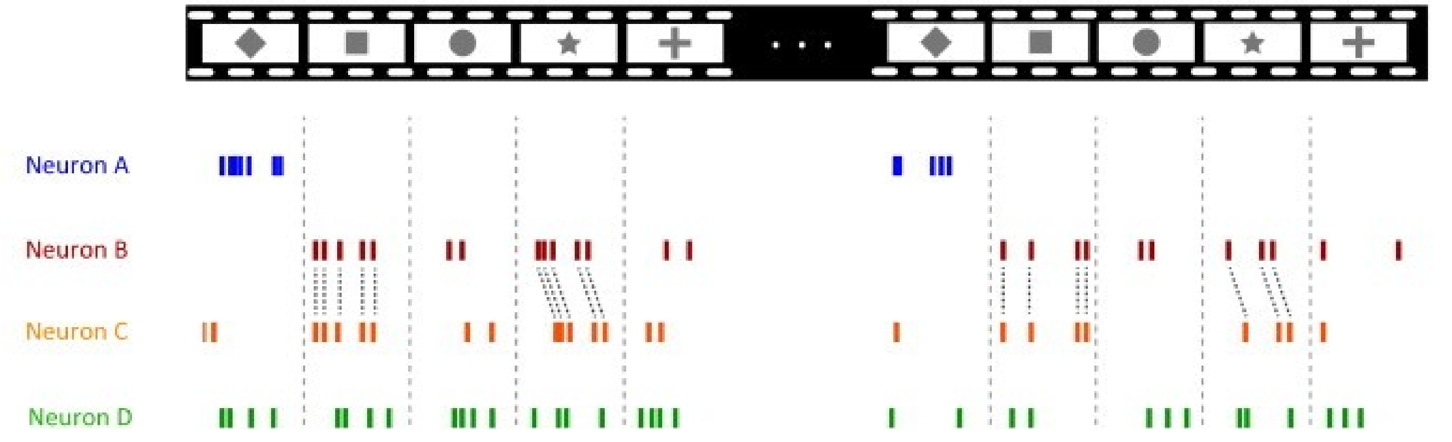
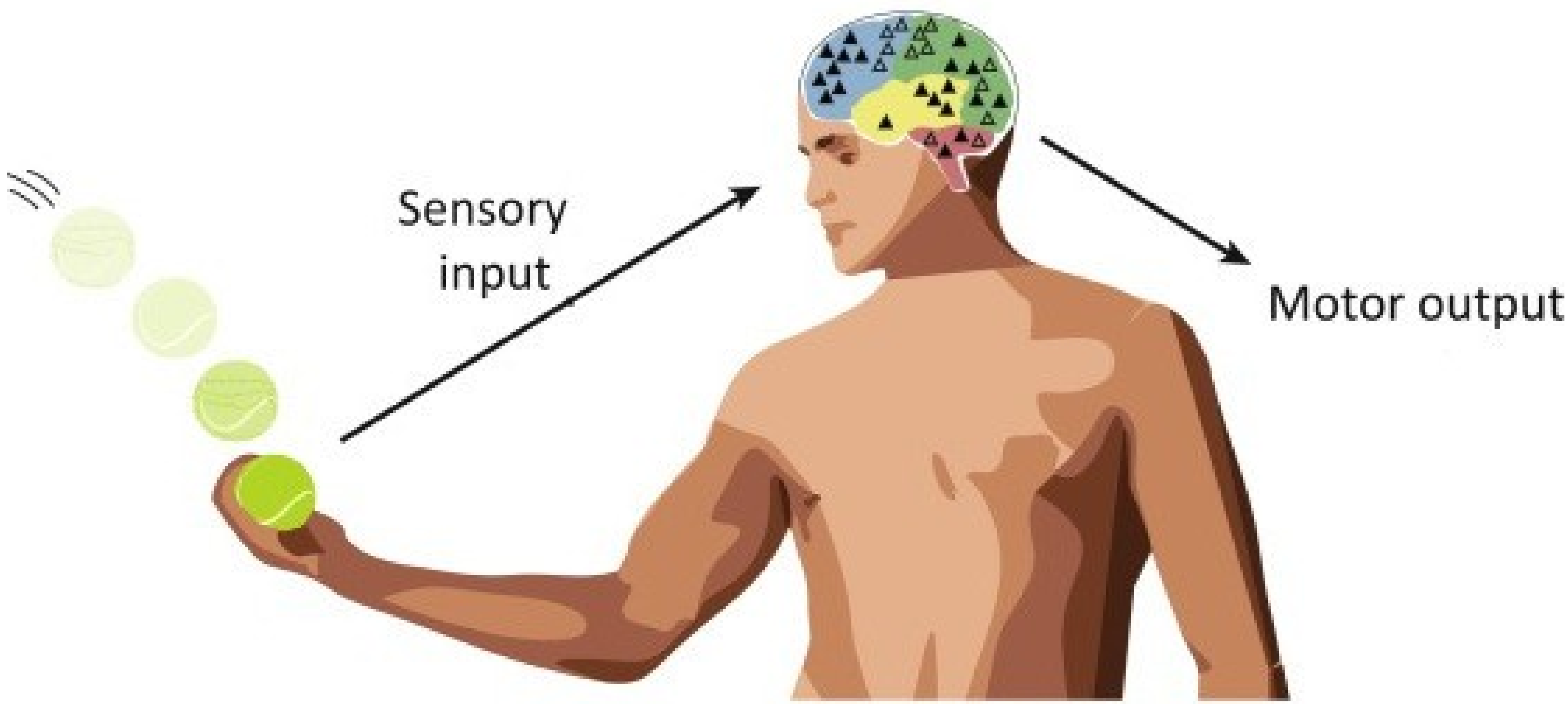


