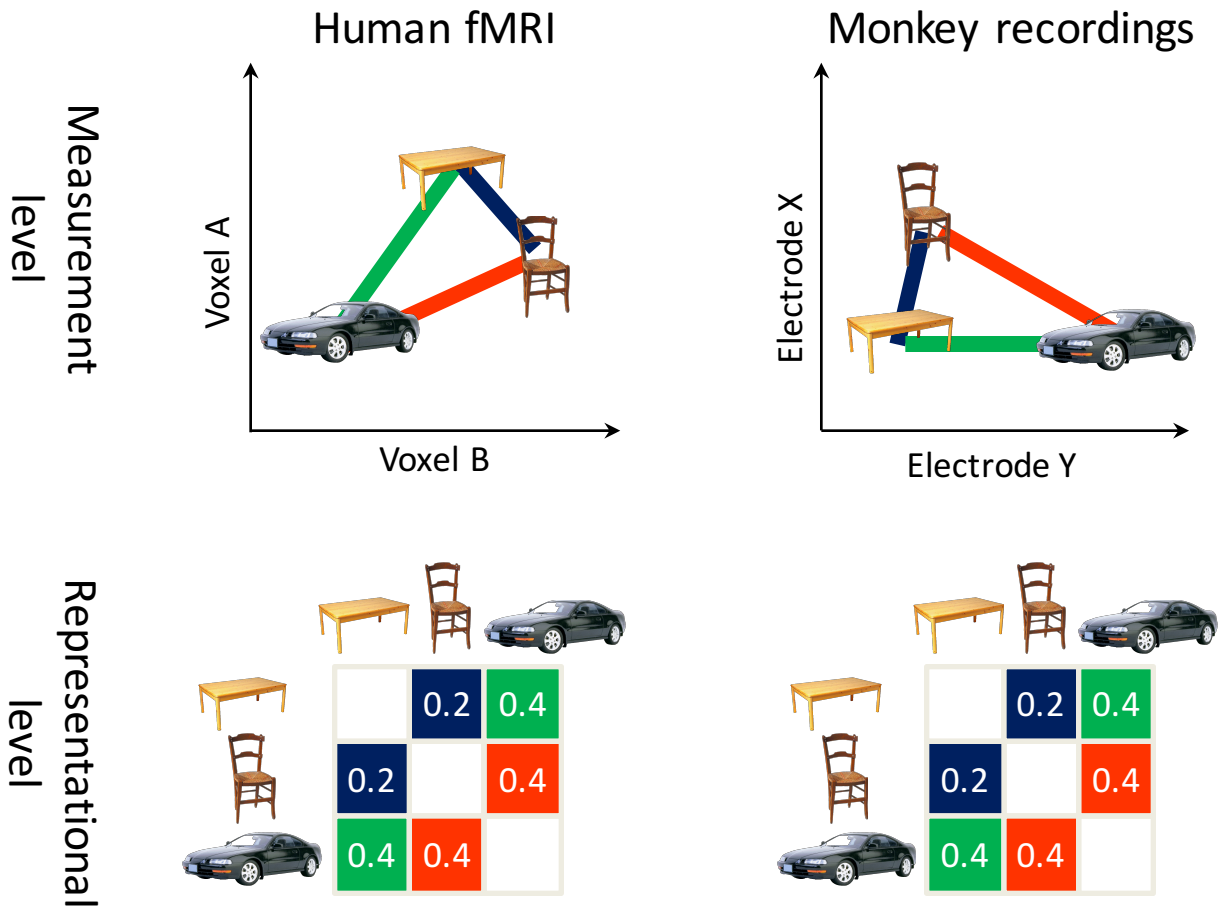


milliseconds

Kriegeskorte & Kievit (2013) – TICS

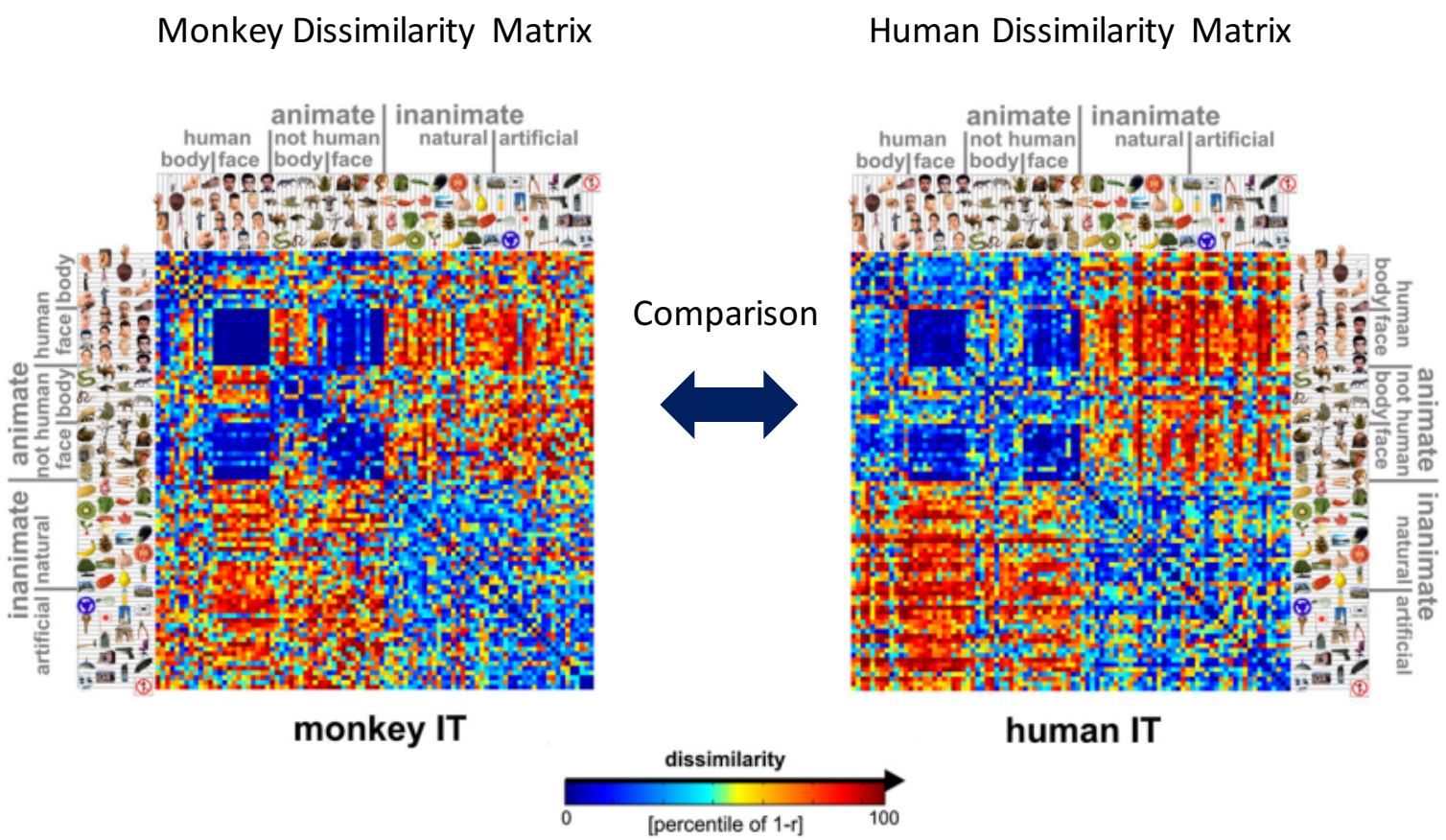
More Recent Developments

Idea of a representational geometry



Kriegeskorte & Kievit (2013) – TICS

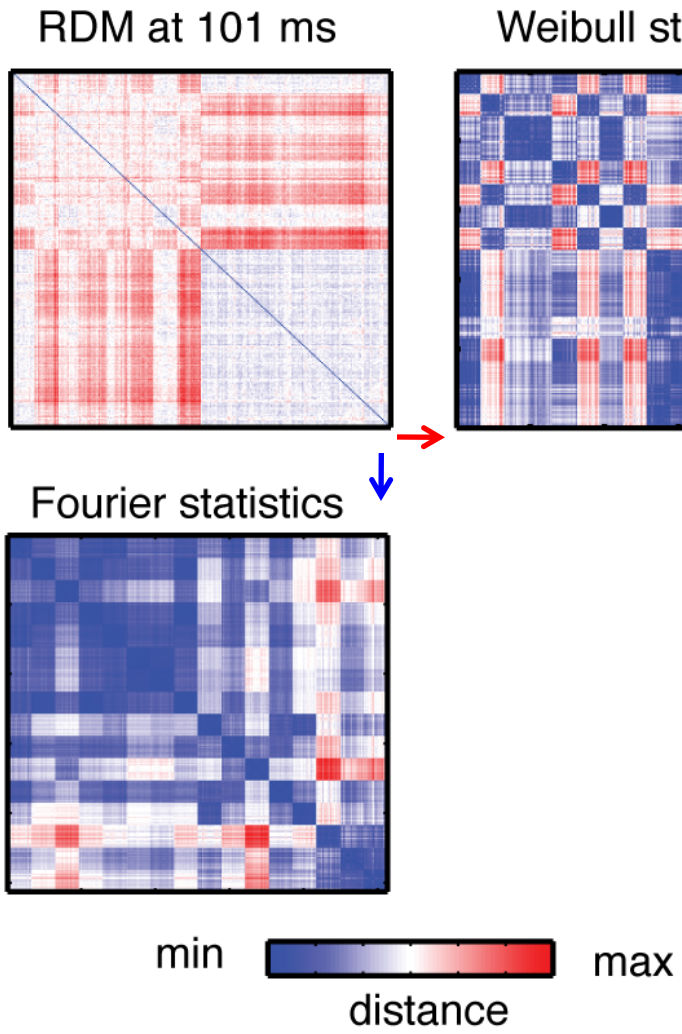
Representational Similarity Analysis

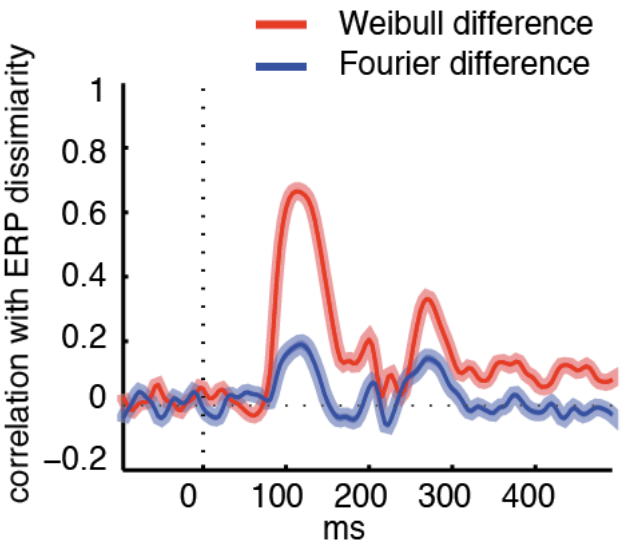


Relative similarity of pairs of patterns can be compared

Kriegeskorte et al (2008) – Neuron

EEG-based Model Comparison

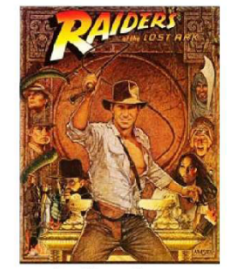




