Functional analysis of cortical activity statistics

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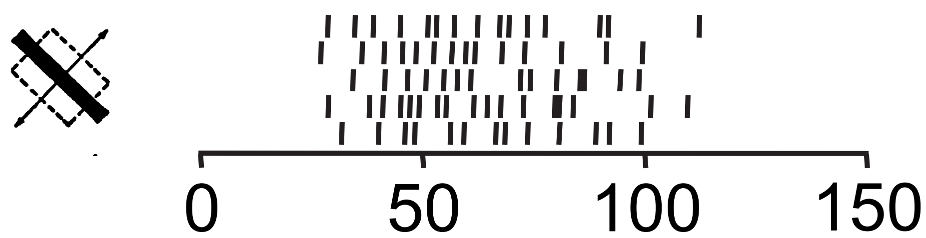
Computational Systems Neuroscience Lab

- Wigner Research Centre for Physics
- Department of Computational Sciences
- modelling of neural computations
- modelling human behaviour
- http://golab.wigner.mta.hu/

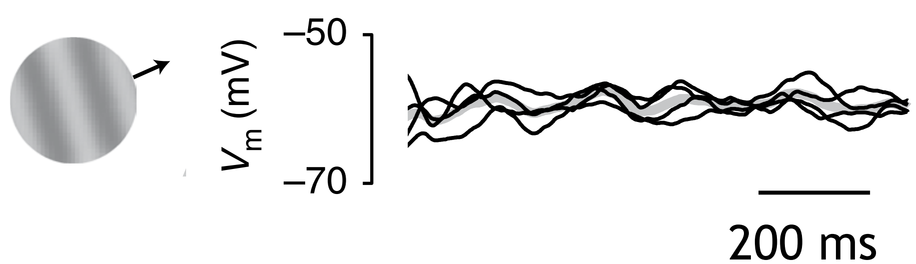
Variability in the activity of neurons

V1 spike train-variability



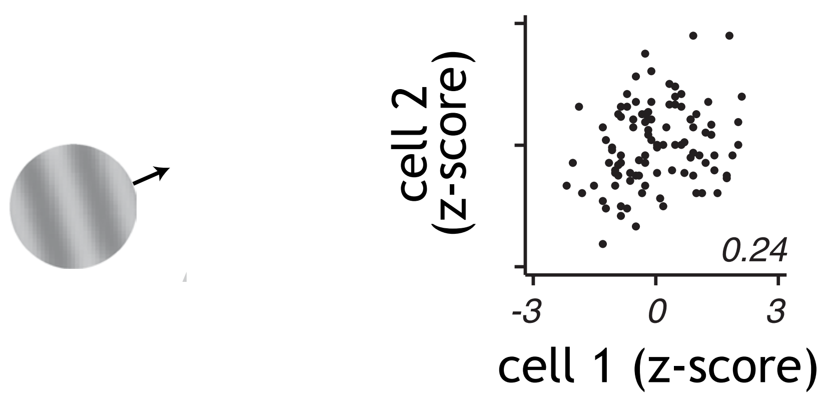
Gur & Snodderly, Cereb Cortex 2006

V1 membrane potential variability



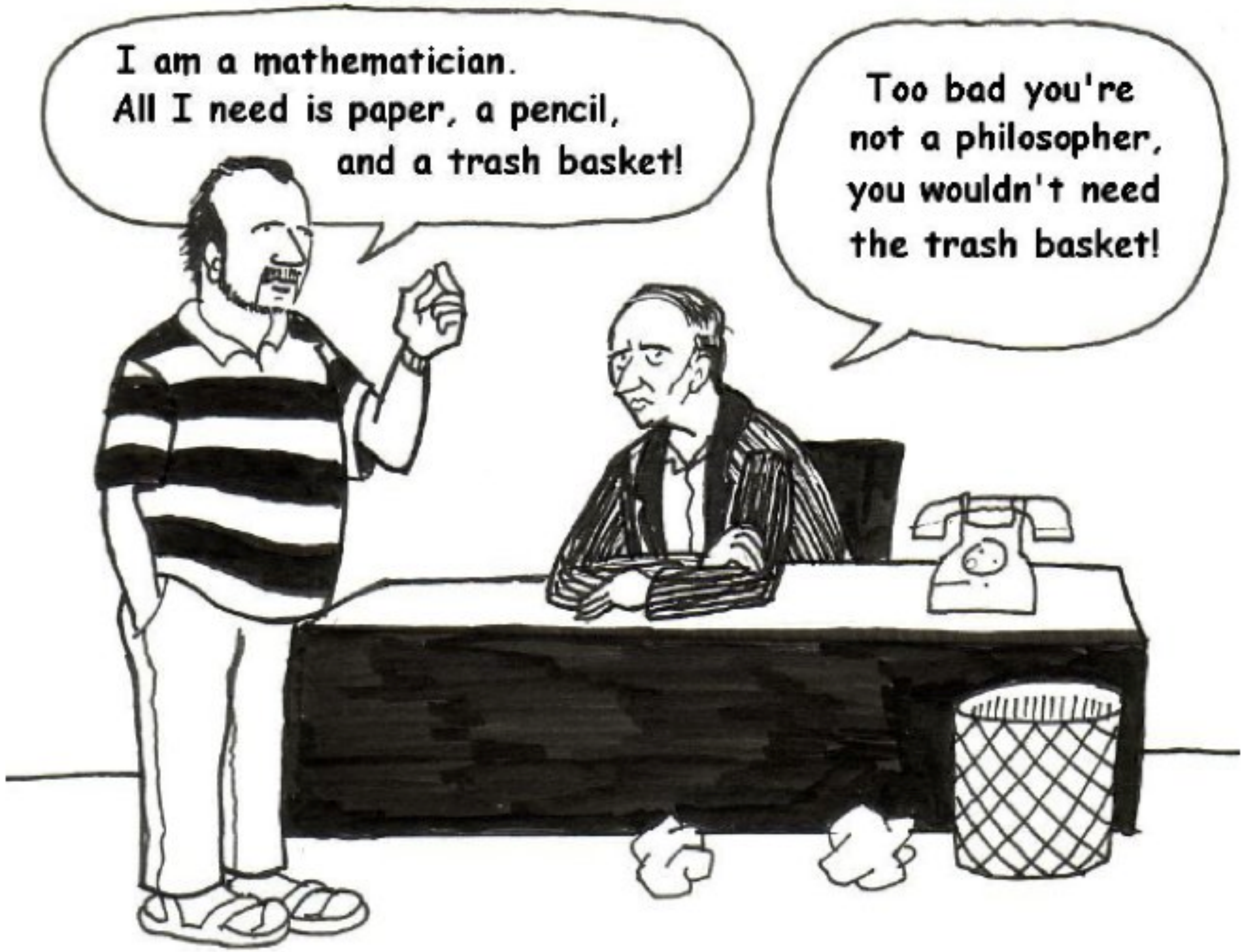
Finn et al, Neuron 2007; Churchland et al, Nat Neurosci 2010

V1 spike count covariability



Kohn & Smith, J Neurosci 2005

- Only noise?
- Does only the average response matter?
- Can we **predict** the statistics of the responses?
- Could the nervous system use this variability for something?