Neural coding

NAIL087
Ján Antolík
MFF UK, 2025

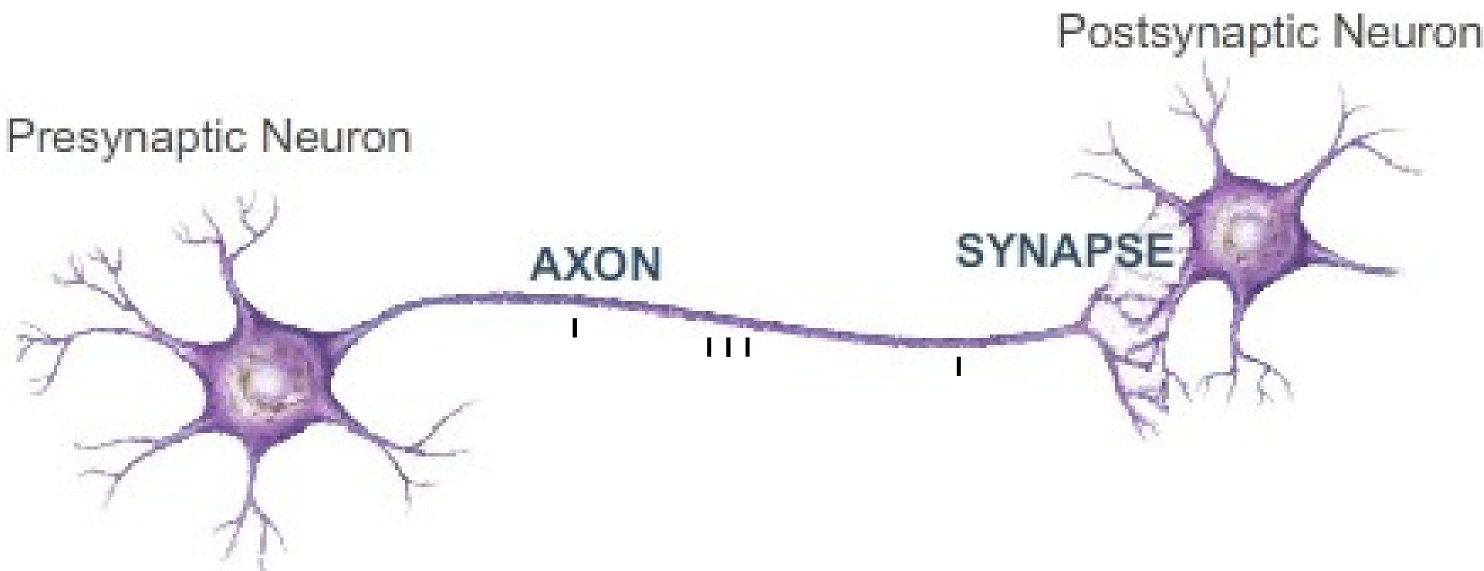
Perkel and Bullock (1968): The problem of neural coding is to elucidate "the representation and transformation of information in the nervous system."

The sensory–motor arc



Neural coding encompasses all the information processing in the brain starting from the sensory input arriving on the sensory periphery, to the motor system output activating the muscles.

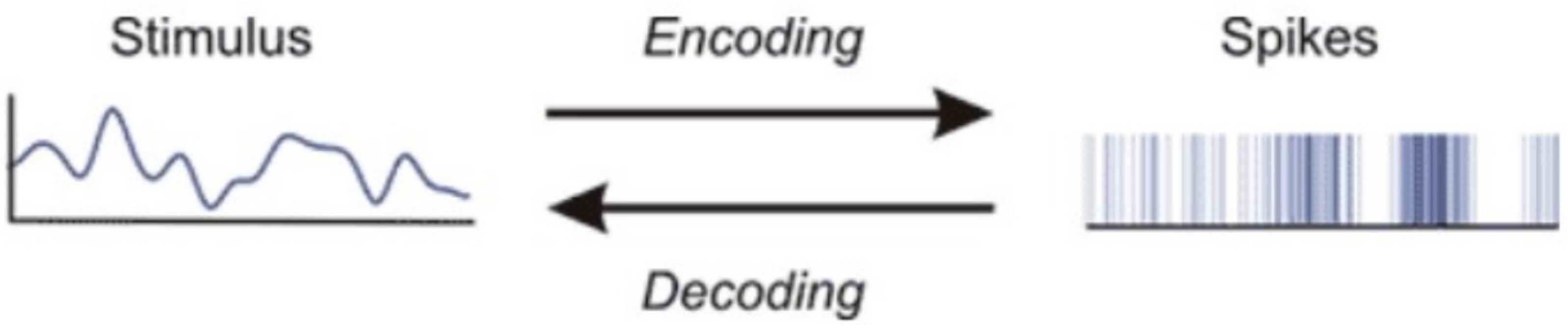
Spike as an elementary unit of information transmission



In this class we will restrict ourselves to the view of spikes being the primary carrier of information in neural system.

Can you give examples showing this view is a simplification?

Encoding vs. Decoding



External world

Brain

- ENCODING: How is information about stimulus transformed into spikes
- DECODING: How to infer stimulus (or output variable) given spikes

Encoding vs. Decoding

S – Stimulus
R – Response

Encoding $P(R|S)$ vs *Decoding* $P(S|R)$

Encoding vs. Decoding

S – Stimulus
R – Response

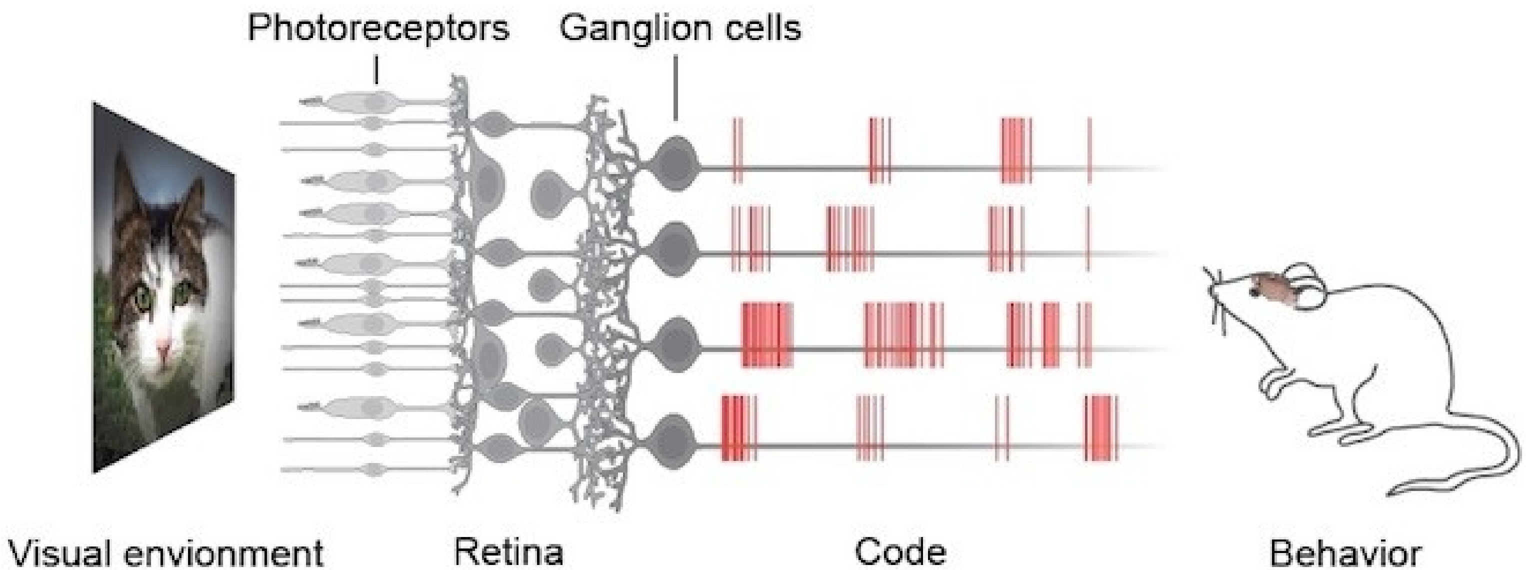
Encoding		*Decoding*
$P(R\|S)$	vs	$P(S\|R)$

Encoding and decoding are related by **Bayes theorem**:

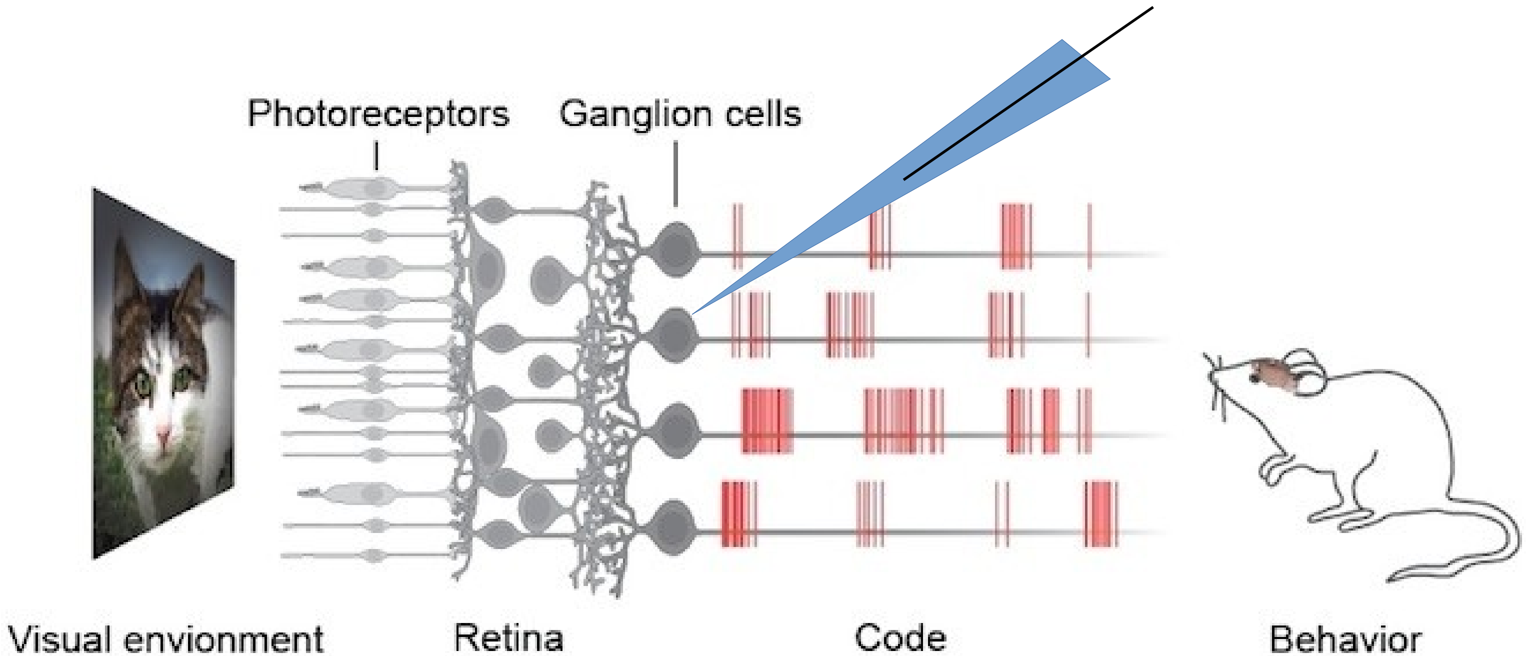
$$P(R,S) = P(R|S)P(S) = P(S|R)P(R)$$

$$P(S|R) = \frac{P(R|S)P(S)}{P(R)}$$

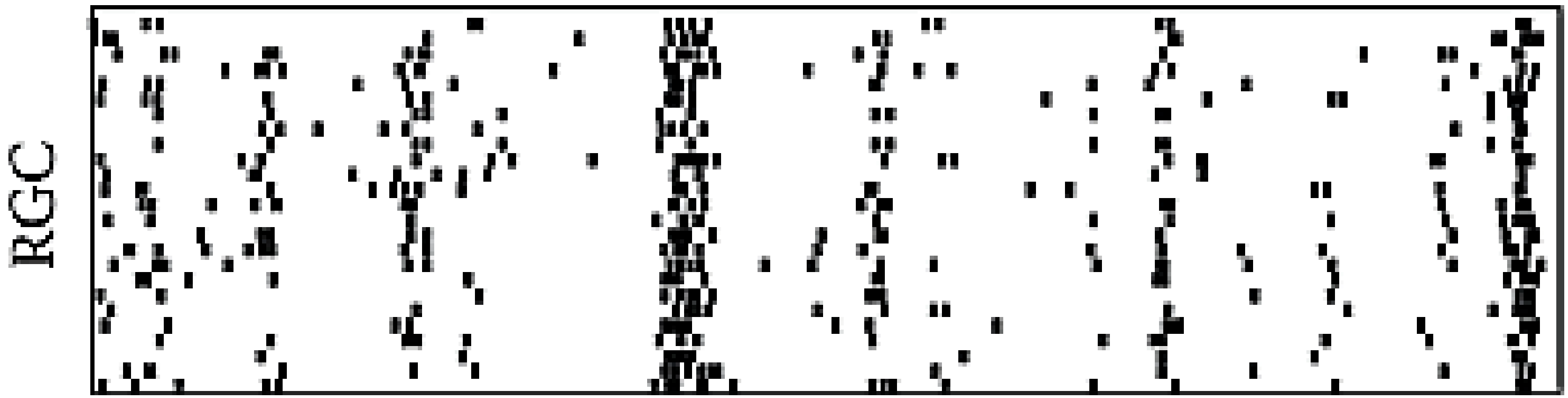
Let's brainstorm!
How could this retinal ganglion cell encode information?



Let’s brainstorm!
How could this retinal ganglion cell encode information?

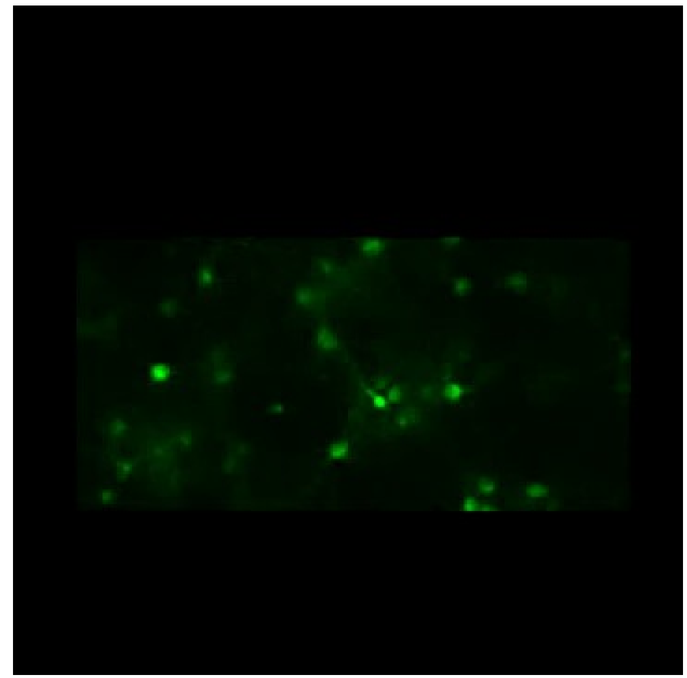


Let's brainstorm!
How could this retinal ganglion cell encode information?

