The similar object spaces are represented in the primate IT cortex and deep learning networks

THBI Seminar Series

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Peking University


AMERITT

High-level
Cognitive processes

Object recognition

Memory

Attention

Decision making

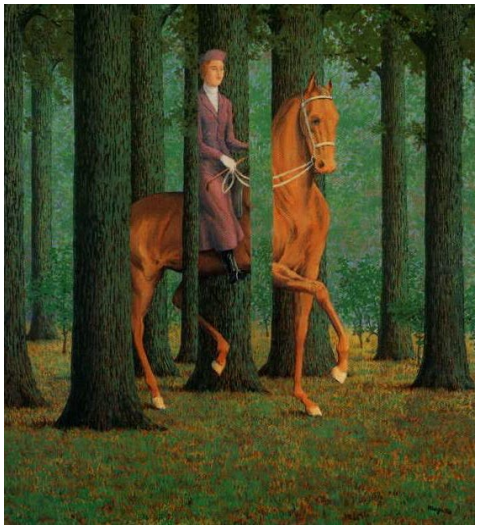
Social cognition

The space of the object is huge

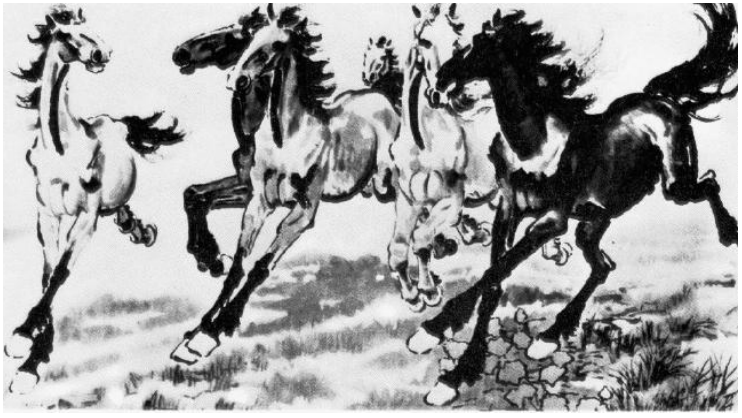
Invariant object recogntion

Different views

Occlusion

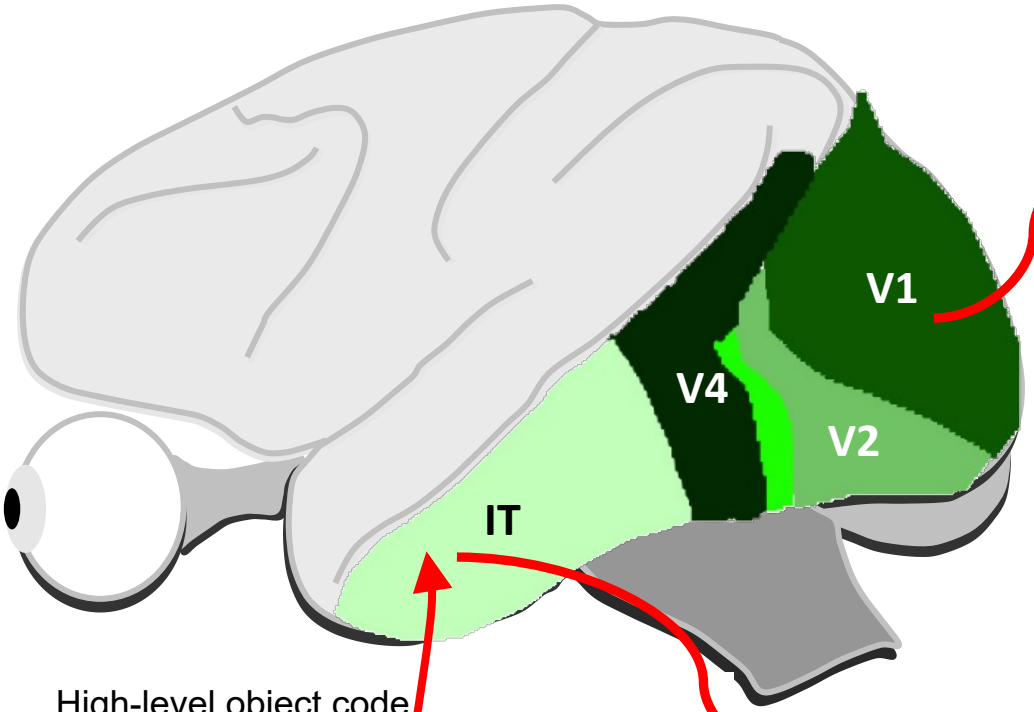


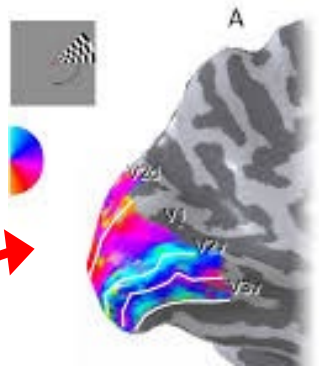
Deformation



Clutter background

Pathway for visual object representation





Sereno et al. Science 1995

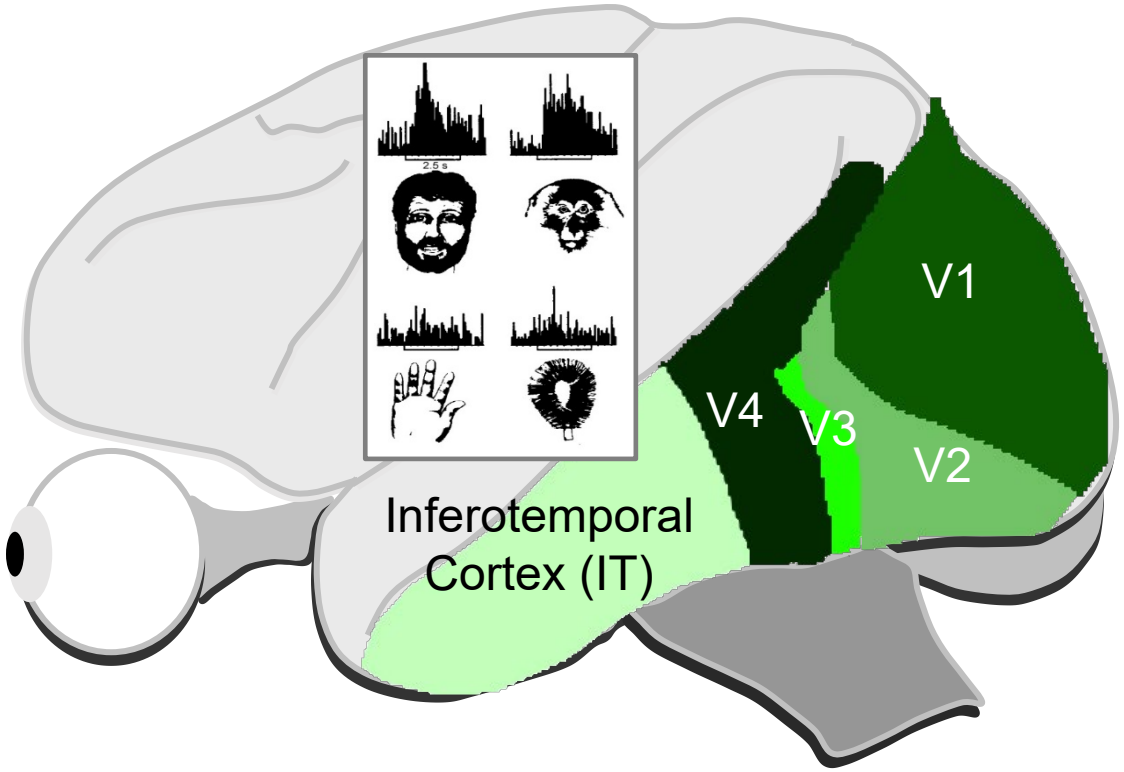
High-level object code



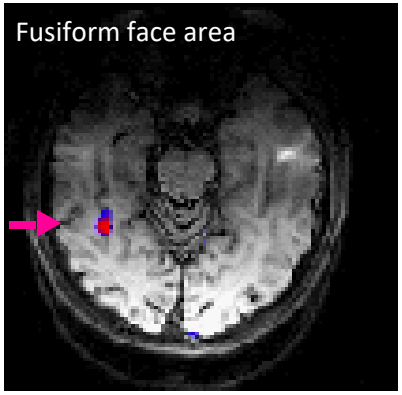
Organization is still unknow

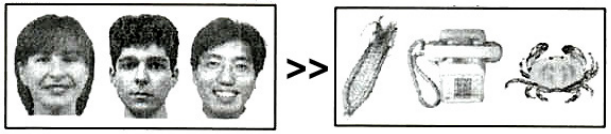
Discovery of face cells

Charles Gross



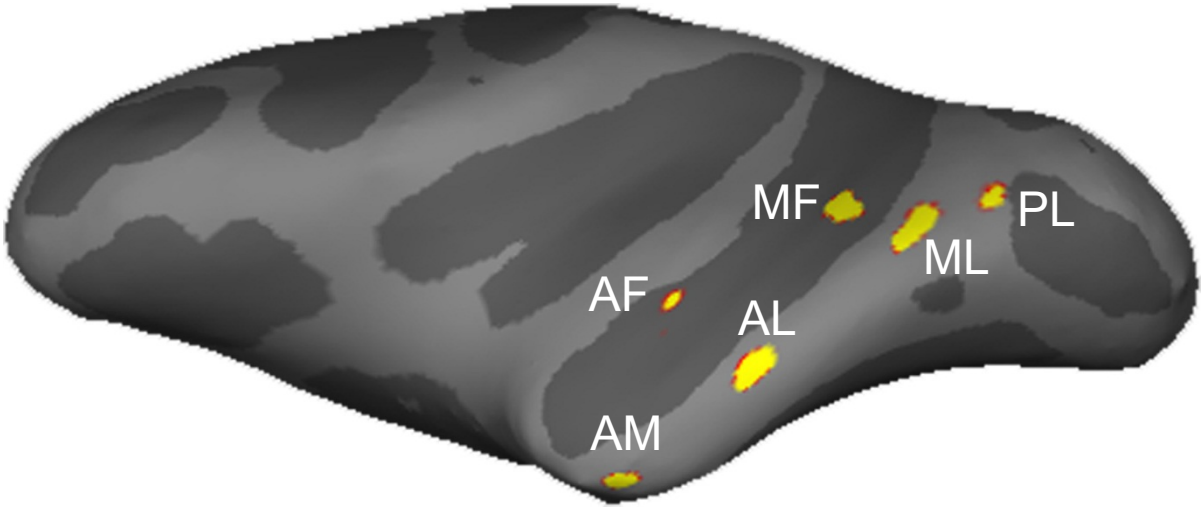
Discovery of a face area

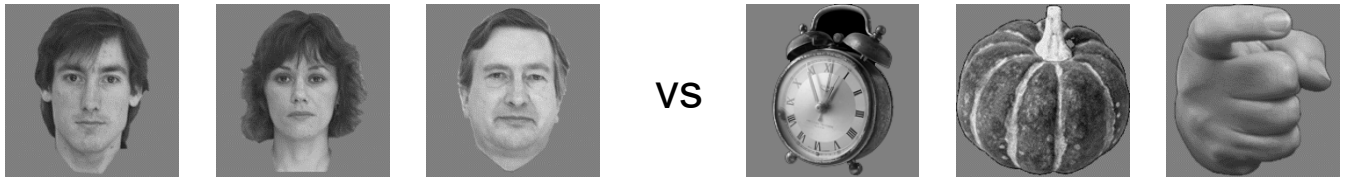




Kanwisher, McDermott, & Chun, J. Neurosci, 1997

Six patches of face-selective cortex in the macaque brain



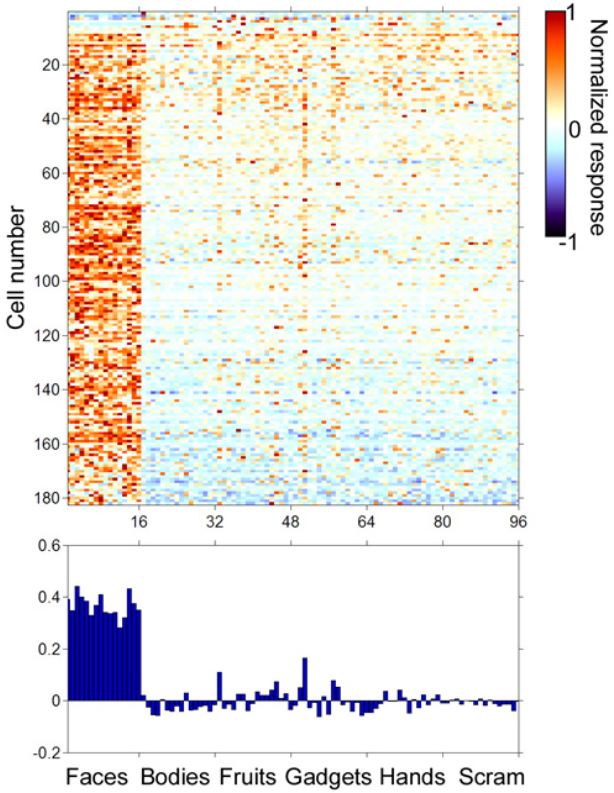


Tsao et al., Nature Neuroscience 2002

Face network

Organization

- Cells within the network show consistent selectivity
- A network of connected patches.
- Increasing view invariance along the network.



Tsao et al., Nature Neuroscience 2002

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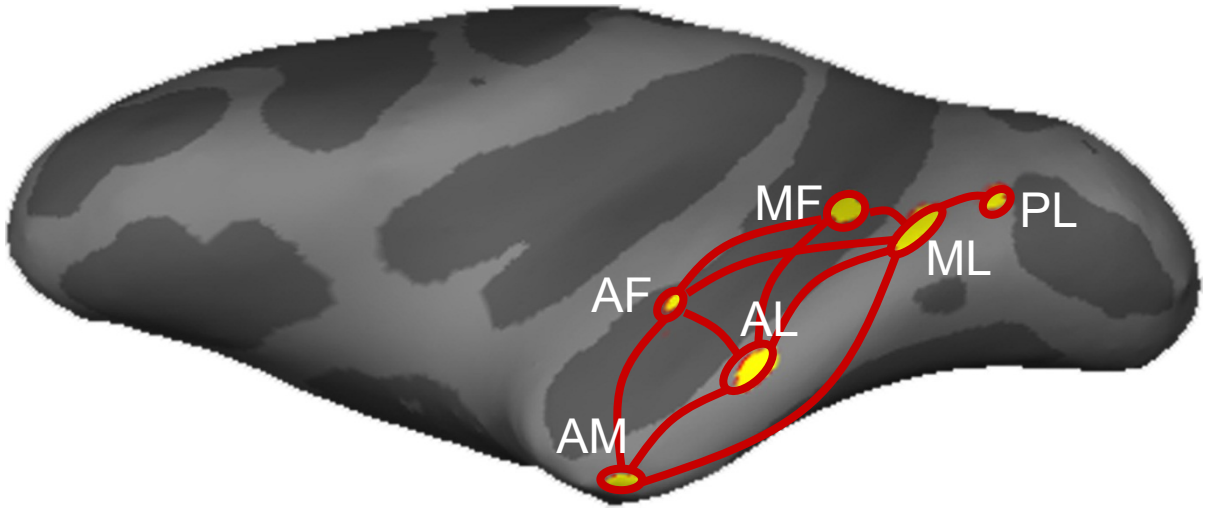

Moeller et al. Science 2008
Grimaldi et al., Neuron, 2016

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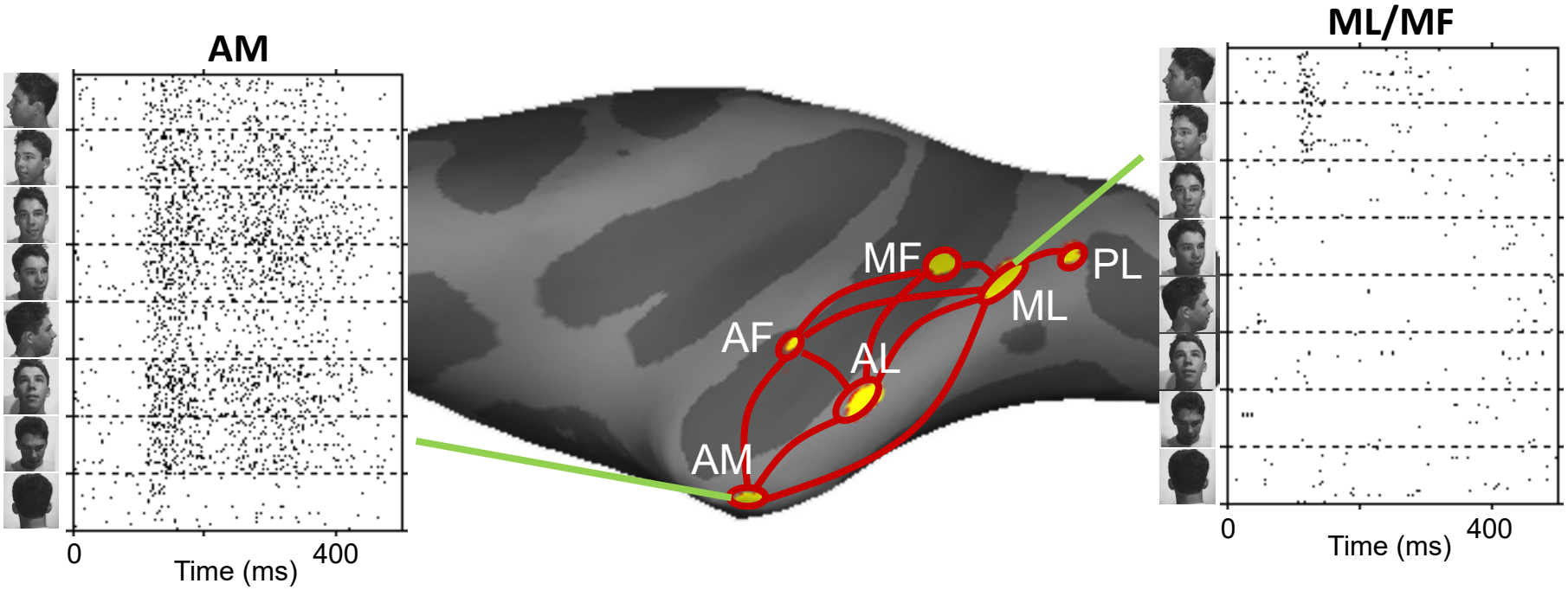


Specialized networks in IT cortex

Bodies

Popivanov & Vogels, J Neurosci 2014

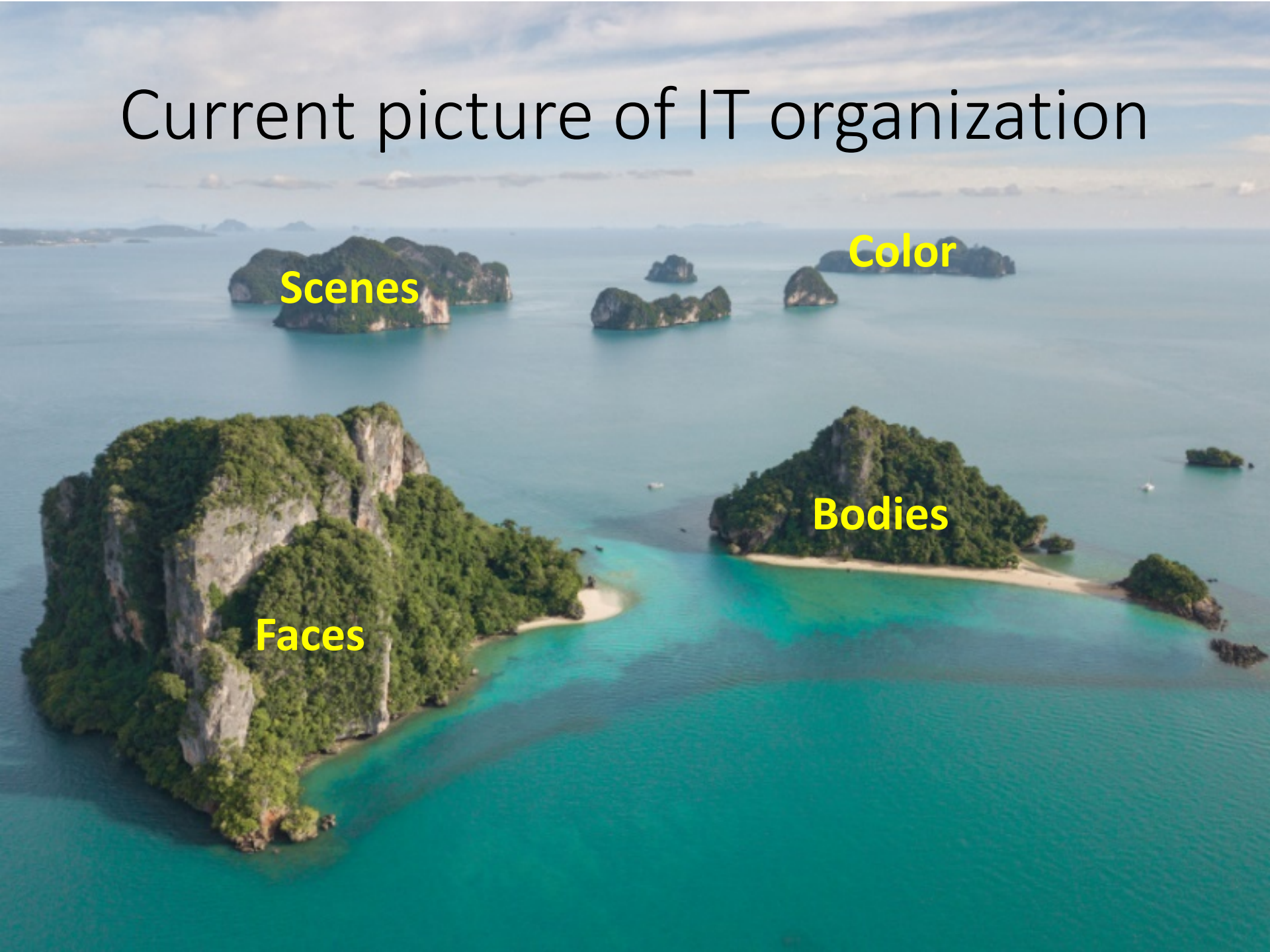
Scenes

Kornblith & Tsao, Neuron 2013

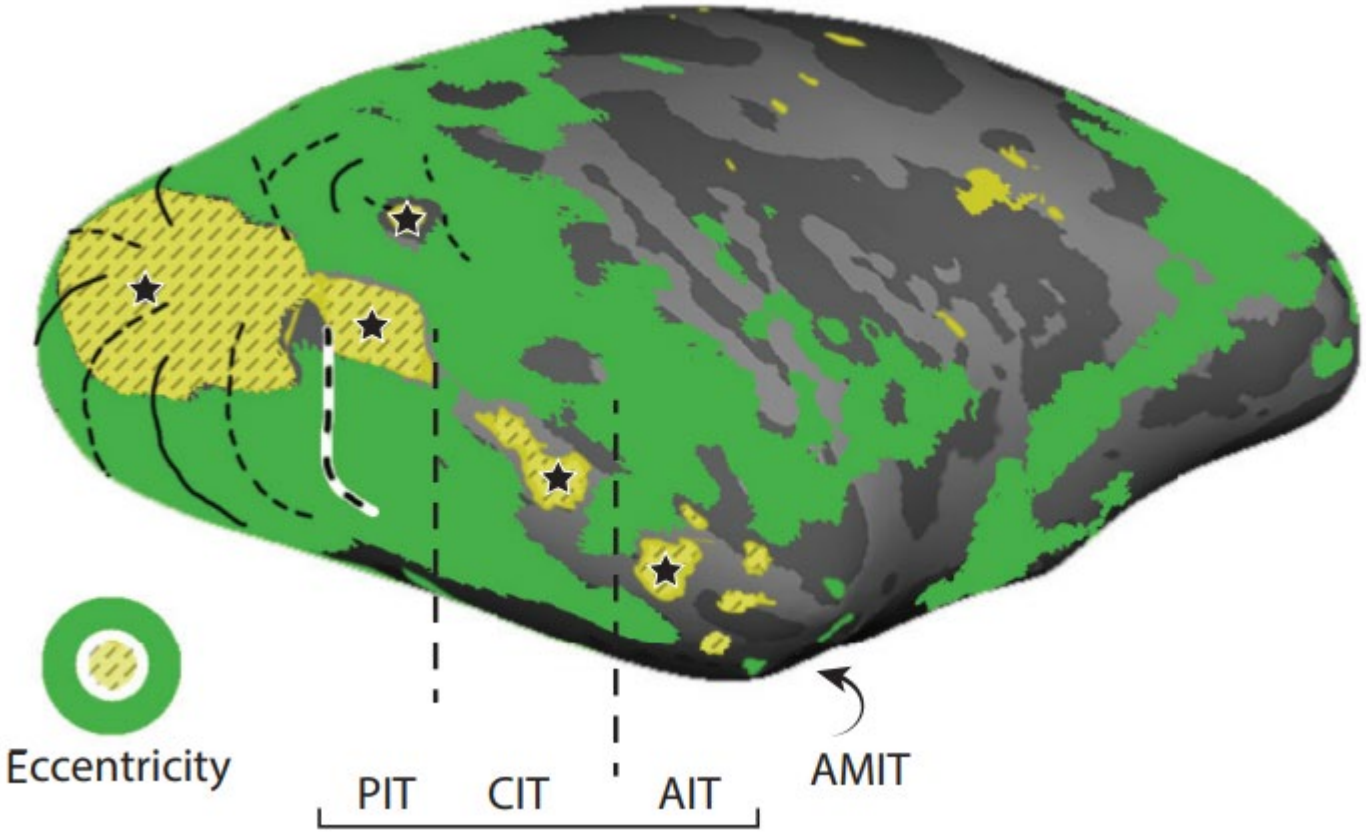
Colored objects

Lafer-Sousa & Conway, NN 2014

Current picture of IT organization

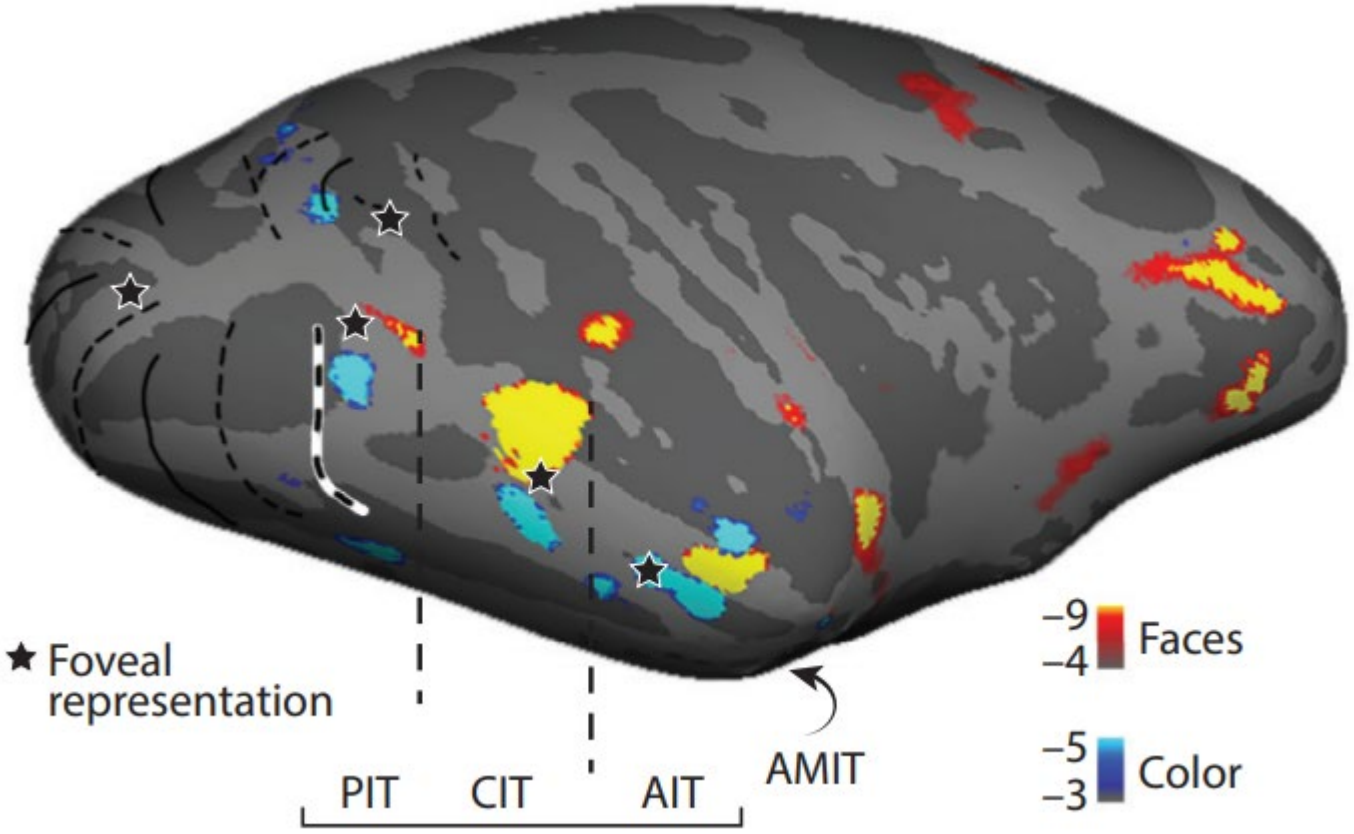


Retintopic hypothesis of IT organization



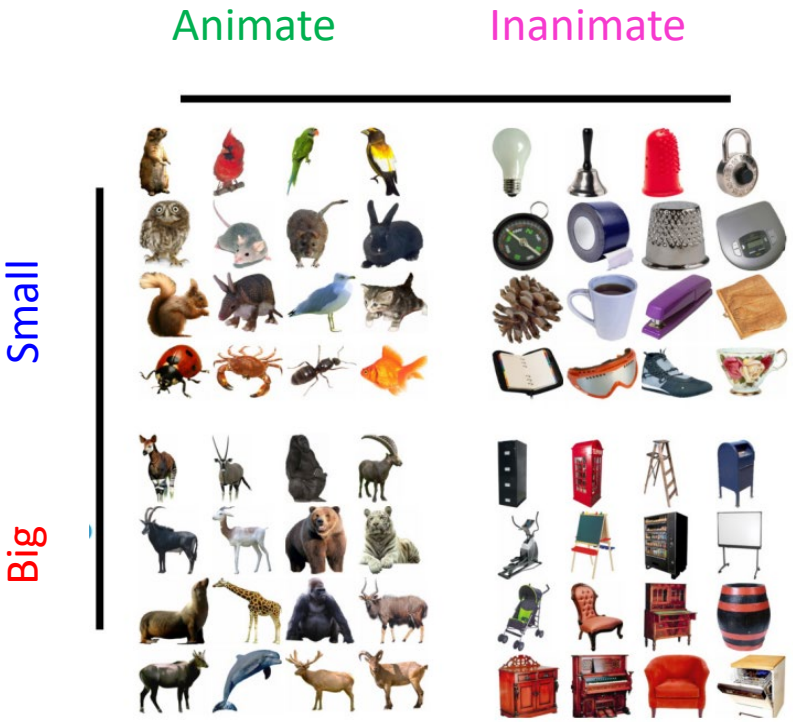
Conway 2018
Levy & Malach 2001

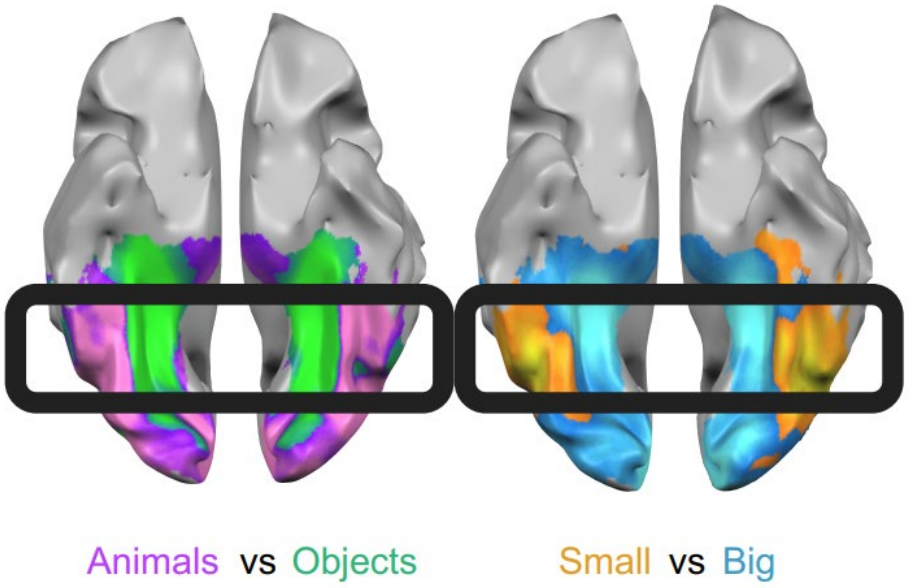
Retintopic hypothesis of IT organization



