Neural Coding
Lecture 1. Introduction

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SoSe, 2025

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Mathematical Faculty

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Max-Planck-Institut für
Mathematik
in den Naturwissenschaften

MPI for Mathematics
in the Sciences

Institute of Science and Technology Austria

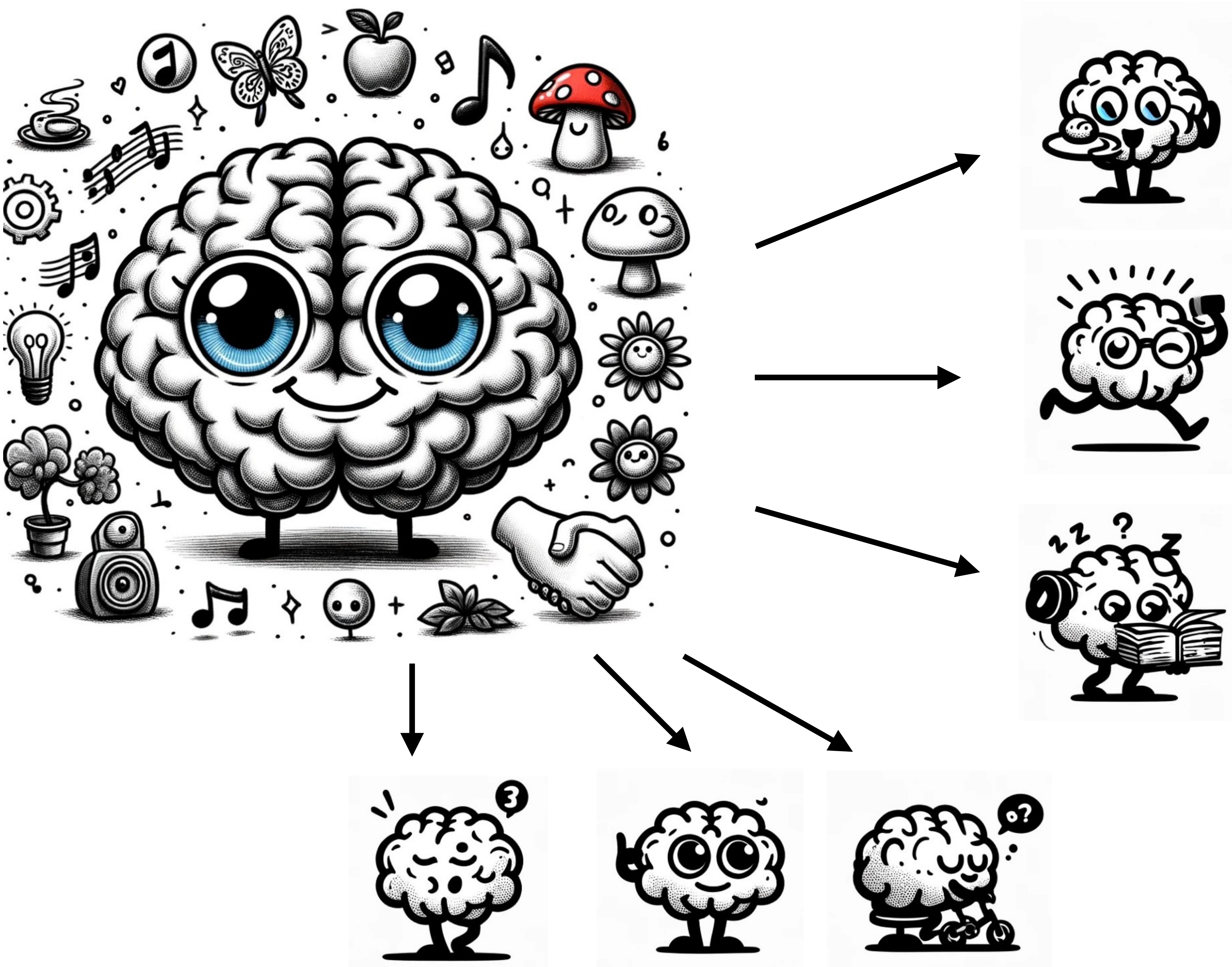
IST AUSTRIA
Institute of Science and Technology

SEVENTH FRAMEWORK PROGRAMME

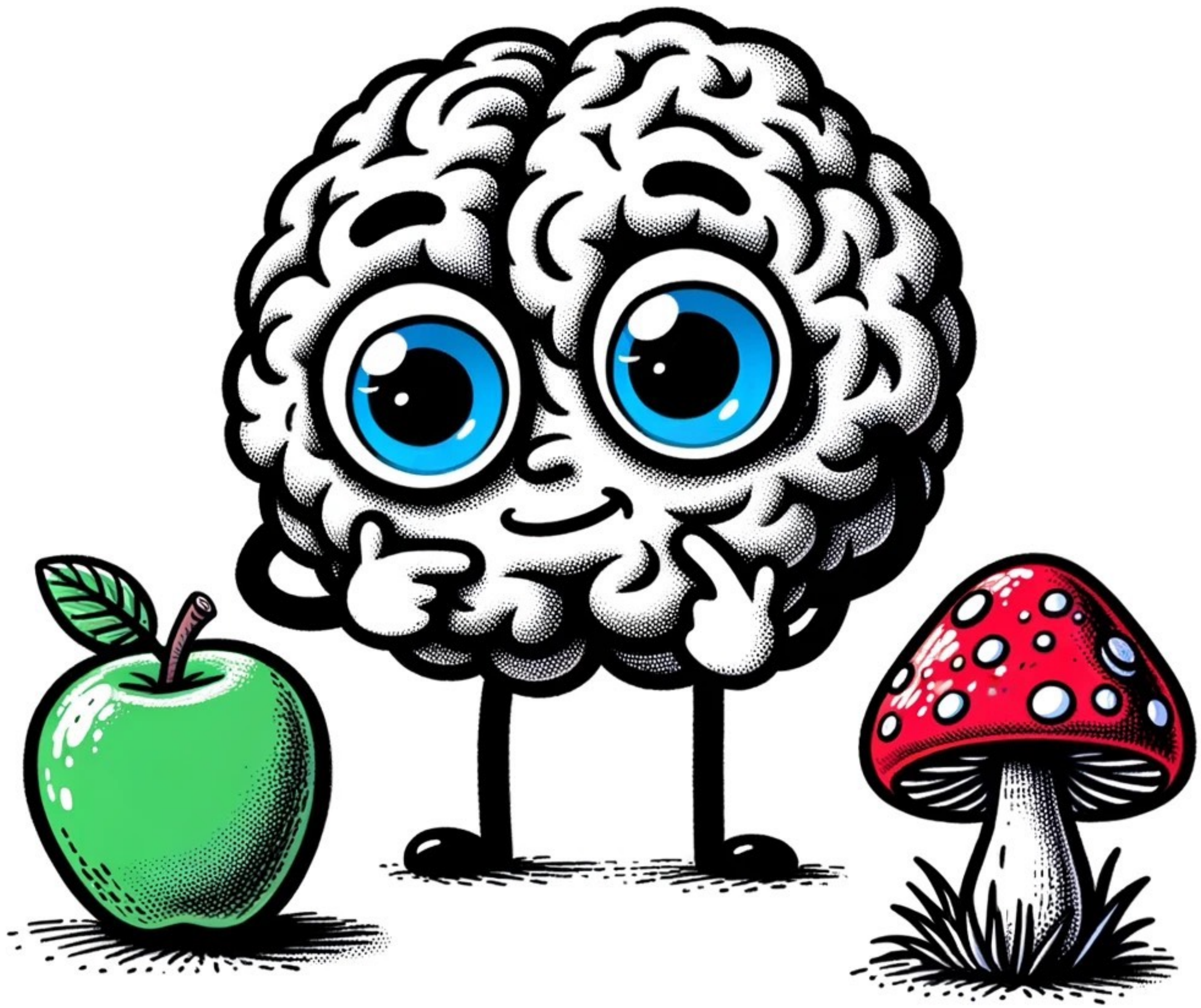
MARIE CURIE ACTIONS

What is the main thing the brain is doing?

Brain has to represent stimuli to generate behavior



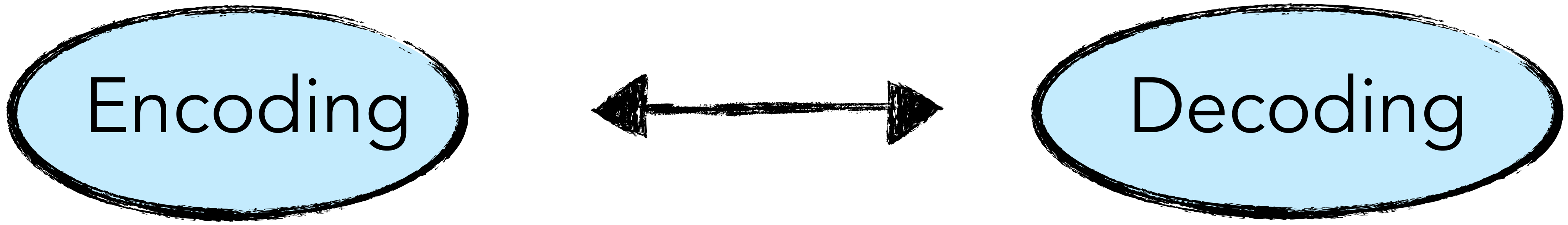
Simpler problem



Our main question

How does the brain represent information about the external world “well enough” to produce the behavior?

Encoding - decoding



stimulus → responce

responce → stimulus

P(response | stimulus)

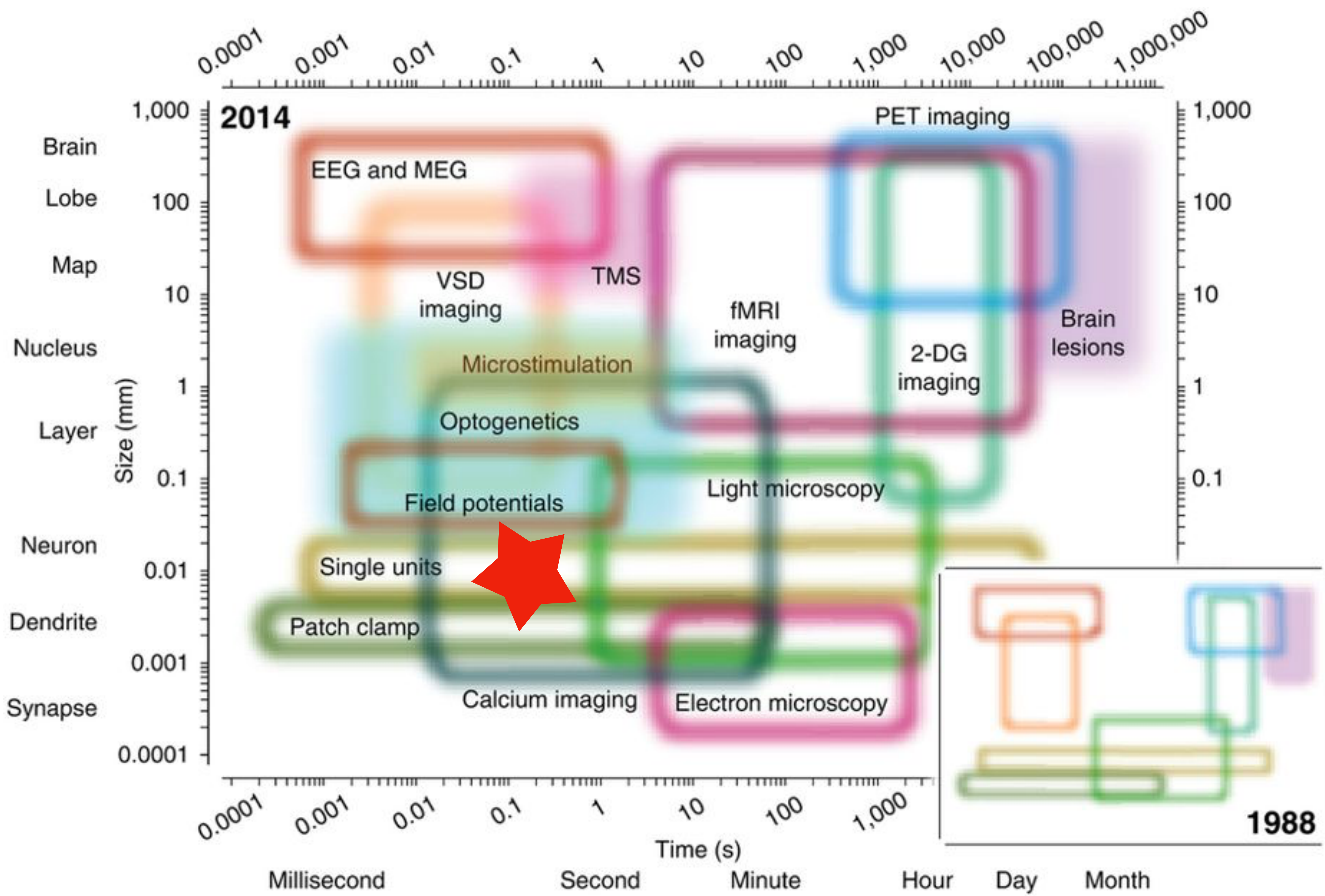
P(stimulus | response)

What is the response?

What is the stimulus?

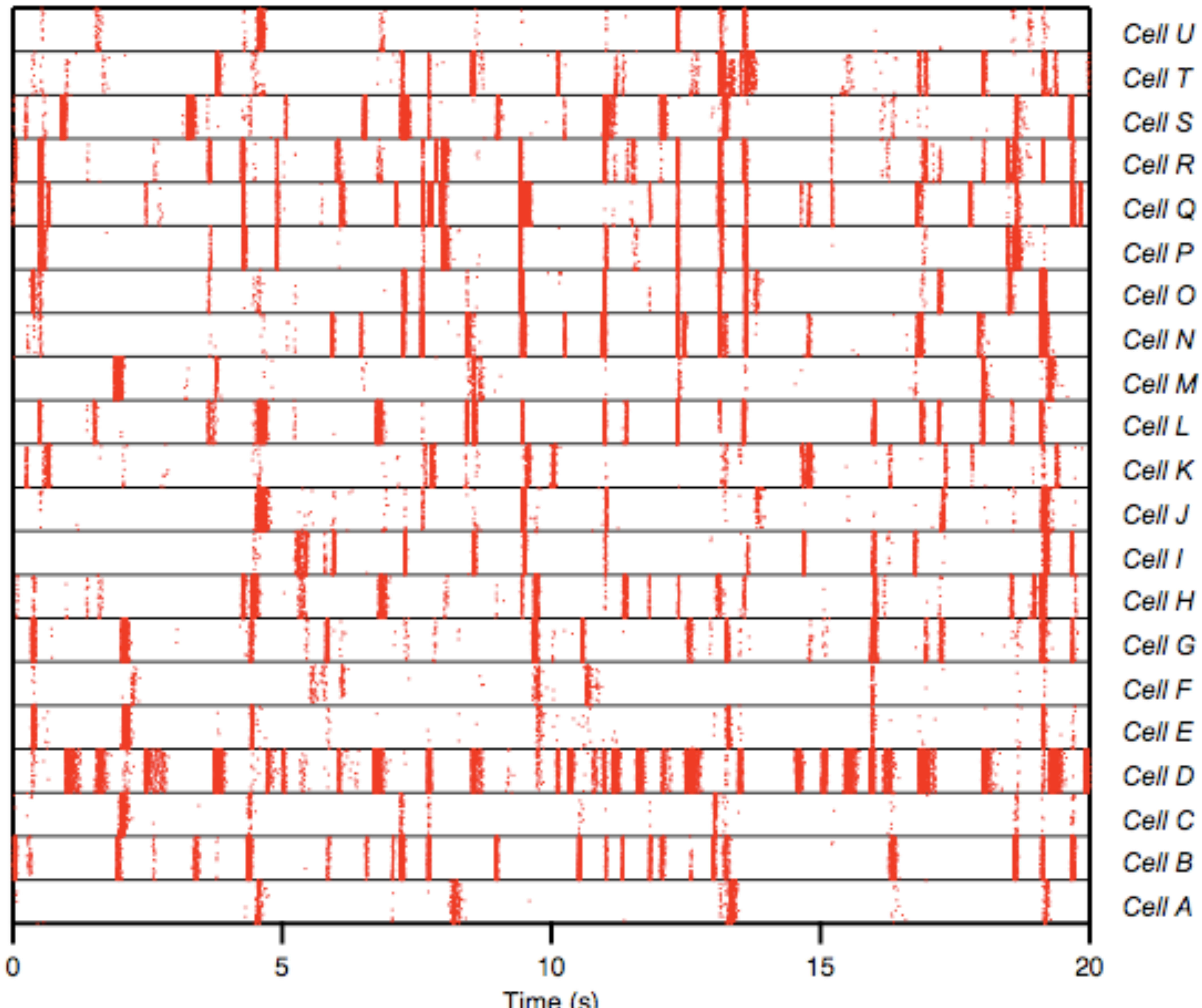
What is the relationship between them?

