The Neural Code:

From temporal to rate coding, and single neurons to networks.

Introduction to Neuroinformatics.

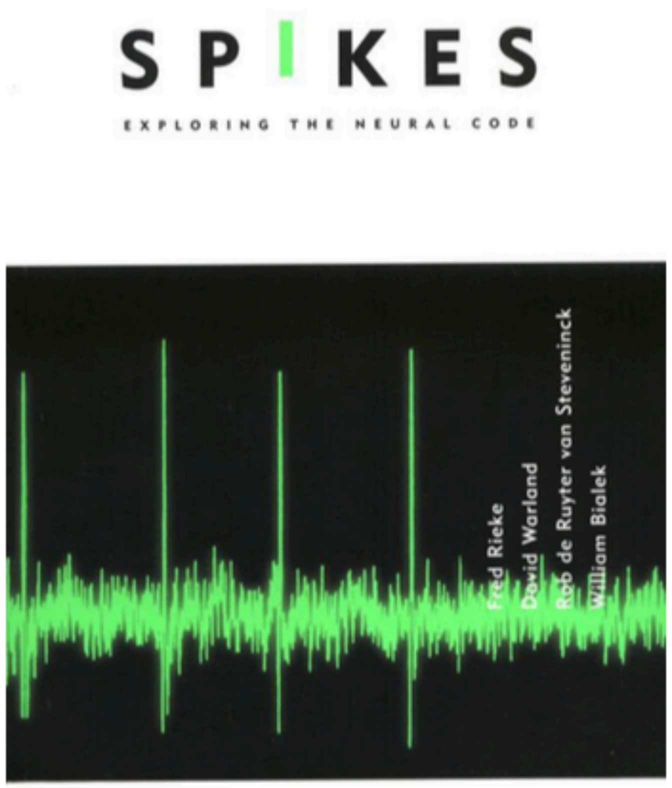
Benjamin F. Grewe

Thursday, Nov. 7th, 2019

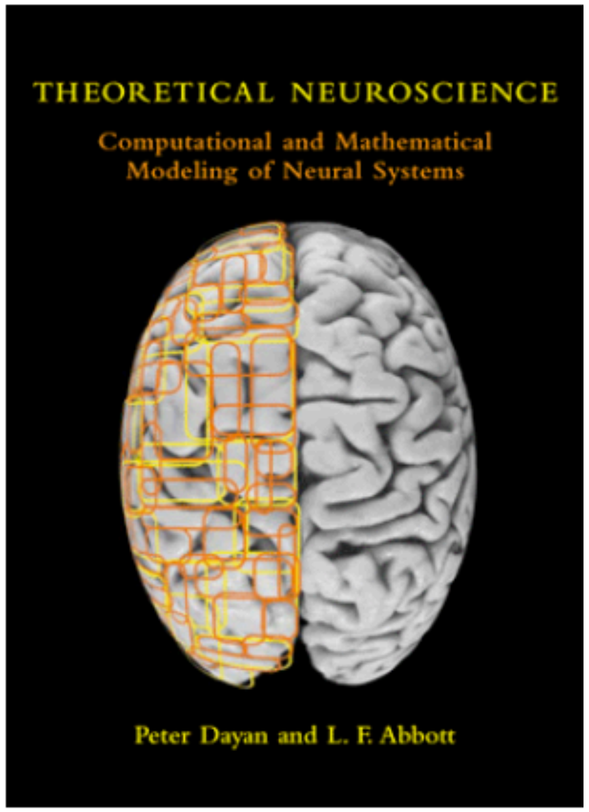
ETH Zürich

University of Zurich UZH

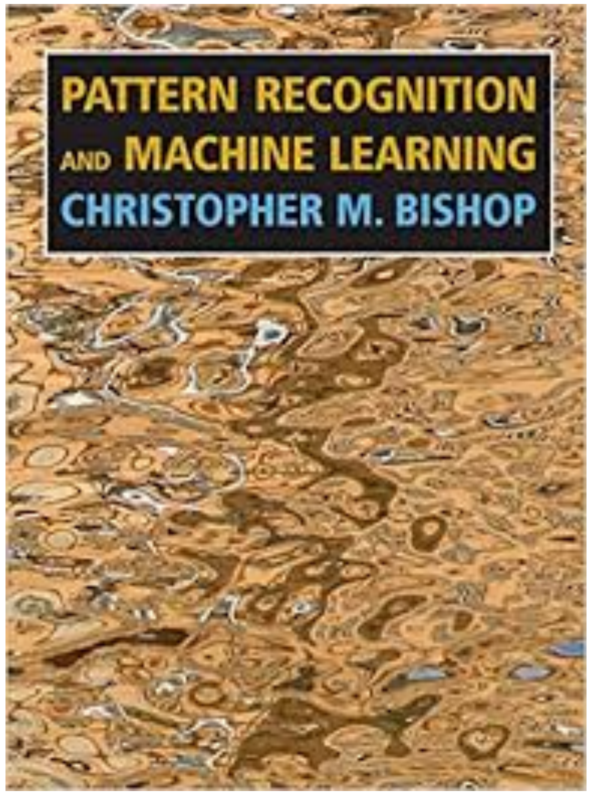
Literature/Books:



Rieke et al. 1997



Dayan and Abbott

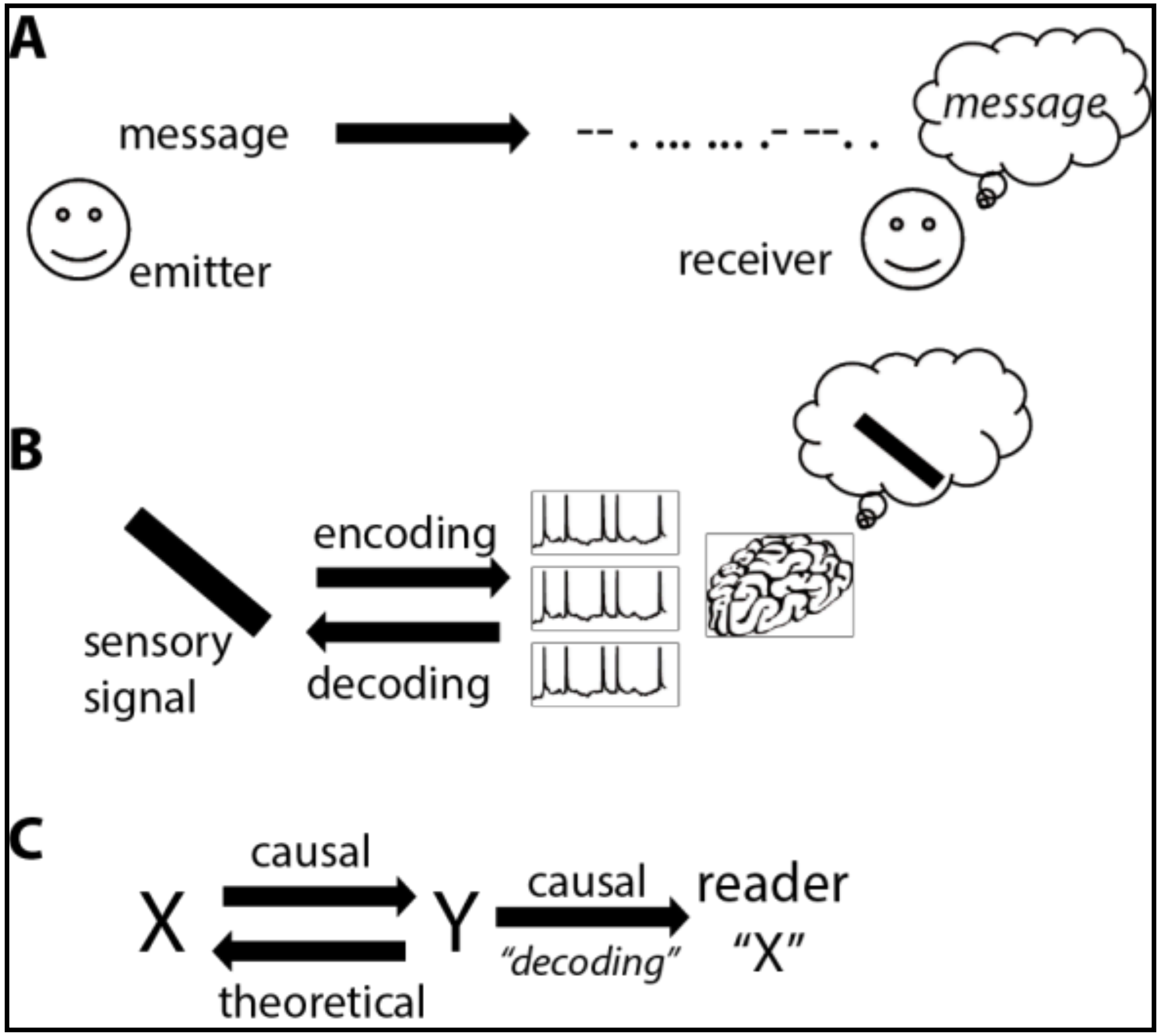


Bishop 2011

Paper and Reviews:

- Brette 2017, 10.1101/168237
- deCharms and Zador, 2000, 10.1146/annurev.neuro.23.1.613
- Perkel and Bullock, 1968, https://ntrs.nasa.gov/search.jsp?R=19690022317
- Quiroga et al, 2005, 10.1038/nature03687
- Georgopoulus et al., 1988, 10.1523/JNEUROSCI.08-08-02928
- Grewe et al., 2017, 10.1038/nature21682

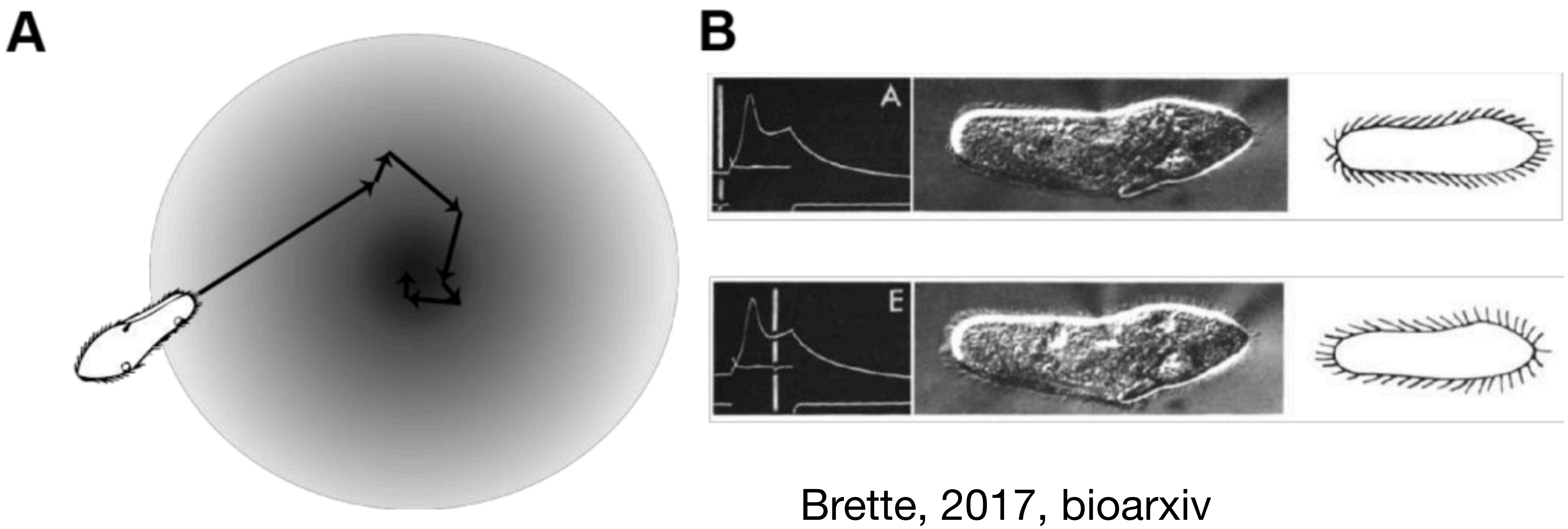
The Coding Metaphor.



Brette, 2017, bioarxiv

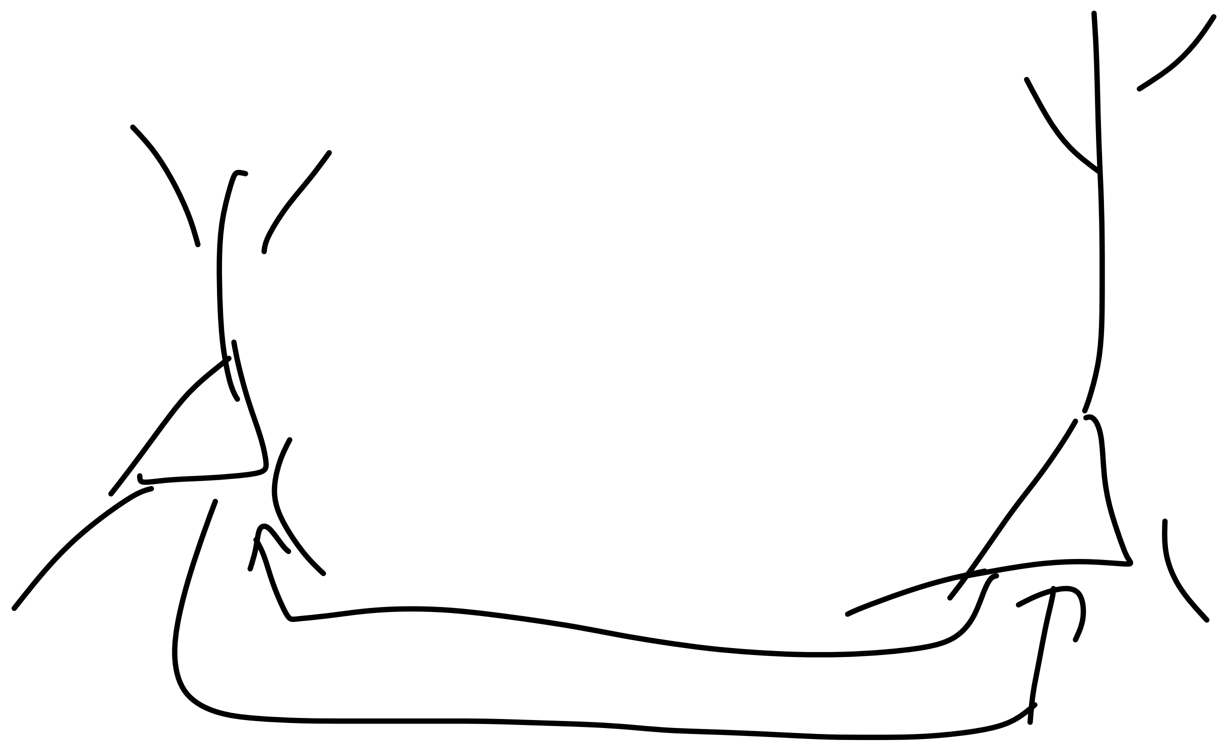
Perkel and Bullock (1968): The problem of neural coding is to elucidate "the representation and transformation of information in the nervous system."

The Paramecium a ‘*Swimming Neuron*’.



Brette, 2017, bioarxiv

Representation and Transformation of Information.



The Coding Metaphor.

Considering three elements (correspondence, representation, causality)):

1. **The technical sense of a code is a correspondence between two domains, e.g. visual signals and spike trains. We call this relation a code to mean that spike trains specify the visual signals, as in a cipher: one can theoretically reconstruct the original message (visual signals) from the encoded message (spike trains) with some accuracy, a process called *decoding*.**

2. **Not all cases of correlations in nature are considered instances of coding. Climate scientists, for example, rarely ask how rain encodes atmospheric pressure.**

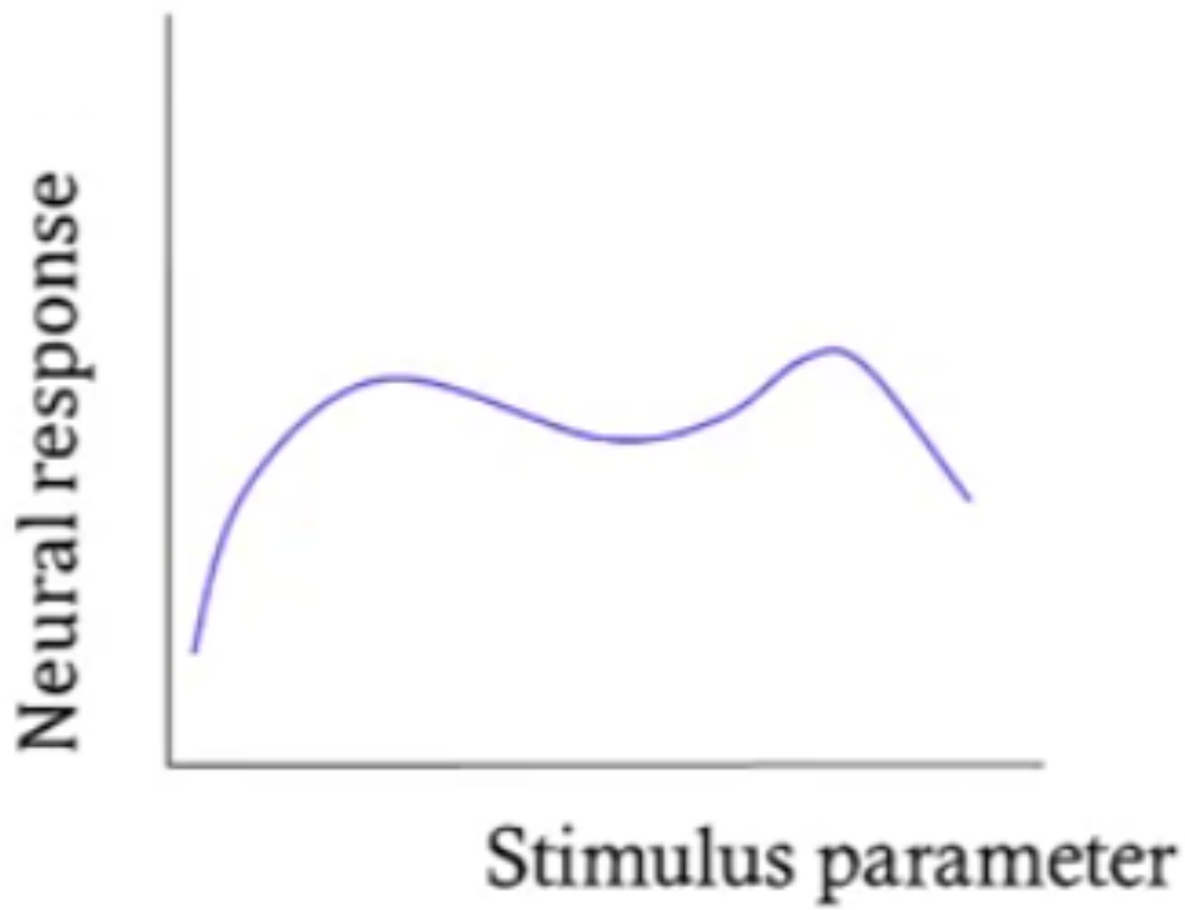
3. **Finally, we would not say that visual signals encode retinal spike trains, even though this would comply with the technical sense. The reason is the communication metaphor implicitly assumes a causal relation between the original message and the encoded message; here, spike trains result from visual signals by a causal process (transduction).**

Encoding and Decoding of Information.

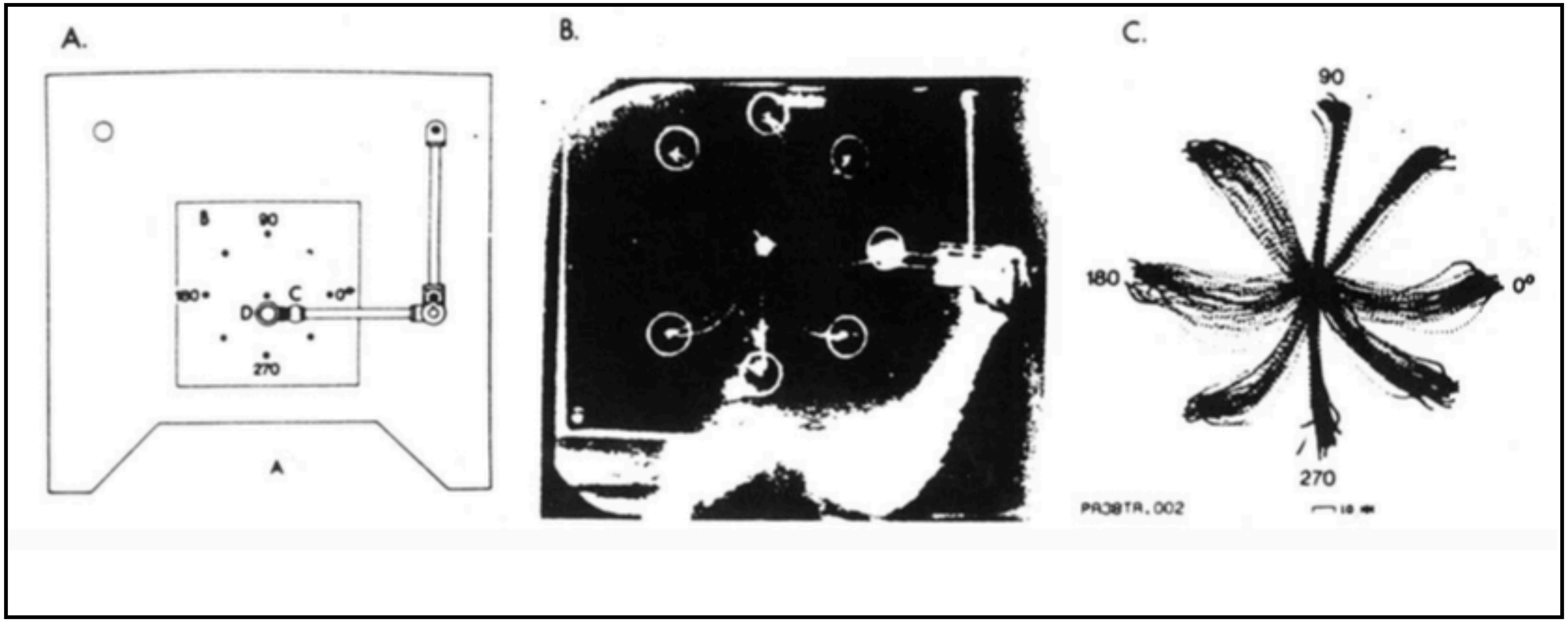
Encoding: How does a stimulus cause a pattern of responses?
- Building a approximate mechanistic model of the world.

Decoding: What do the responses tell us about the stimulus?
- How can we reconstruct the stimulus?

Finding the Stimulus-Response Relation.

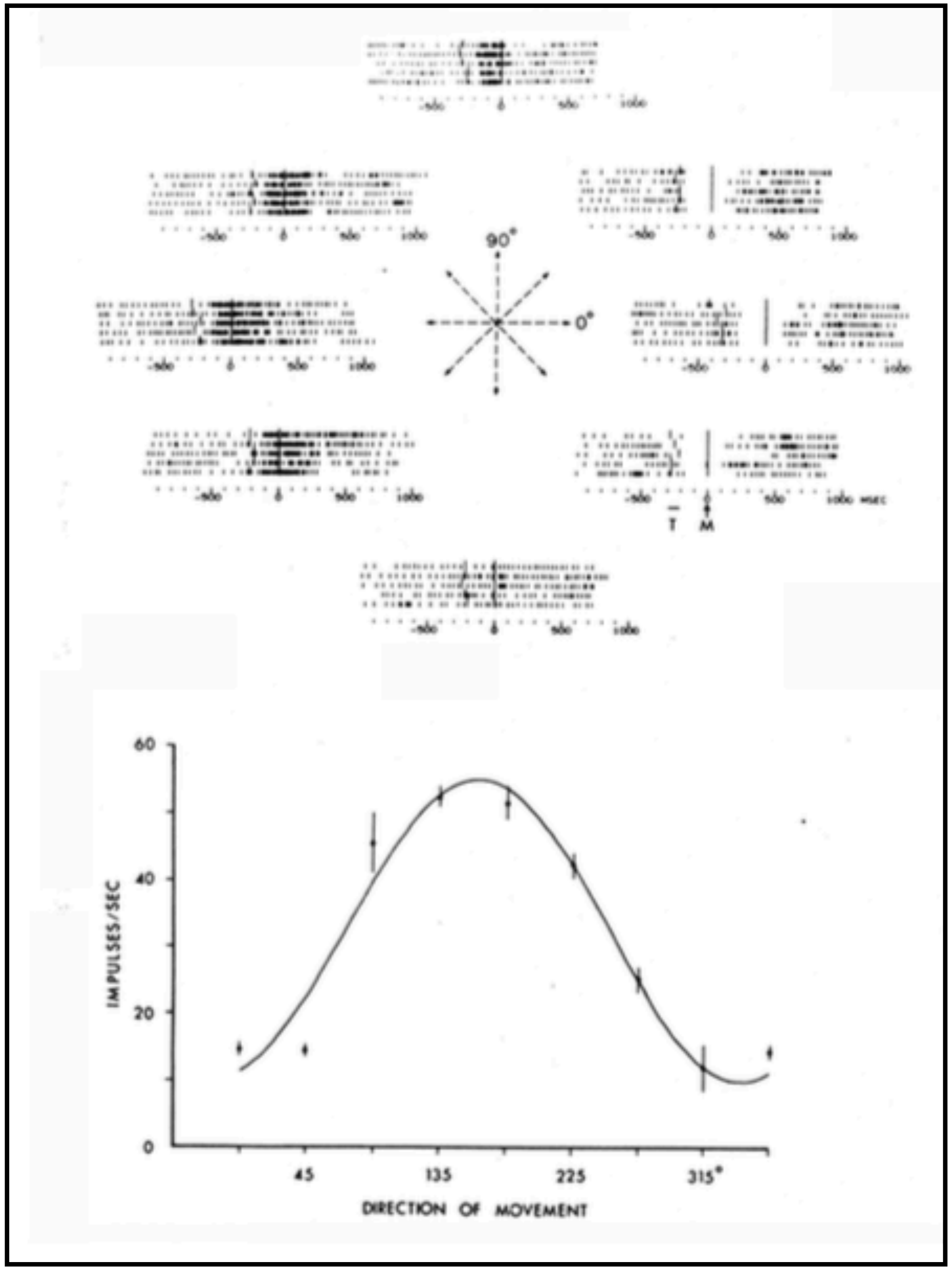


Encoding Motor Output in Primates.



Georgopoulus et al, 1982

Encoding Motor Output in Primates.



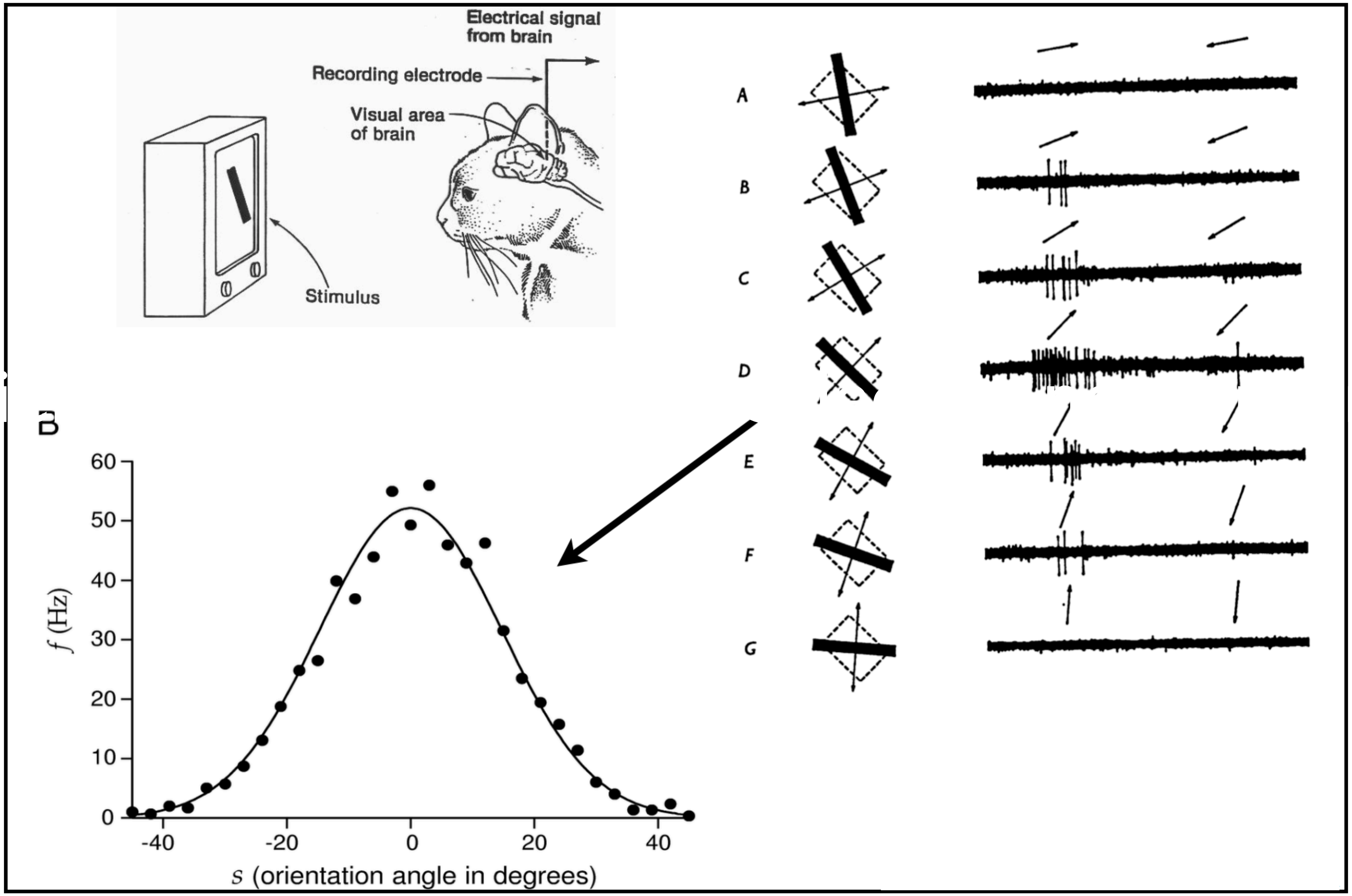
Georgopoulus et al, 1982

Recording Neuronal Responses in Cat V1

What is the stimulus parameter encoded by V1 neurons?