Conway 2018
Arcaro et al. 2017
Rajimehr et al. 2014

Animacy/size hypothesis of IT organization

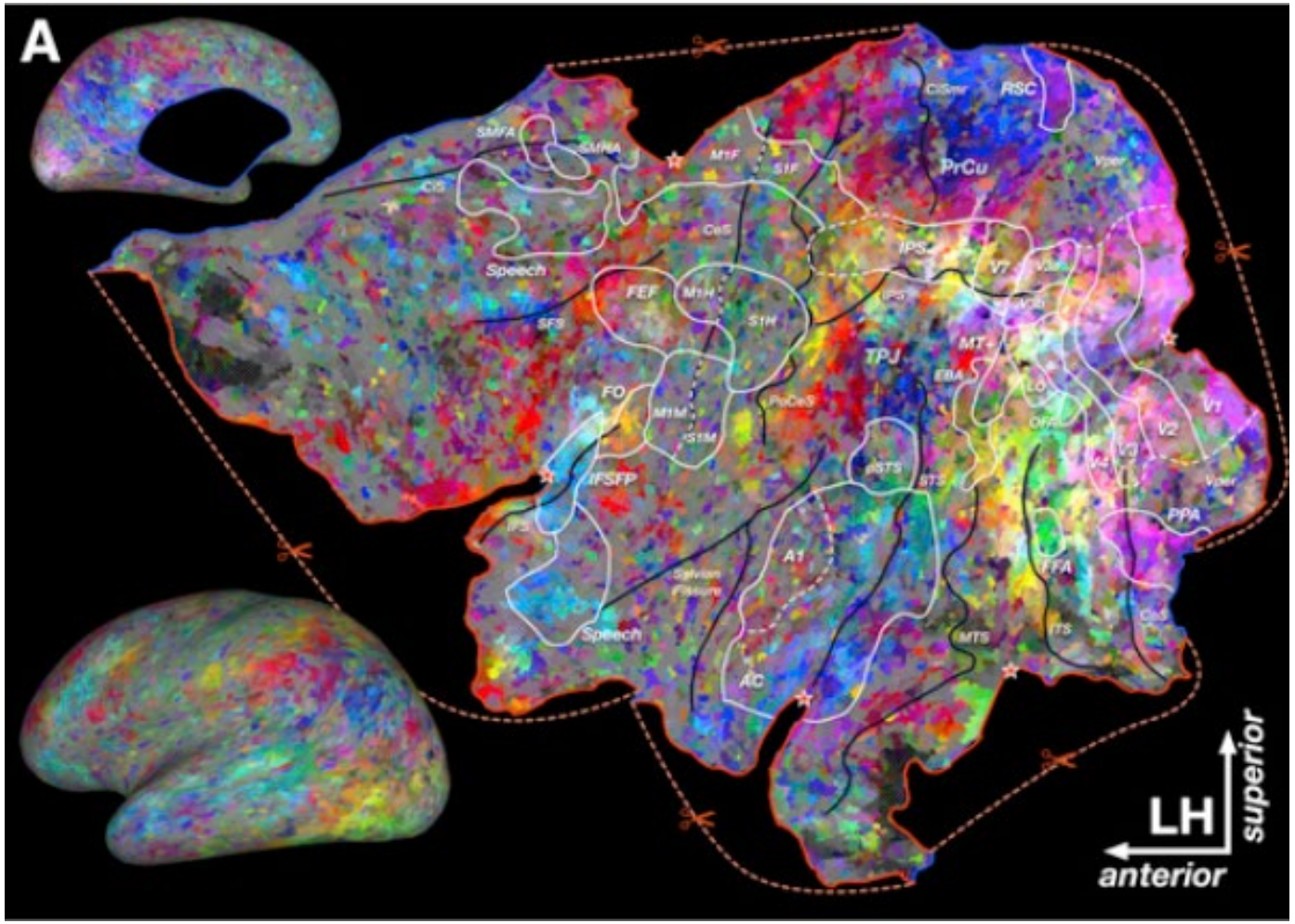




Kriegeskorte et al., 2008

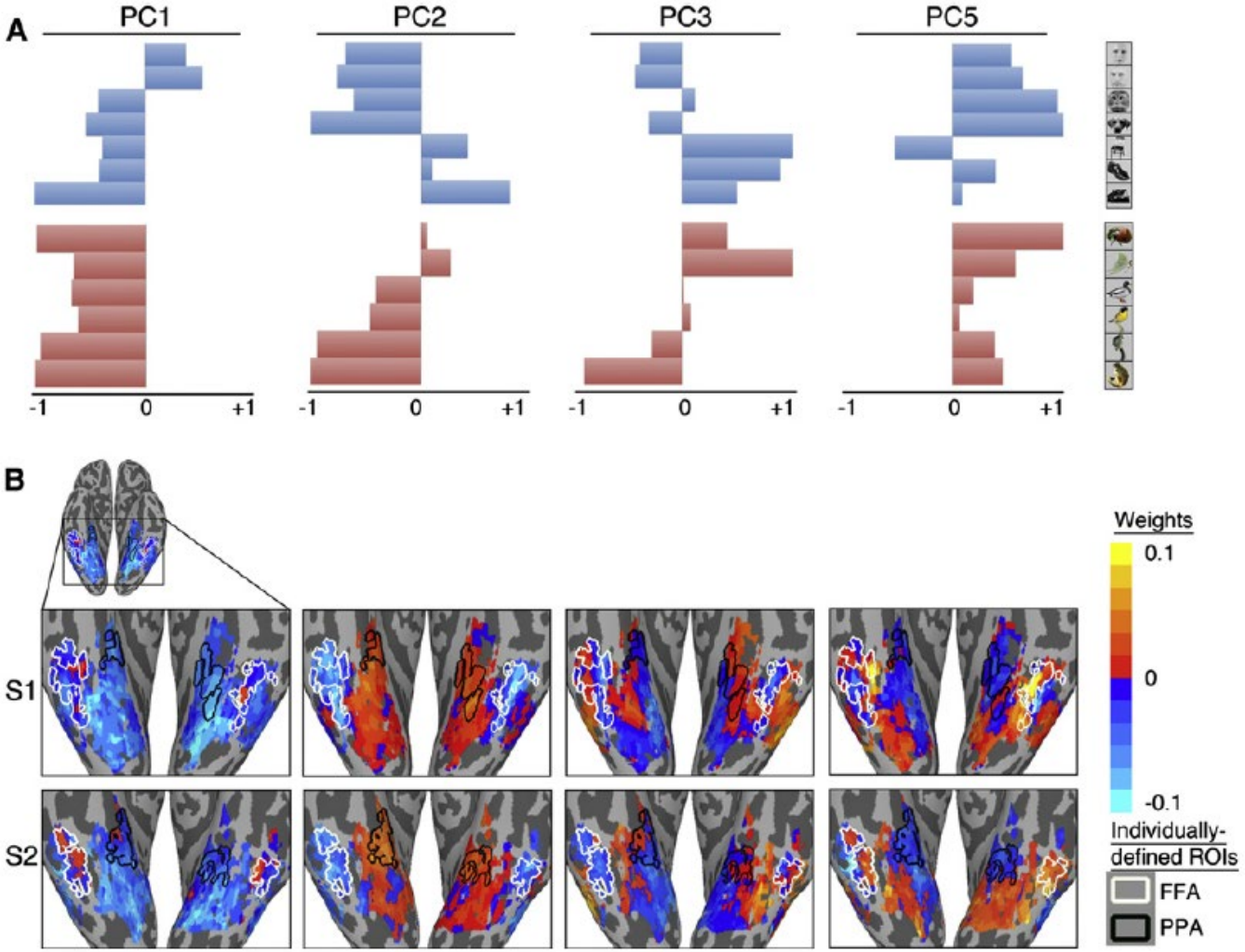
Konkle & Caramazza 2013

High dimension models (1)



Huth et al., 2012

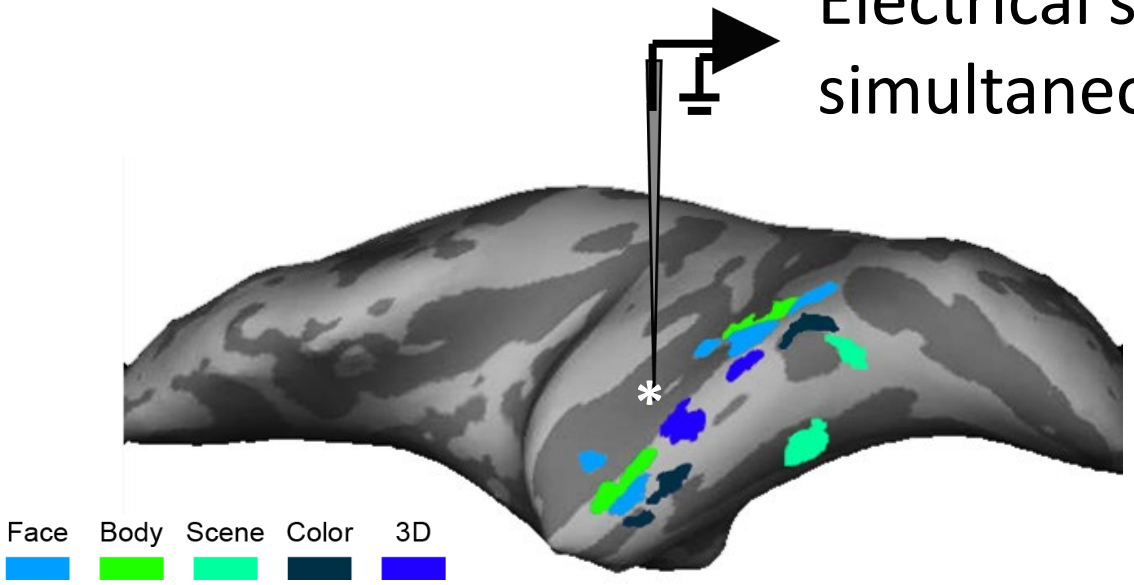
High dimension models (2)



Haxby et al., 2011

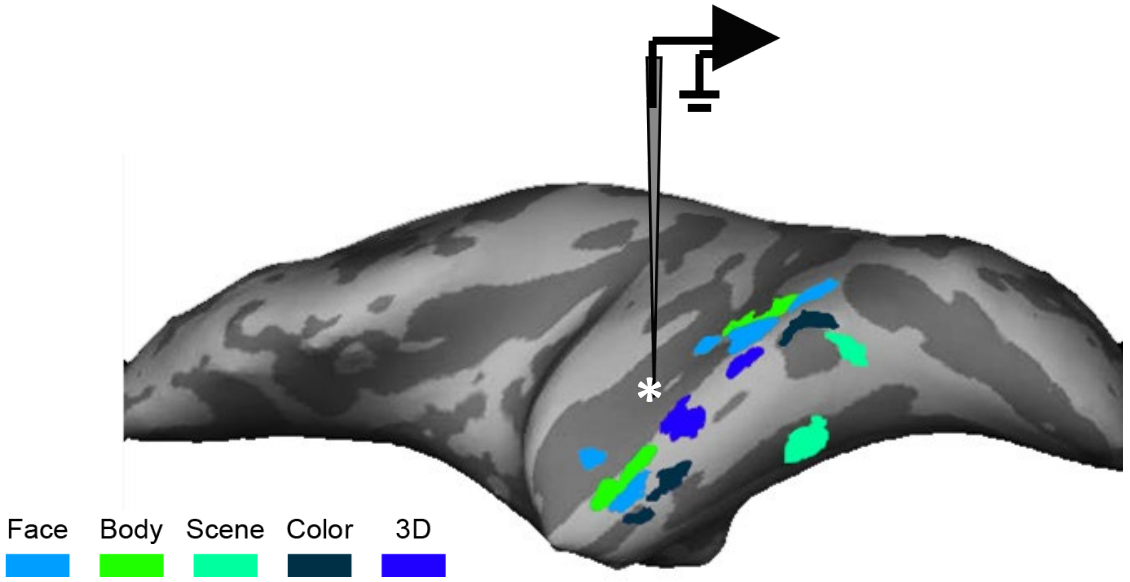
Are there specialized networks beyond those already known?

Electrical stimulation + simultaneous fMRI



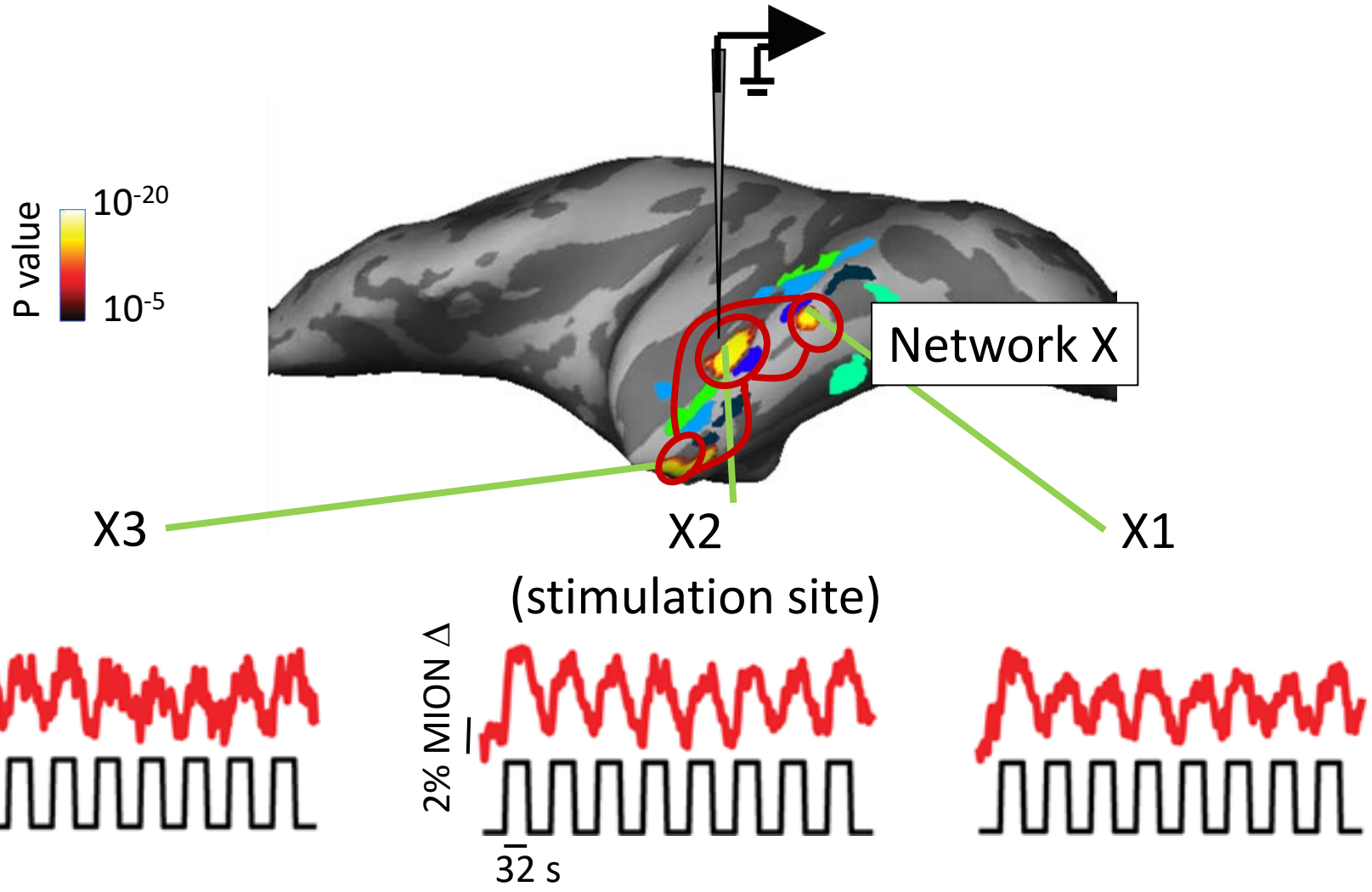
Bao et al., 2020

Electrical microstimulation + fMRI reveals a new network in IT cortex



Bao et al., 2020

Electrical microstimulation + fMRI reveals a new network in IT cortex



Stimulus set

Animals

Vehicles

Faces

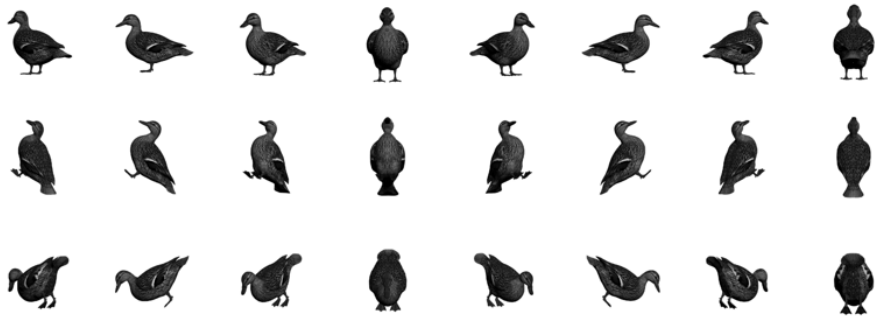
Vegfruits

Houses

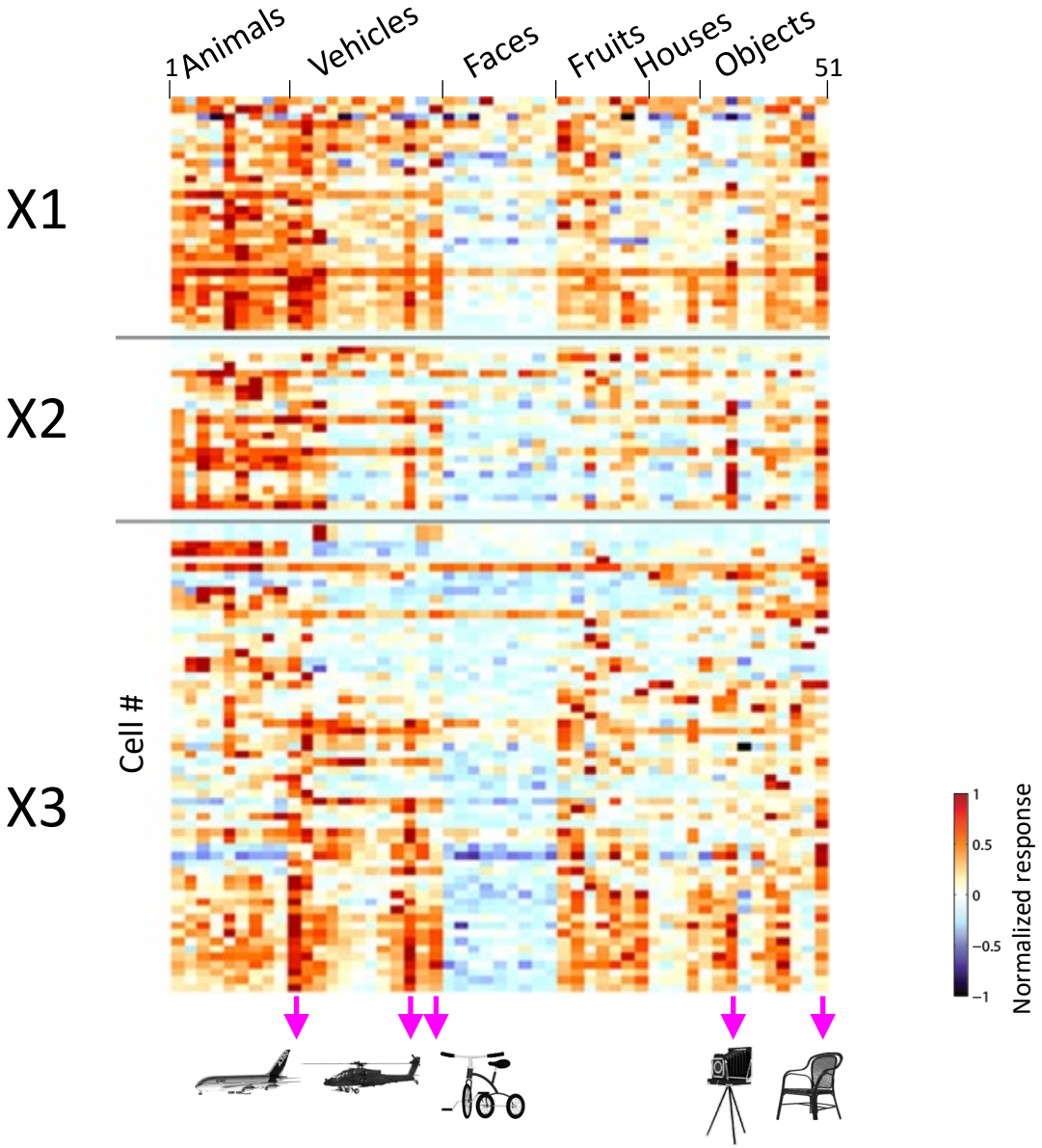
Manmade objects

×

24 views



Cells with similar selectivity are clustered



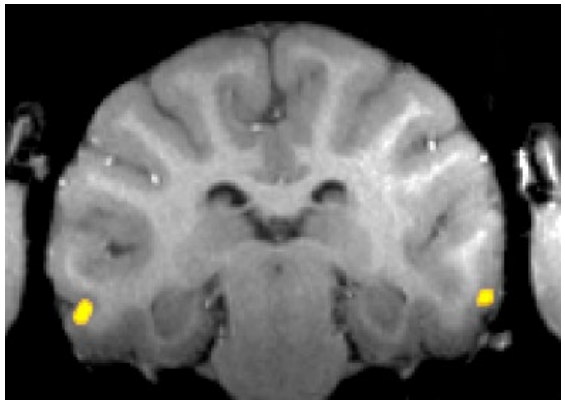
Does network X exist across animals?

Most preferred

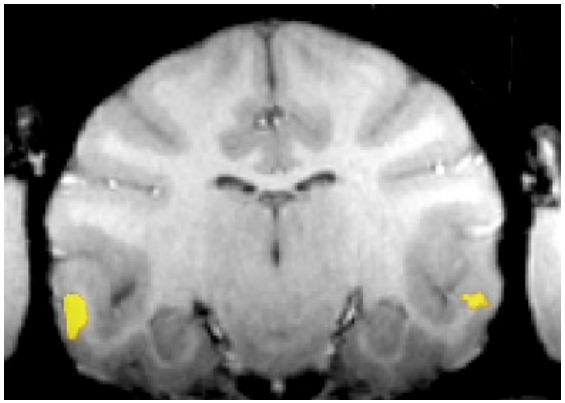
Least preferred

Monkey 1

X1



X2



X3

10

3

fMRI localizer

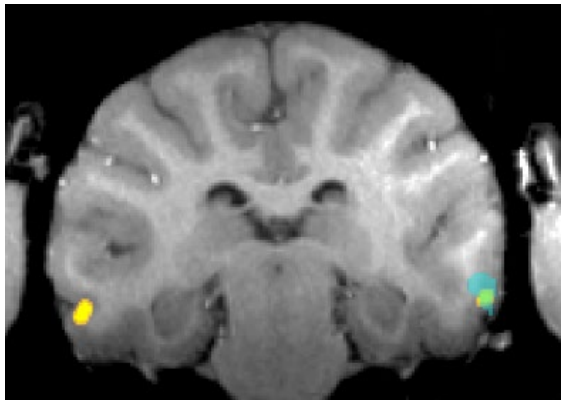
Does network X exist across animals?

Most preferred

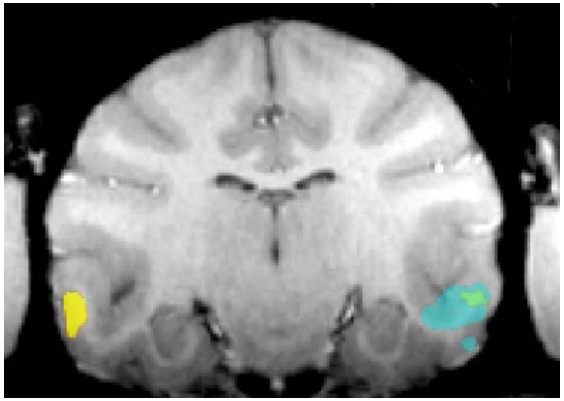
Least preferred

Monkey 1

X1



X2



X3

Microsimulation

fMRI localizer

10

3

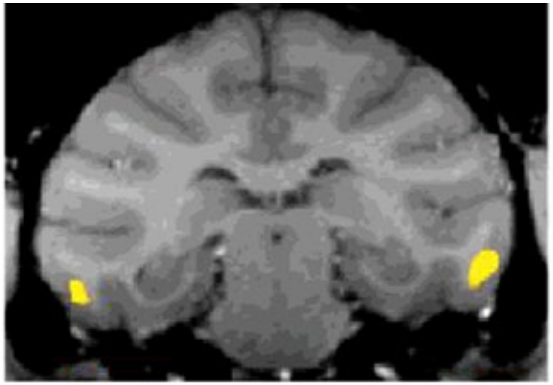
Does network X exist across animals?

