Multivariate pattern analyses

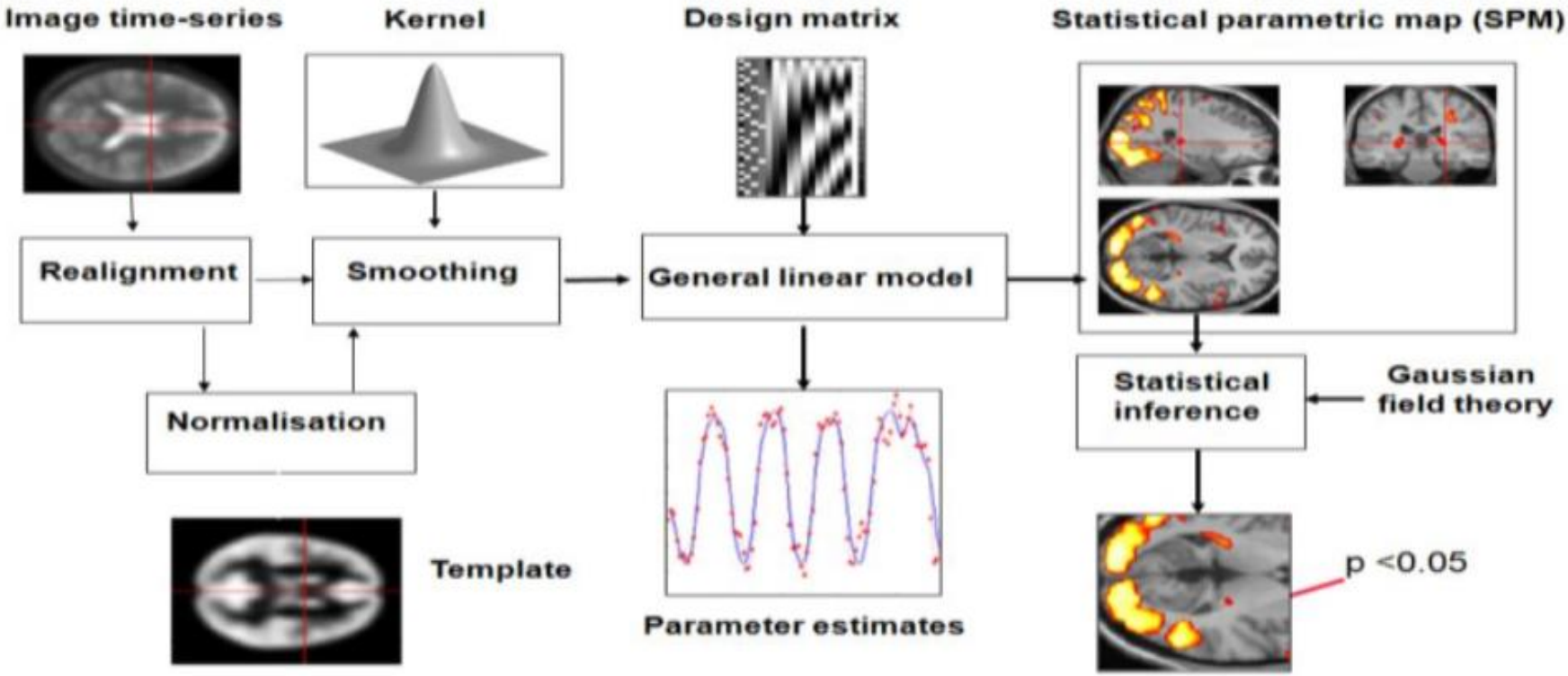
… and other cool stuff

KU LEUVEN

Hans Op de Beeck

Brain & Cognition, KU Leuven, Belgium

What have we done up to now?



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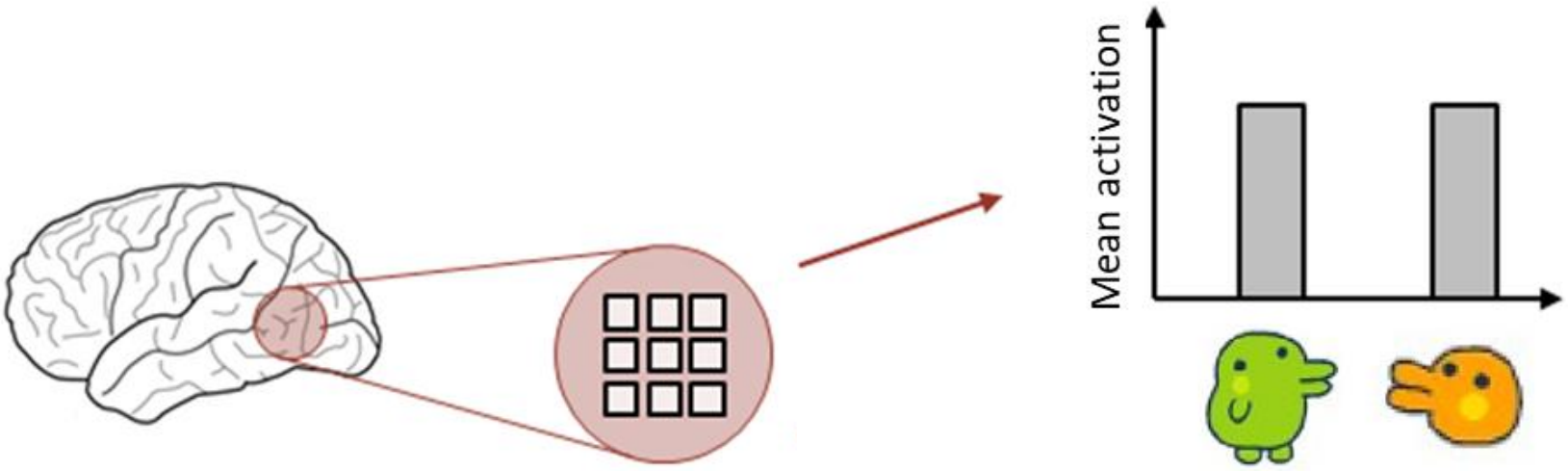
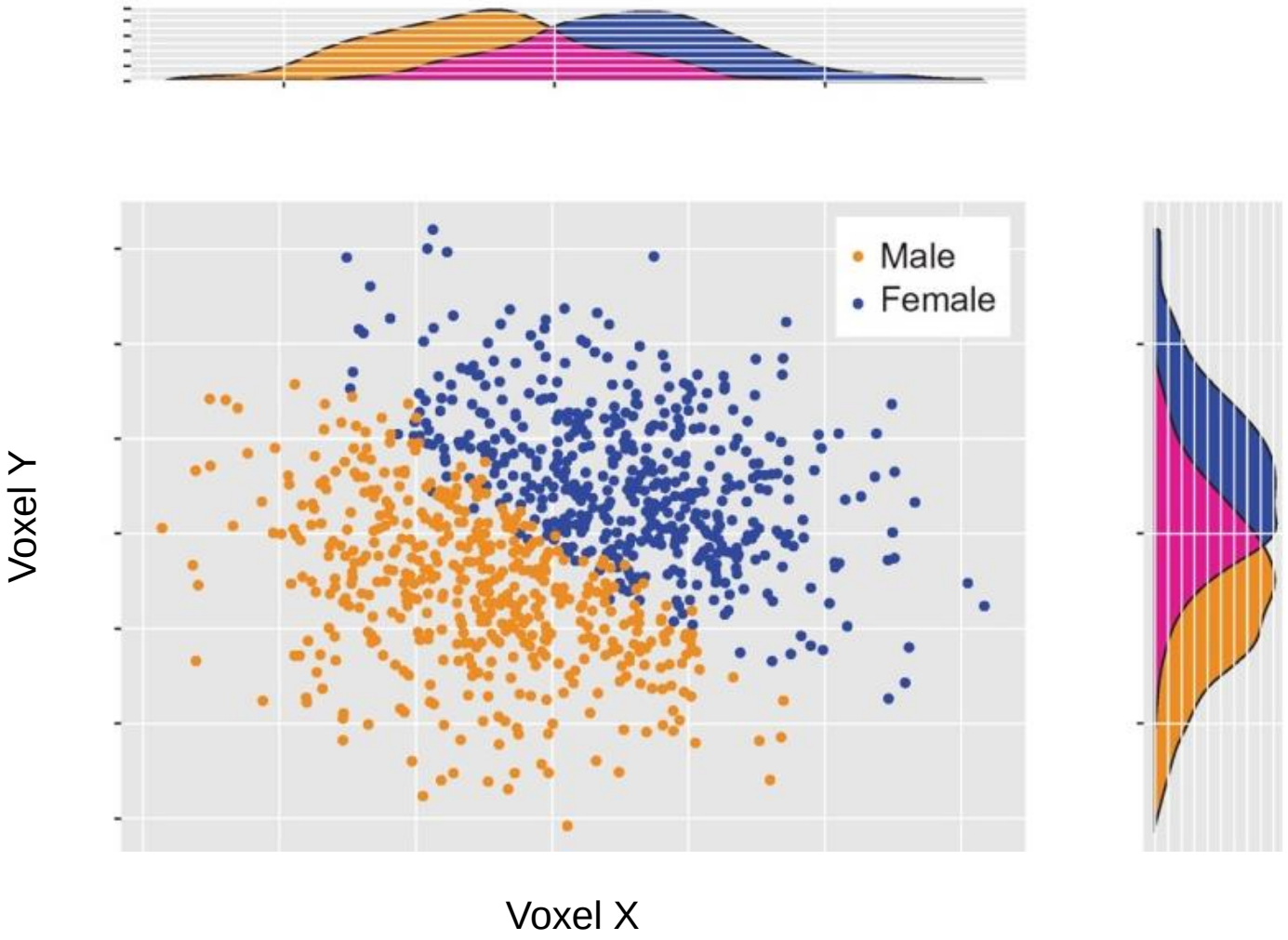
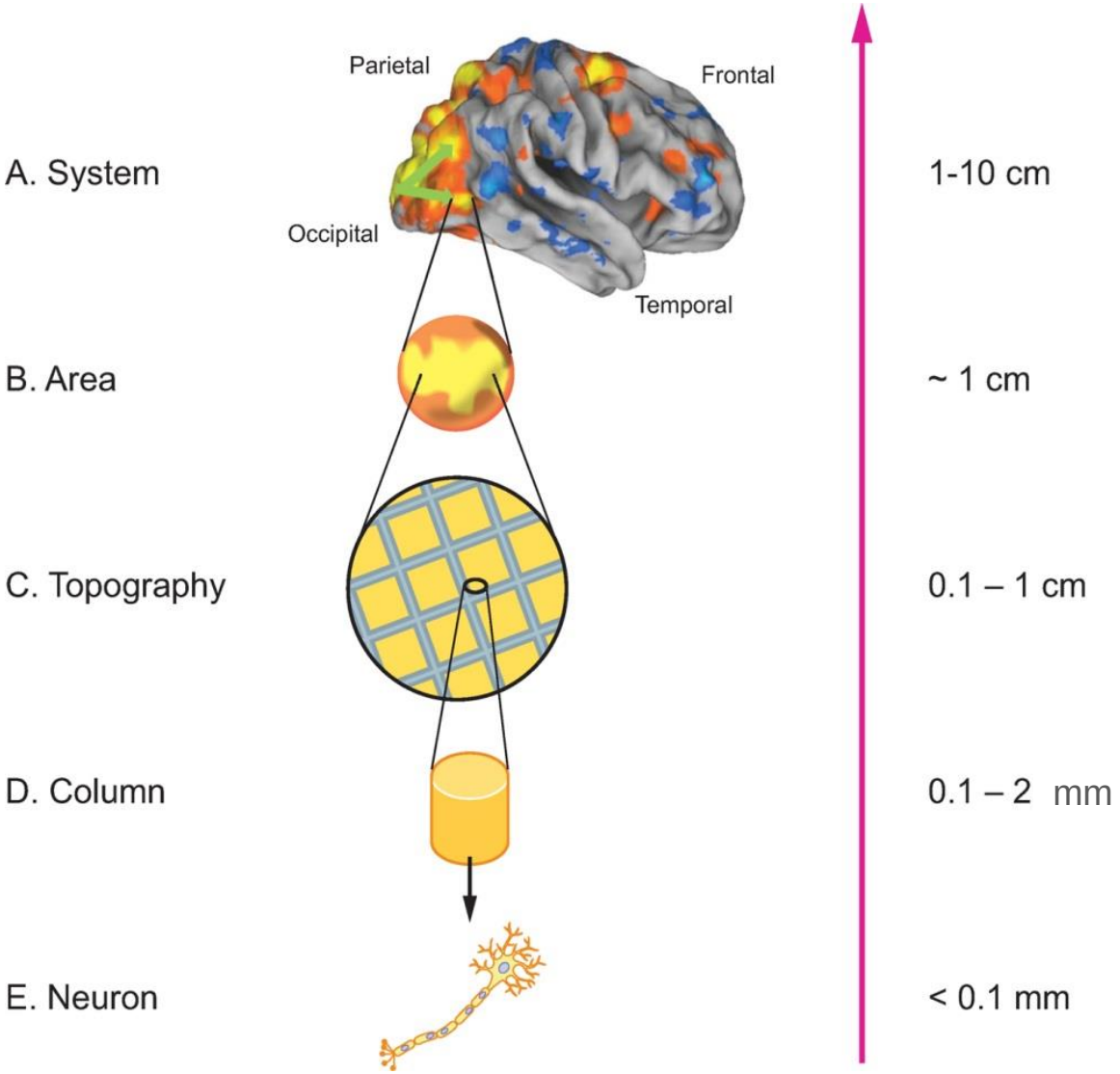


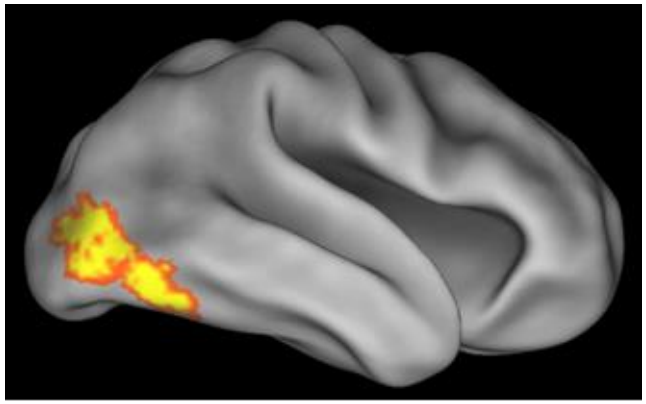
Why this is not enough: The engineer

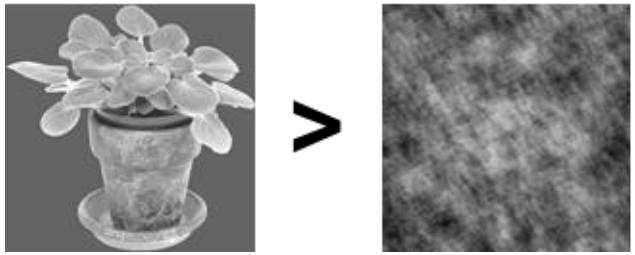


Why this is not enough: The neuroscientist



Why this is not enough: The psychologist





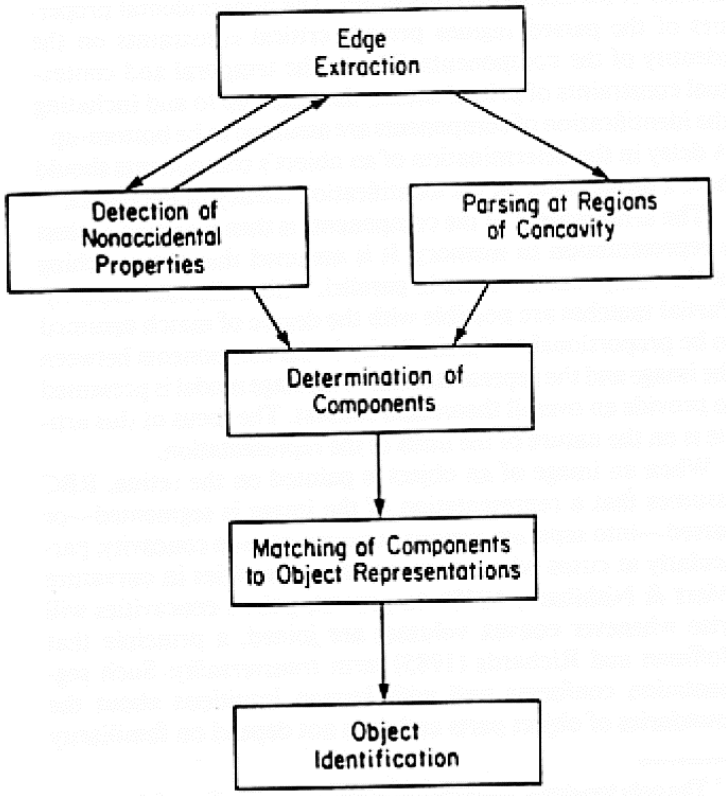


Figure 2. Presumed processing stages in object recognition.