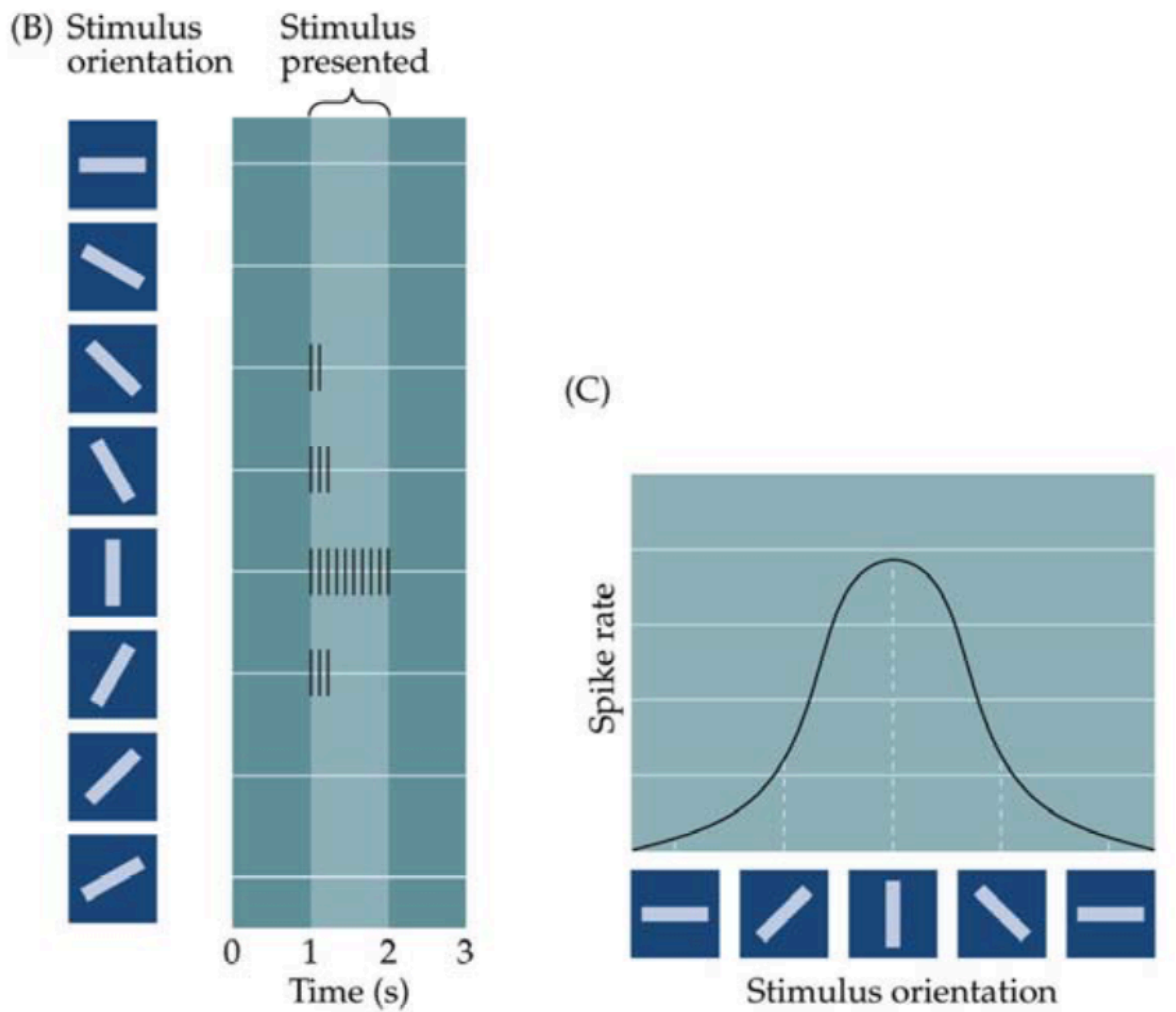
Hubel and Wiesel, 1959 and 1962

Orientation and Direction selective Neurons in V1.

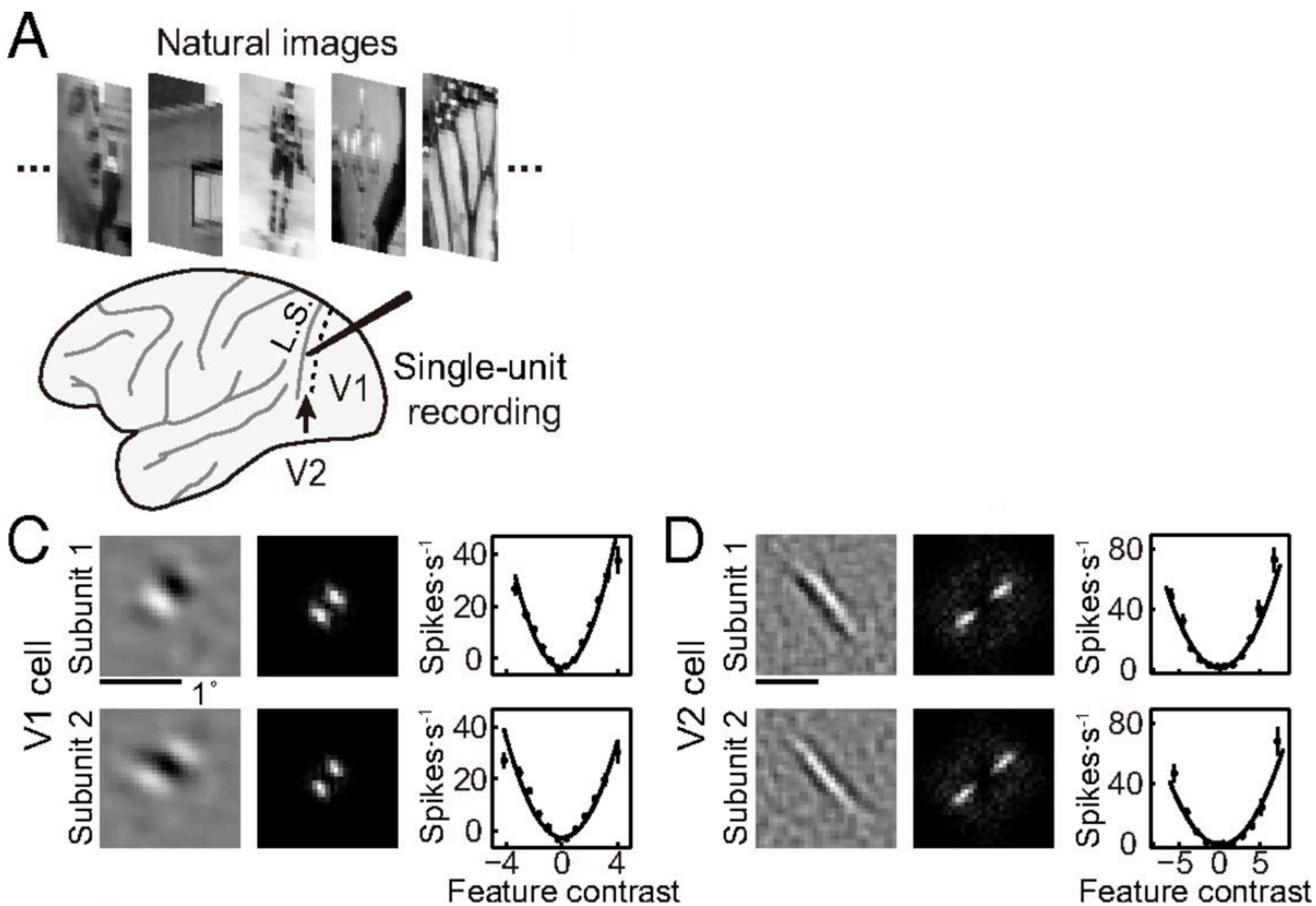


Hubel and Wiesel, 1962 and 1968

Orientation and Direction selective Neurons in V1.



Edge Filters in Primate Visual Cortex.



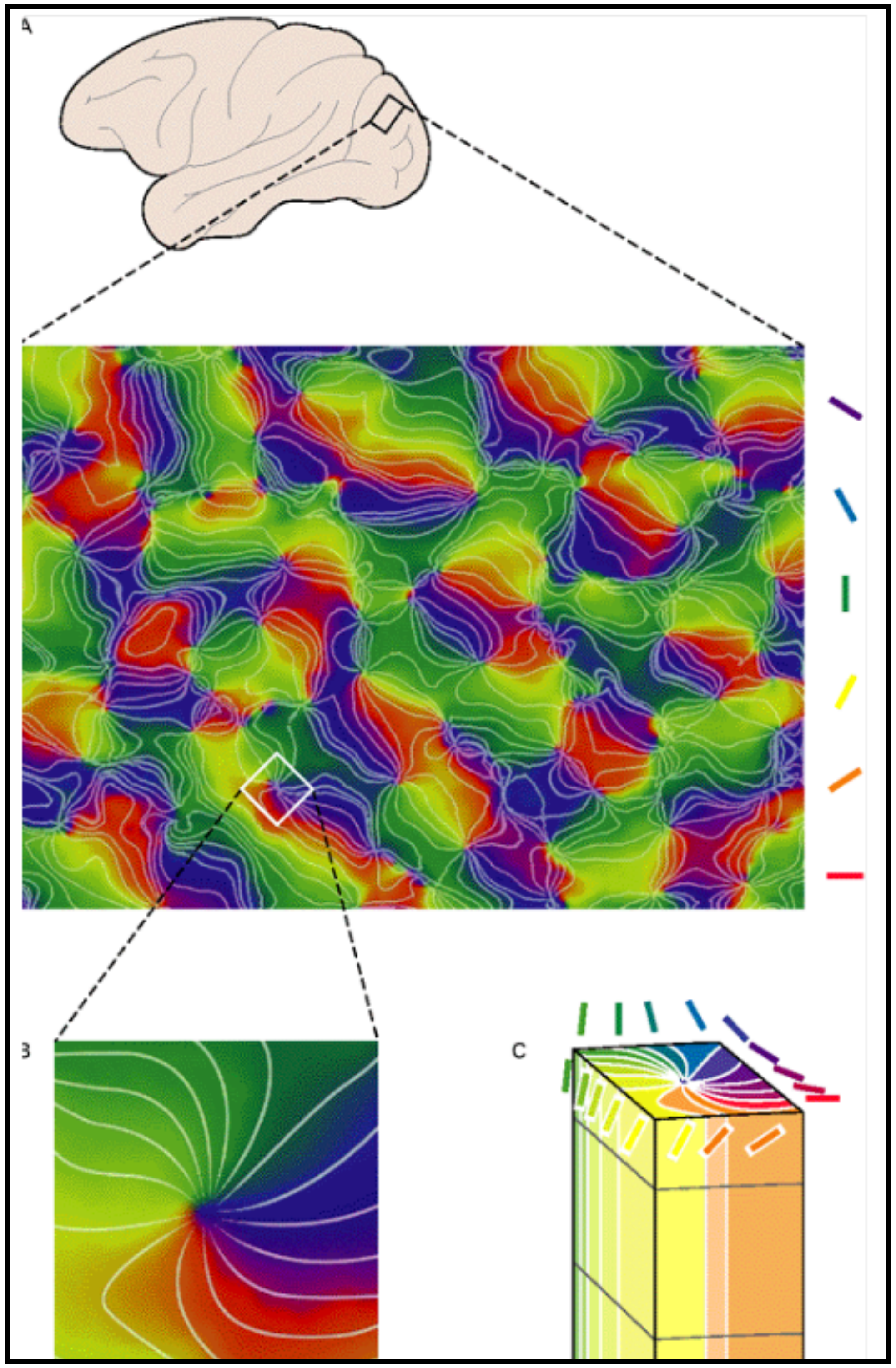
Spatial structure of neuronal receptive field in awake monkey secondary visual cortex (V2)

Lu Liu, Liang She, Ming Chen, Tianyi Liu, Haidong D. Lu, Yang Dan, and Mu-ming Poo

PNAS February 16, 2016 113 (7) 1913-1918; first published February 2, 2016 https://doi.org/10.1073/pnas.1525505113

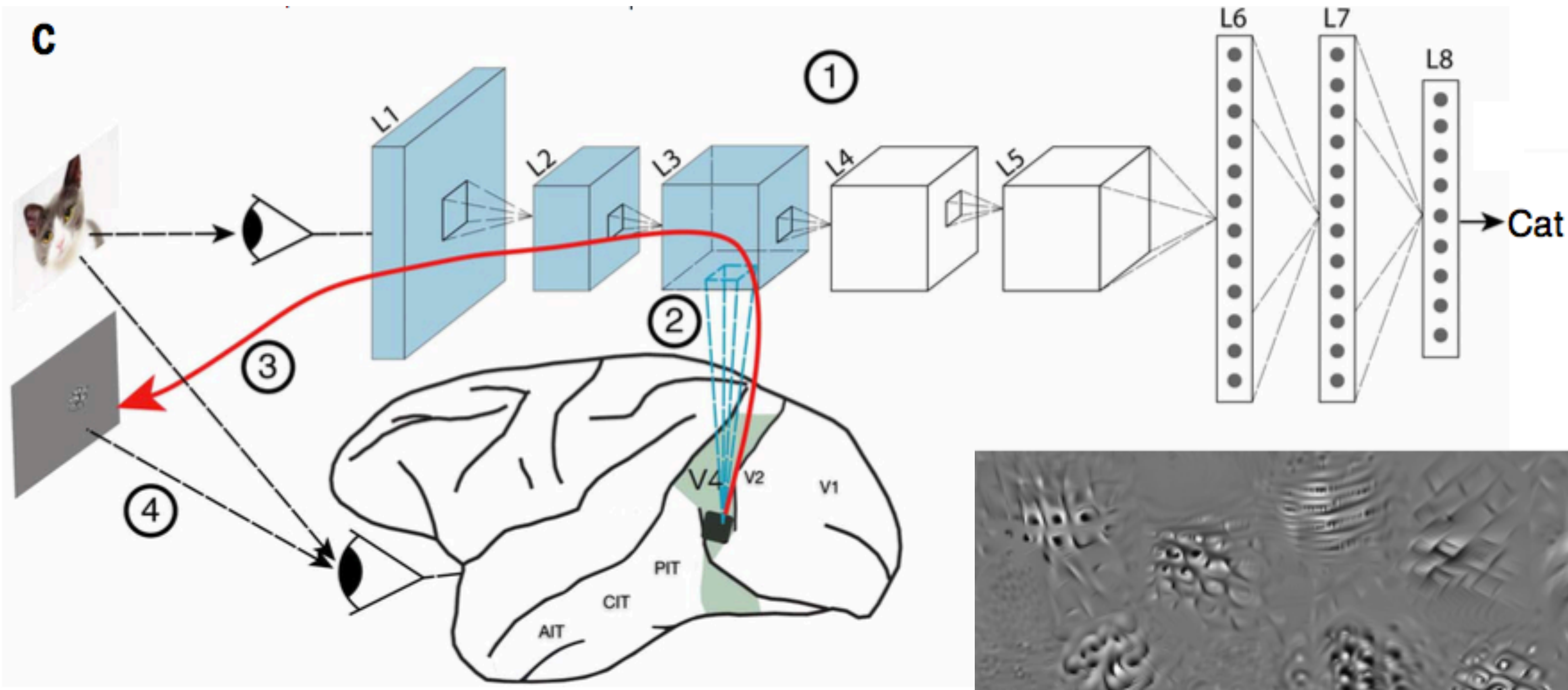
Contributed by Mu-ming Poo, January 6, 2016 (sent for review October 12, 2015; reviewed by Judith Hirsch and Doris Y. Tsao)

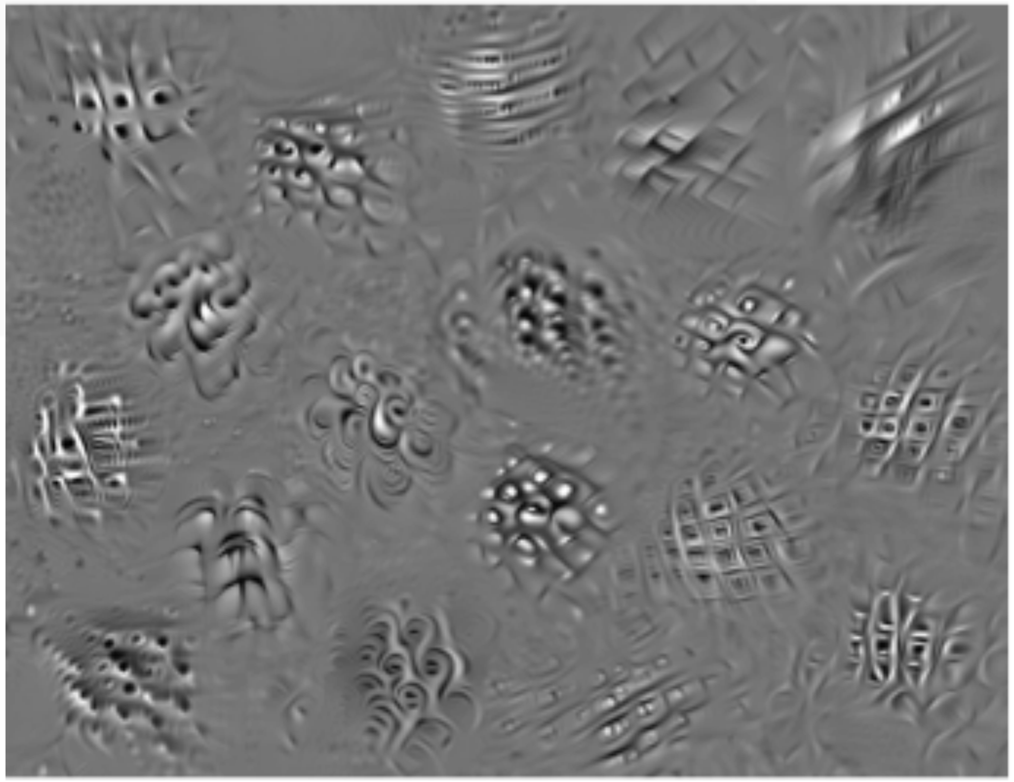
Orientation Specific Organization in Cat V1

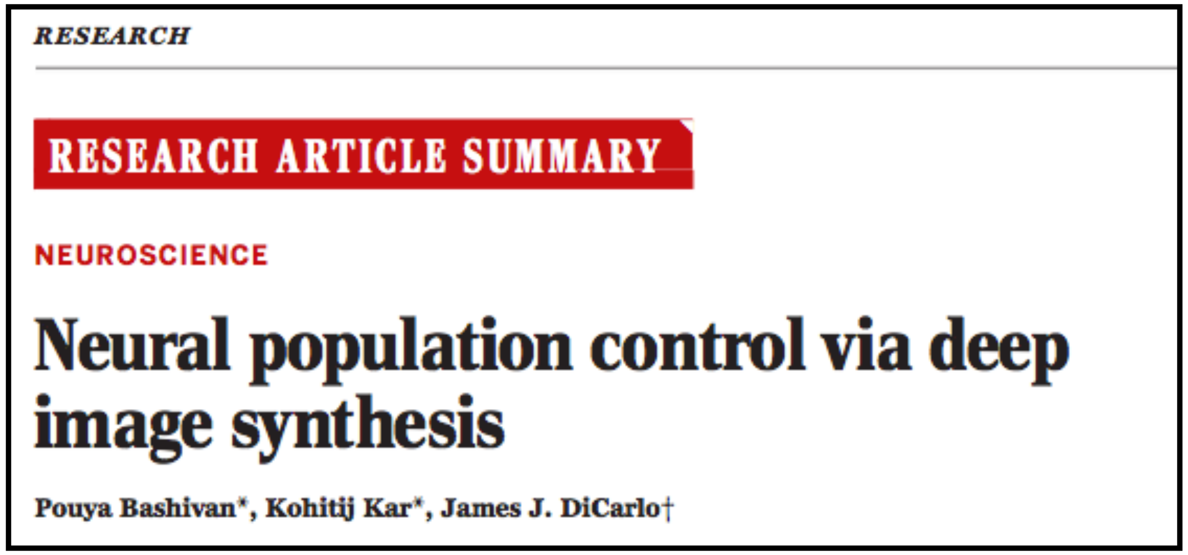


Pinwheel structure.

Encoding complex Stimuli in Primate V4






RESEARCH

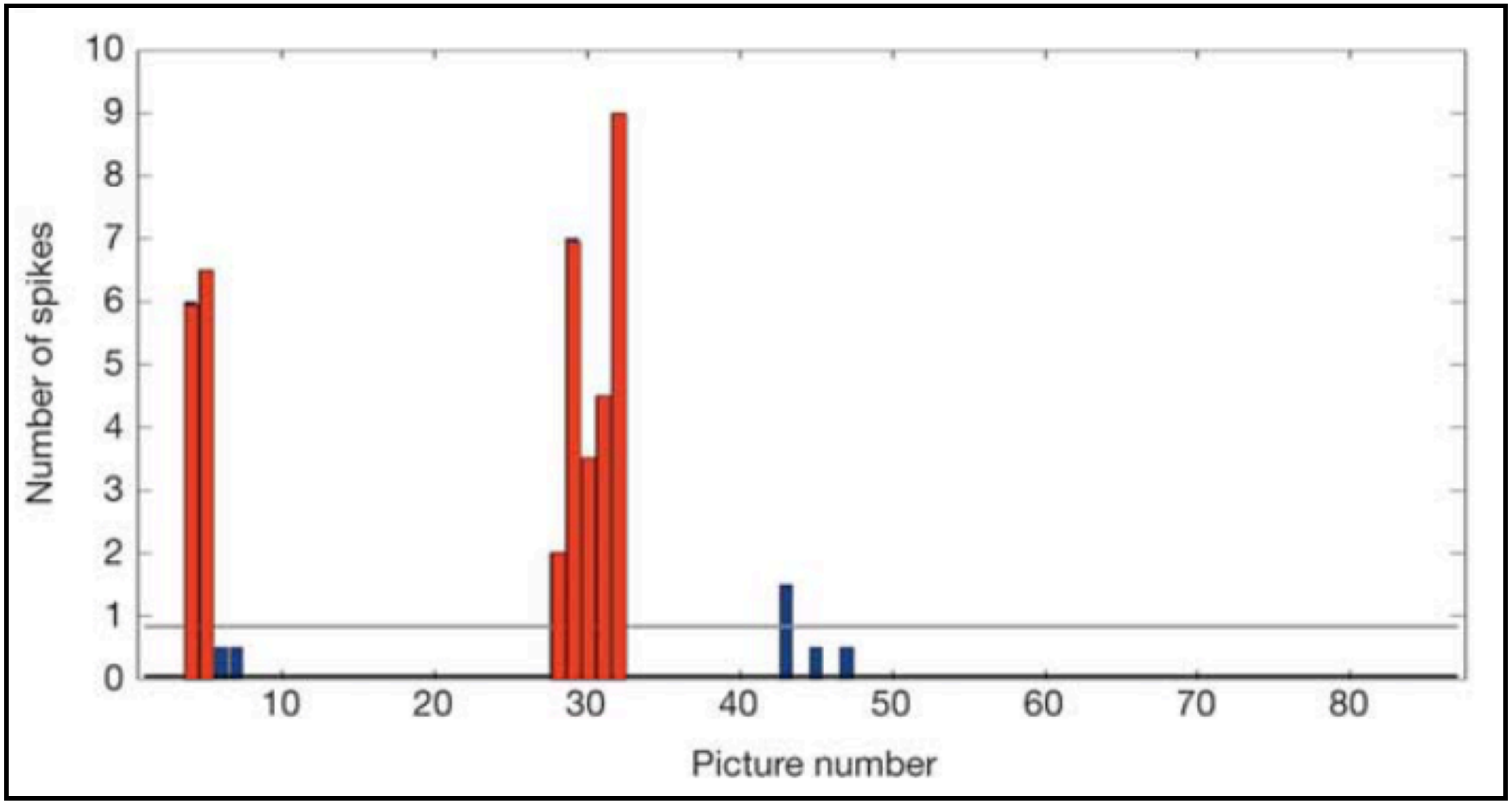
RESEARCH ARTICLE SUMMARY

NEUROSCIENCE

Neural population control via deep image synthesis

Pouya Bashivan*, Kohitij Kar*, James J. DiCarlo†

Encoding Visual Stimuli in the Human Brain (area MTL)



Quiroga et al., 2005

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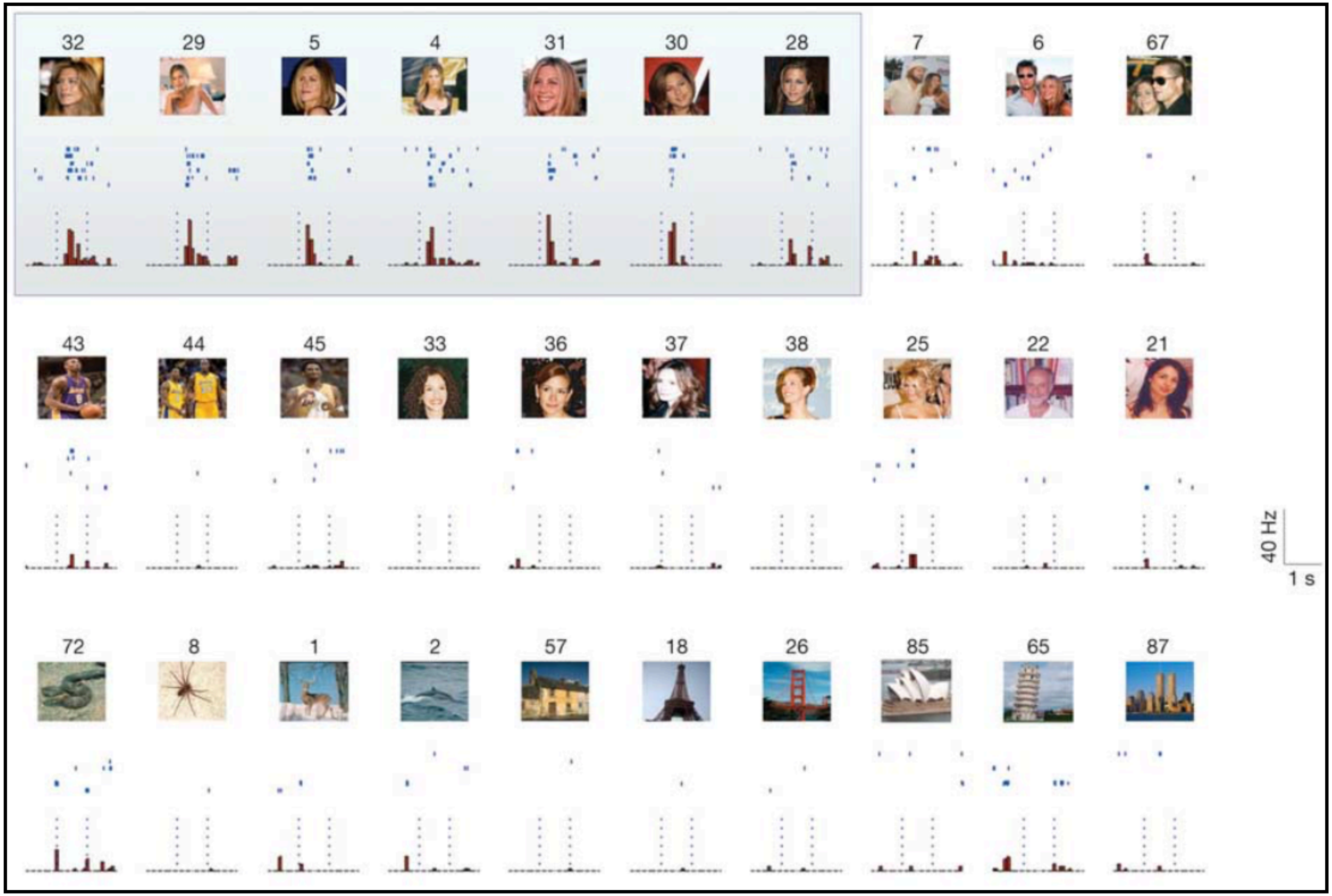

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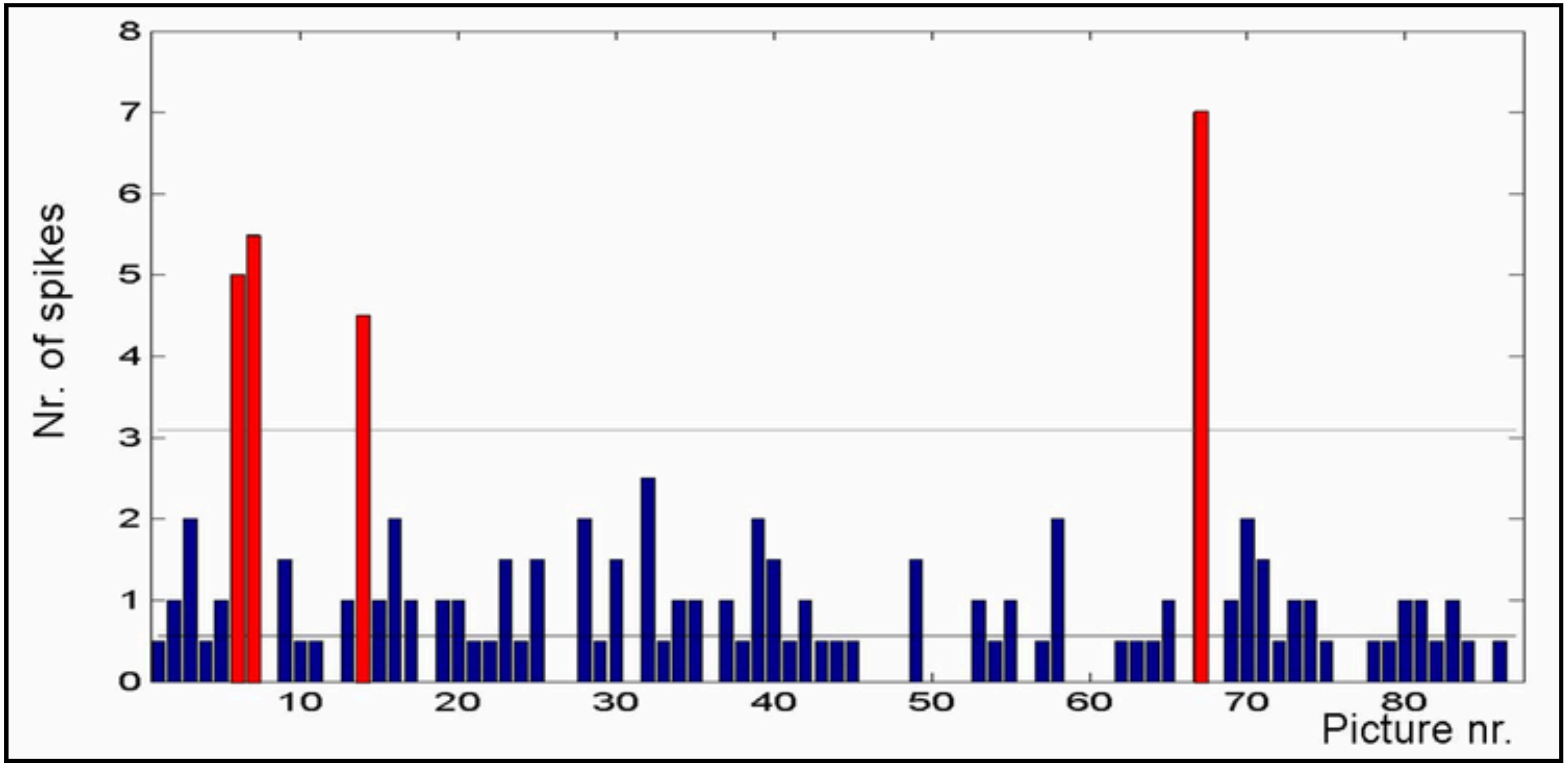

Quiroga et al., 2005

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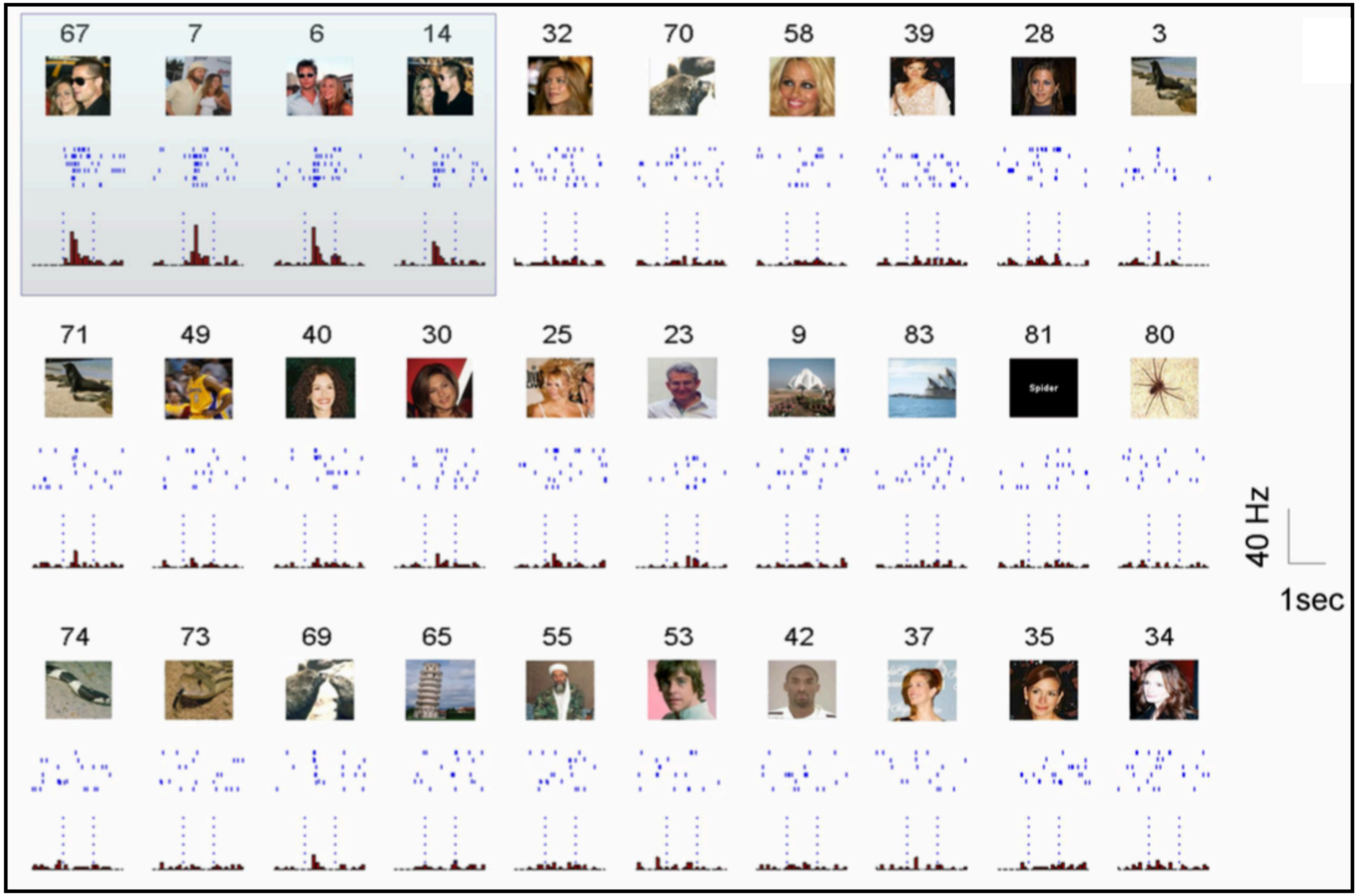

Quiroga et al., 2005

Encoding Spatial Information in Rat Hippocampus.