Most preferred

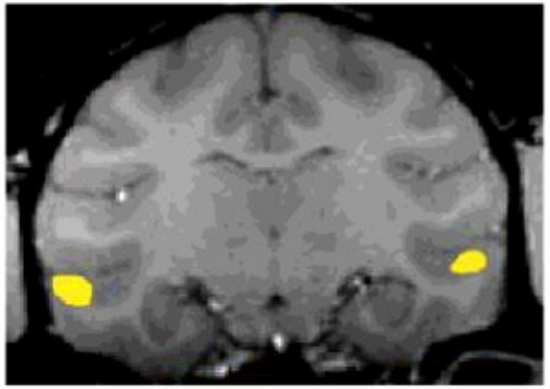
Least preferred

Monkey 2

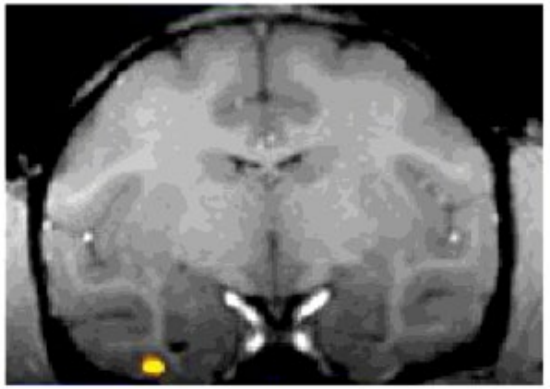
X1

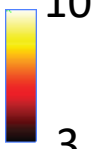


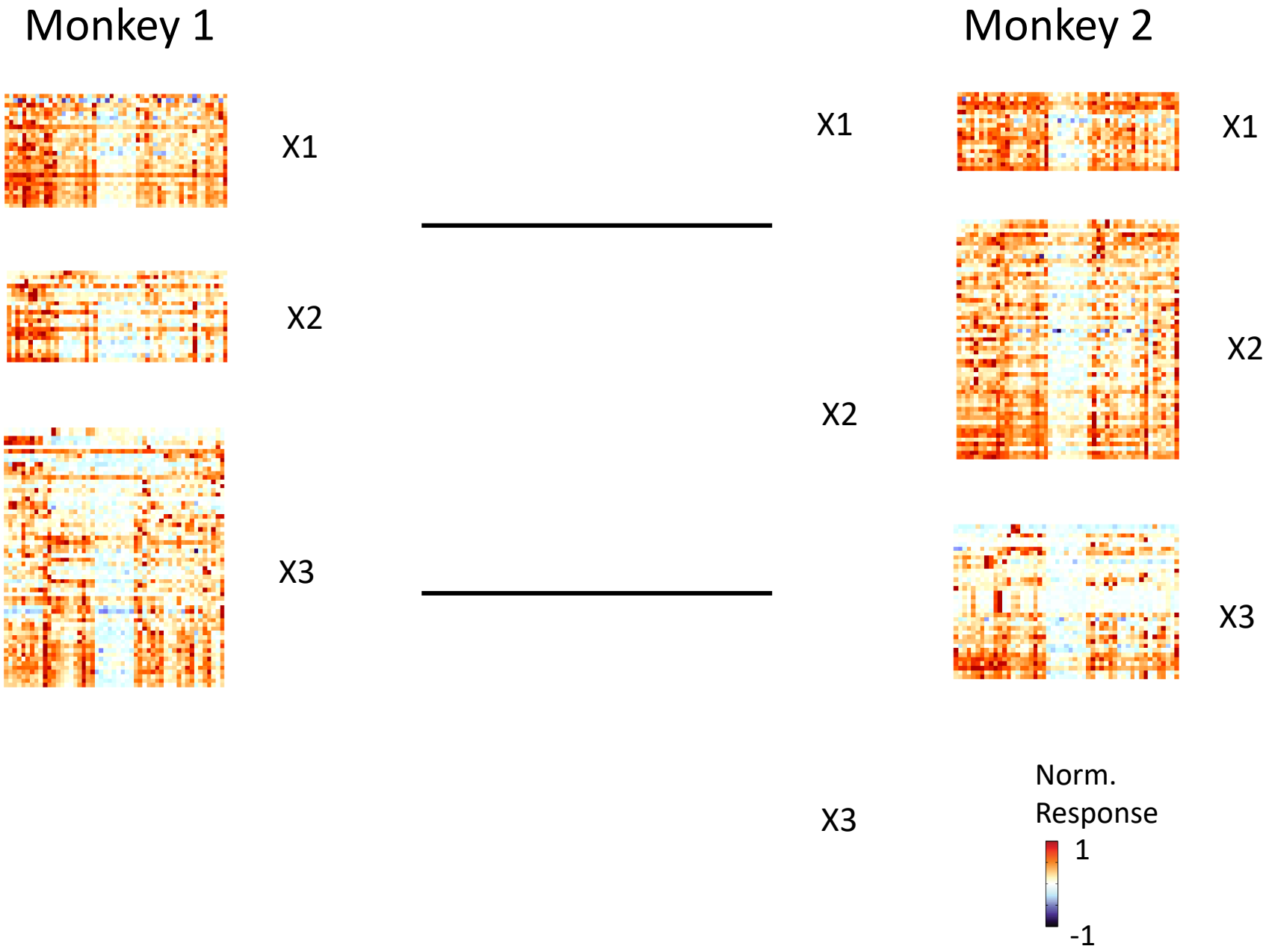
X2



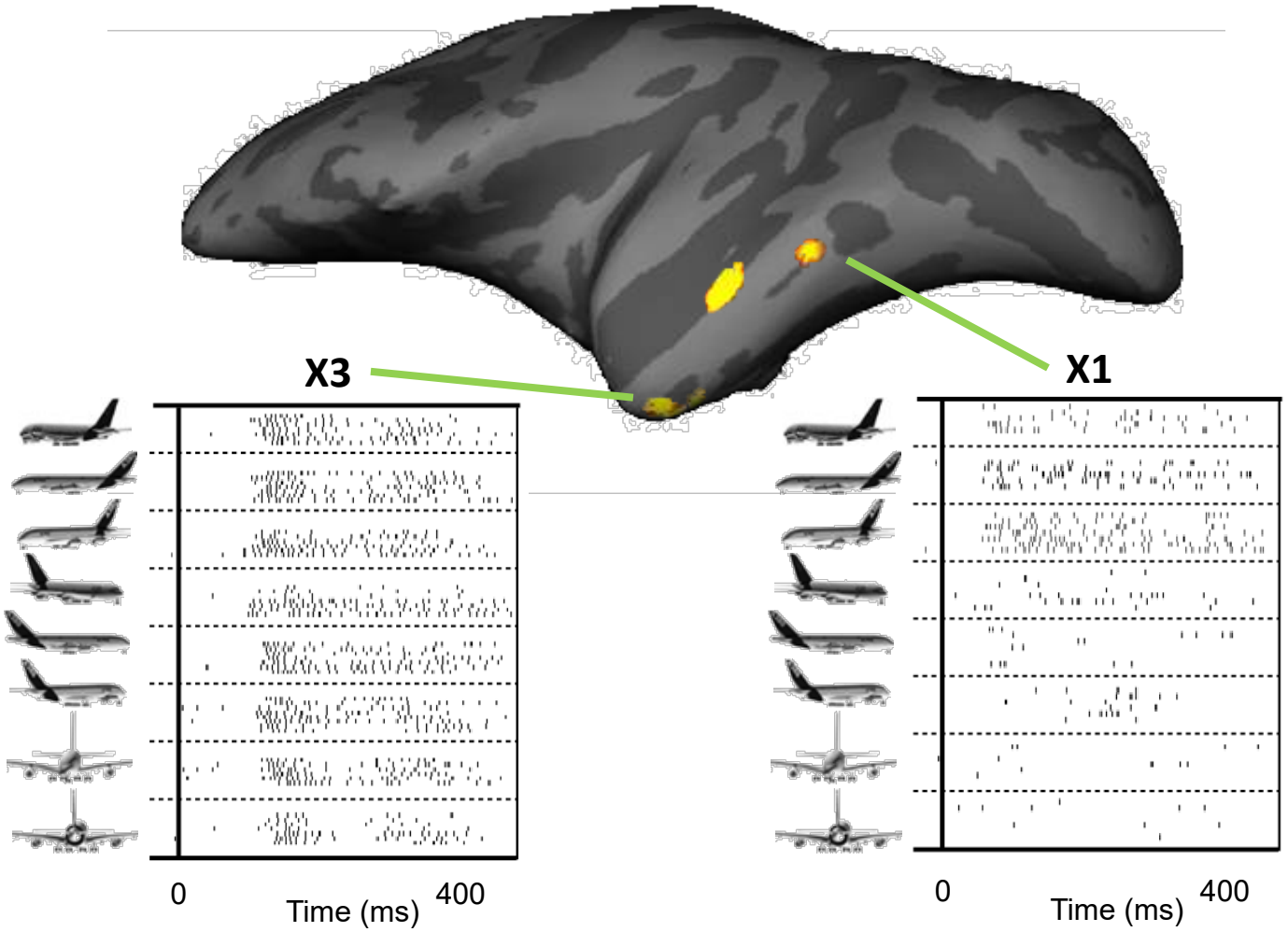
X3

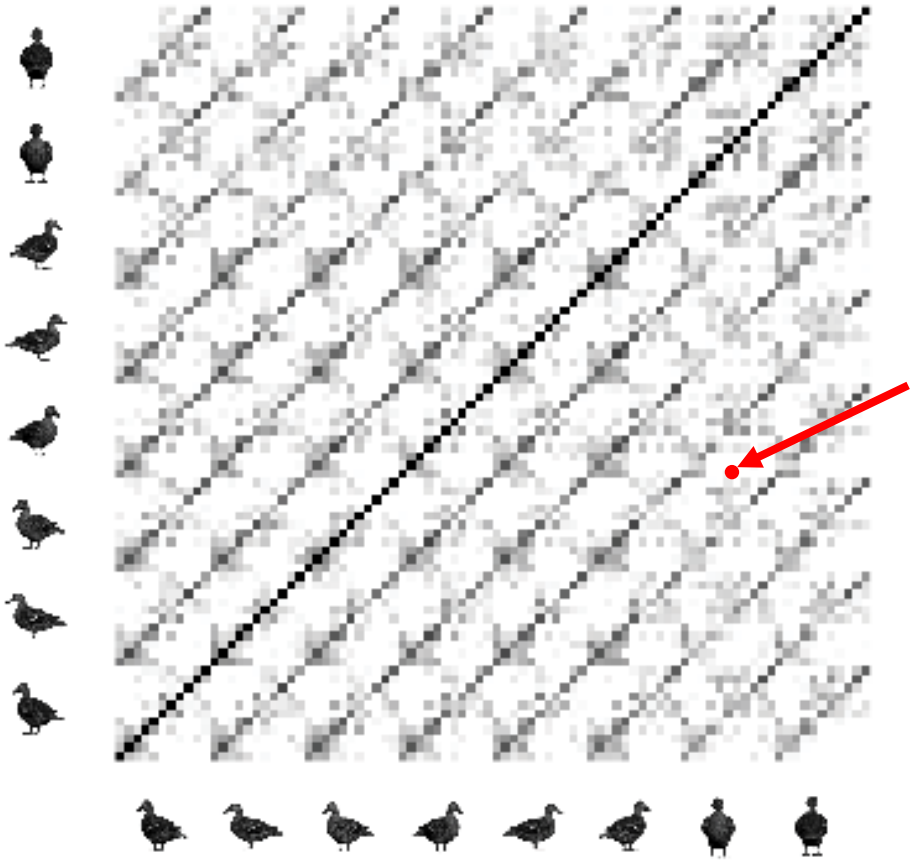


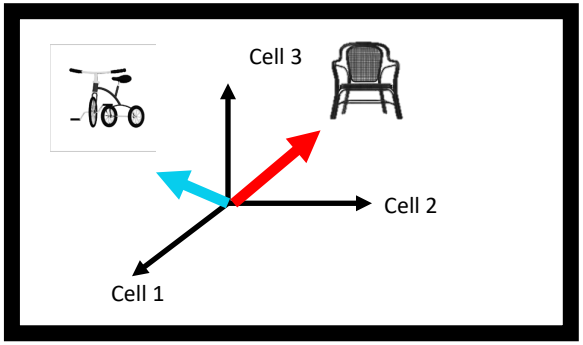


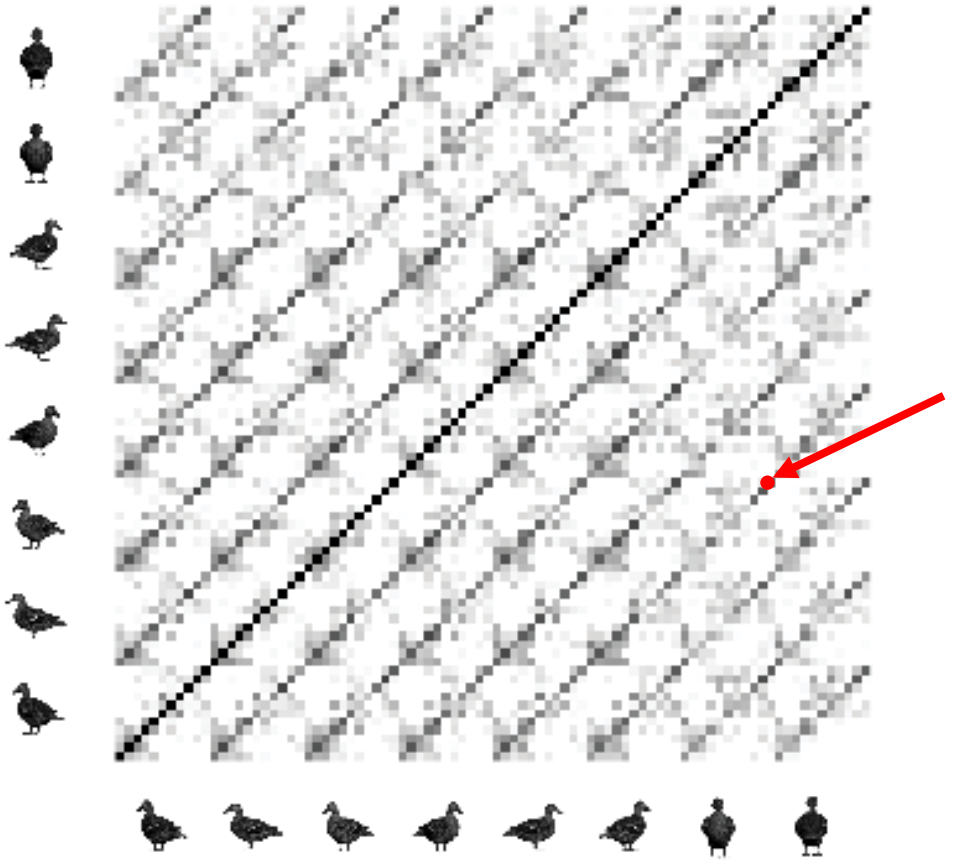

Monkey 1
Monkey 2
X1
X2
X3
X1
X2
X3
X1
X2
X3
Norm.
Response
1
-1

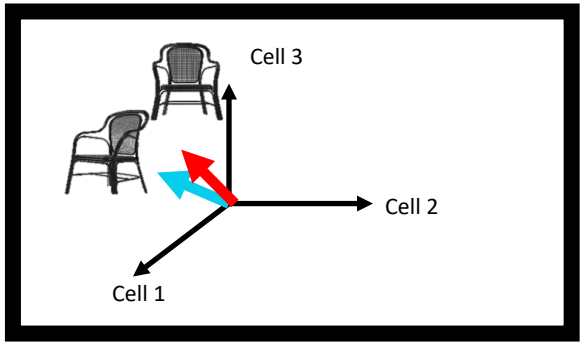
Increasing view invariance along Network X



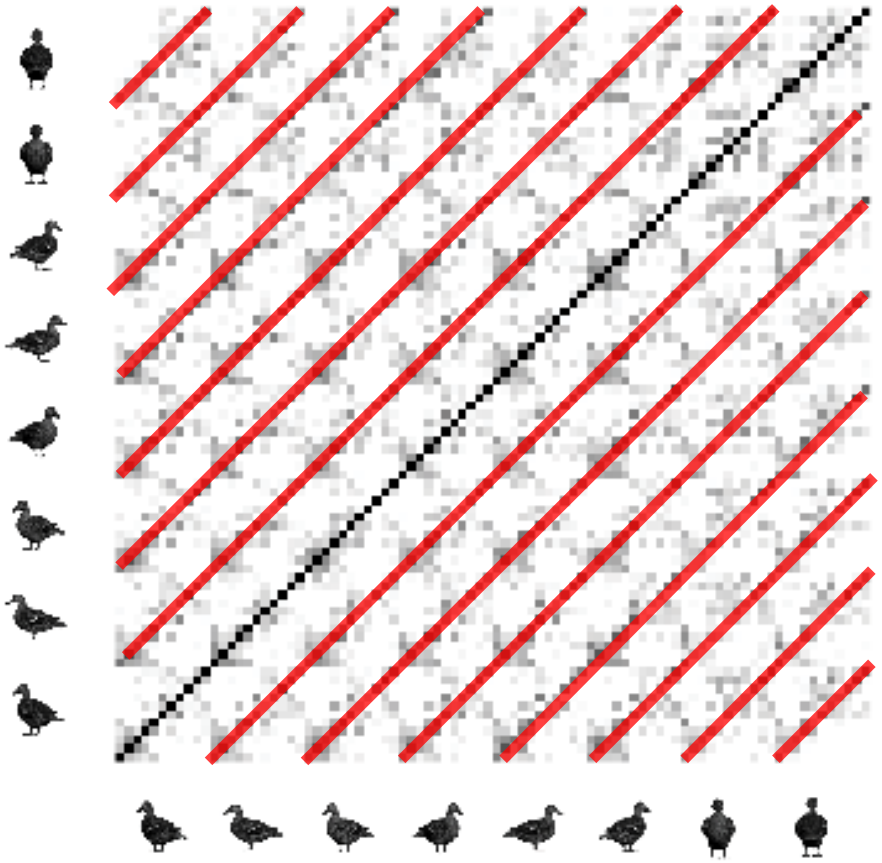



Cell 3
Cell 2
Cell 1



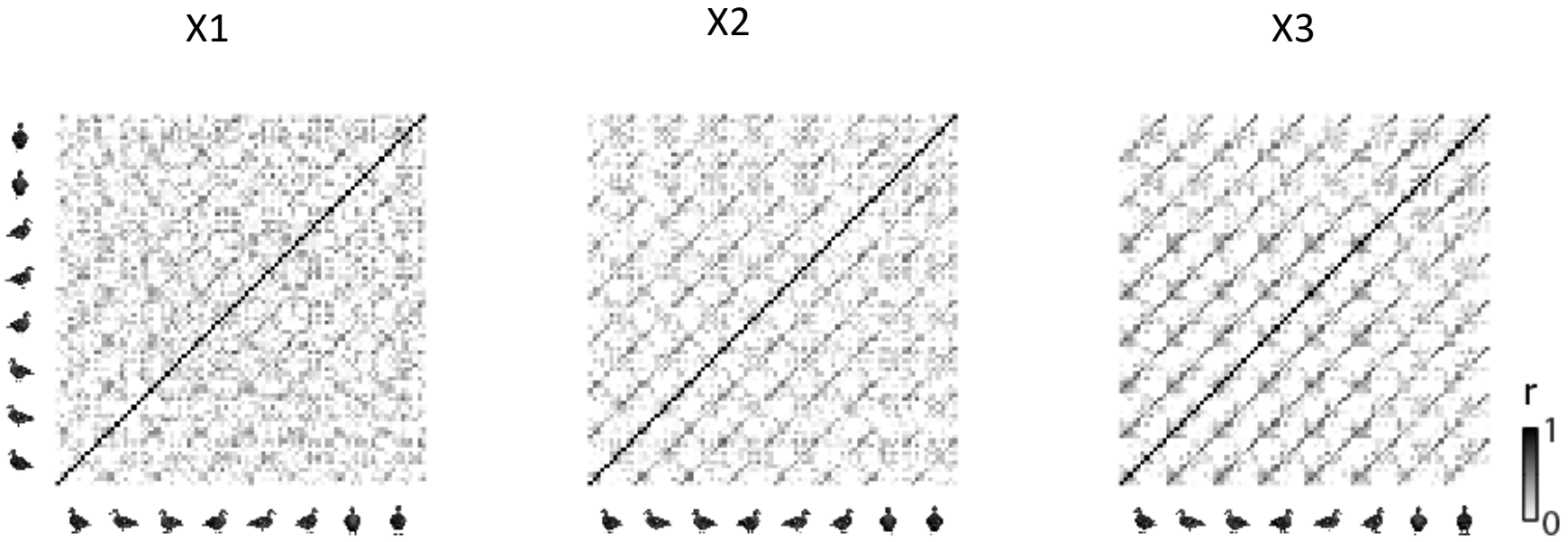


Make two gray bars



The corr. between same object
Across different views

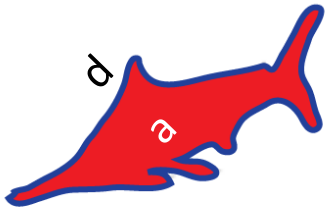
Representations between patches differ in their view invariance



What is this network coding?

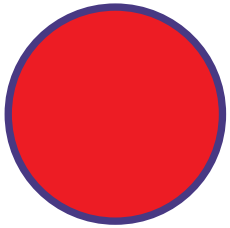
Most Preferred

Least Preferred

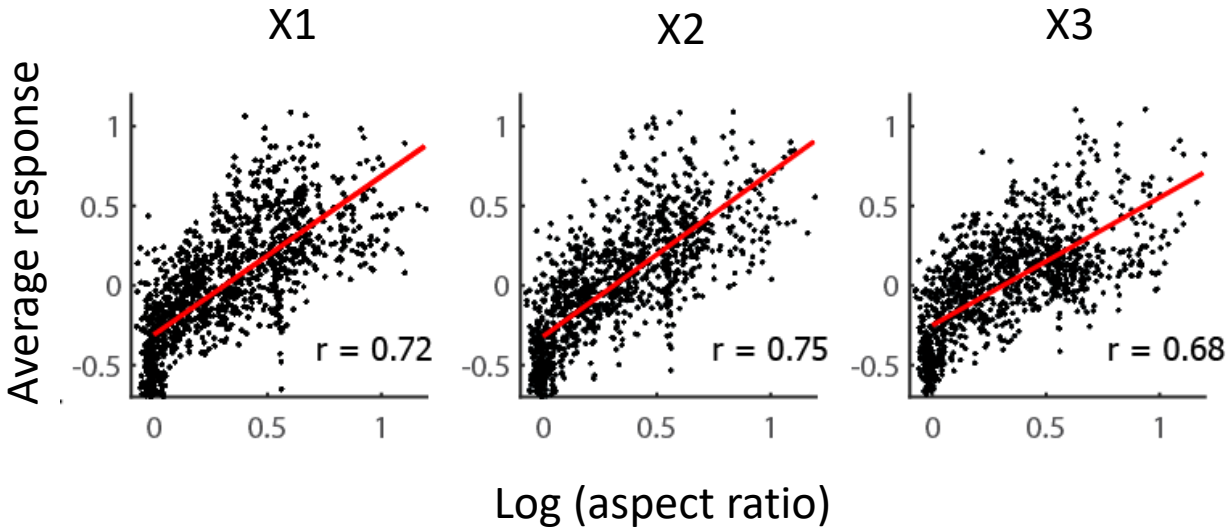


$$Aspect\ ratio = \frac{d^2}{4\pi a}$$

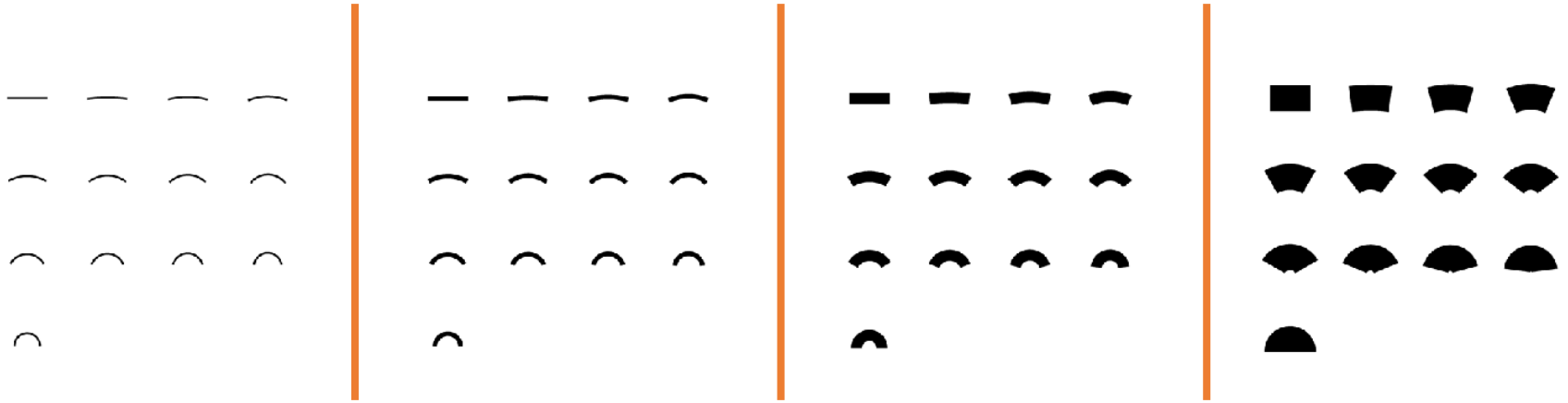
$$Aspect\ ratio = 5.03$$



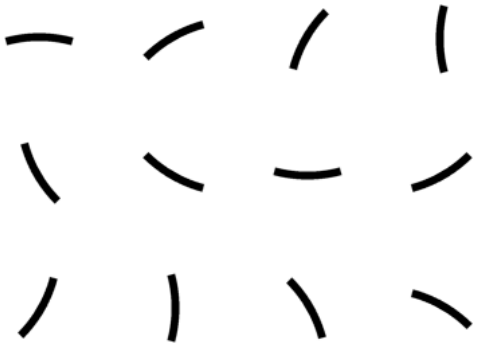
$$Aspect\ ratio = 1$$



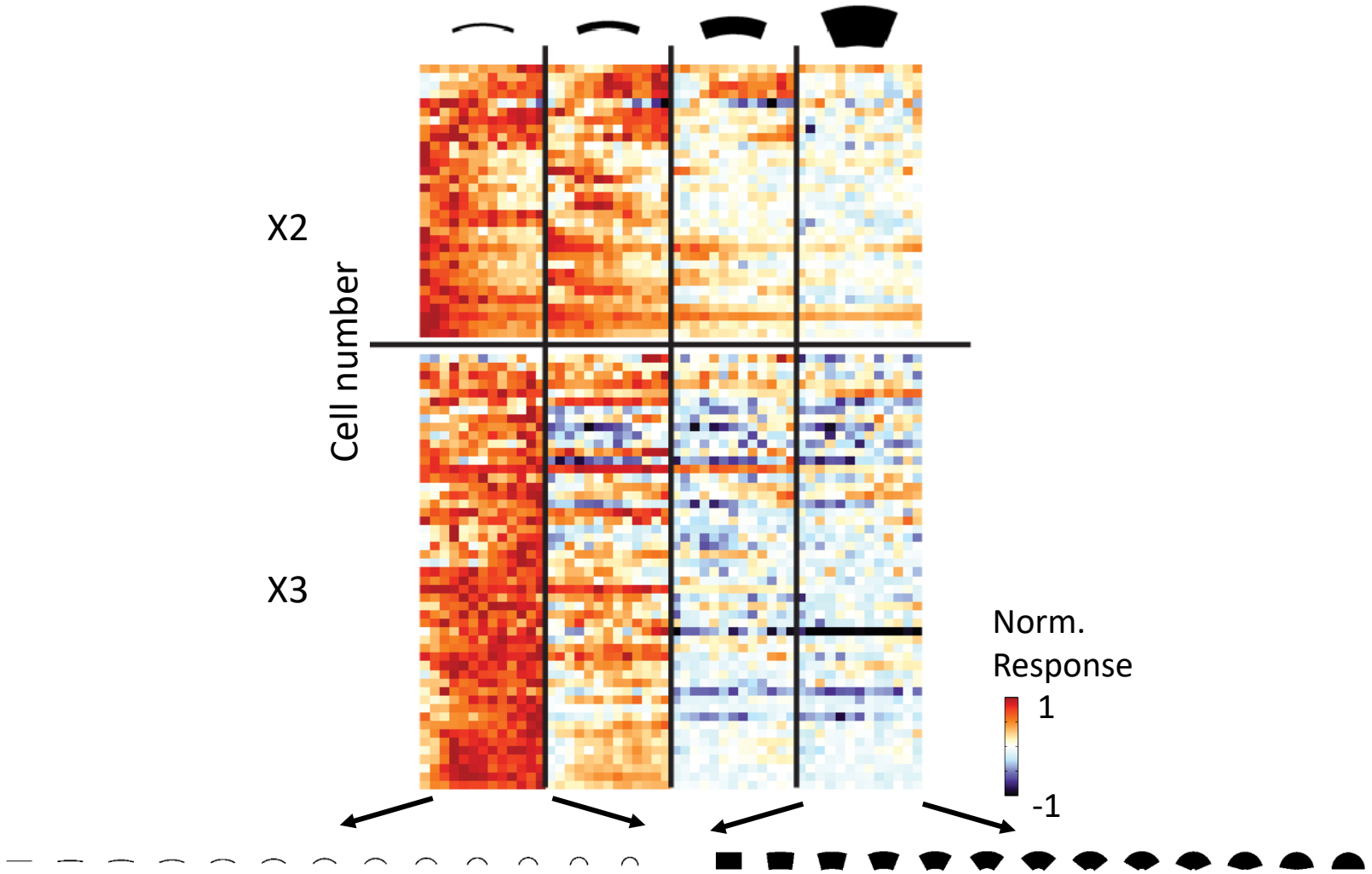
A simplified stimulus set



x



Cells are strongly tuned to aspect ratio

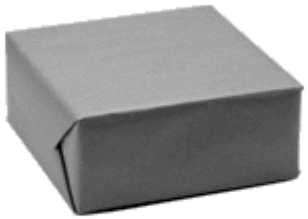


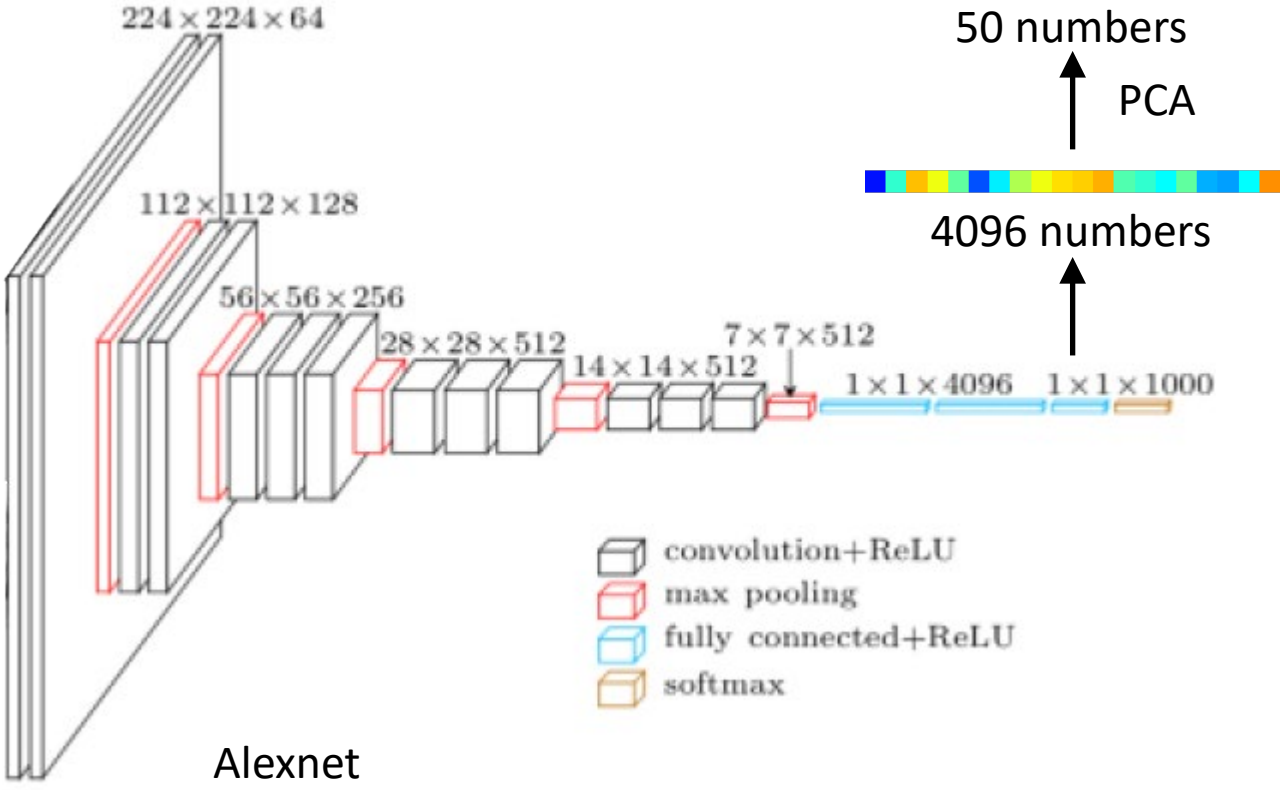
Is there a systematic way to understand what network X is coding?

How can we parametrize arbitrary objects?

→ Small set of numbers

Generating a parametric object space

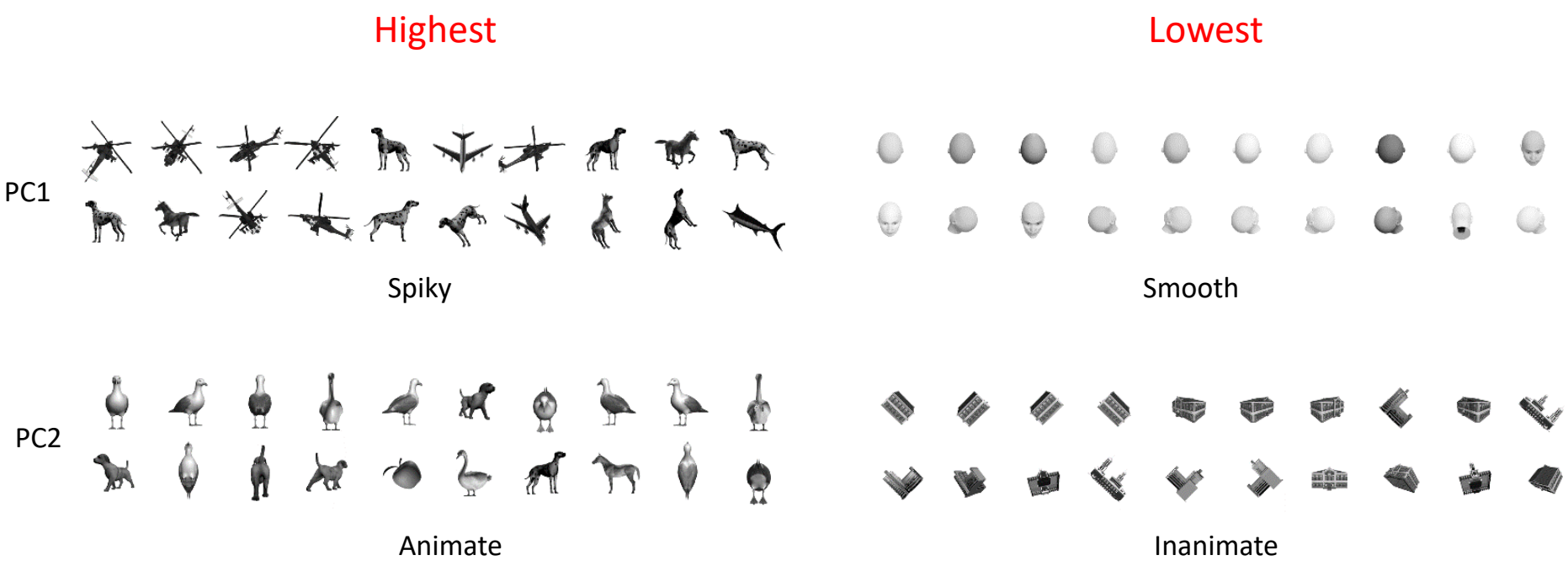




Alexnet

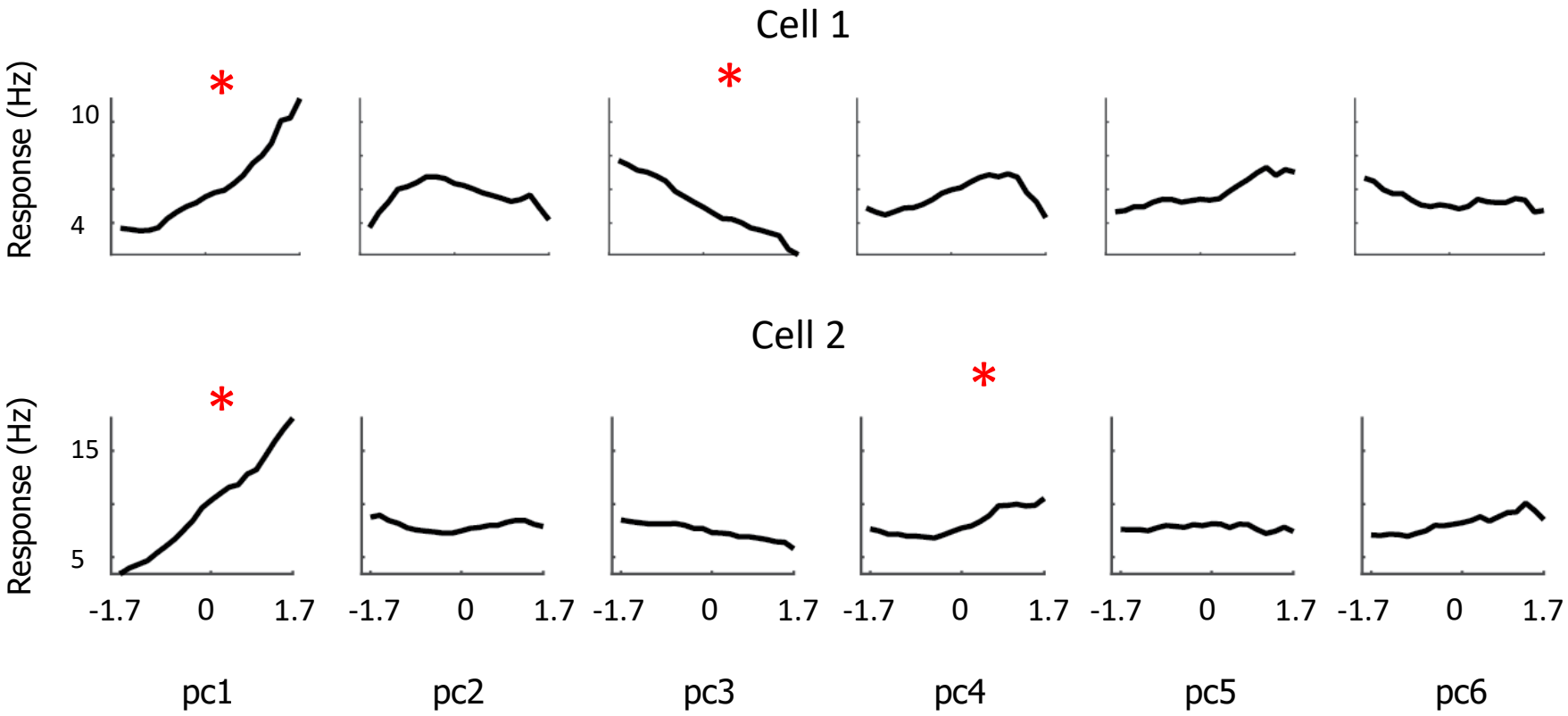
Yamins & DiCarlo, PNAS 2014

Object axes: Principal components of the penultimate layer of Alexnet

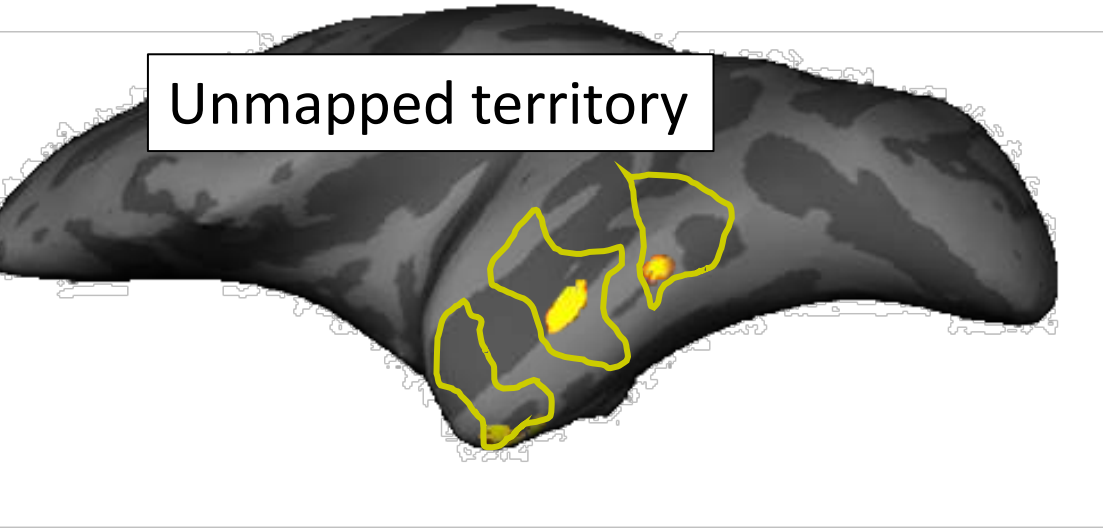


AlexNet (8 layers): Layer fc6

Ramp-shaped tuning to subsets of features for two example cells



Spatial organization of IT cortex



- Network of connected patches
- Consistent selectivity
- Increasing view invariance
- Single cells use axis code

Is there a general principle governing how networks are arranged in IT cortex?