Our data



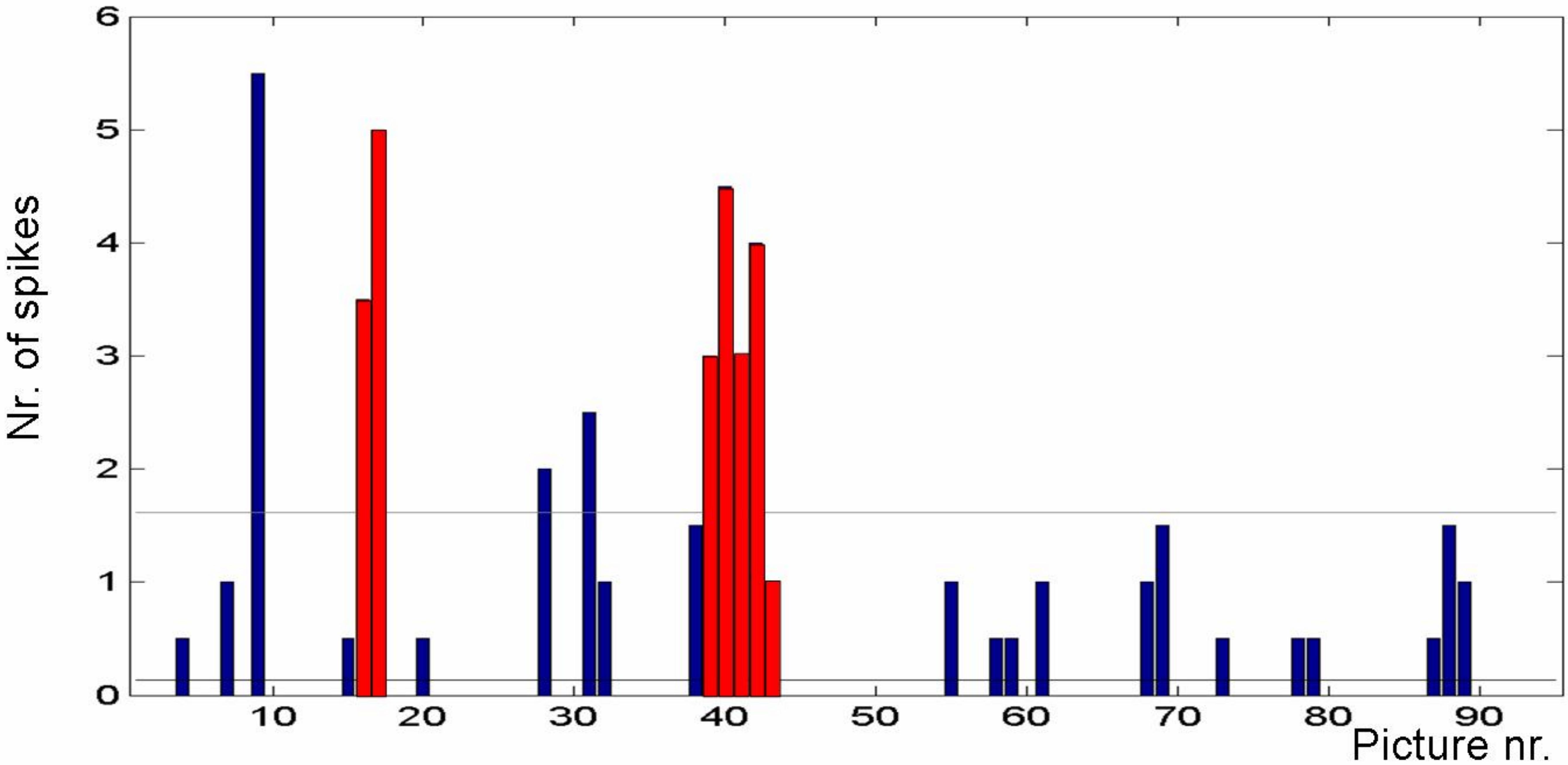
Sejnowski, Churchland, Movshon, Nature Neuro 2014

What spikes code for?



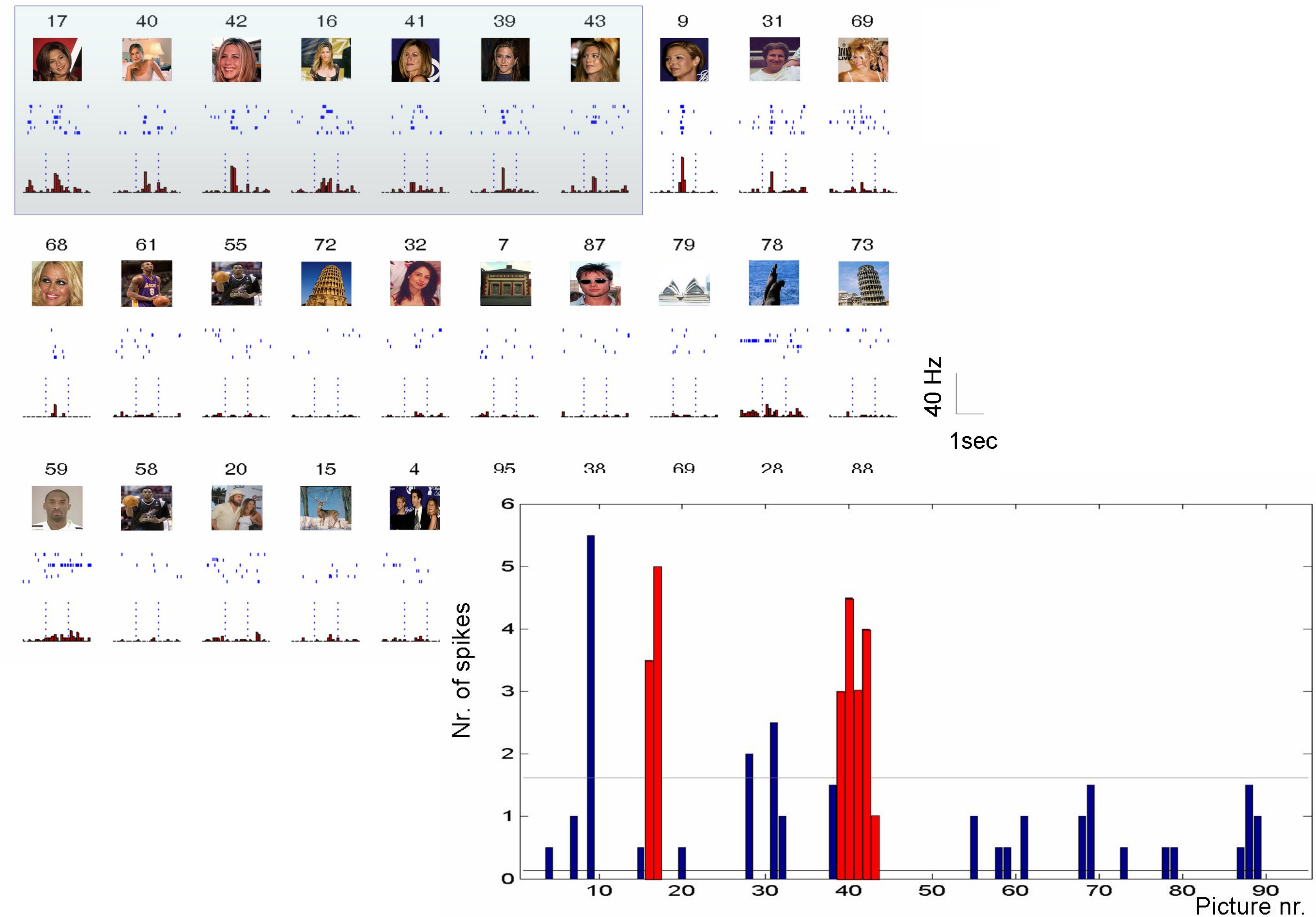
Michael J. Berry II

Anecdotal example

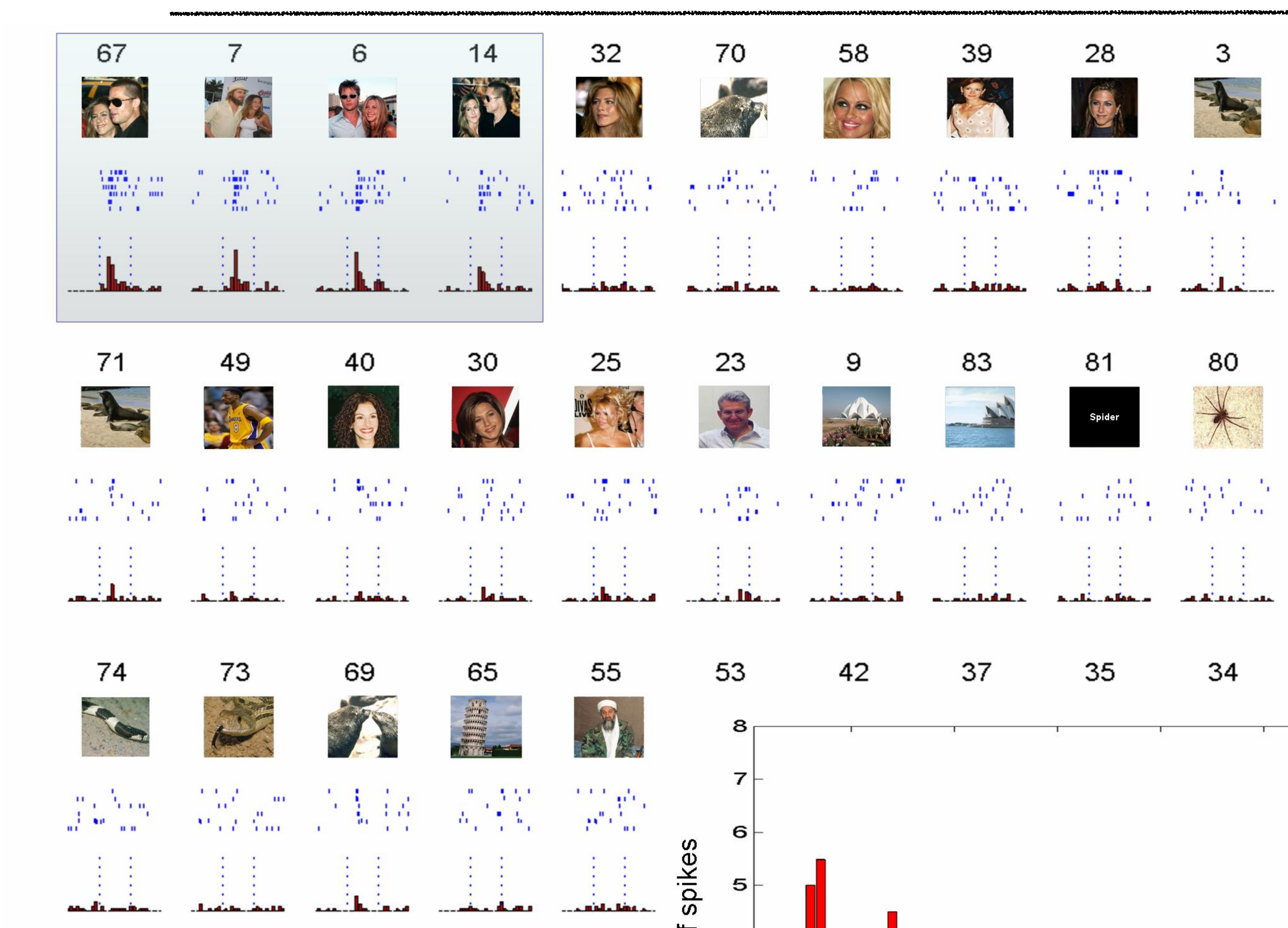


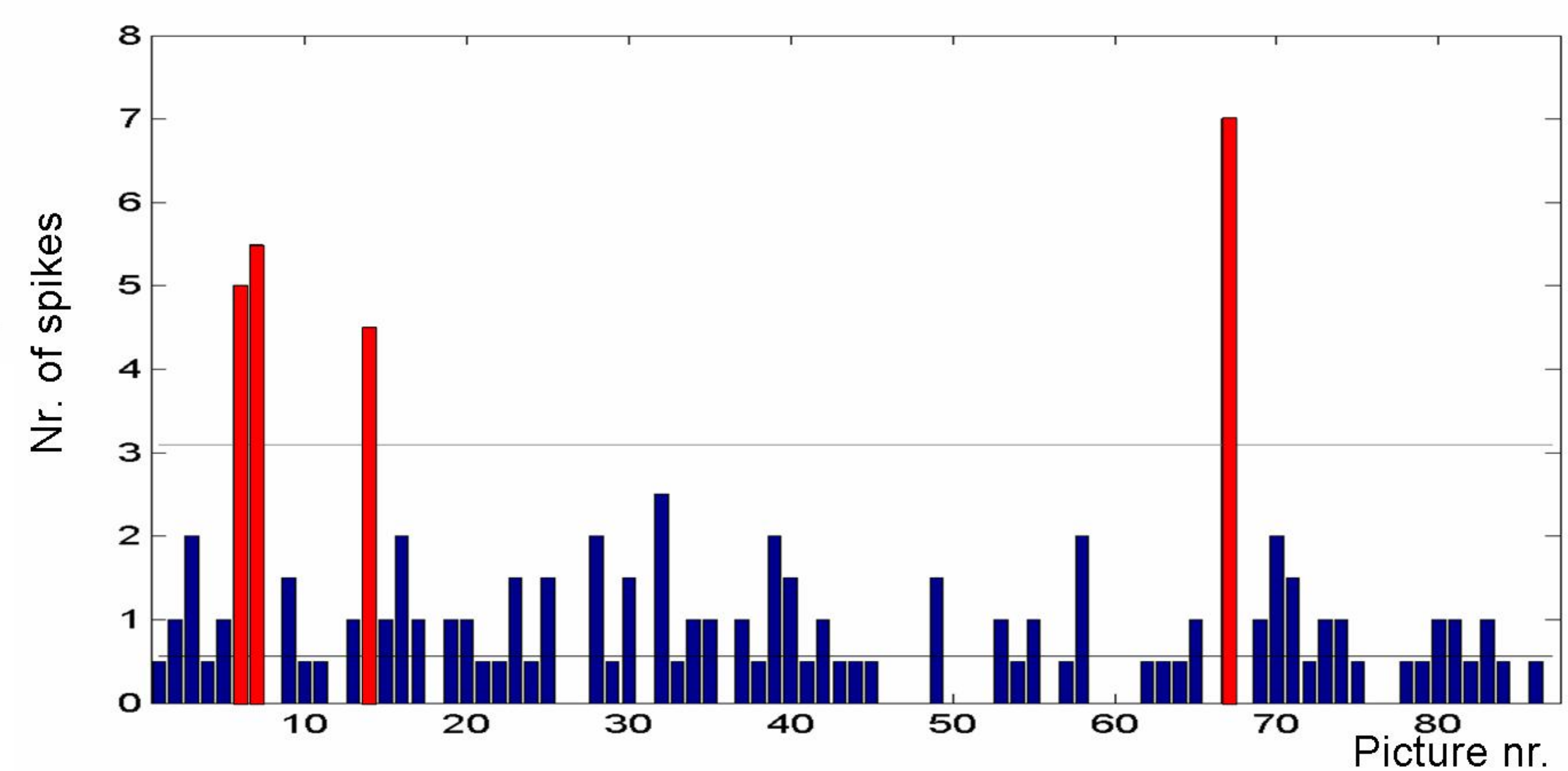
Quiroga et al., Nature 2005

Jennifer Aniston neuron!



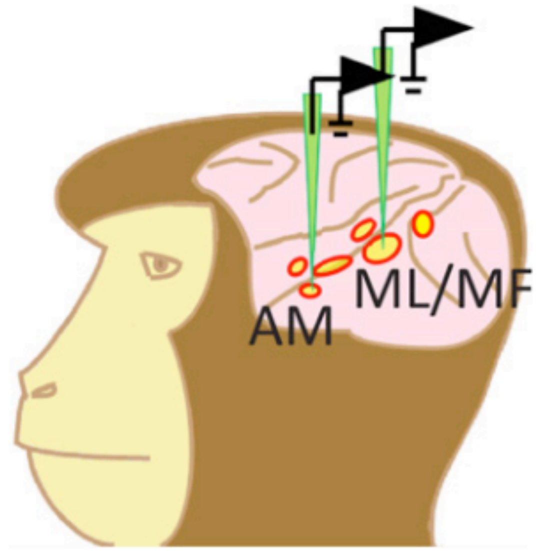
Quiroga et al., Nature 2005





Quiroga et al., Nature 2005

Are there concept cells in the primates?



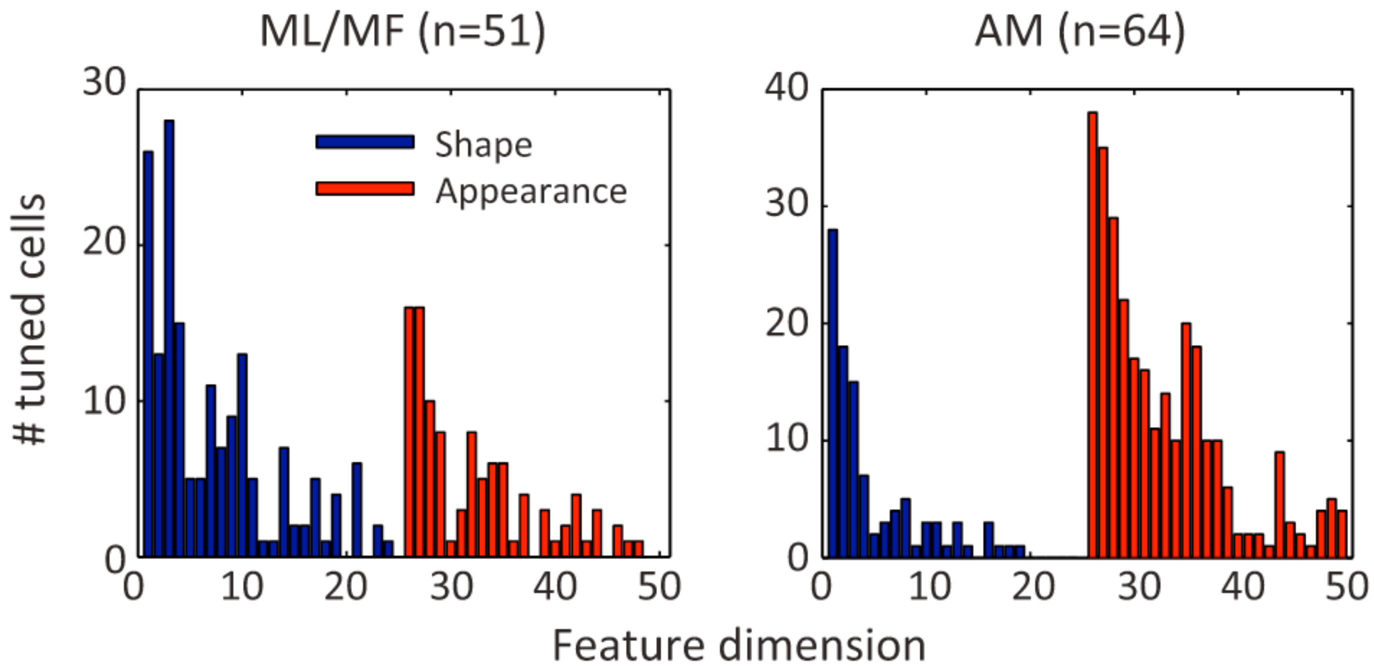
Shape

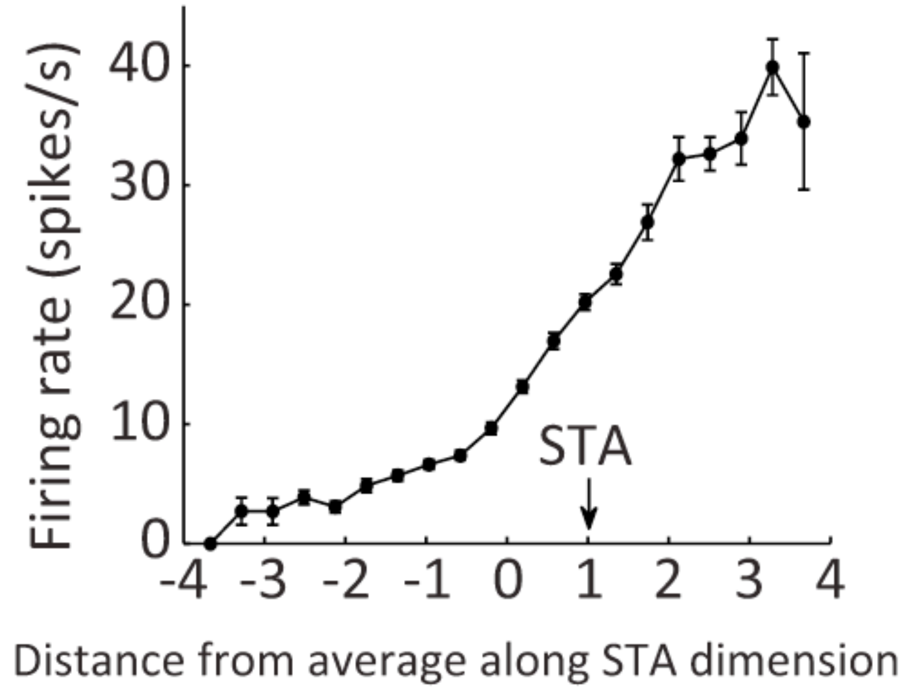
Shape-free appearance

PCA on shape (location of landmarks) and shape-free (landmarks are morphed to standard positions) faces. 50 dim representation