The Nobel Prize in Physiology or Medicine 2014
John O'Keefe, May-Britt Moser, Edvard Moser

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The Nobel Prize in Physiology or Medicine 2014

Photo: David Bishop, UCL
John O'Keefe
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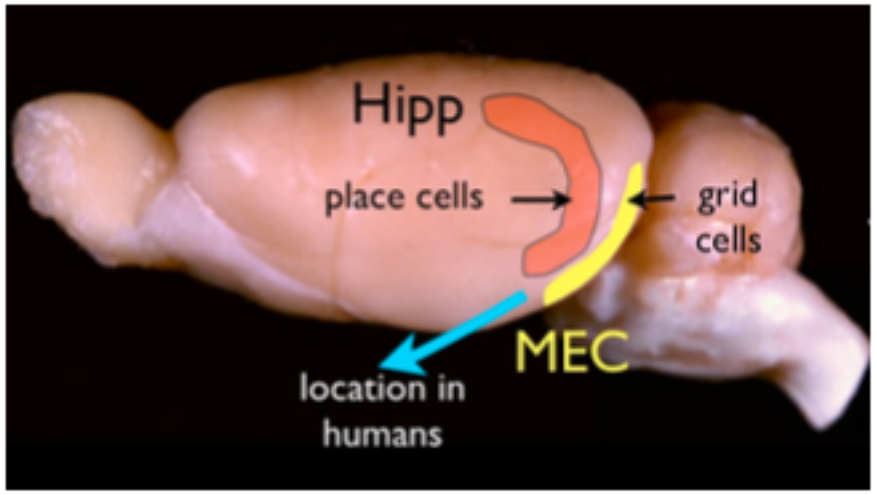
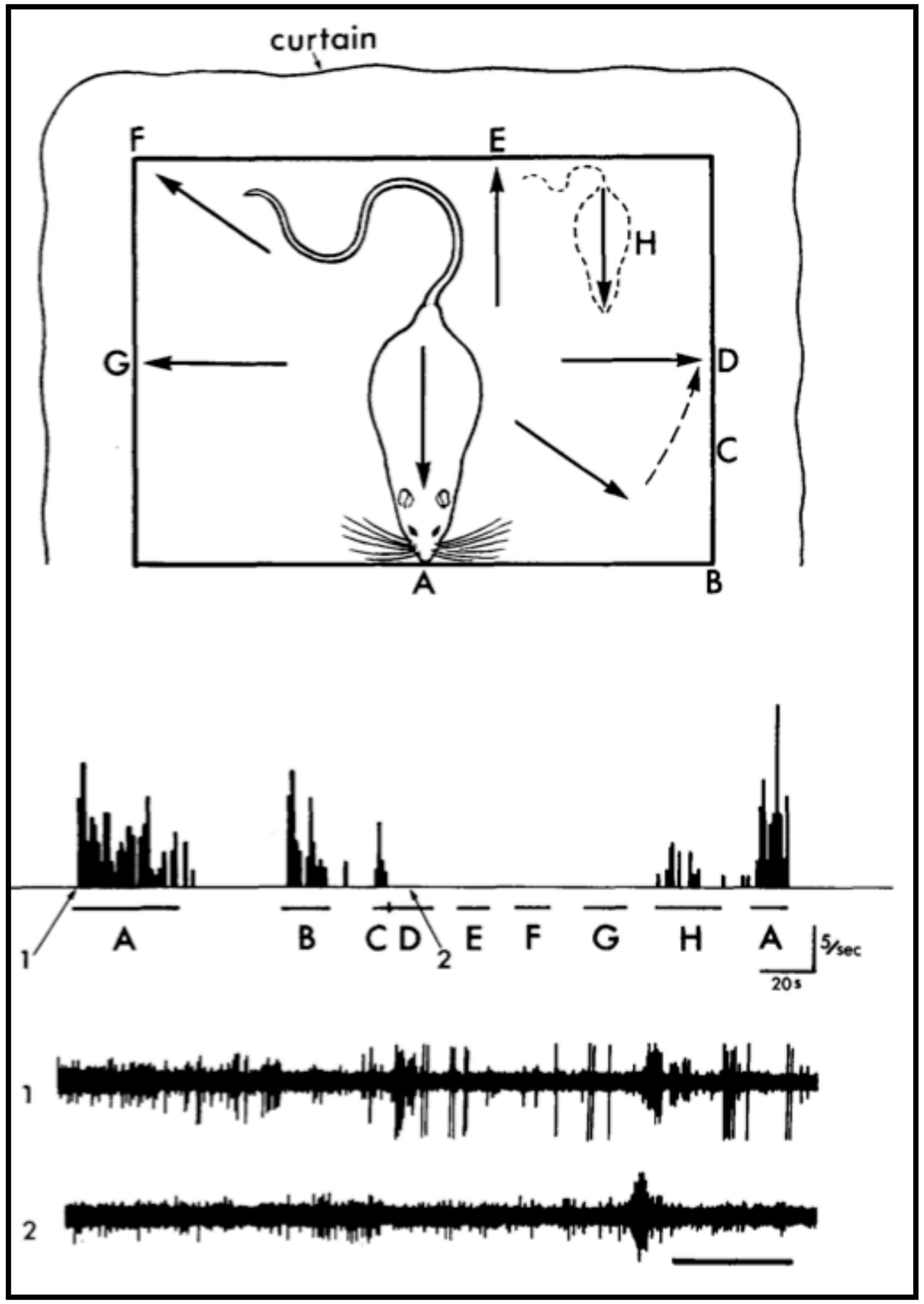
May-Britt Moser
Prize share: 1/4

Photo: G. Mogen/NTNU
Edvard I. Moser
Prize share: 1/4

Encoding Spatial Information in Rat Hippocampus.

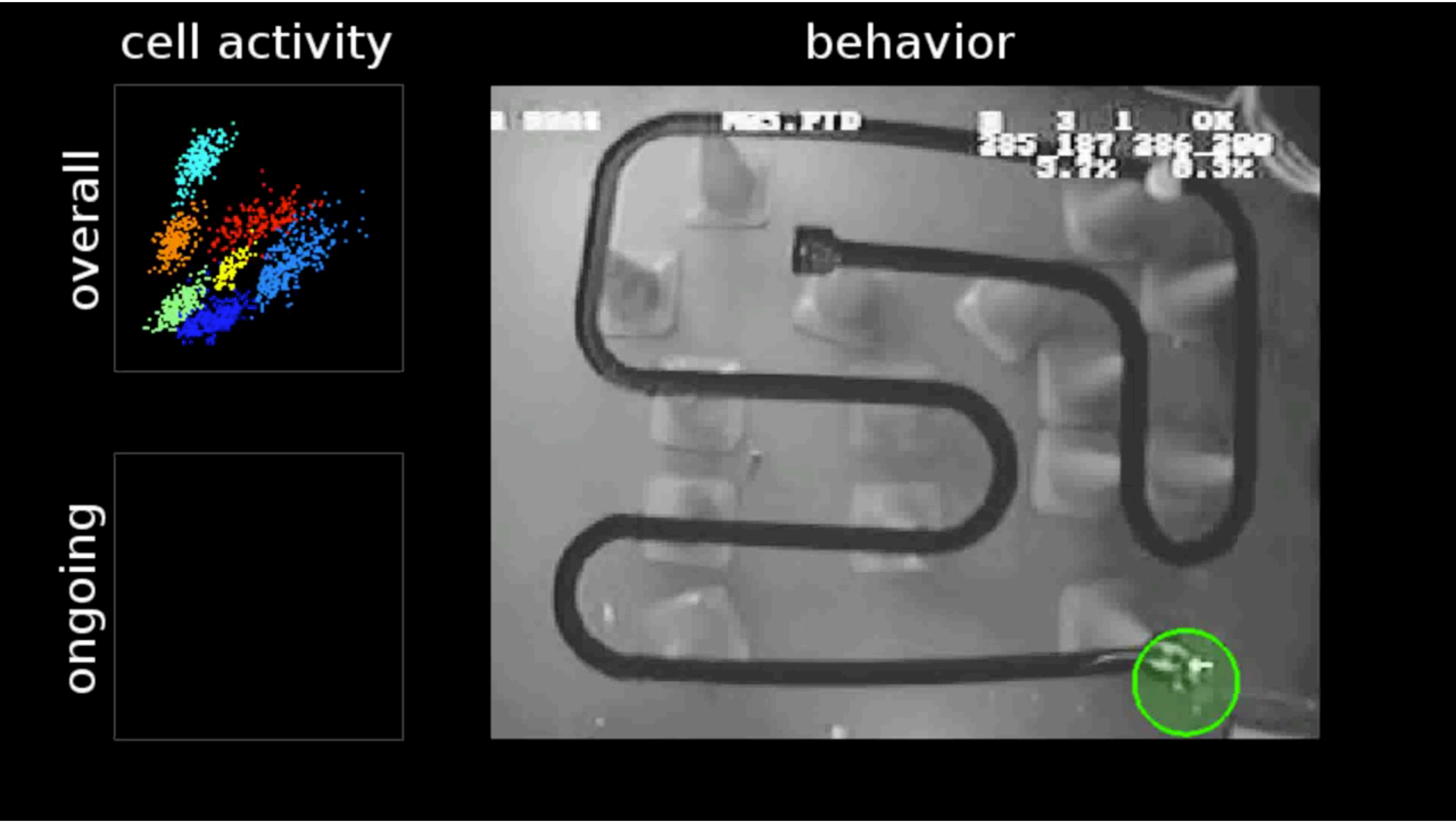
Rat Brain



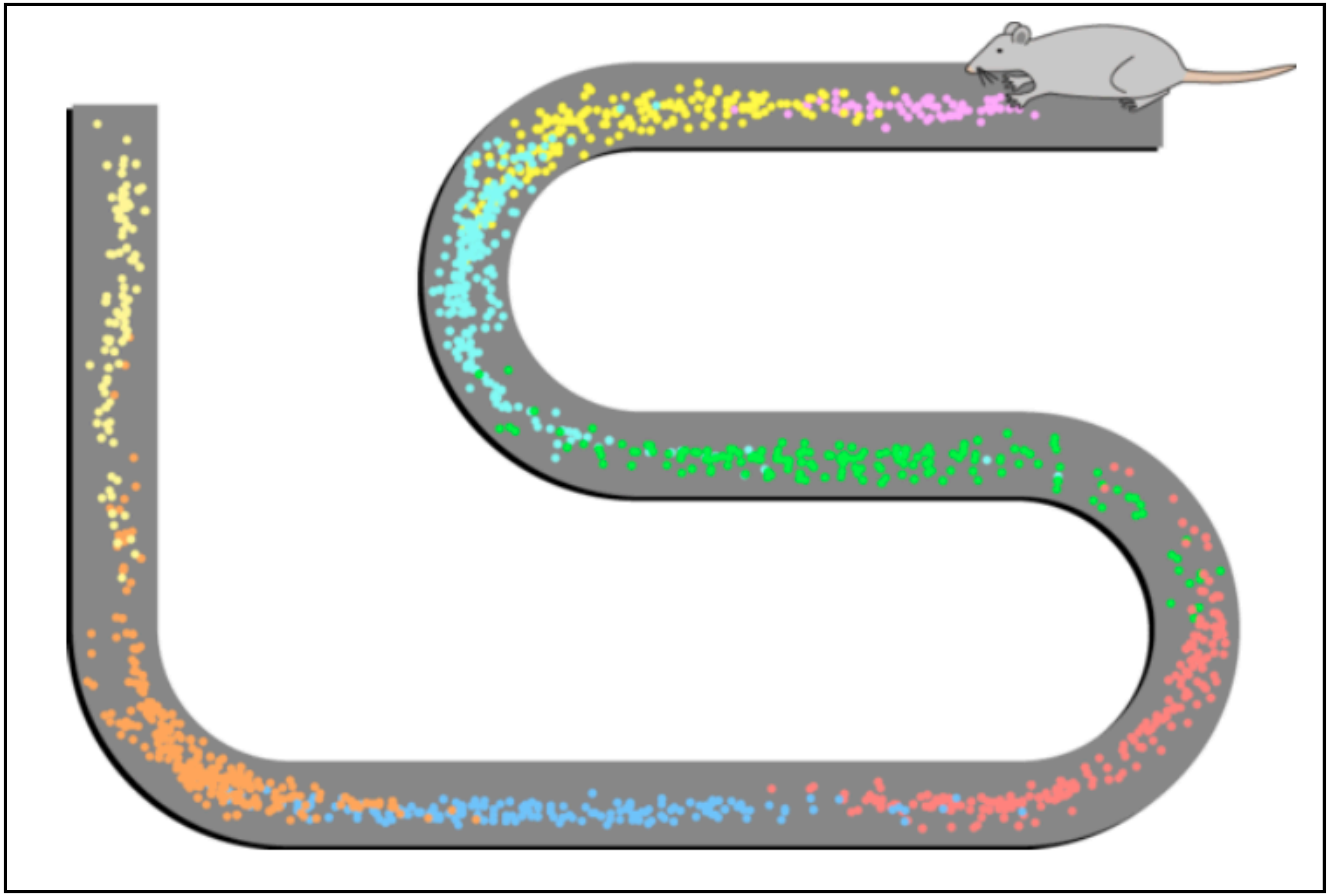


O'Keefe et al. 1971

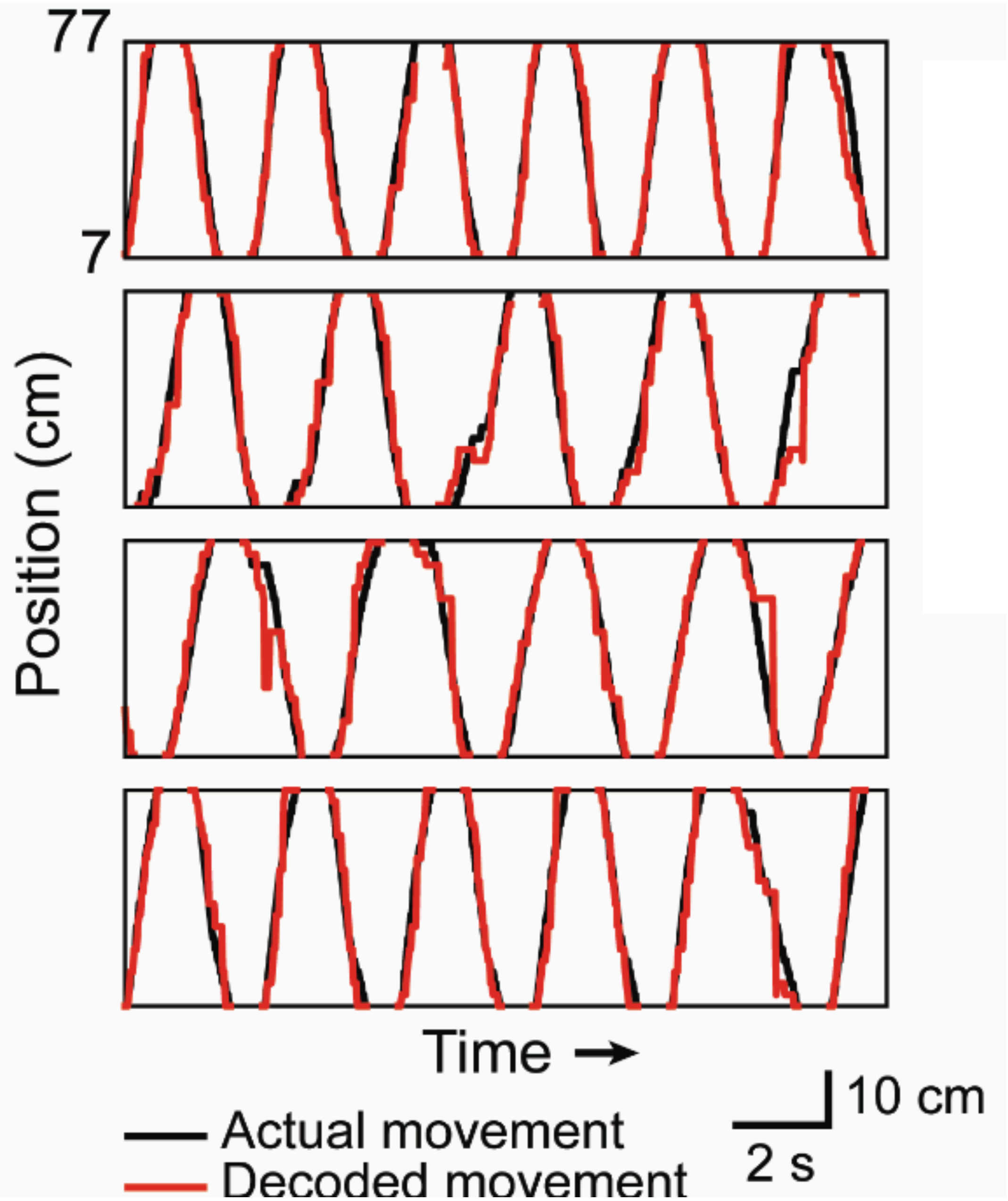
Encoding Space via Hippocampal Place Cells



Encoding Space via Hippocampal Place Cells

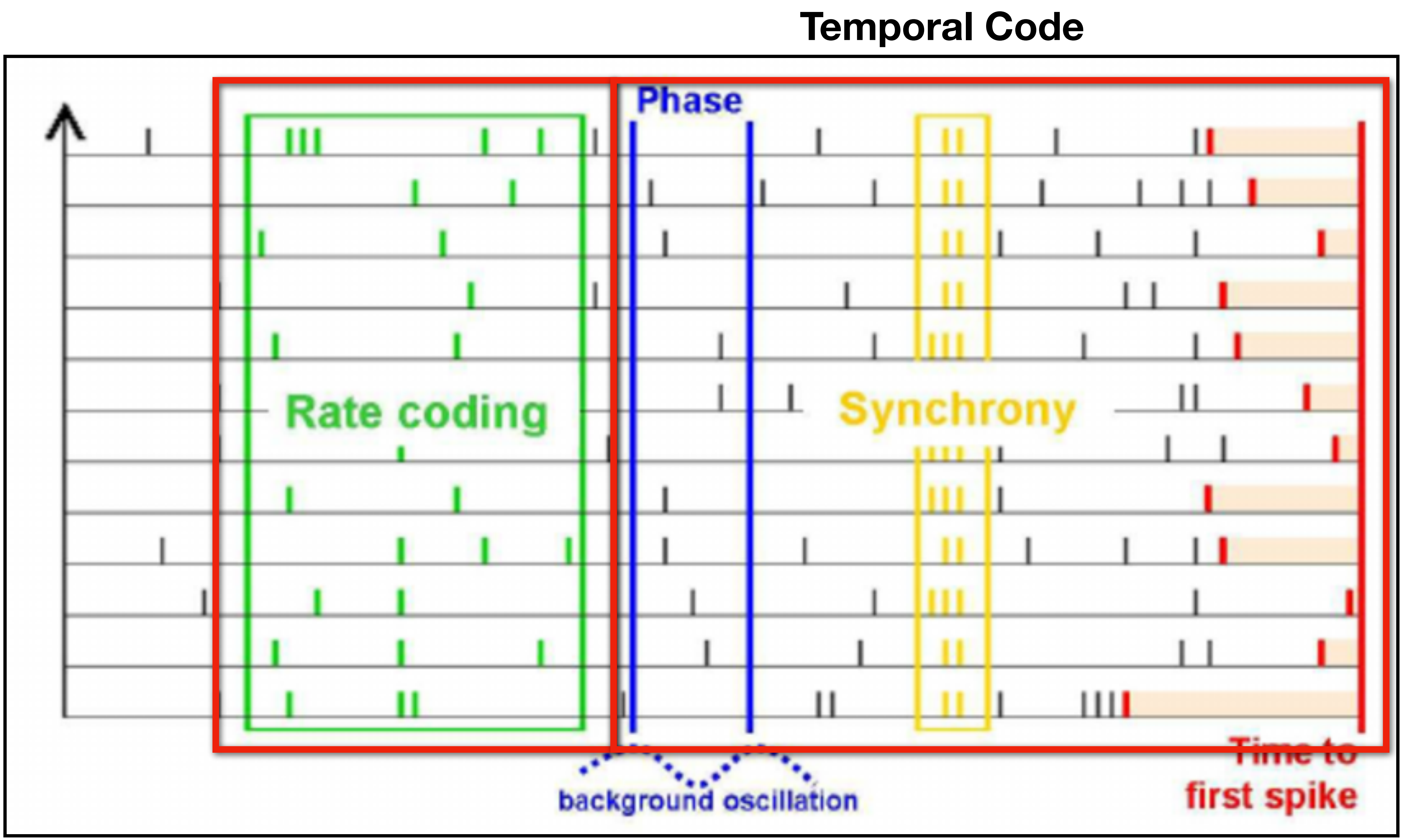


Decoding the Rats Position from Population Activity.



Ziv and Schnitzer, 2013

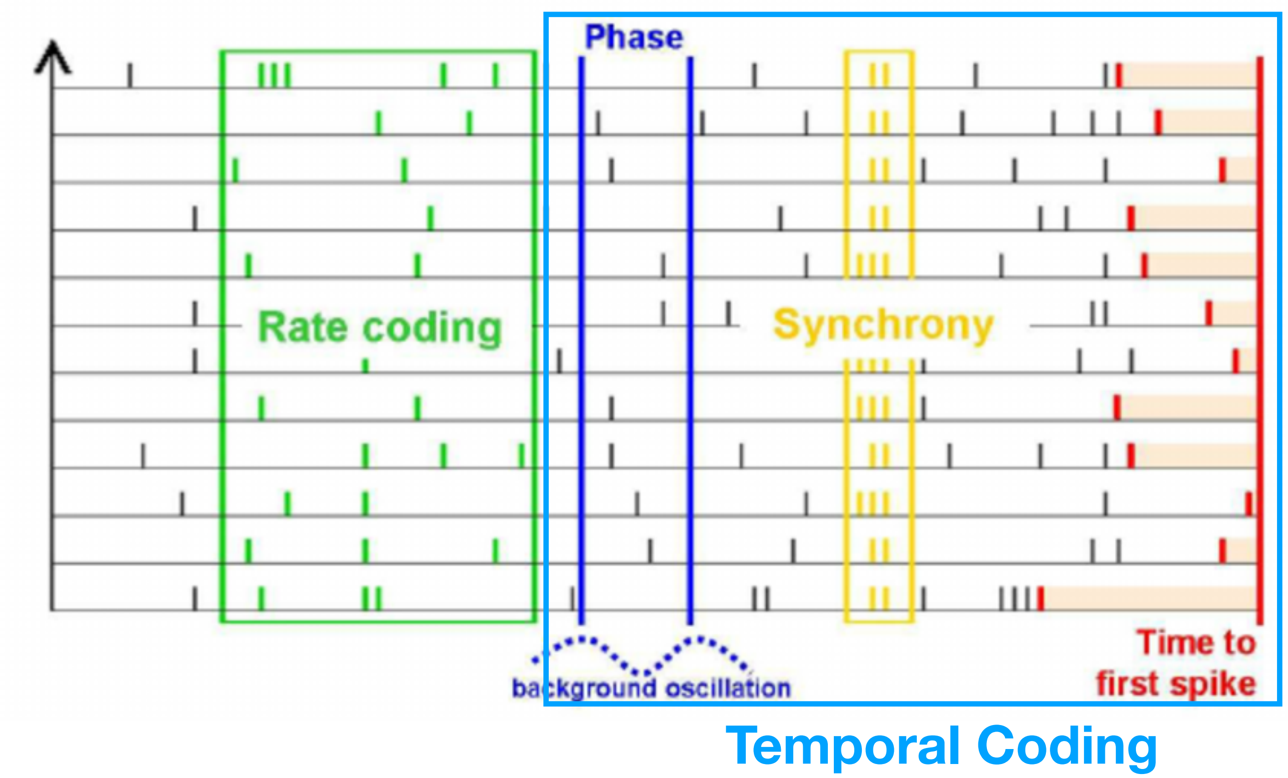
Which Features of the Spike Trains are the Signal?



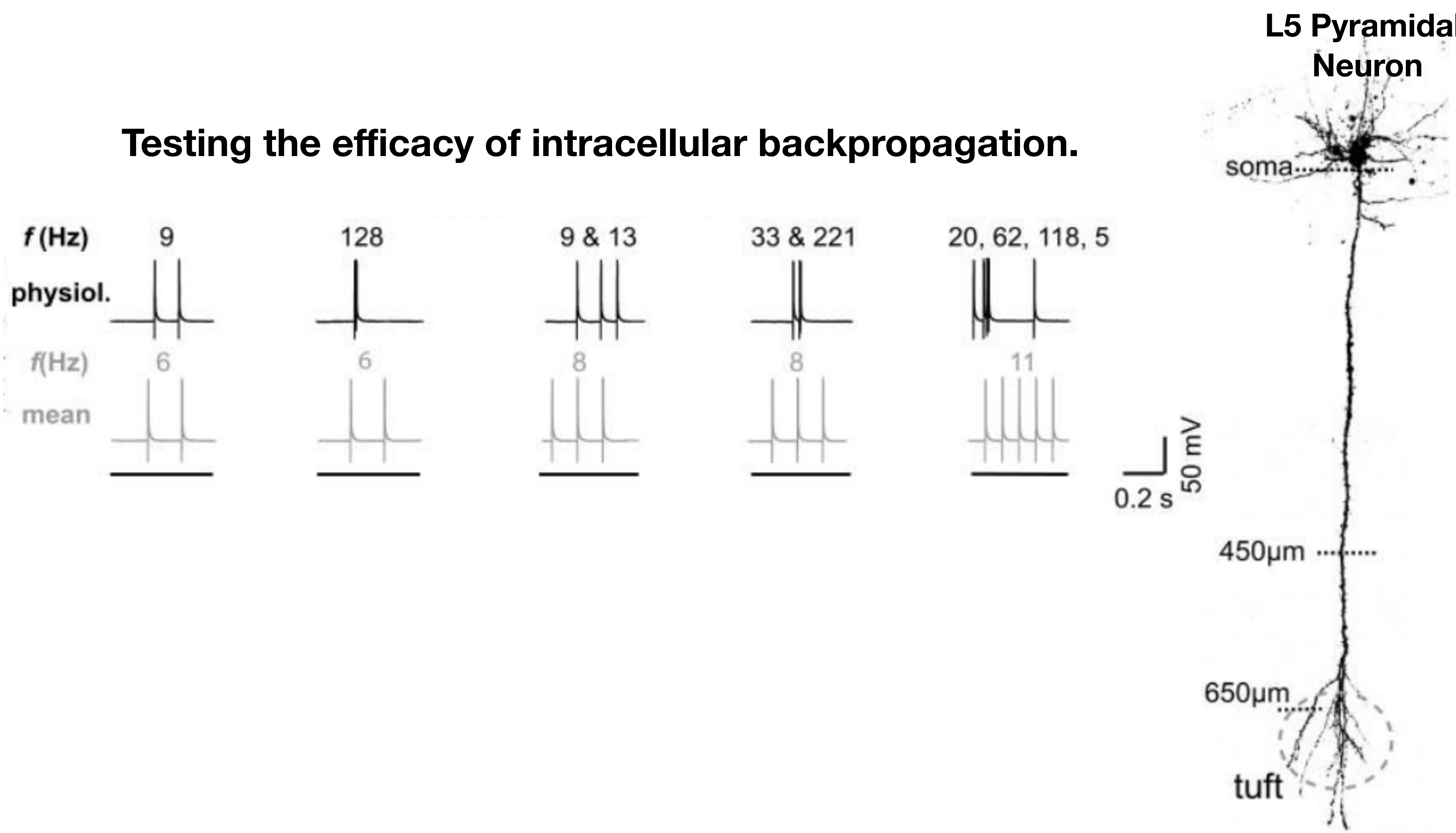
Temporal v.s. Rate Code.