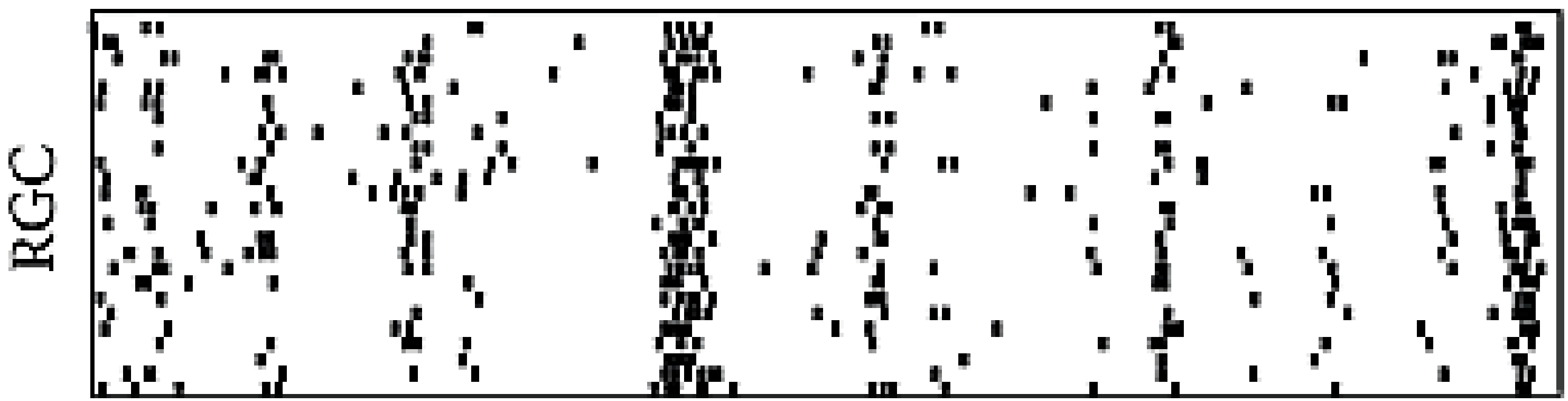


Little detour: Spontaneous noise

- the majority of neurons fire without any “stimulation”
- Internal biophysical sources
  - Thermal noise
  - Channel noise
  - Vesicle release failure
- Incoming network noise
- Noise can play its role
  - e.g., learning / optimization
  - probability representation



Let's brainstorm!
How could this retinal ganglion cell encode information?



Major types of neural coding

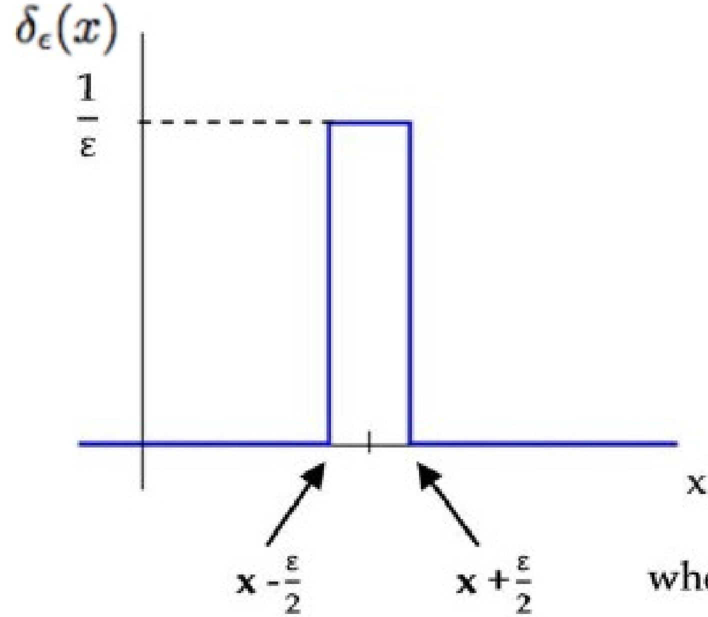
- Rate based coding
  - Information is encoded in the number of spikes fired per unit of time, not their exact timing
- Temporal coding
  - Information is encoded in the exact timing of the spikes. E.g. by the inter-spike intervals or synchronous arrival of spikes.
- Population coding
  - Information is distributed across multiple neurons

RATE CODE

Firing–rate hypothesis

- Only the frequency is important
  - small vs. large change of *s(t)* causes small vs. large change in the firing frequency: **rate code** [Abott I/37]

The Dirac delta function



$$\delta(x) = \lim_{\epsilon \to 0} \delta_\epsilon(x)$$

where $\varepsilon \to 0$

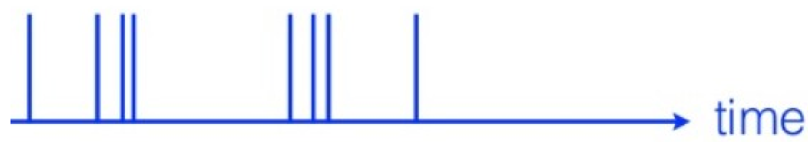
The Dirac delta function is defined by the properties

$$\delta(x) = \begin{cases} 0 & \text{for } x \neq 0, \\ \infty & \text{for } x = 0, \end{cases} \qquad \text{and} \qquad \int_{-\infty}^{\infty} \delta(x)\, \mathrm{d}x = 1.$$

Representation of spike trains

- Spike train as a sum of delta functions:

$$\rho(t) = \sum_{i=1}^{n} \delta(t - t_i)$$



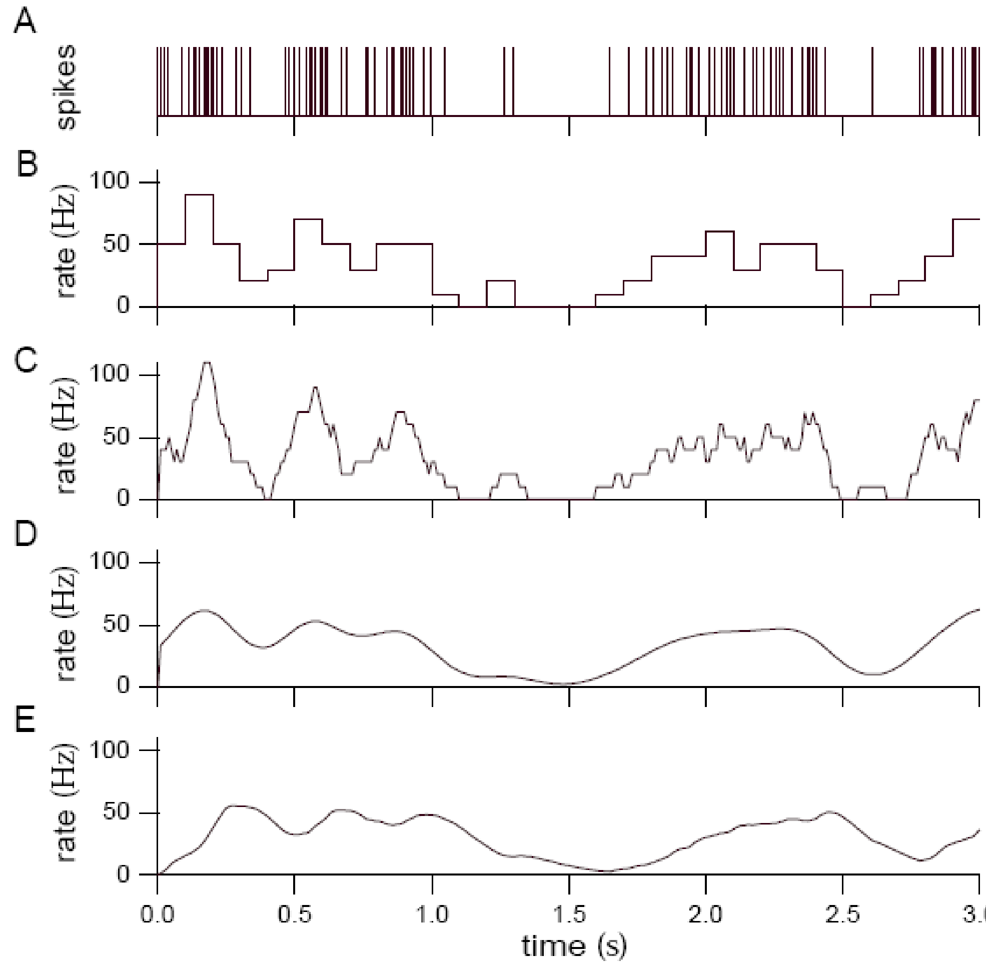
- Firing rate *r(t)* formalization:

$$\mathrm{r}(t) = \frac{1}{\Delta t} \int_{t}^{t+\Delta t} d\tau \, \langle \rho(\tau) \rangle$$

Rate–code in detail

- Spiking -> rate code
- Options
  - bin
  - sliding a window
  - filter kernel:
    - Gauss vs. alpha

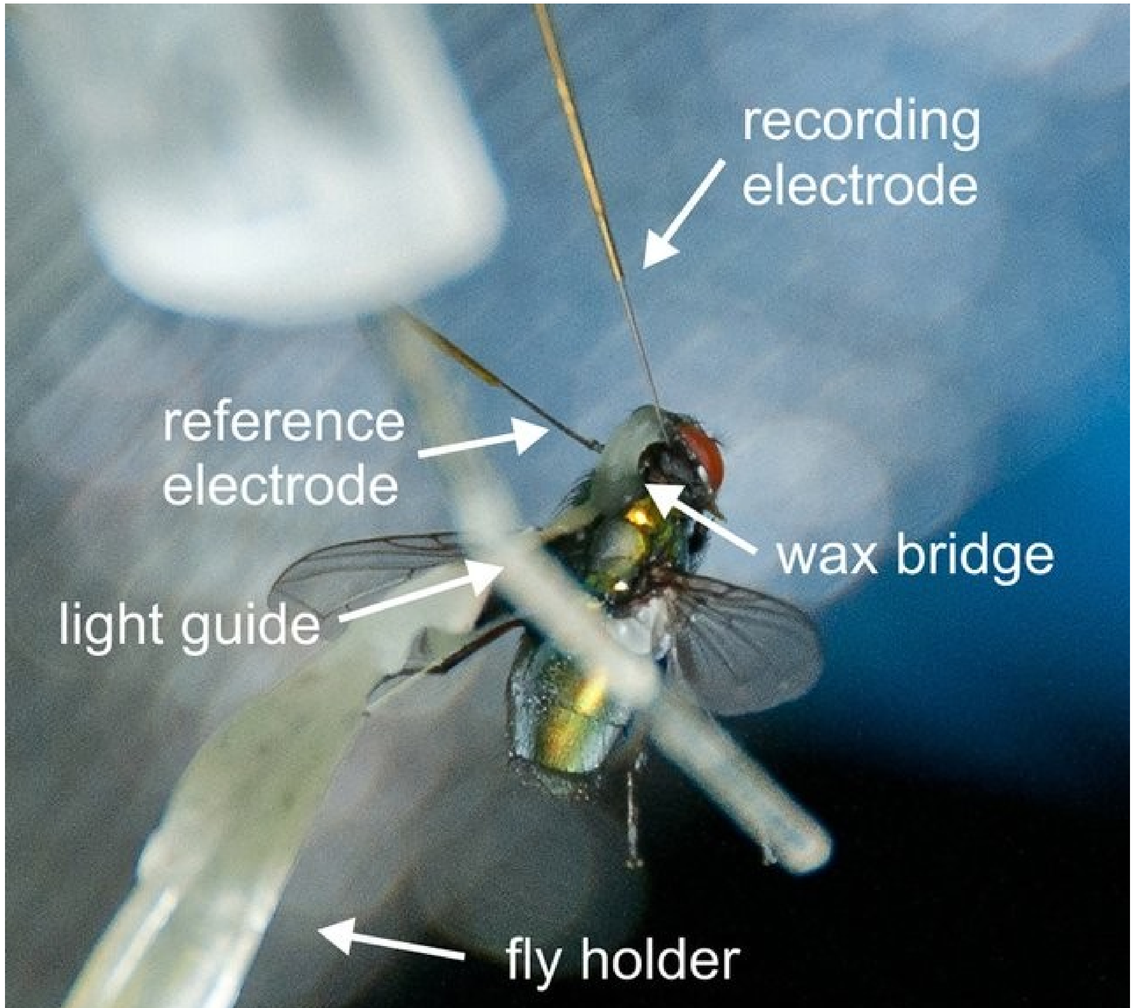
$$\mathrm{r}_{\mathrm{approx}}(t) = \int_{-\infty}^{\infty} d\tau\, w(\tau)\rho(t-\tau)\,.$$



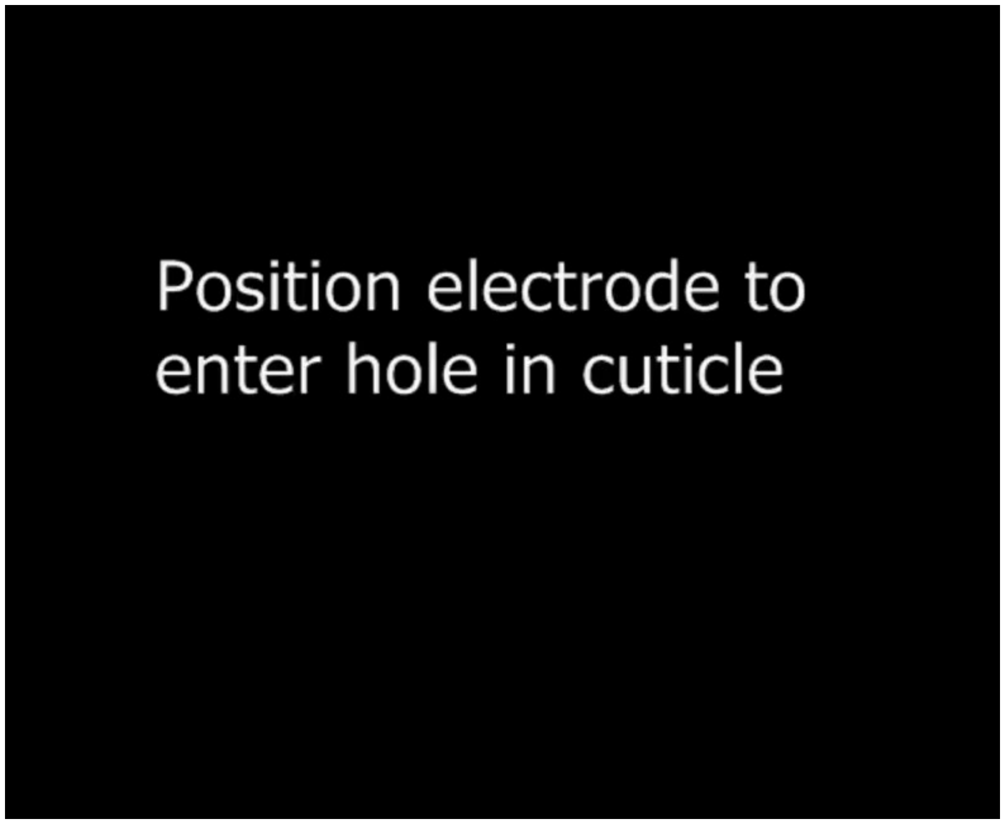
Gauss vs. alpha filter

What’s the difference?