Le Chang, Doris Tsao, *Cell*, 2017

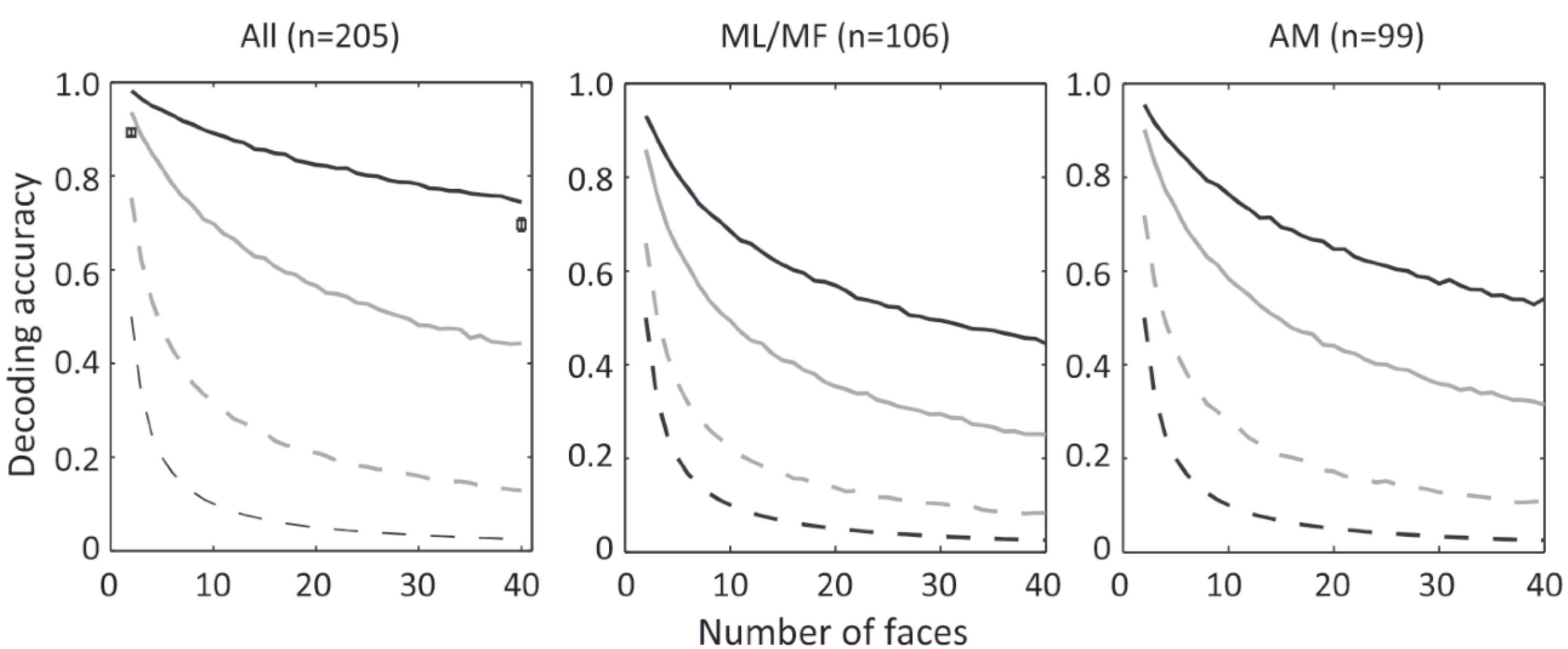
Are there concept cells in the primates?

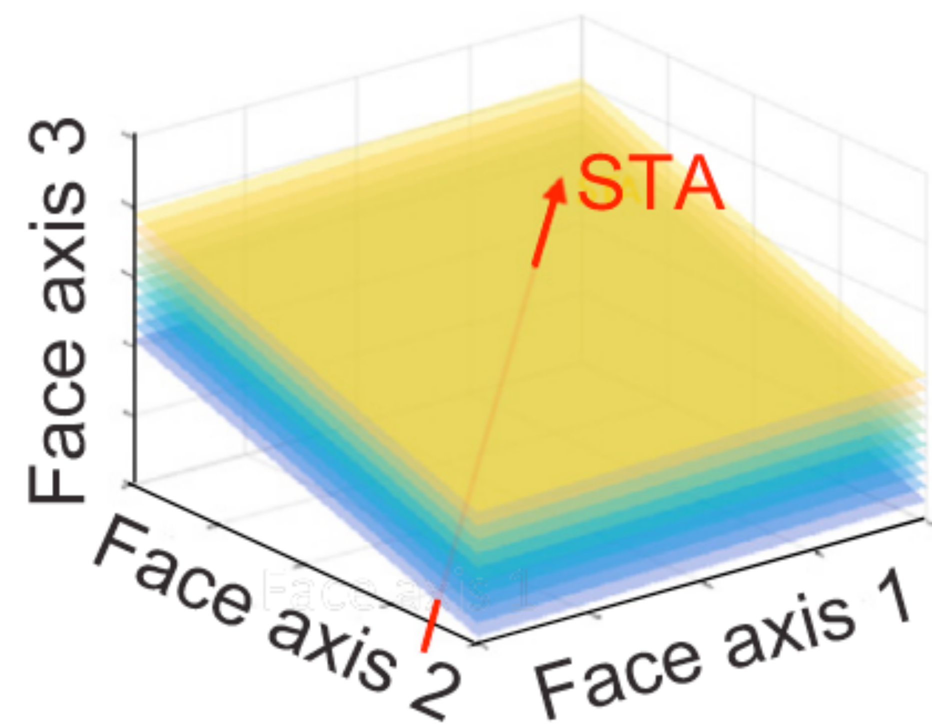




spike-triggered average (STA) stimulus = the average stimulus that triggered the neuron to fire, typically ~6 dim

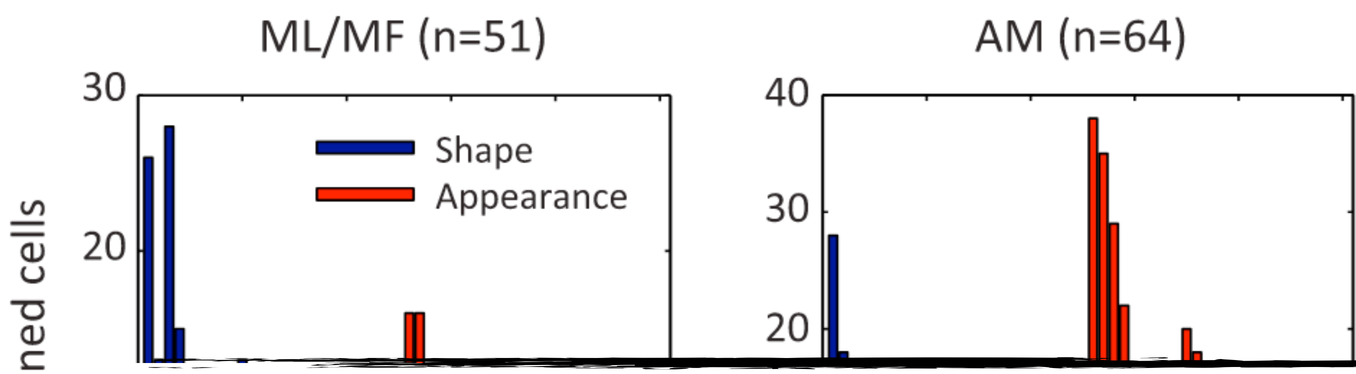
Decoding accuracy

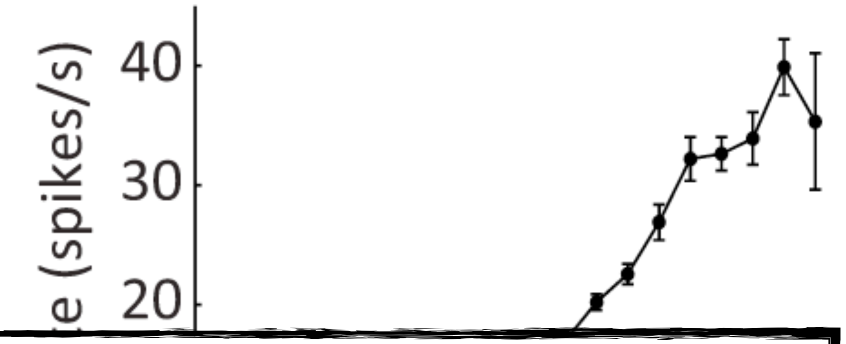




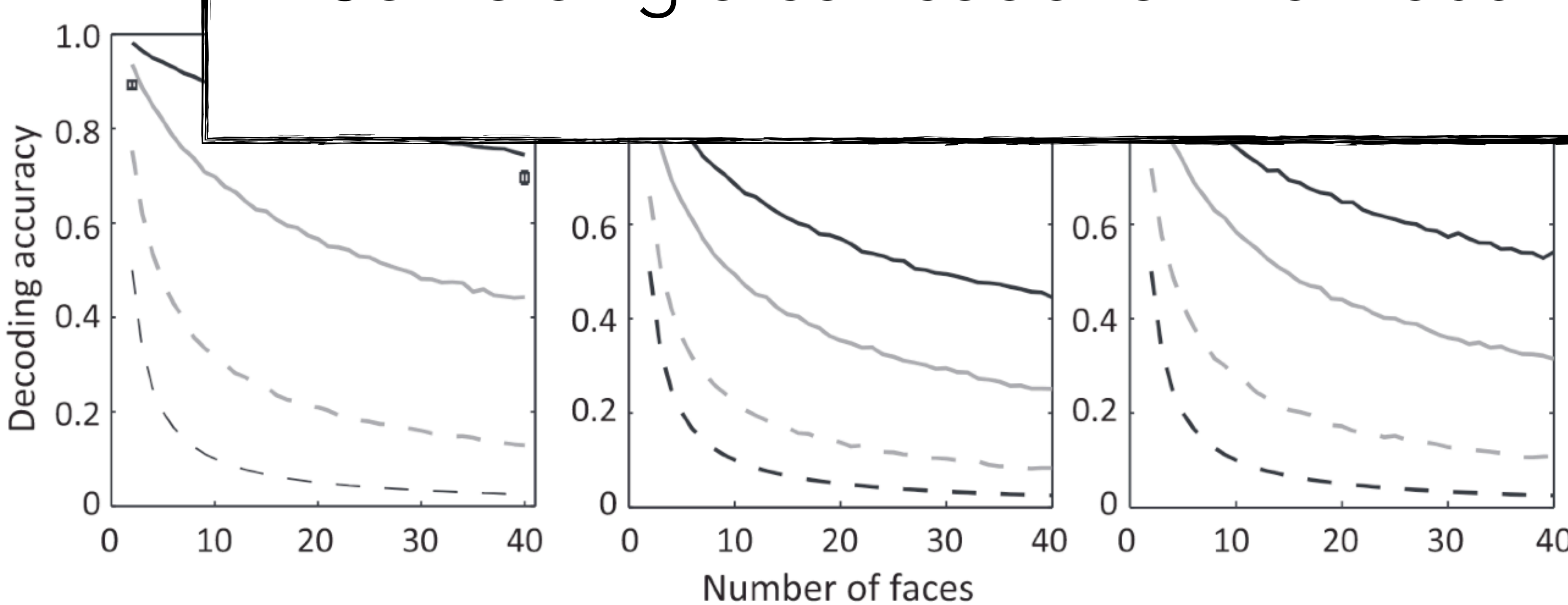
Le Chang, Doris Tsao, *Cell*, 2017

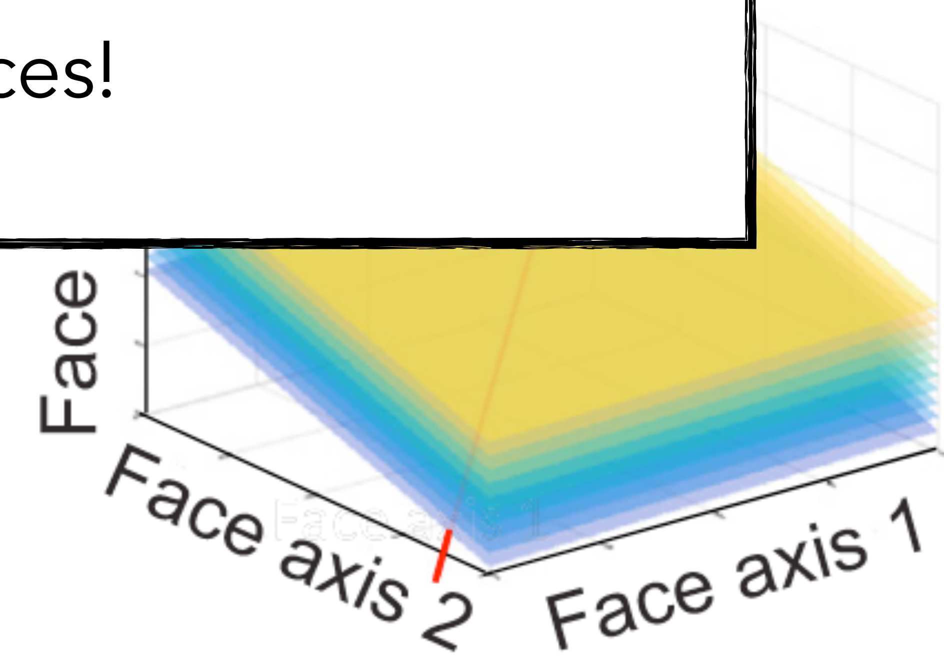
Are there concept cells in the primates?





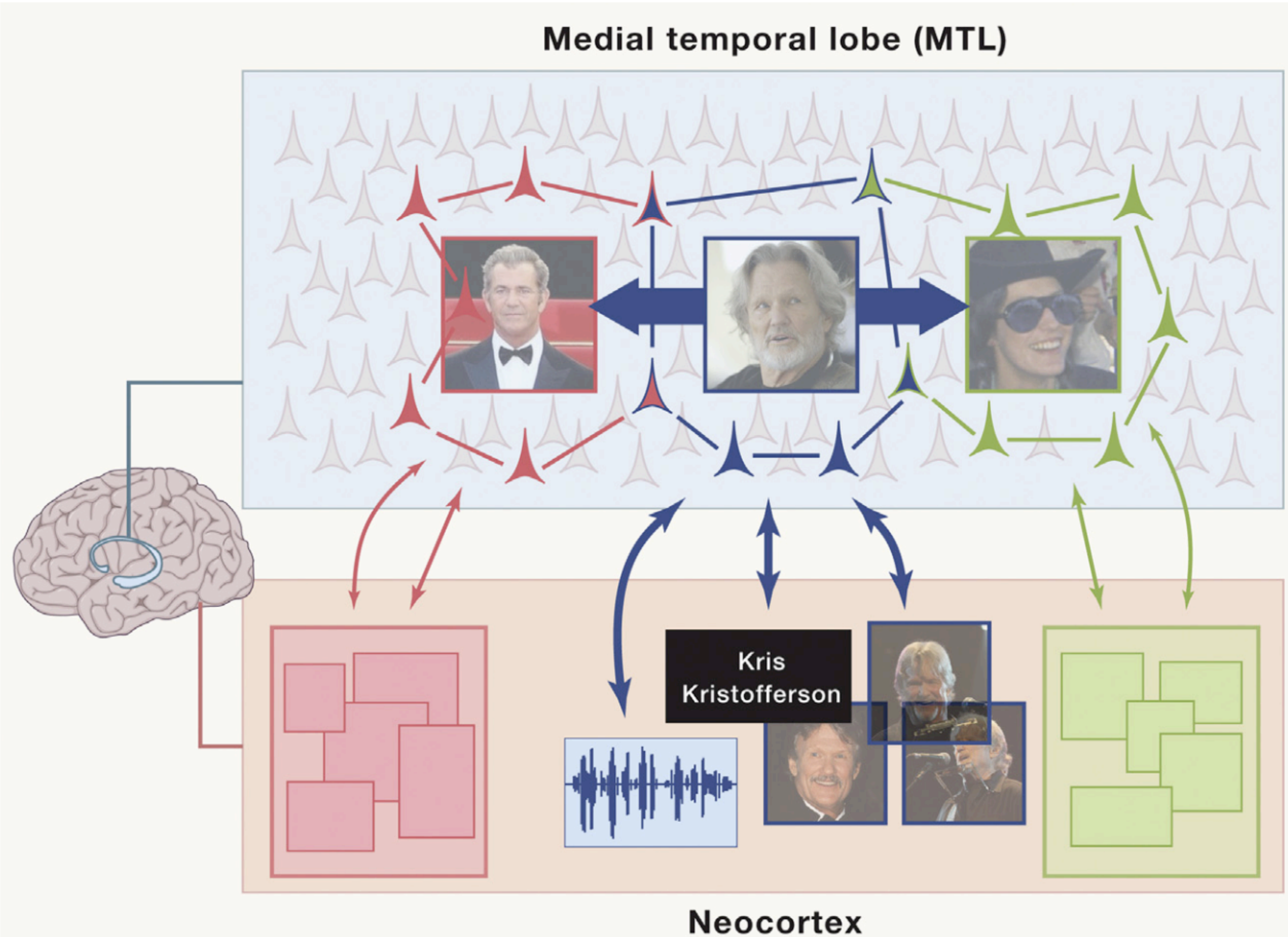
- Facial identity can be decoded from simple feature-code along specific feature axis.
- Perpendicular to the main feature axis, the response does not change if the face is varied
- So no single-cell code for individual faces!





Le Chang, Doris Tsao, *Cell*, 2017

Wait, not so simple!