– Eugene M. Izhikevich: *Dynamical Systems in Neuroscience: The Geometry of Excitability and Bursting*

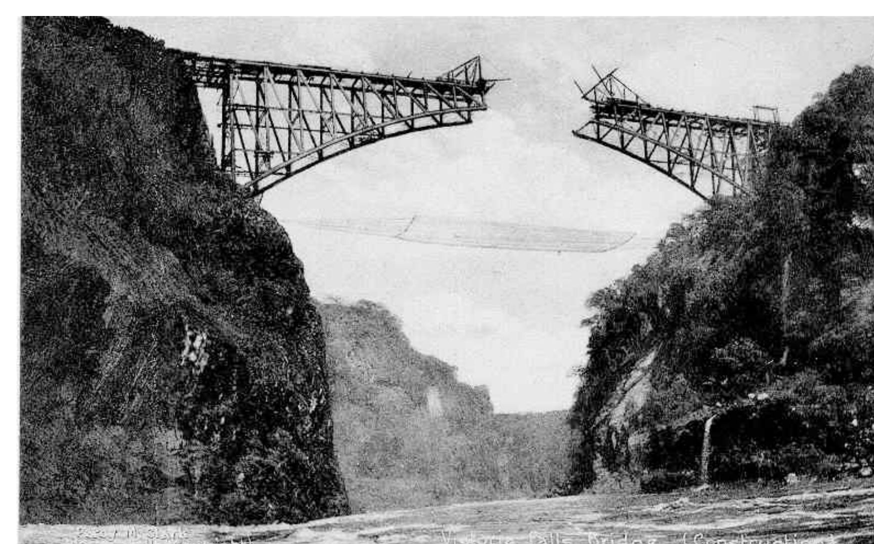
Formulating functional hypotheses

Levels of abstraction in neuroscience according to David Marr:

- **Computation** - specification of the brain function as an input-output mapping

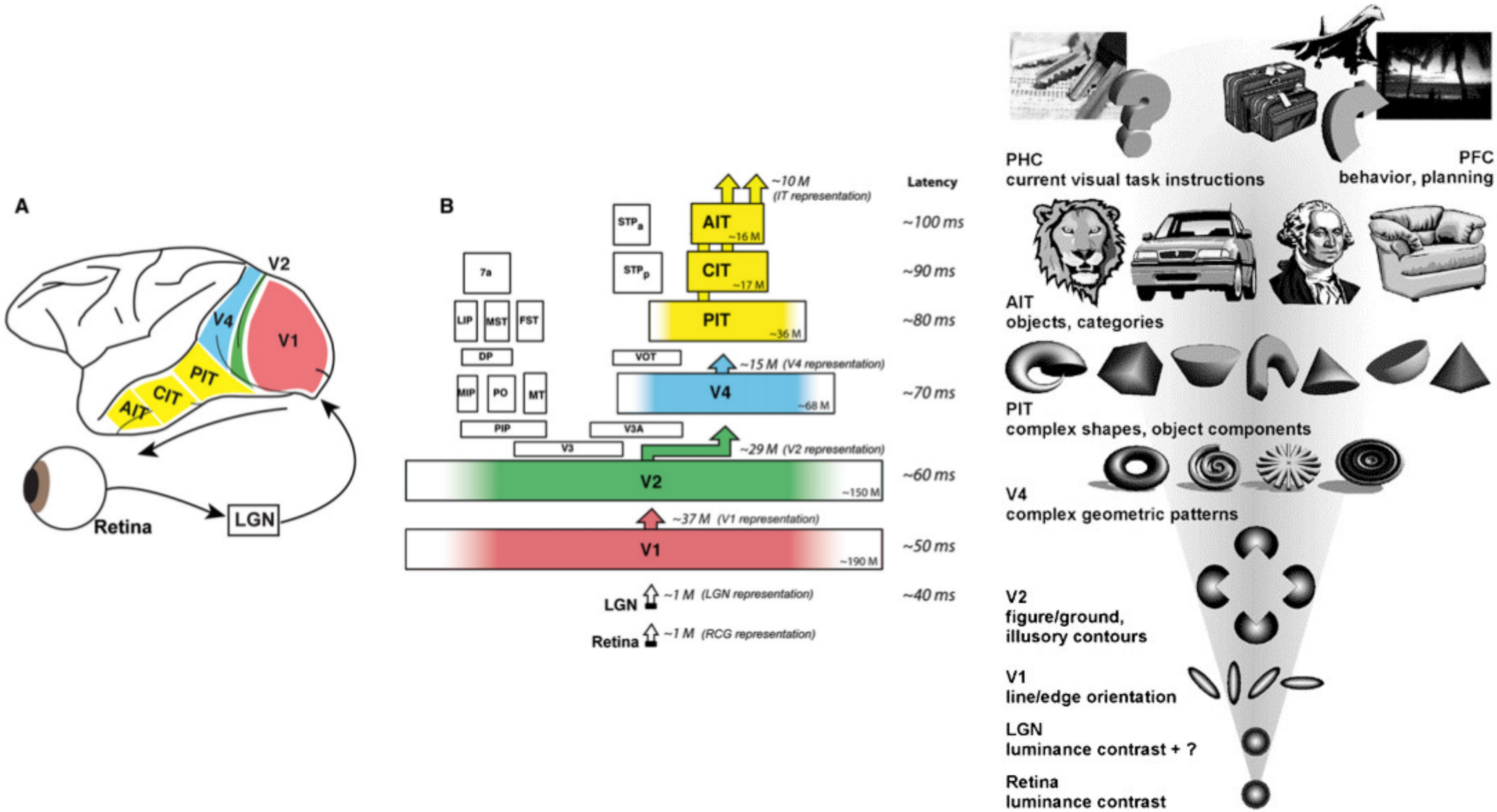
- **Algorithm** - a step-by-step mathematical description of how to calculate the mapping

- **Implementation** - realisation of the algorithm by biological structures and their dynamical properties