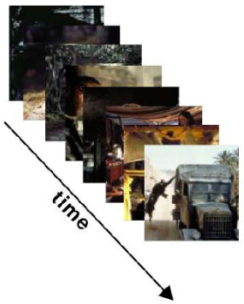
Groen et al (2012) – PLoS Comput Biol

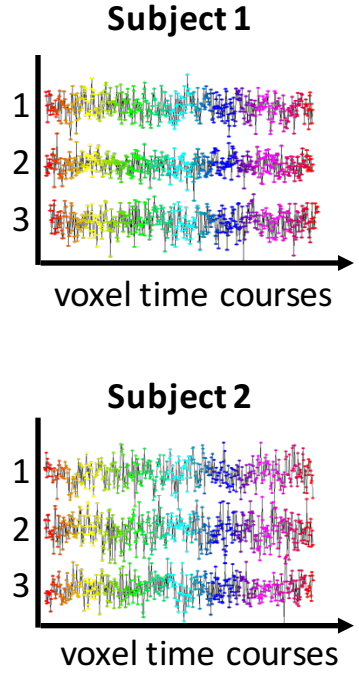
Hyperalignment

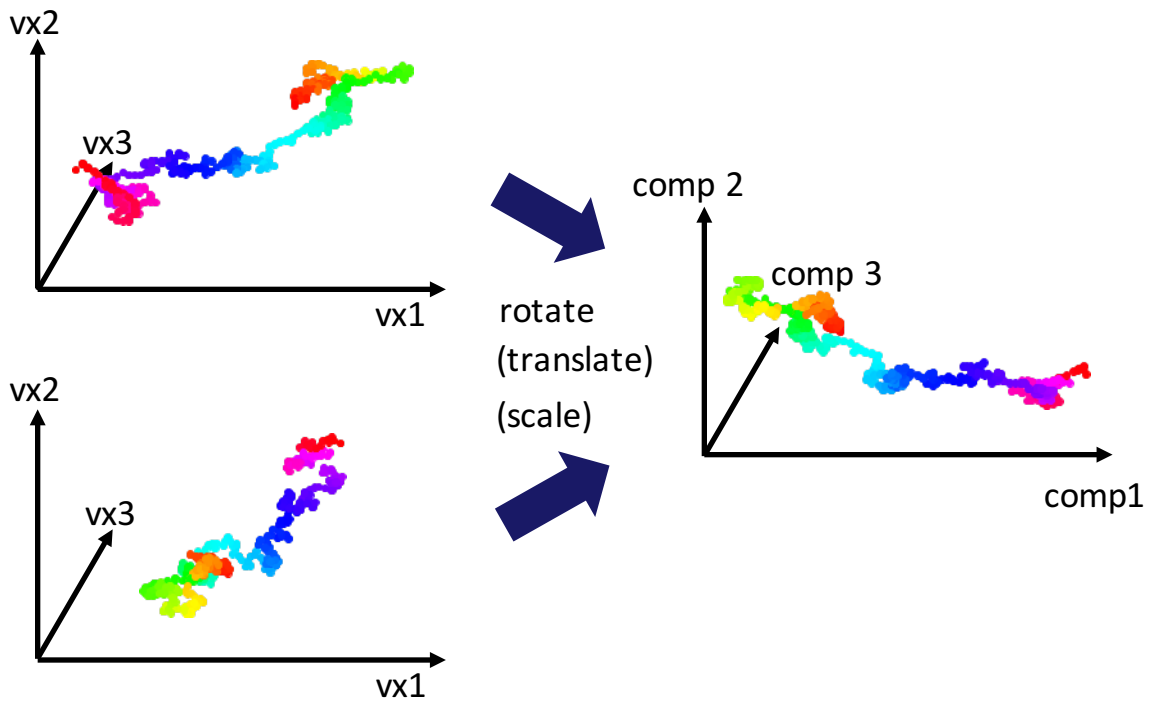
- Brings subjects functionally in common space
- Allows predicting one brain from another



Indian Jones:
Raiders of the Lost Ark







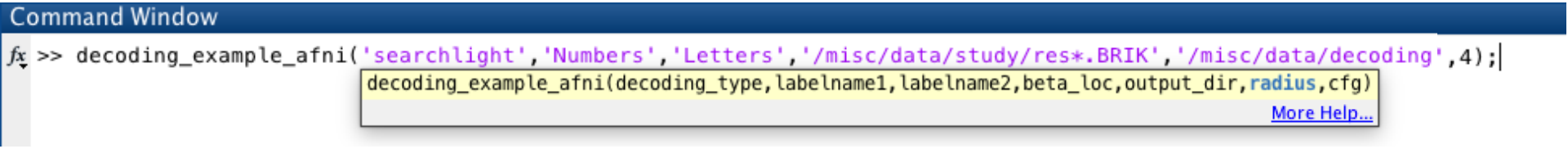
Haxby, Guntupalli et al (2011) – Neuron

Summary

- MVPA is more sensitive than classical univariate approaches and can reveal representational content
- MVPA works by combining information across voxels and using their covariation
- Investigating brain activity vs. informational content are two different approaches
- MVPA can be used to identify and localize information in space and time, can test associations and reveal the structure of representations
- Non-independence needs to be avoided for representative data
- Representational geometries allow comparing people, modalities, species and testing models of cognition

The Decoding Toolbox

- Fast and easy to use MVPA software package in Matlab (for Python, we recommend PyMVPA and Scikit-Learn)
- Provides searchlight, ROI and wholebrain analyses
- Comes with a wide range of options, classifiers and similarity analysis
- Runs with SPM and now also with AFNI



https://sites.google.com/site/tdtdecodingtoolbox/

Hebart MN*, Görgen K*, Haynes JD (2015). The Decoding Toolbox (TDT): A versatile software package for multivariate analyses of functional imaging data. Front. Neuroinform. 8:88.

Thank you for your attention

Martin N. Hebart
Laboratory of Brain and Cognition
NIMH