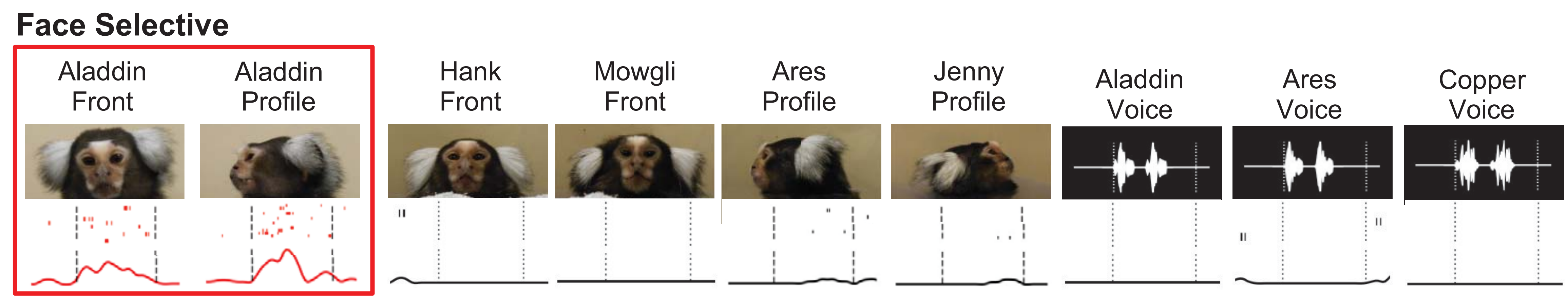


Concept cells is potentially something solely human. *(response latency to faces in humans is double of other primates)*

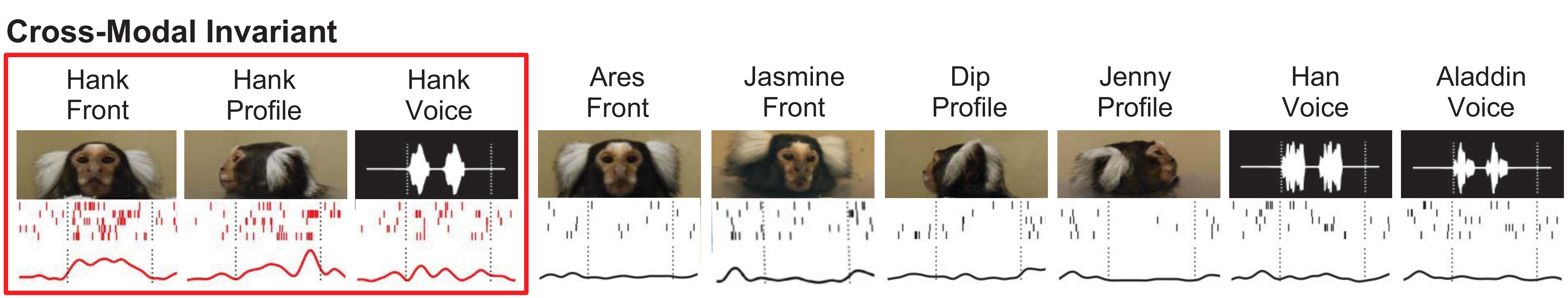
R.Q. Quiroga, *Cell*, 2019

Is it an end?

Face (images) and sounds selective neurons in the hippocampus of marmosets

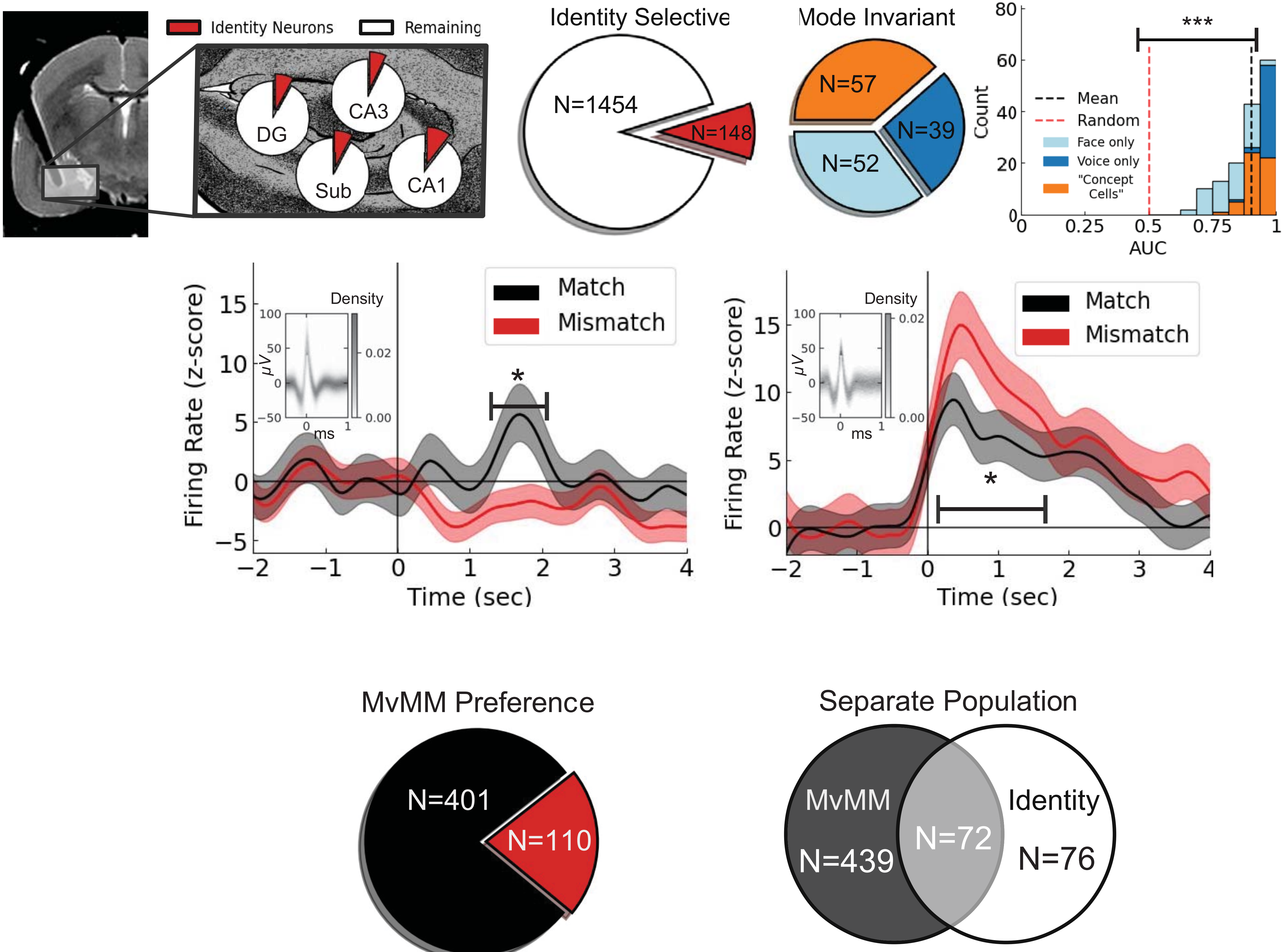


There are cross-modal neurons that respond to face and voice

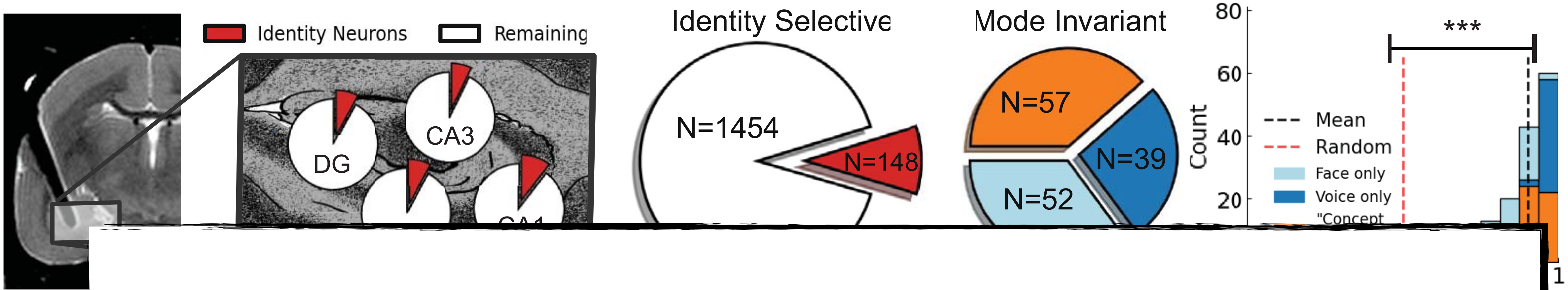


Tyree, Metke, Miller, *Science*, 2023

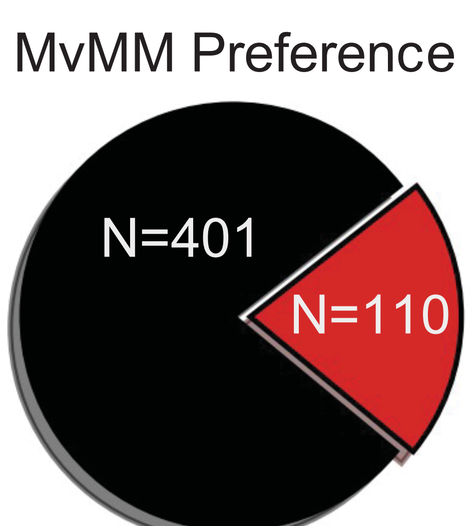
Multi-selectivity

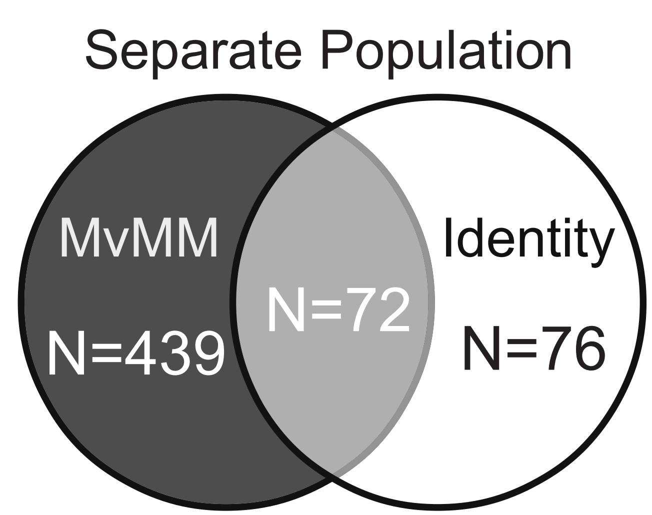


Multi-selectivity



- There are "identity cells"- candidates
- The coding of conspecifics relies *also* on distributed code
- (and they had a different criterion for "selective cells" so the question is still open)

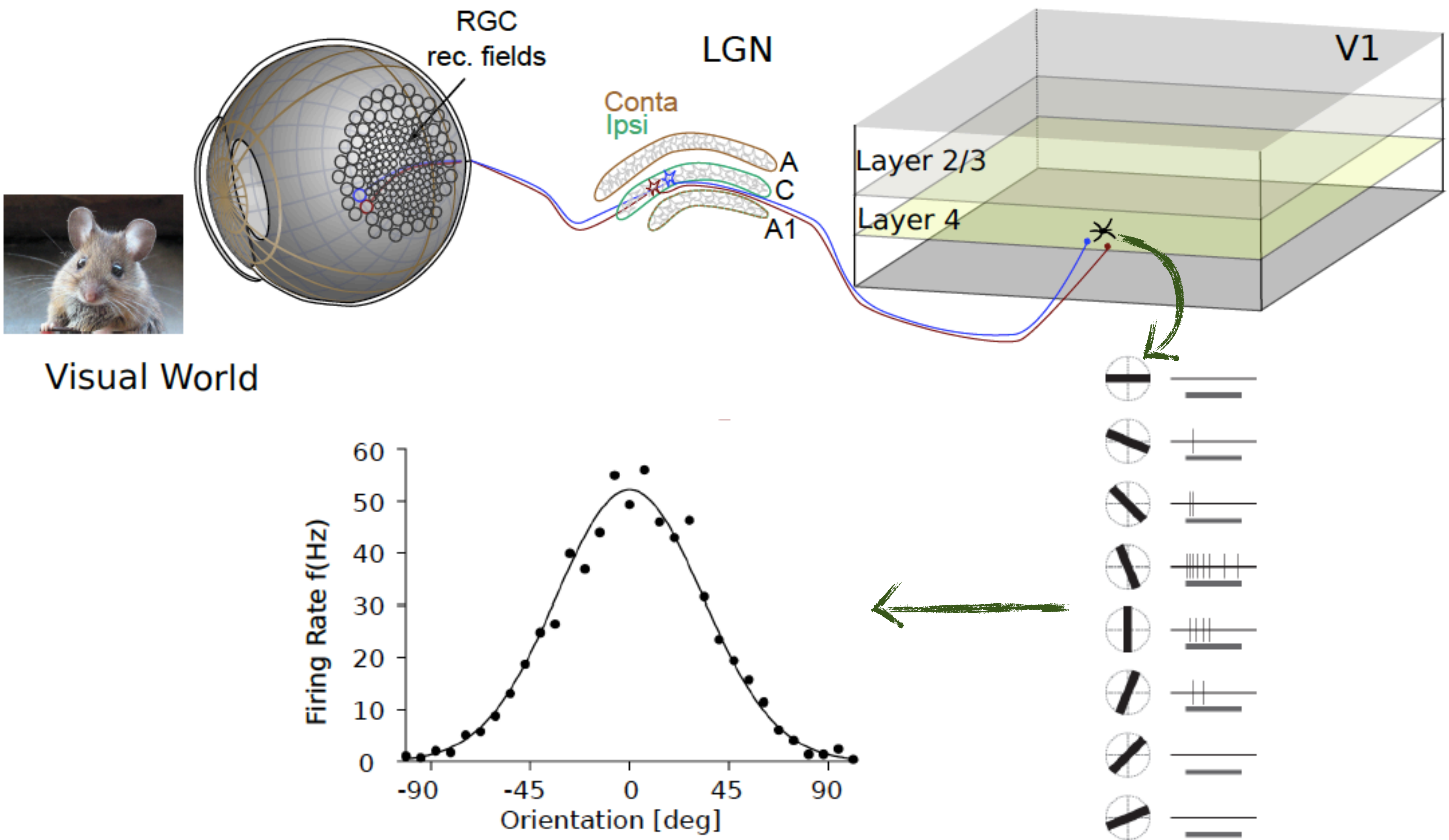




Approaching the problem form the other side

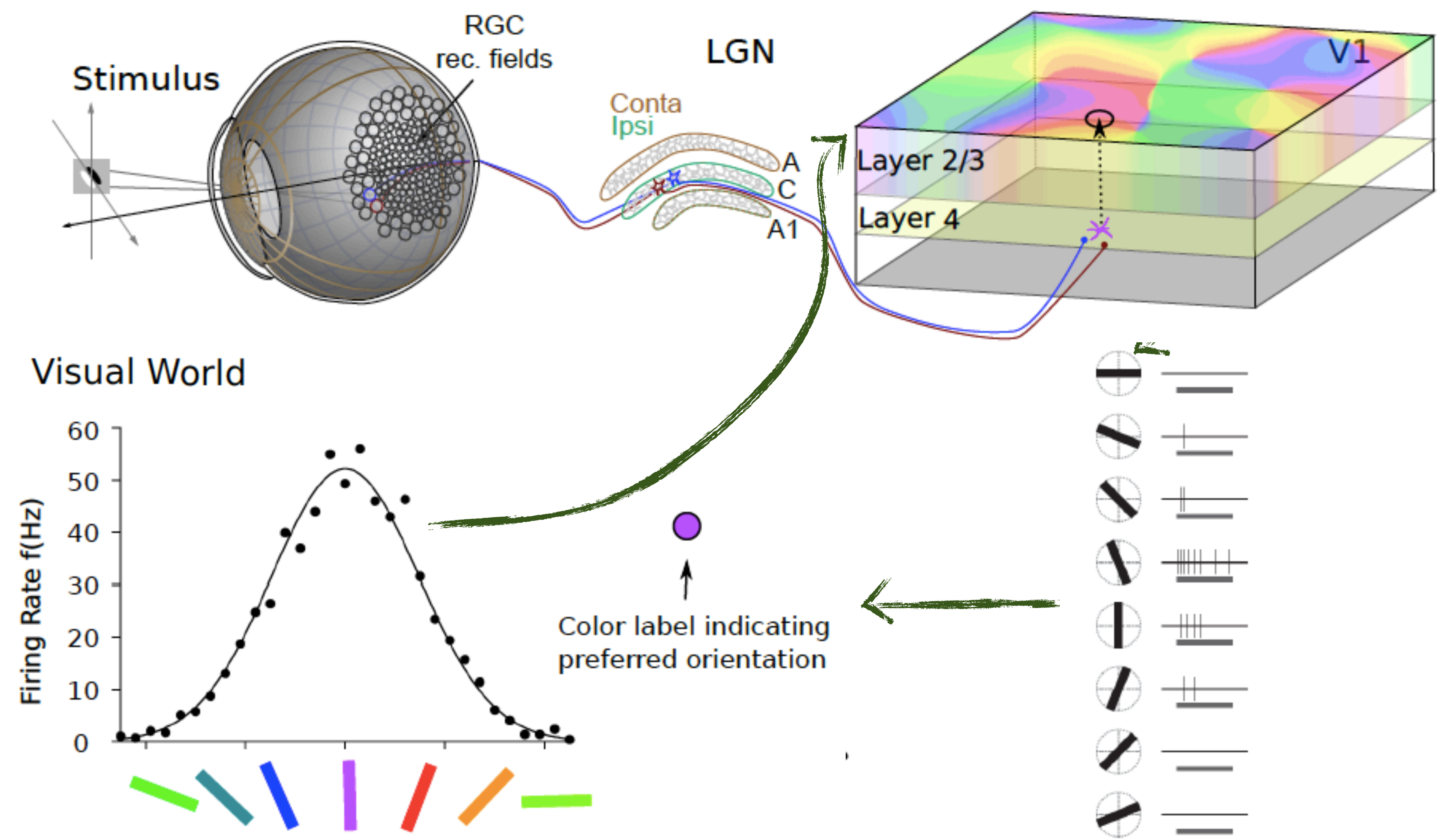
Are there interesting irregularities in neuronal firing that could be something important for optimising coding?