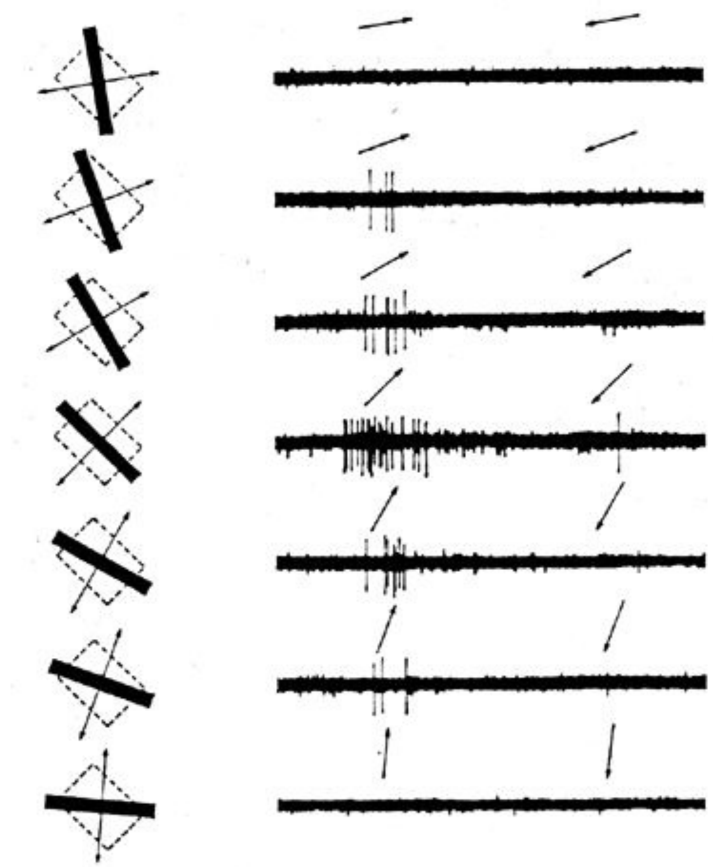
> "A wing would be a most mystifying structure if one did not know that birds flew."
>
> *Horace Barlow*

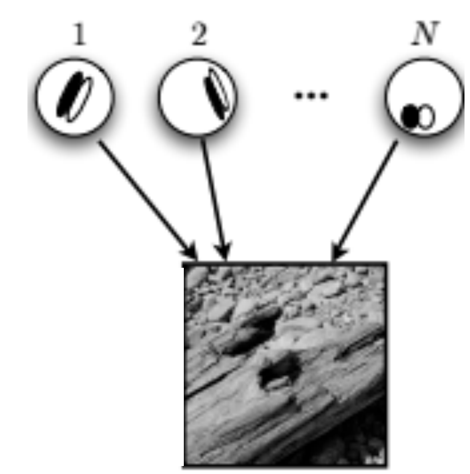
Hierarchy of object recognition



Relating environmental quantities to biophysics

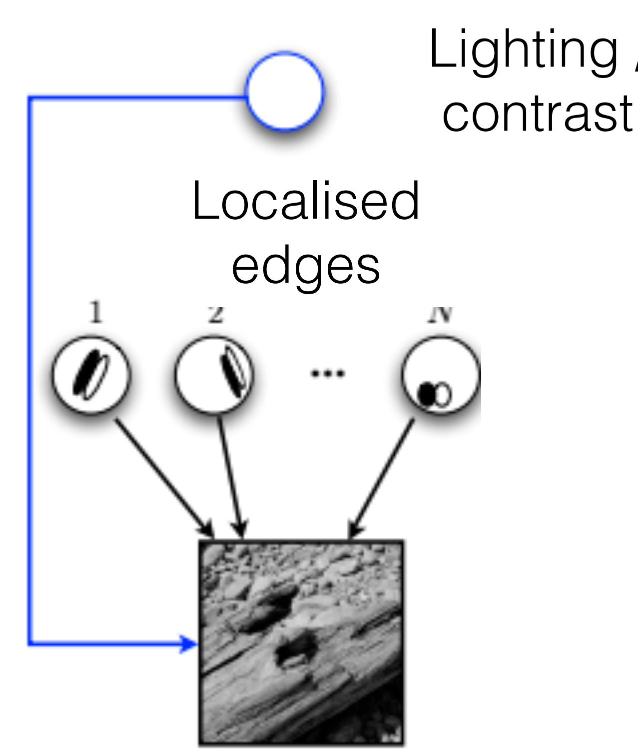
- receptive field: range of some parameters defining a stimuli in which the cell shows increased firing activity
- V1 simple cells: localised oriented edges
- can be used to predict the average number of spikes generated by a cell in response to the repeated presentation of a stimulus





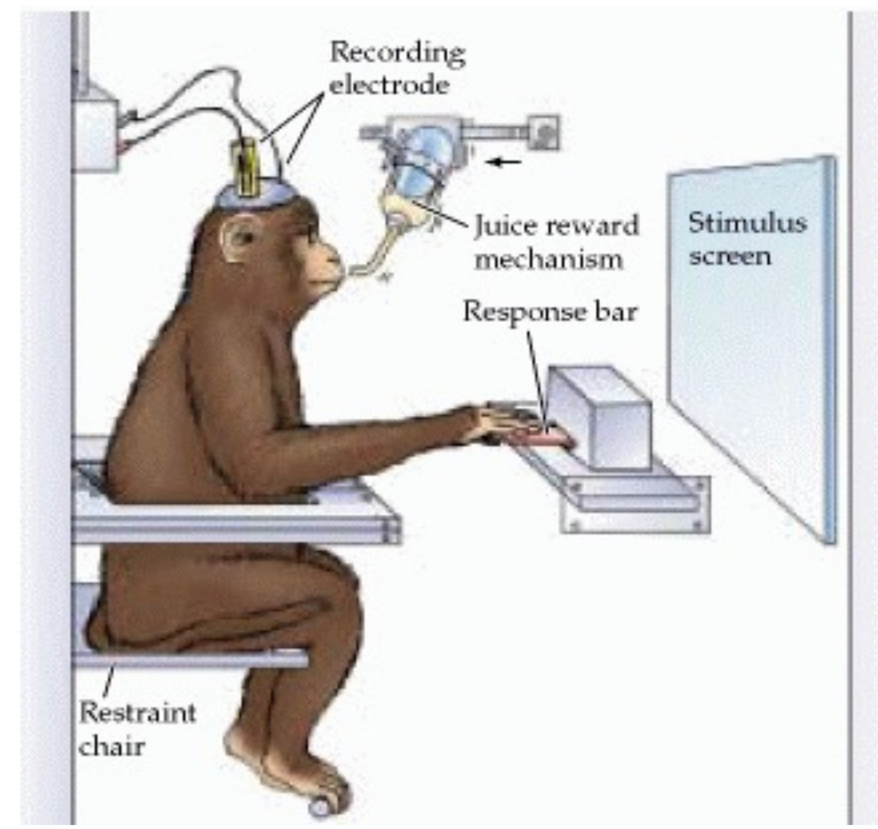
The role of variability

- animals need to estimate their uncertainty about various quantities in order to make decisions
- Hypothesis: the variability of neural responses codes for the uncertainty about the quantity encoded in the receptive field
- in case of vision, a simple way to control the animal's uncertainty about a stimulus is adjusting the contrast
- Prediction: higher contrast -> lower variability