Rate–code example: blowfly

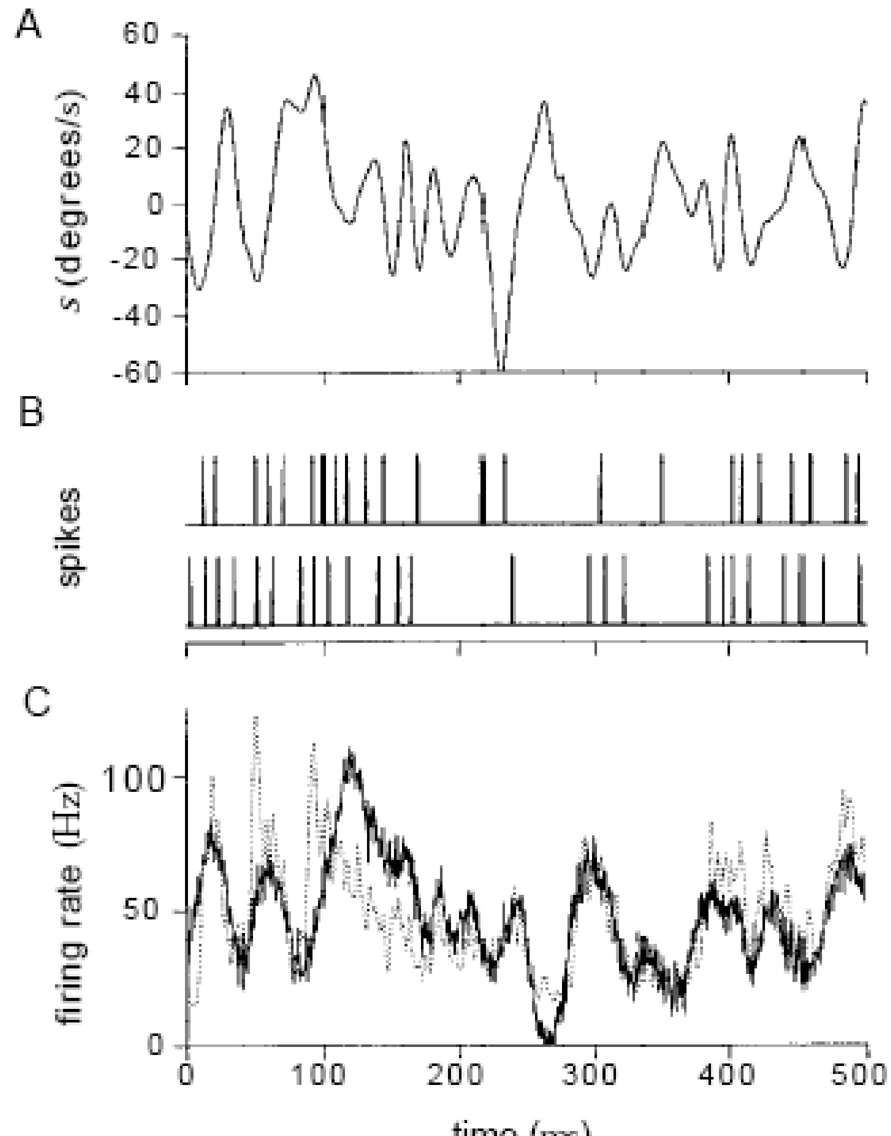


Rate–code example: blowfly



Rate–code example: blowfly

A) Artificial, continuously changing stimulus *s(t)*: changing „landscape“ [angular velocity]
B) H1 movement-sensitive visual neuron of a blowfly [Abbott, I/22]
C) Calculated (gray) and predicted (black) firing rate.



Rate–code example: blowfly

- H1 movement-sensitive visual neuron of a blowfly [Abbott, I/22]
- Artificial, continuously changing stimulus *s(t)*: changing „landscape“ [angular velocity]
- Issues:
  - What is the first thing you should care about?

Rate–code example: blowfly

- H1 movement-sensitive visual neuron of a blowfly [Abbott, I/22]
- Artificial, continuously changing stimulus *s(t)*: changing „landscape“ [angular velocity]
- Issues:
  - does H1 respond systematically on *s(t)*?

Rate–code example: blowfly

- H1 movement-sensitive visual neuron of a blowfly [Abbott, I/22]
- Artificial, continuously changing stimulus *s(t)*: changing „landscape“ [angular velocity]
- Issues:
  - does H1 respond systematically on *s(t)*?
  - OK, but is it a rate code?

Rate–code example: blowfly

- H1 movement-sensitive visual neuron of a blowfly [Abbott, I/22]
- Artificial, continuously changing stimulus *s(t)*: changing „landscape" [angular velocity]
- Issues:
  - does H1 respond systematically on *s(t)*?
  - predicting a firing frequency of H1 based on *s(t)*

Rate–code example: blowfly

- H1 movement-sensitive visual neuron of a blowfly [Abbott, I/22]
- Artificial, continuously changing stimulus *s(t)*: changing „landscape“ [angular velocity]
- Issues:
  - does H1 respond systematically on *s(t)*?
  - predicting a firing frequency of H1 based on *s(t)*
  - predicting s(t) based on a firing frequency of H1
    - Does success in previous analysis guarantees success in this one?

Rate–code example: blowfly

- H1 movement-sensitive visual neuron of a blowfly [Abbott, I/22]
- Artificial, continuously changing stimulus *s(t)*: changing „landscape“ [angular velocity]
- Issues:
  - does H1 respond systematically on *s(t)*?
  - predicting a firing frequency of H1 based on *s(t)*
  - predicting s(t) based on a firing frequency of H1
  - What if it doesn’t work?