Visual system, technical design



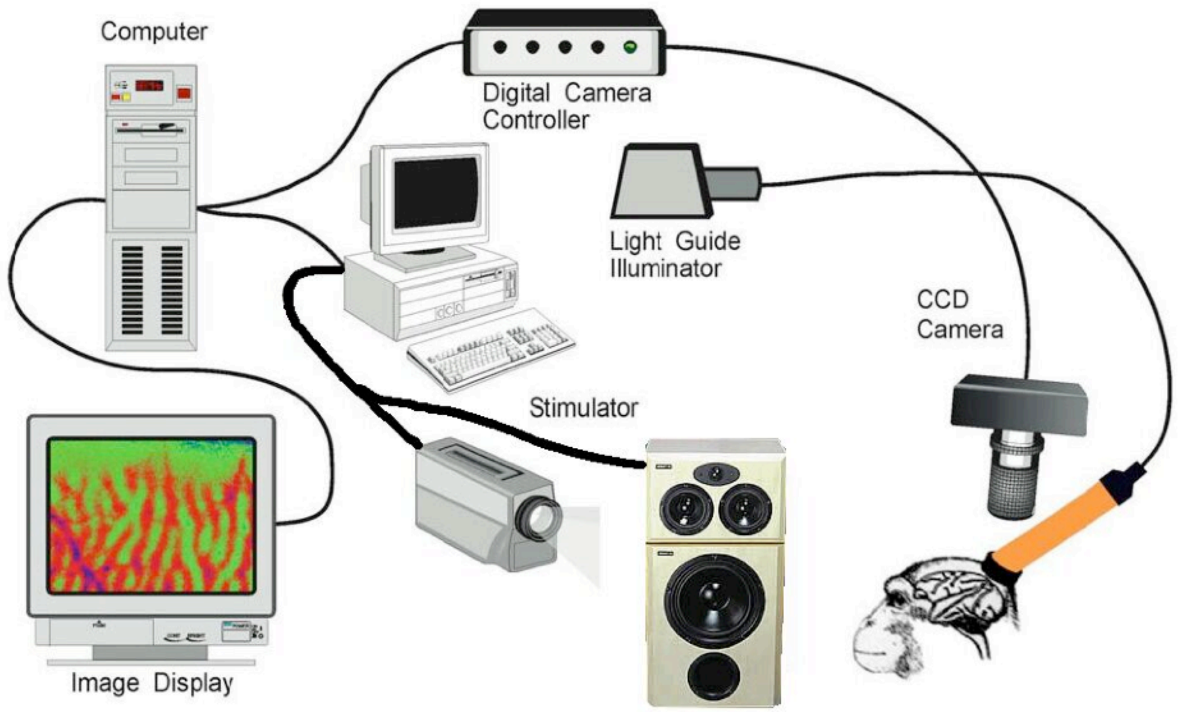
[Hubel & Wiesel J Physiol 1962, Grinvald et al. Nature 1986]

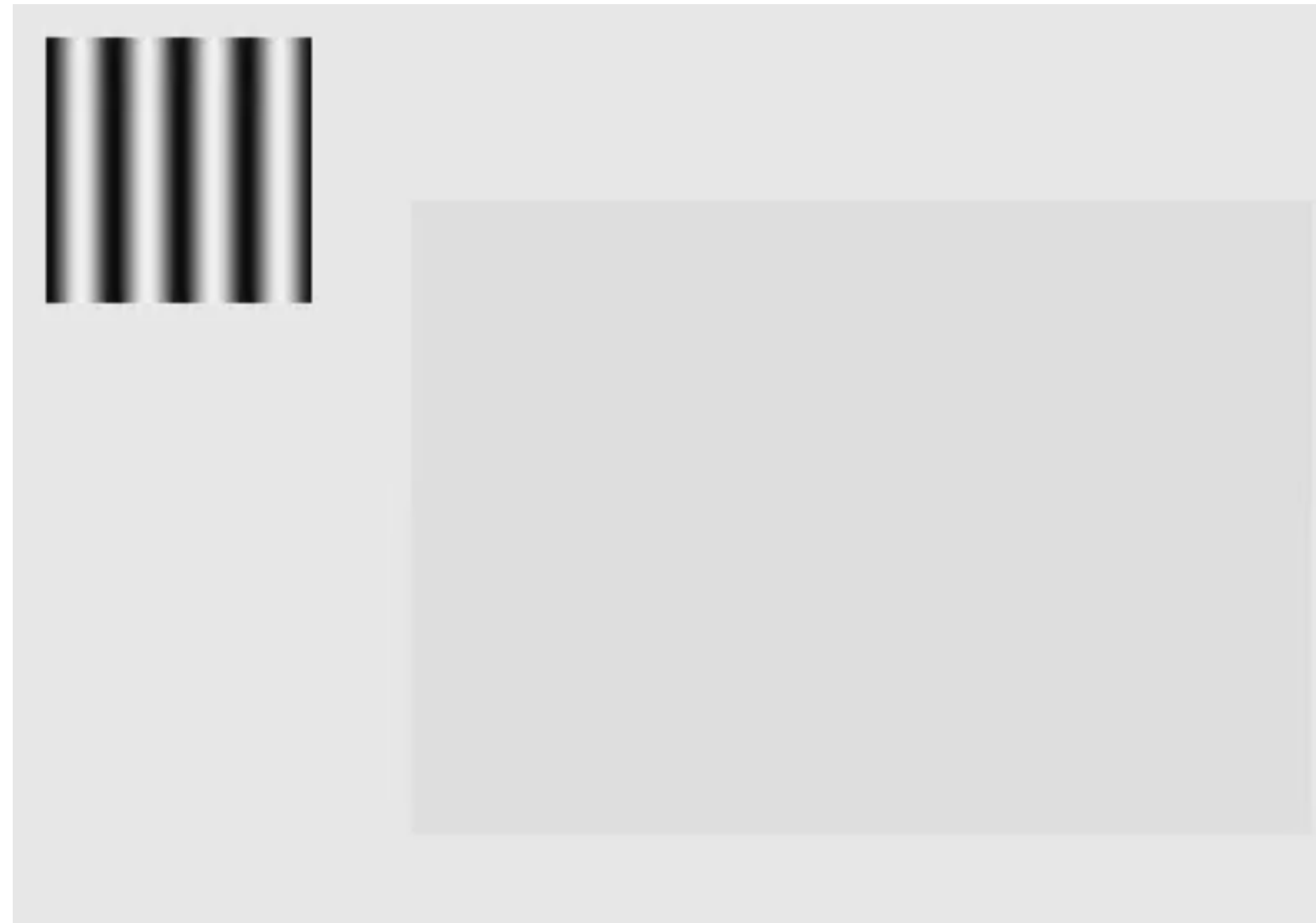
Visual system, technical design



[Hubel & Wiesel J Physiol 1962, Grinvald et al. Nature 1986]

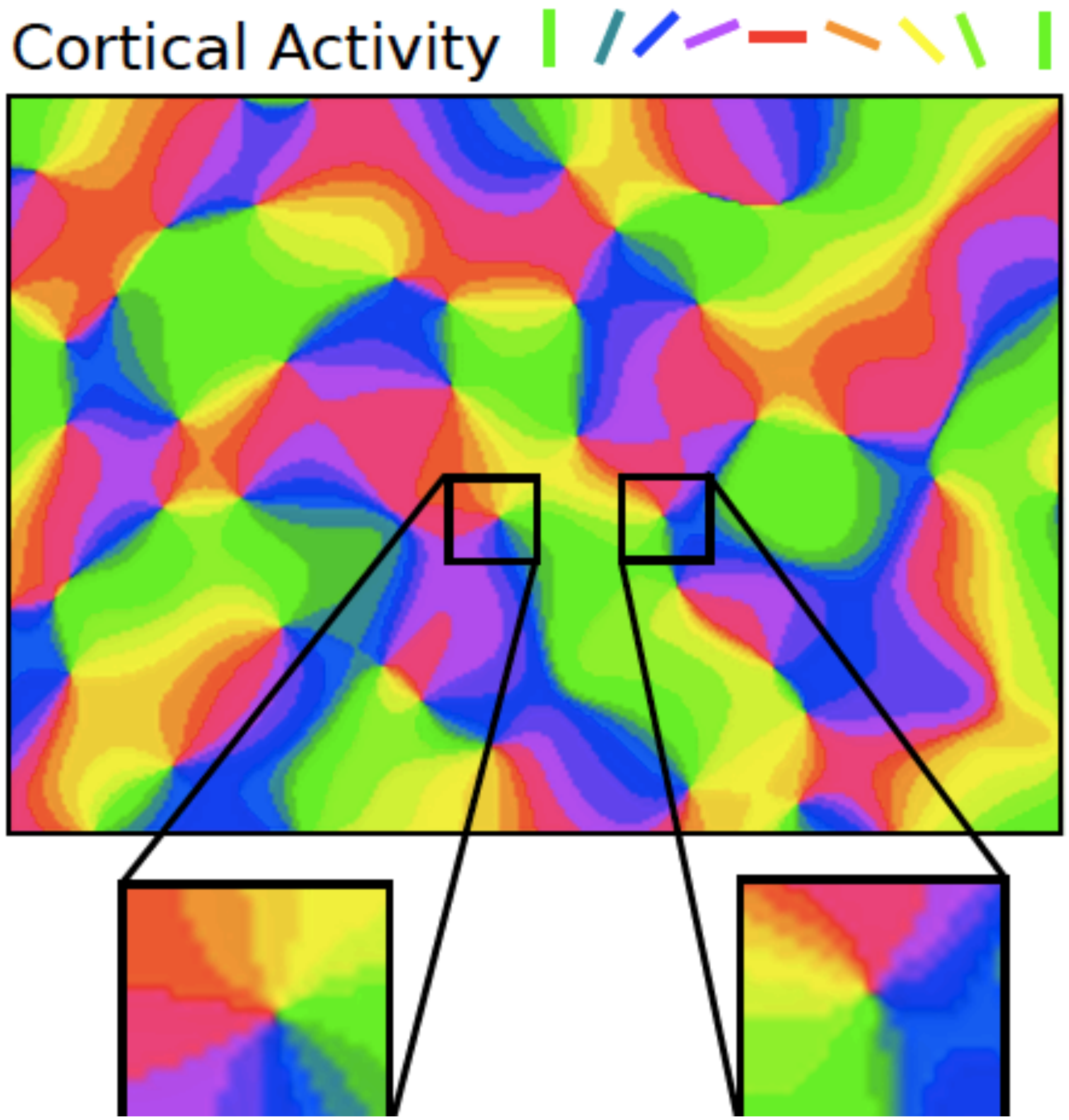
Optical imaging



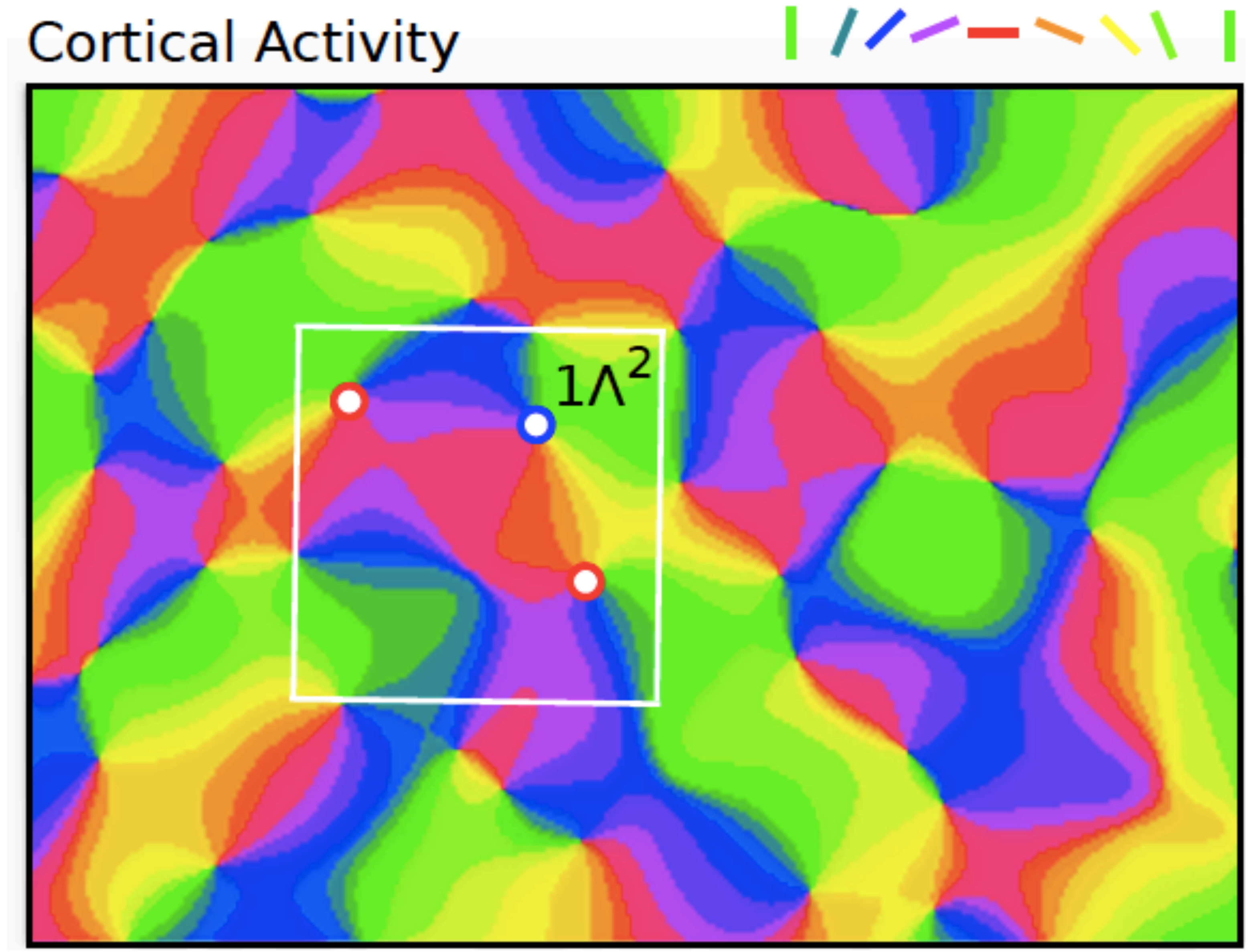


[Ferret intrinsic signal by D. Coppola (Fitzpatrick Lab); Animation M. Kaschube]

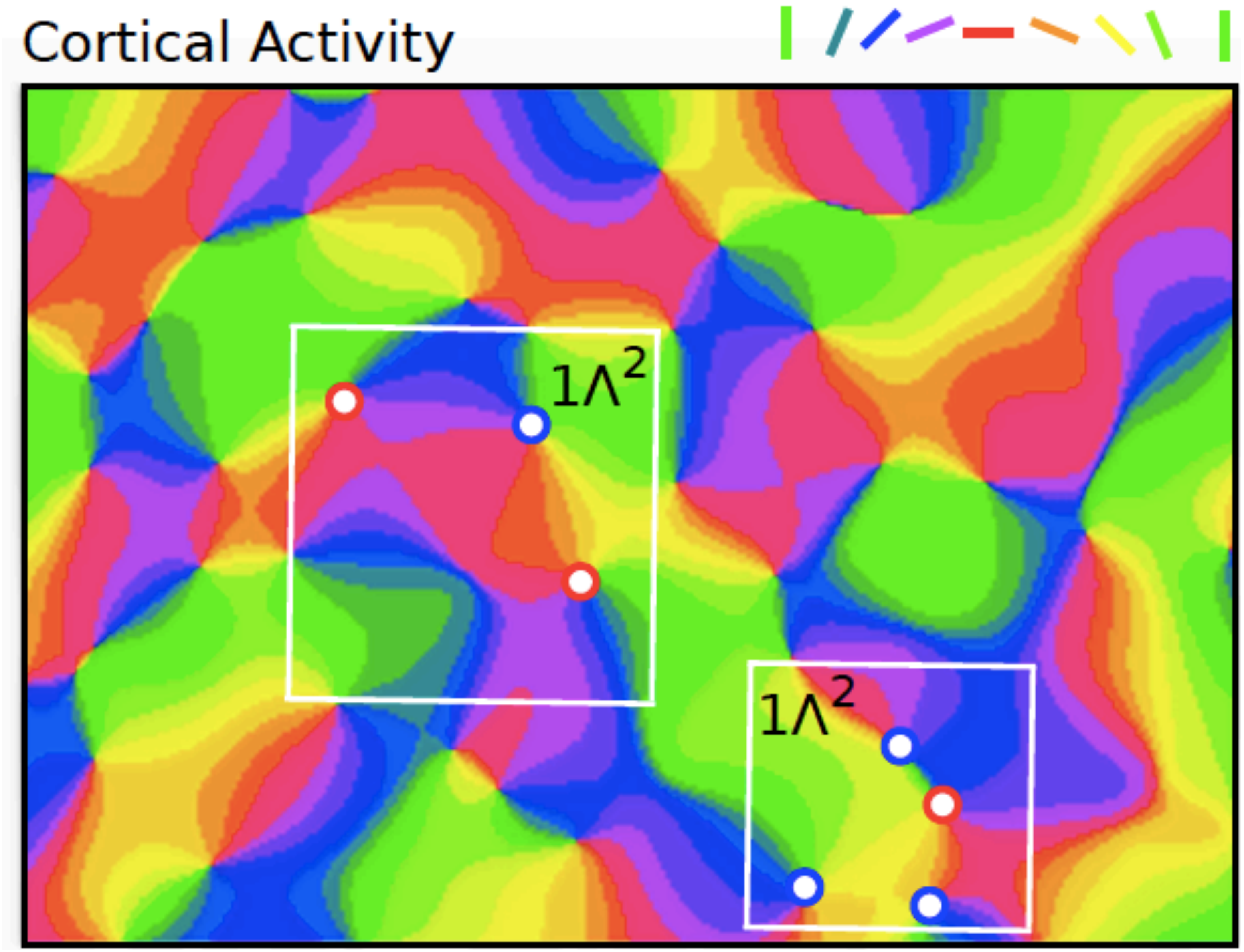
Pinwheels



[Ferret intrinsic signal by D. Coppola (Fitzpatrick Lab); Animation M. Kaschube]