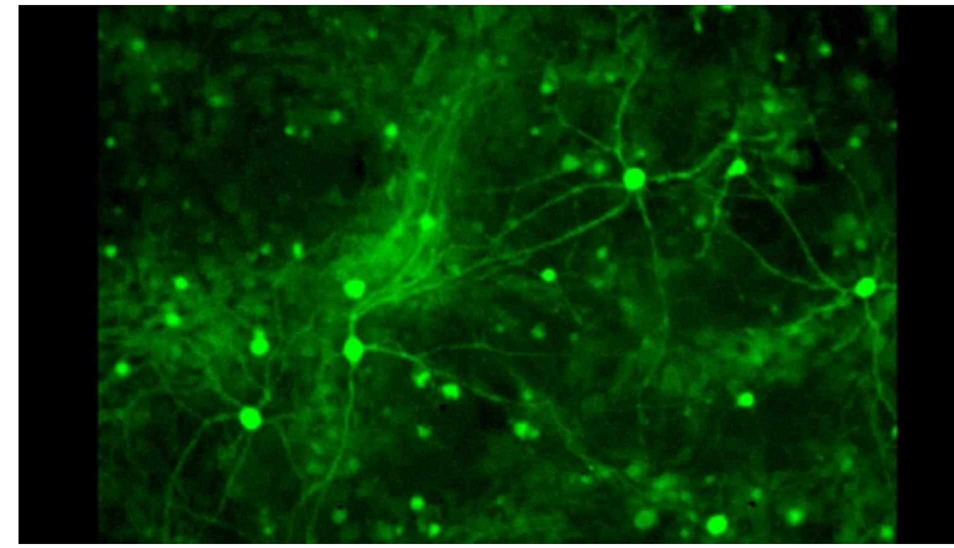
Electrophysiological experiments with awake monkeys

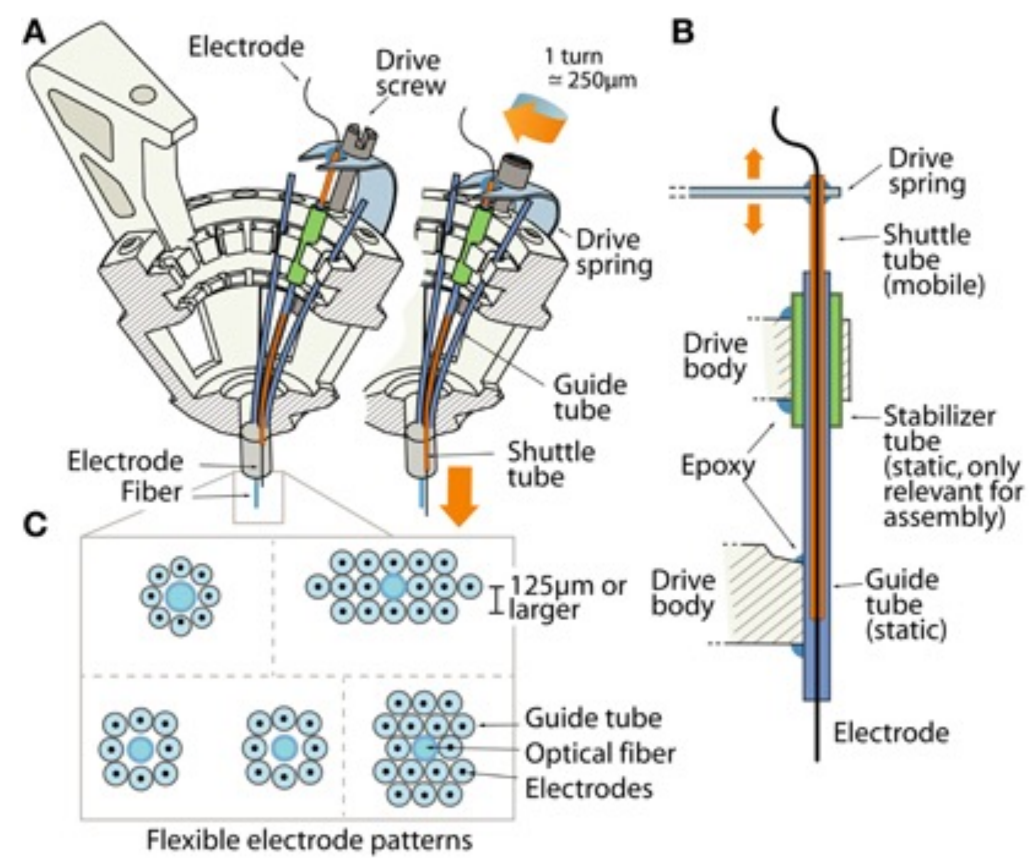
- you can teach a monkey to fixate, as opposed to almost any other animal
- one can measure under anesthesia, but different anesthetics will modulate neural response statistics in arbitrary ways (acting as a common input to cells, it especially disrupts response correlations)



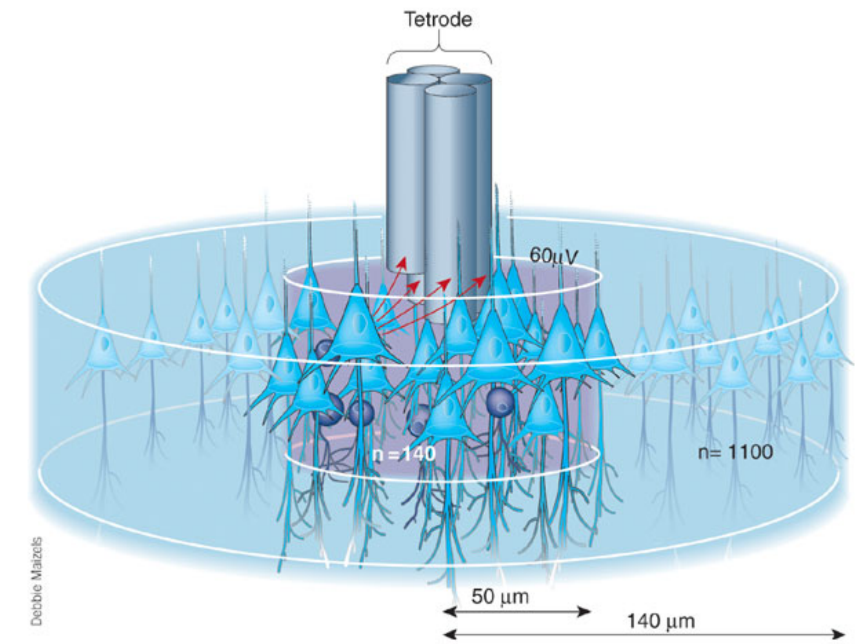
Measurable quantities in the nervous system

- we would like to measure a lot of cells at once (for our simple example it's not really required, but very often it is)
- calcium imaging
    - low temporal resolution
- extracellular electrodes
    - mixed signal coming from multiple cells