A remarkable coincidence

Network X

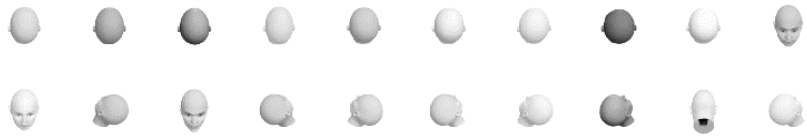
Most Preferred

Least Preferred

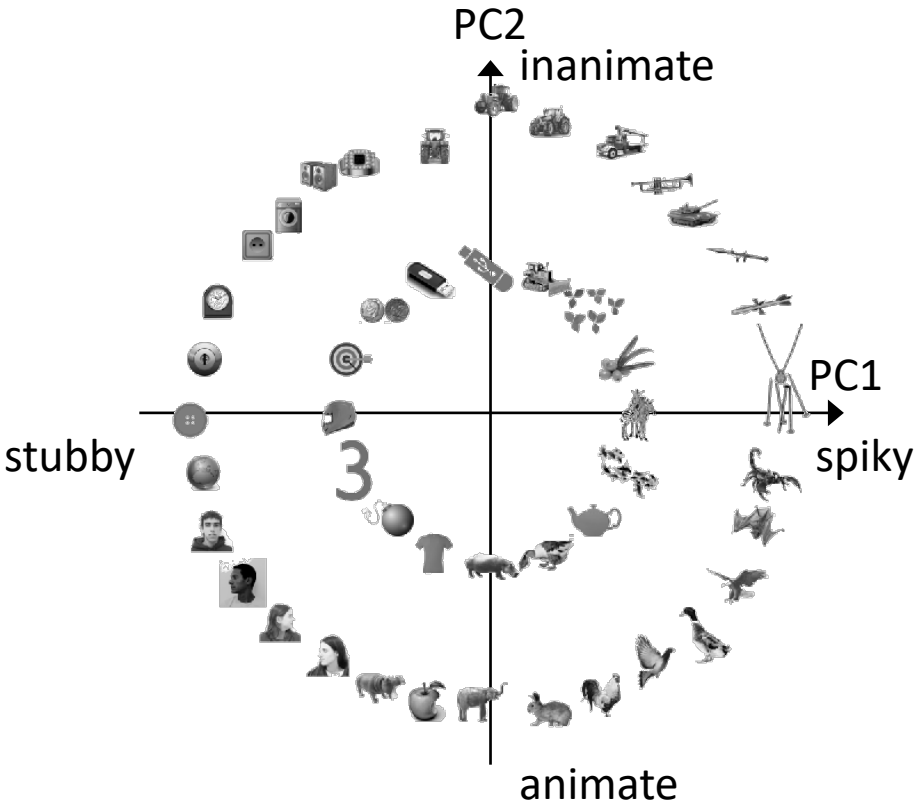
AlexNet (fc6)

Highest

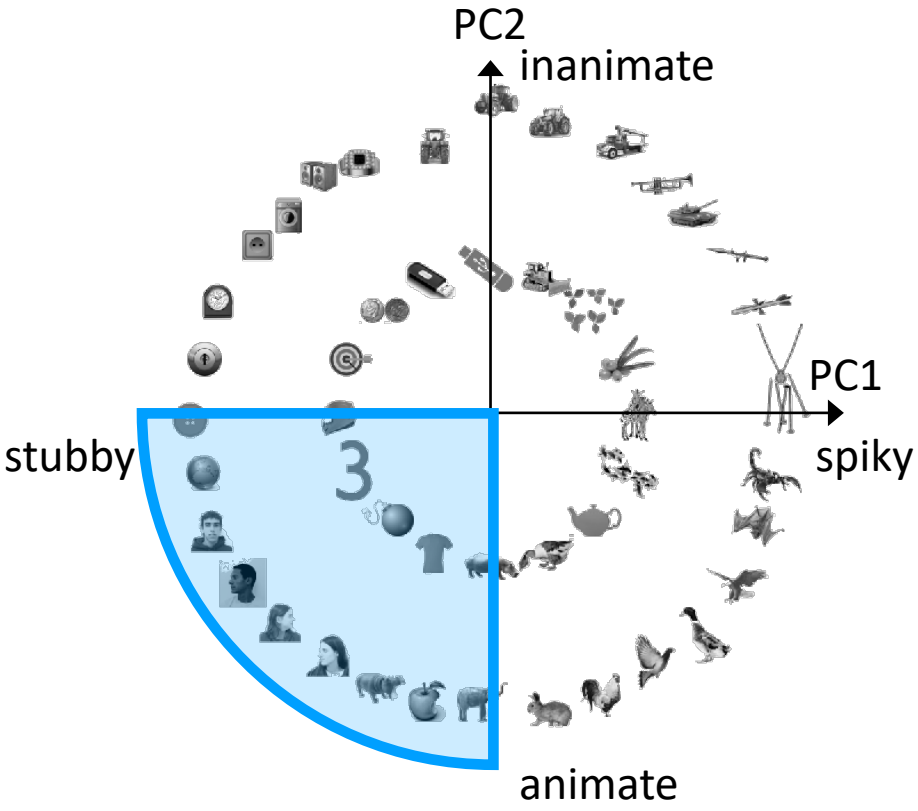
Lowest



Spatial organization of IT cortex

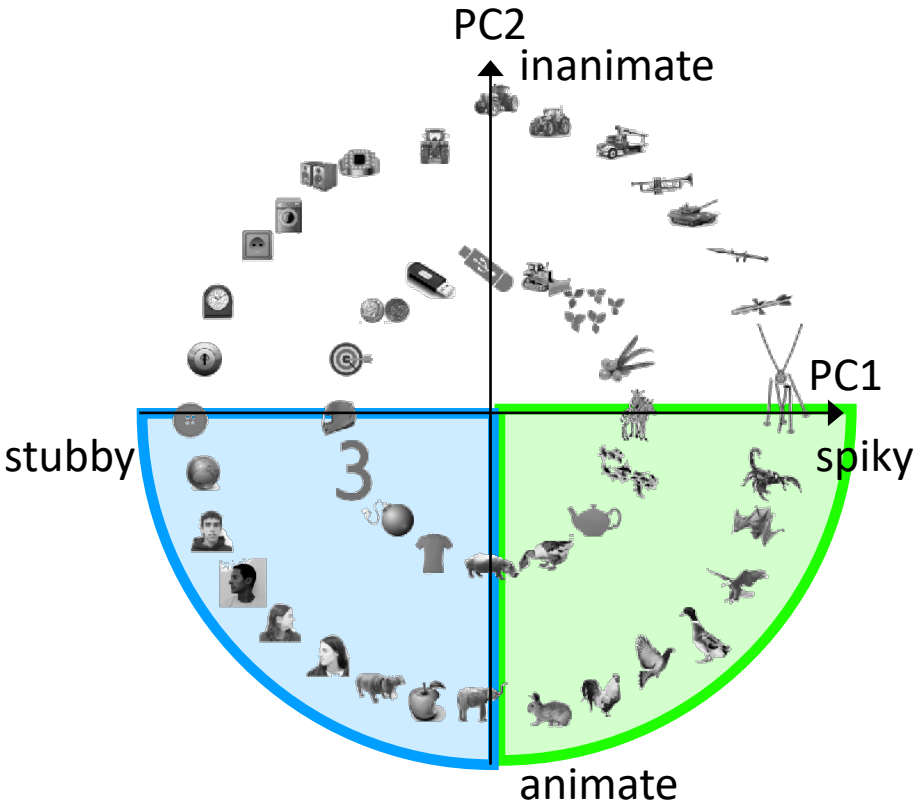


Spatial organization of IT cortex



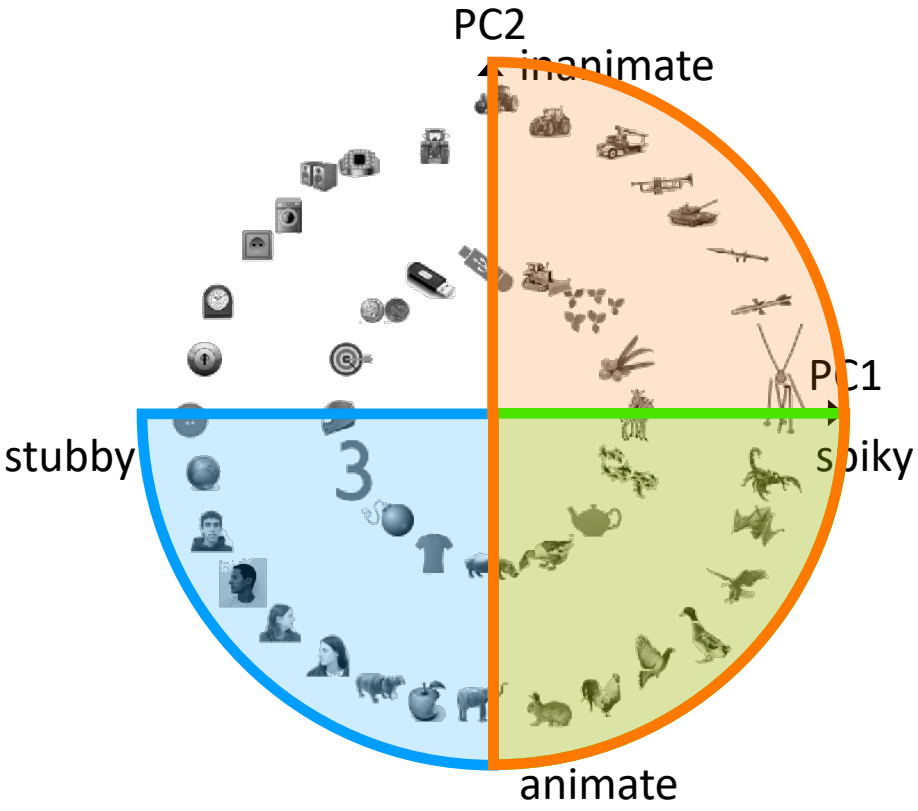
Face

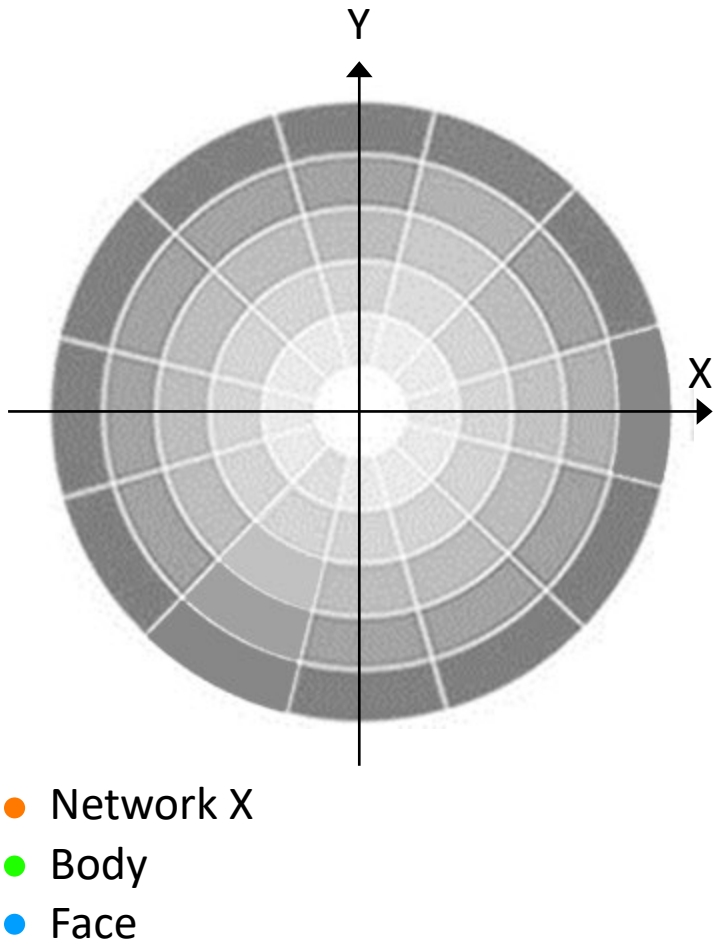
Spatial organization of IT cortex



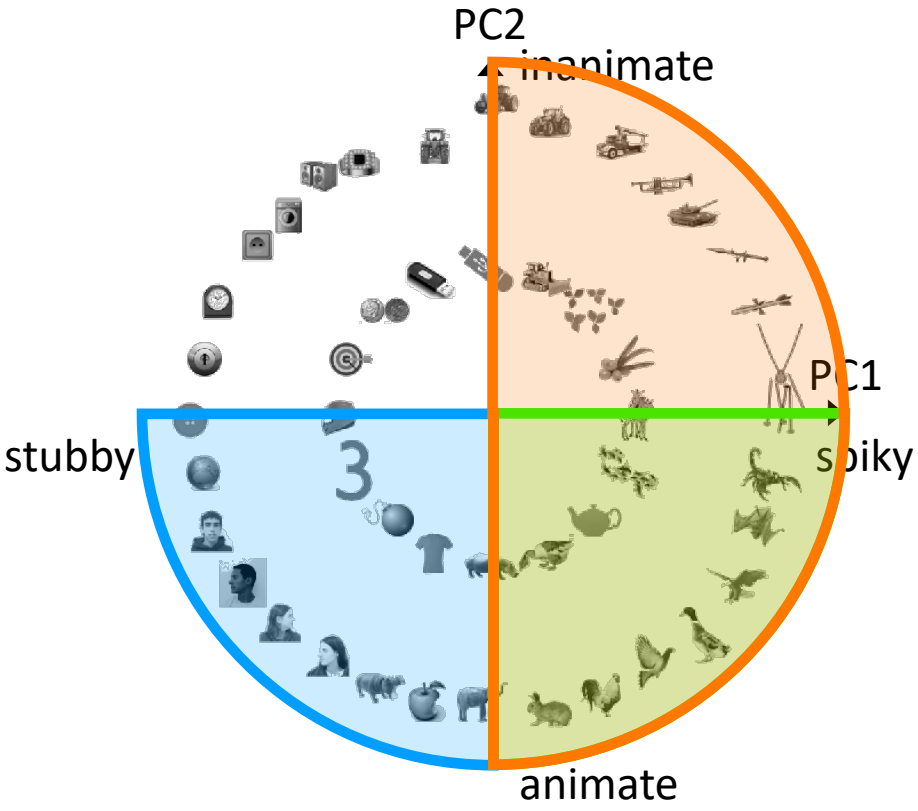
- Body
- Face

Spatial organization of IT cortex

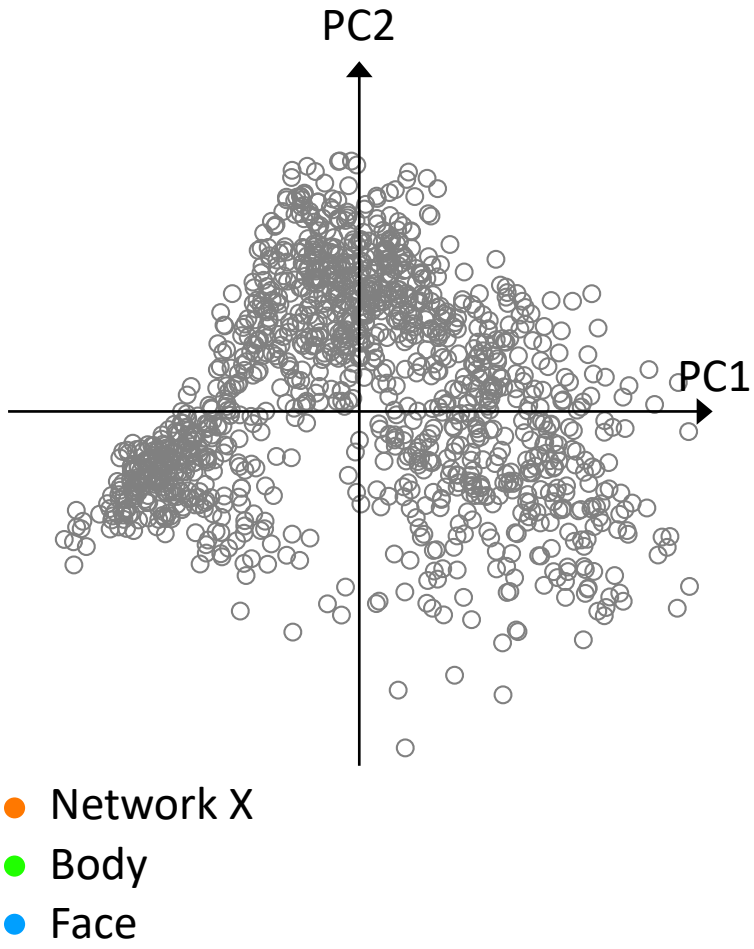




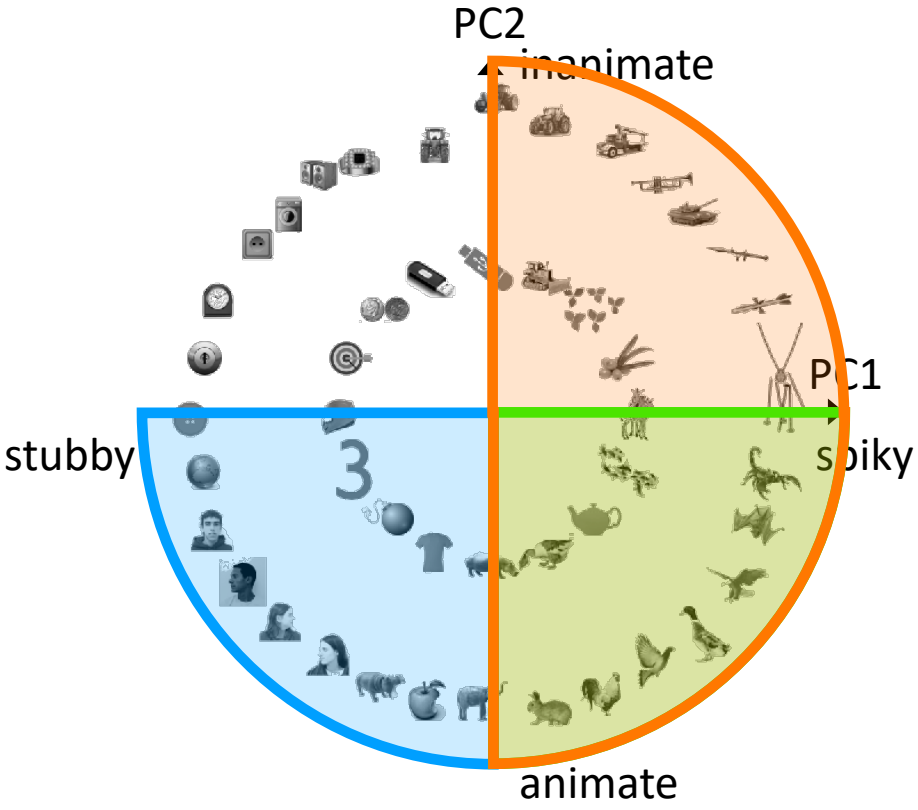
A map of object space



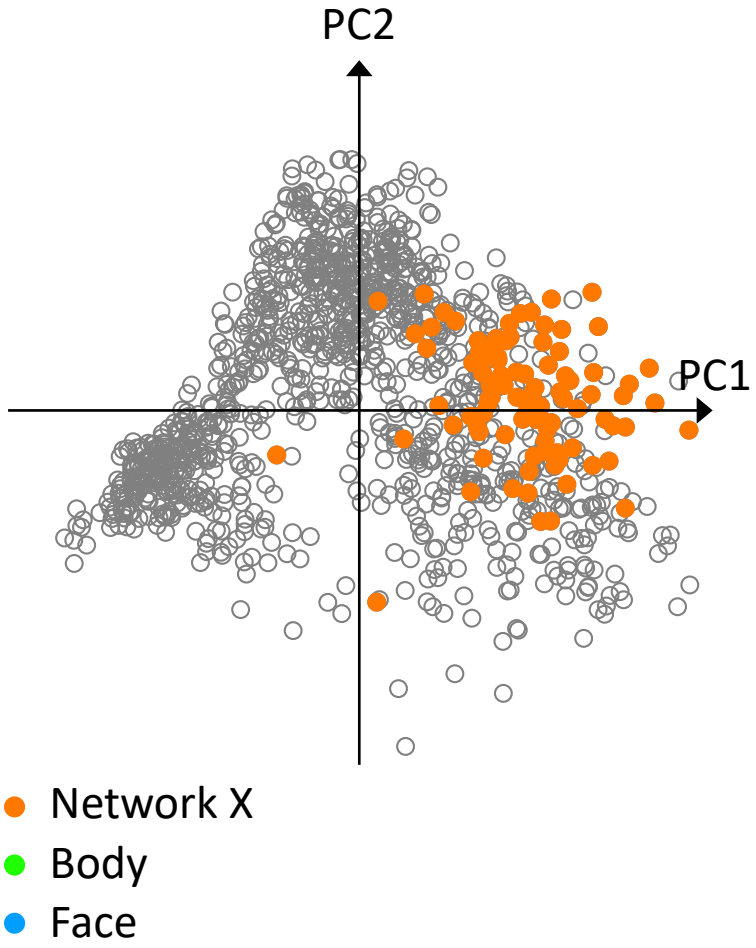
Projection of images shown to monkey onto first two PCs of object space



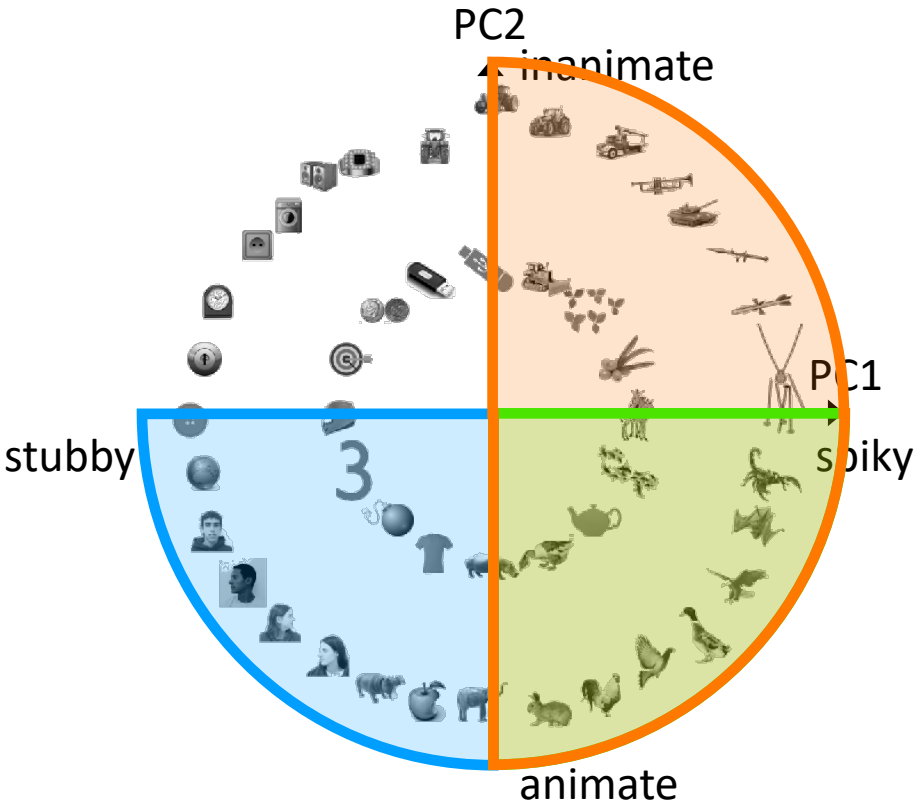
A map of object space



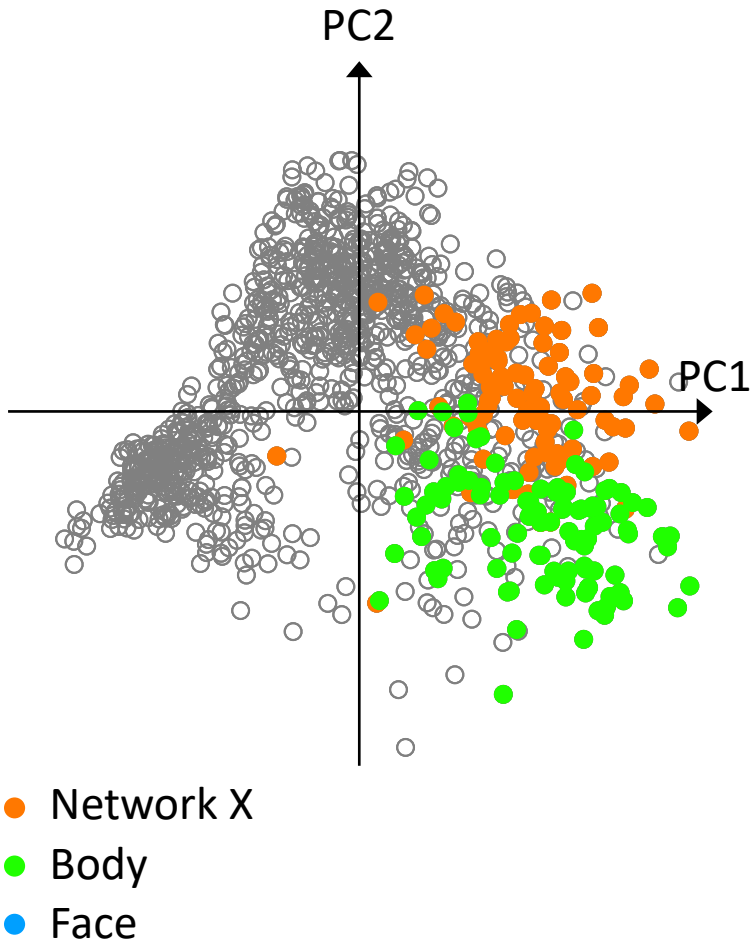
Projection of images shown to monkey onto first two PCs of object space



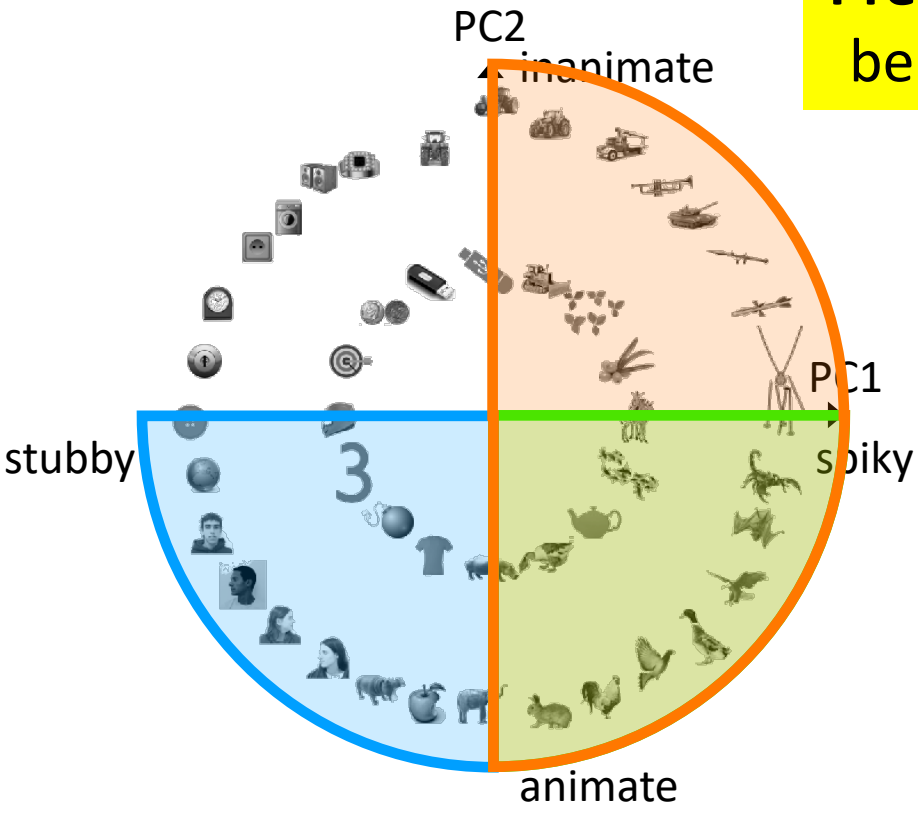
A map of object space



Projection of images shown to monkey onto first two PCs of object space

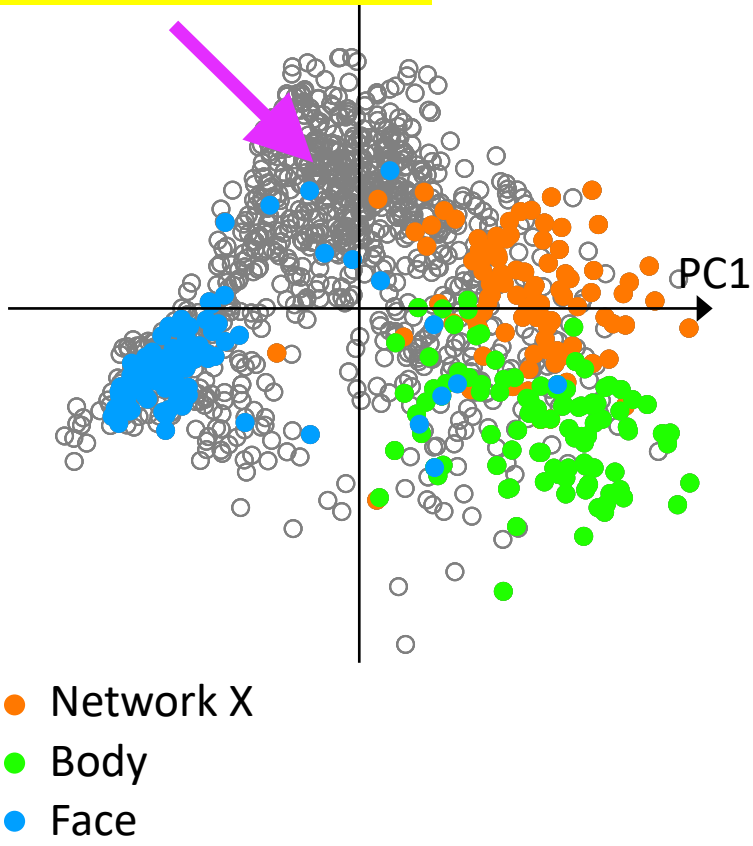


A map of object space

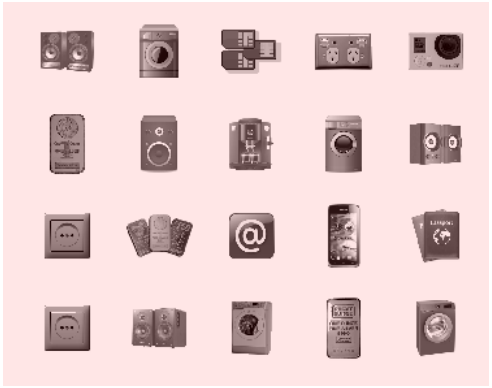


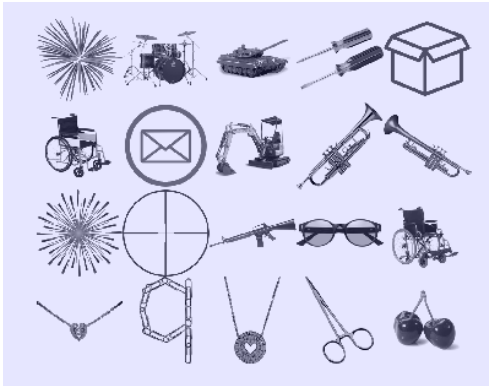
Projection of images shown to monkey object space

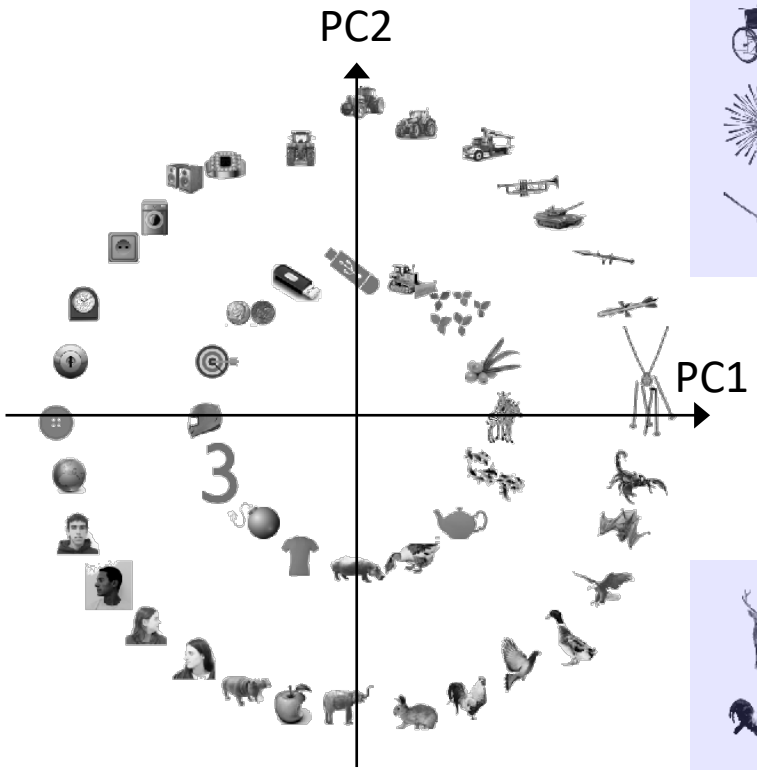
Prediction: There should be a "stubby" network.