Biederman, 1987, Psych. Rev.

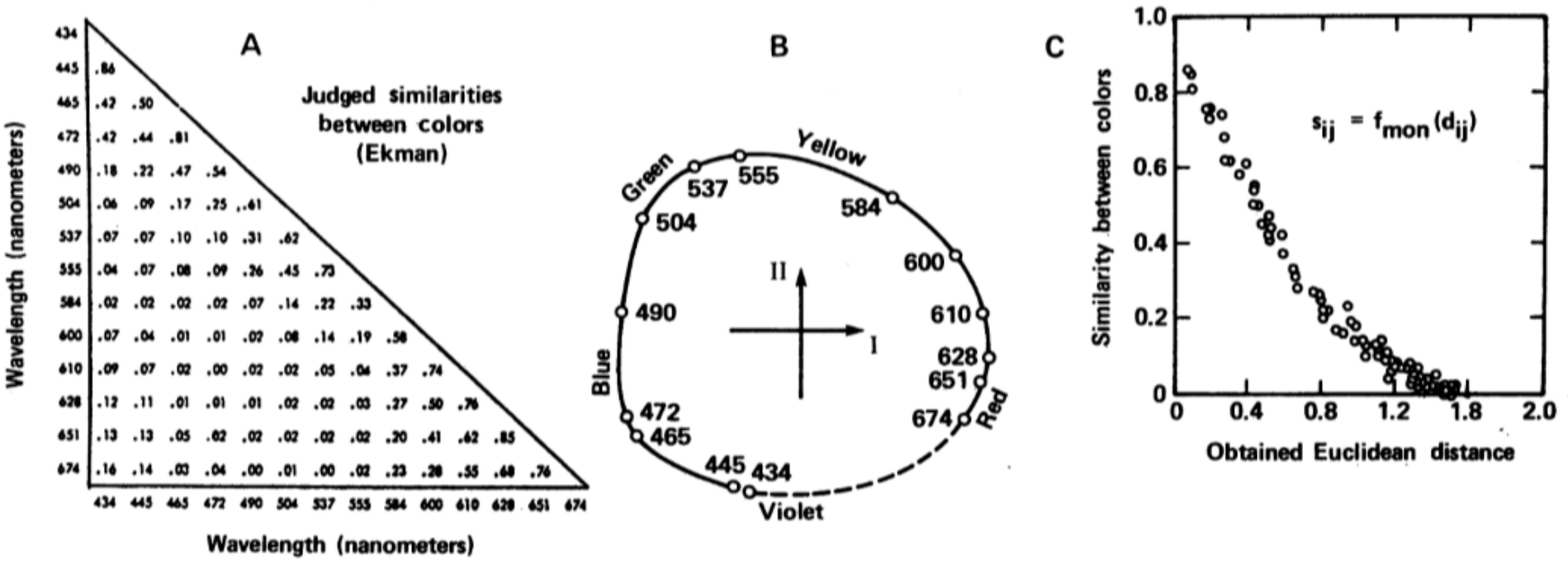
Why this is not enough: The psychologist

Roger Shepard

It is argued that, while there is no structural resemblance between an individual internal representation and its corresponding external object, an approximate parallelism should nevertheless hold between the relations among different internal representations and the relations among their corresponding external objects. In support of this “second-order” type of isomorphism, …

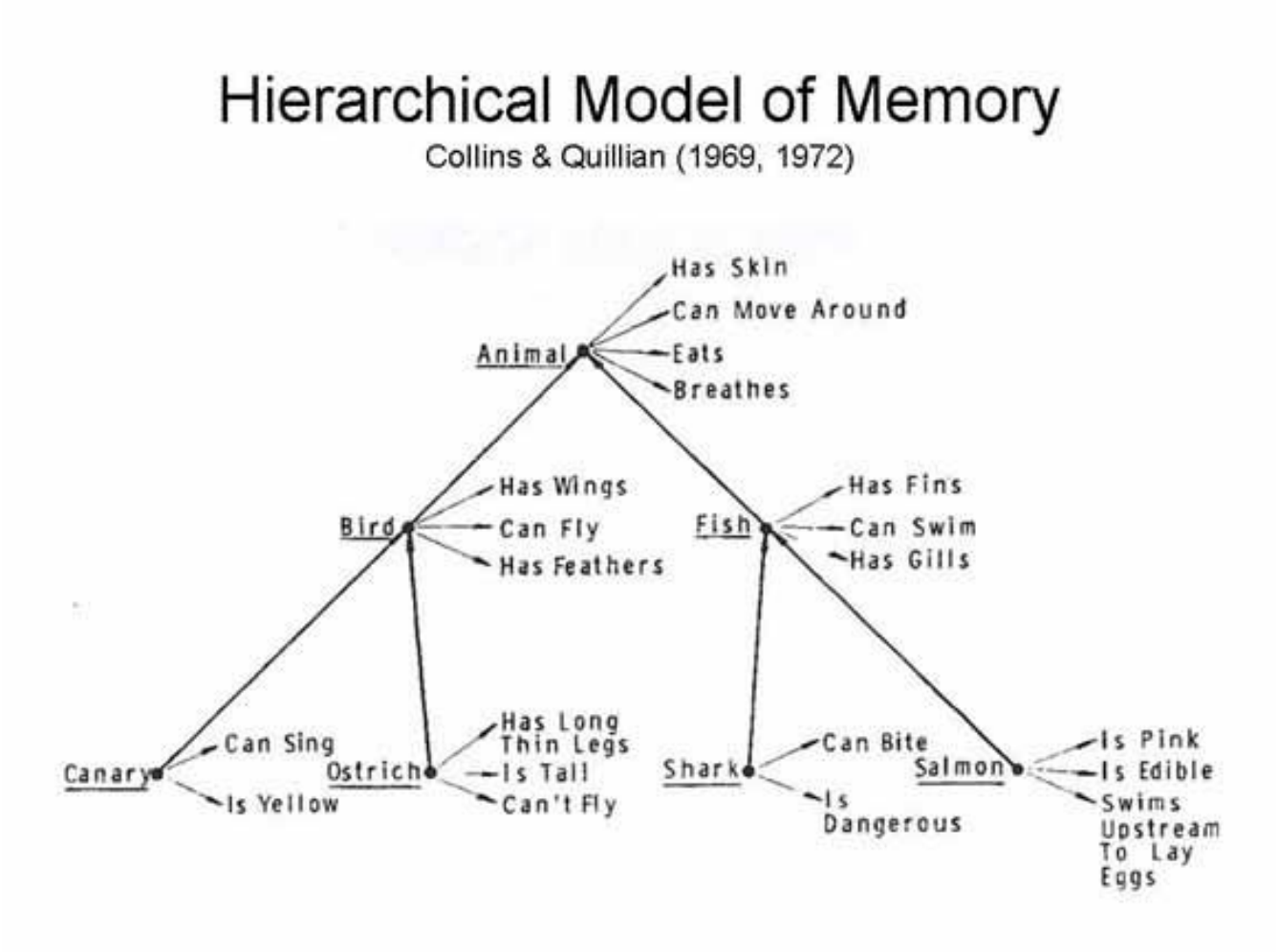
Quote from Shepard & Chipma, 1970

Understanding the geometry of representations

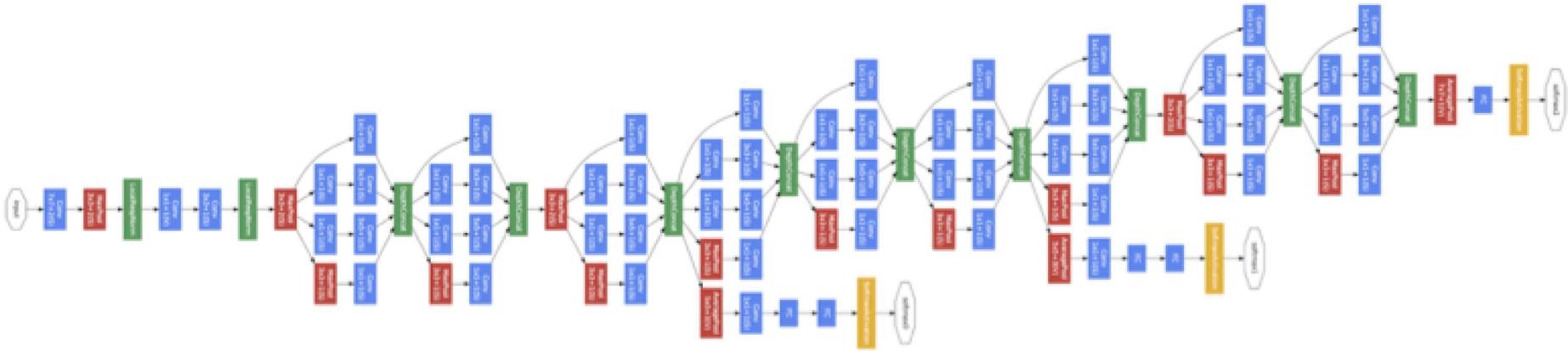


Shepard, 1962, 1980

Understanding the geometry of representations



Why this is not enough: The computational scientist

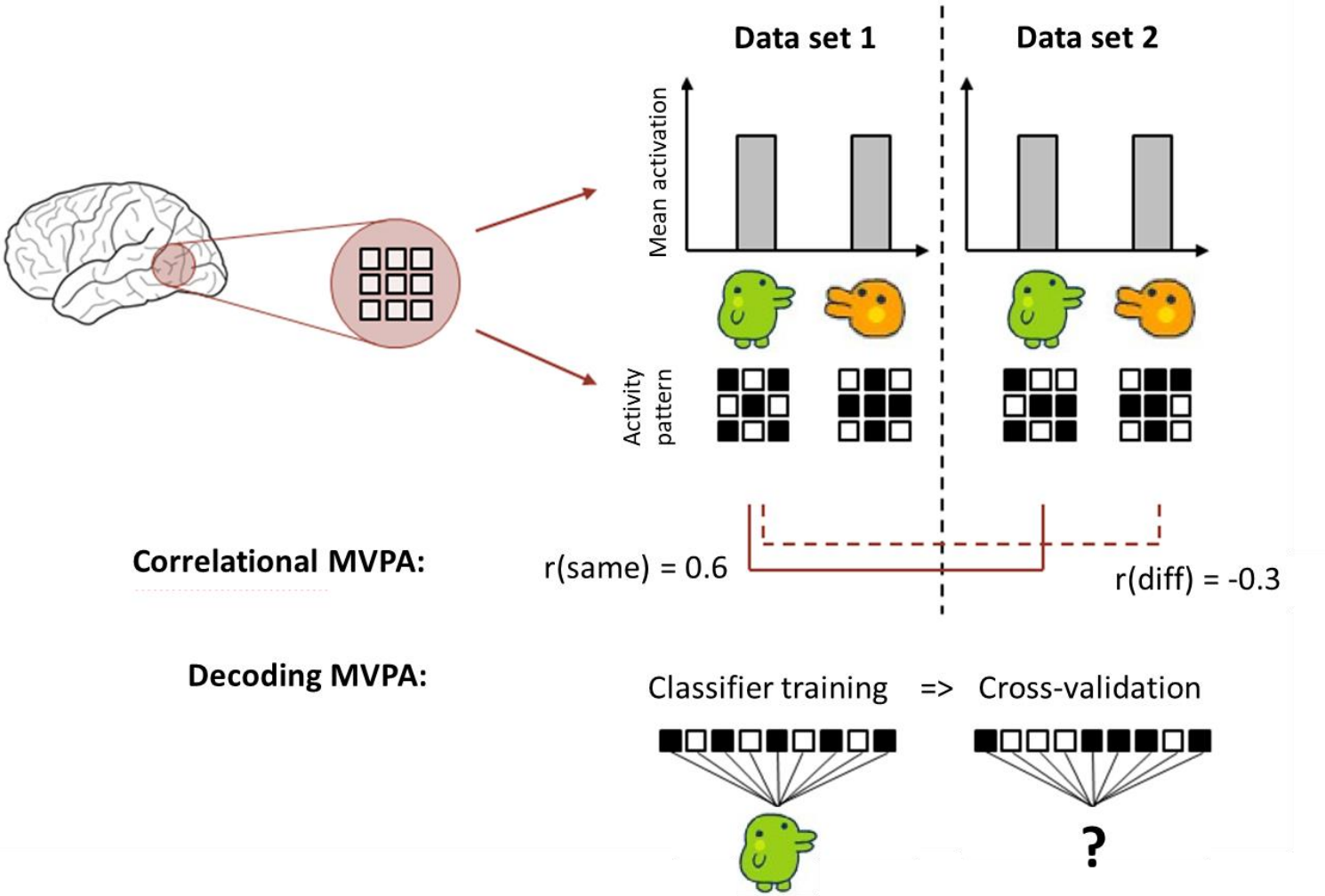


Convolution
Pooling
Softmax
Other

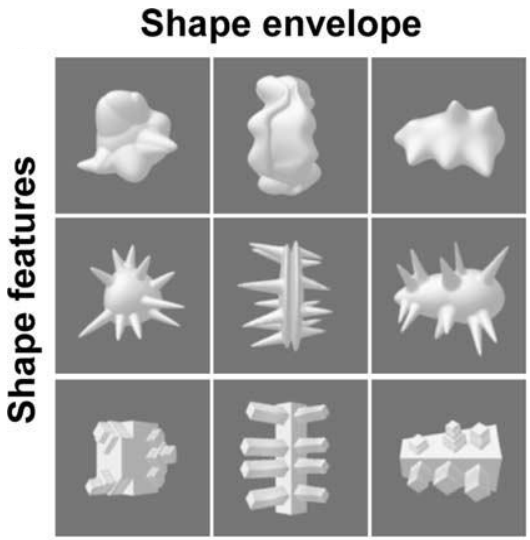
Many deep network architectures & applications:

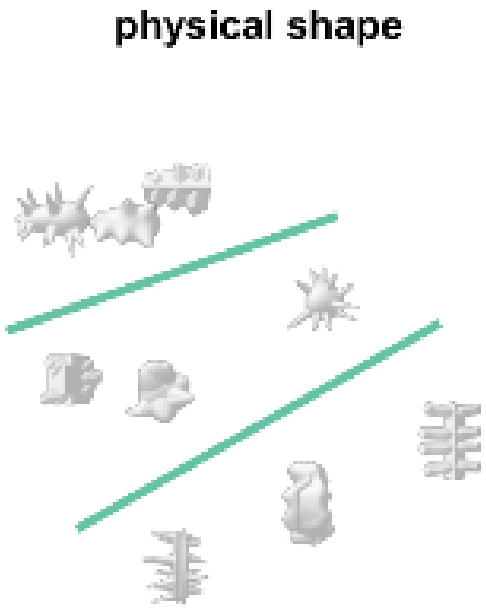
CaffeNet, AlexNet, **GoogLeNet**, FaceNet, ResNet, CORnet, …

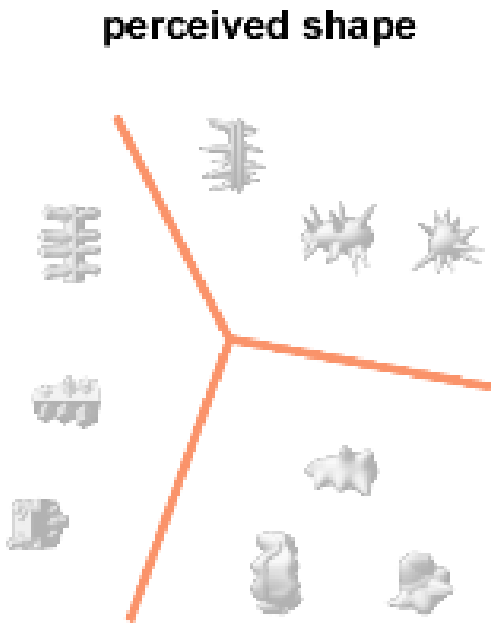
Solution to all our problems: Multivariate pattern analysis



Simple example study: Shape processing



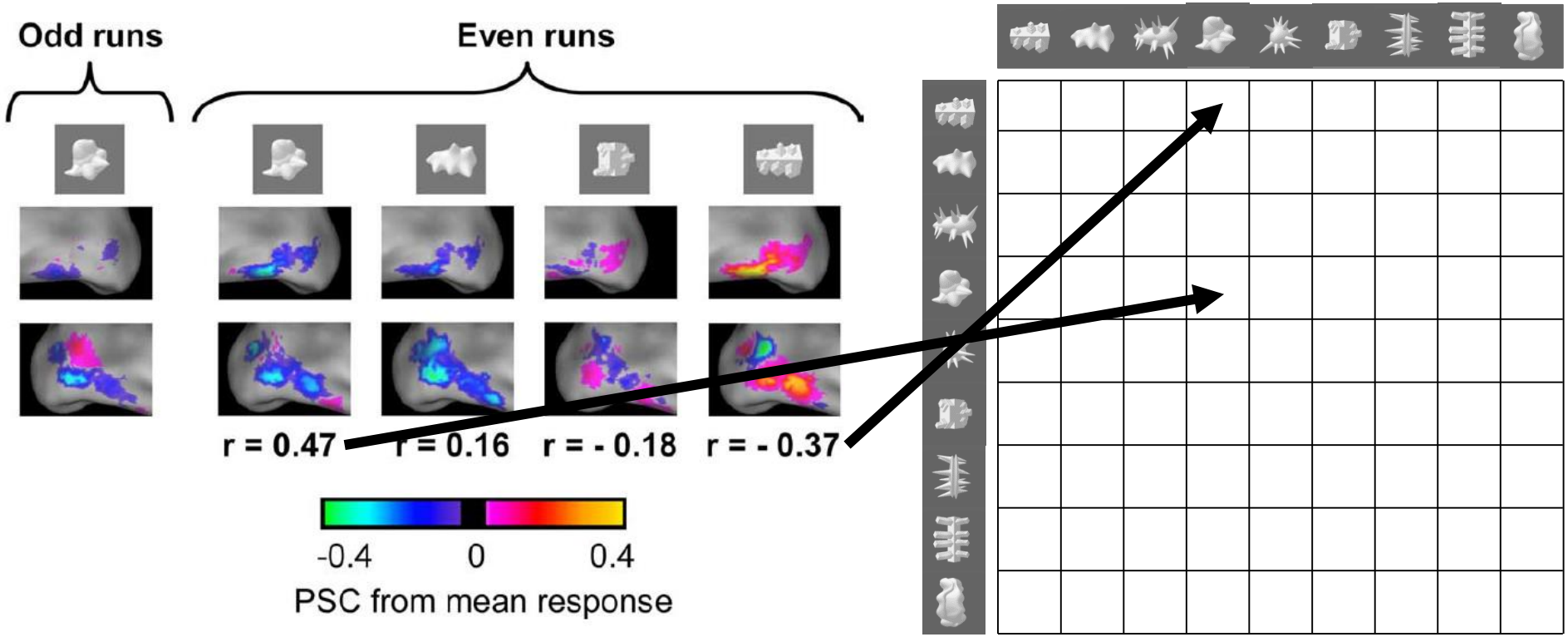




Also see: Biederman

Op de Beeck et al., 2008

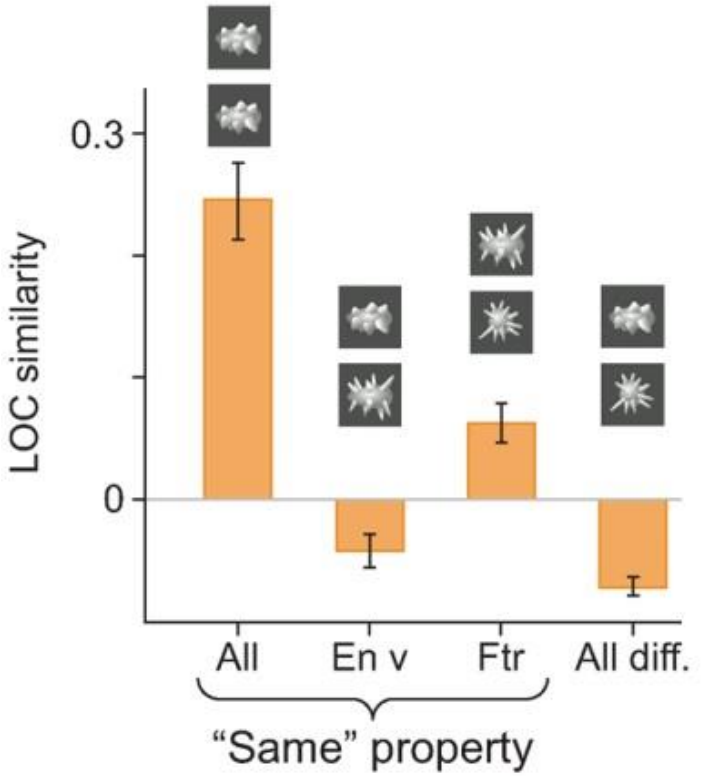
Simple example study: Shape processing



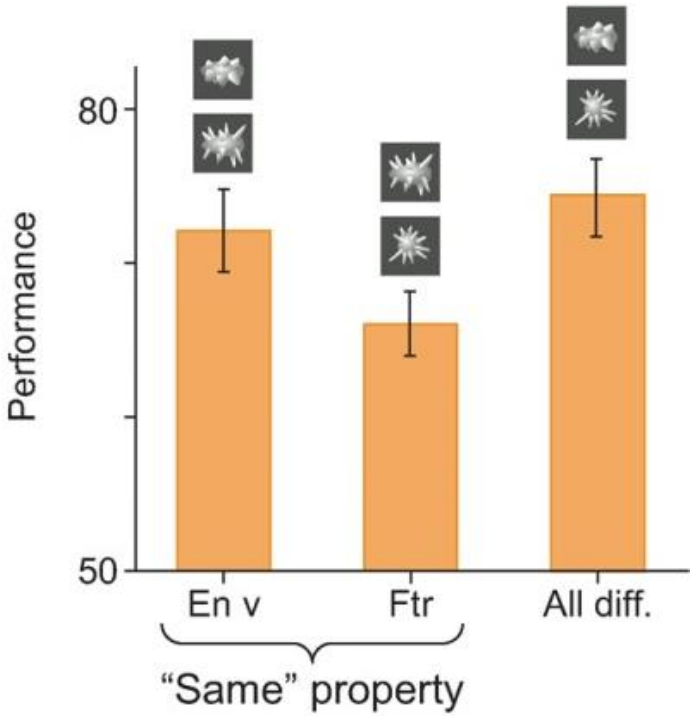
Op de Beeck et al., 2008

Analysis of similarity matrix:

Correlational MVPA



Decoding MVPA



Op de Beeck et al., 2008

Visualization with multidimensional scaling

Op de Beeck et al., 2008

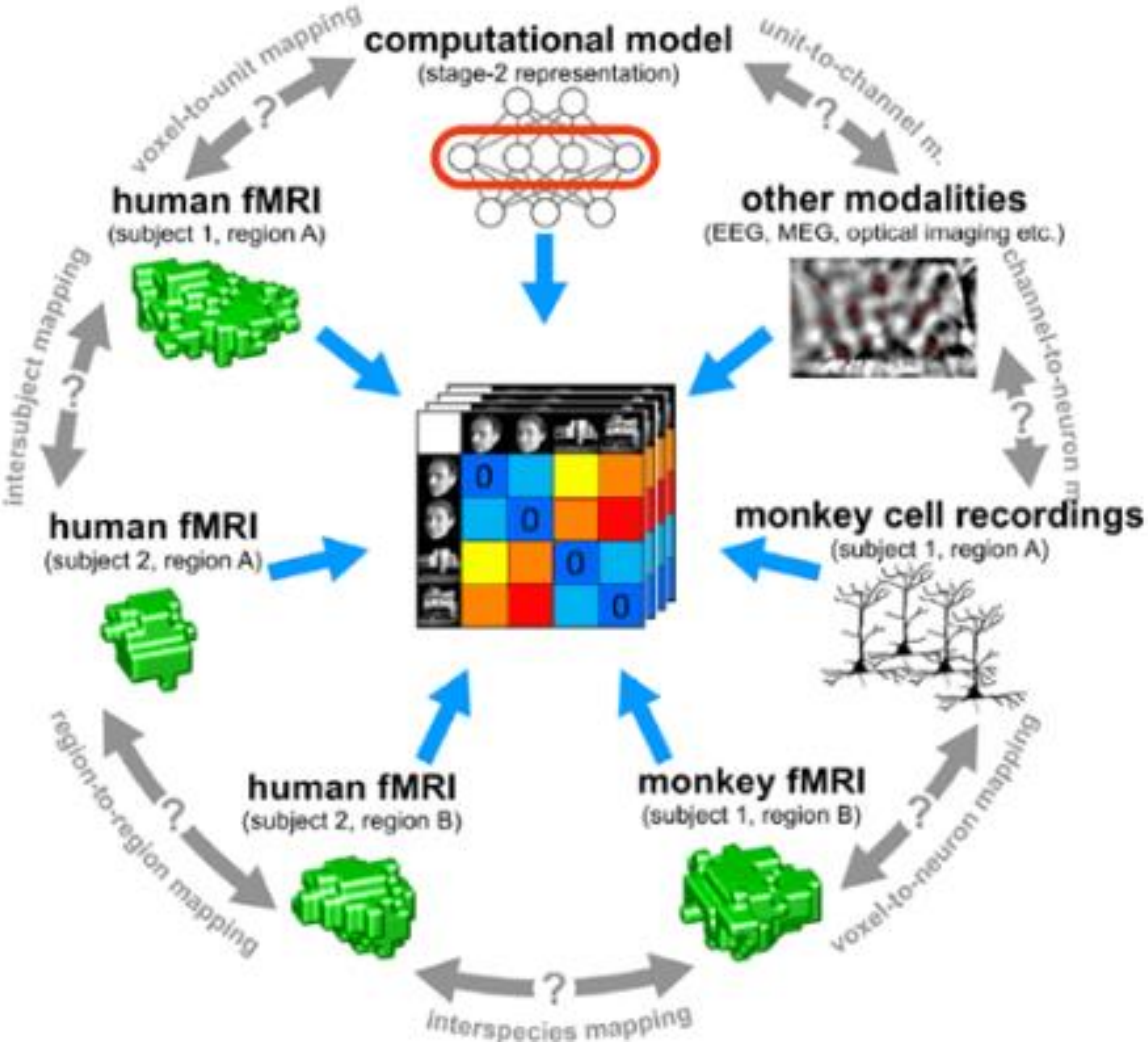
Different flavors of MVPA:

1) Analyses of representation geometry

2) Decoding and classification

3) Encoding and stimulus reconstruction

Representational similarity analyses (RSA)