Rate coding refers to information being carried by the firing rate. It is often argued, or assumed, that firing rate captures essentially all relevant information.

Temporal coding may refer to several quite different ideas: (i) Much of the information may be transmitted by a neuron during certain small intervals of time, (ii) synchronous, or what one could call quasi-synchronous, firing of neurons within and across ensembles may carry important information, (iii) the precise timing, or pattern, of spikes may carry information.

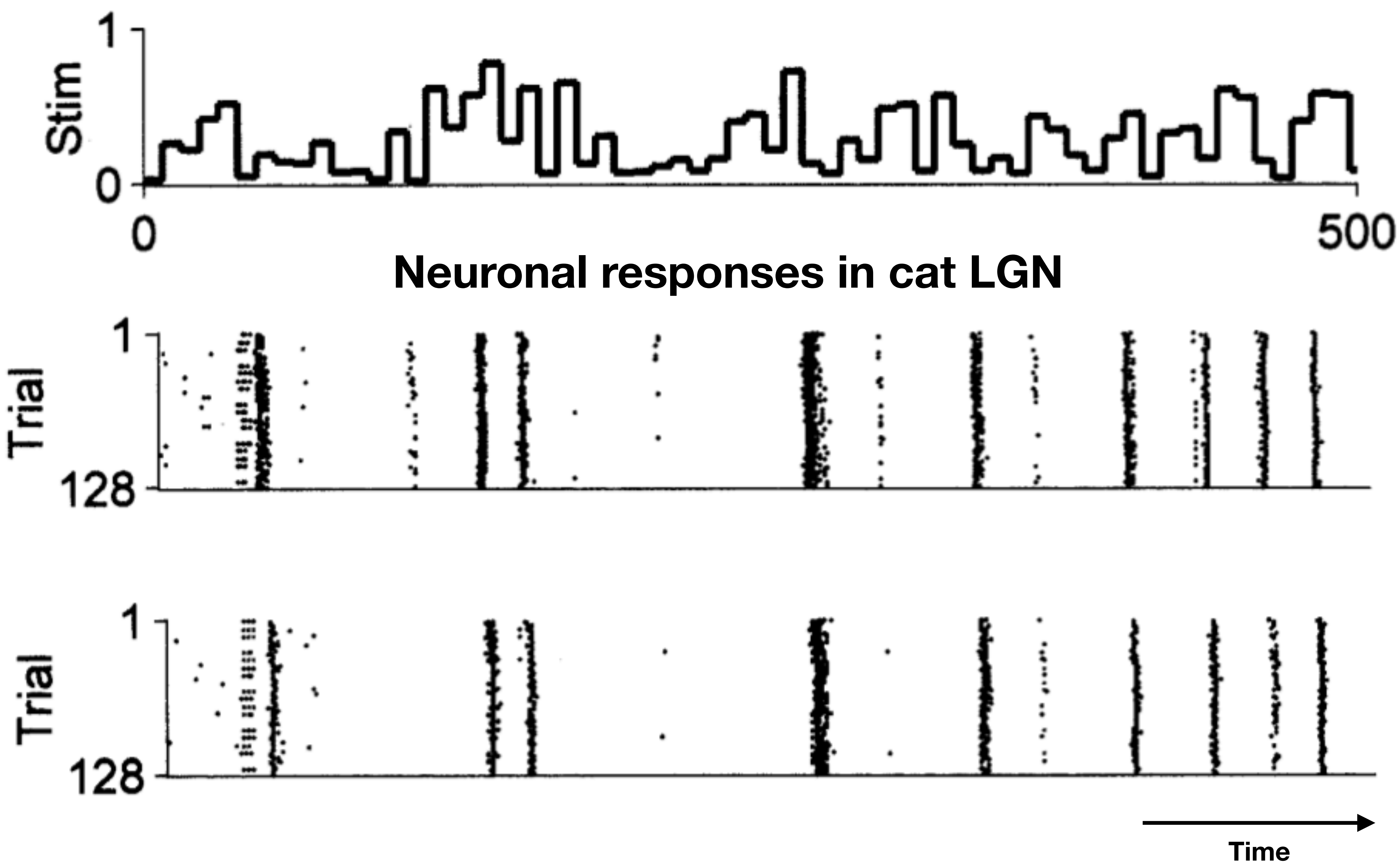


Temporal v.s. Rate Code.



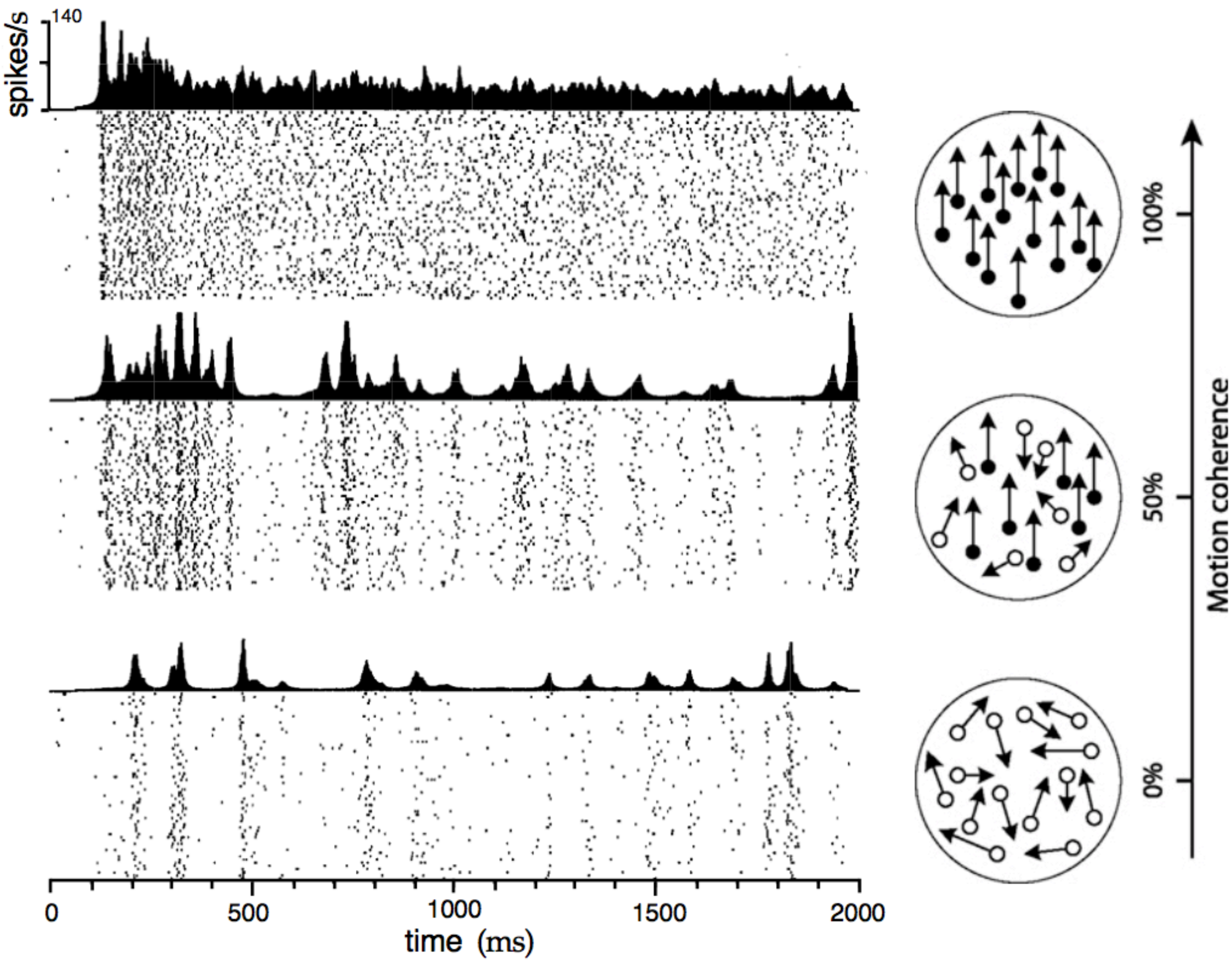
Grewe et al., 2010

Temporal v.s. Rate Code - QUIZ!



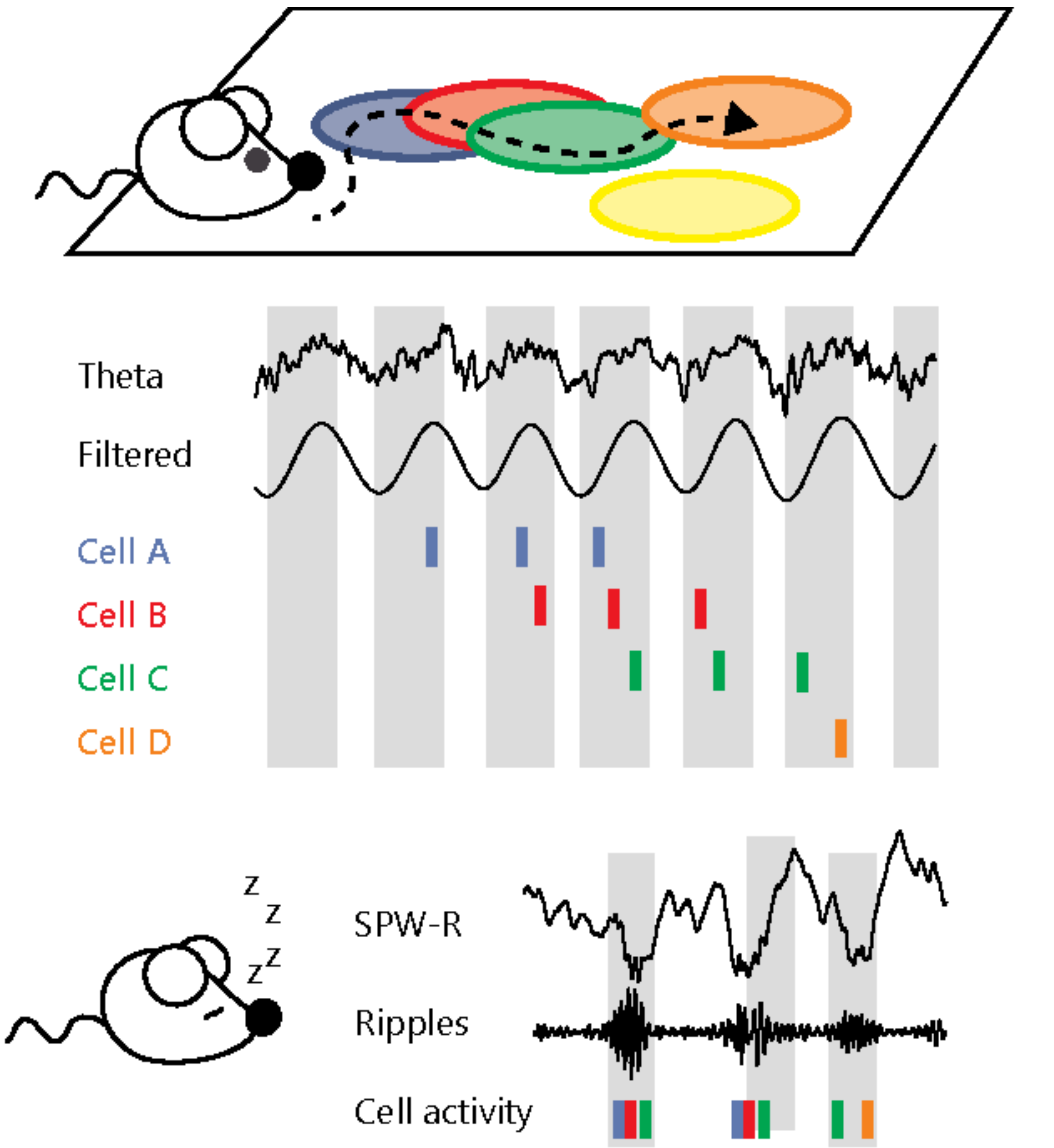
Reinagel et al., 2002

Temporal v.s. Rate Code - QUIZ!

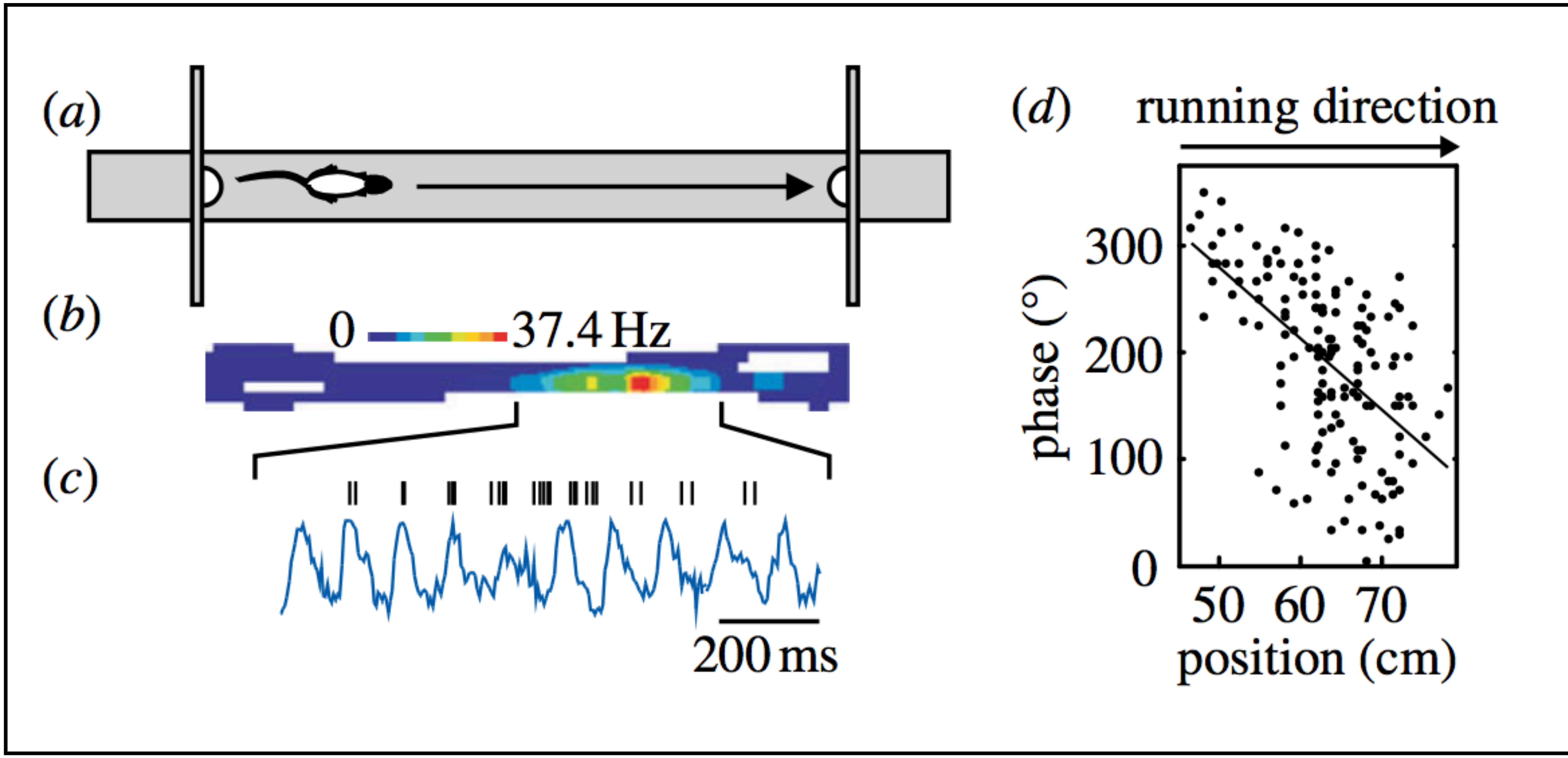


Bair and Koch, 1996

Phase Coding in Hippocampus.



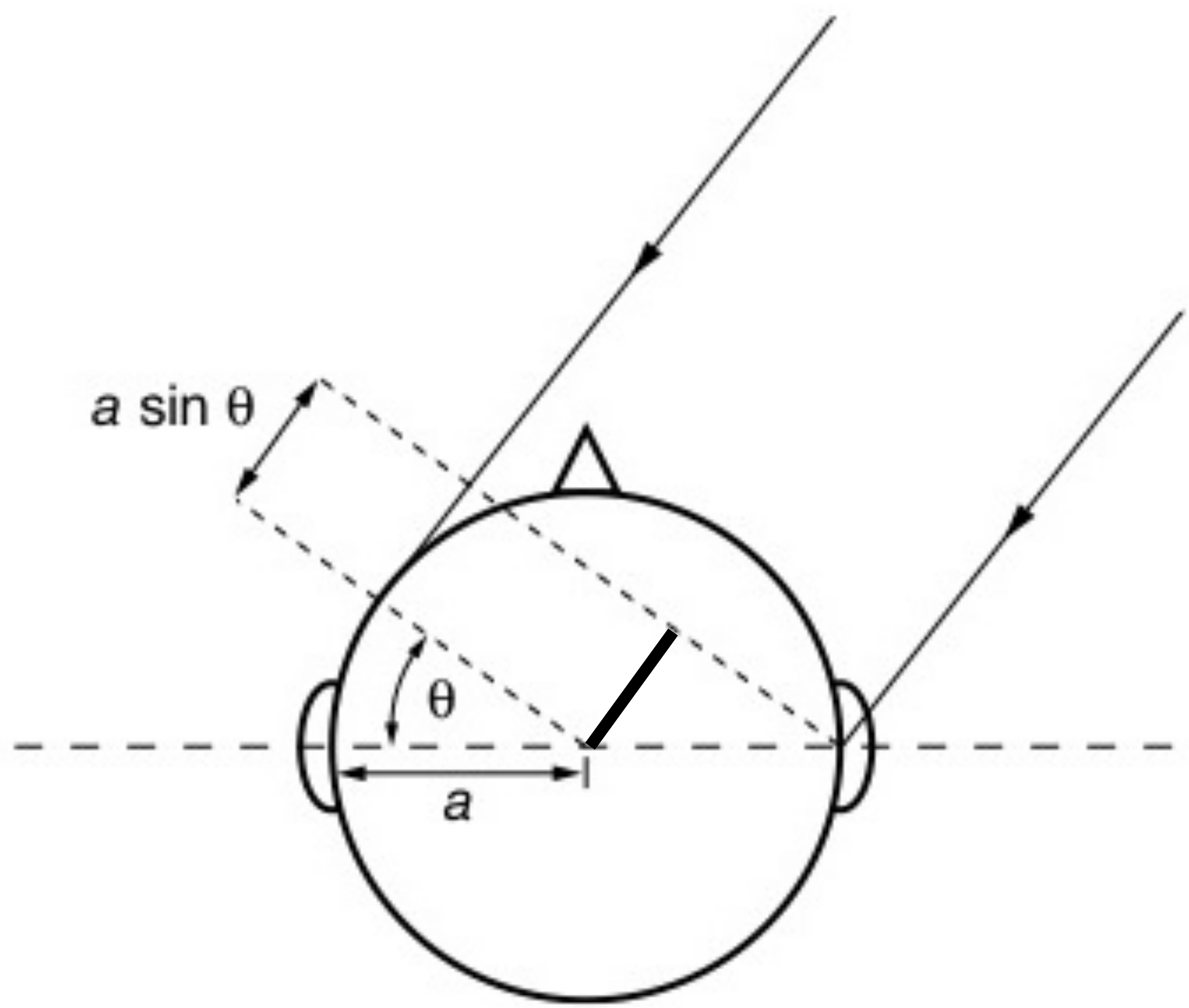
Phase Coding in Hippocampus.

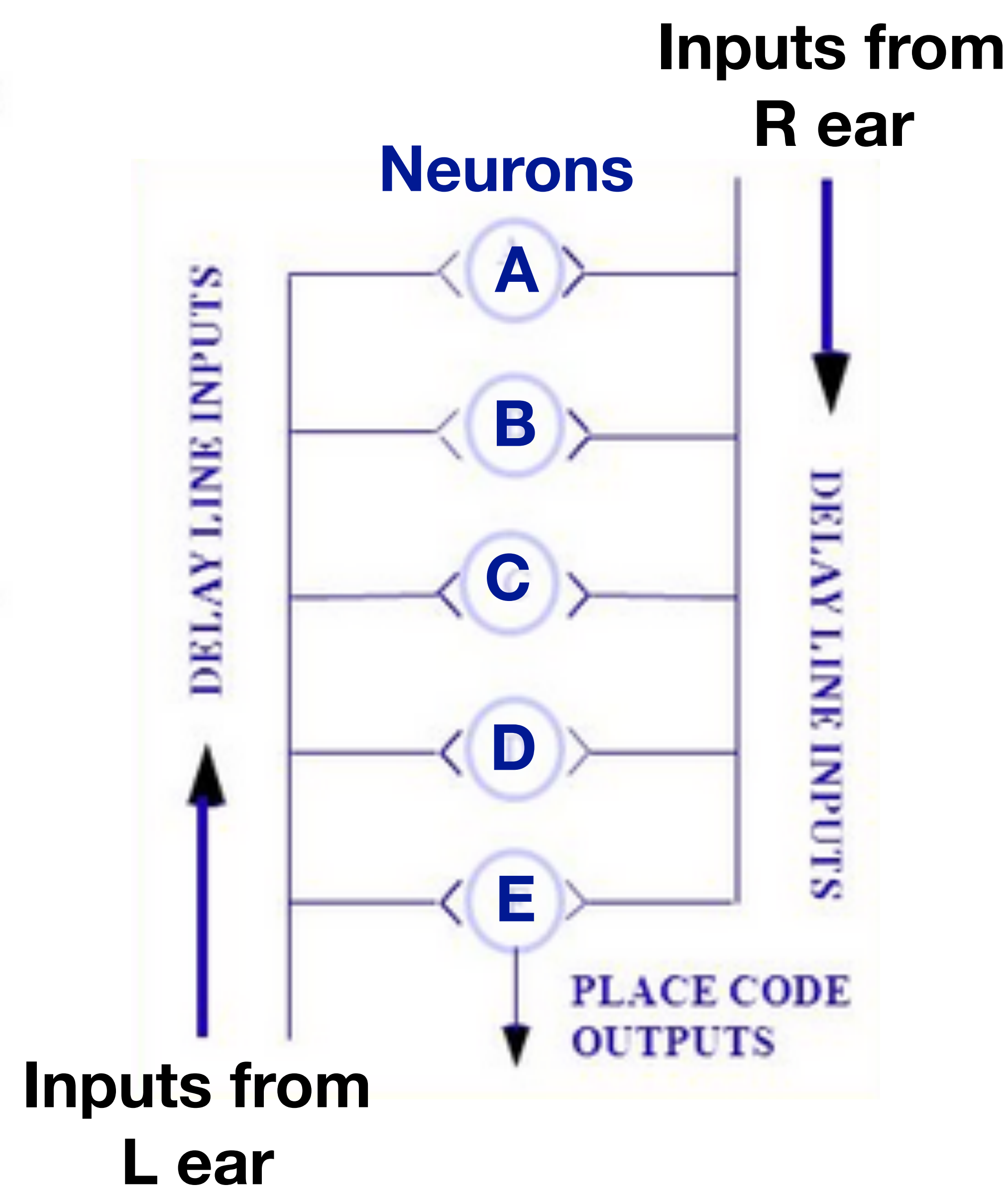


O'Keefe and Recce, 1993

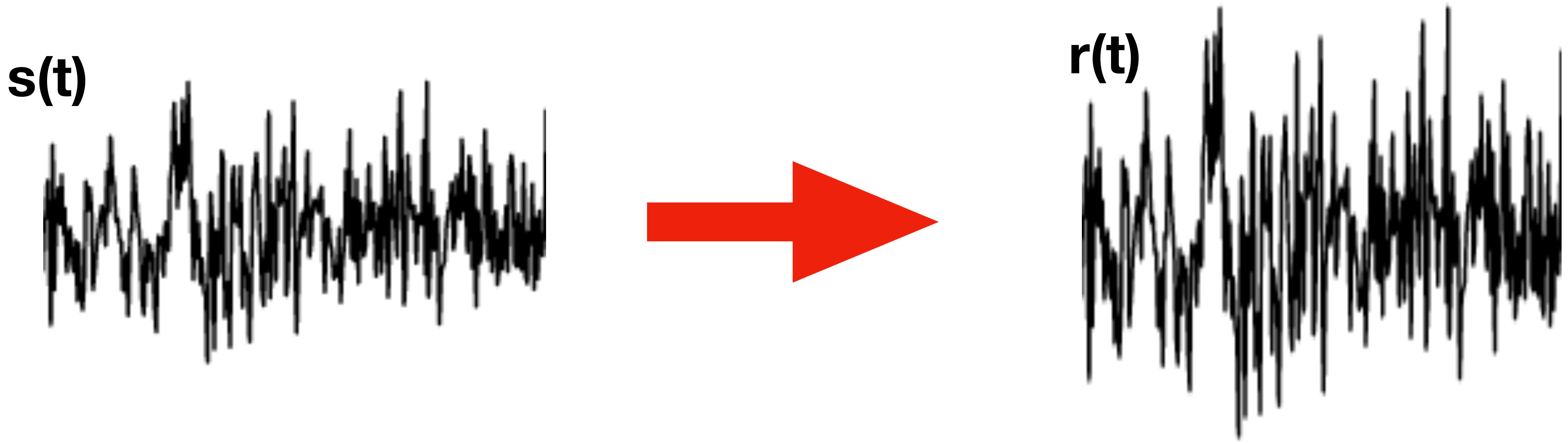
Hartley et al., 2014

Sound Localization by measuring the Interaural Time Difference (ITD)





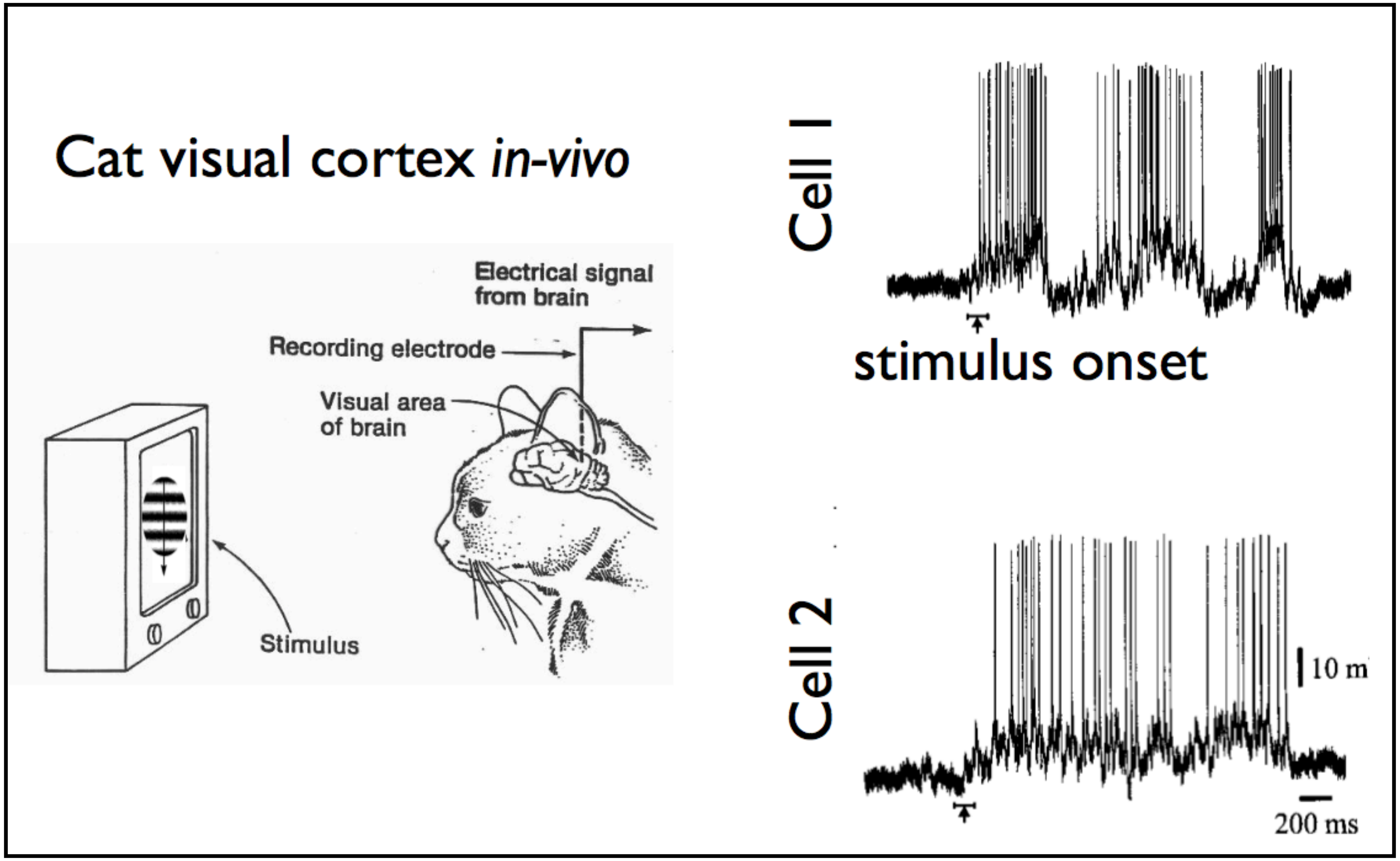
How to investigate the Stimulus Encoding of a Neuron?