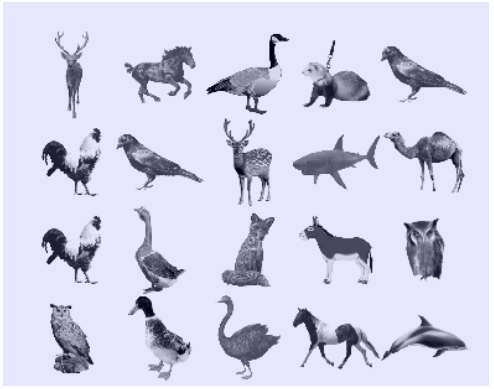


Object-topic fMRI mapping



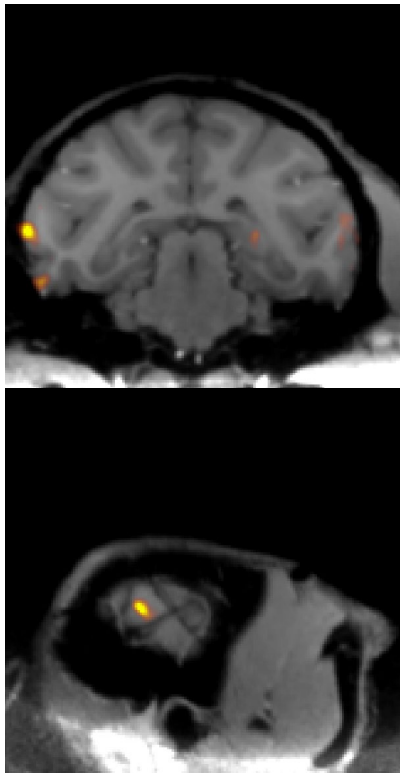




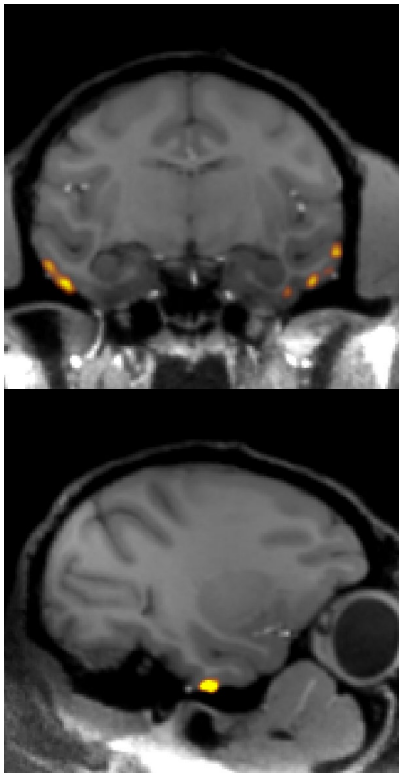


fMRI activation to stubby objects

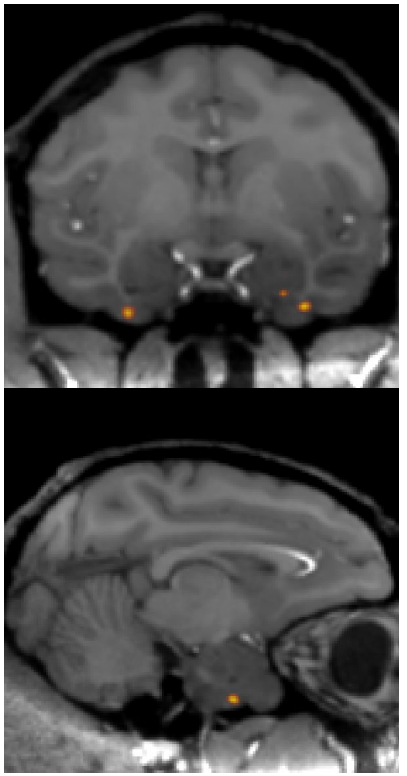
Stubby1

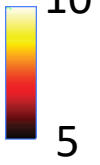


Stubby2

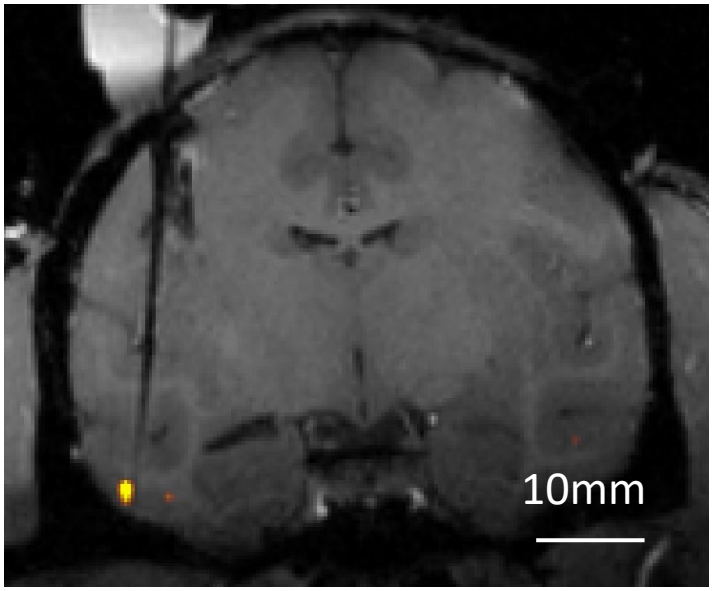


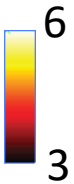
Stubby3

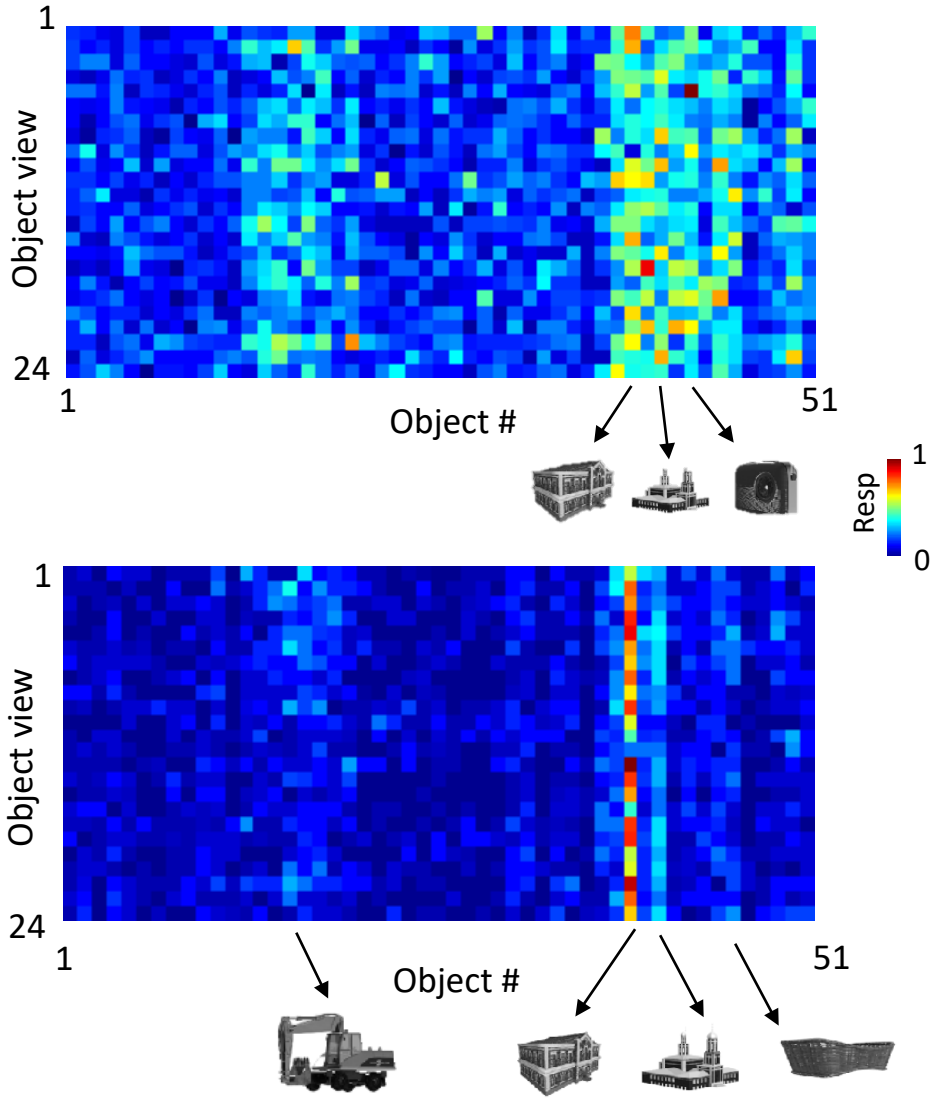




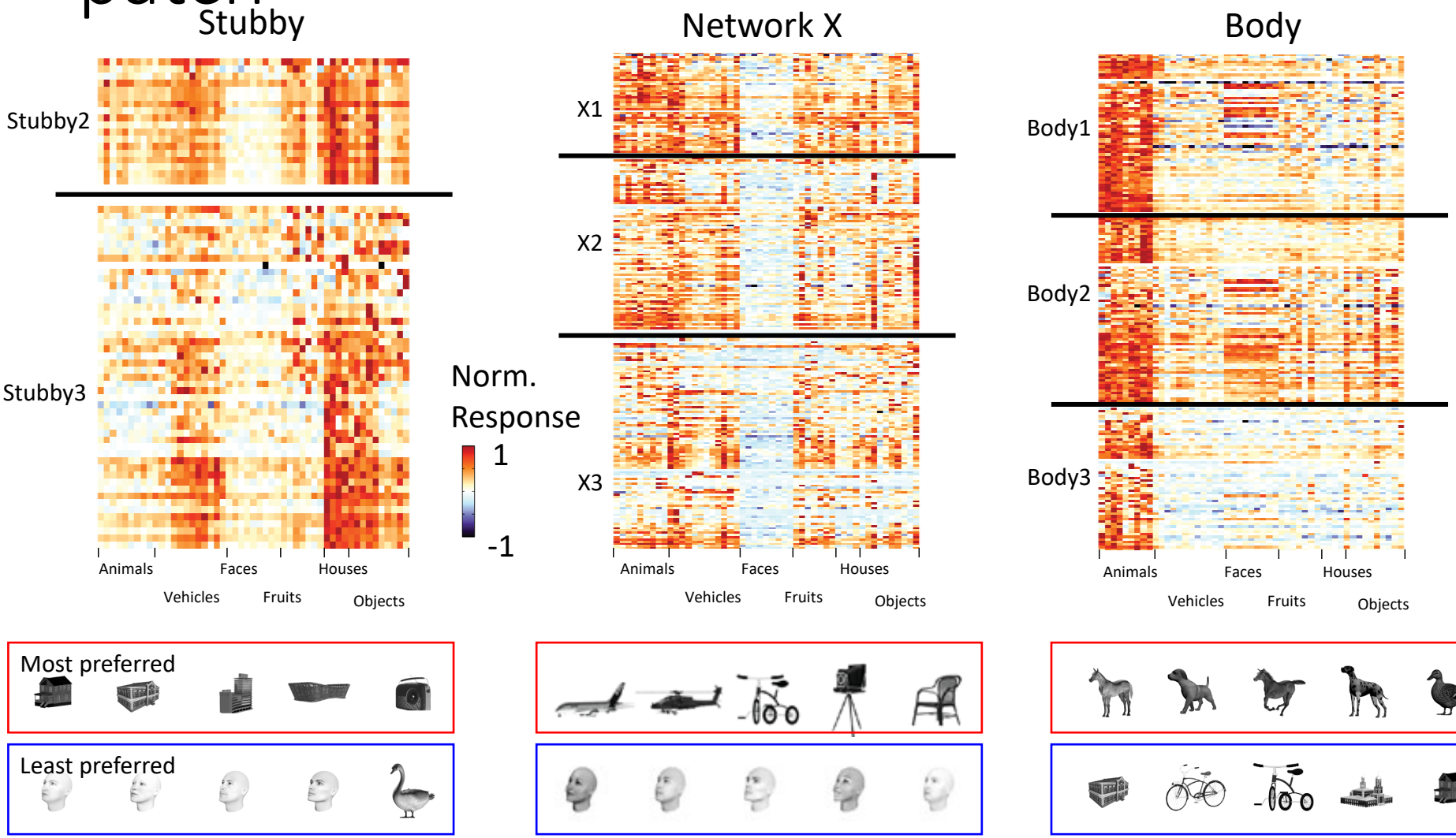
Responses of example cells from a stubby patch



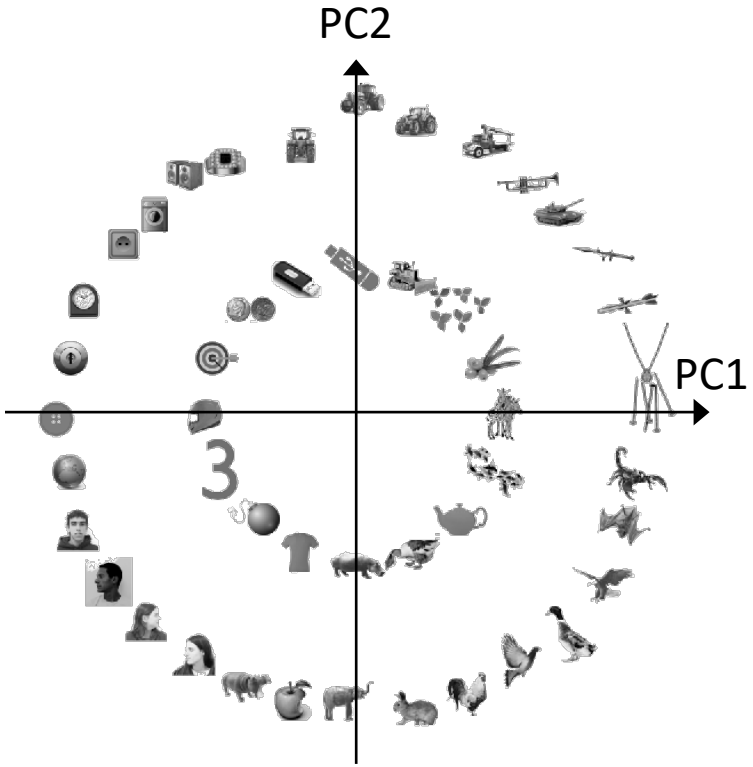




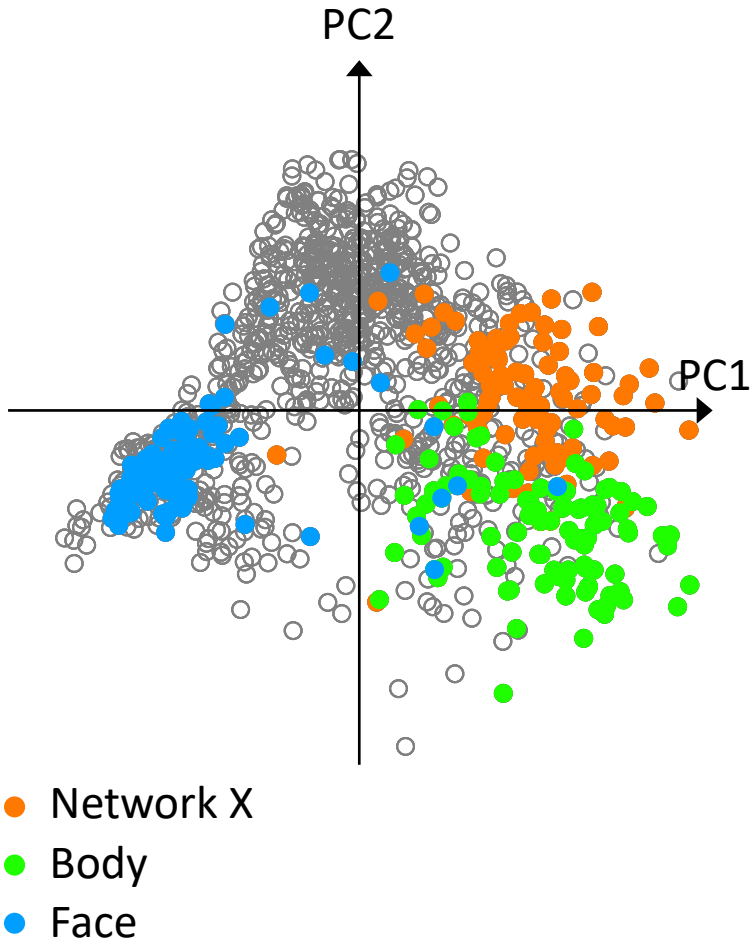
Population response from the stubby patch



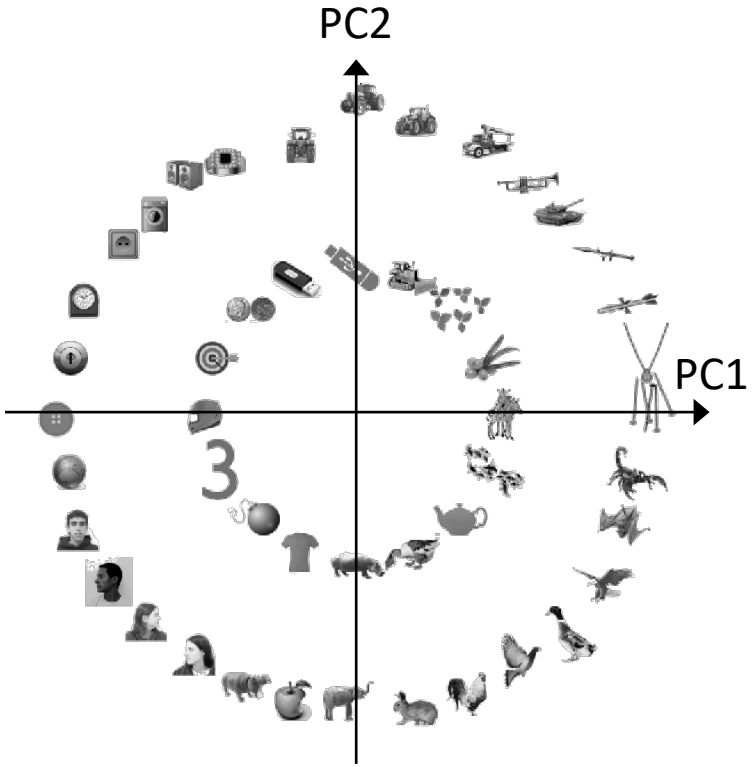
A map of object space



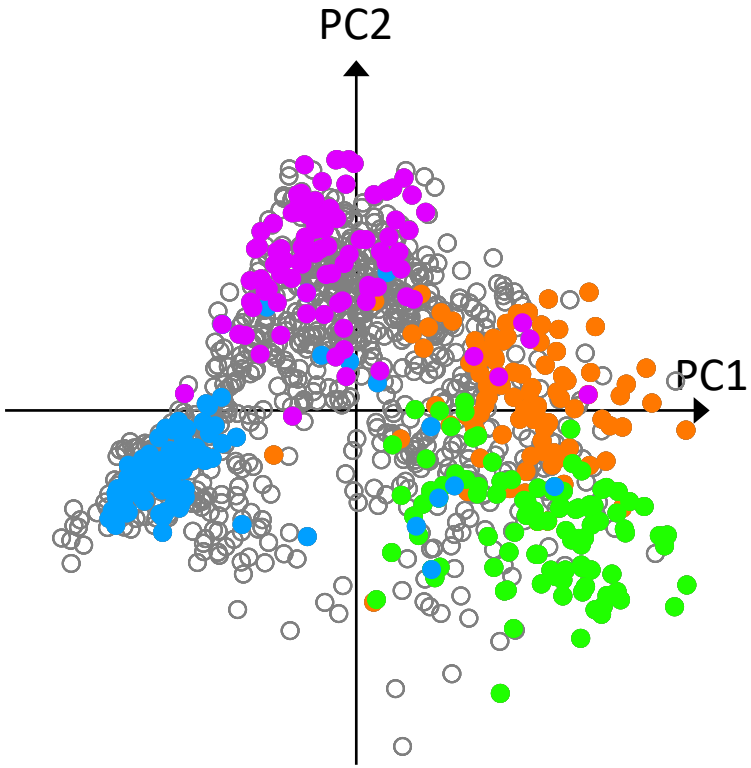
Projection of images shown to monkey onto first two PCs of object space



A map of object space



Projection of images shown to monkey onto first two PCs of object space

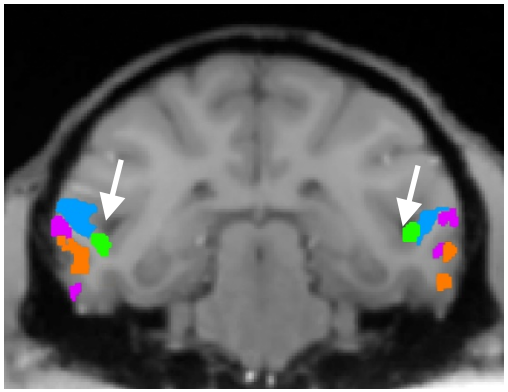


- Network X
- Body
- Face
- Stubby

Spatial organization of IT cortex

Posterior

M1

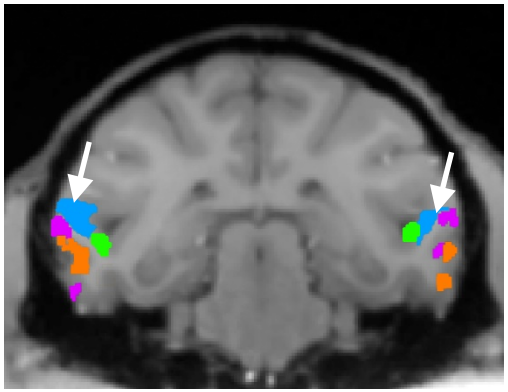


- Body
- Face
- Stubby
- Spiky

Spatial organization of IT cortex

Posterior

M1

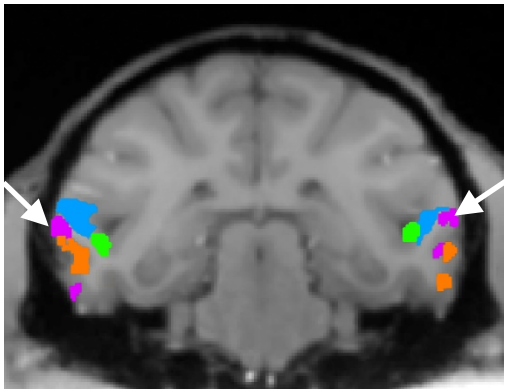


- Body
- Face
- Stubby
- Spiky

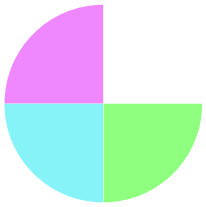
Spatial organization of IT cortex

Posterior

M1



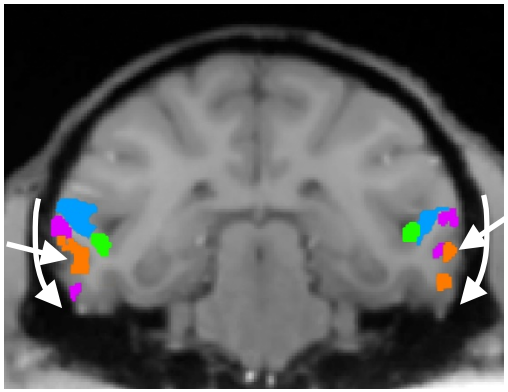
- Body
- Face
- Stubby
- Spiky



Spatial organization of IT cortex

Posterior

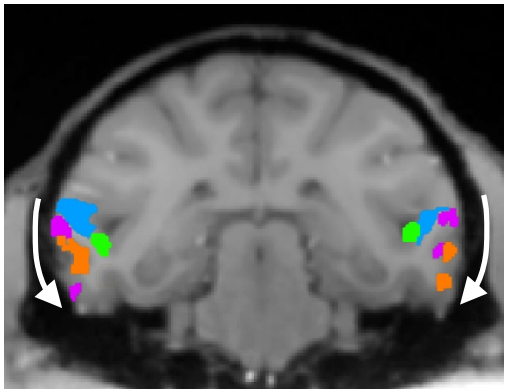
M1



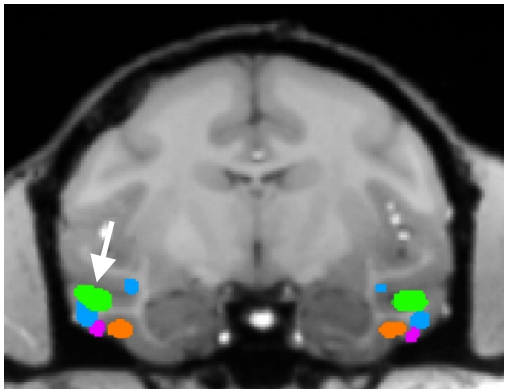
- Body
- Face
- Stubby
- Spiky

Spatial organization of IT cortex

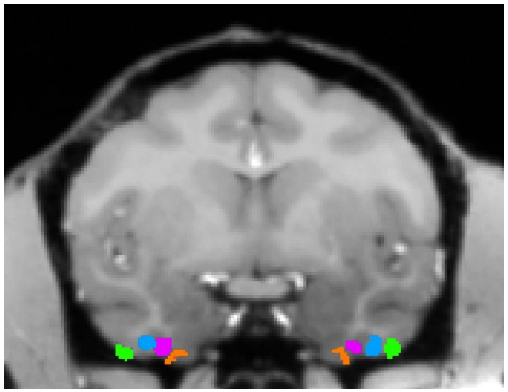
Posterior



Middle



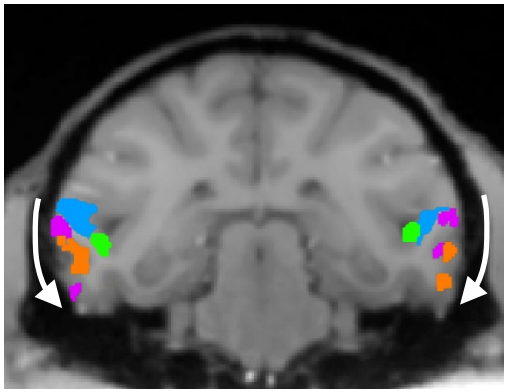
Anterior



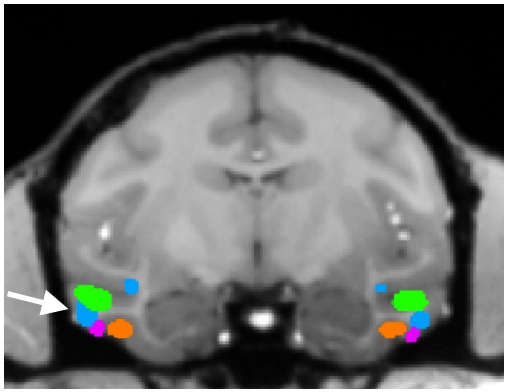
- Body
- Face
- Stubby
- Spiky

Spatial organization of IT cortex

Posterior



Middle



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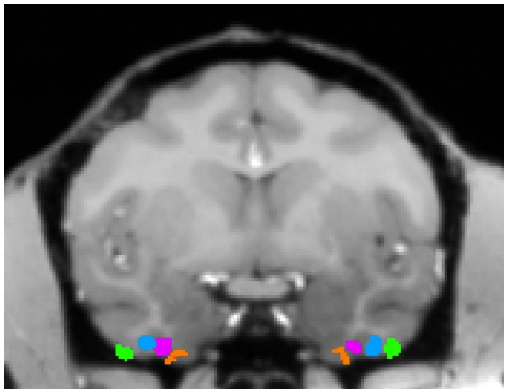
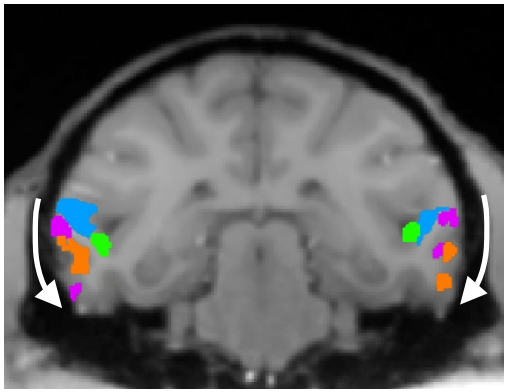