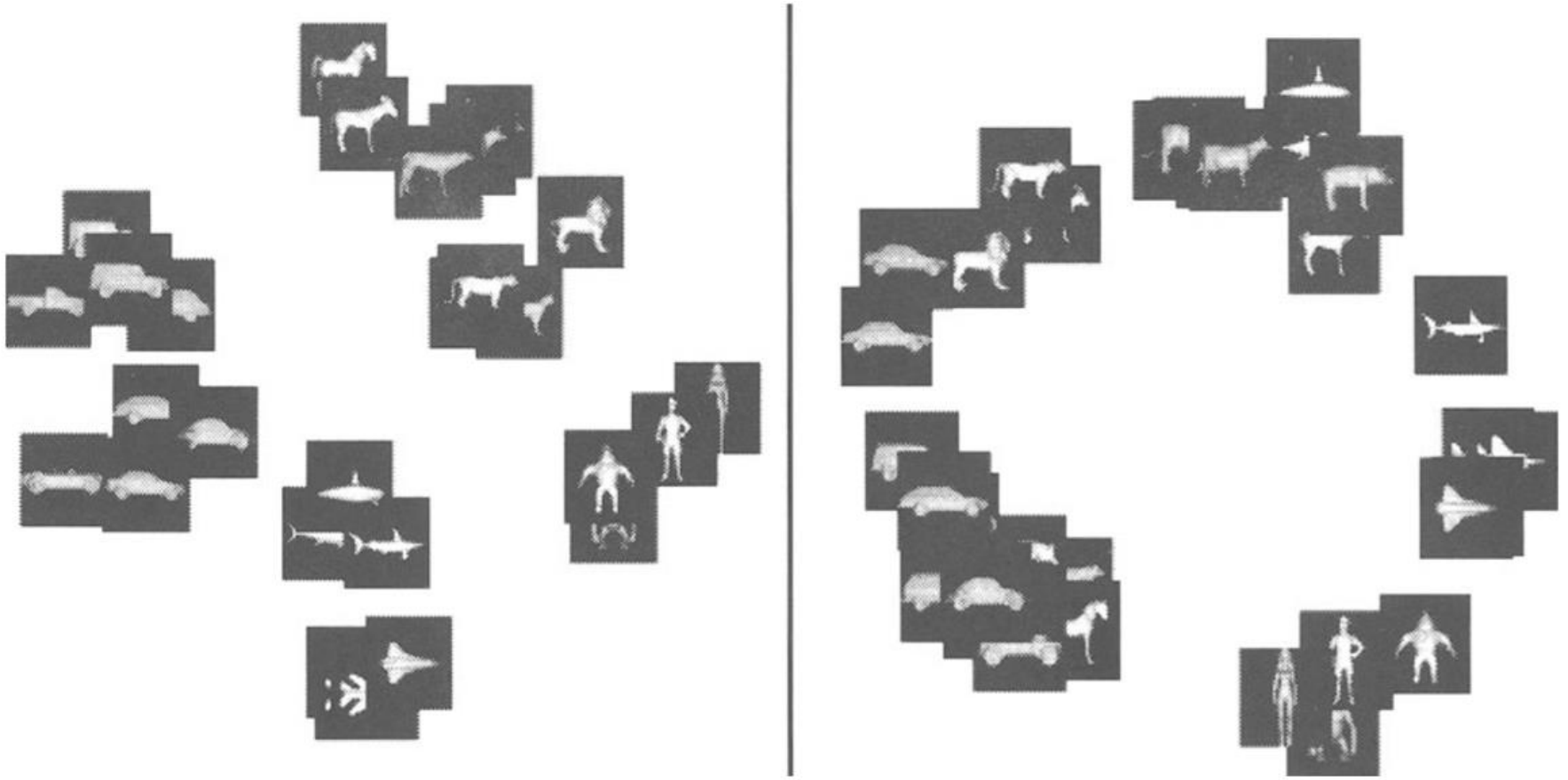


Kriegeskorte et al., 2008

Representational geometry: Where it started for fMRI

Behavioral space:

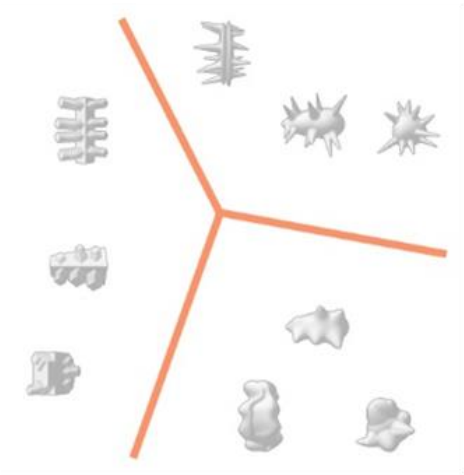
Neural space:



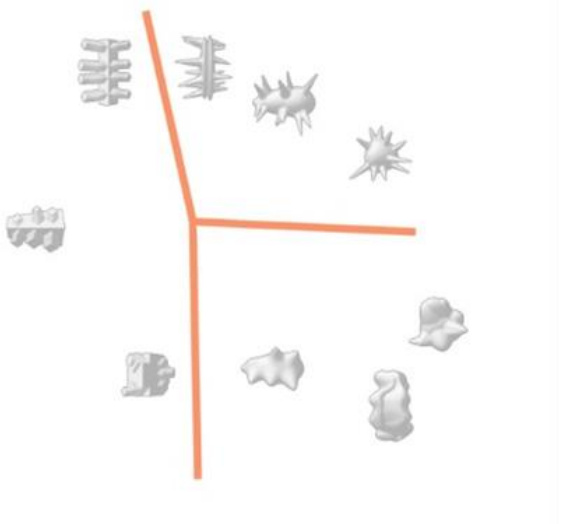
Edelman, Grill-Spector, et al., 1998

Representational similarity analyses

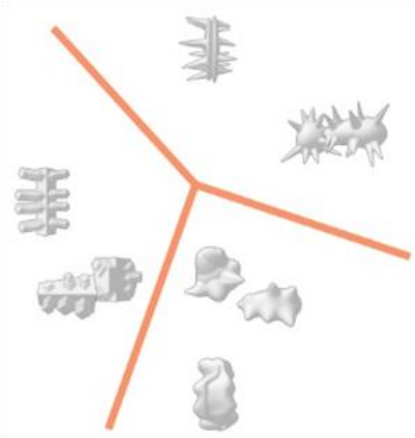
Perceived shape



Neural shape (LOC)

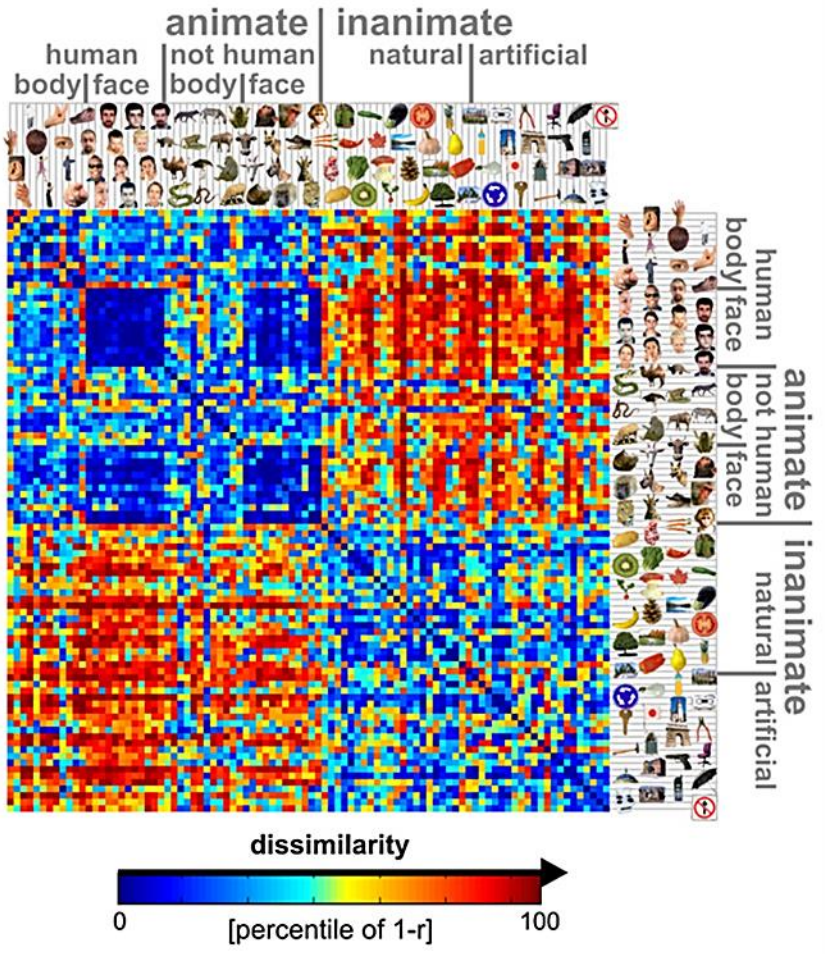


Deep shape (GoogLeNet)



Op de Beeck et al., 2008; Kubilius et al., 2016

Evolution towards stimulus-rich designs



Kriegeskorte et al., 2008

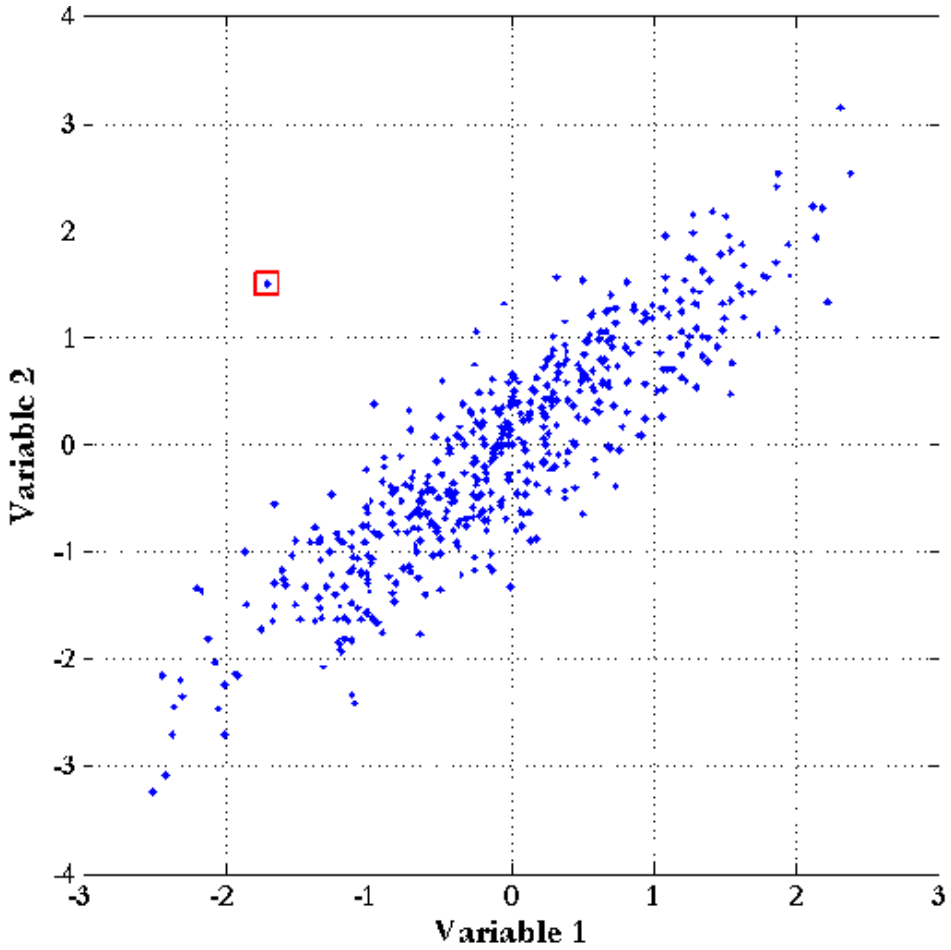
How to compute distance?

Correlation	<->	**Decoding accuracy**
- Can give distorted view		- Binarized
- Linear relationship		- Loss of information

Cross-validated Mahalanobis distance

Walther et al., 2016

Cross-validated Mahalanobis distance



$$d^2_M = (x - g)' \Sigma^{-1} (x - g)$$

Covariance matrix,

estimated on training data

Walther et al., 2016

Old-school psychology literature:

There is no universally good distance metric!

Minkowski metric:

$$d_{ij} = \left[\sum_{a} \left| x_{ia} - x_{ja} \right|^{p} \right]^{1/p}$$

Special cases:

1) Euclidean space, p = 2 (rotation invariance!)

2) City-block space, p = 1

Psychological validity of these metrics?

integral (1) versus separable (2) dimensions

Different flavors of MVPA:

1) Analyses of representation geometry

2) Decoding and classification

3) Encoding and stimulus reconstruction

Some questions call for a decoding approach

Wide variety of applications of multivariate decoding:

- All sorts of images: functional, structural, …
- Multi-modal information
- Classification of all sorts of dimensions:

  Stimuli, tasks, people

The more data, the better the decoding!

(but not always more meaningful)

Multivariate searchlight **classification** of structural magnetic resonance imaging in children and adolescents with **autism**

LQ Uddin, V Menon, CB Young, S Ryali, T Chen... - Biological ..., 2011 - Elsevier

Background **Autism** spectrum disorders (ASD) are neurodevelopmental disorders with a prevalence of nearly 1: 100. Structural imaging studies point to disruptions in multiple brain areas, yet the precise neuroanatomical nature of these disruptions remains unclear ...

Multivariate classification of **autism** spectrum disorder using frequency-specific resting-state functional connectivity—a multi-center study

H Chen, X Duan, F Liu, F Lu, X Ma, Y Zhang... - Progress in Neuro ..., 2016 - Elsevier

Background Resting-state functional magnetic resonance imaging studies examining low frequency fluctuations (0.01–0.08 Hz) have revealed atypical whole brain functional connectivity patterns in adolescents with **autism** spectrum disorder (ASD), and these atypical ...

[HTML] Functional connectivity **classification** of **autism** identifies highly predictive brain features but falls short of biomarker standards

M Plitt, KA Barnes, A Martin - NeuroImage: Clinical, 2015 - Elsevier

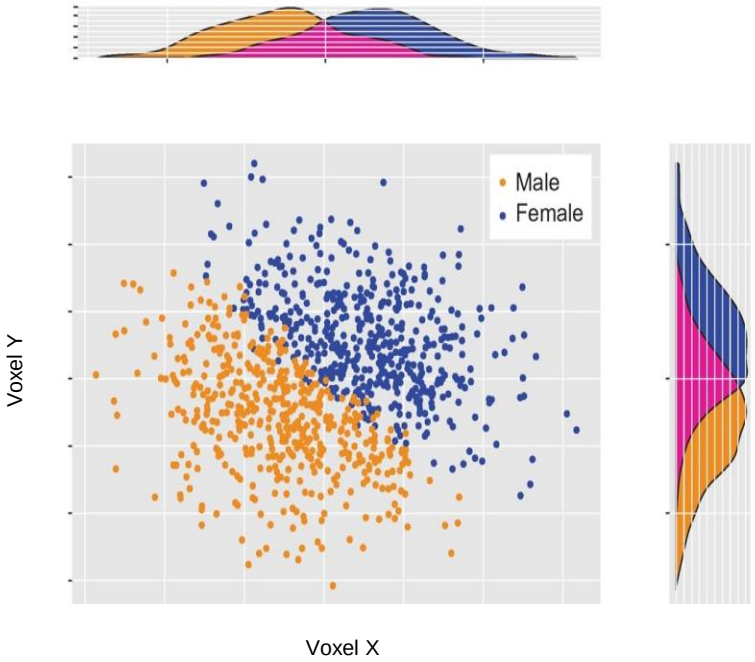
... These **multivariate** techniques have provided convergent evidence about brain differences that ... a clinical measure of social impairment designed to interrogate **autistic** symptoms ... awareness, social cognition, social communication, social motivation, and **autism** mannerisms) were ...