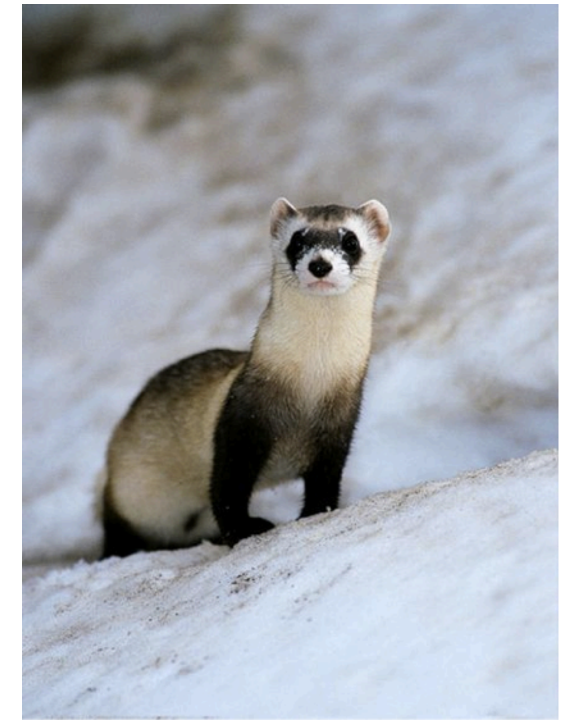


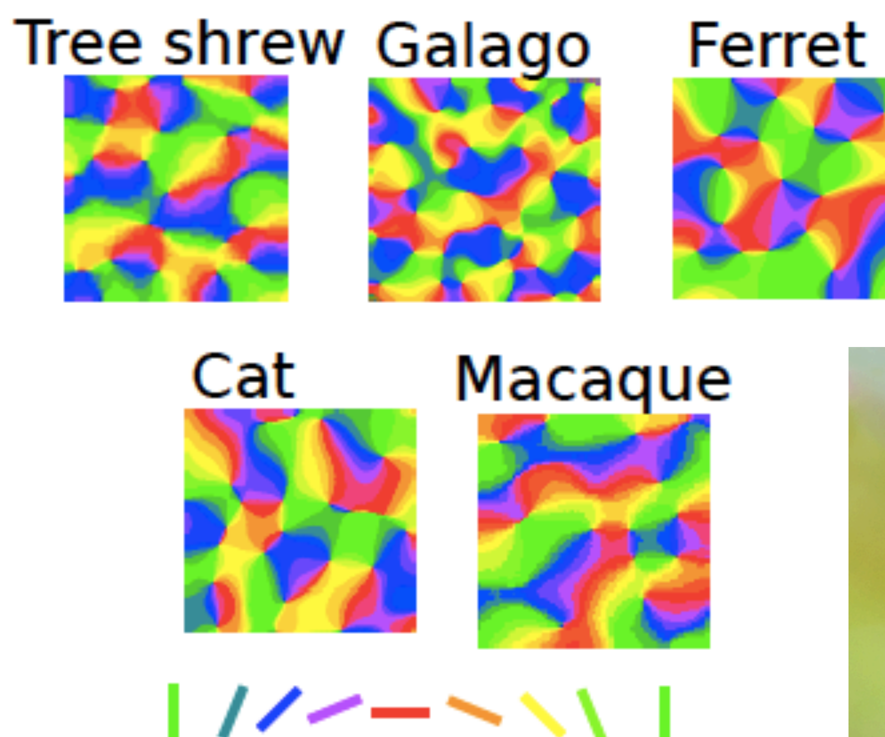
[Kaschube et al. J Neurosc 2002, Kaschube et al. Europ J Neurosc 2003, Keil et al. PNAS 2010]

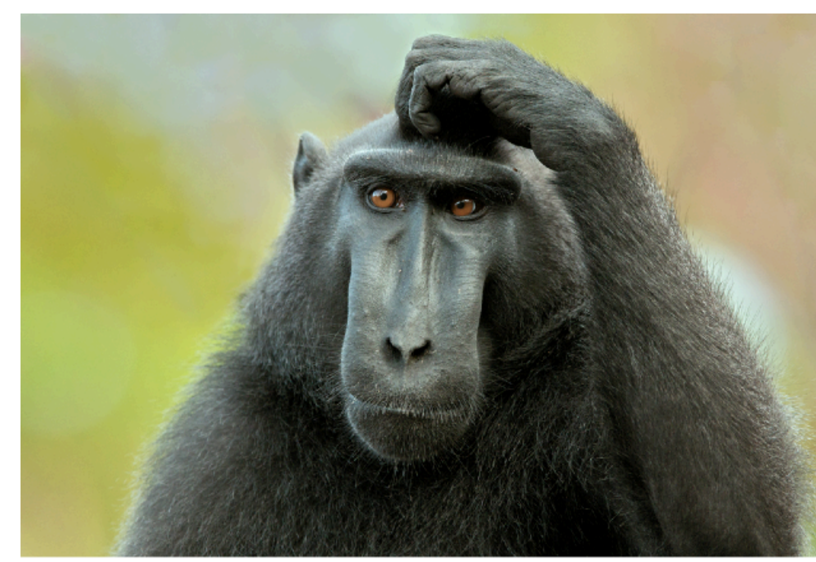


[Kaschube et al. J Neurosc 2002, Kaschube et al. Europ J Neurosc 2003, Keil et al. PNAS 2010]

Different animals with cortical maps

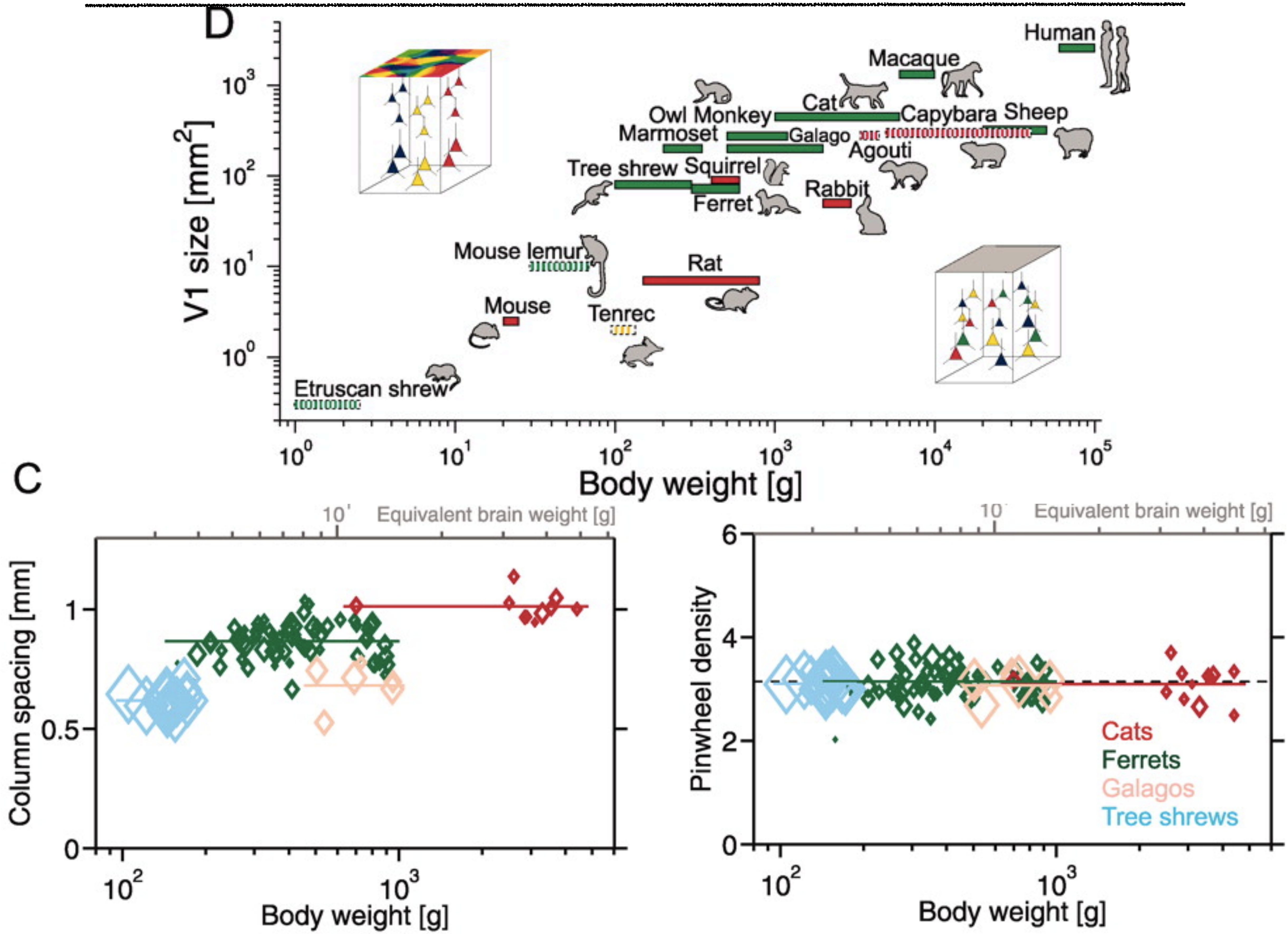






[Kaschube et al. Science 2010, Keil et al. Science 2012]

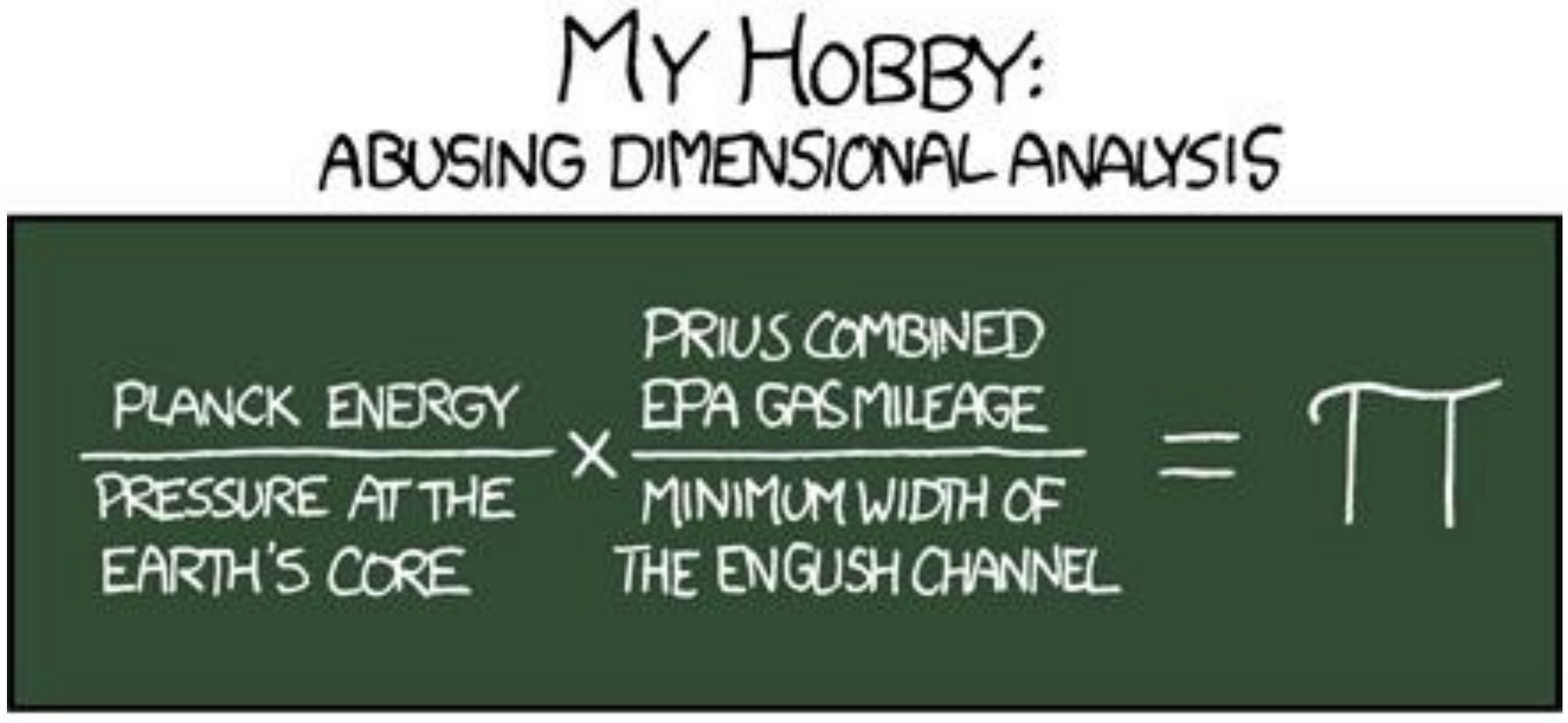
Universality



[Kaschube et al. Science 2010, Keil et al. Science 2012, Schottdorf et al. PLOS CB 2016]

Universality 3

Pinwheel density = 3.14 ± 0.04



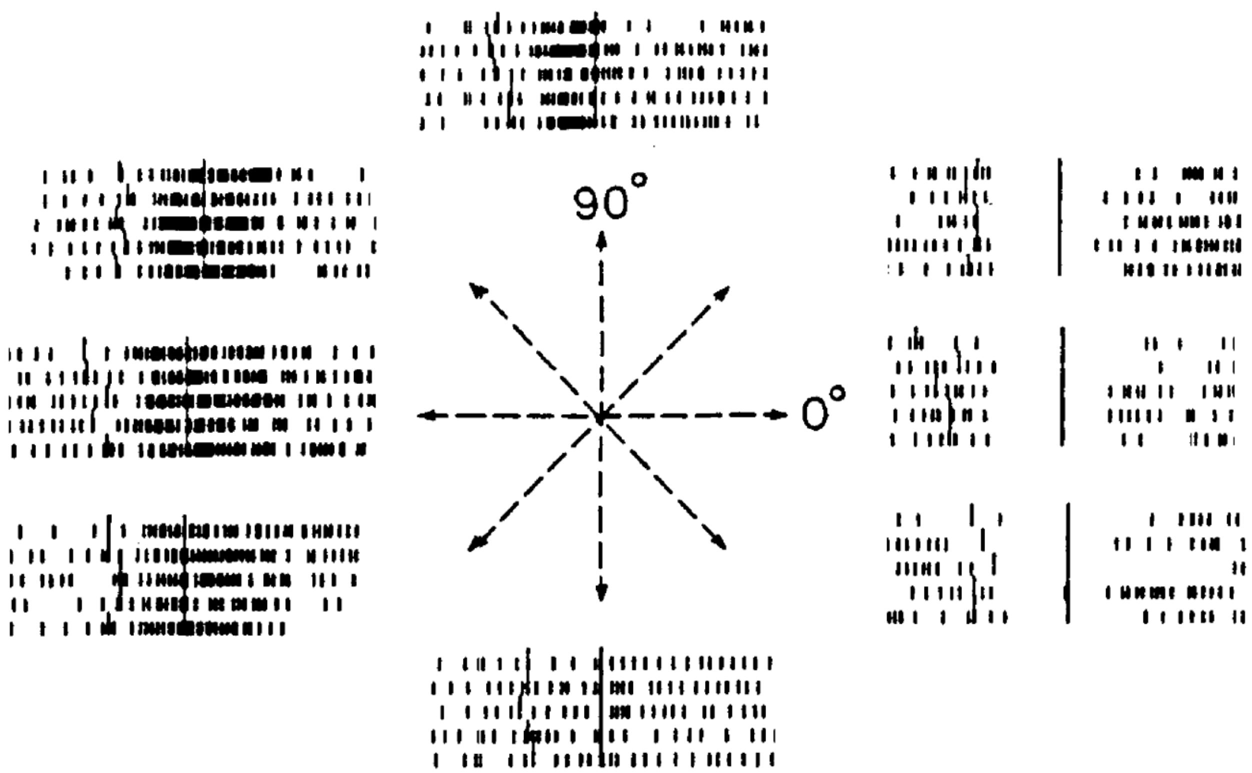
Different option for coding

Rate Coding:

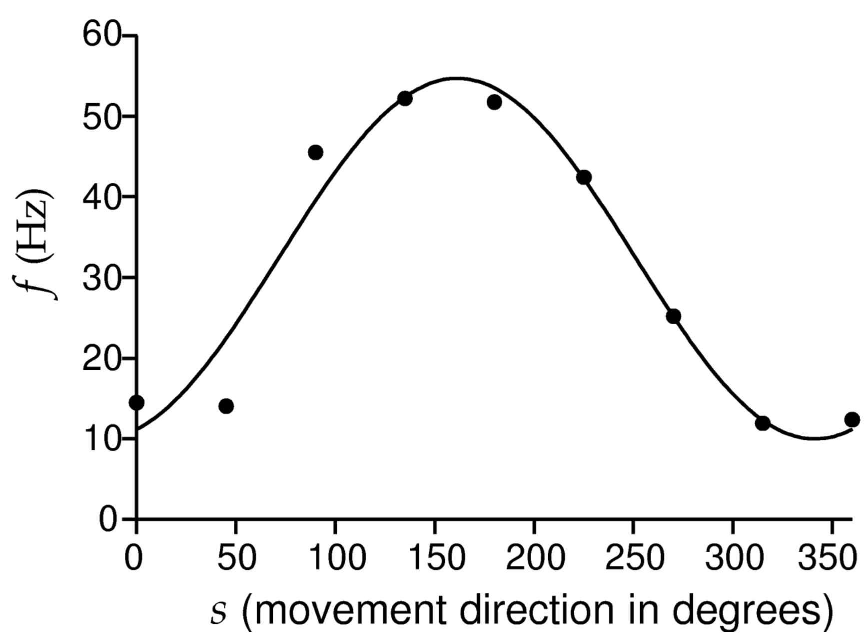
Stronger stimulus - higher firing rate of neuron/population

“+” robust against noise

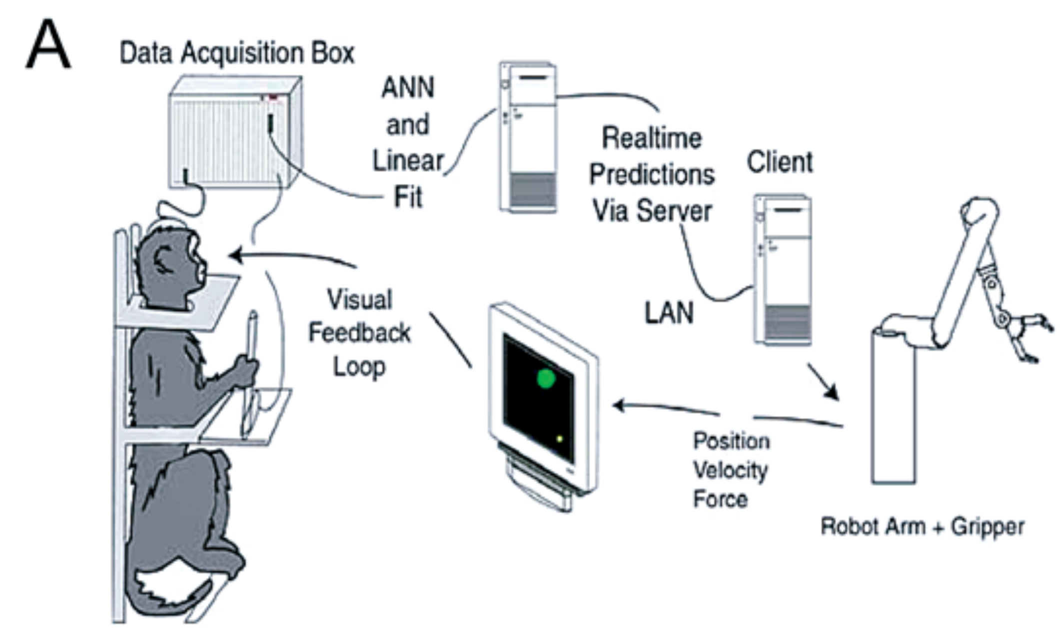
“–” inefficient



Hand reaching direction



Decoding:



from Dayan and Abbott, adapted from Georgopoulus et al. 1982

Carmena et al., PLOS Biol 2003

Different option for coding

Rate Coding:

Stronger stimulus - higher firing rate of neuron/population

“+” robust against noise

“–” inefficient

Temporal Coding:

Precise spike timing (or very rapidly changing rate) carry information about stimulus

“+” could be very fast and efficient

“–” noise prone

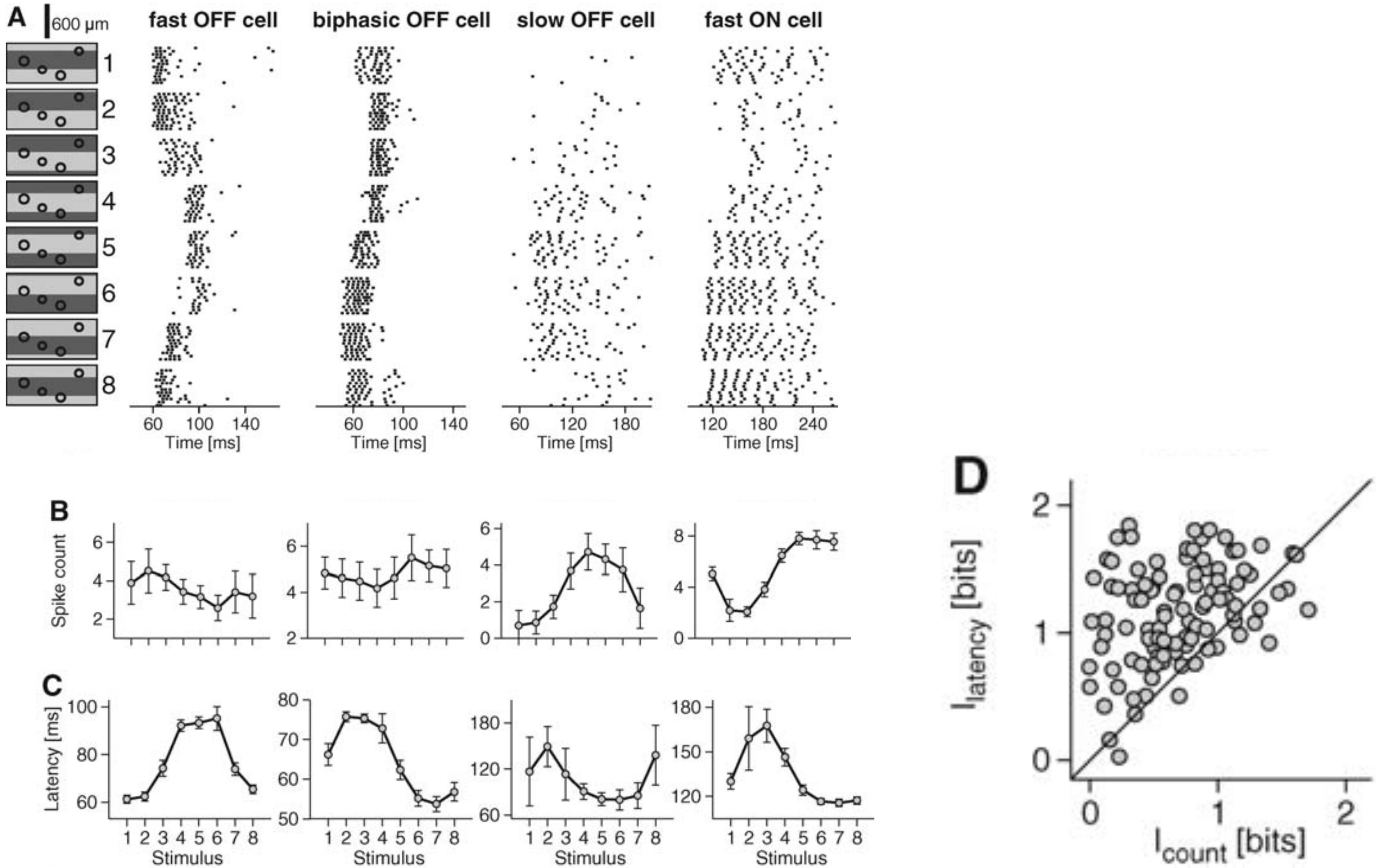
Spike Latency Coding:

Spike timing of the first spike after the stimulus onset

Latency code in the retina

Spike Latency Coding:

Spike timing of the first spike after the stimulus onset



Gollisch, Meister, Science 2008

Different option for coding

Rate Coding:

Stronger stimulus - higher firing rate of neuron/population

Temporal Coding:

Precise spike timing (or very rapidly changing rate) carry information about stimulus

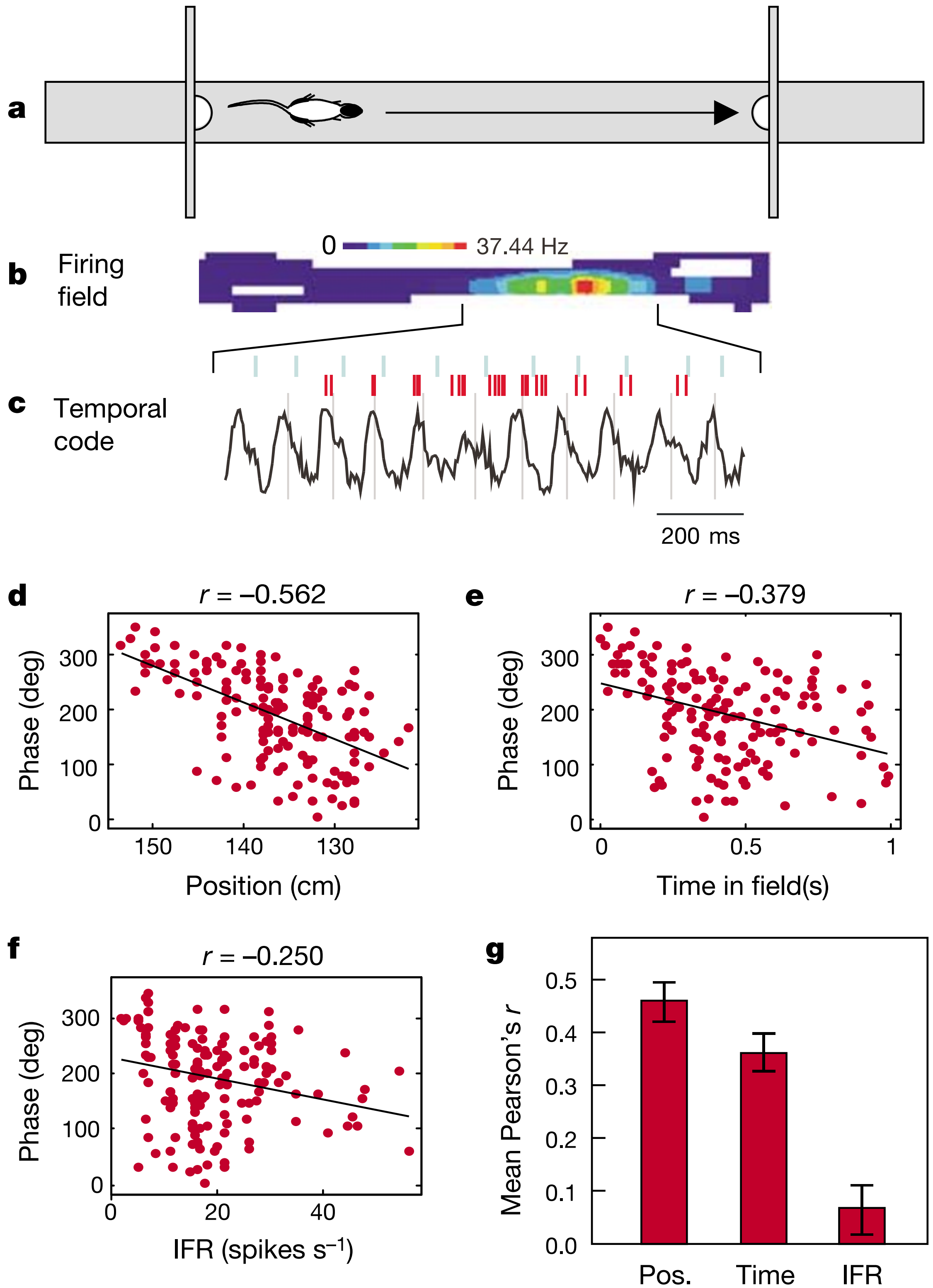
Spike Latency Coding:

Spike timing of the first spike after the stimulus onset

Relative phase coding

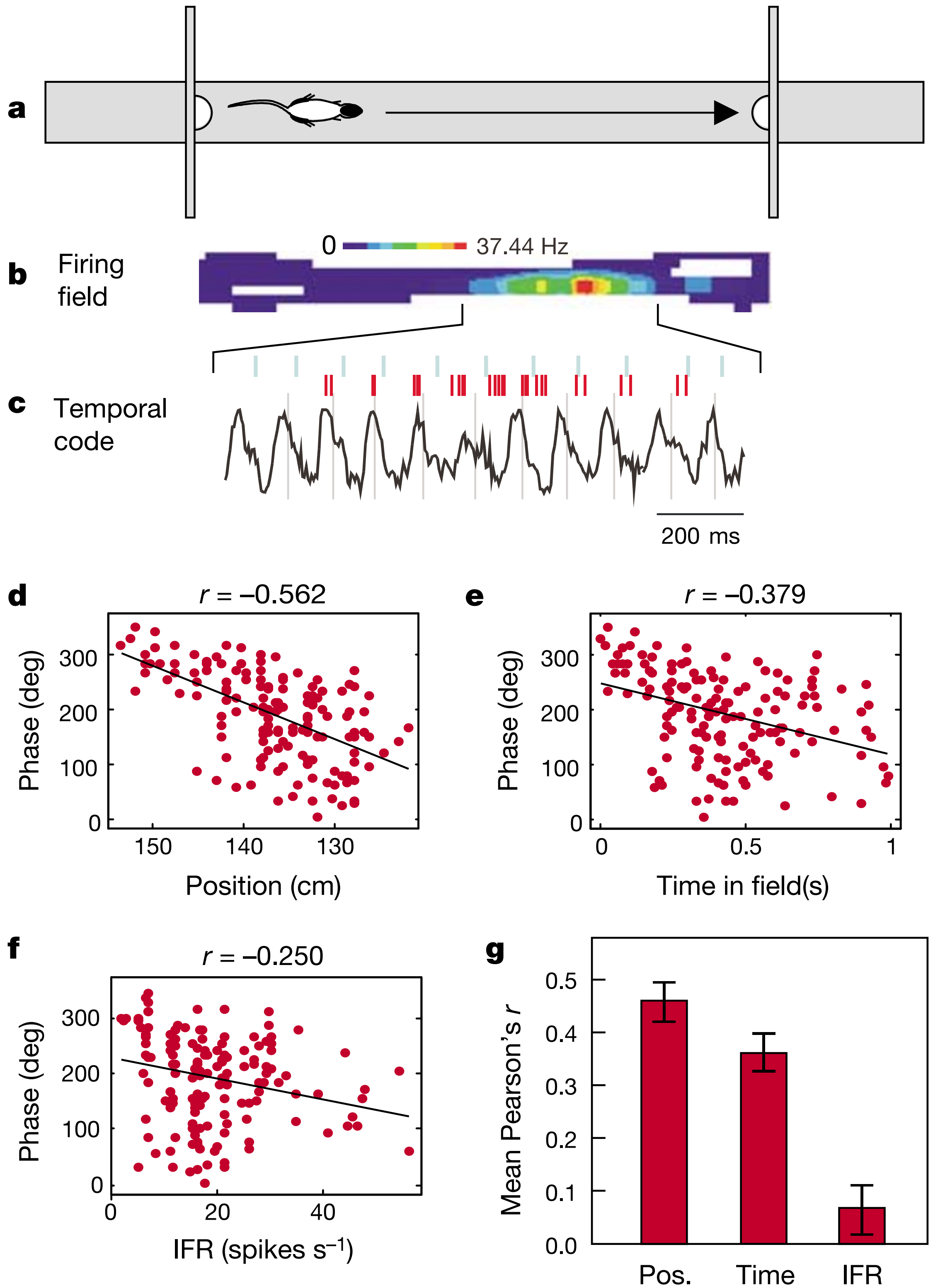
Firing rates or spikes of neurons relative to the phase of global oscillation (i.e. communication through coherence, Pascal Fries)