Stimulus

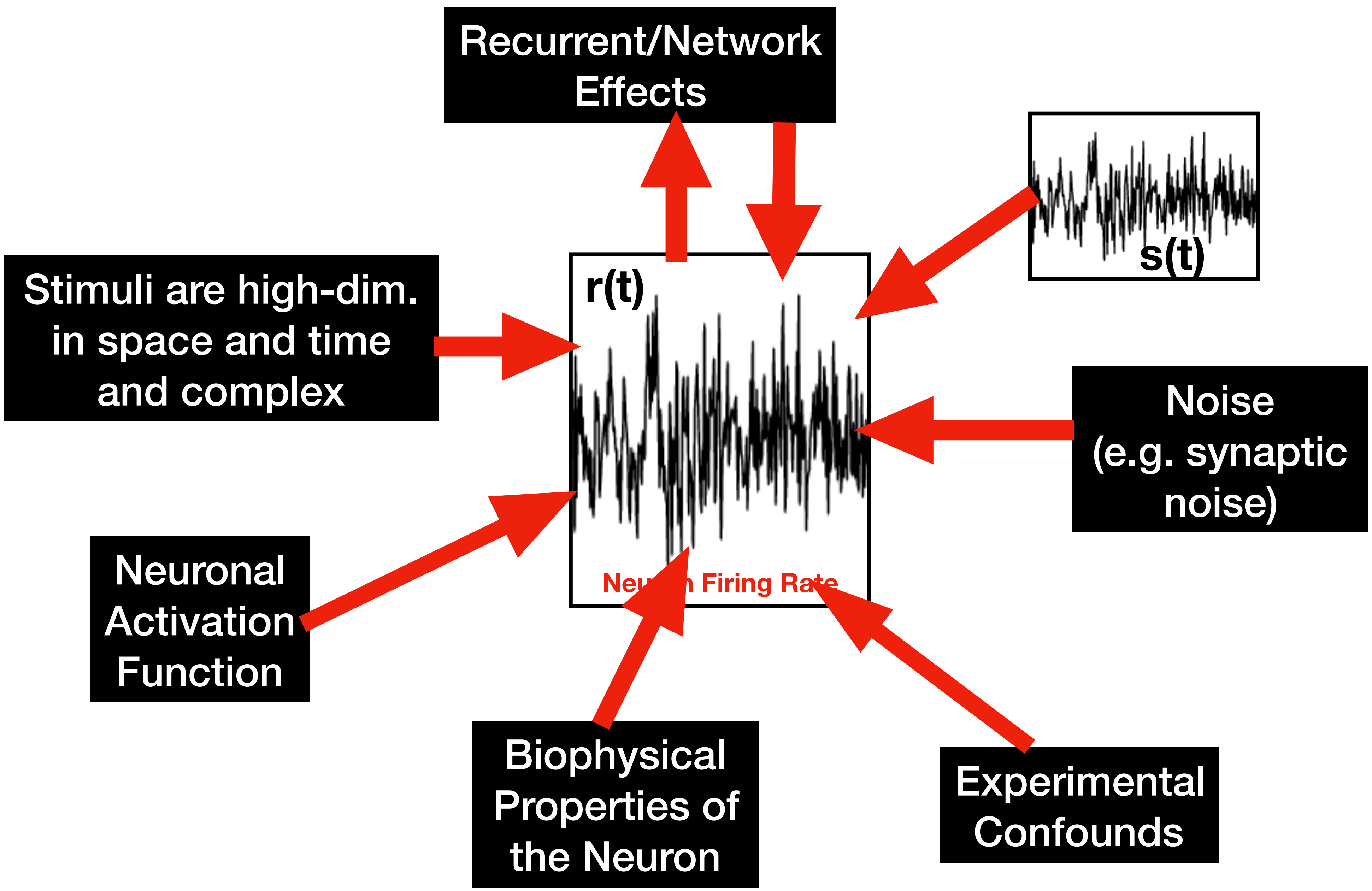
Neuron firing rate.

How to investigate the Stimulus Encoding of a Neuron?



Azouz et al., 1999

How to investigate the Stimulus Encoding of a Neuron?



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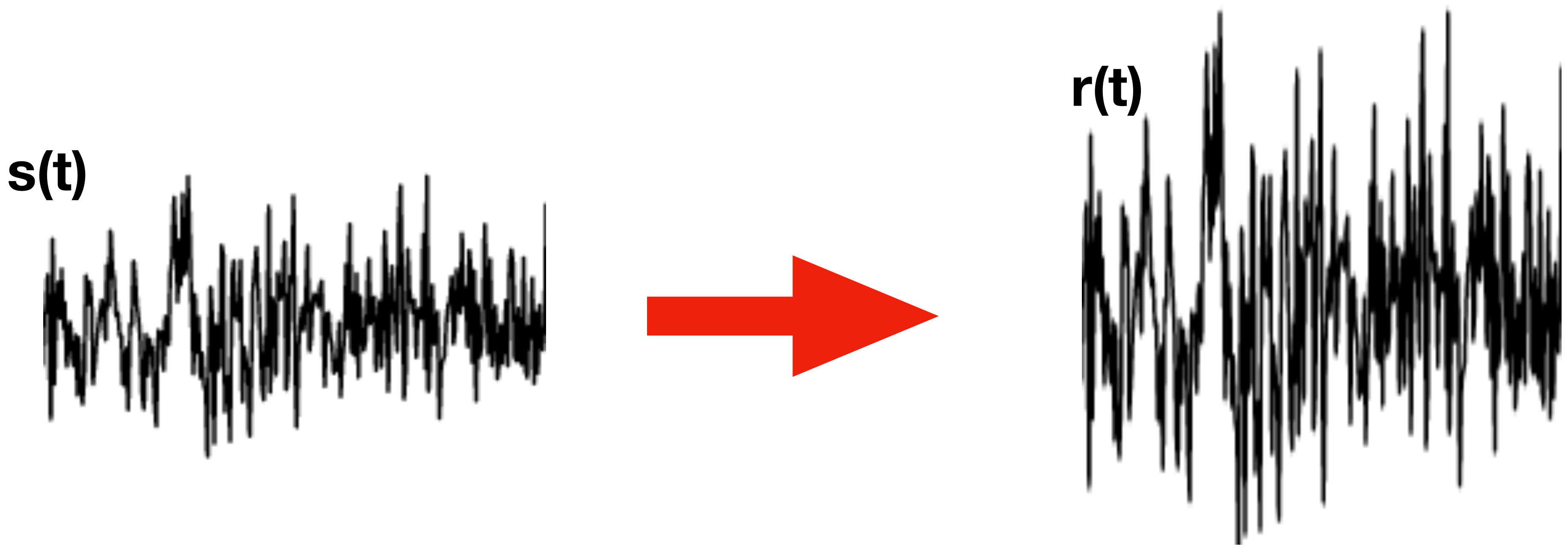
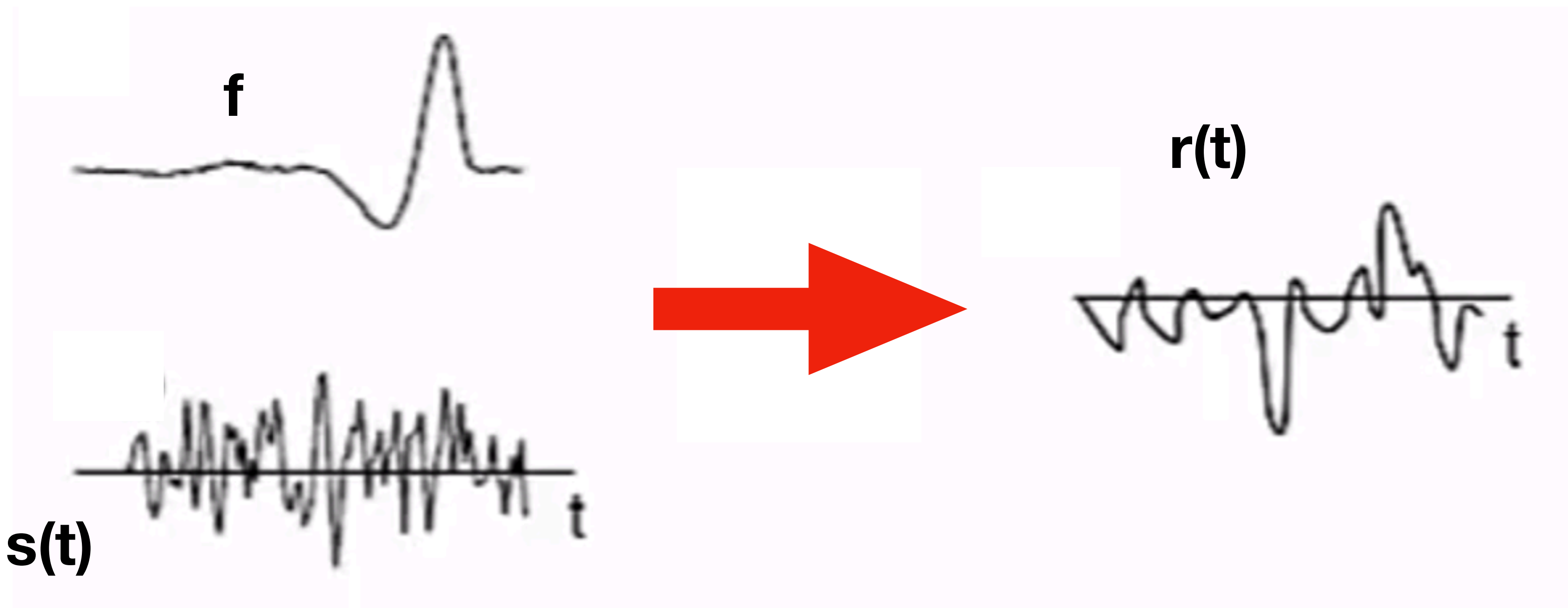


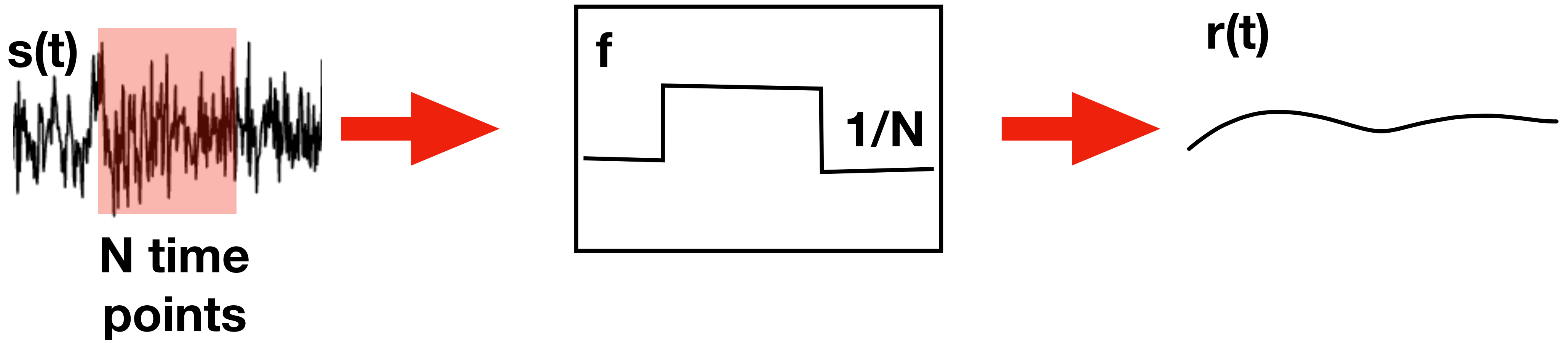
The Neuron as Temporal Filter.



Linear Temporal Filter: $r(t) = \sum_{k=0}^{n} s_{t-k}\, f_k$

$$r(t) = \int_{-\infty}^{t} d\tau\, s(t-\tau) f(\tau)$$

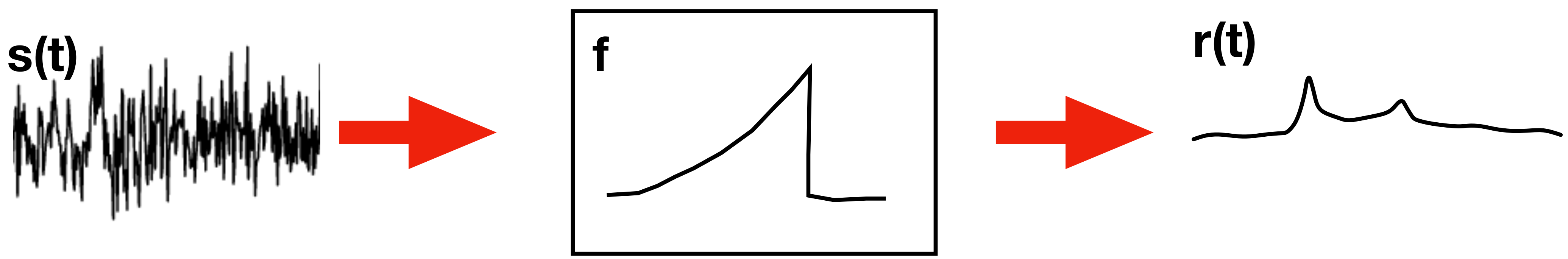
Example #1: The Running AVG Filter.



Linear Temporal Filter: $r(t) = \sum_{k=0}^{n} s_{t-k}\, f_k$

$$r(t) = \int_{-\infty}^{t} d\tau\, s(t-\tau) f(\tau)$$

Example #2: The Leaky AVG Filter.

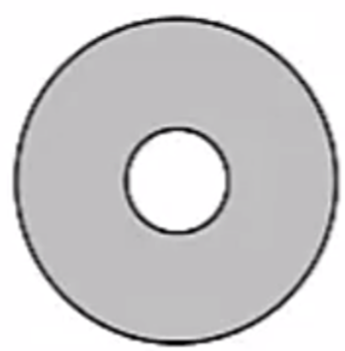


Example II: The Leaky Avg. Filter

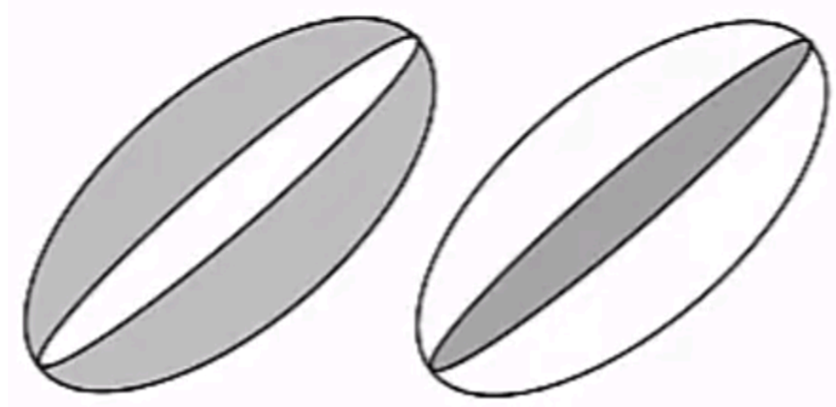
Linear Temporal Filter: $r(t) = \sum_{k=0}^{n} s_{t-k}\, f_k$

$$r(t) = \int_{-\infty}^{t} d\tau\, s(t-\tau) f(\tau)$$

Basic Model of Linear Spatial Filtering.



Retina Ganglion Cell

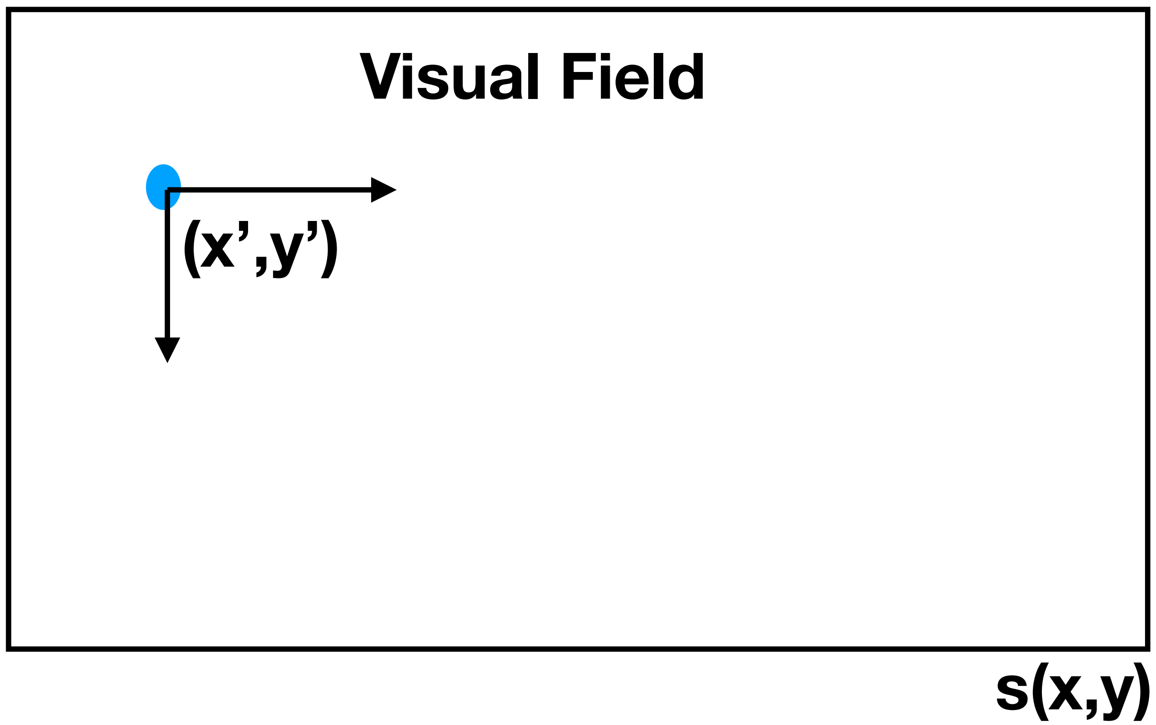


V1 Pyramidal Cell

Linear Filter: $r(t) = \sum_{k=0}^{n} s_{t-k} \, f_k$

$$r(t) = \sum_{x=n,y=n}^{n} s_{x-x',y-y'} \, f_{x',y'}$$

Basic Model of Linear Spatial Filtering.

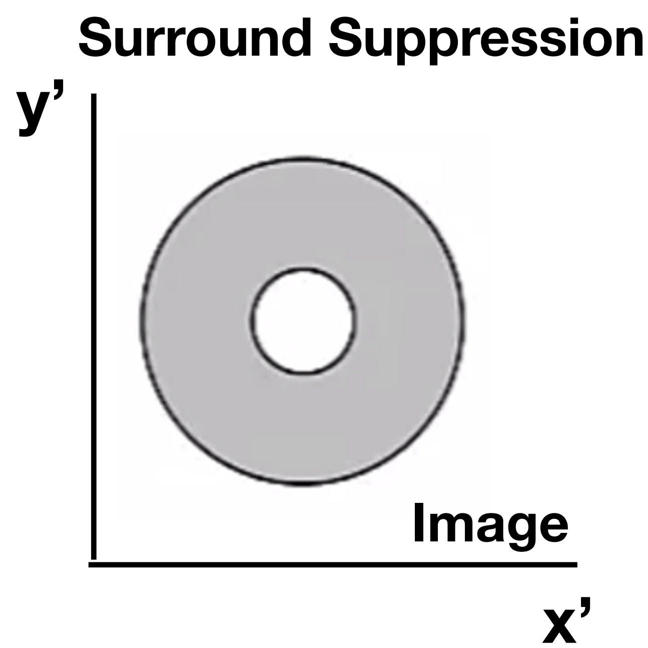


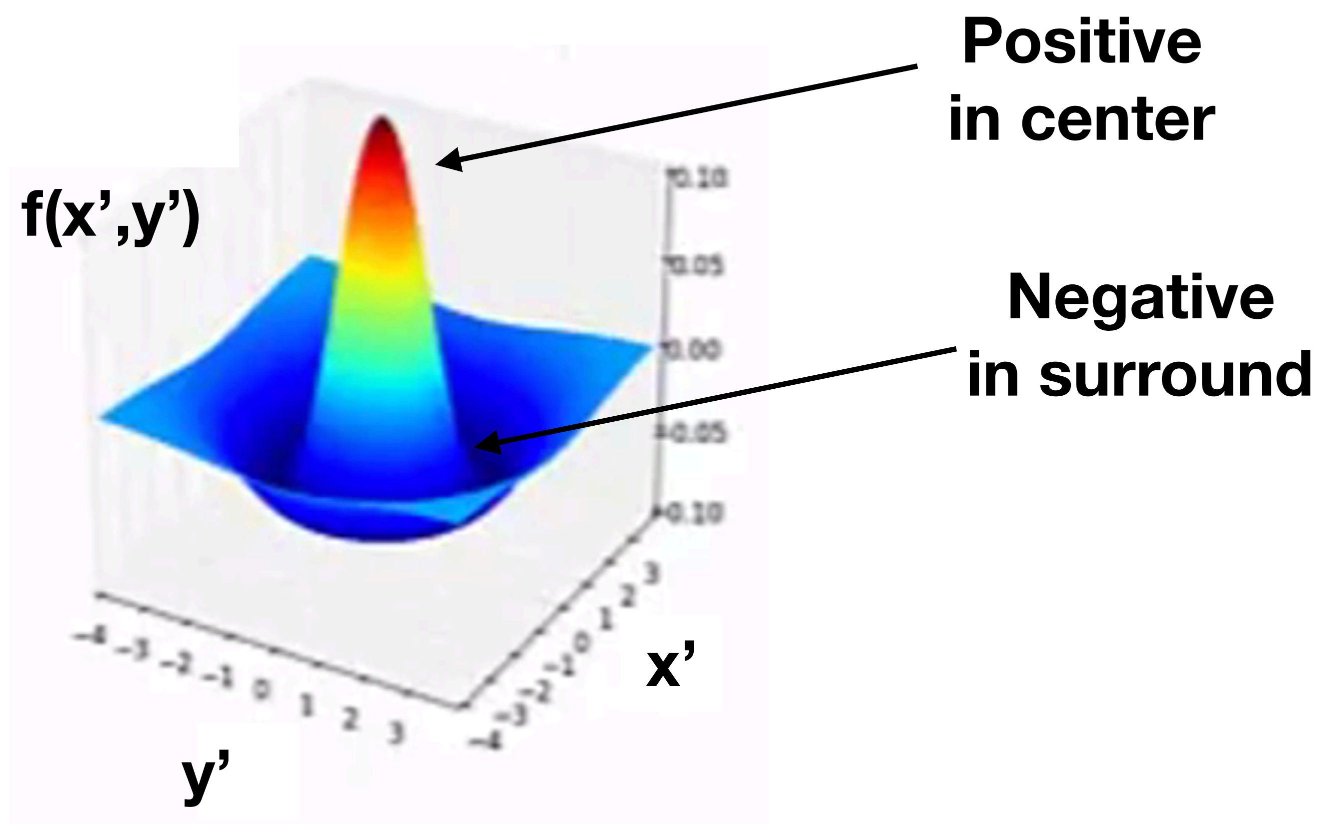
$$r(t) = \sum_{x=n,y=n}^{n} s_{x-x',y-y'} \boxed{f_{x',y'}}$$

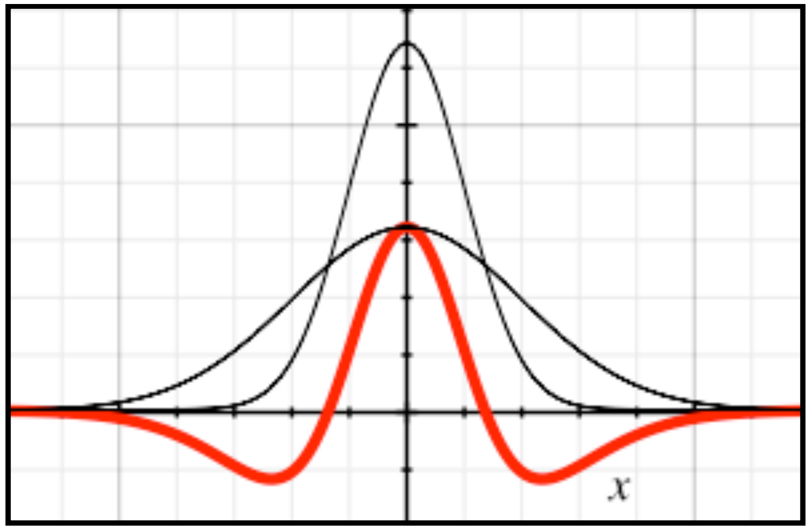
Spatial Filter f

$$r(t) = \int_{-\infty}^{\infty} dx'dy'\, s(x-x',y-y') \boxed{f(x',y')}$$

Basic Model of Linear Spatial Filtering.



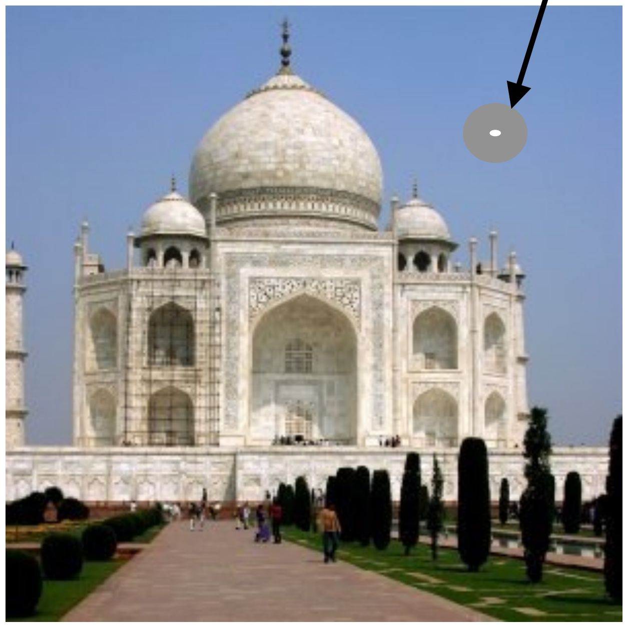




Difference of Gaussians Filter

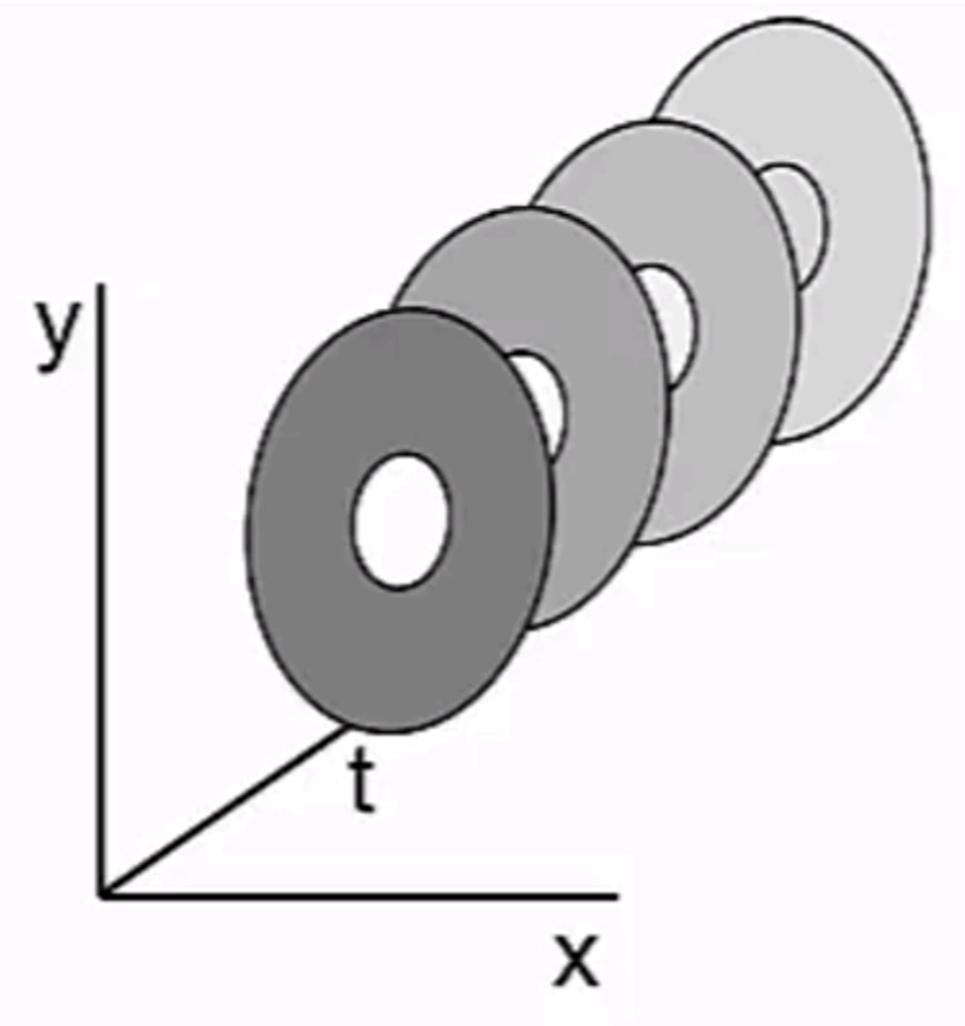
Example #1: Linear Spatial Filtering.

Filter



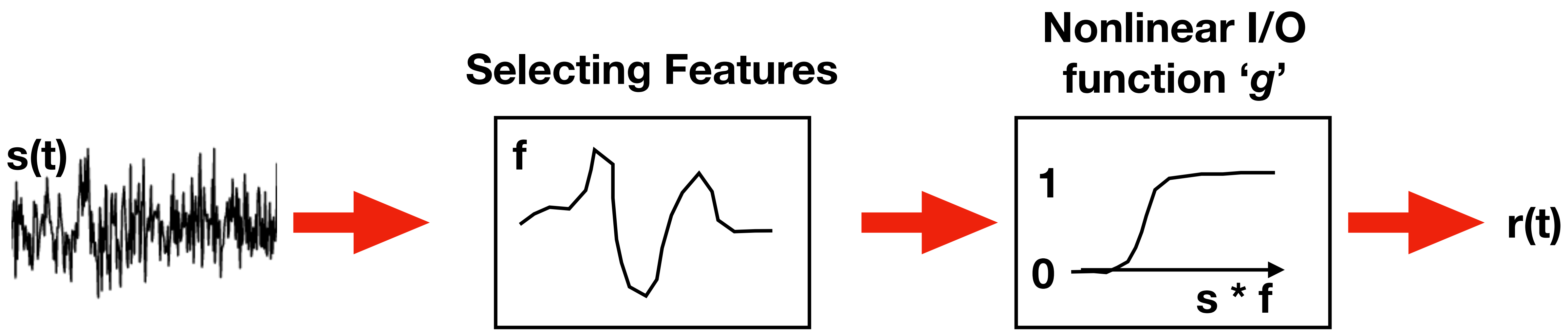
Original Image

Combining Temporal and Spatial Filtering.



$$r_{x,y}(t) = \iiint dx'dy'd\tau\, f(x',y',\tau)\, s(x-x',y-x',t-\tau)$$

Combining Filtering with a Nonlinearity.



- Can spike rates be negative?
- What happens if the stimulus becomes stronger and stronger? Can firing rates increase indefinitely?

Linear Filter + Nonlinearity:

$$r(t) = g\left(\int s(t-\tau)\, f(\tau)\, d\tau \right)$$

Recap QUIZ.