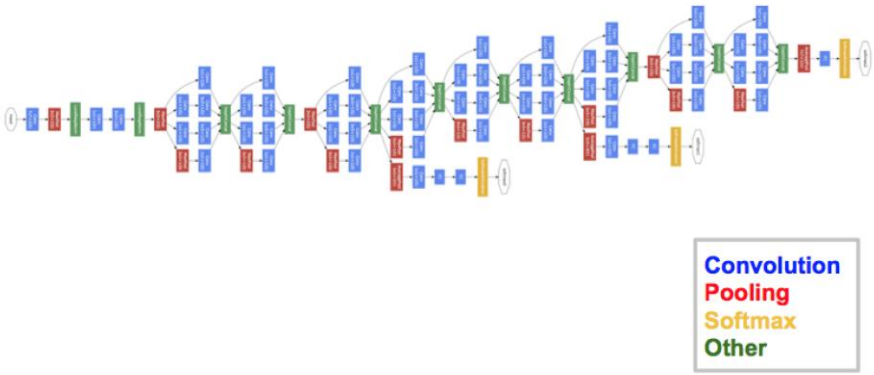
[HTML] Disorder-specific predictive **classification** of adolescents with attention deficit hyperactivity disorder (ADHD) relative to **autism** using structural magnetic ...

L Lim, A Marquand, AA Cubillo, AB Smith... - PloS one, 2013 - journals.plos.org

... ASD diagnosis was made using ICD-10 research diagnostic criteria [27] confirmed by the **Autism** Diagnostic Interview-Revised (ADI-R) [28] and the **Autism** Diagnostic Observation Schedule ... **Multivariate** pattern recognition approach: Gaussian Process **Classification** ...

Which decoder to use?





- Small number of examples => Linear support vector machine

- Consider what do you want to optimize:
  overall performance or pattern (cf. RSA)?

Different flavors of MVPA:

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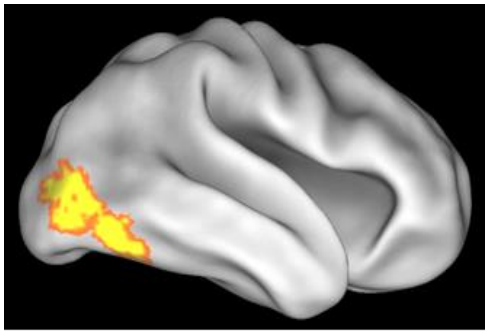
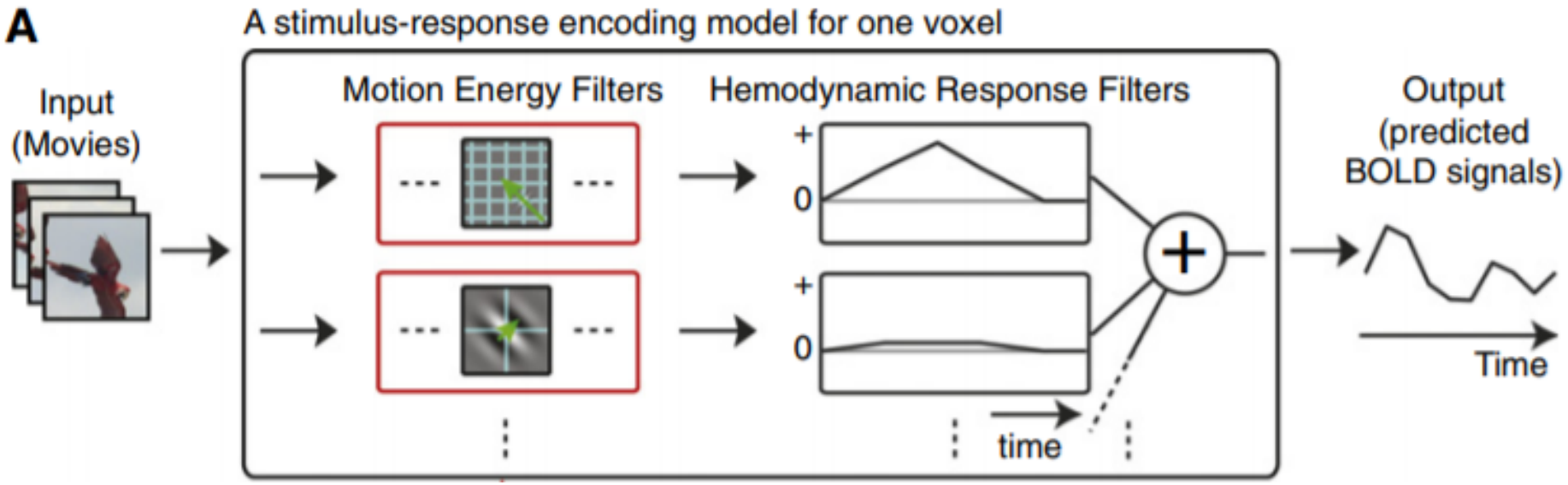
Decoding versus encoding



Decoding

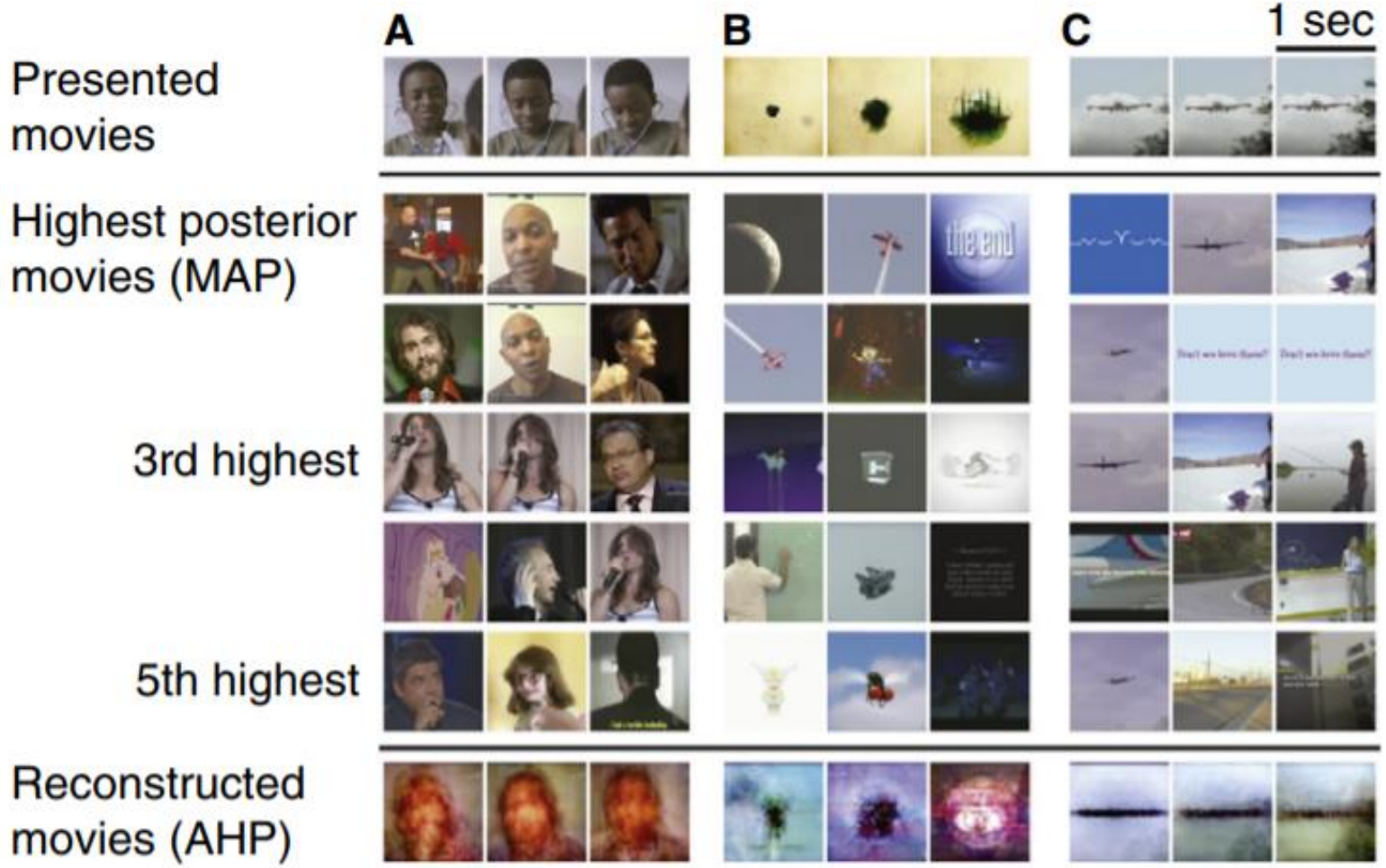
Encoding

Diagram of an encoding model:



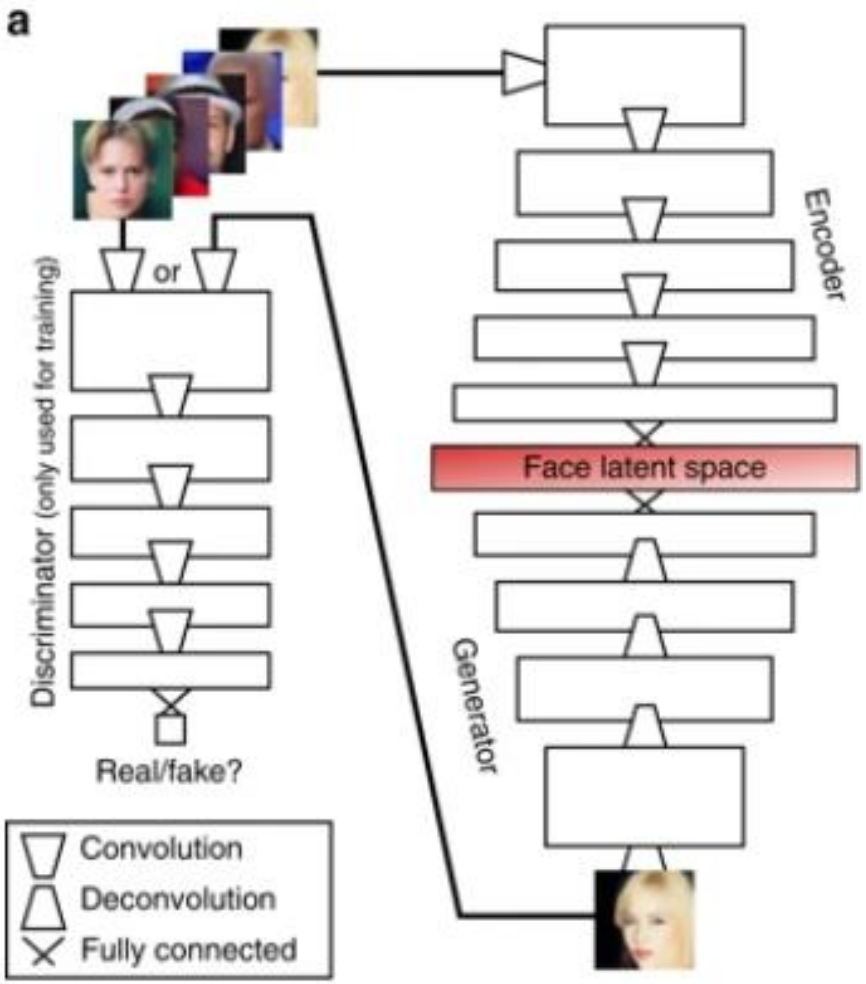
Studies by Gallant et al. (Kay; Nishimoto; Naselaris; …)

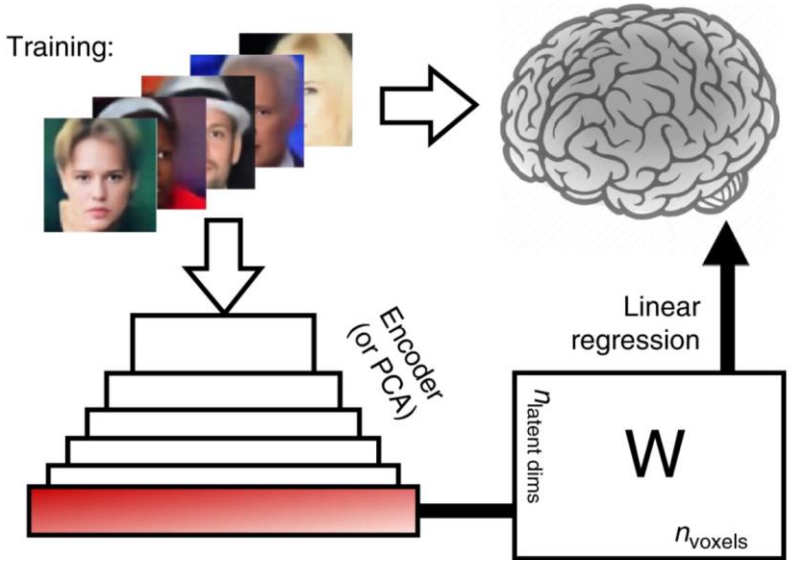
Results from encoding model:

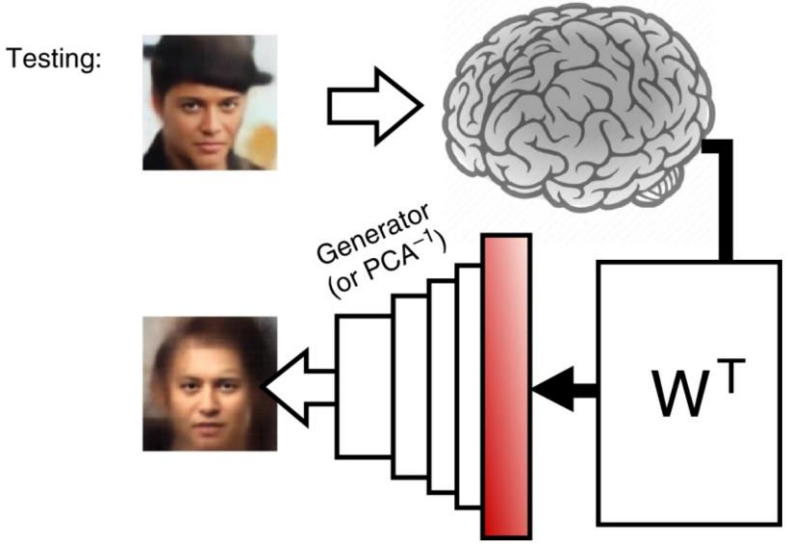


Studies by Gallant et al. (Kay; Nishimoto; Naselaris; …)

Encoding combined with deep neural networks:

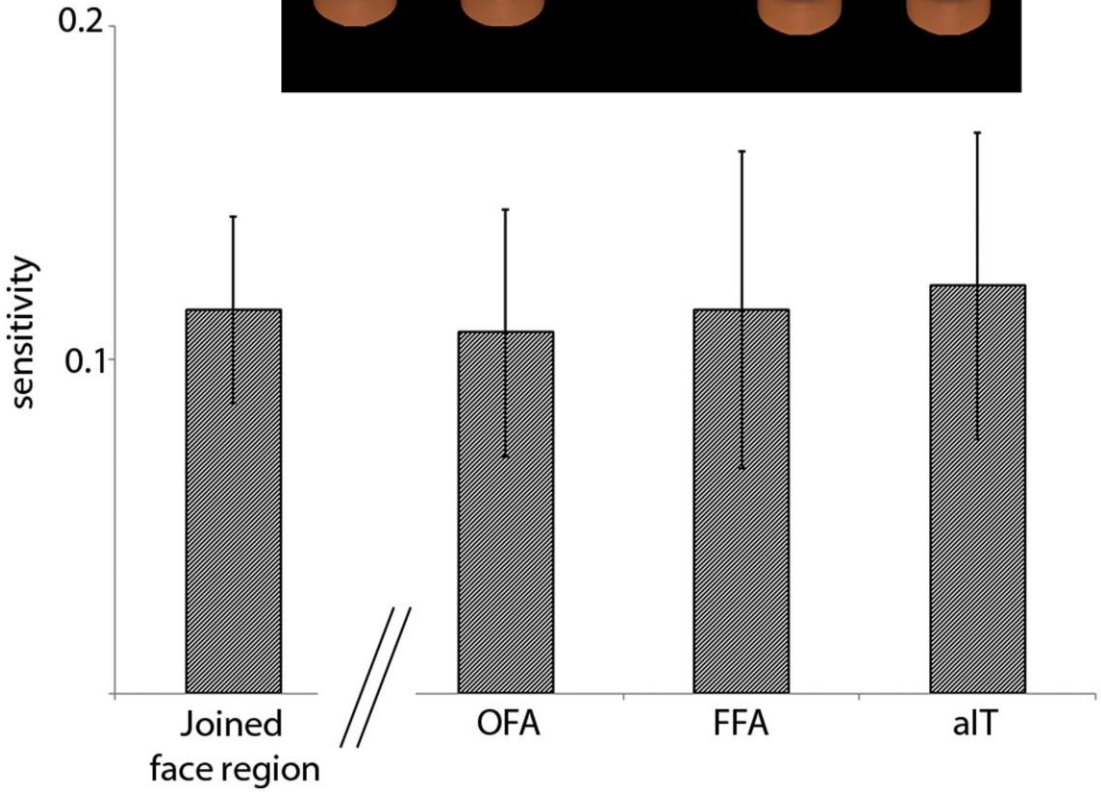






Van Rullen & Reddy, 2019

Contrast with decoding approach !!!



Goesaert & Op de Beeck, 2013

Caveats and points of attention with MVPA:

- Ethics
- MVPA and brain organization
- Effect size
- Experimental design
- ROI-based or whole-brain?
- Other technical considerations

What about the ethics of this?

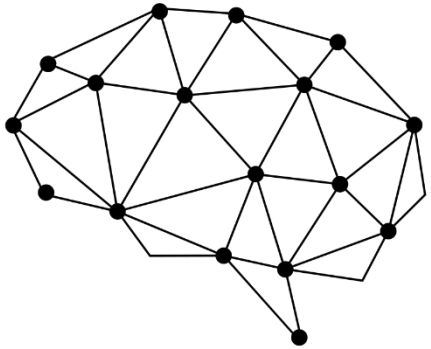
BRAIN READING !!!

However:

- Need for many hours of training data
- Highest possible quality of imaging (fMRI/MEG/EEG)
- These requirements impede large-scale use (~forever !)

What about the ethics of this? BRAIN READING !!!

Apple, Google: We've stopped listening to your private Siri, Assistant chat, for now

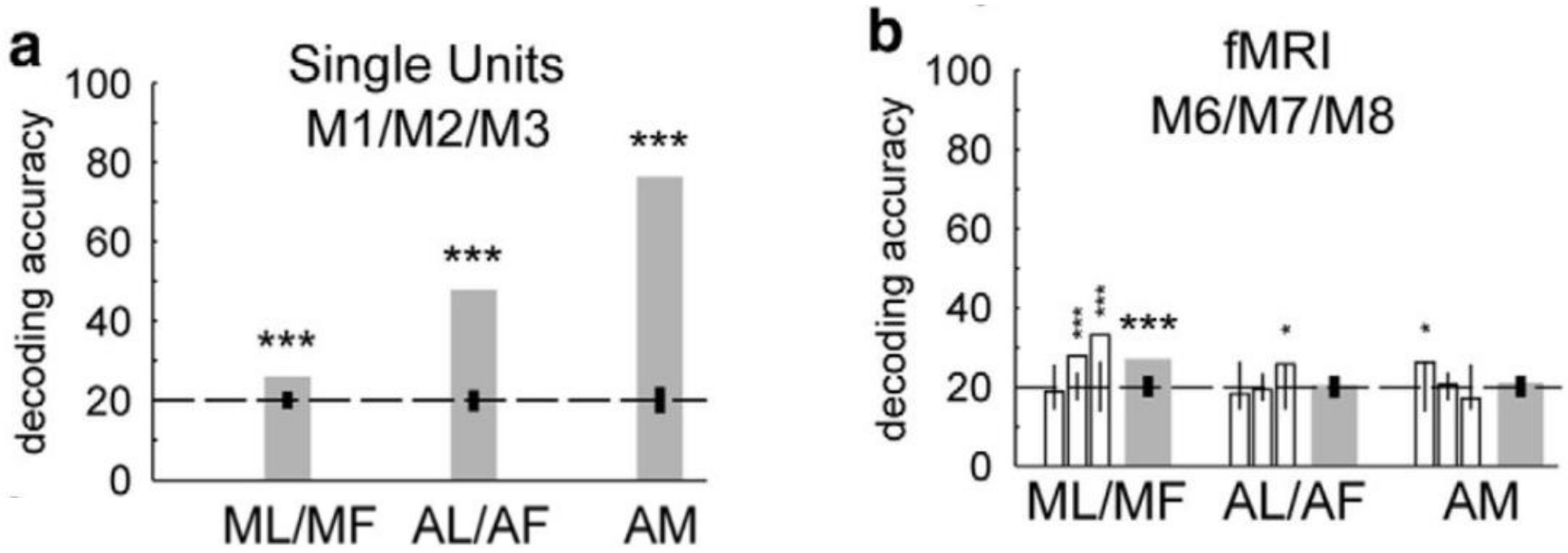


Cambridge Analytica

Cambridge Analytica Ltd (**CA**) was a British political consulting firm which combined misappropriation of digital assets, data mining, data brokerage, and data analysis with strategic communication during the electoral processes.[5][6]

MVPA and brain organization

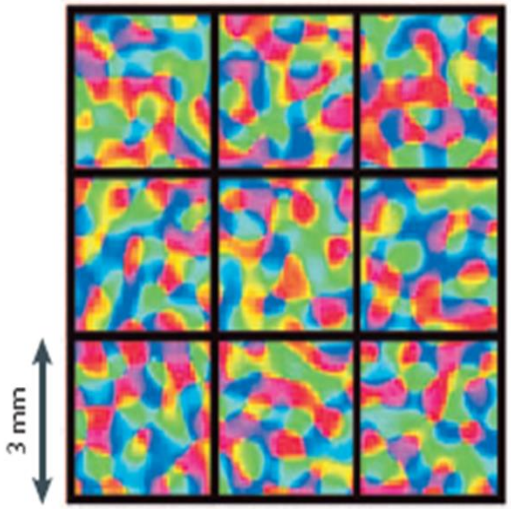
1) MVPA needs clustering, e.g. for face identity decoding

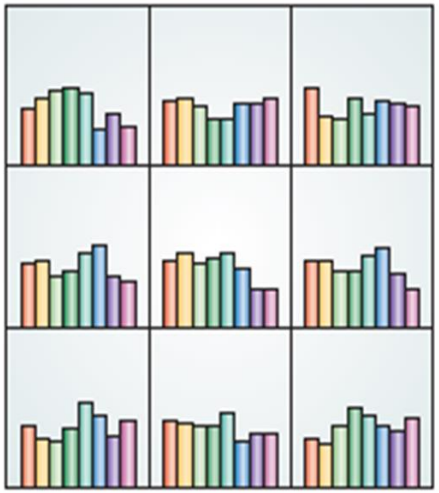


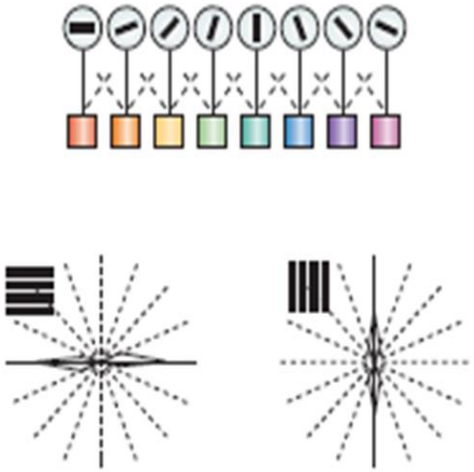
Dubois et al., 2015

MVPA and brain organization

2) Probing sub-voxel columnar organization, ‘hyperacuity’ ?



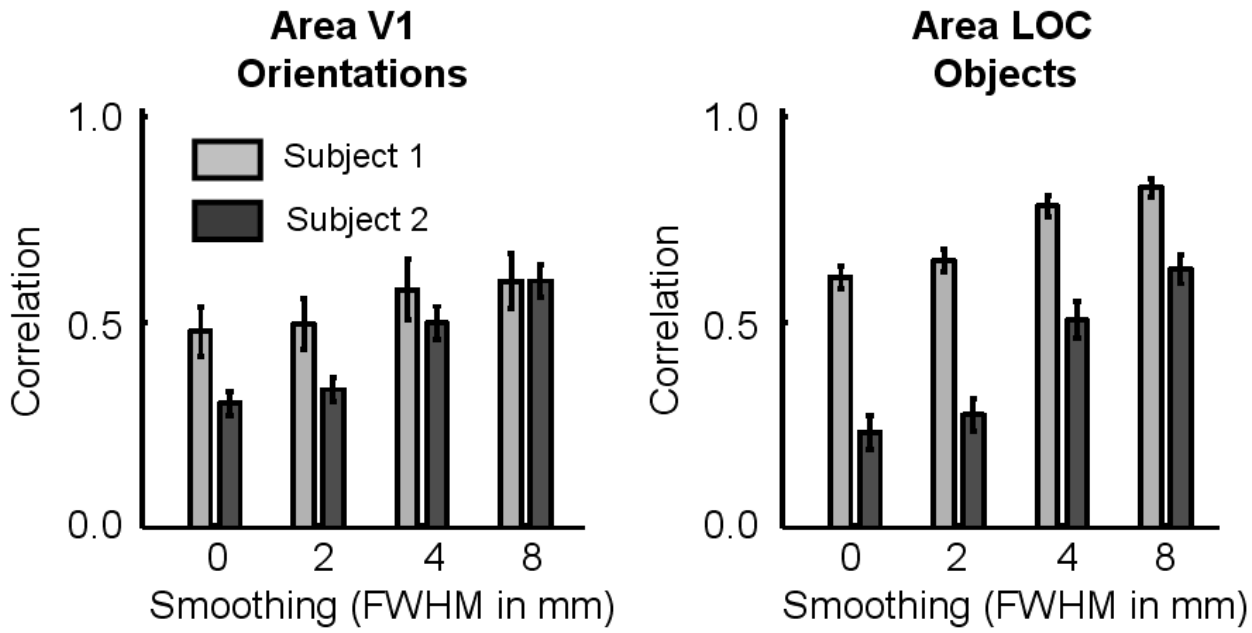




Haynes & Rees, 2006; Kamitani & Tong, 2005

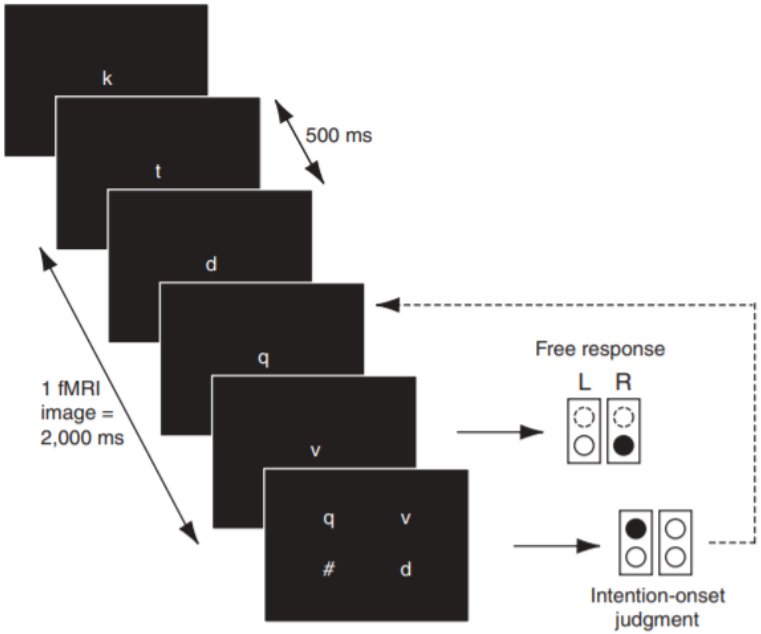
MVPA and brain organization

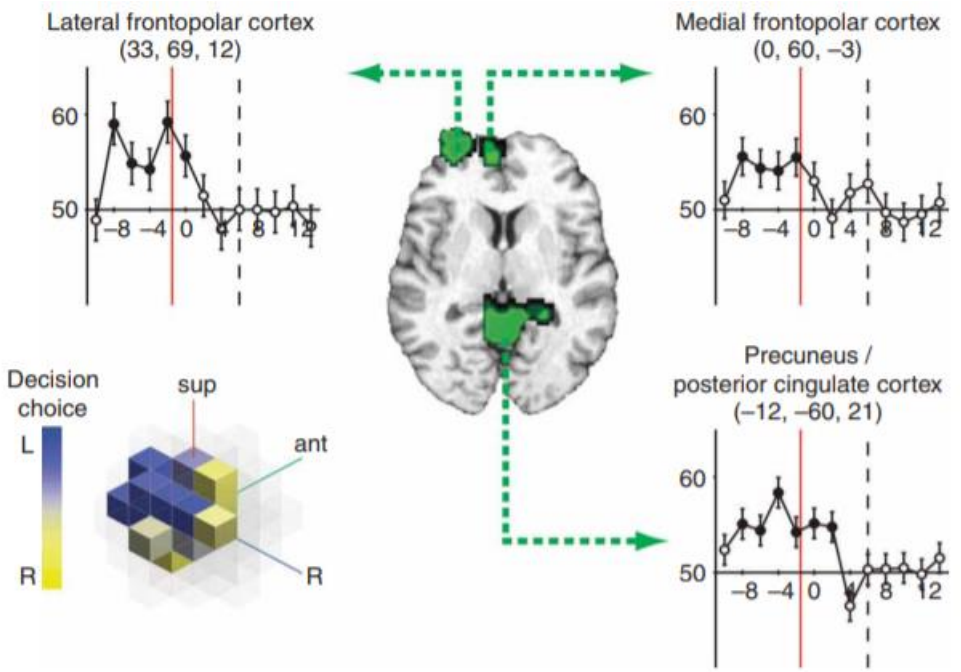
2) Hard to say whether ever evidence of ‘hyperacuity’



Op de Beeck, 2009, 2010

How to interpret small effect sizes?