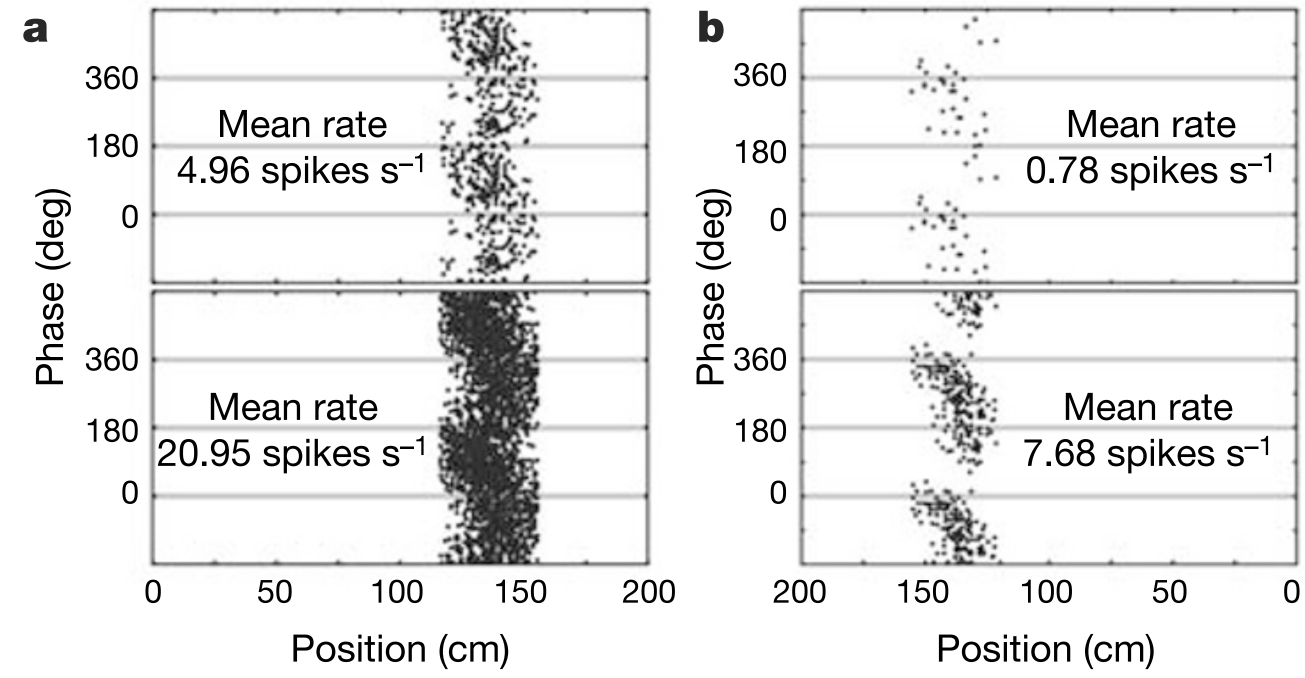
Relative code example



Huxter, Burgess, O'Keefe, Nature 2003

Relative code example

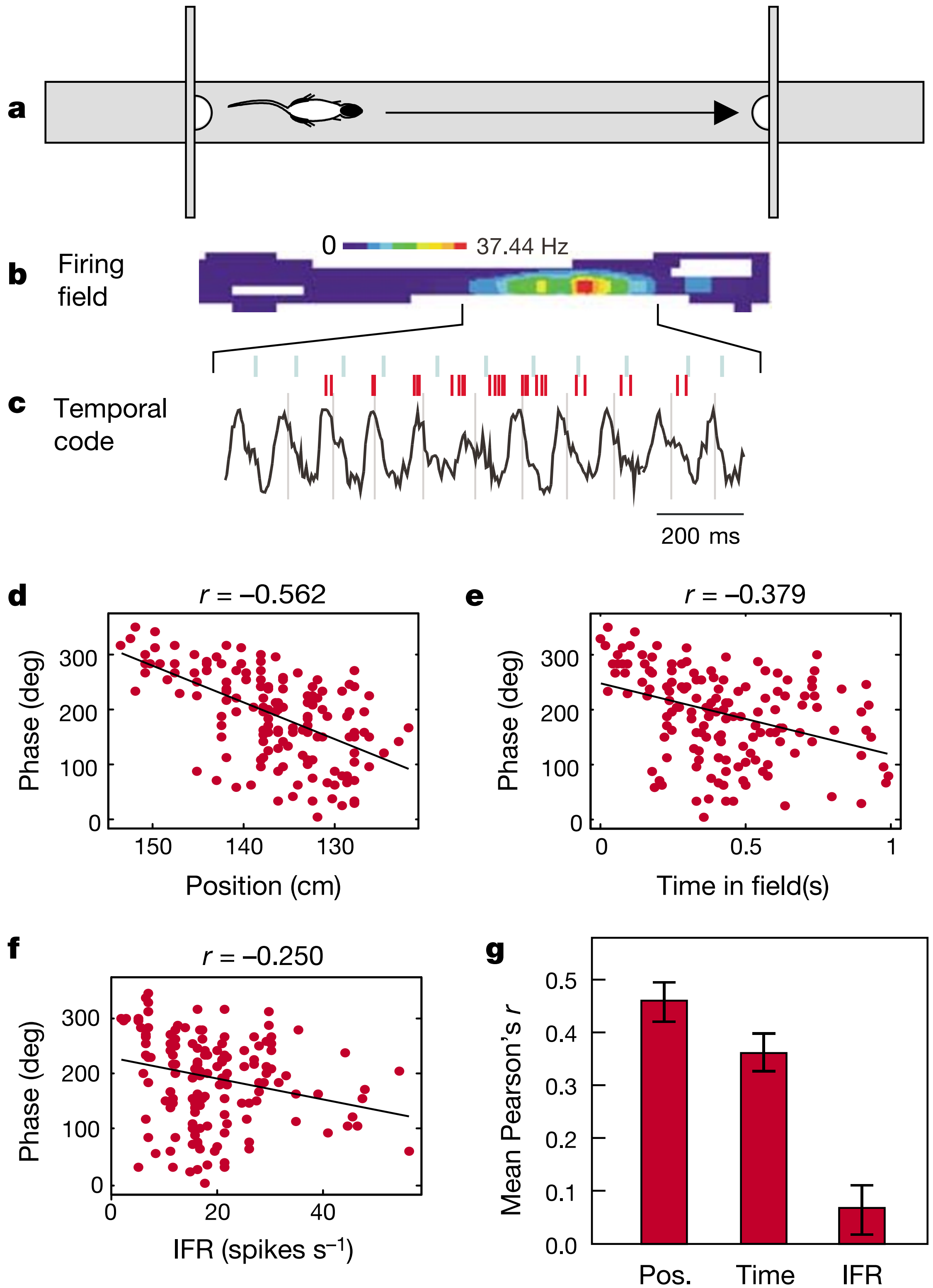


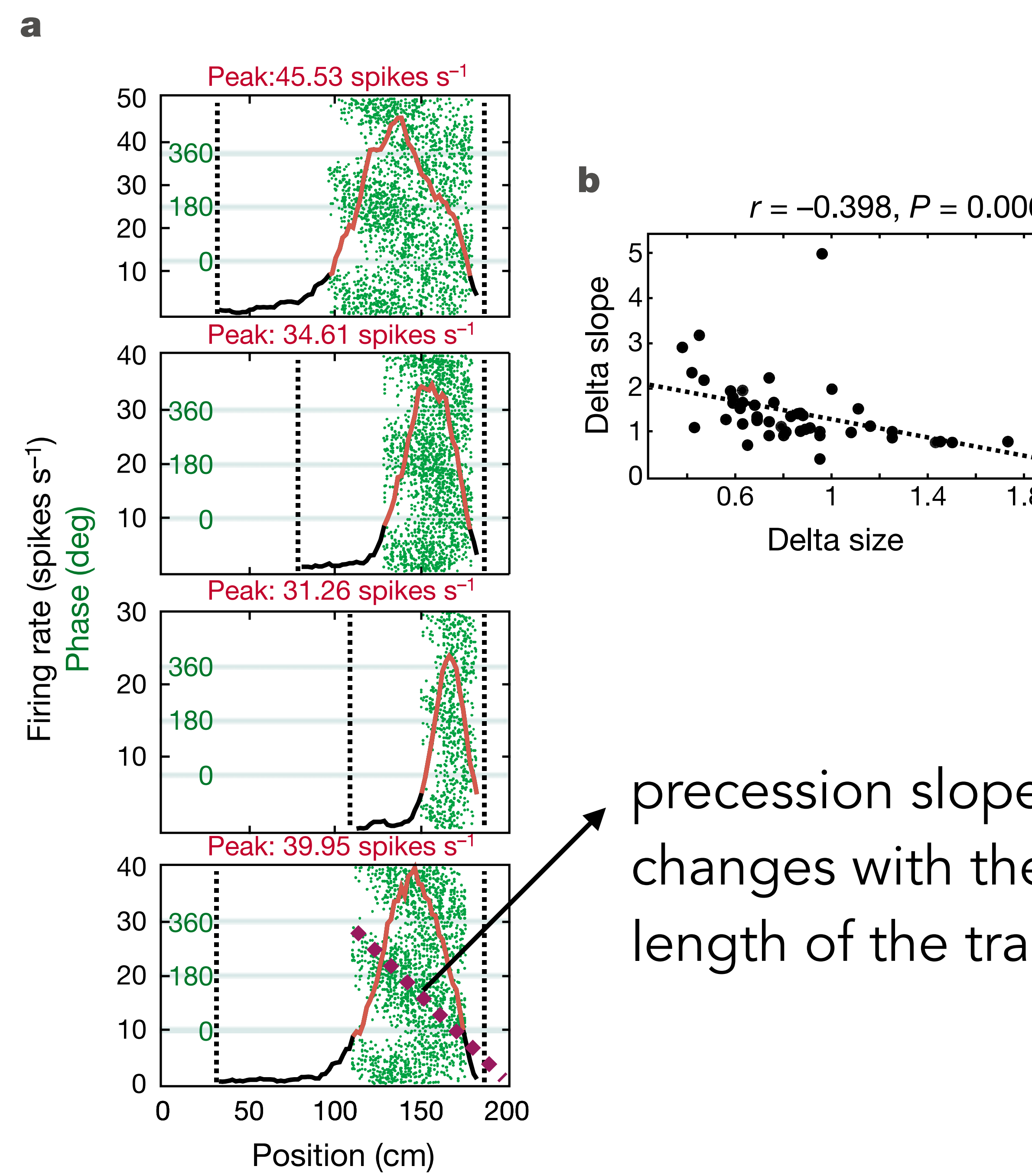


Phase precession: later in the track spikes occur at the lower phase (thats why the diagonal lines structure)

Huxter, Burgess, O'Keefe, Nature 2003

Relative code example





precession slope, changes with the length of the track

We tentatively conclude that the phase is coding for the proportion of the field traversed

Huxter, Burgess, O'Keefe, Nature 2003

Different option for coding

Rate Coding:
Stronger stimulus - higher firing rate of neuron/population

Temporal Coding:
Precise spike timing (or very rapidly changing rate) carry information about stimulus

Spike Latency Coding:
Spike timing of the first spike after the stimulus onset

Relative phase coding
Firing rates or spikes of neurons relative to the phase of global oscillation (i.e. communication through coherence, Pascal Fries)

Correlation coding
Information is carried by the relationships in spikes of one or many neurons

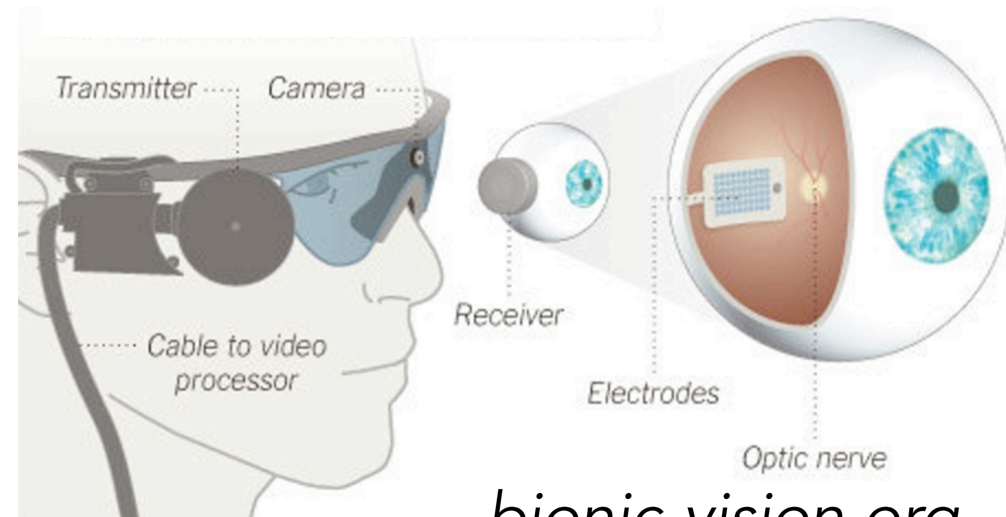
Why care about neural coding?

I. Basic science

- Learn how the actual brain encodes information.
- Generate predictions for theories and models (e.g., is the brain a Bayesian prediction device?)
- Build brain-inspired systems

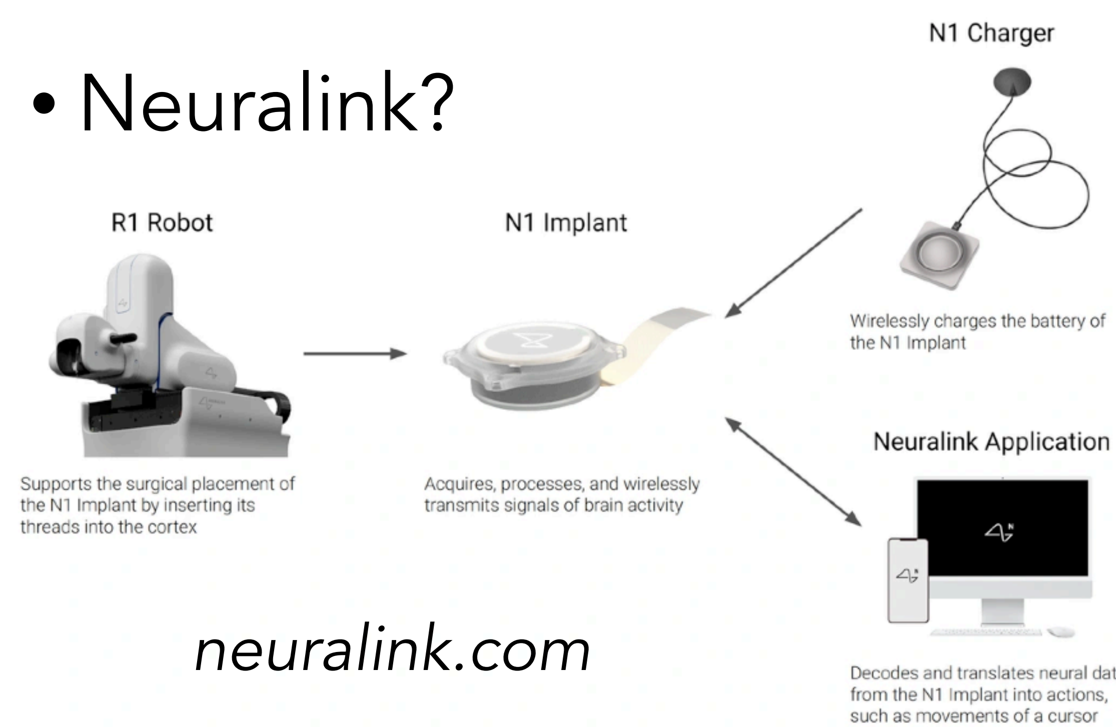
II. Brain-computer-interface applications

- Argus II, retinal implant



bionic-vision.org

- Neuralink?



neuralink.com

Models terminology

Descriptive

Question: What?

Compact representation of the data

Mechanistic

Question: How?

Finding “mechanisms” for generating neural code

Interpretive

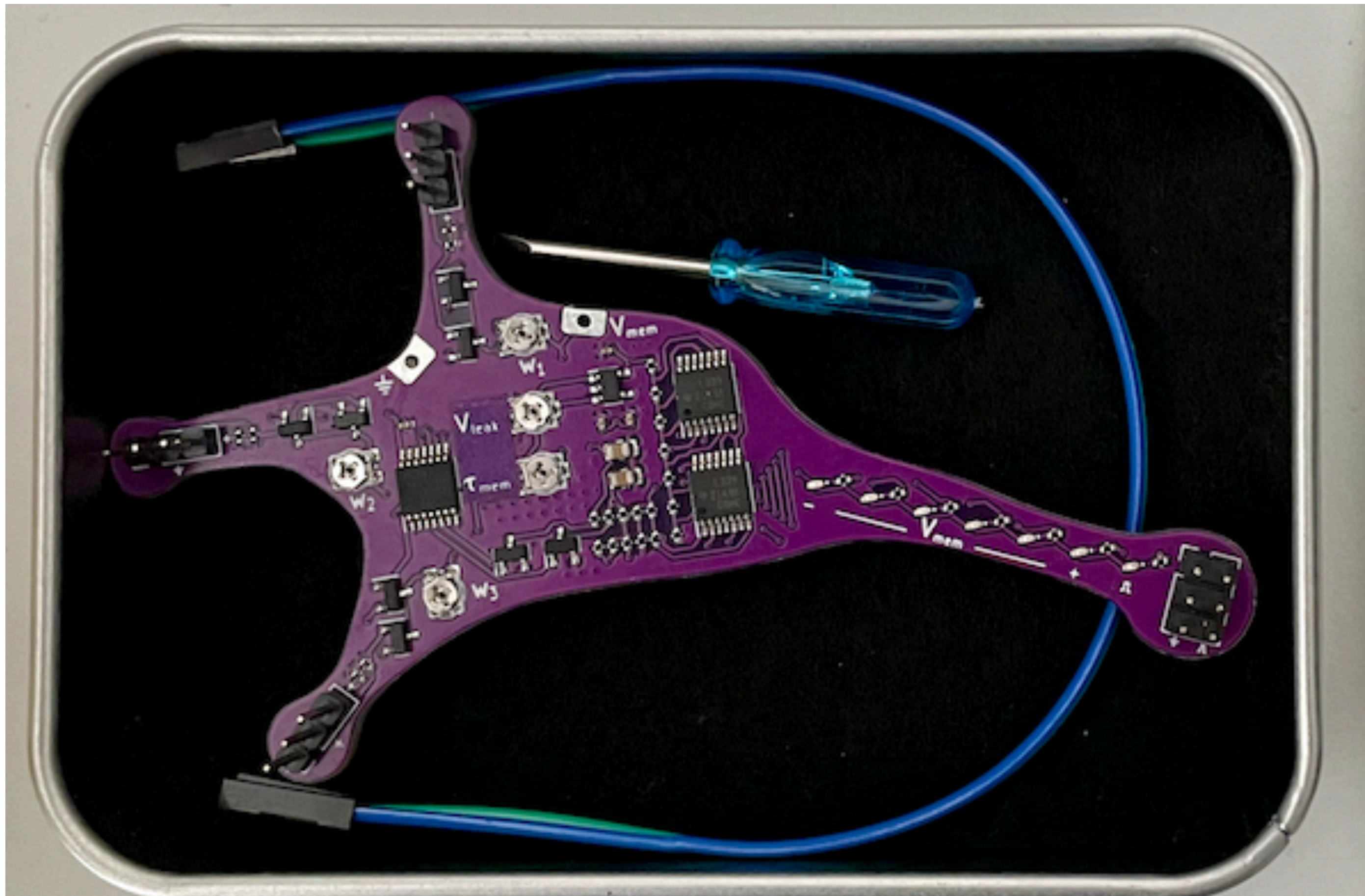
Question: Why?

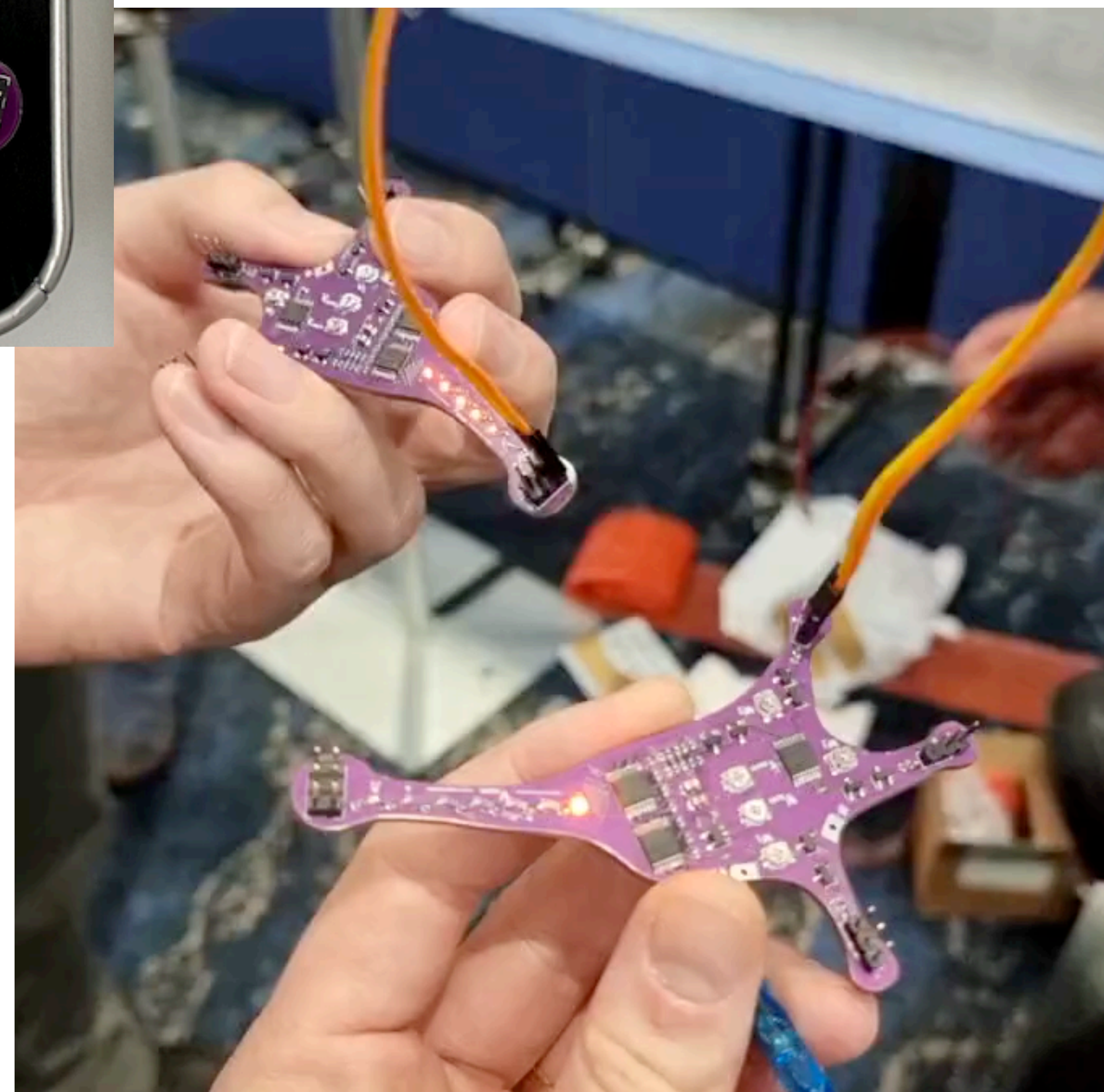
Optimality of the code

Lectures plan

16.04.	Introduction to neural coding	
23.04.	Point processes as a model of spike trains	Foundation Descriptive level
30.04.	Inhomogeneous Poisson process	
07.05	Encoding and decoding. Tuning curves.	
14.05.	Fisher Information. Stimulus discrimination	
21.05.	Potentially: Marion Silies Talk	
28.05.	Correlated variability: theory	
04.06.	Different views on correlated variability	Mainly interpretive
11.06.	Break	
18.06.	Information theory for neuroscience.	
25.06	Efficient coding in different flavors	
02.07.	Efficient coding networks	
09.07.	Predictive coding	
16.07.	Plasticity and learning I	Mechanistic level
23.07.	Plasticity and learning II	

Special Tutorial





Evaluation criteria

Homeworks:
- Need to get at least 50% of the total score
- Paper + Python (Jupyter Notebooks)

Final grade: exam + bonus points from homework

Additional Information

Do not take this course if you:

- do not know how to program in python
- never took a probability theory/statistics course

Next steps:

- add your picture to ILIAS profile (especially if you are from GTC - CN)

Important things to remember from this lecture:

Types of codes

- Which type of codes you have already encountered?

Types of models

- invent your examples for descriptive, mechanistic and informative models (in neuroscience or other fields, e.g. weather or social science).

Next time

Mathematical language to describe spike timings and rates