Rate–code example: blowfly

- H1 movement-sensitive visual neuron of a blowfly [Abbott, I/22]
- Artificial, continuously changing stimulus *s(t)*: changing „landscape“ [angular velocity]
- Issues:
  - does H1 respond systematically on *s(t)*?
  - predicting a firing frequency of H1 based on *s(t)*
  - predicting s(t) based on a firing pattern of H1
  - Repeat, but with two neurons responding to opposing angular velocities

Rate–code example: blowfly

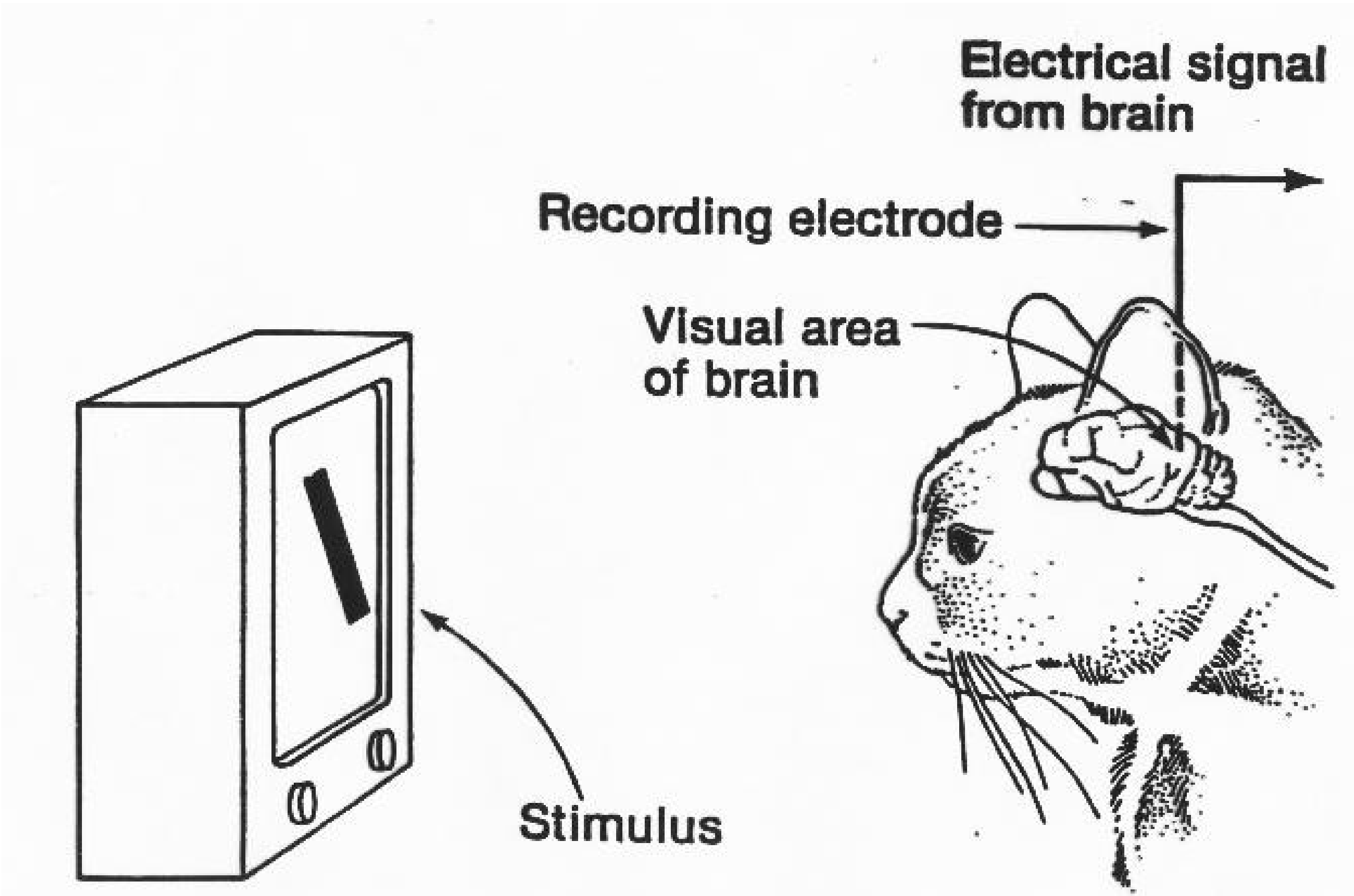
- H1 movement-sensitive visual neuron of a blowfly [Abbott, I/22]
- Artificial, continuously changing stimulus *s(t)*: changing „landscape“ [angular velocity]
- Issues:
  - does H1 respond systematically on *s(t)*?
  - predicting a firing frequency of H1 based on *s(t)*
  - predicting s(t) based on a firing pattern of H1
  - Repeat, but with two neurons responding to opposing angular velocities
  - All of this still doesn’t work, what could be going on?

Rate–code example: blowfly

- H1 movement-sensitive visual neuron of a blowfly
  [Abbott, I/22]
- Artificial, continuously changing stimulus *s(t)*: changing „landscape“ [angular velocity]
- Issues:
  - does H1 respond systematically on *s(t)*?
  - predicting a firing frequency of H1 based on *s(t)*
  - predicting s(t) based on a firing pattern of H1
  - Repeat, but with two neurons responding to opposing angular velocities
  - Drop firing rates, analyze based on firing patterns.