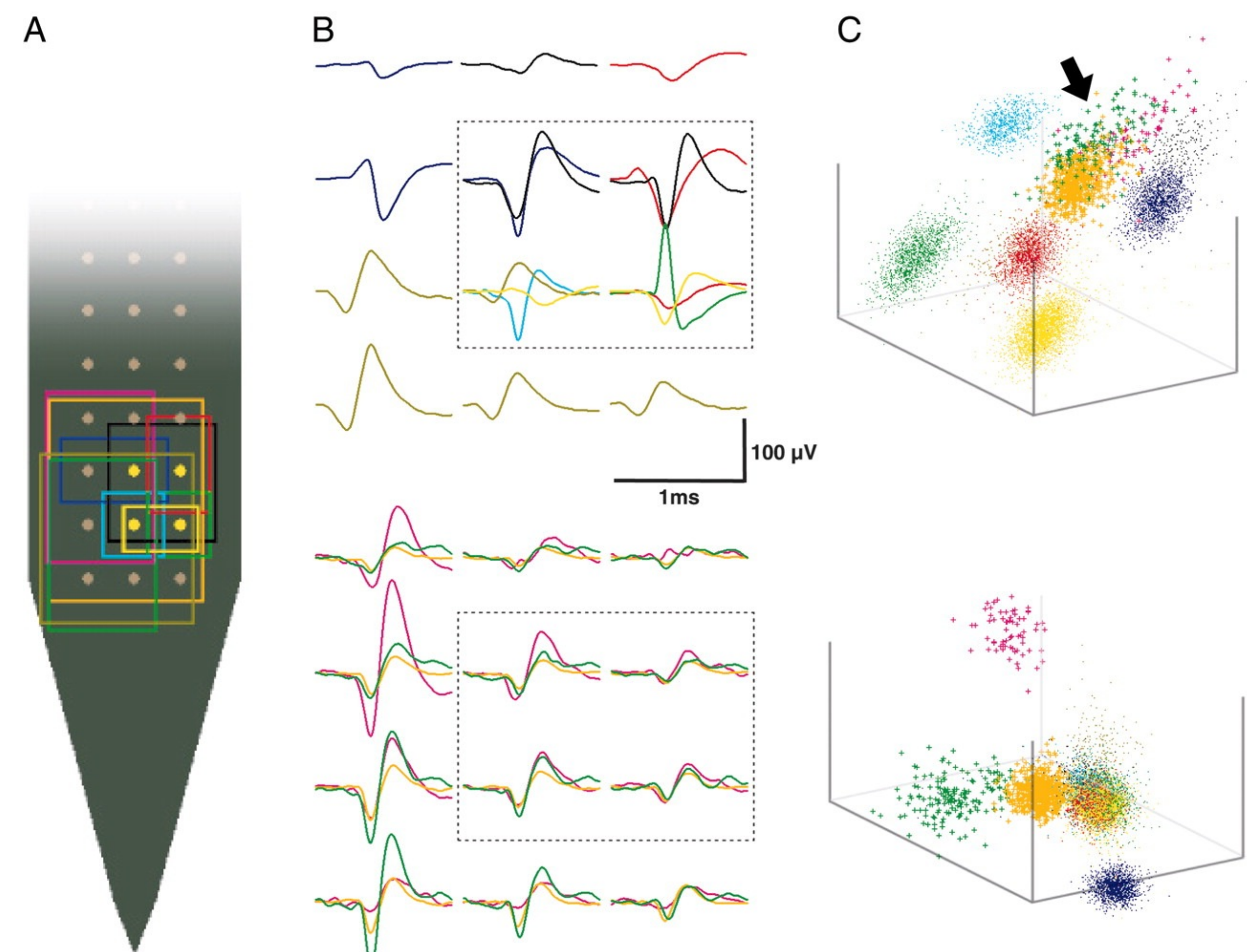




Sorting the signals coming from single neurons

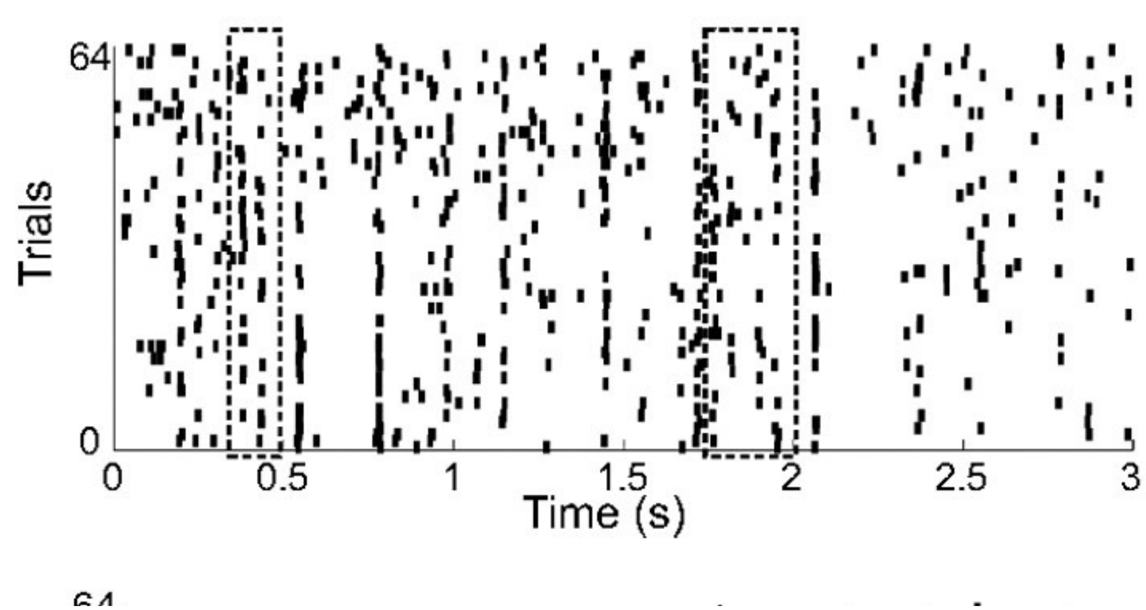


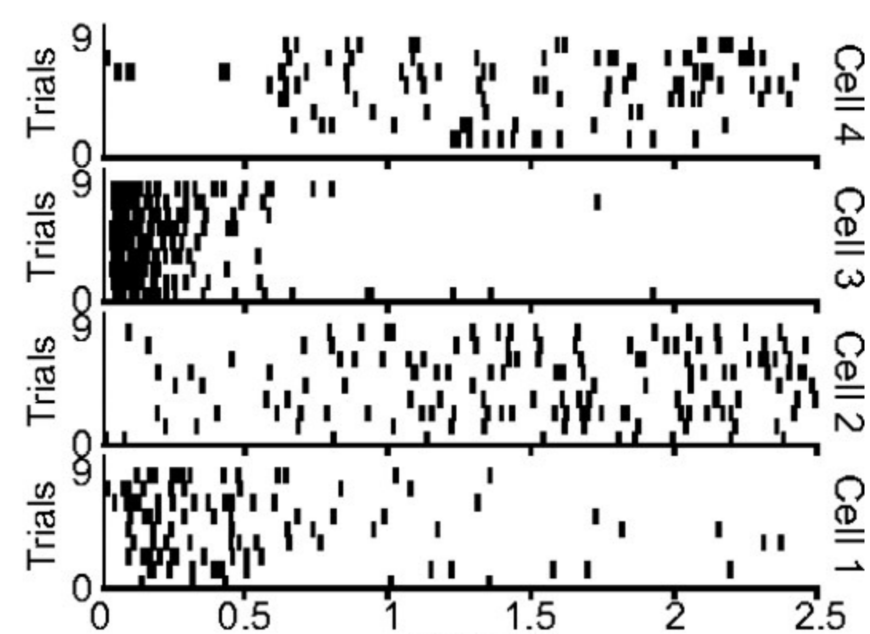
- clustering
- we can recover spike times
- not many ground truth datasets (patch-clamp or juxtacellular parallel with extracellular)
    - however, a big parallel dataset has just been released, so it may change quickly
- it introduces confounds to the response statistics that are hard to characterise



How to measure variability?