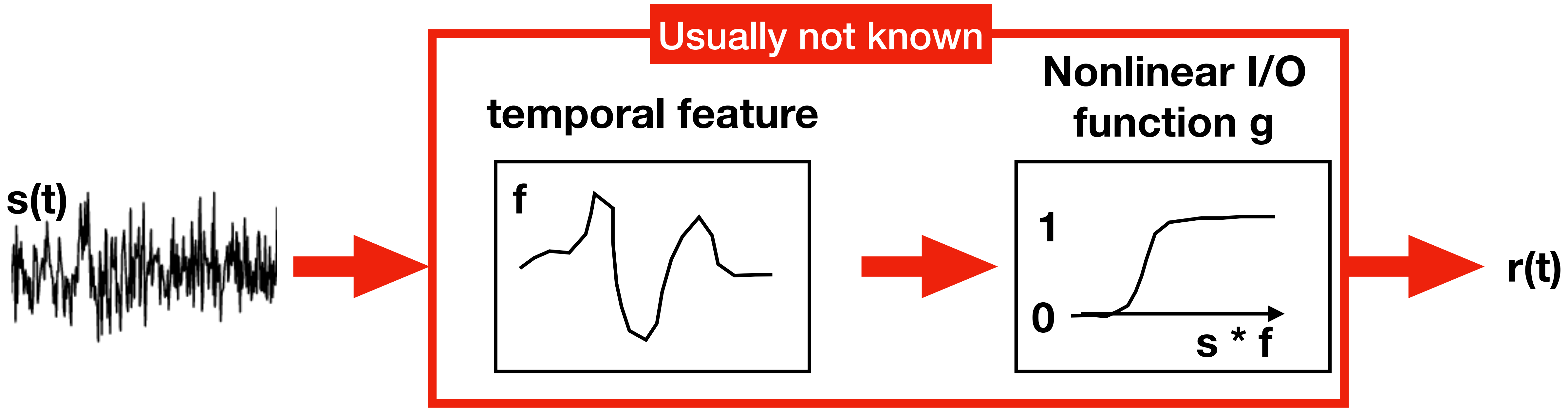
Since this is a linear system, which of the following will always be true?

1. The weighting coefficients always lie on a straight line.
2. If you scale the input by a constant, the output will be scaled by the same constant.
3. The output of a sum of different inputs is equal to the sum of the outputs of each of the individual inputs.
4. The filter is a linear function of the input.

Which of the following inputs might cause a linear system with a positive filter to predict a negative rate?

1. An input that slowly varies between a large positive value and a large negative value.
2. A positive input that decays to zero over time.
3. A positive input with a discontinuity.
4. None of these.

Taking into Account Spatio-temporal Features.



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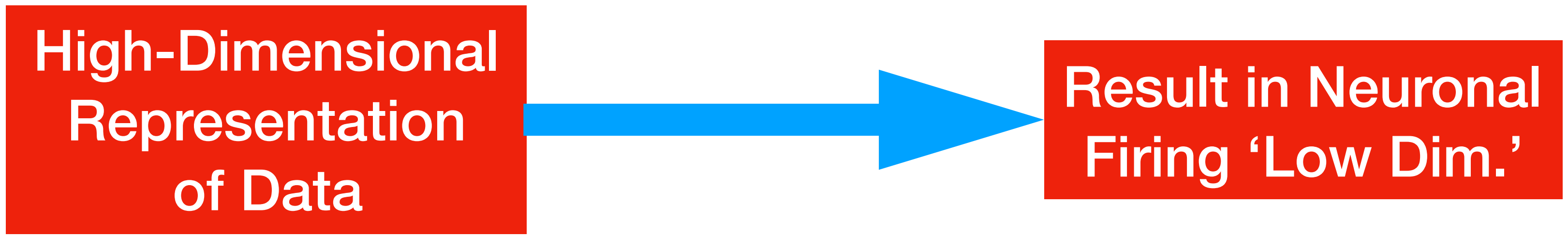
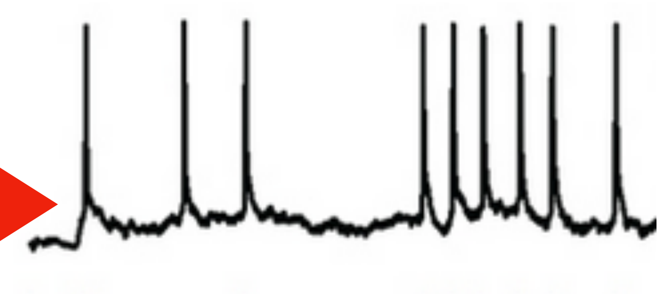


Taking into Account Spatio-temporal Features.

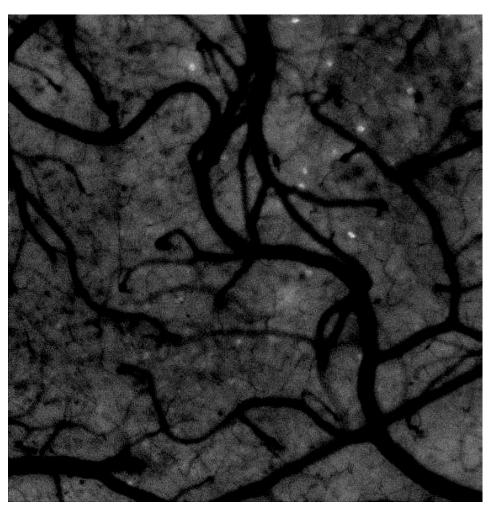
Complex Stimulus

How does a neuron encode stimulus input?

Activity of the Output Neuron r(t)



Neuronal Population Activity

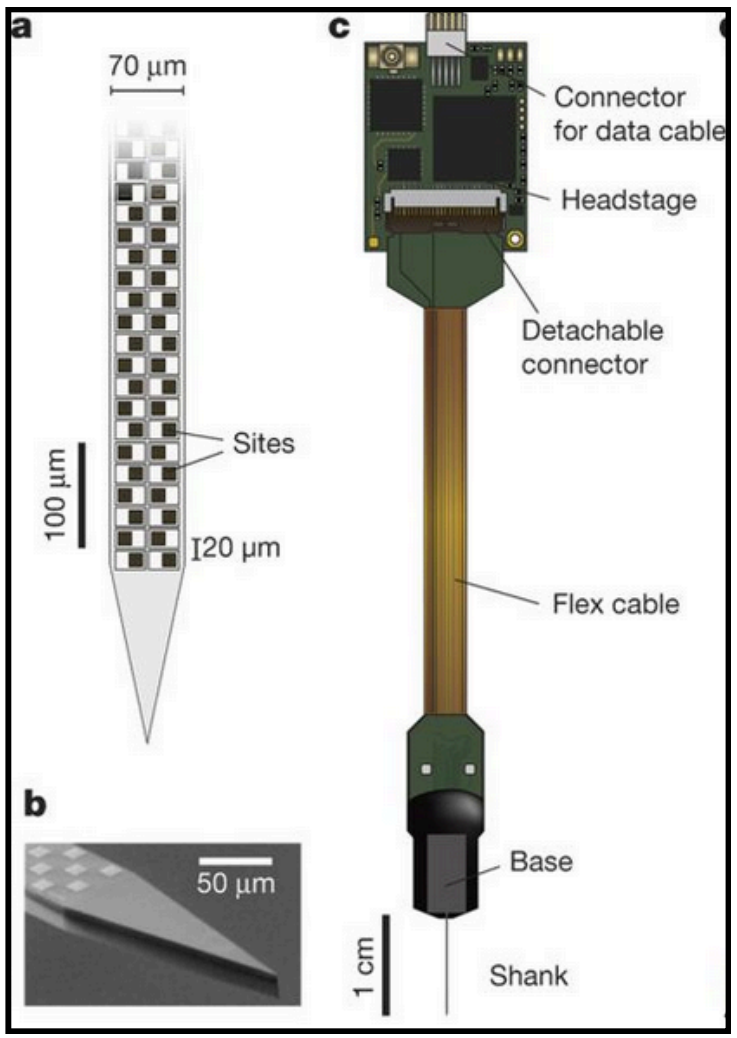


How does a neuronal population encode behavior?

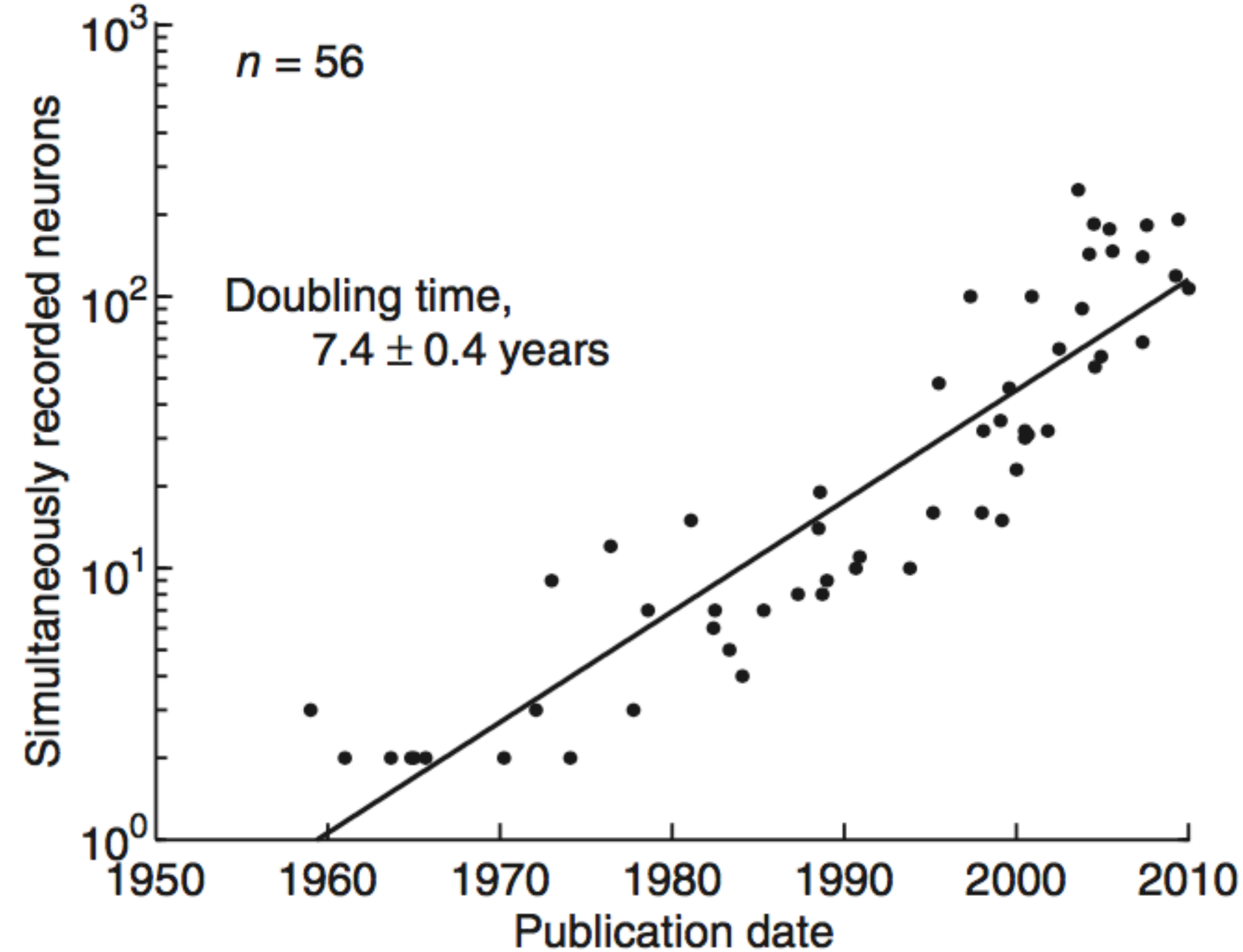
Behavior output of the Animal a(t)

Measuring Population Activity *in vivo* using Electrodes.

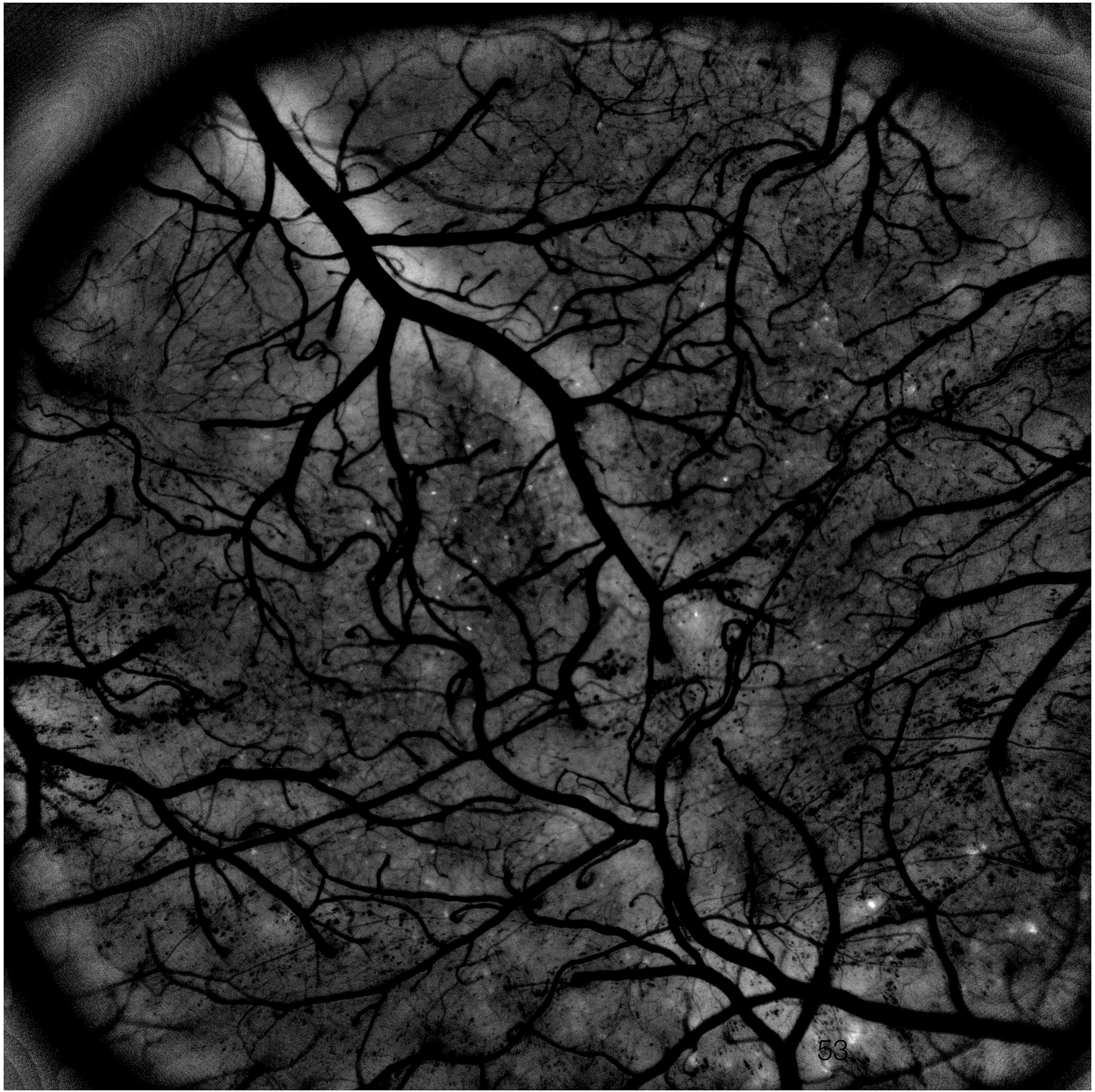
NeuroPixel Probe



Jun et al., 2017



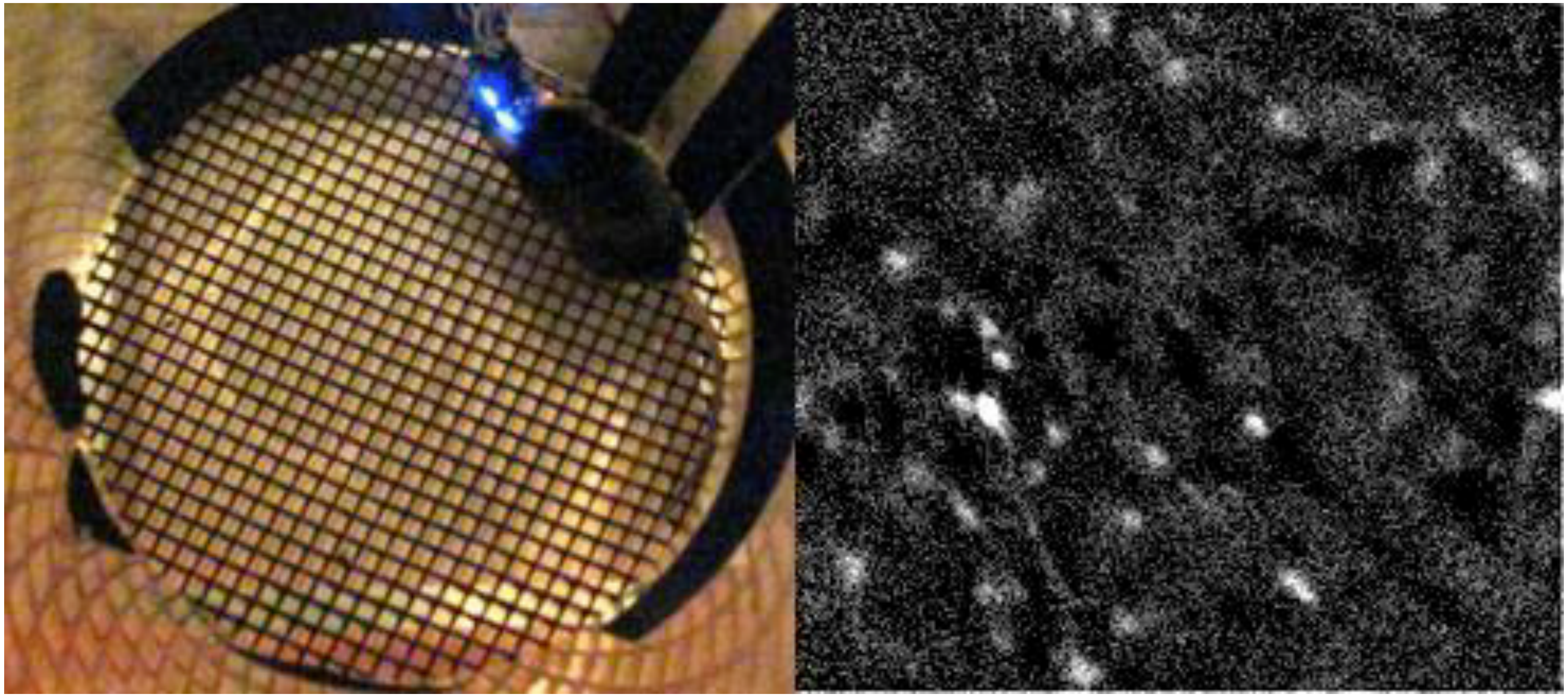
Measuring Population Activity *in vivo with Ca^{2+} Imaging.*



In vivo population calcium imaging in mouse cortex.

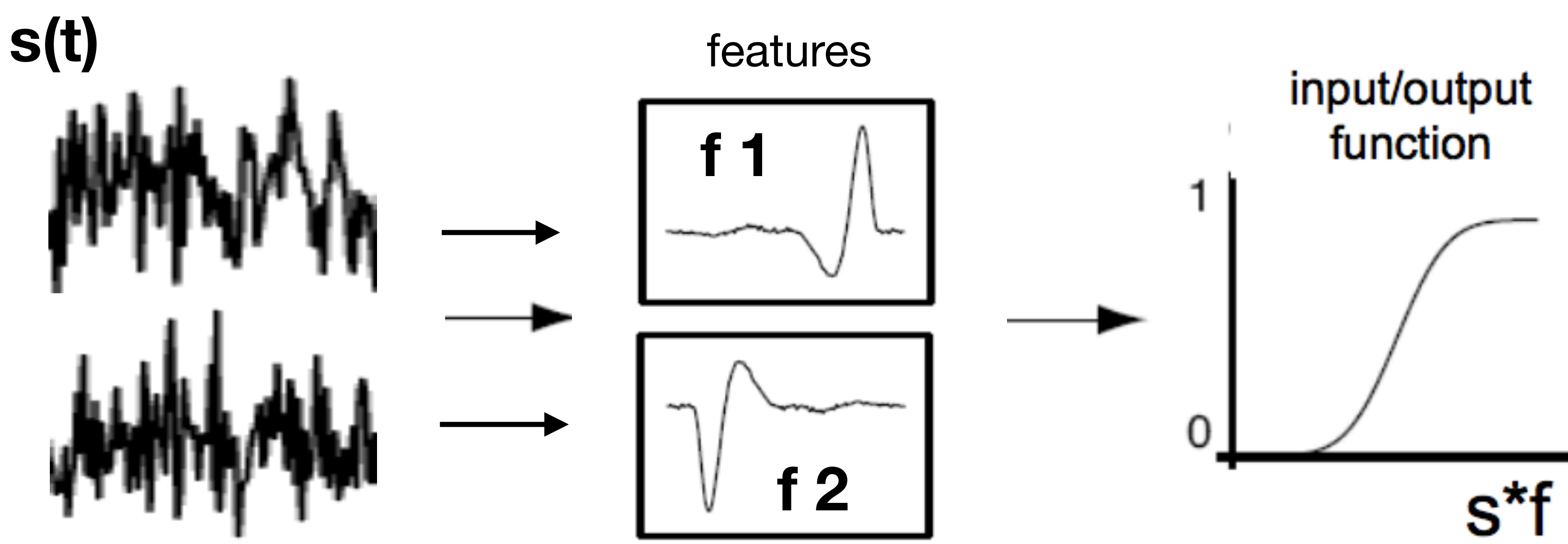
Measuring Population Activity *in vivo with Ca^{2+} Imaging.*

In vivo population
calcium imaging in freely moving mice.

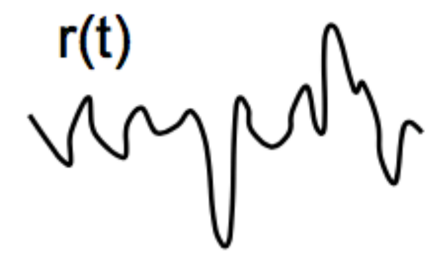


What is the neural 'population' code that determines behavior?

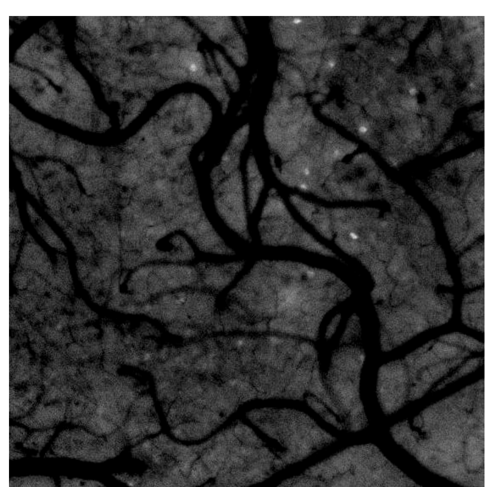
Taking into Account Spatio-temporal Features.



Activity of the Output Neuron r(t)



Neuronal Population Activity

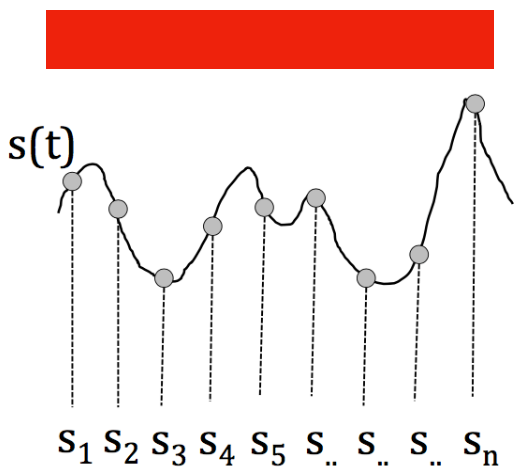


How does a neuronal population encode behavior?

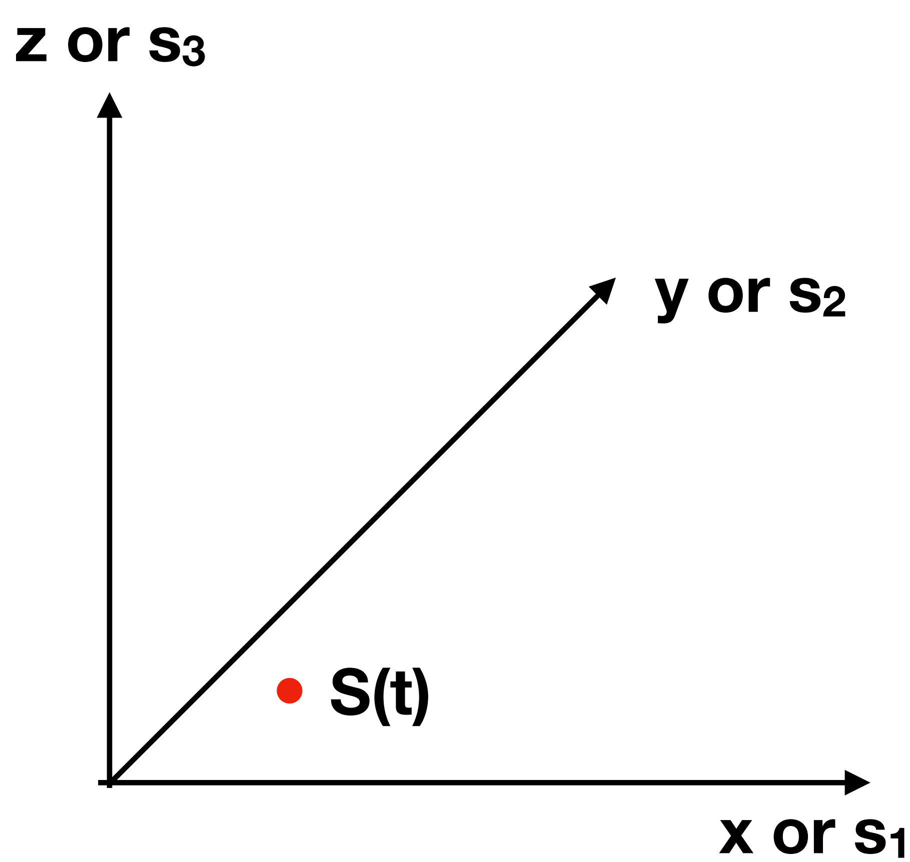
Behavior output of the Animal a(t)

Taking into Account Spatio-temporal Features.

1 Stimulus Presentation



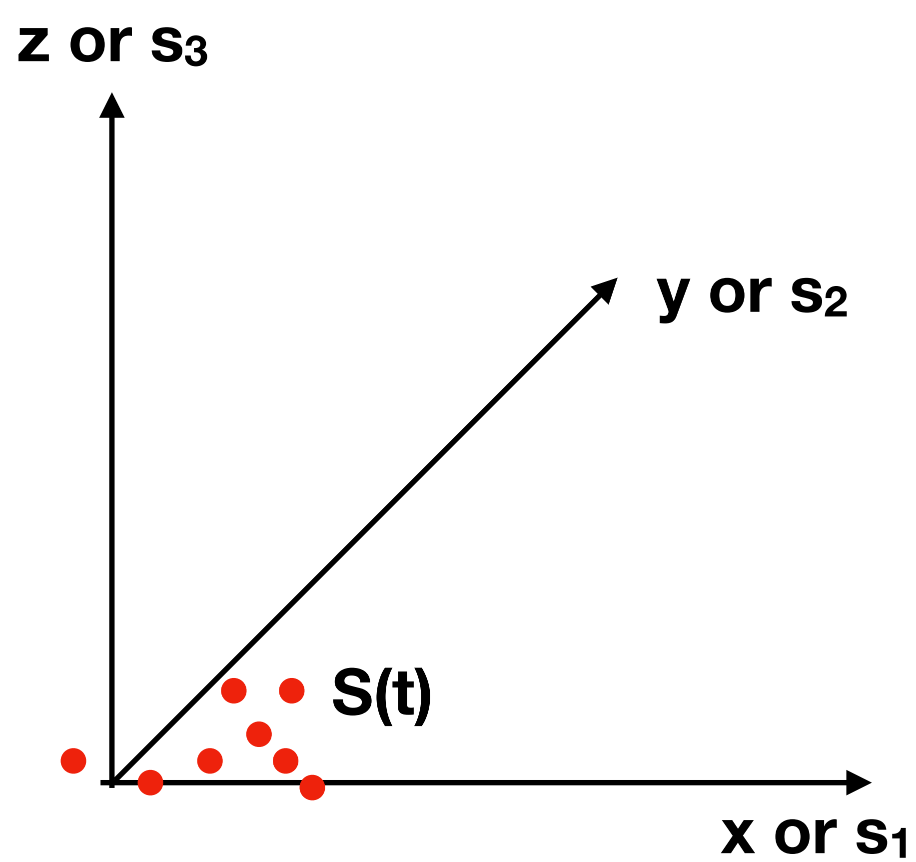
Temporal Features



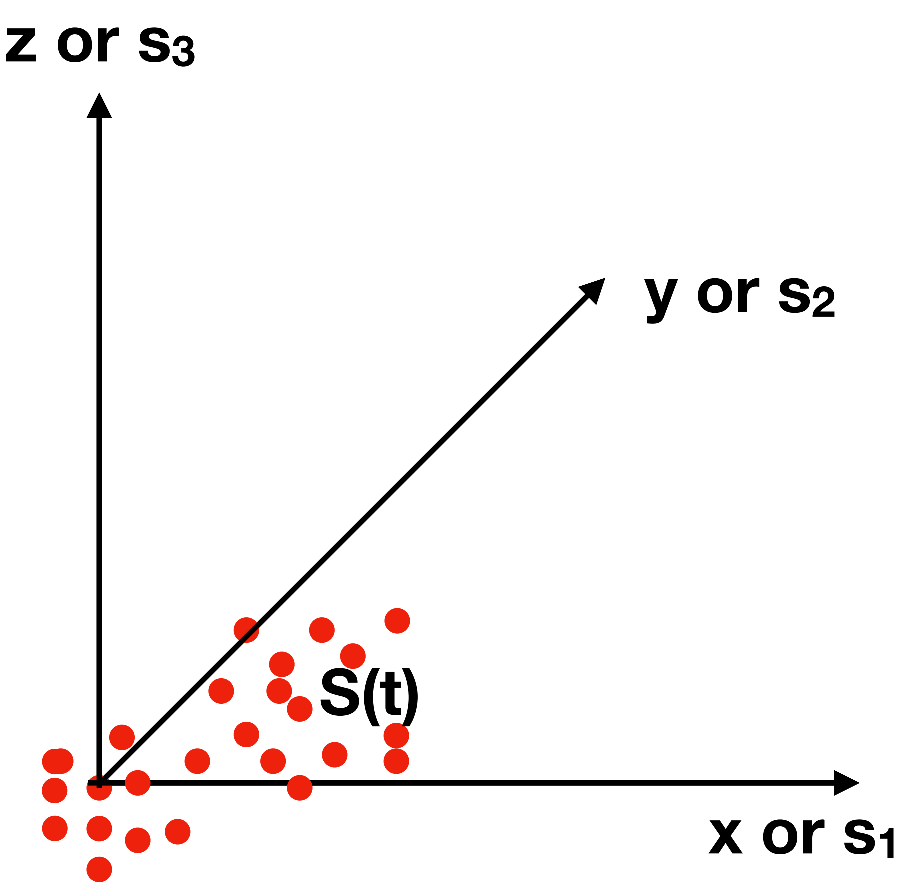
Now we want to repeatedly sample the responses to a variety of stimuli so that we can characterize what feature combination triggers a spike or a behavior.

$$P(\text{response} \mid \text{stimulus}) = P(\text{response} \mid s_1, s_2, s_3, \ldots, s_n)$$

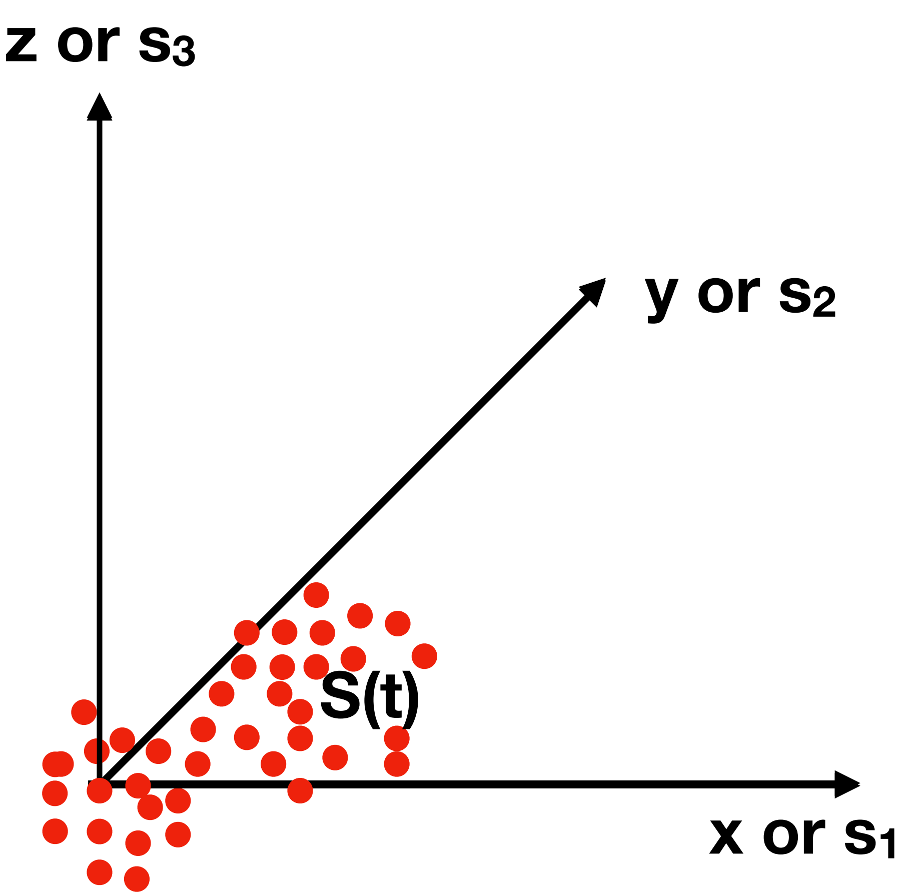
Finding the mean Population Response Vector.