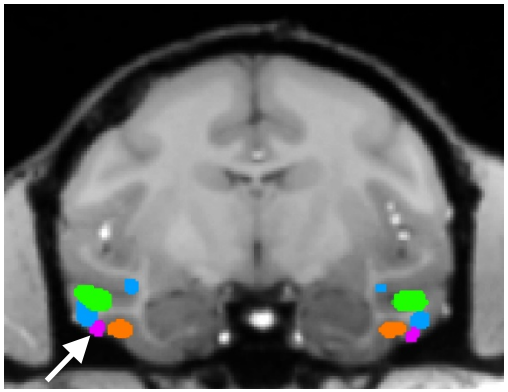
- Body
- Face
- Stubby
- Spiky

Spatial organization of IT cortex

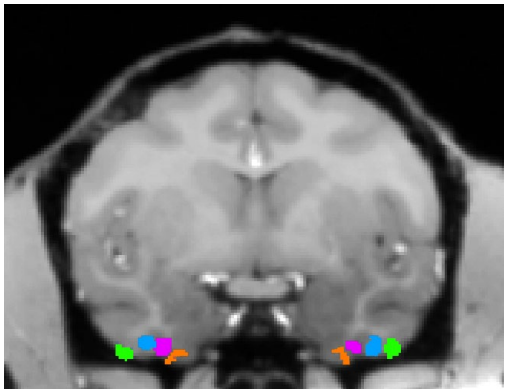
Posterior



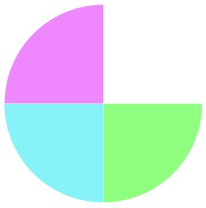
Middle



Anterior

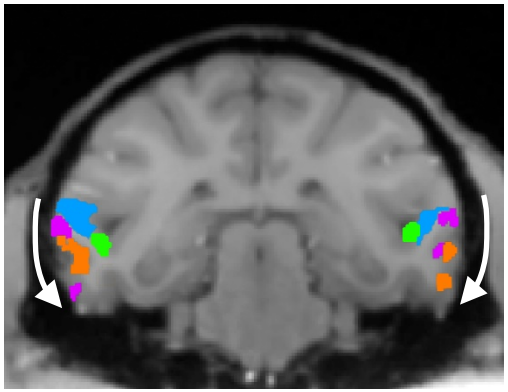


- Body
- Face
- Stubby
- Spiky

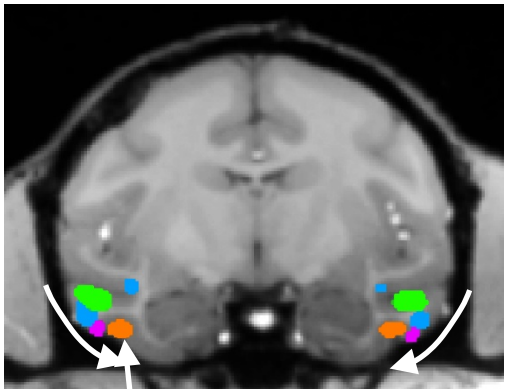


Spatial organization of IT cortex

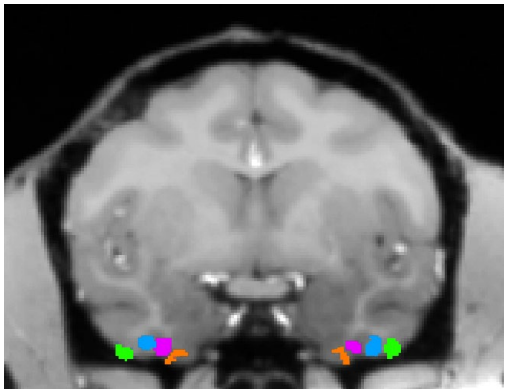
Posterior



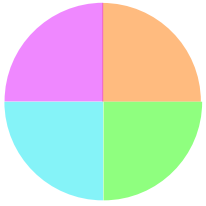
Middle



Anterior

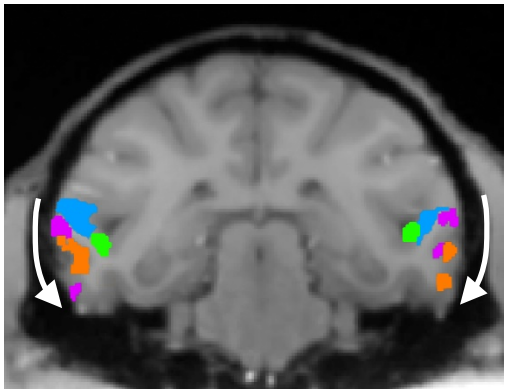


- Body
- Face
- Stubby
- Spiky

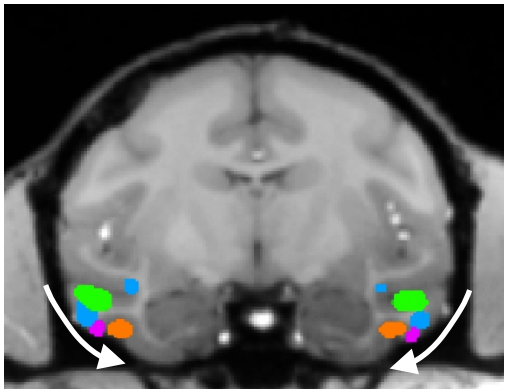


Spatial organization of IT cortex

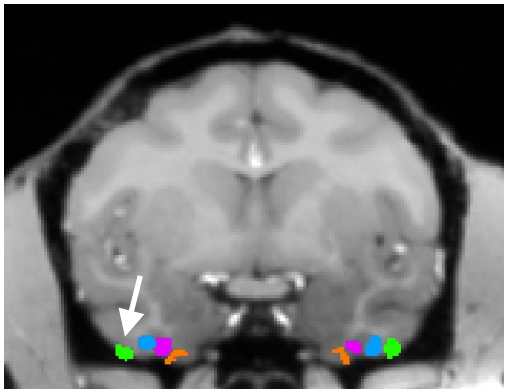
Posterior



Middle



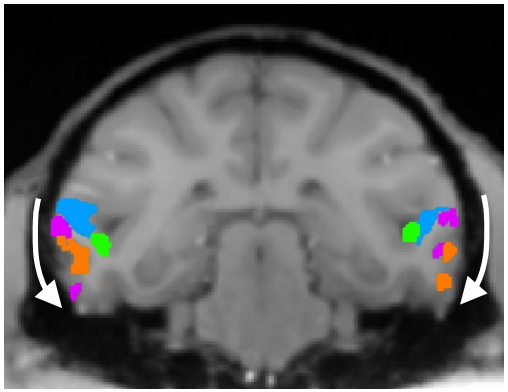
Anterior



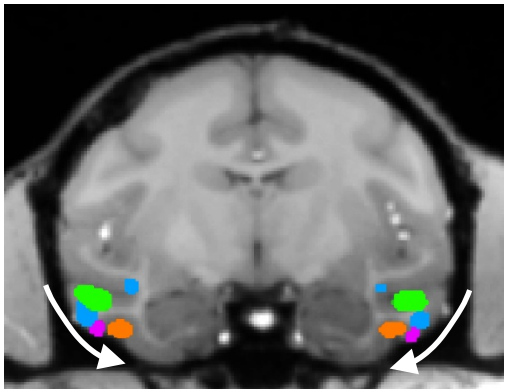
- Body
- Face
- Stubby
- Spiky

Spatial organization of IT cortex

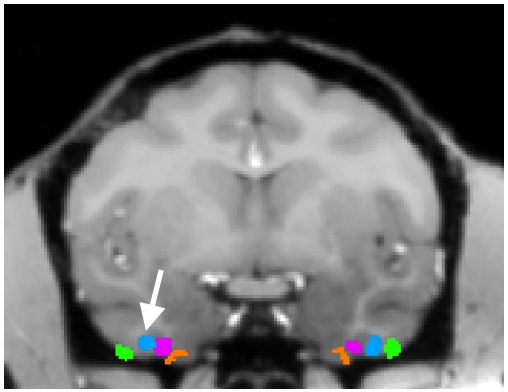
Posterior



Middle



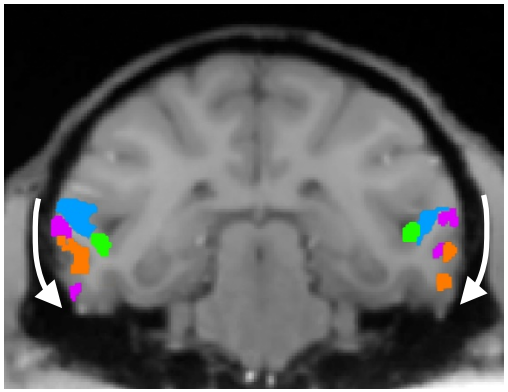
Anterior



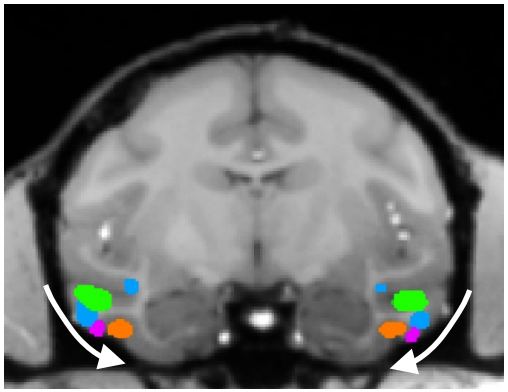
- Body
- Face
- Stubby
- Spiky

Spatial organization of IT cortex

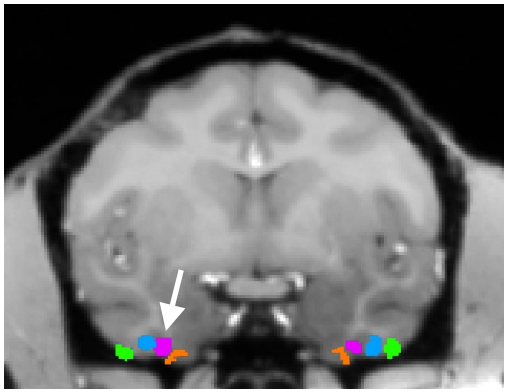
Posterior



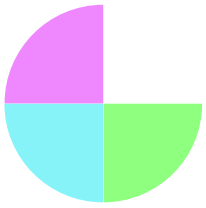
Middle



Anterior

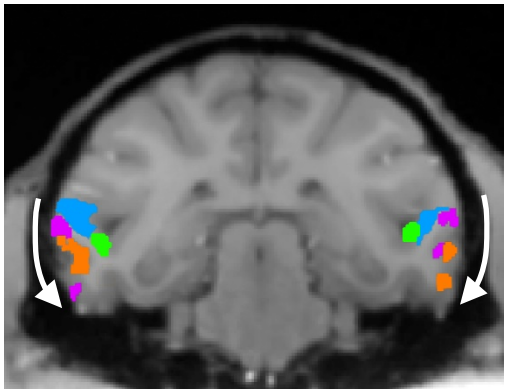


- Body
- Face
- Stubby
- Spiky

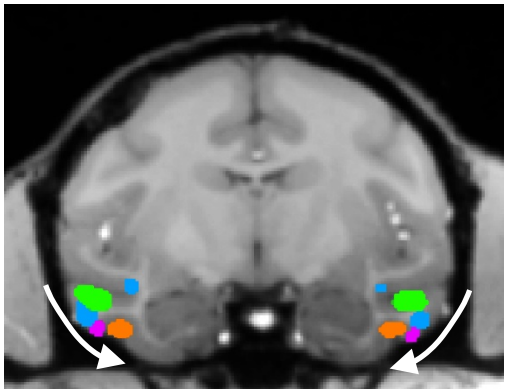


Spatial organization of IT cortex

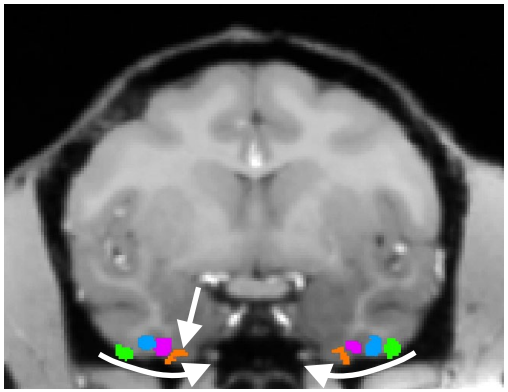
Posterior



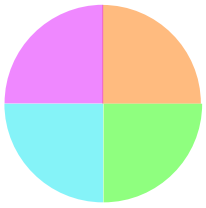
Middle



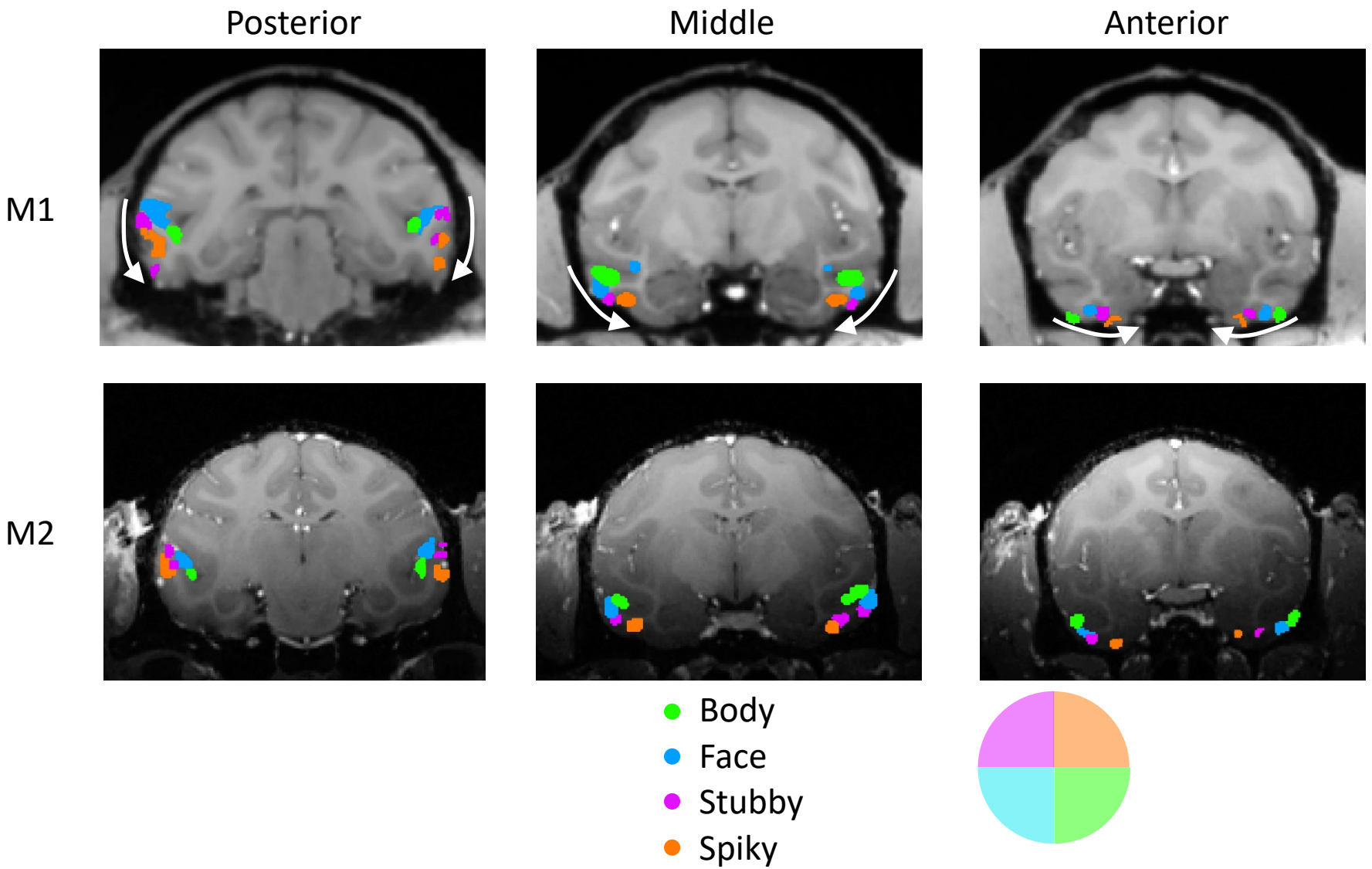
Anterior



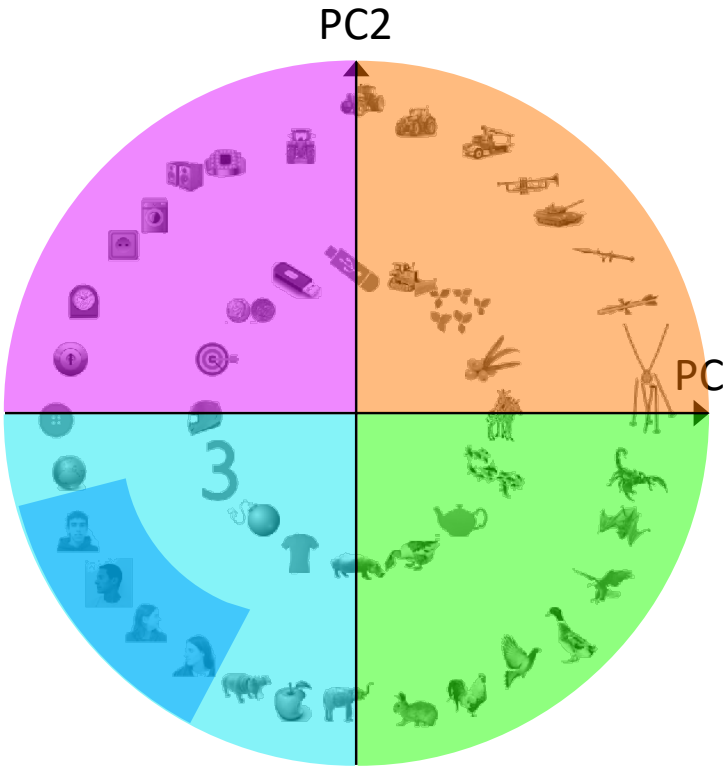
- Body
- Face
- Stubby
- Spiky

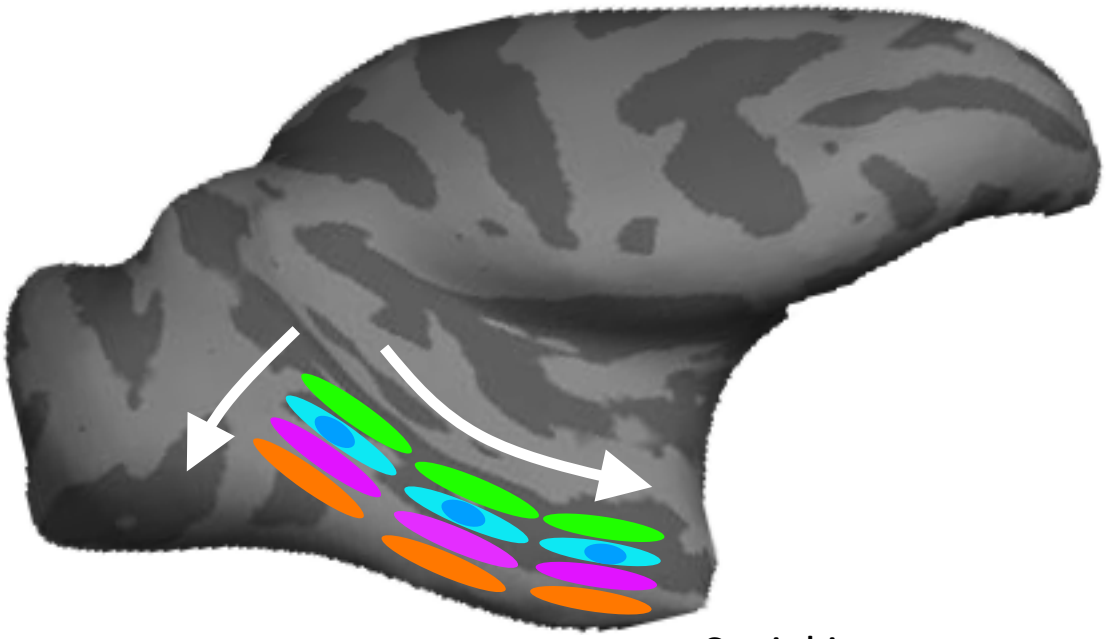


Spatial organization of IT cortex



Spatial organization of IT cortex



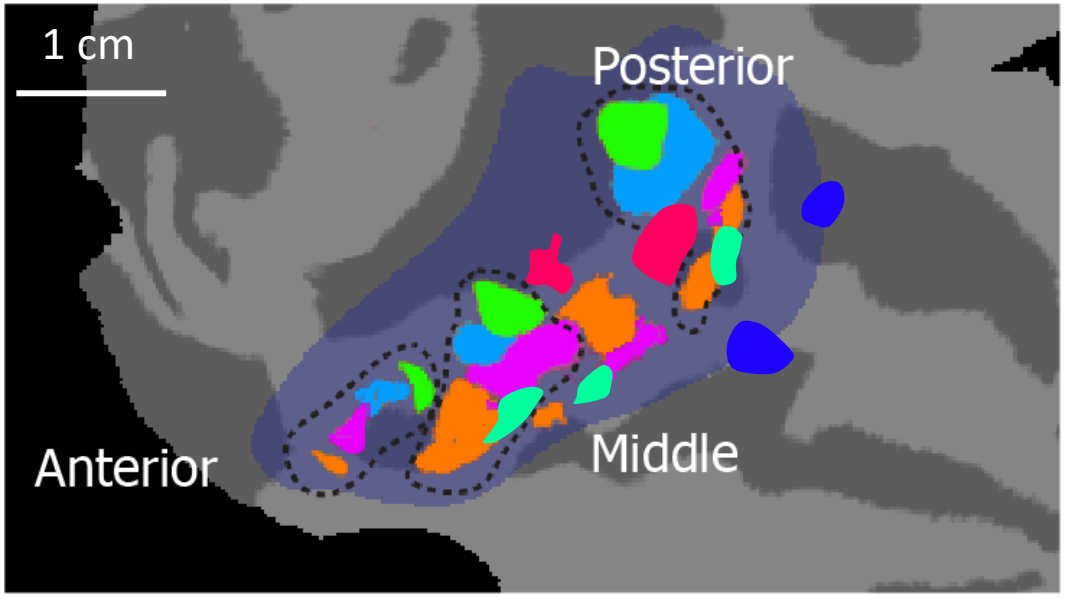


- Body
- Face
- Stubby
- Network X

Social importance

How many islands are there?

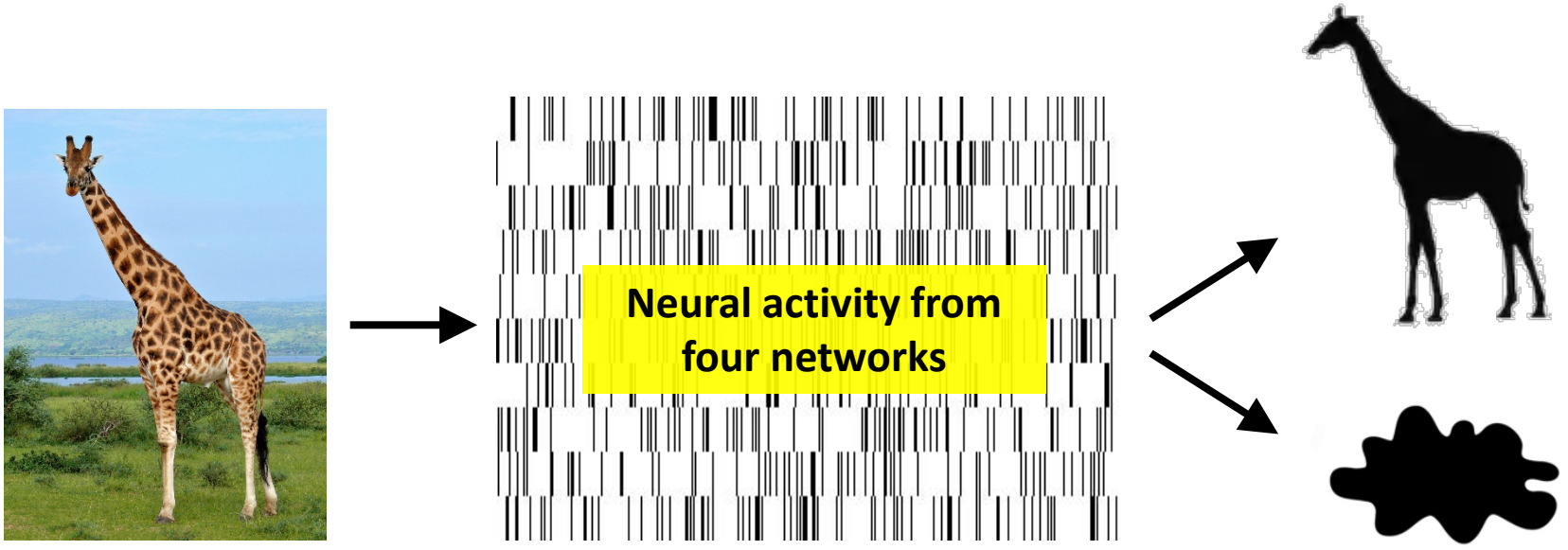
Only part of IT is explained



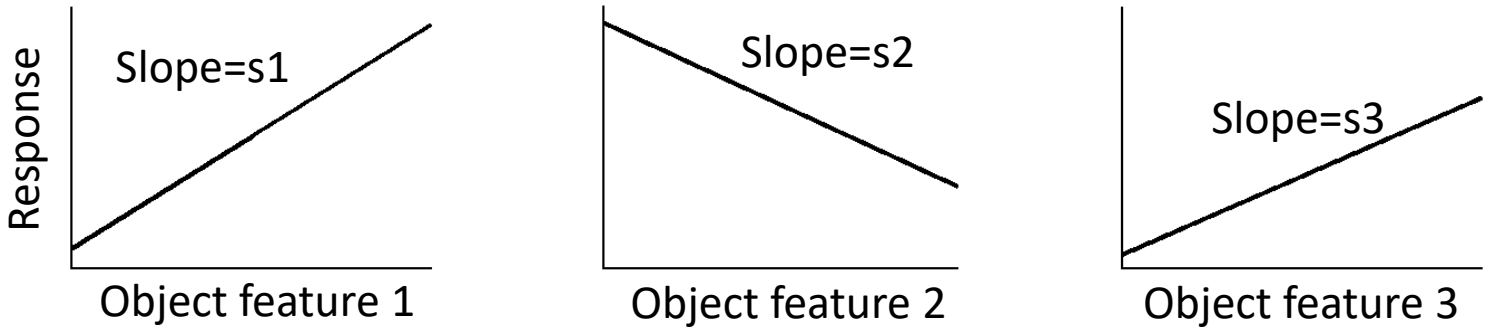
Face	Body	Network X	Stubby	Color	Disparity	Scene	Covered IT	Whole IT	% of IT
90 mm^2	76 mm^2	84 mm^2	85 mm^2	34 mm^2	51 mm^2	35 mm^2	306 mm^2	570 mm^2	**53%**

Four networks carry a complete code

Can we reconstruct arbitrary objects?



Implication of ramp-shaped tuning



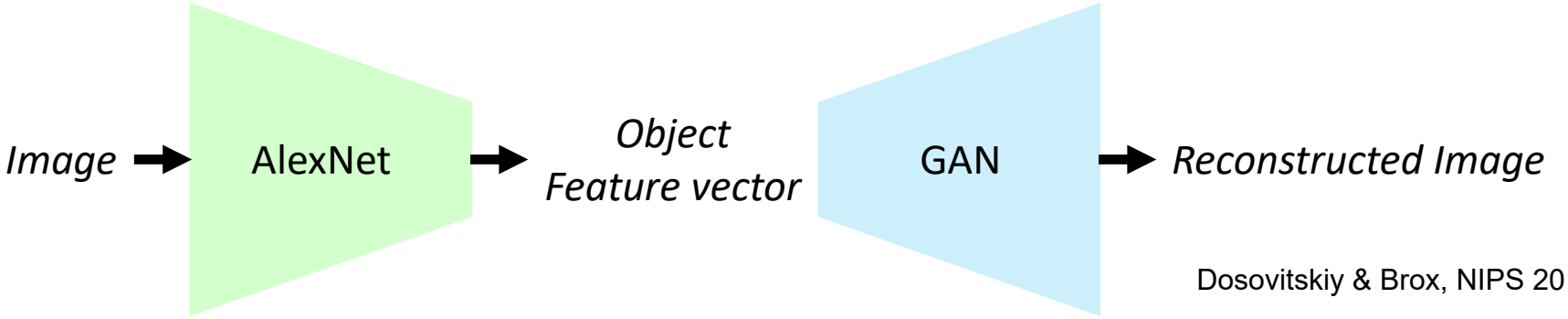
$$Response\ of\ cell = s1 \cdot feature_1 + s2 \cdot feature_2 + \cdots s50 \cdot feature_{50}$$

$$\begin{bmatrix} response_{cell\ 1} \\ response_{cell\ 2} \\ \vdots \\ response_{cell\ N} \end{bmatrix} = \begin{bmatrix} s_{1,1} & \cdots & s_{1,50} \\ s_{2,1} & \cdots & s_{2,50} \\ \vdots & & \vdots \\ s_{N,1} & \cdots & s_{N,50} \end{bmatrix} \begin{bmatrix} feature_1 \\ feature_2 \\ \vdots \\ feature_{50} \end{bmatrix}$$

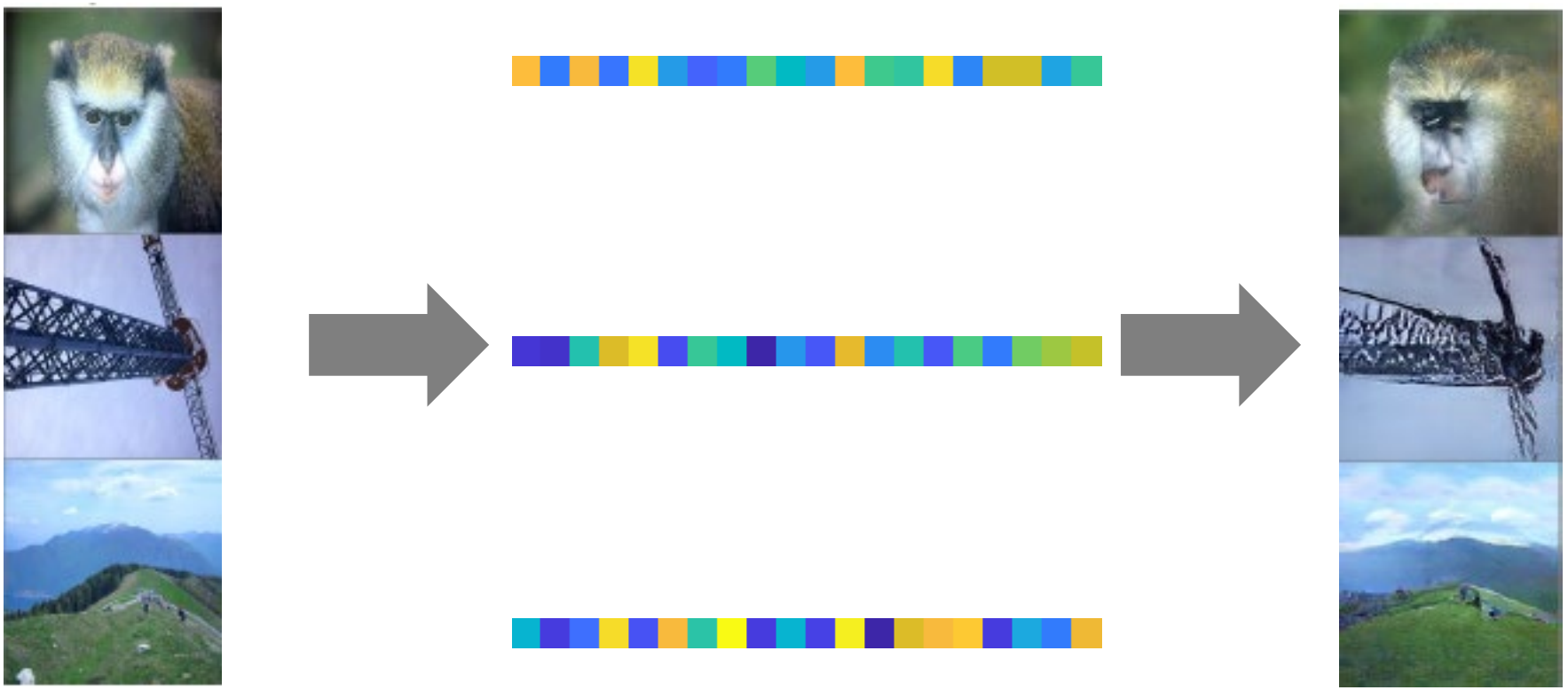
$$\begin{bmatrix} feature_1 \\ feature_2 \\ \vdots \\ feature_{50} \end{bmatrix} = \begin{bmatrix} s_{1,1} & \cdots & s_{1,50} \\ s_{2,1} & \cdots & s_{2,50} \\ \vdots & & \vdots \\ s_{N,1} & \cdots & s_{N,50} \end{bmatrix}^{-1} \begin{bmatrix} response_{cell\ 1} \\ response_{cell\ 2} \\ \vdots \\ response_{cell\ N} \end{bmatrix}$$