- the base quantity number of spikes in a single time window
- variability can be measured in standard deviation of spike counts in all windows, or its square, variance
- if we present a single stimuli for a long time, adaptation makes a lot of our data useless -> we rather record a lot of short trials, each showing on elf our stimuli, in randomised order
- spike count variance can be measured over the trials showing the same stimulus, always in the same time window





Reliability of variance estimation

- statistical measures are random variables themselves
- uncertainty in them depends on the sample size
- how many trials we need?

http://www.rmki.kfki.hu/~banmi/sote/spikingVariability.ipynb
https://colab.research.google.com/

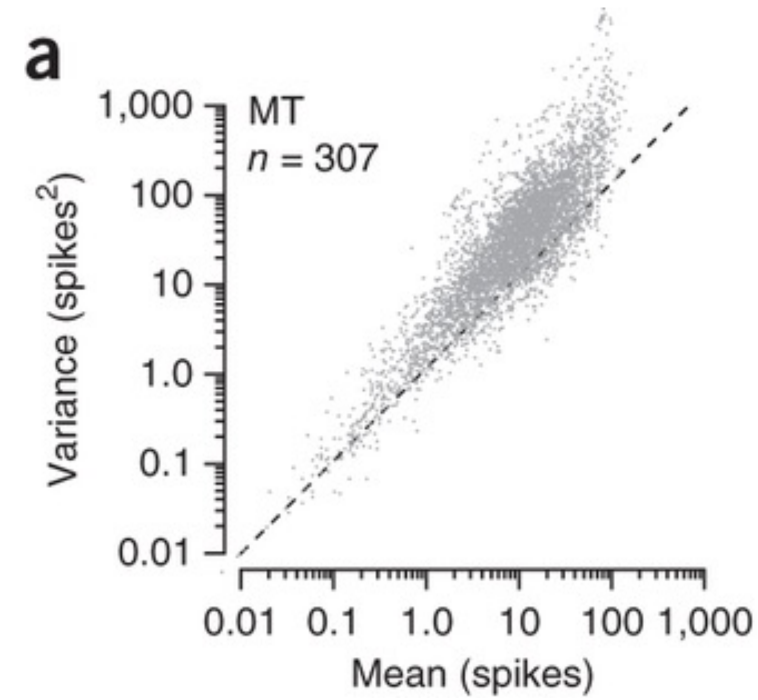
Characteristics of neural spiking statistics

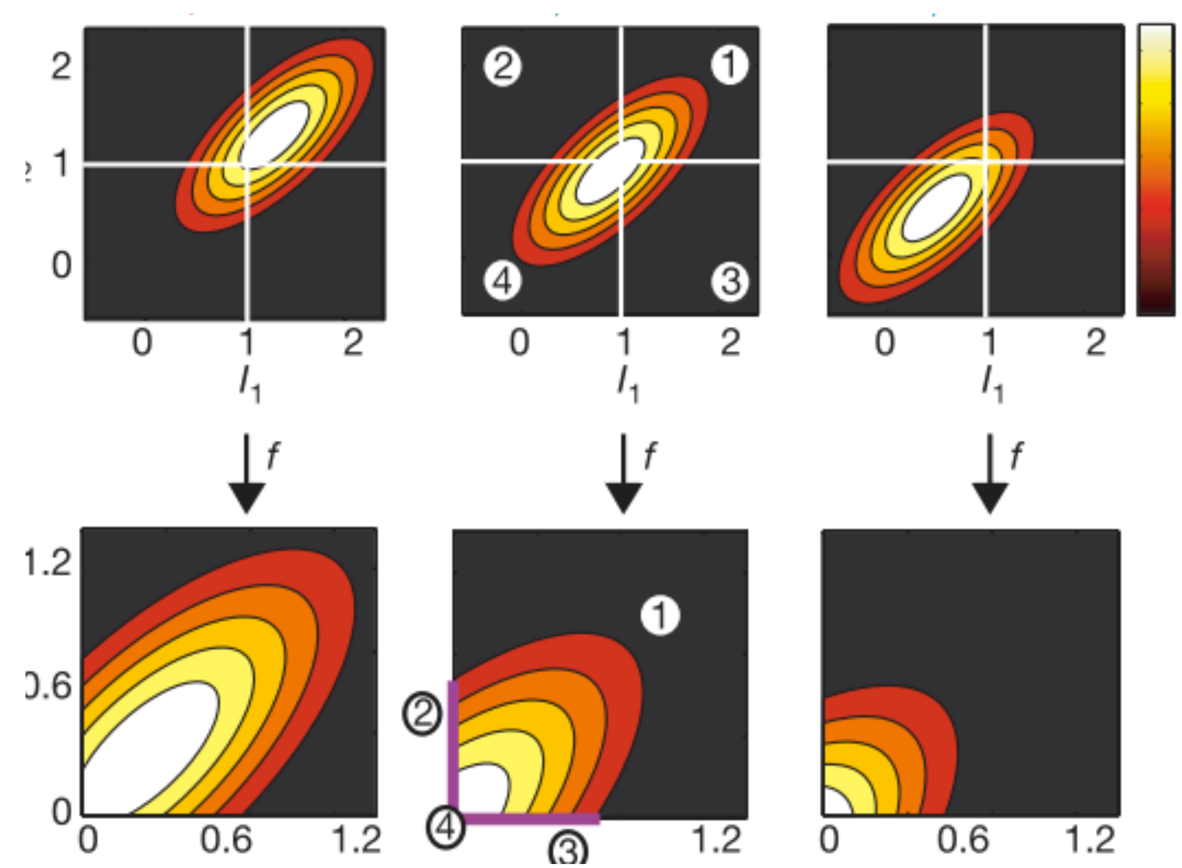
- the mean and the variance of the spike count tend to change together

- this may follow from a Poisson-distributed spike generation procedure

- or simply the effect of the firing threshold

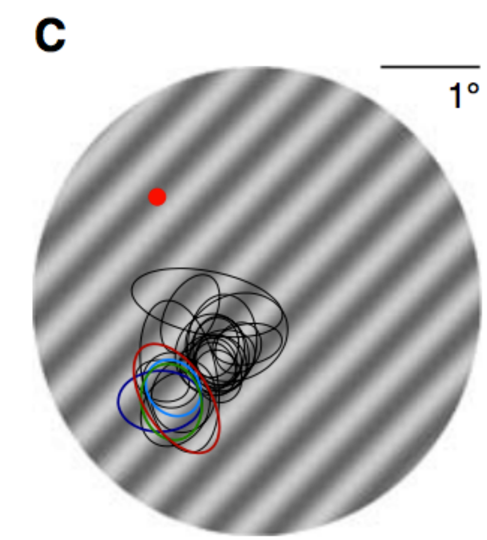
- we are interested in the excess variability relative to the mean -> Fano factor = variance / mean