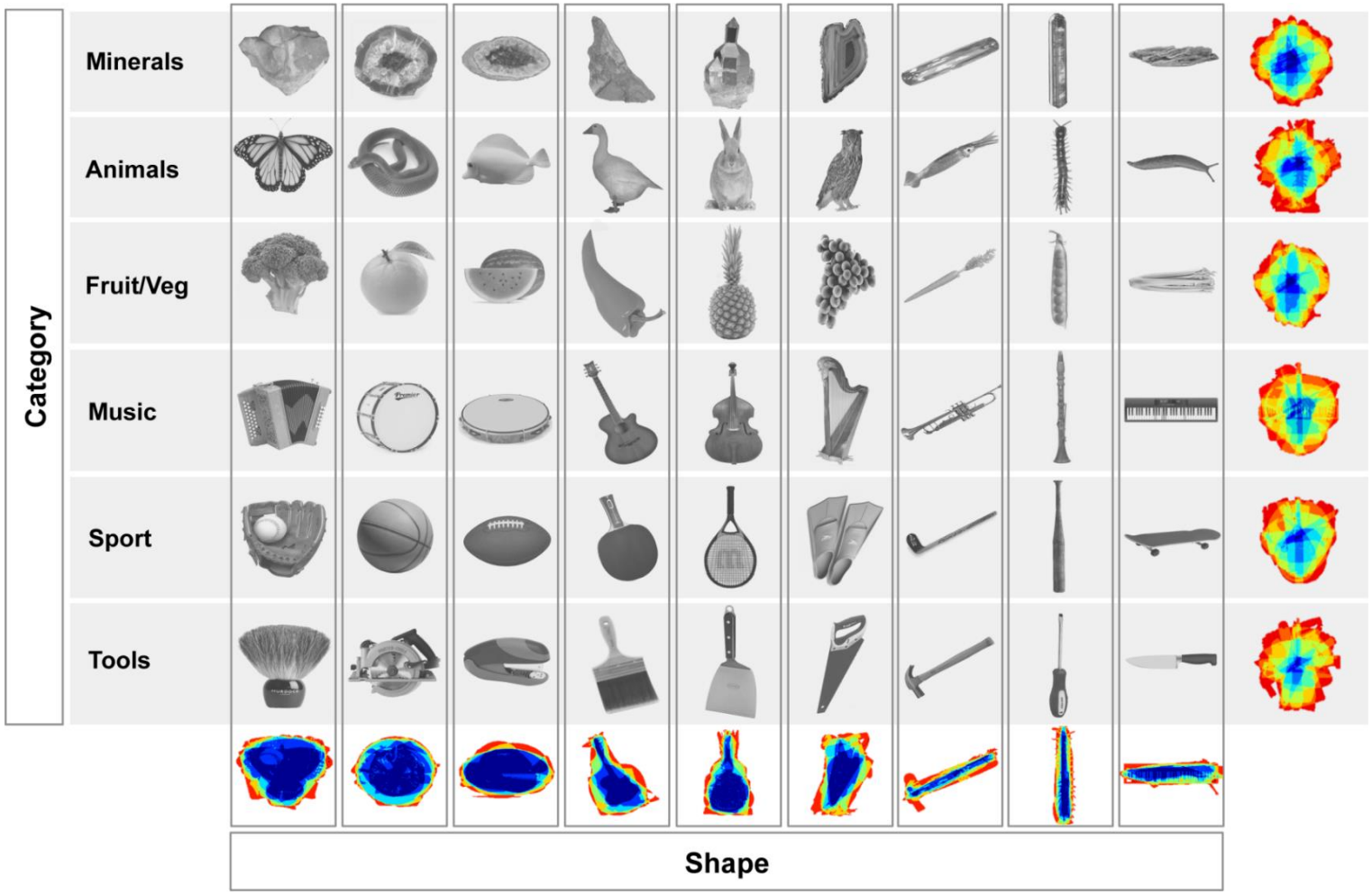




Soon et al., 2008

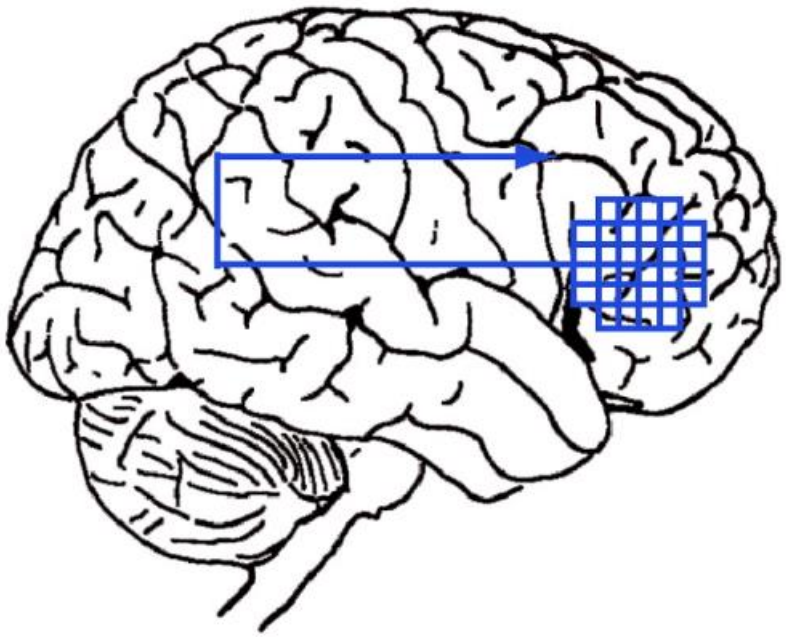
Complex analyses do not make up for design confounds

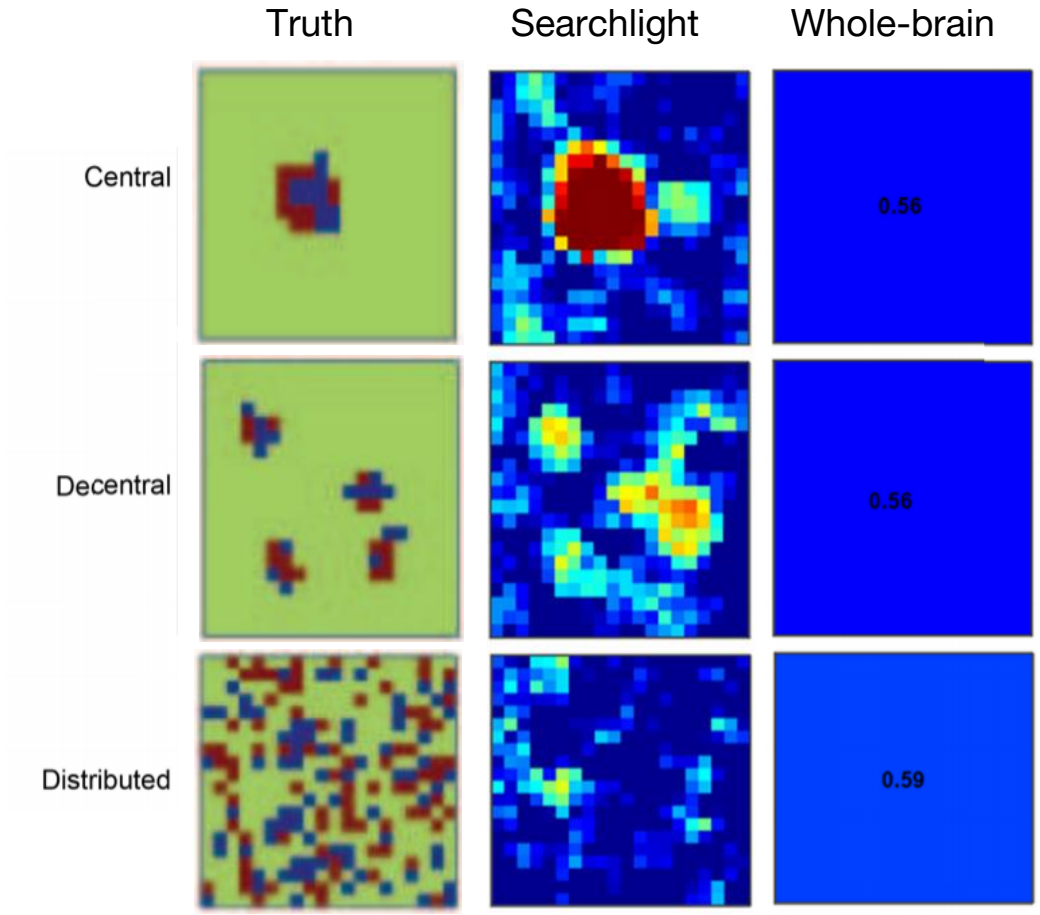
Complex analyses do not make up for design confounds



Bracci et al., 2016

Whole-brain approach to MVPA: Searchlight analyses





Kriegeskorte et al., 2006

Bulthé et al., 2014

Various technical considerations:

- How much data do we need?
- How to model the data?
    - Trials or runs?
    - Length of runs?
    - ***B***-estimates or ***t***-values?
- To smooth or not to smooth?
- Software? PyMVPA; CoSMoMVPA; Decoding Toolbox (TDT)

Advanced applications:

1) Network analyses

- Second-order RSA
- Relationship to functional connectivity

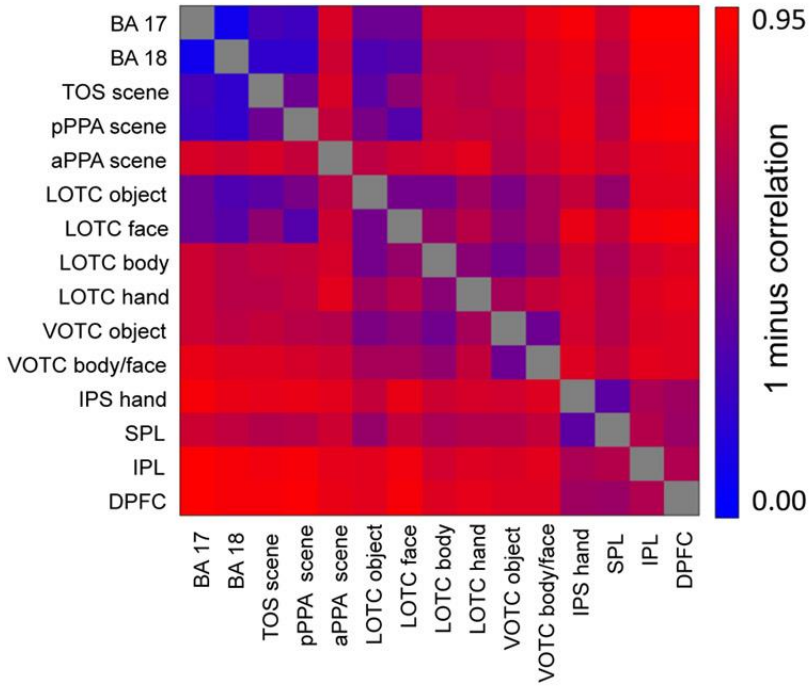
Interesting combination!