50 Object features = Weight matrix * Response of object cells

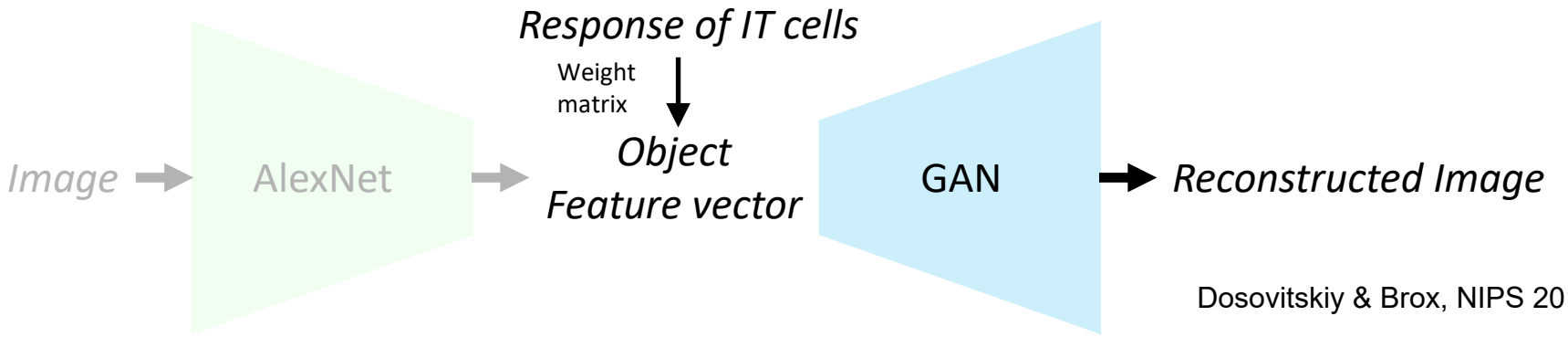
Direct reconstruction from neural activity using a Generative Adversarial Network



Dosovitskiy & Brox, NIPS 2016

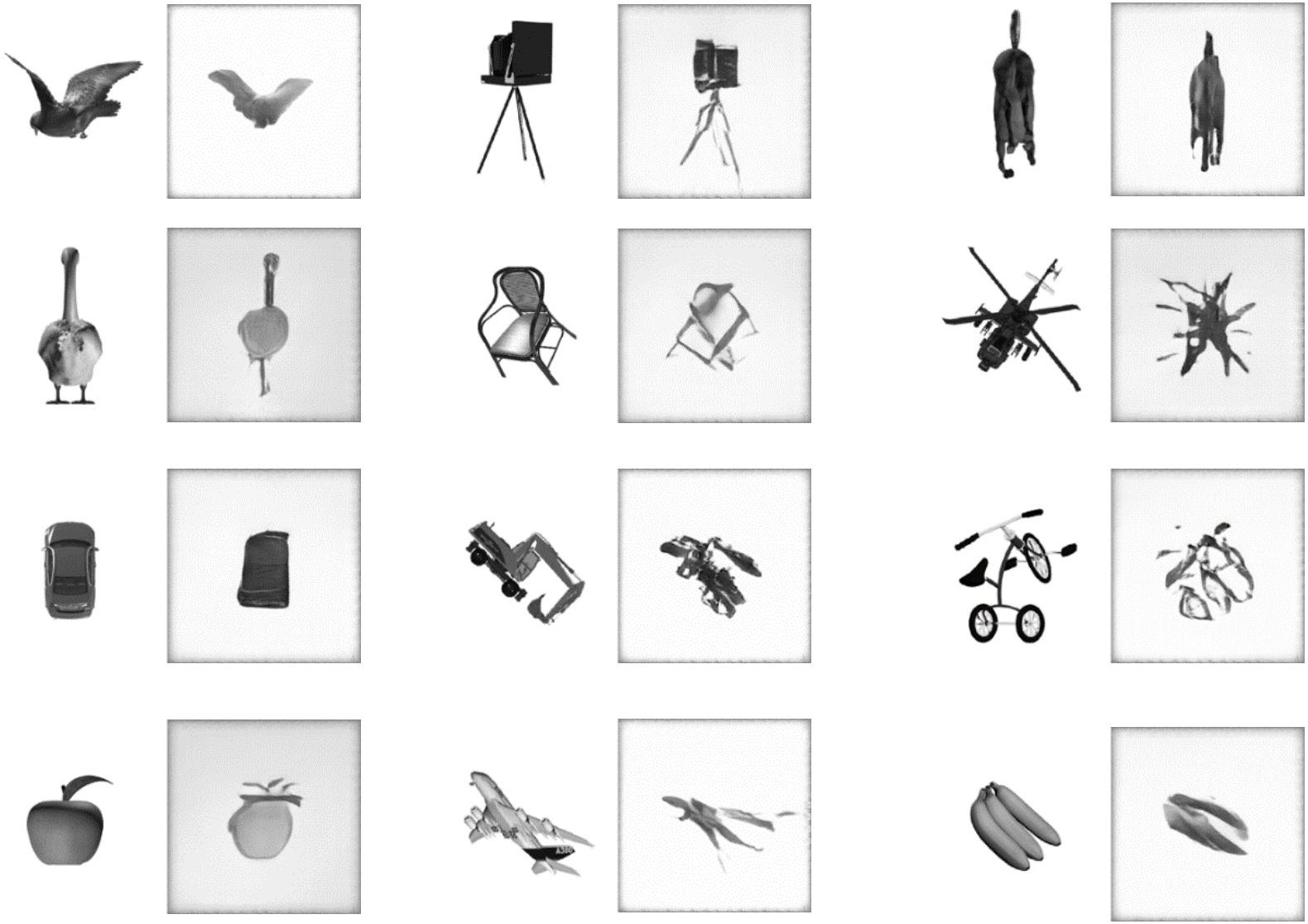


Direct reconstruction from neural activity using a Generative Adversarial Network



Dosovitskiy & Brox, NIPS 2016

Direct reconstruction from neural activity using a Generative Adversarial Network




Object
space

A **unified** model for the functional organization of inferotemporal cortex

Our model makes many predictions that we can confirmed

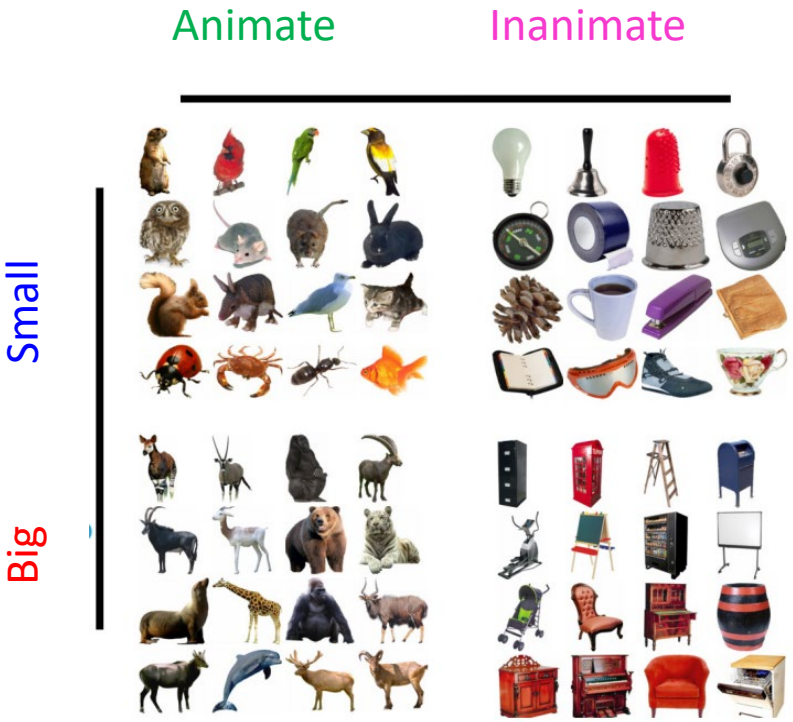
Predictions

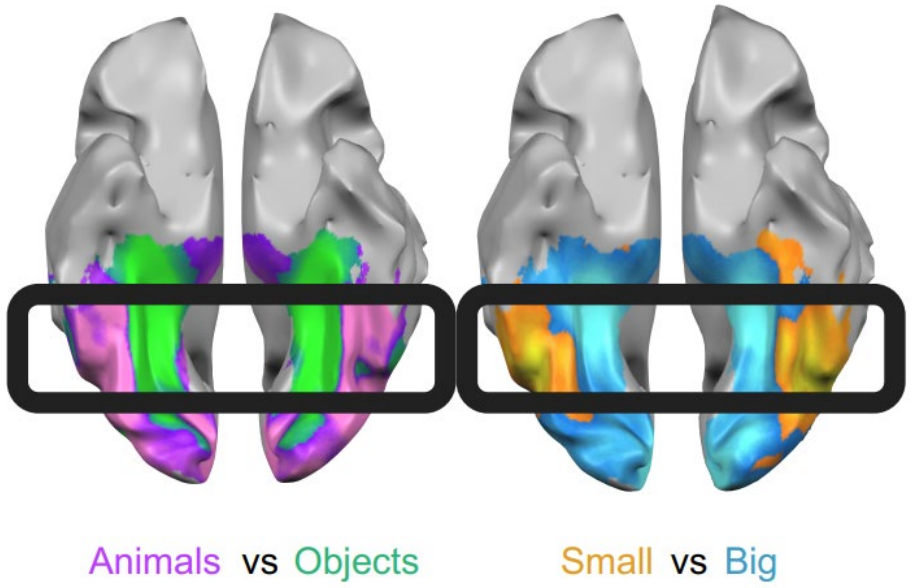
- Predicting previous accounts of IT organization
- Predicting shape rather than semantic selectivity
- Predicting responses to new stimuli

Predictions

- Predicting previous accounts of IT organization
- Predicting shape rather than semantic selectivity
- Predicting responses to new stimuli

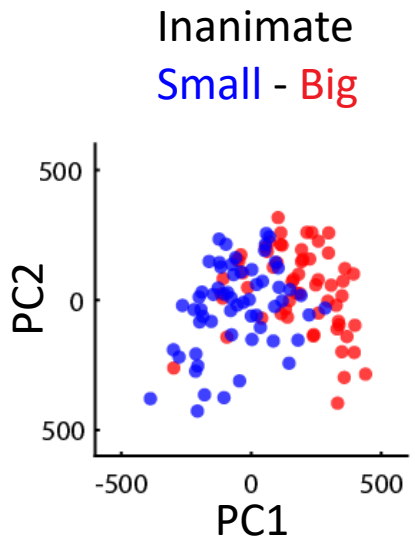
Animacy/size hypothesis of IT organization



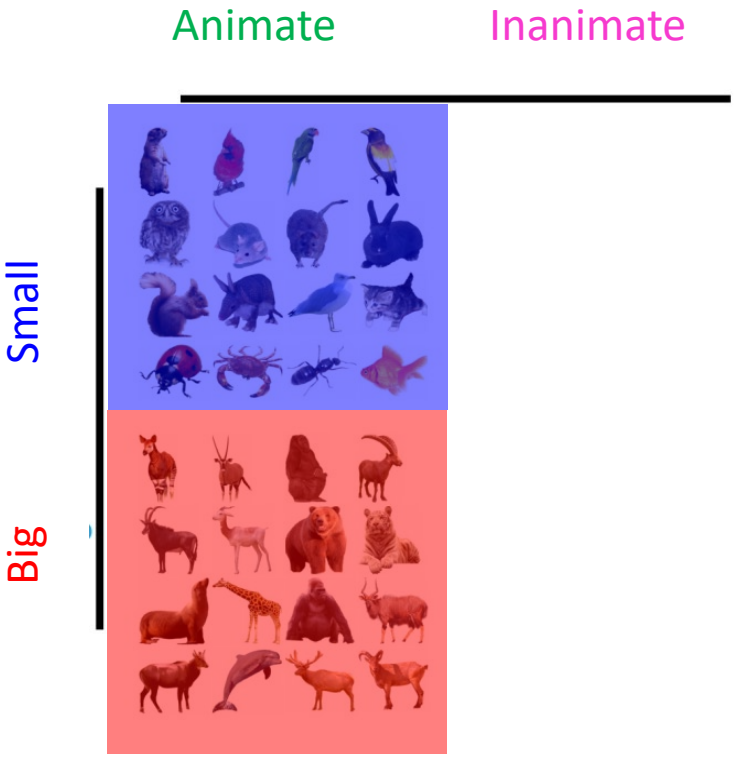


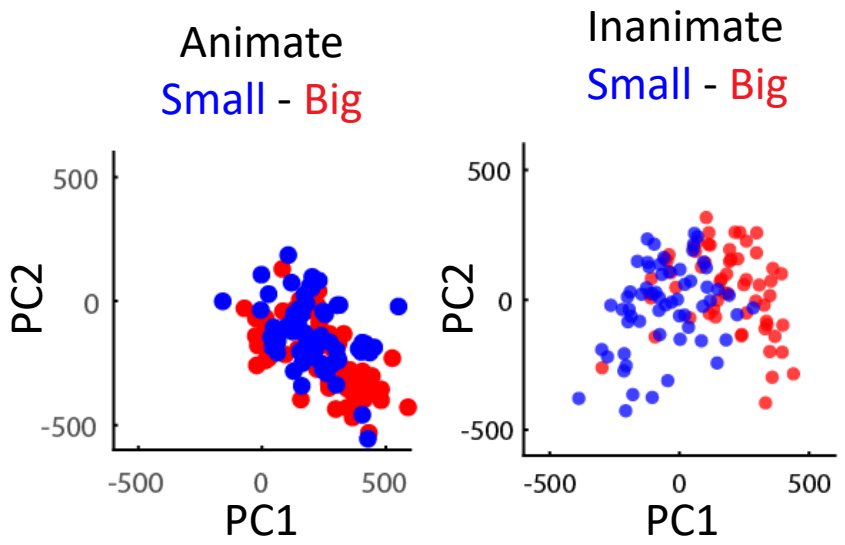
Konkle & Caramazza 2013

Animacy/size hypothesis of IT organization

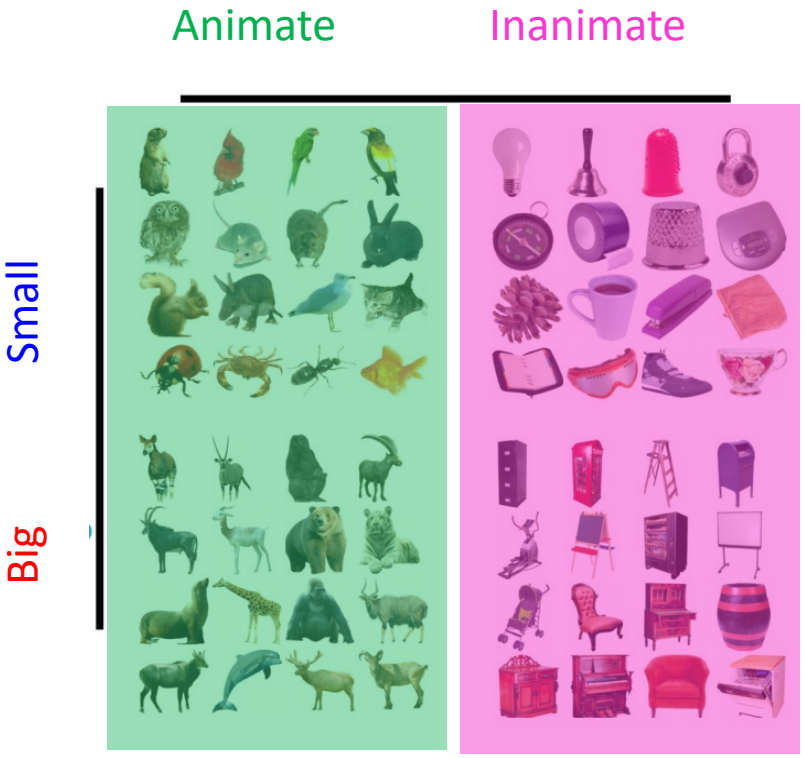


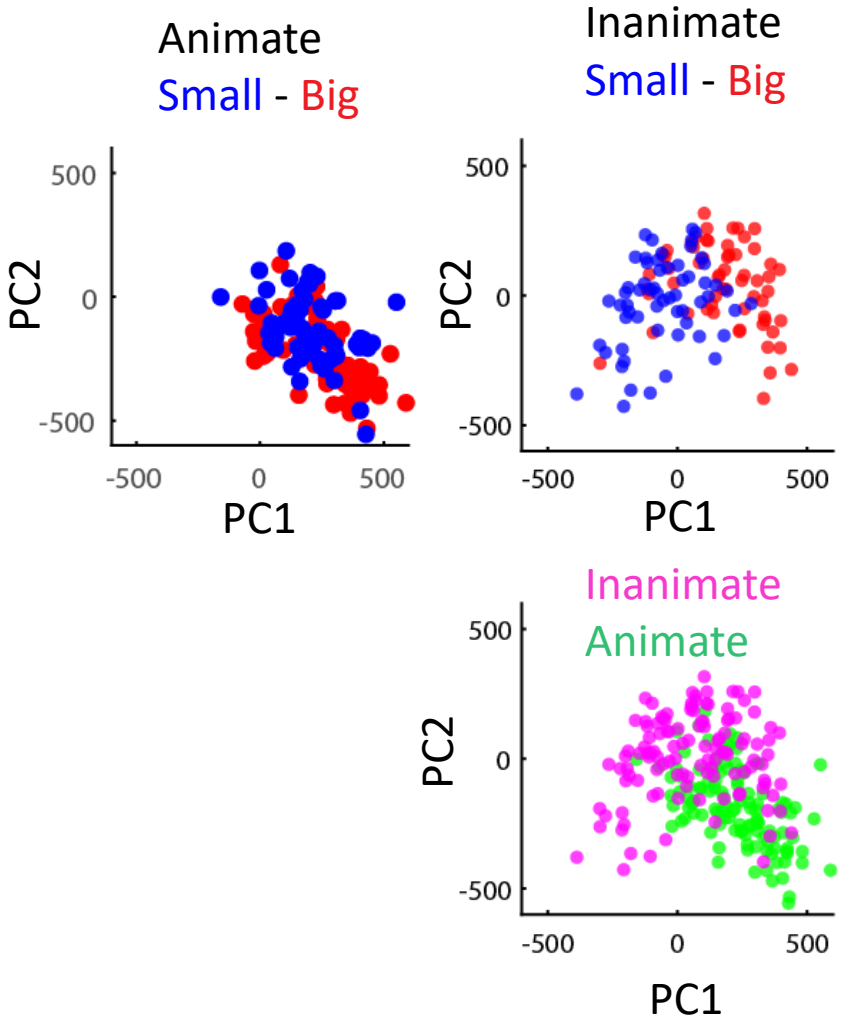
Animacy/size hypothesis of IT organization



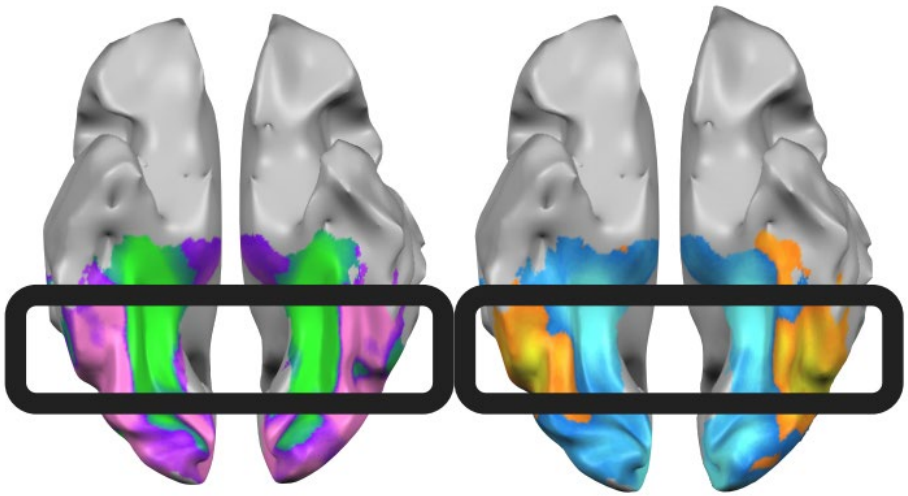


Animacy/size hypothesis of IT organization





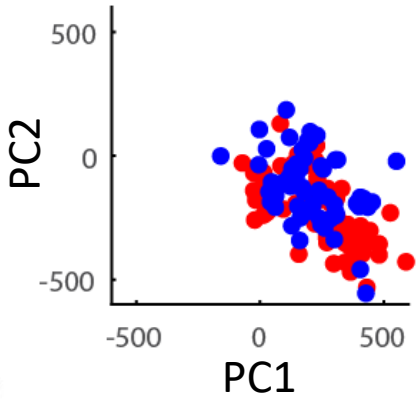
Animacy/size hypothesis of IT organization



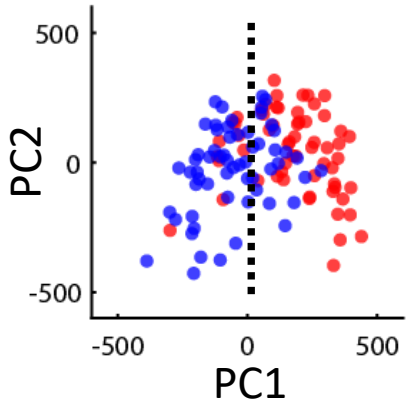
Inanimate
Animate

Small - Big

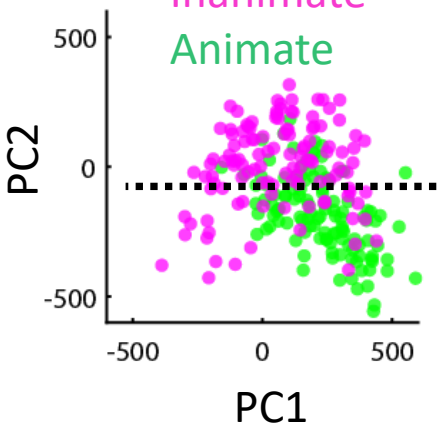
Animate
Small - Big



Inanimate
Small - Big



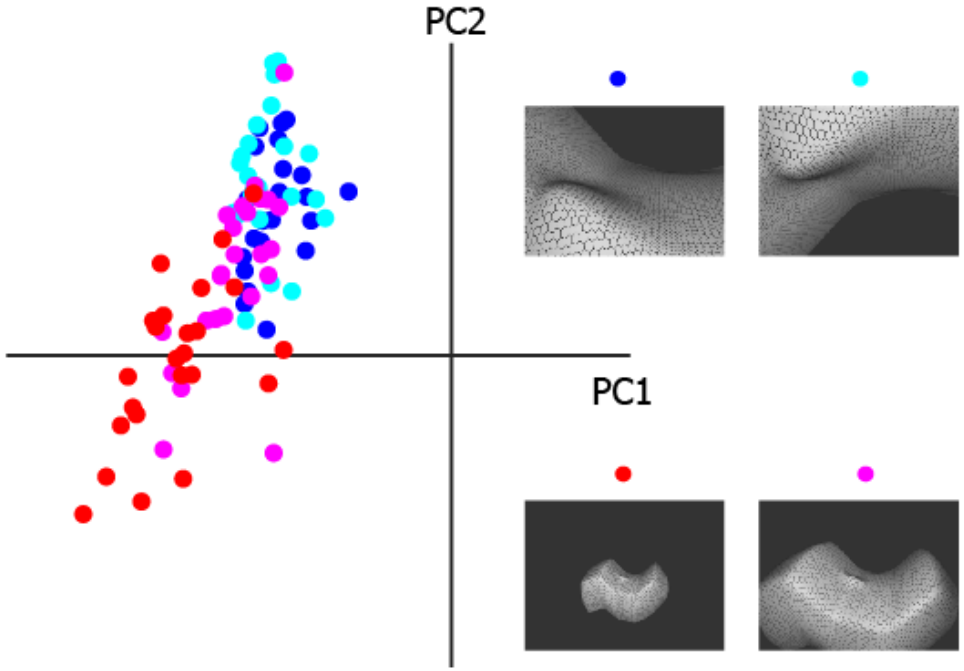
Inanimate
Animate



Study 2: object vs scene-like

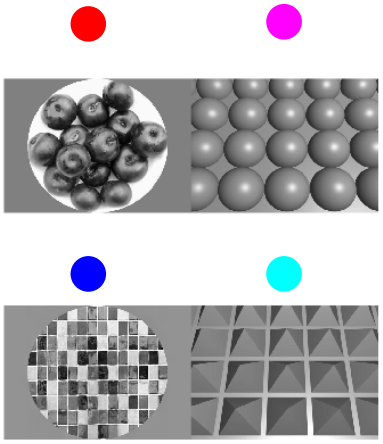
Preferred by the neurons in the lower STS bank

Preferred by the neurons in the TEd

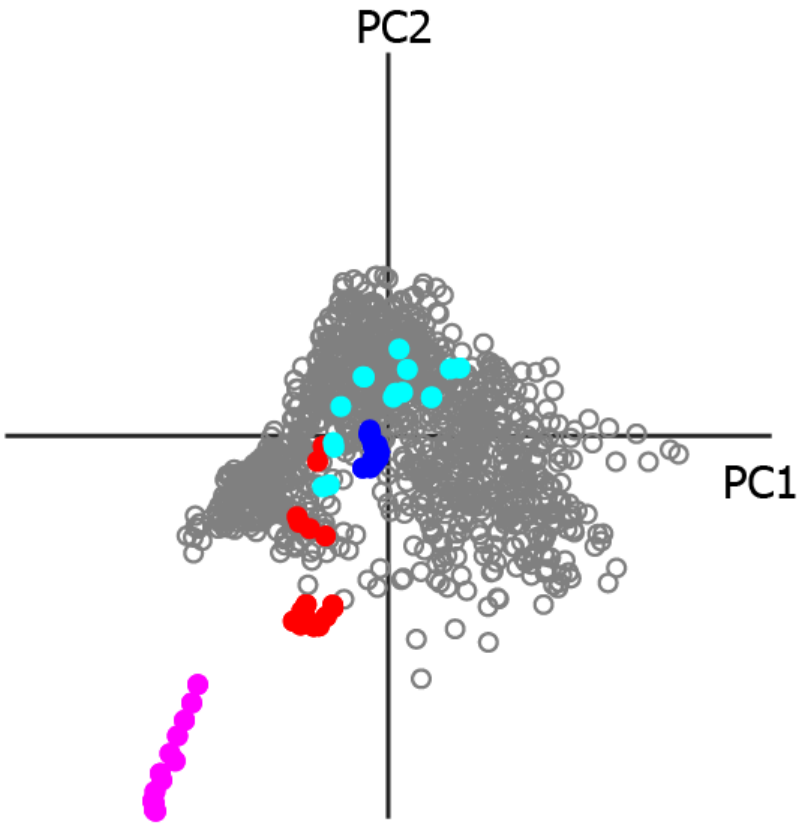


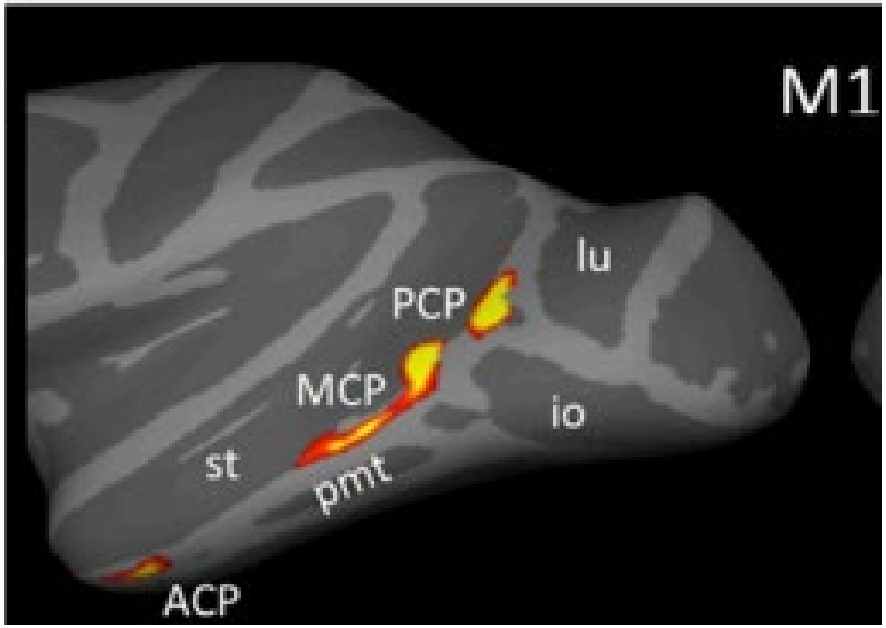
Vaziri et al., *Neuron* 2014

Study 3: Curvature network



Vaziri et al., *PNAS* 2014



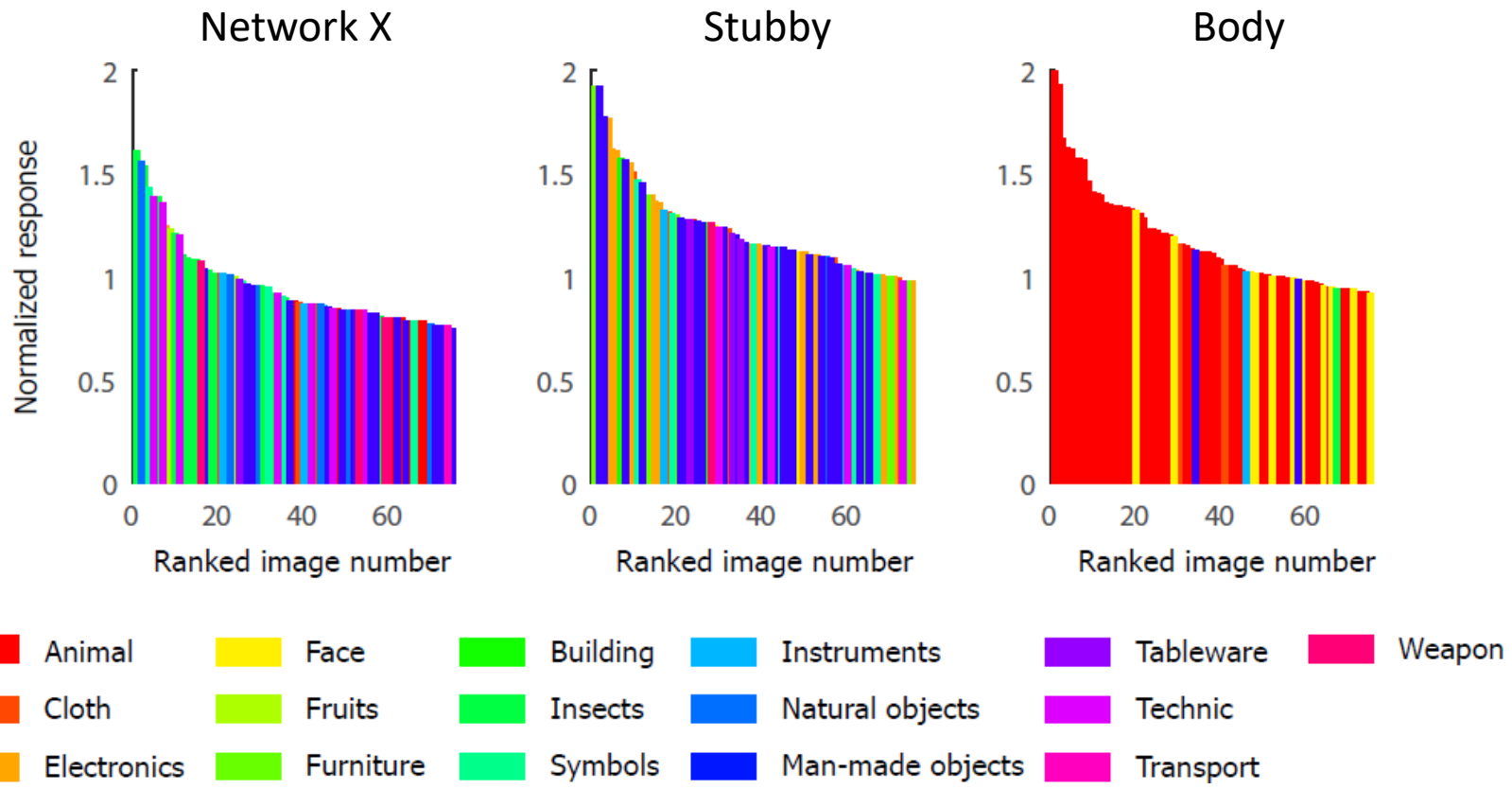


Yue et al., 2014

Predictions

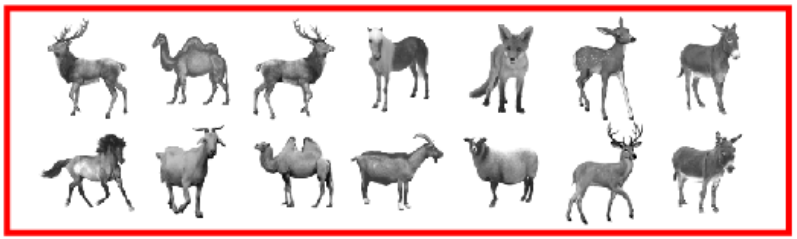
- Predicting previous accounts of IT organization
- Predicting shape rather than semantic selectivity
- Predicting responses to new stimuli