Publicly available data

- http://bethgelab.org/datasets/v1gratings/
- Awake monkeys
- Multielectrode recording from V1
- Clustered spikes
- Static grating stimuli (they have moving too)
- Stimuli with low and high contrast levels



http://www.rmki.kfki.hu/~banmi/sote/spikingVariability.ipynb

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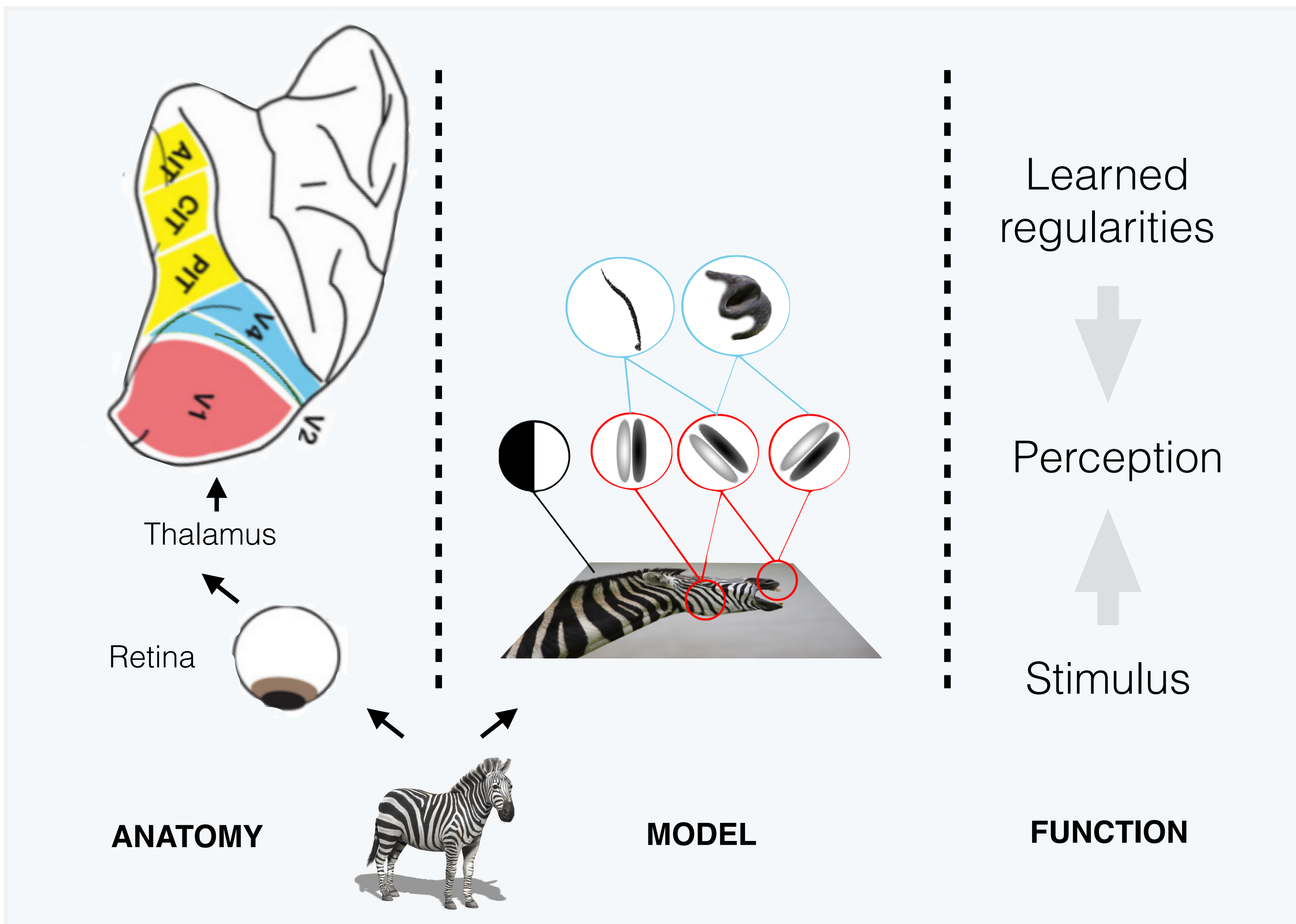
Further possible controls

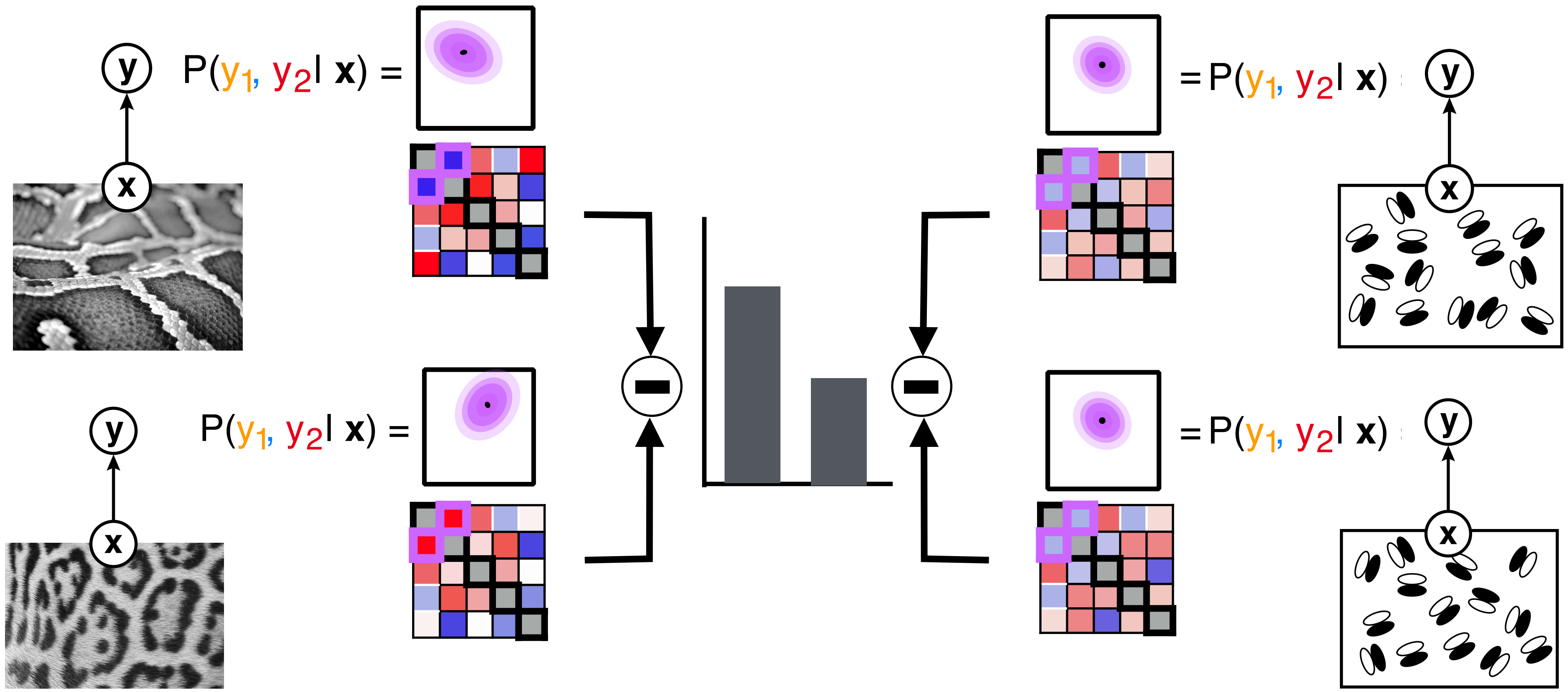
- We can throw out units deemed unreliable by the clustering algorithm
- Units with low firing rates may be filtered out, as few spikes mean unreliable statistics
- As changing contrast causes the mean and the variance change together, we may try to separate effects of the changing mean on the Fano factor