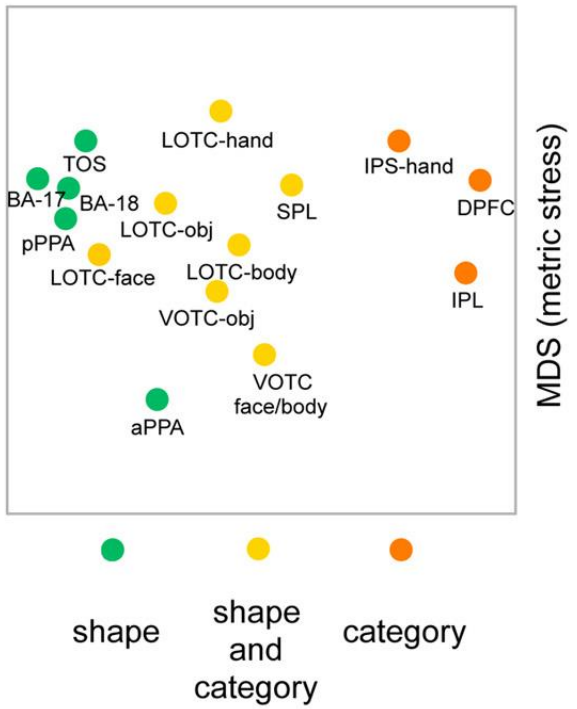
- Multivariate connectivity

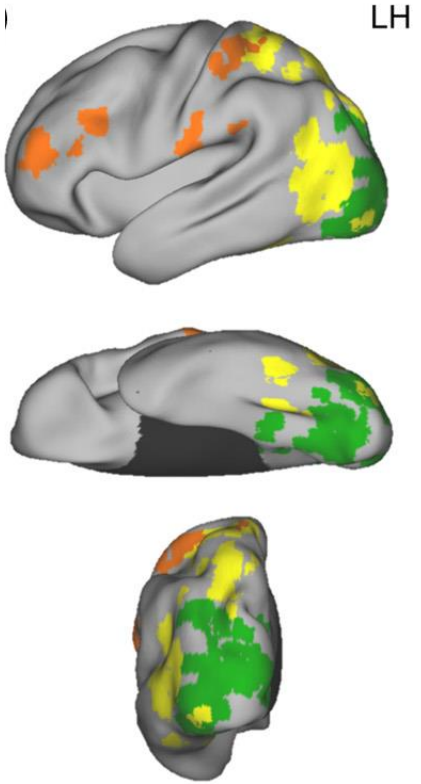
2) Temporal RSA on (M/E)EG data,

possibly combined with fMRI

Second-order RSA: Representational hierarchies



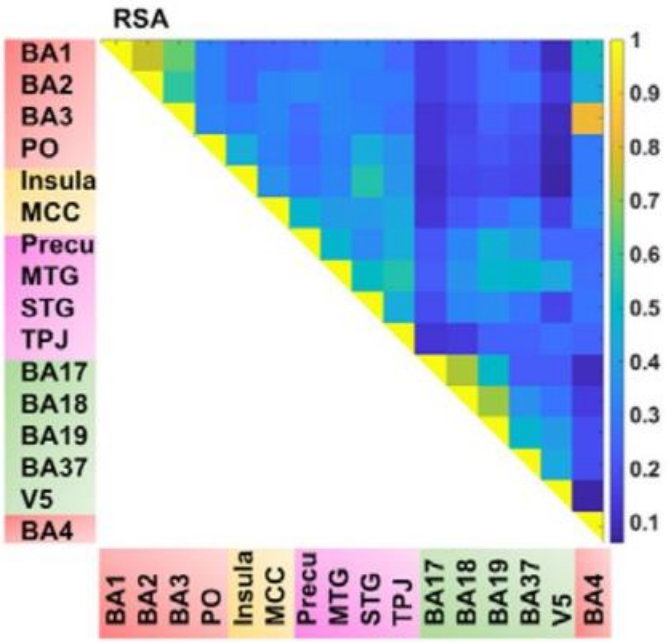


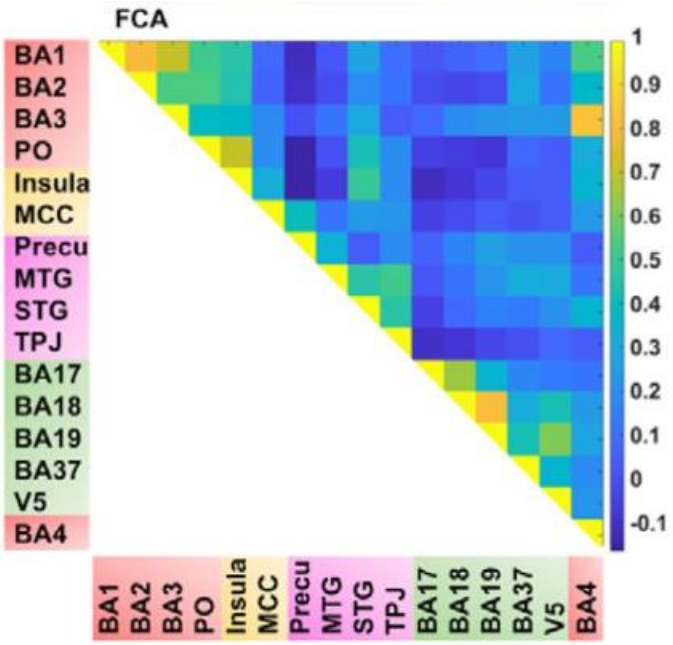


Bracci et al., 2016

Relationship to functional connectivity:

Similar networks, when representations exist





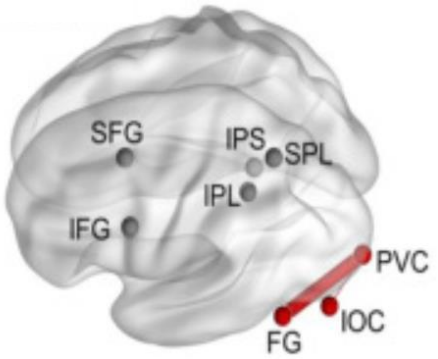
Pillet et al., 2019

Studies that combine MVPA & connectivity:

Interesting dissociations

Examples:

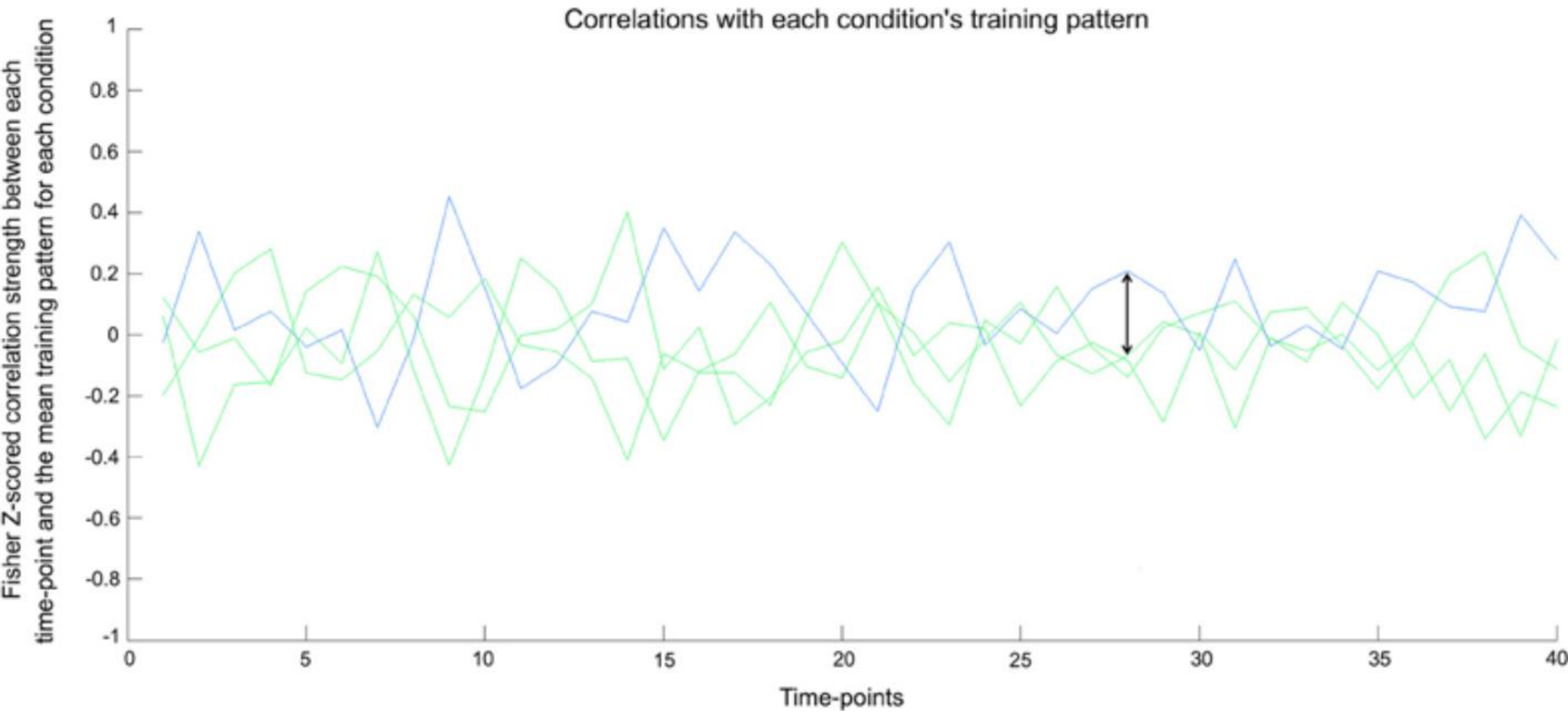
- Dyslexia: normal decoding; less connectivity
- Dyscalculia: lower decoding; equal or higher connectivity



- Autism: domain-specific changes in each

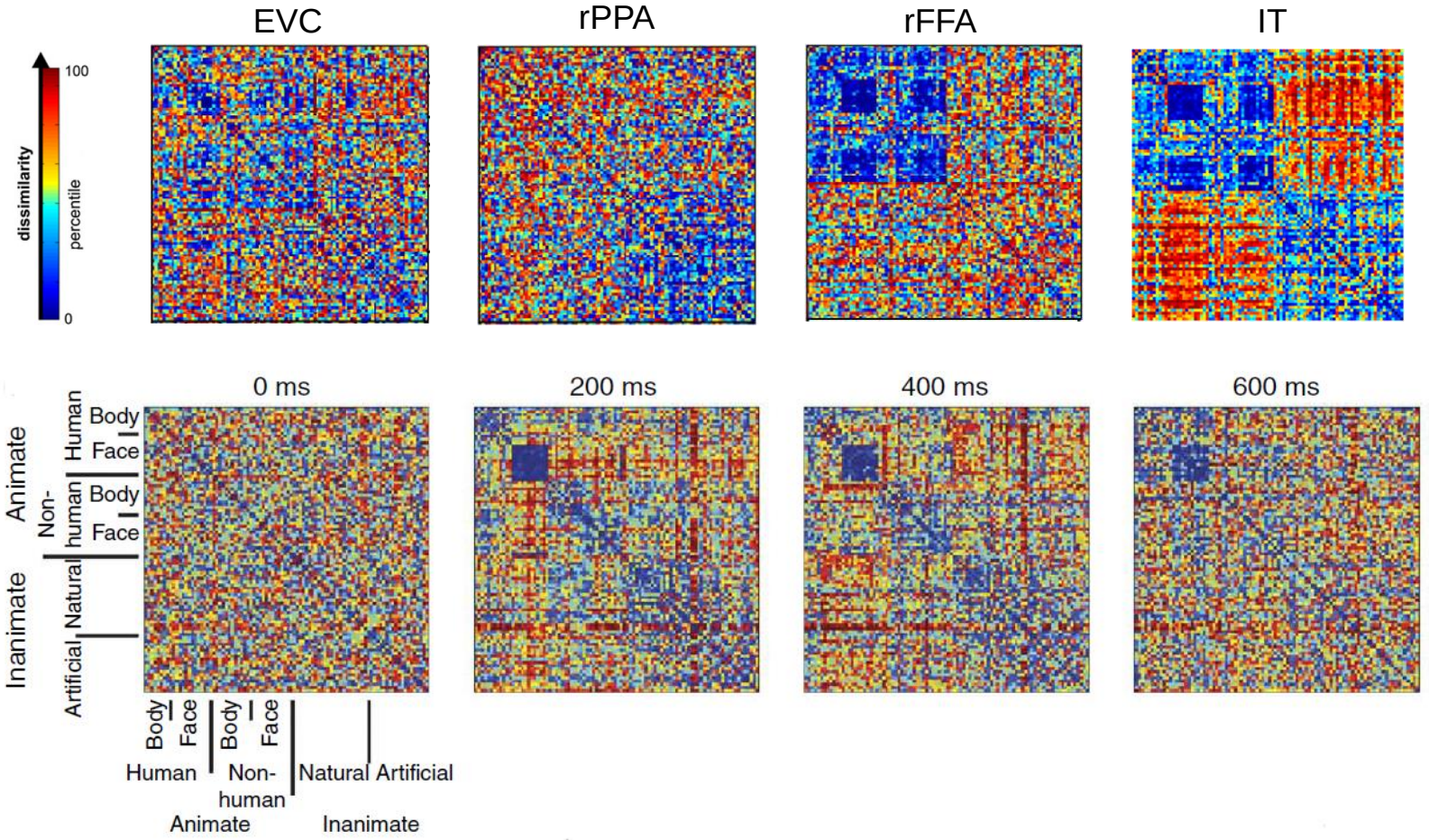
Boets et al., 2013; Bulthé et al., 2018; Pegado et al., in press; Lee-Masson et al., in press

Multivariate connectivity



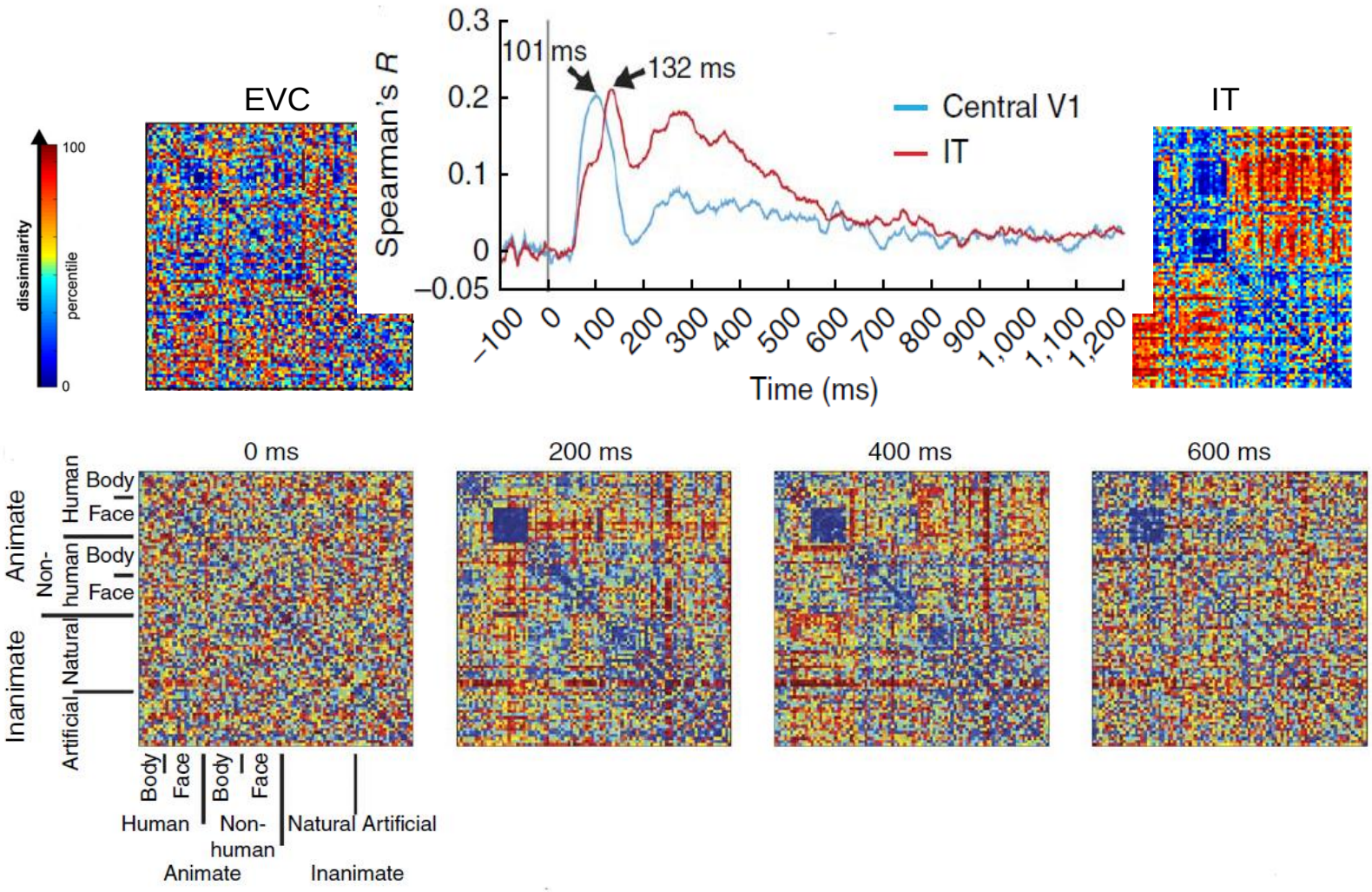
Anzellotti & Coutanche, 2018; Coutanche & Thompson-Schill, 2013;

Temporal RSA on (M/E)EG data, possibly combined with fMRI



Cichy et al., 2014

Temporal RSA on (M/E)EG data, possibly combined with fMRI



Cichy et al., 2014

CAMBRIDGE FUNDAMENTALS OF NEUROSCIENCE IN PSYCHOLOGY

Introduction to Human Neuroimaging

HANS OP DE BEECK
AND CHIE NAKATANI