Network X and the stubby network cannot be explained by semantic meaning



Body patch selectivity

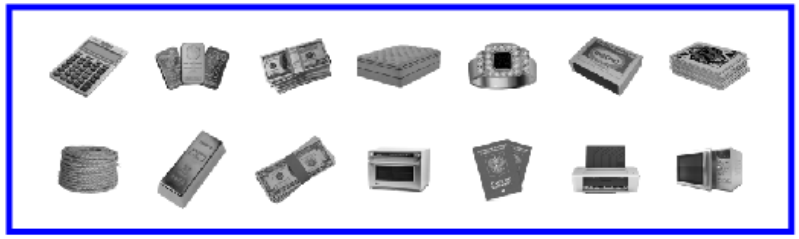
Group 1

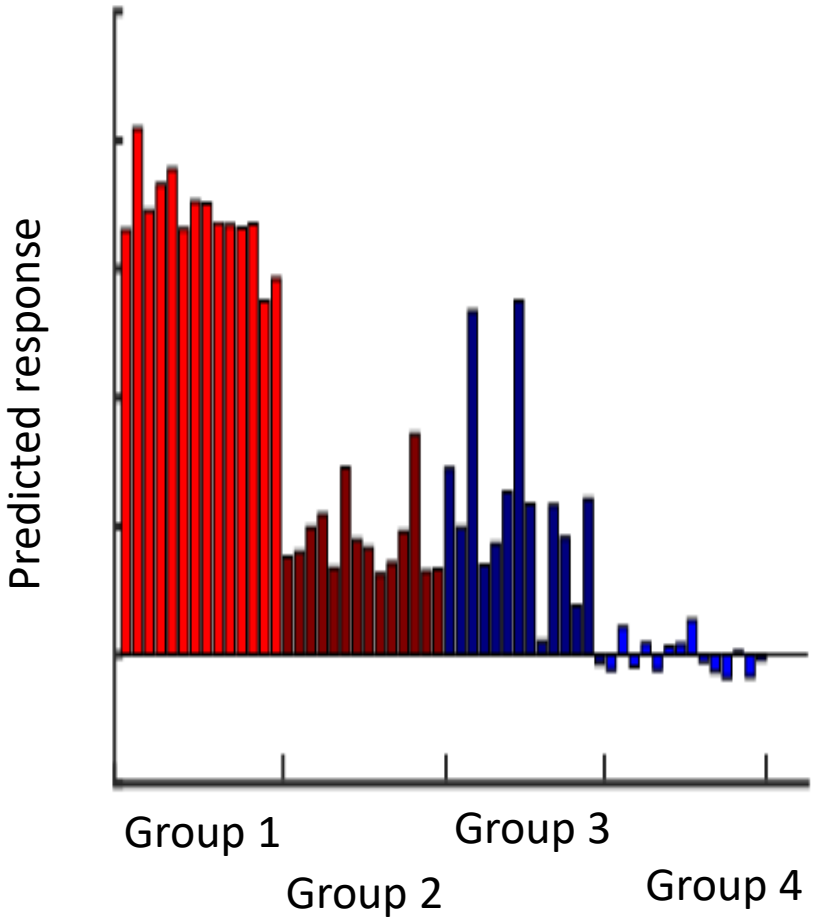


Group 2

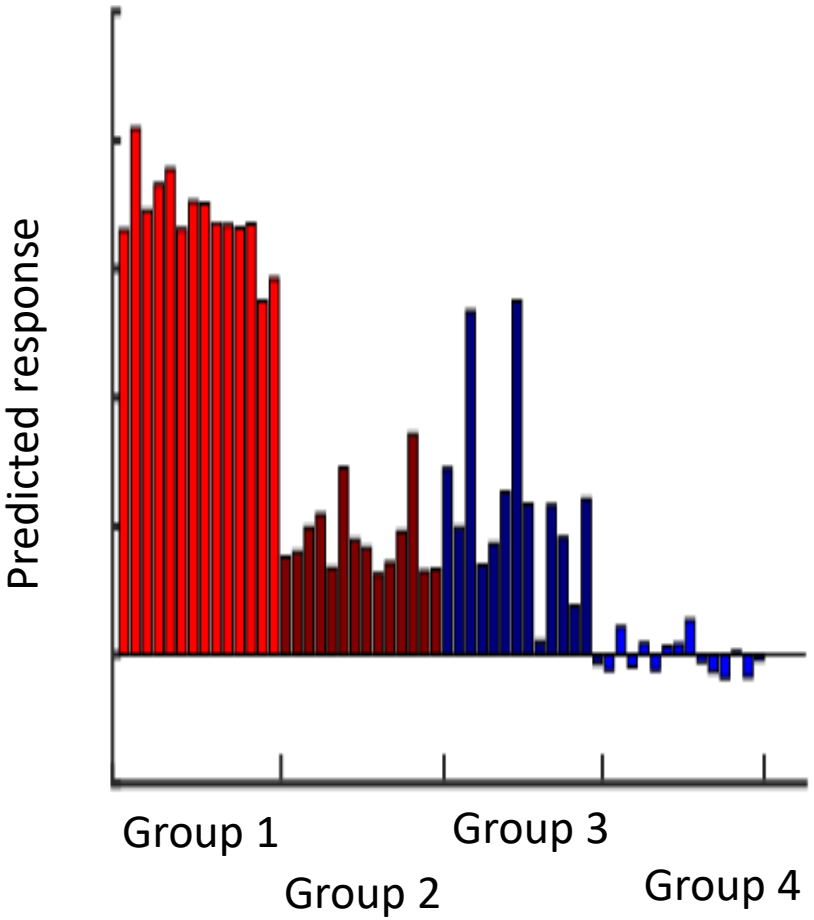
Group 3

Group 4

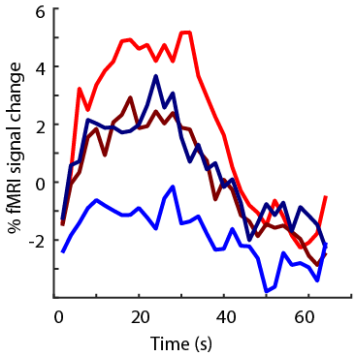




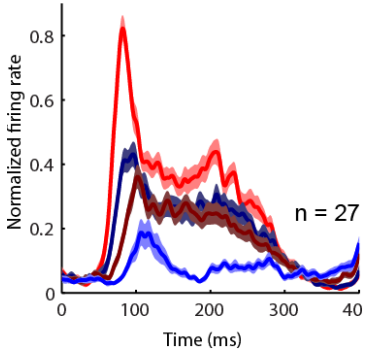
Body patch selectivity



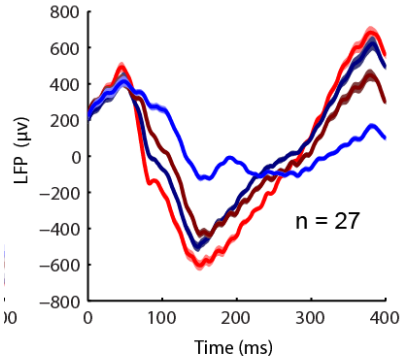
fMRI



SUA



LFP

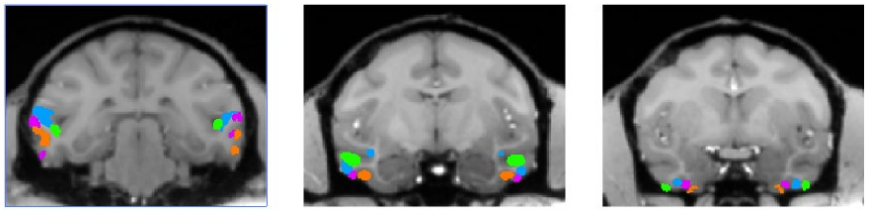


Predictions

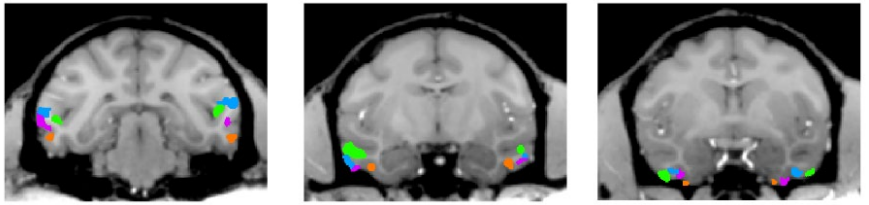
- Predicting previous accounts of IT organization
- Predicting shape rather than semantic selectivity
- Predicting responses to new stimuli

fmri experiments with new stimuli

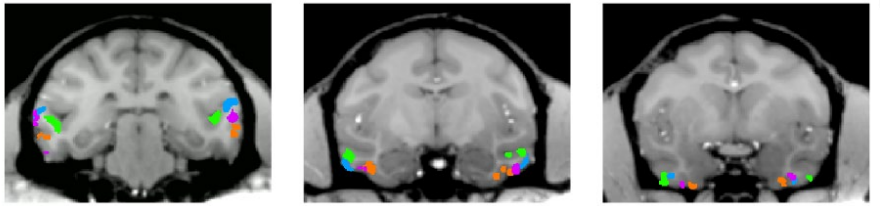
Real objects



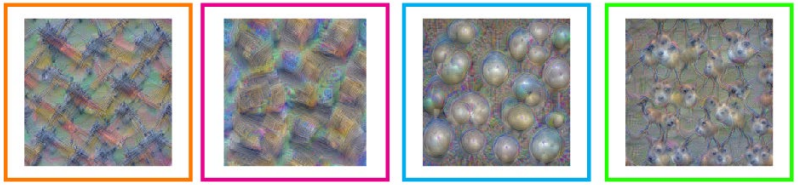
Silhouettes

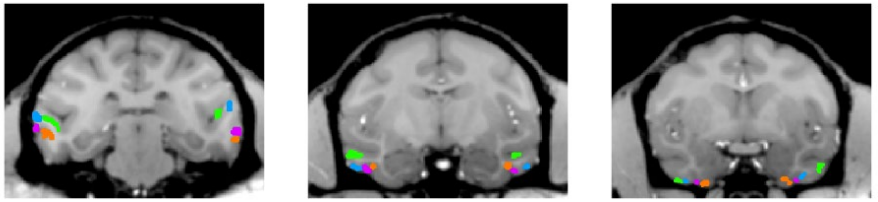


Fake objects

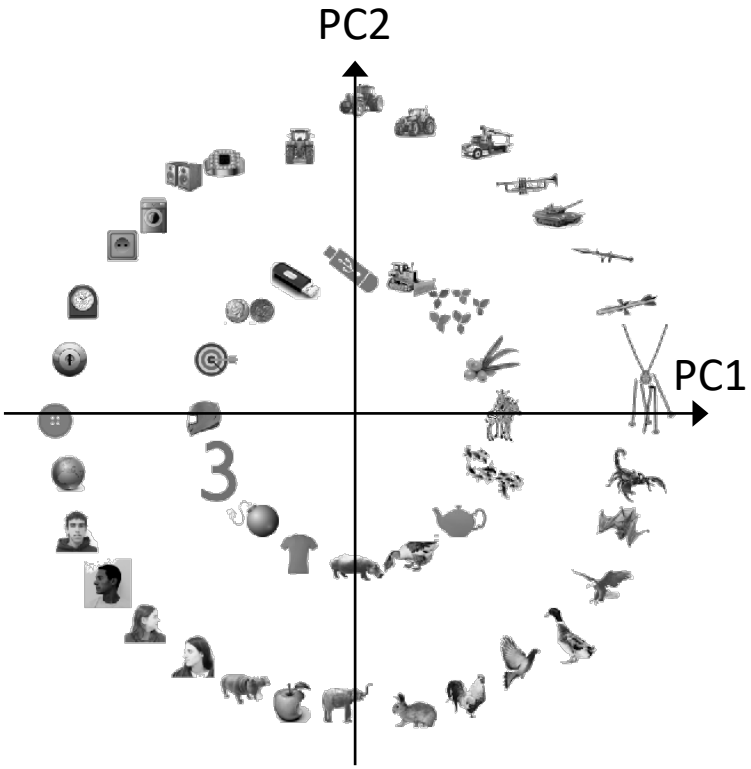


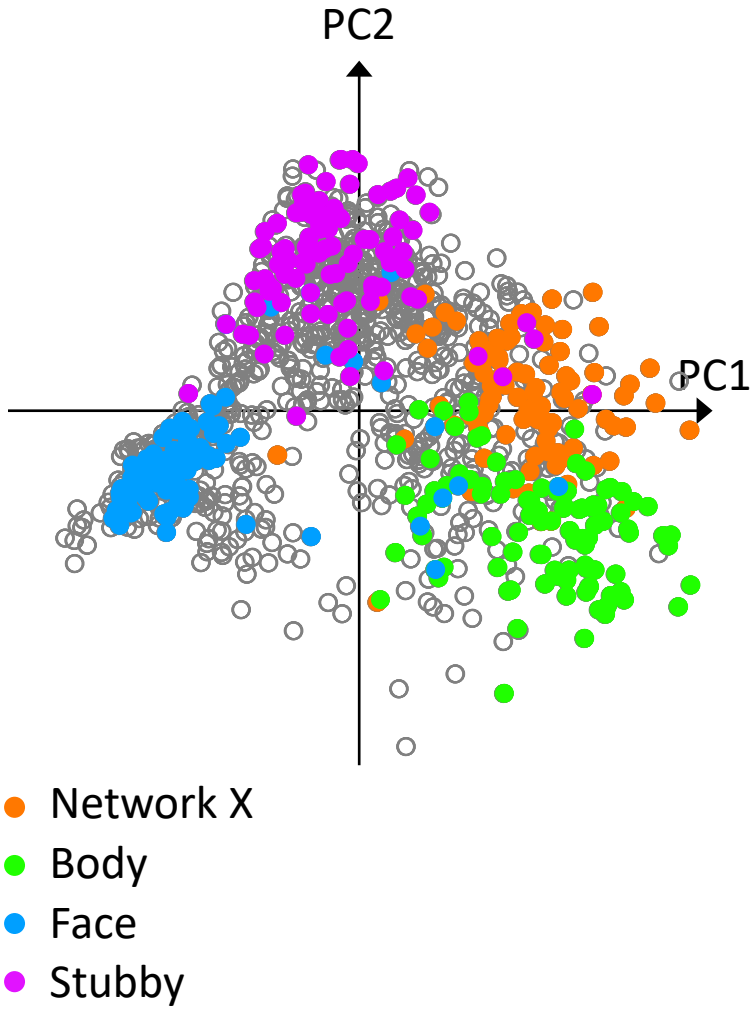
Deep dream





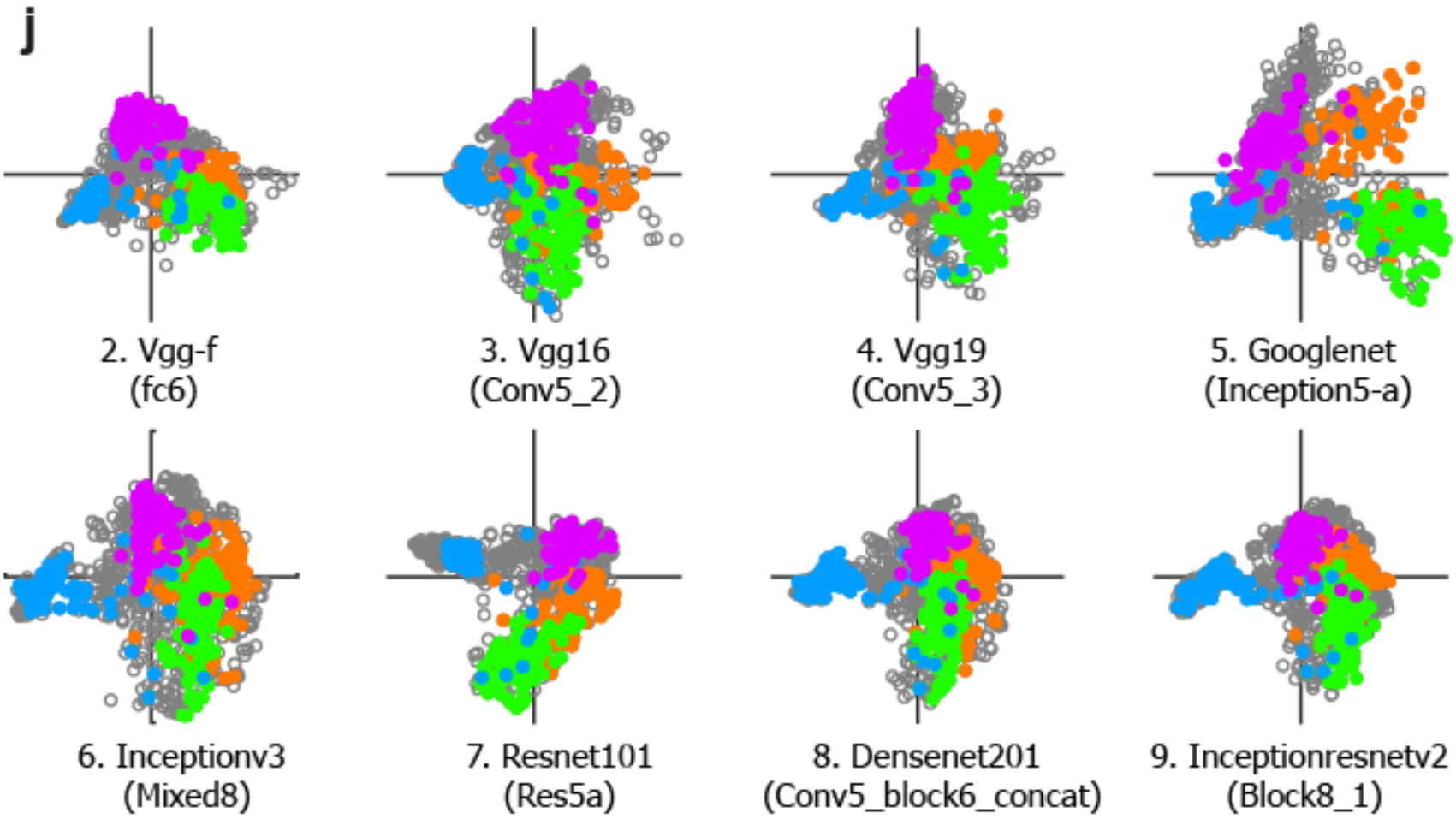
The similar object spaces exist in other supervised-learning networks



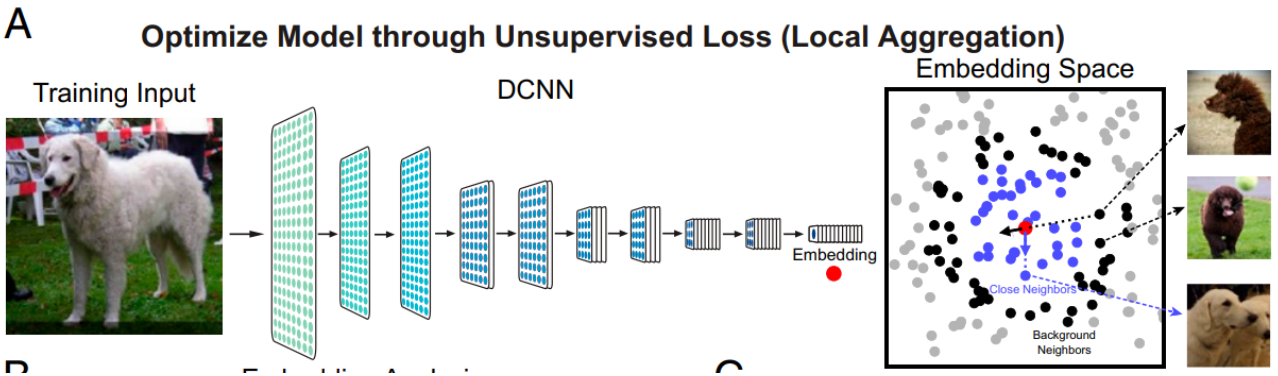


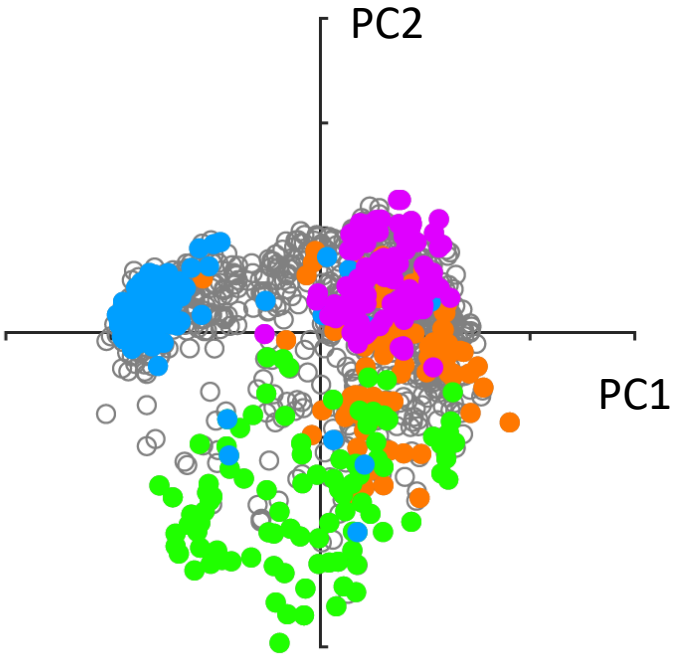
- The structure of the network
- Supervised learning and Unsupervised learning
- The images used in the training set (the visual experience)

The structure of the network



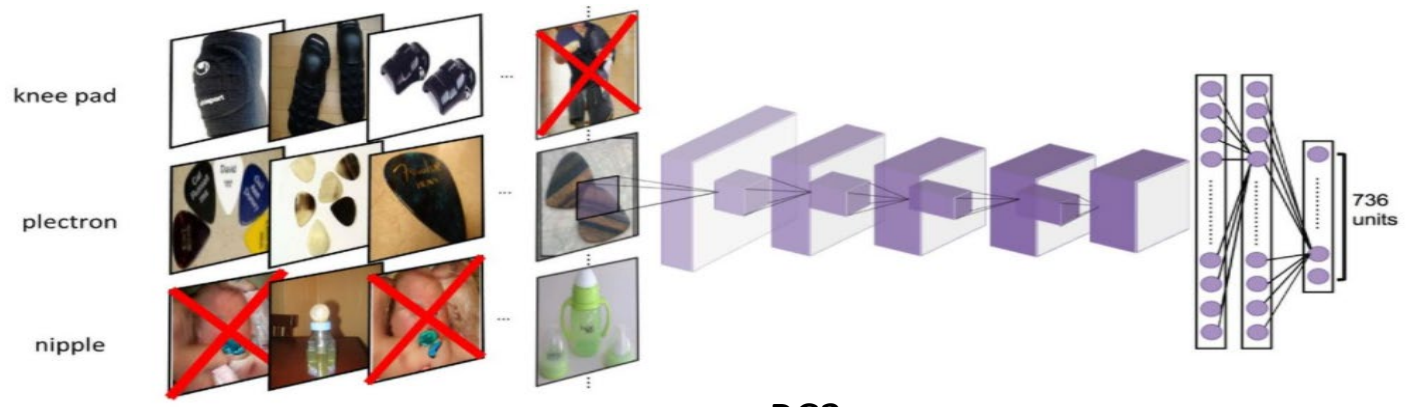
Unsupervised learning

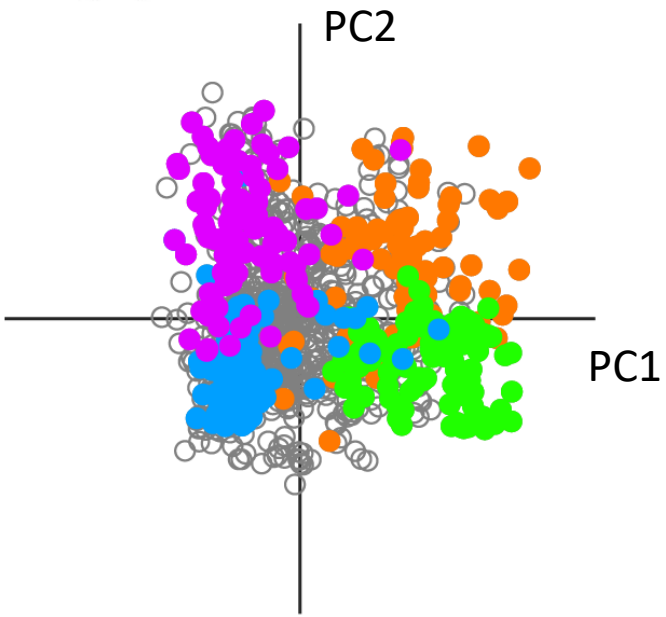




Zhuang et al., 2021

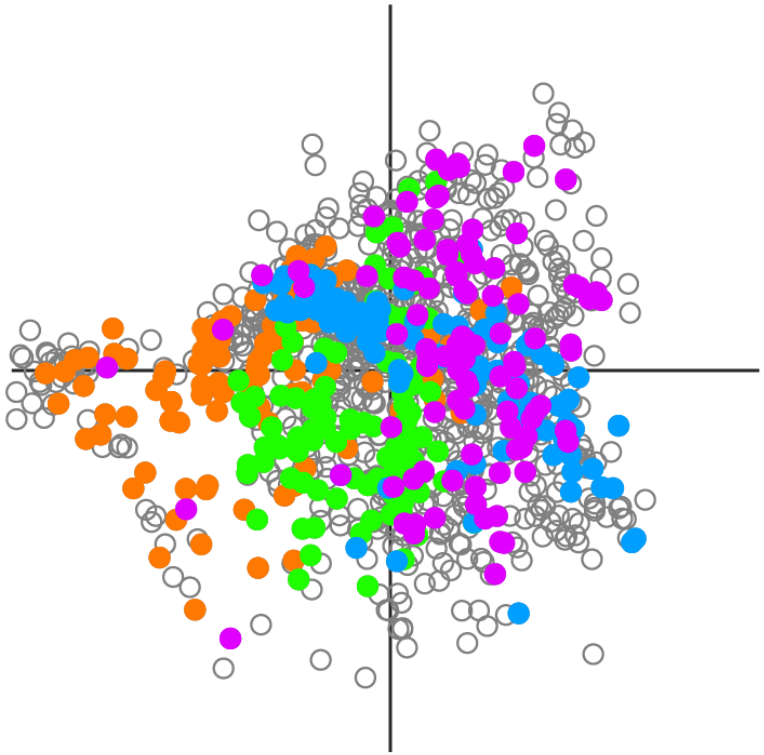
Visual experience





Xu et al., 2021

The object space doesn’t exist in the un-trained network



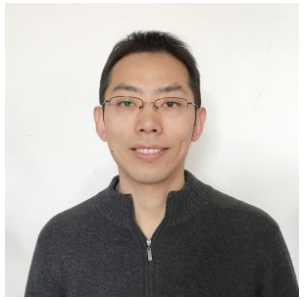
IT organization

- Cells are anatomically clustered into four networks according to the first two components of their preferred axes, forming a map of object space.
- This map is repeated across three stages of increasing view invariance.
- Cells comprising these maps harbor sufficient coding capacity to approximately reconstruct objects.
- Similar object spaces can be observed in trained networks.

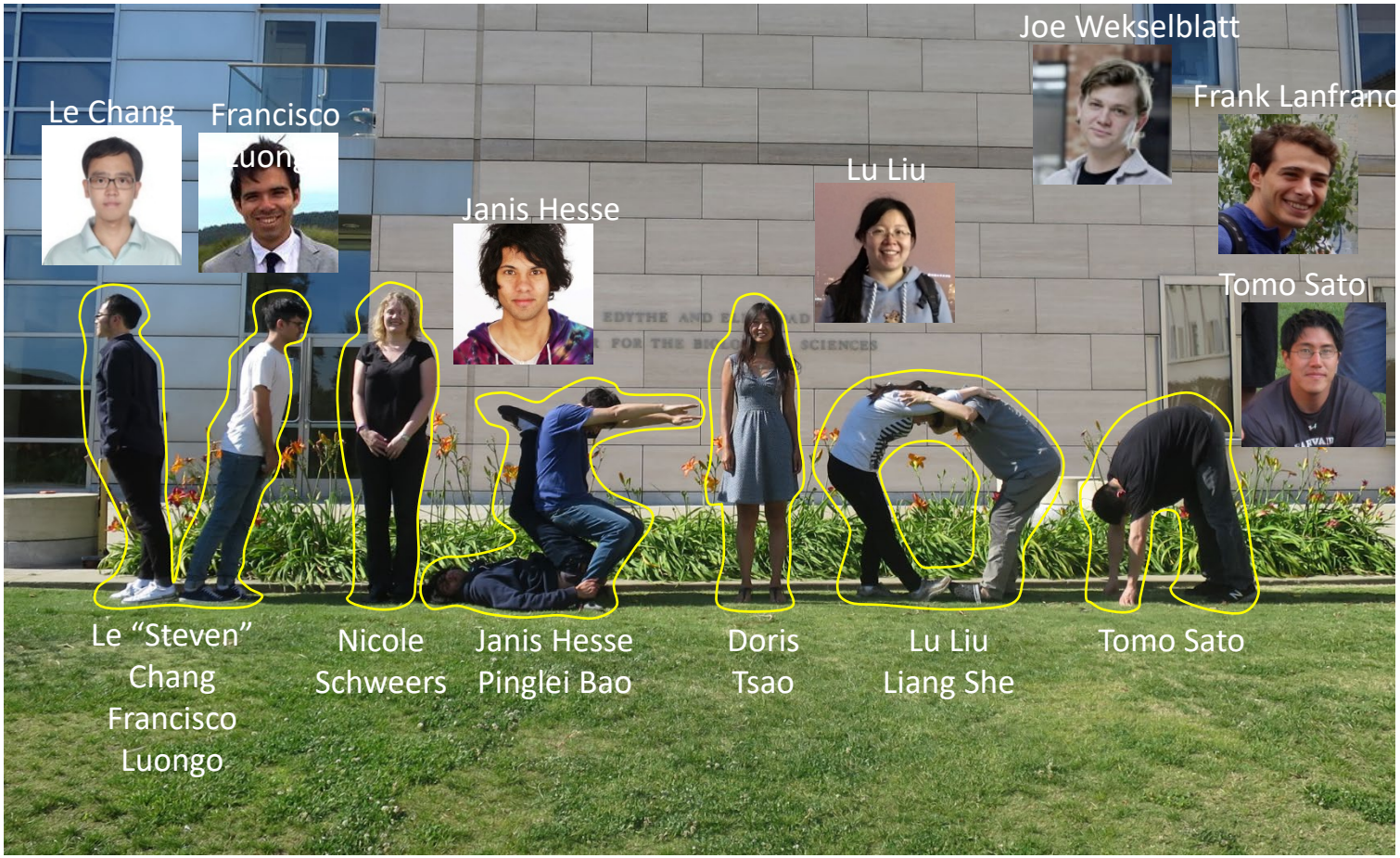
Thank you!

Doris Tsao

Liang She



Mason McGill



Funding: NIH, HHMI, Mcknight, Simons, HFSP, TC Chen Institute