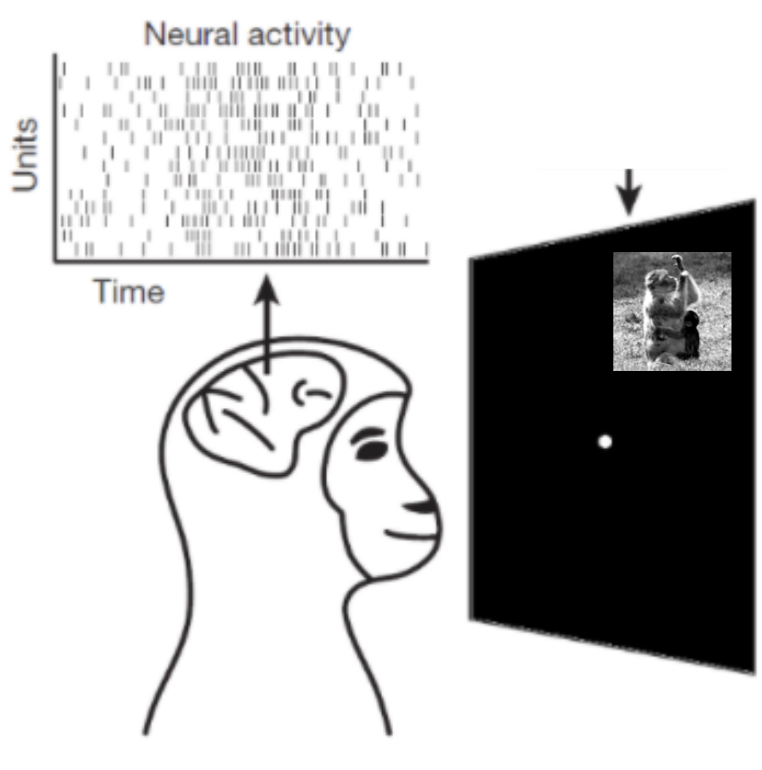
Functional hypotheses about co-activation statistics

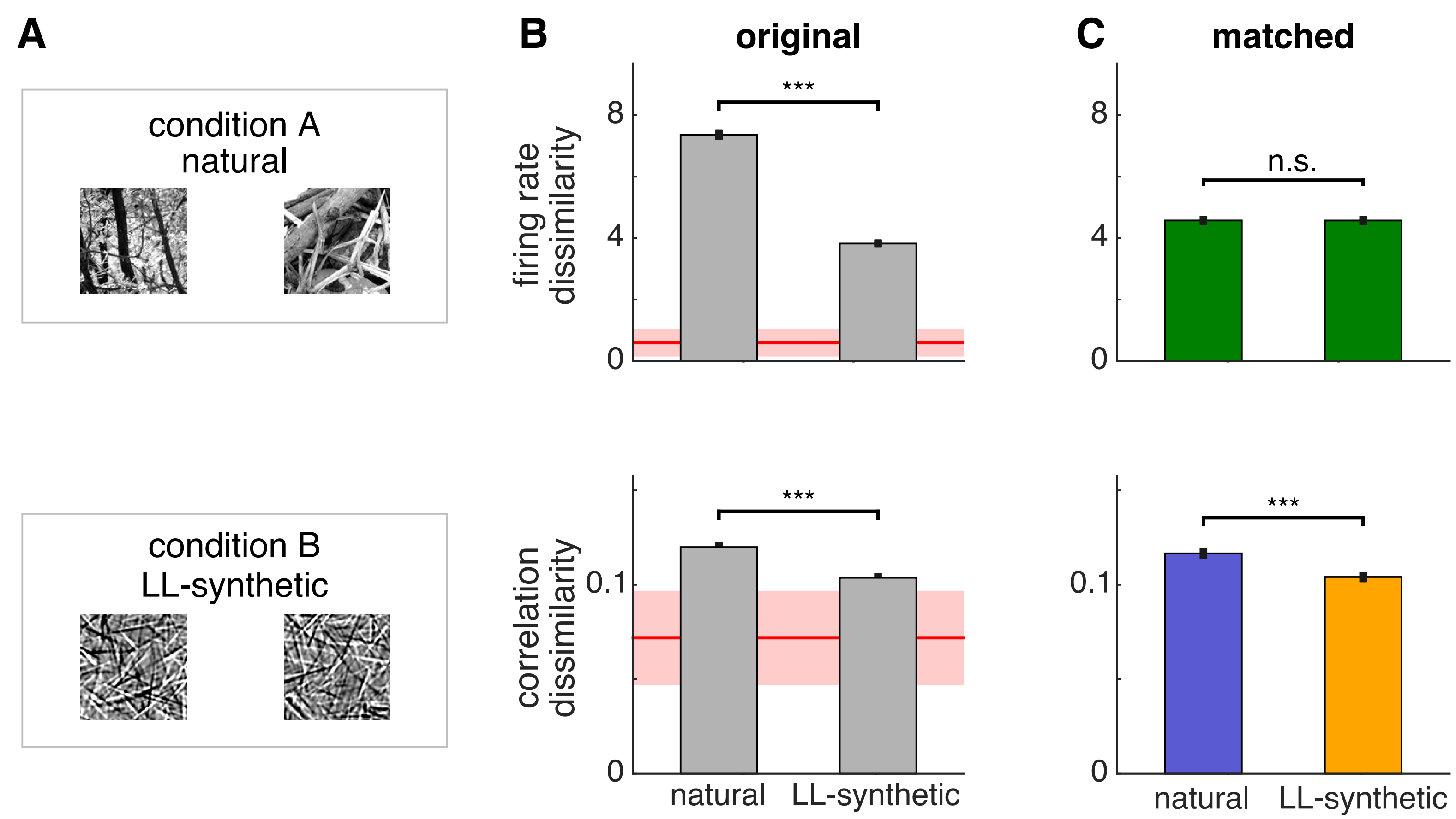
- Combination of edges -> texture/contour detection -> object recognition



Predicting co-activation statistics







Perception as probabilistic inference

- variability reflects uncertainty in a single feature
- covariability reflects expectations about the co-occurrence of features
- perception, all the way up to object recognition can be formalised as probabilistic inference of unobserved quantities (features, objects) based on observed ones (pixels, retinal activations)
- probabilistic models provide a unifying framework for understanding many brain functions and make connections to artificial intelligence solutions