Finding the mean Population Response Vector.



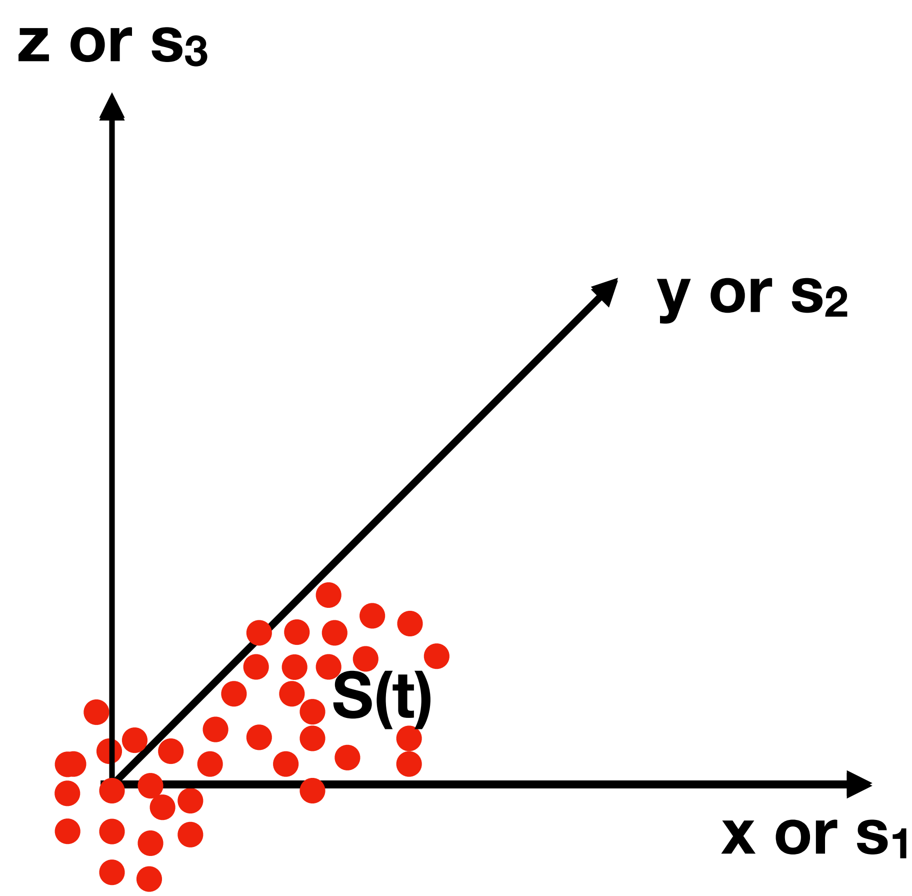
Finding the mean Population Response Vector.



What do we do next? Two possibilities.

1. We don't know the important features. We don't have any labels for the stimuli. → **Unsupervised/clustering Approaches**

Finding the mean Population Response Vector.



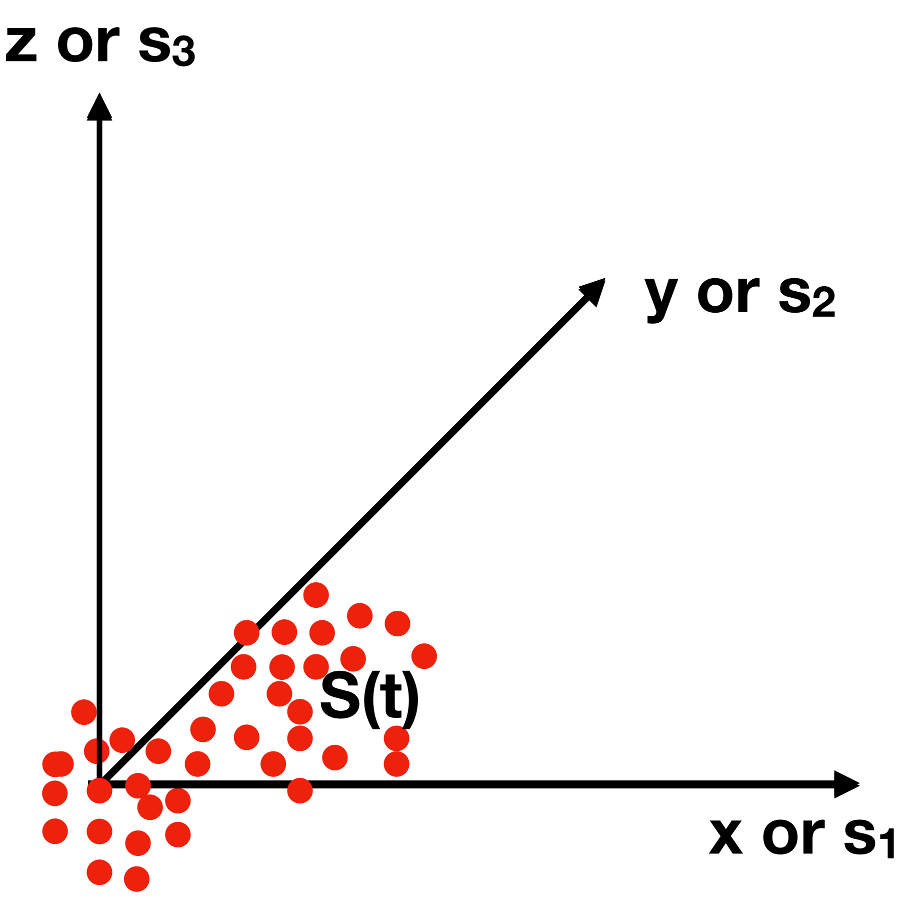
What do we do next? Two possibilities.

1. **We don't know the important features. We don't have any labels for the stimuli.**
2. **We have labels for all stimuli classes. We know the features of interest.**

Unsupervised/clustering Approaches

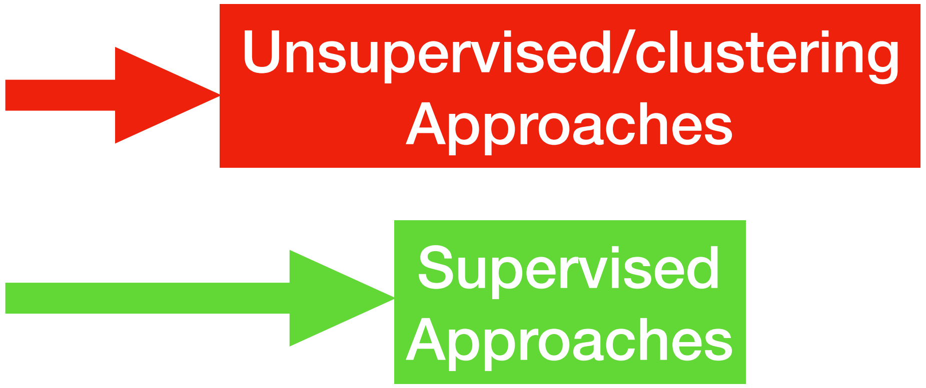
Supervised Approaches

Finding the mean Population Response Vector.

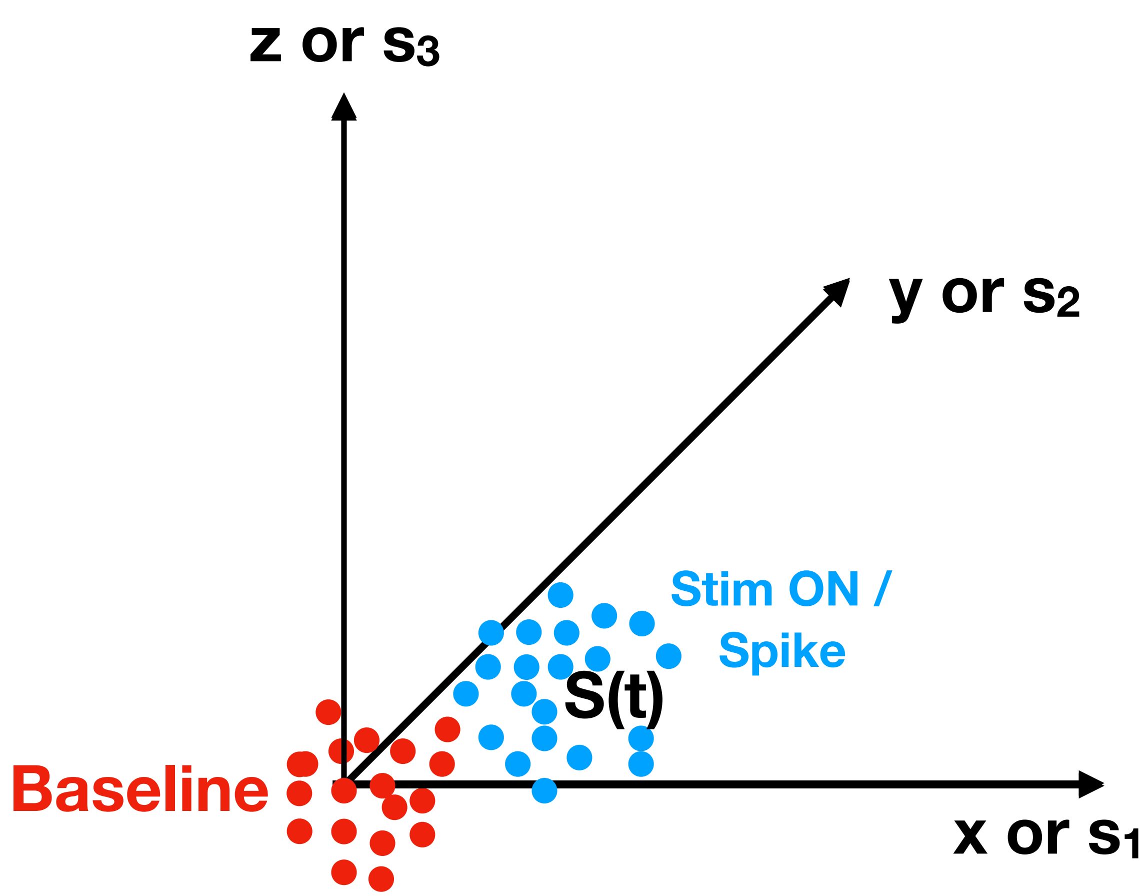


What do we do next? Two possibilities.

1. We don’t know the important features. We don’t have any labels for the stimuli.
2. We have labels for all stimuli classes. We know the features of interest.



Finding the mean Population Response Vector.

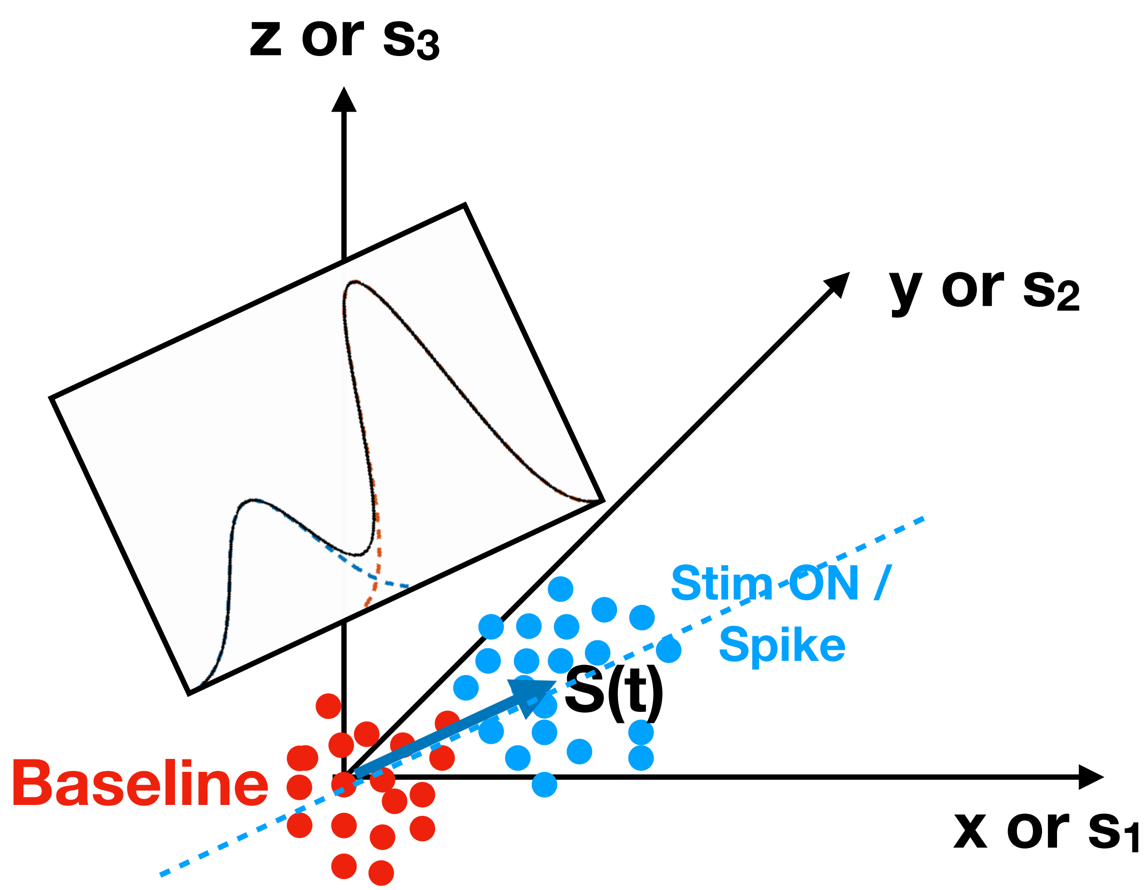


What do we do next? Two possibilities.

1. We don't know the important features. We don't have any labels for the stimuli. → **Unsupervised/clustering Approaches**

2. We have labels for all stimuli classes. We know the features of interest. → **Supervised Approaches**

Finding the mean Population Response Vector.



What do we do next? Two possibilities.

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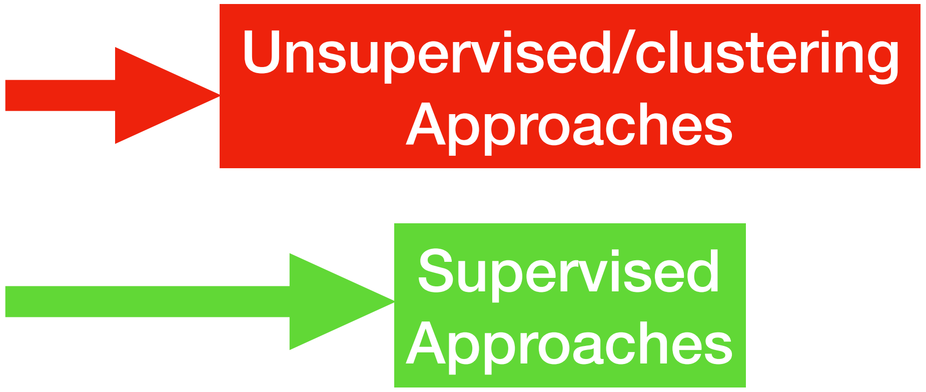
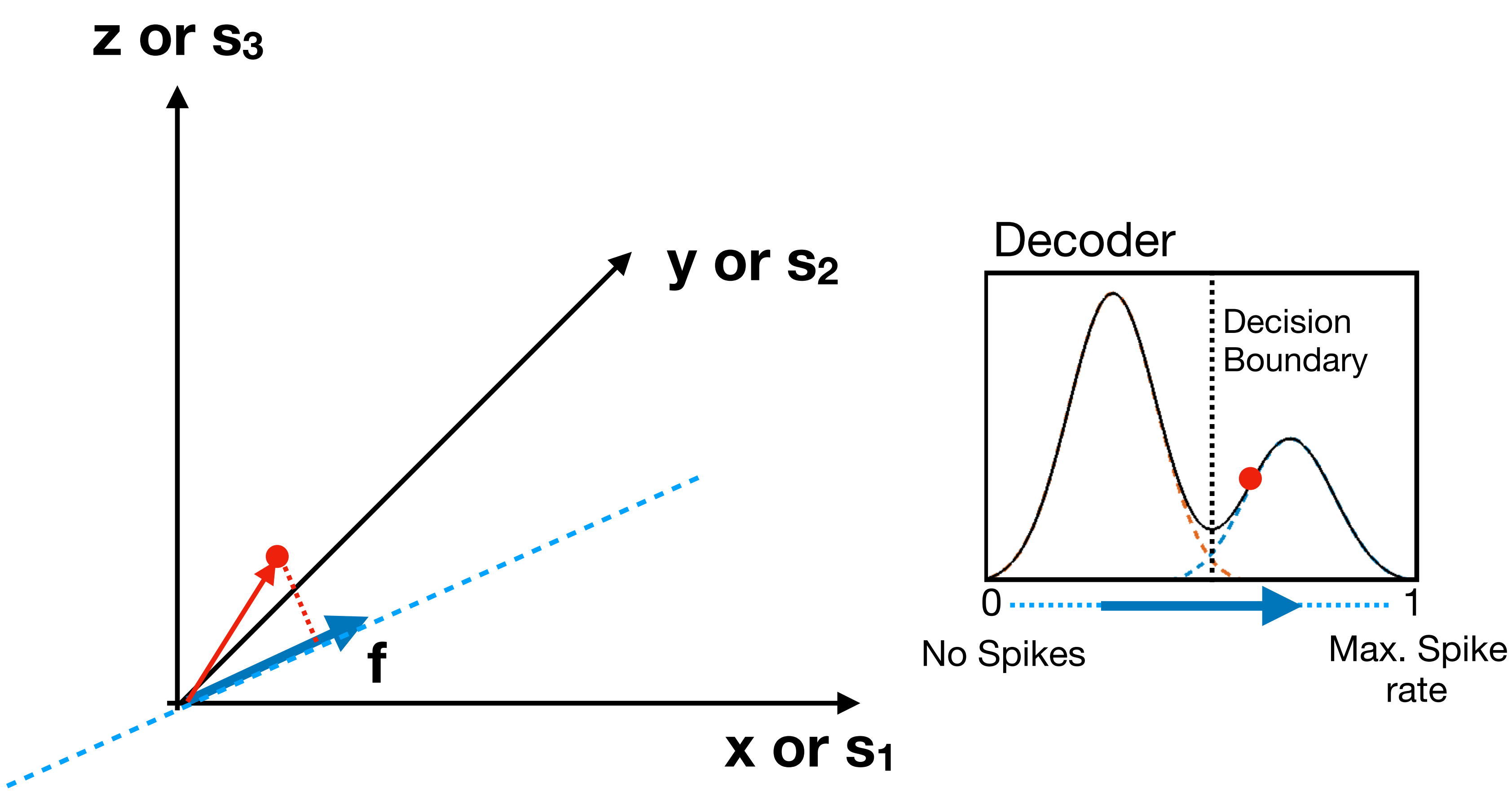
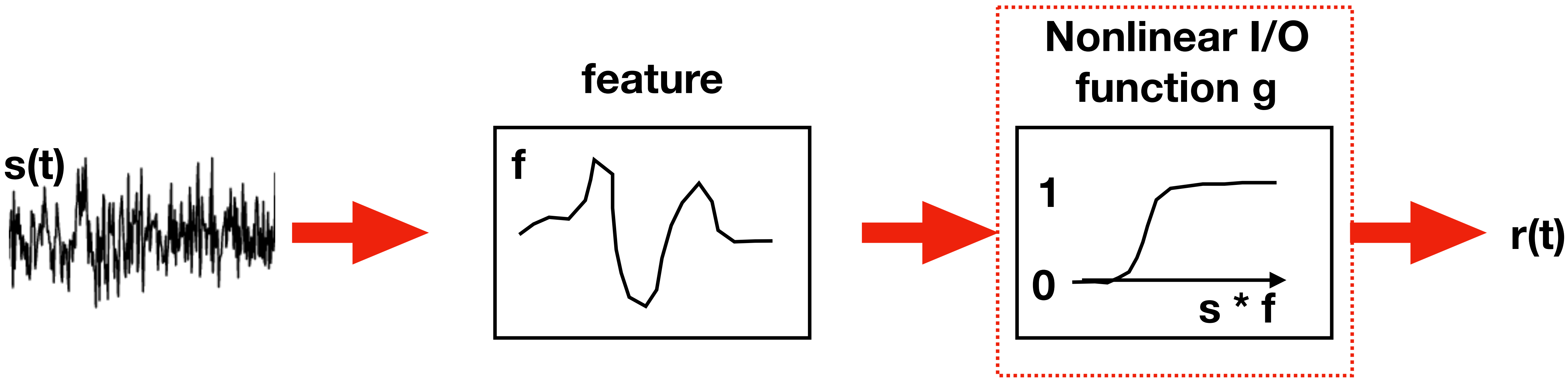


Projecting Stimuli in the direction of Neur. Responses.



Projecting Stimuli into the Direction of the Neuronal Response (Encoding/Filtering).

Finding the I/O Function for a Single Neuron.



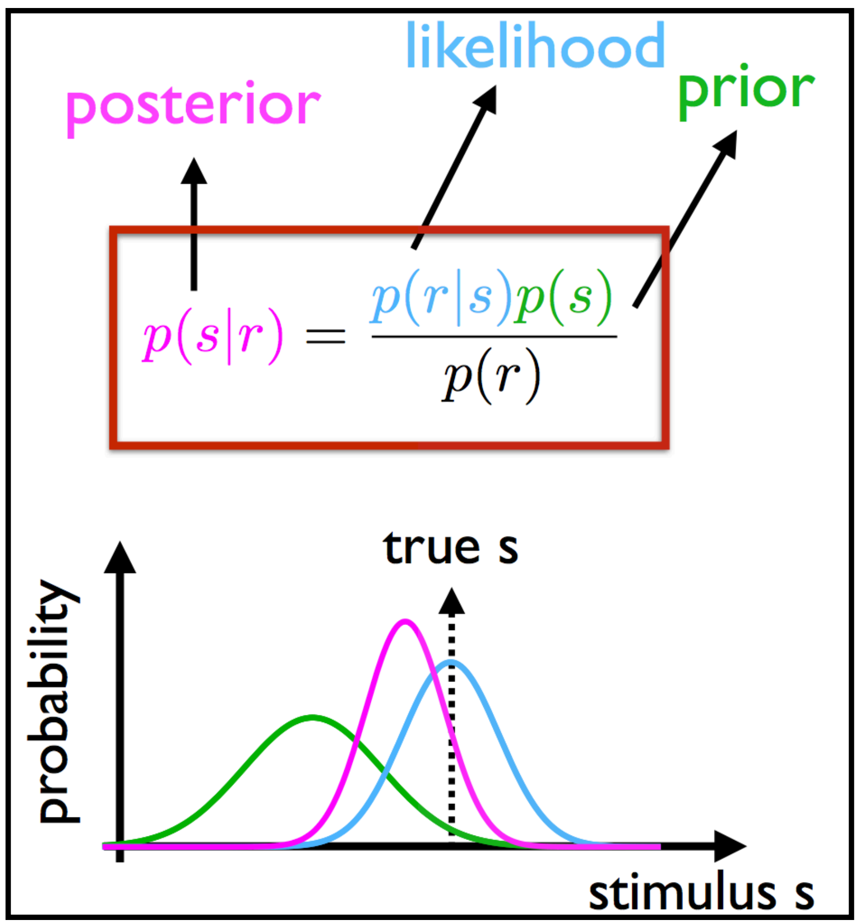
The I/O function is:

$$P(\text{spike} \mid \text{stimulus}) = P(\text{spike} \mid s_1)$$

S1 as identified by our linear filter

Finding the I/O Function for a Single Neuron.

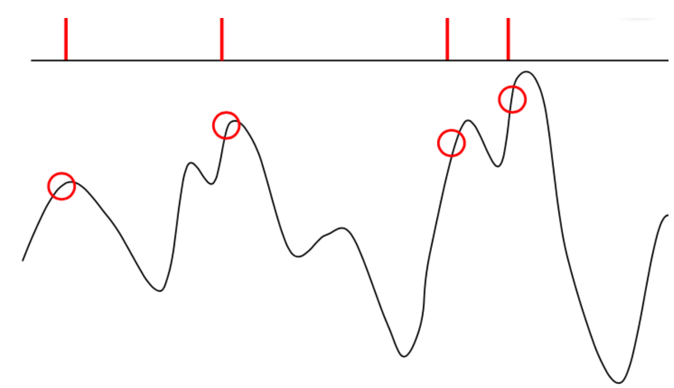
The I/O function can be found from data using the Bayes' rule:

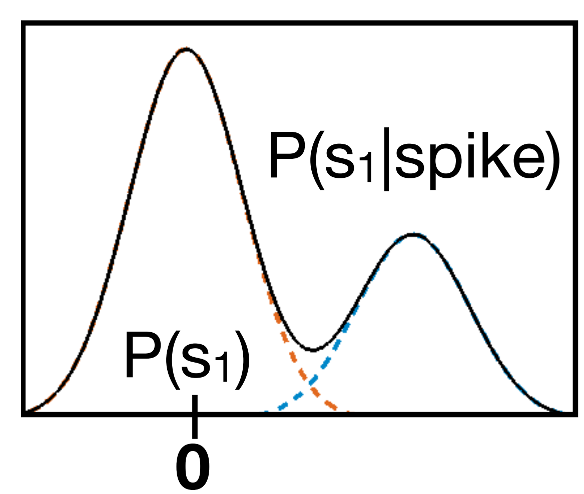


$$\overset{\text{pattern}}{P(\text{spike}|s_1)} = \frac{\overset{\text{pattern}}{P(s_1|\text{spike})}\,\overset{\text{pattern}}{P(\text{spike})}}{P(s_1)}$$

$P(s_1)$

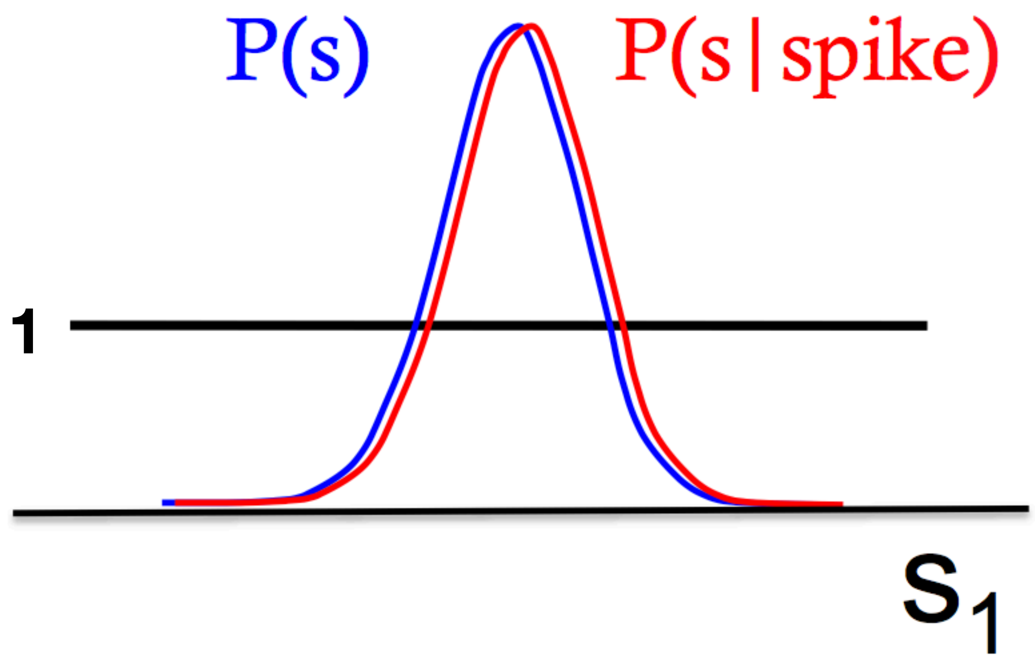
$P(s_1|\text{spike})$



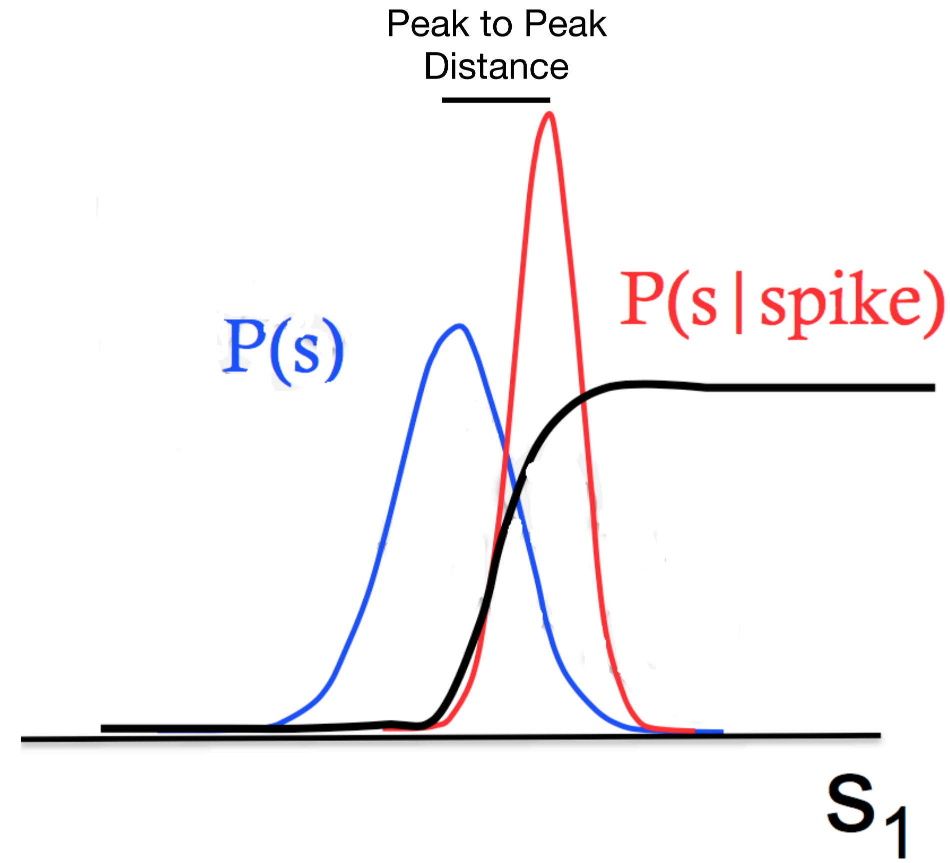


Finding the I/O Function for a Single Neuron.

$$P(spike|s_1) = P(s_1|spike)\ P(spike)\ /\ P(s_1)$$

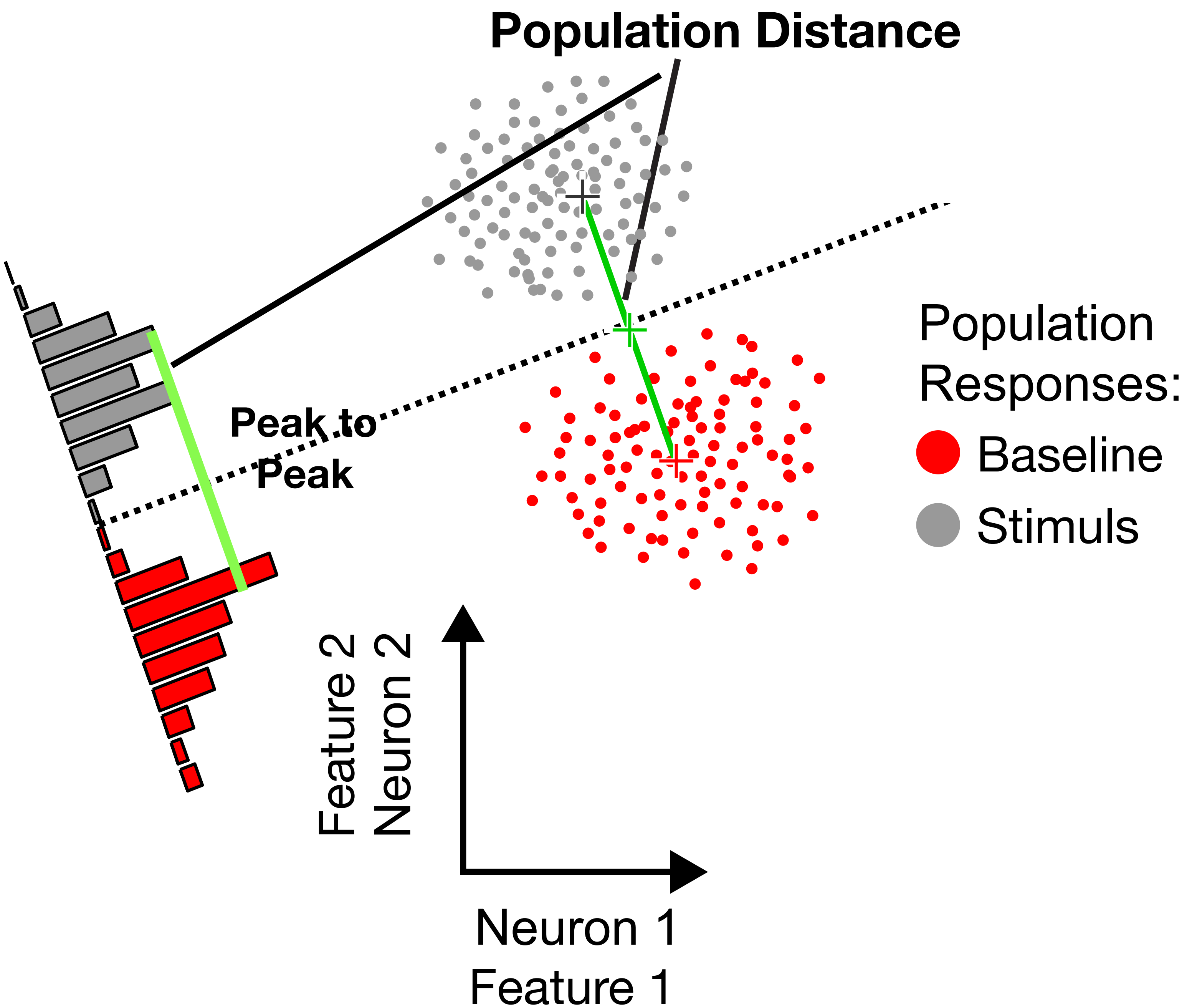


Spikes are unrelated to stimulus.



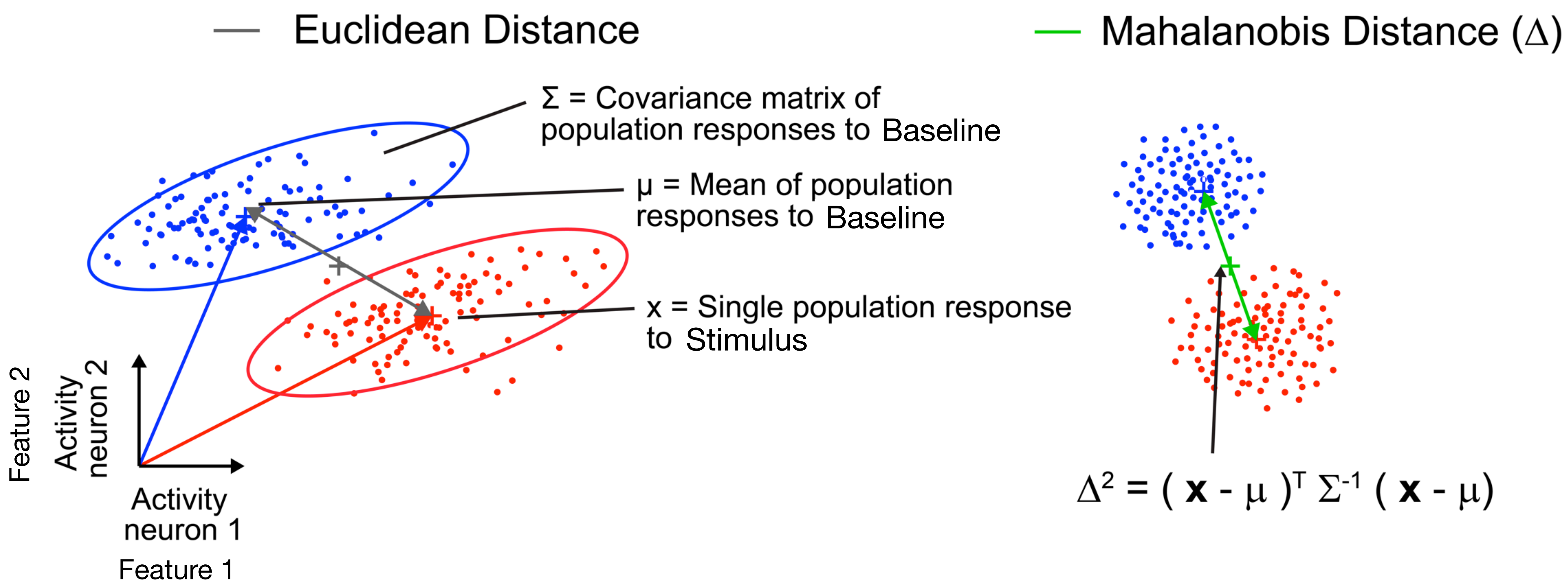
Spikes are selective!

Population Distance Metrics.



Grewe at al., 2017

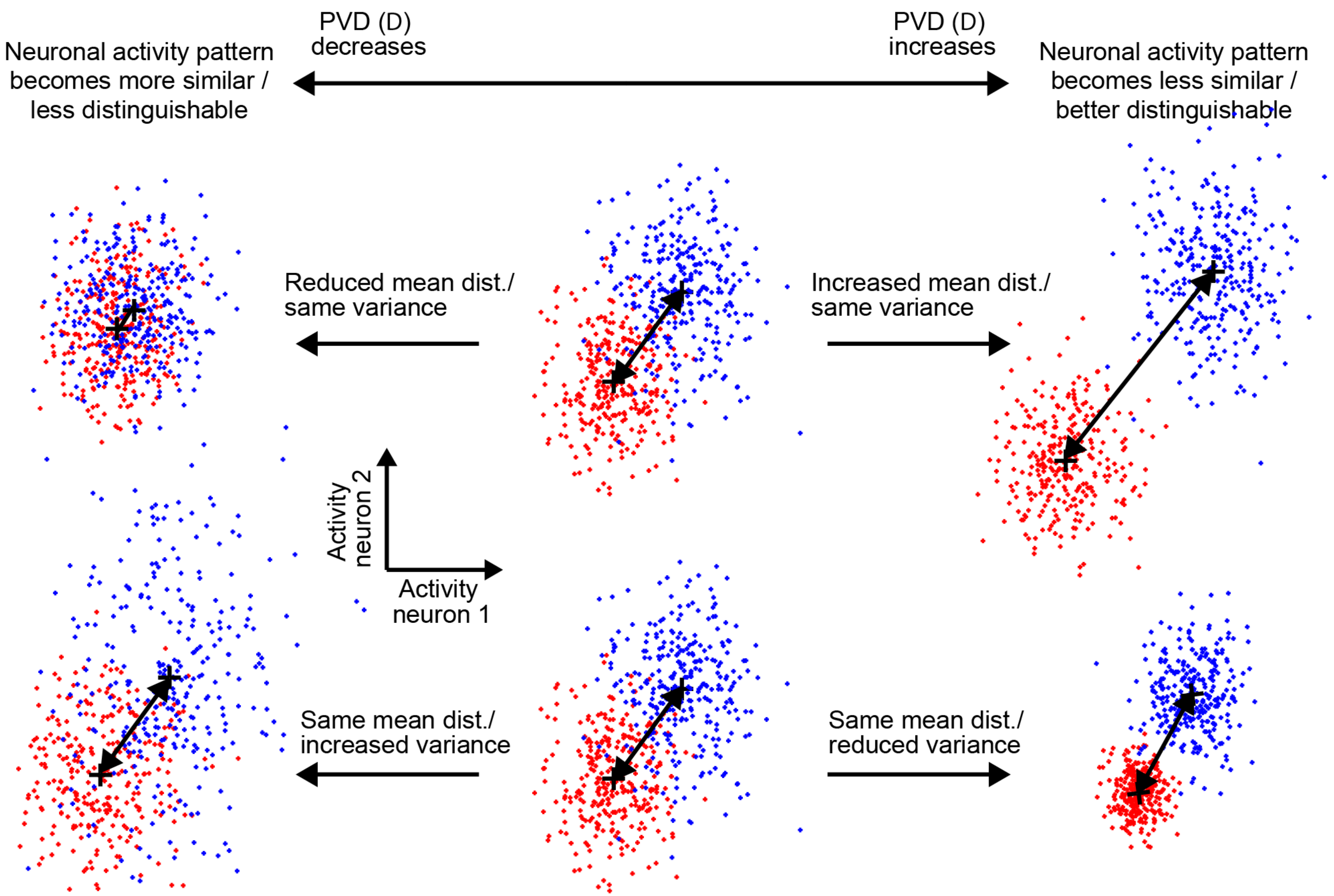
Population Distance Metrics.



$$\Delta^2 = (\mathbf{x} - \mu)^T \Sigma^{-1} (\mathbf{x} - \mu)$$

Grewe at al., 2017

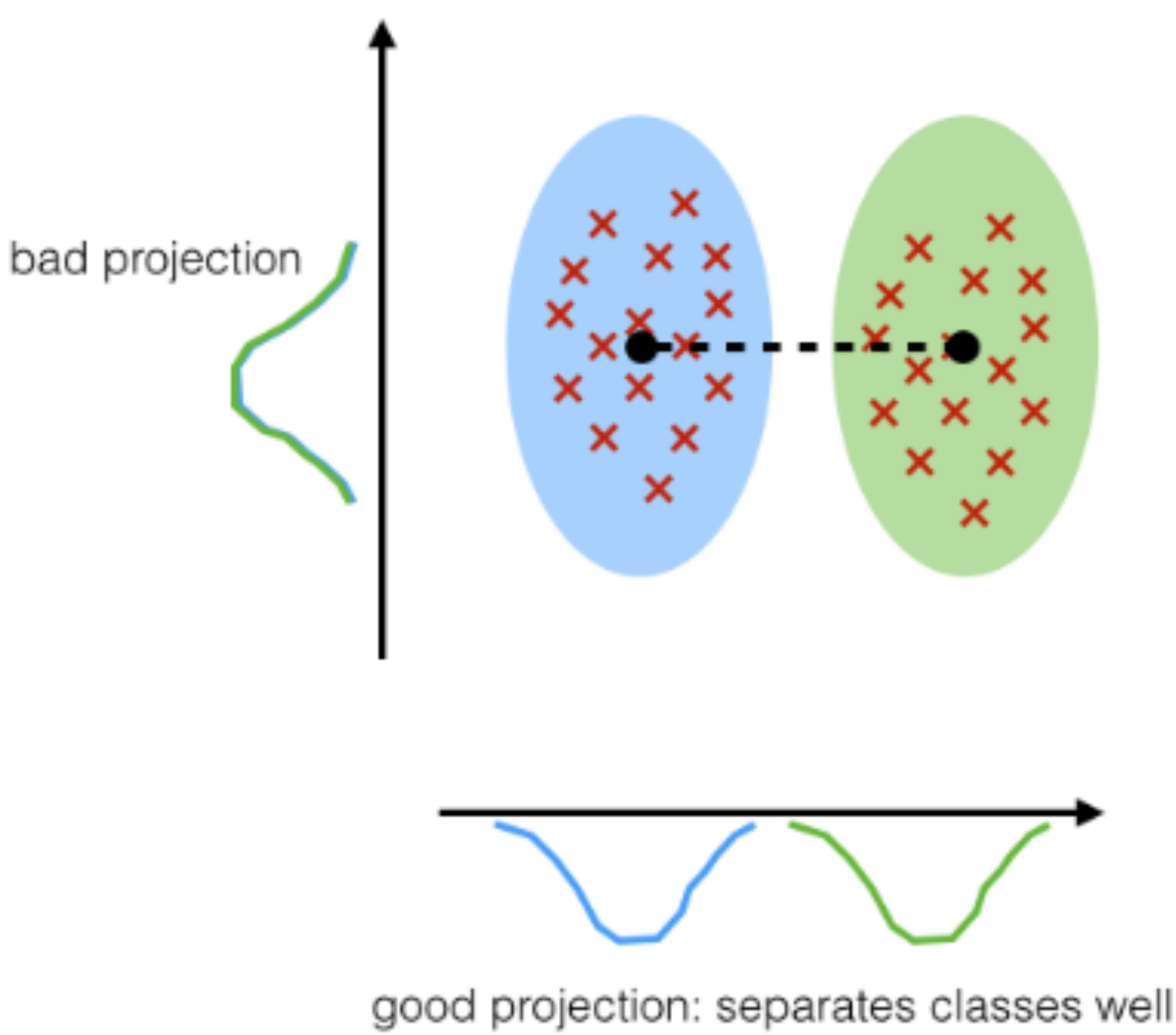
Population Distance Metrics.

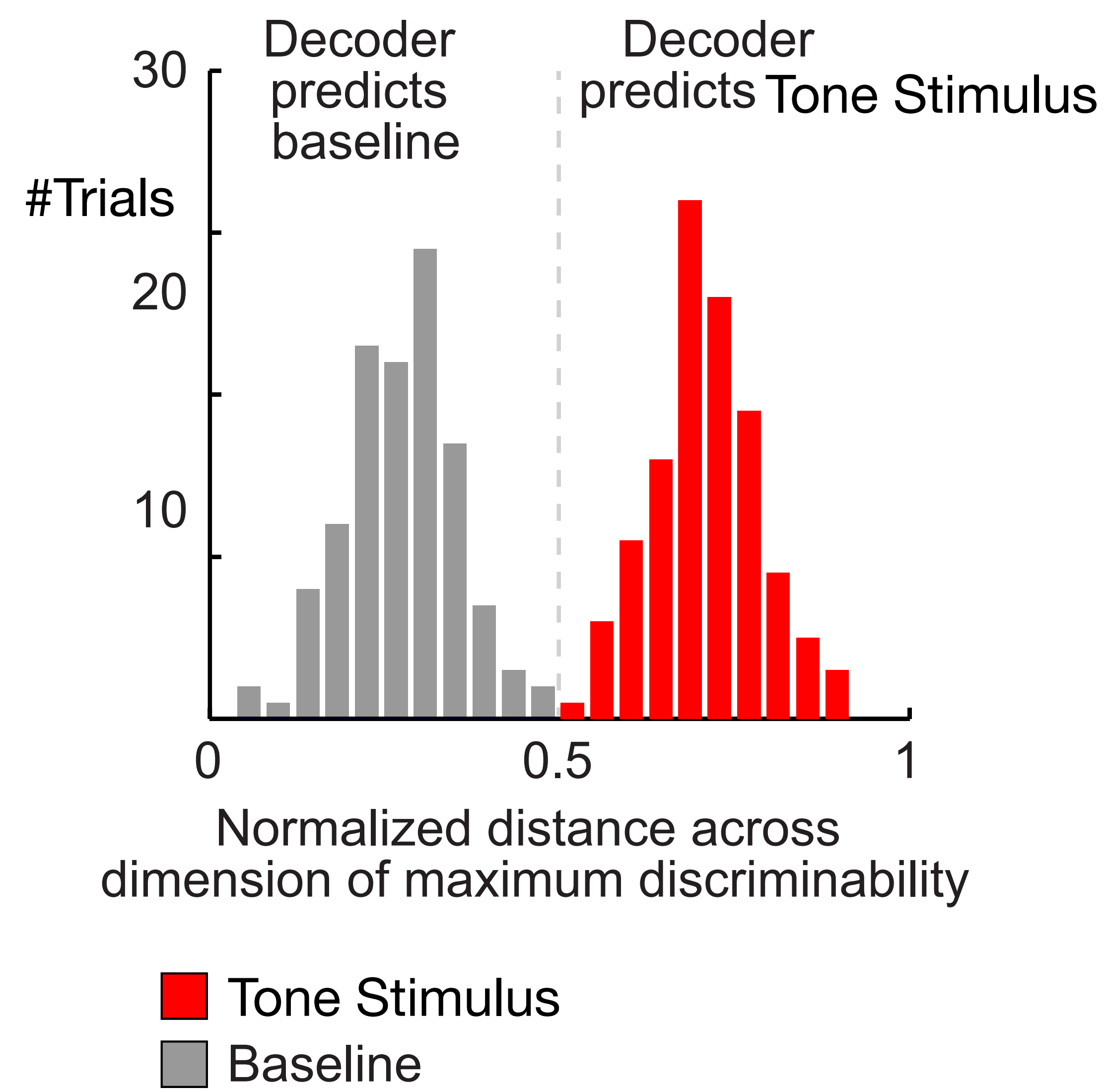


Grewe at al., 2017

Supervised Decoding via LDA

LDA: Linear Discriminant Analysis

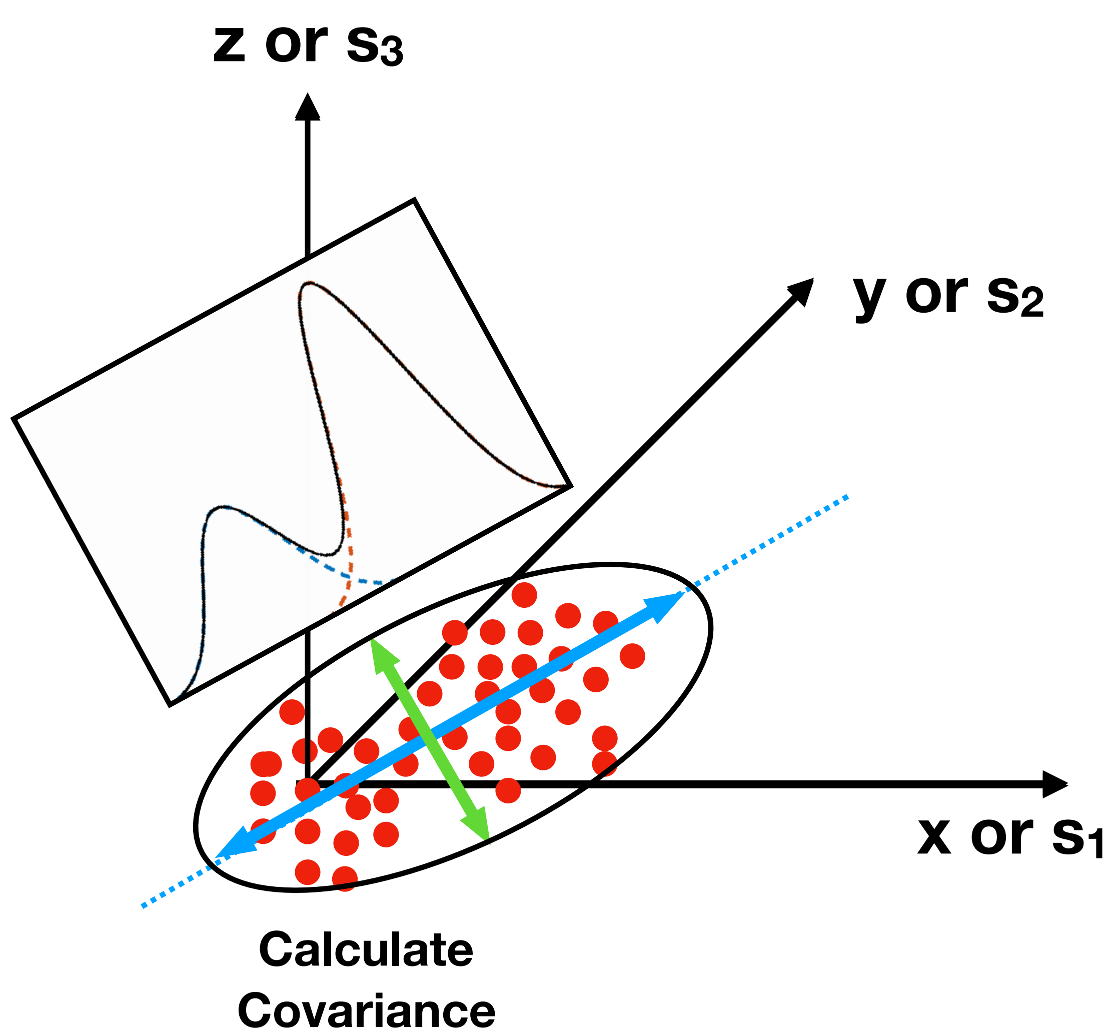


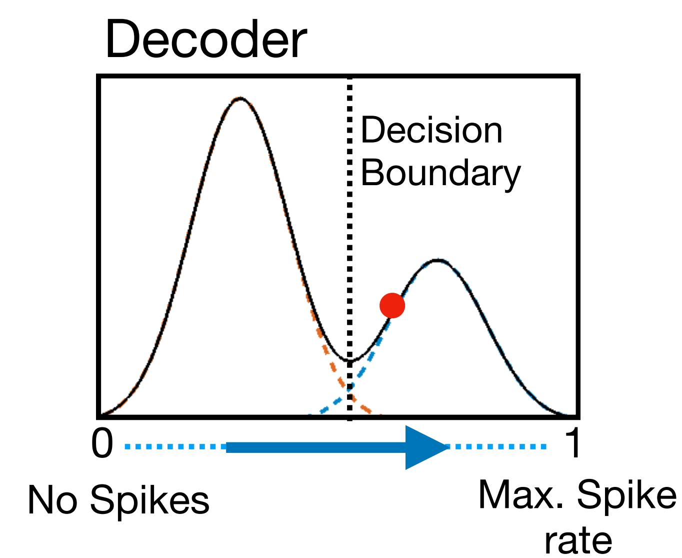


Grewe at al., 2017

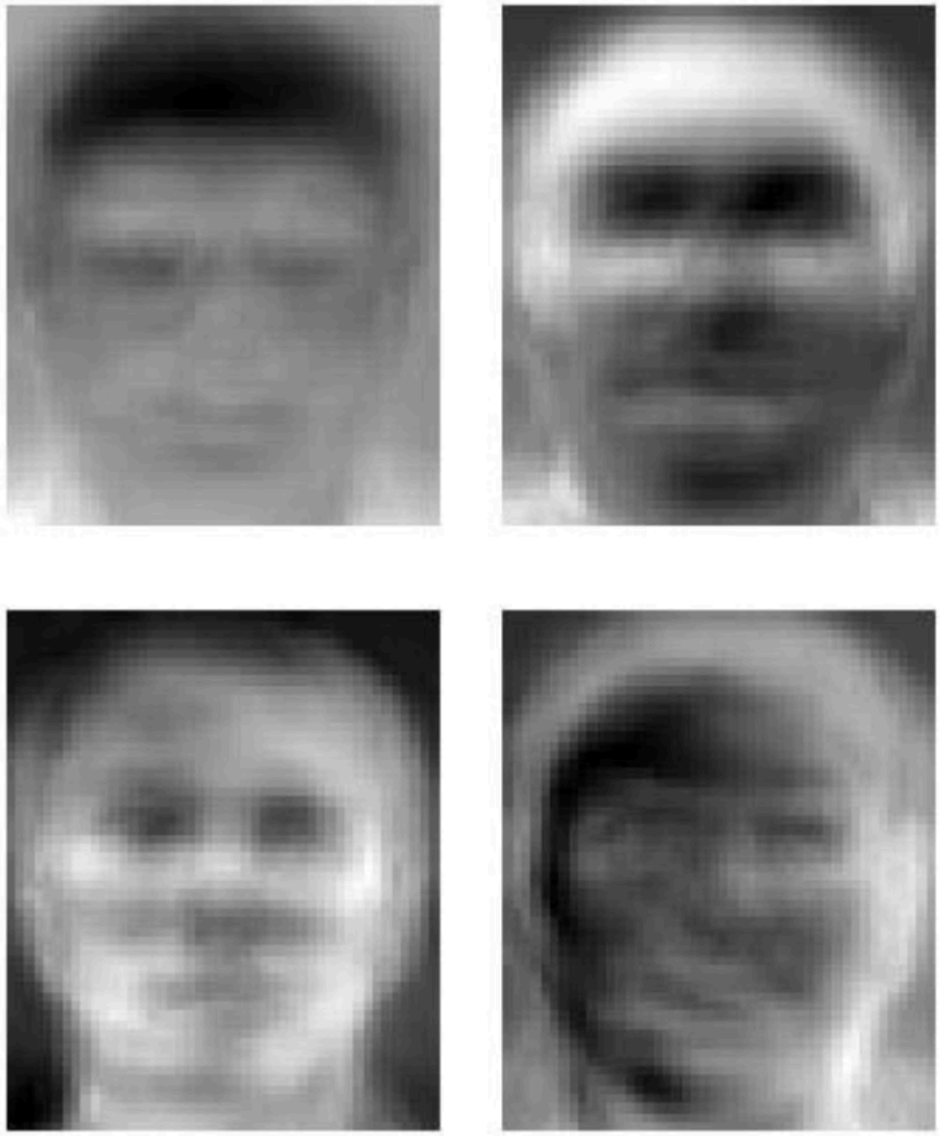
Unsupervised Clustering via PCA

PCA: Principal Component Analysis





PCA Example: The Eigenfaces.



From Pixels (high-dim.) to 7-8 Eigenfaces.

ATT Labs, Cambridge

Short Recap QUIZ.

If we discretize a stimulus waveform in time, we can represent it as a vector in some vector space. What is the dimensionality of this vector space?

1. The standard deviation of the stimulus.
2. The number of presentations of the stimulus.
3. The length of the stimulus (in seconds).
4. The number of points used in the discretization.

When we plot P(spike | s1) as a function of s1, why does P(spike) only act as a scaling factor, rather than as something that changes the general shape of the function?

1. This is not correct. P(spike) has a large effect on the shape of the conditional distribution plotted as a function of s1.
2. P(spike) influences the spike-triggered average.
3. P(spike) is the first moment of the spike-conditional distribution.
4. P(spike) is not a function of s1.

Short Recap QUIZ.

Principal component analysis (PCA) gives us a method to:

1. Find a representation of our data which has lower dimensionality, giving us a computationally easier problem to work with.

2. Find the vectors along which the variation of our data is maximal in our feature space.

3. Neither of these

4. Both of these


Thank you for your Attention!