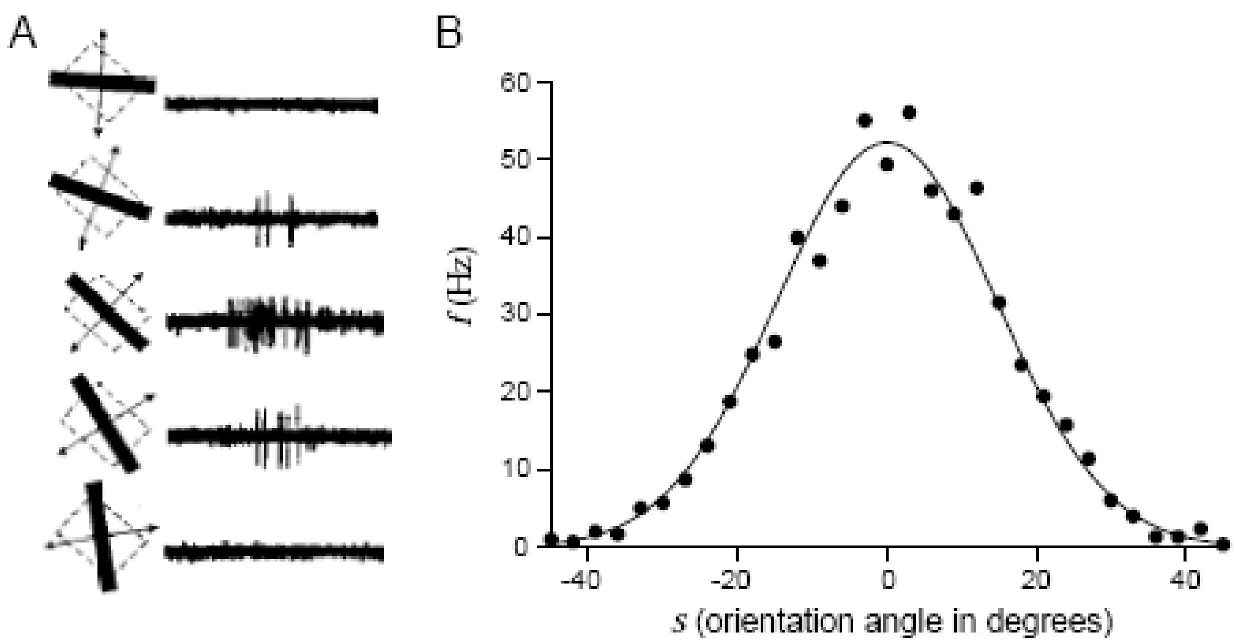
Tuning Curve
and
Receptive Field

Receptive Field Concept



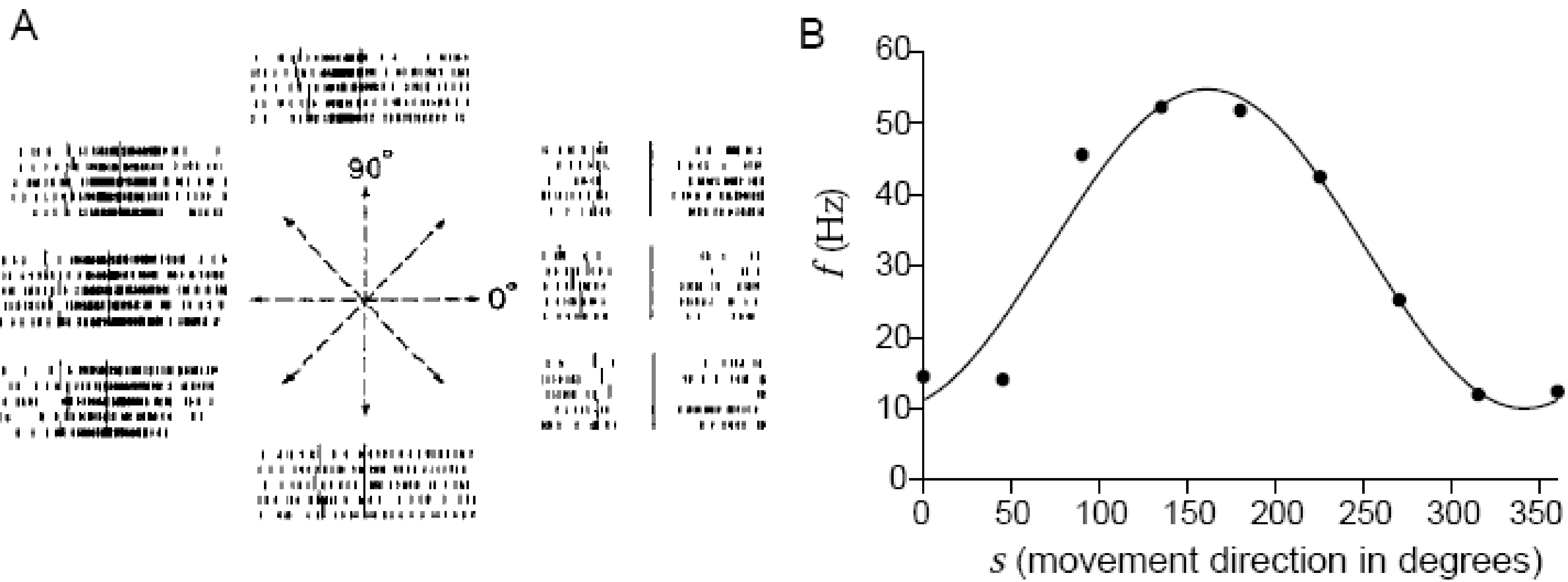
Tunning curves

- Descriptive models of neuronal responses on a particular set of stimuli
- V1, monkey: angular orientation of a moving bart in the neuron's receptive field
  - Gauss

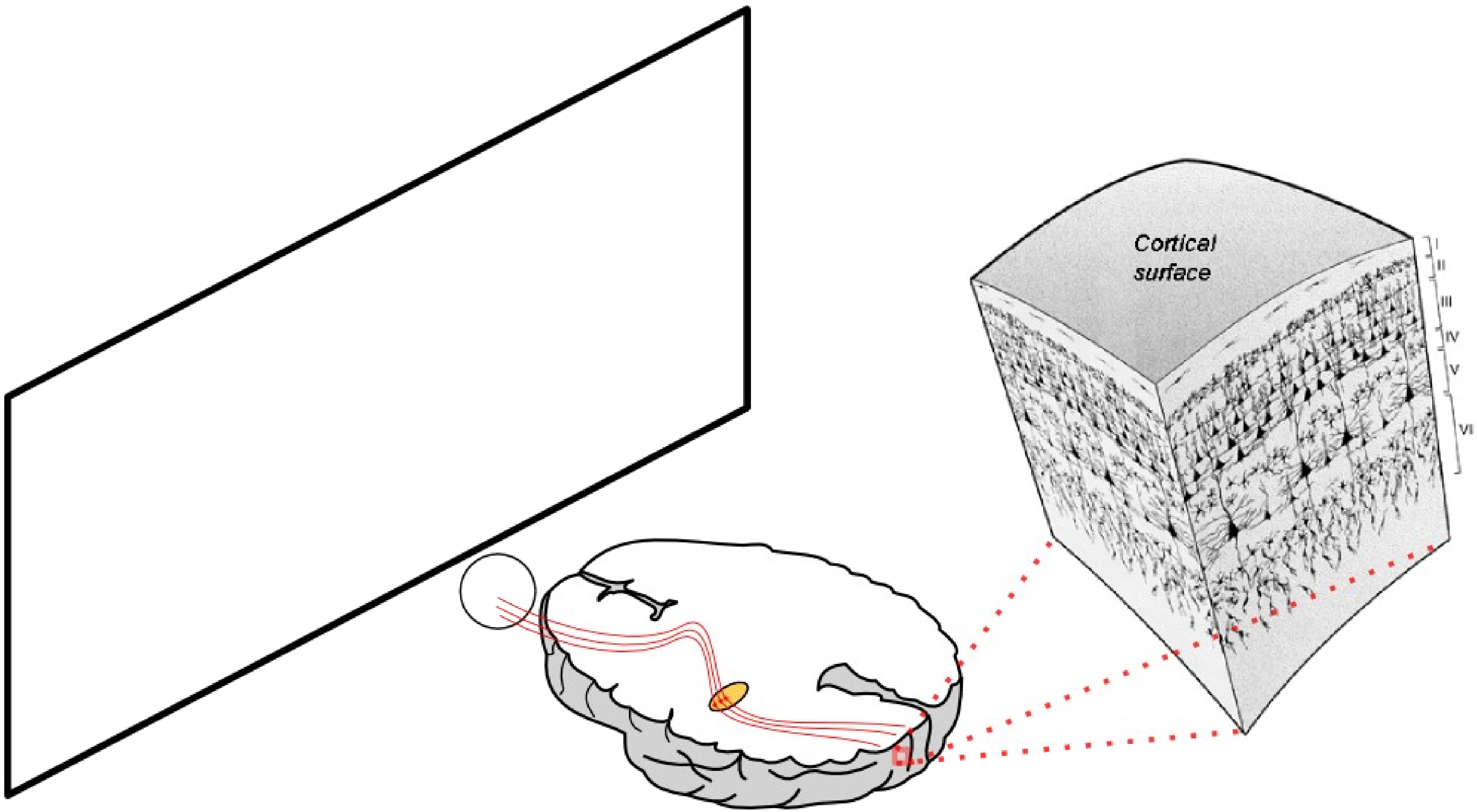


Tunning curves: motor cortex

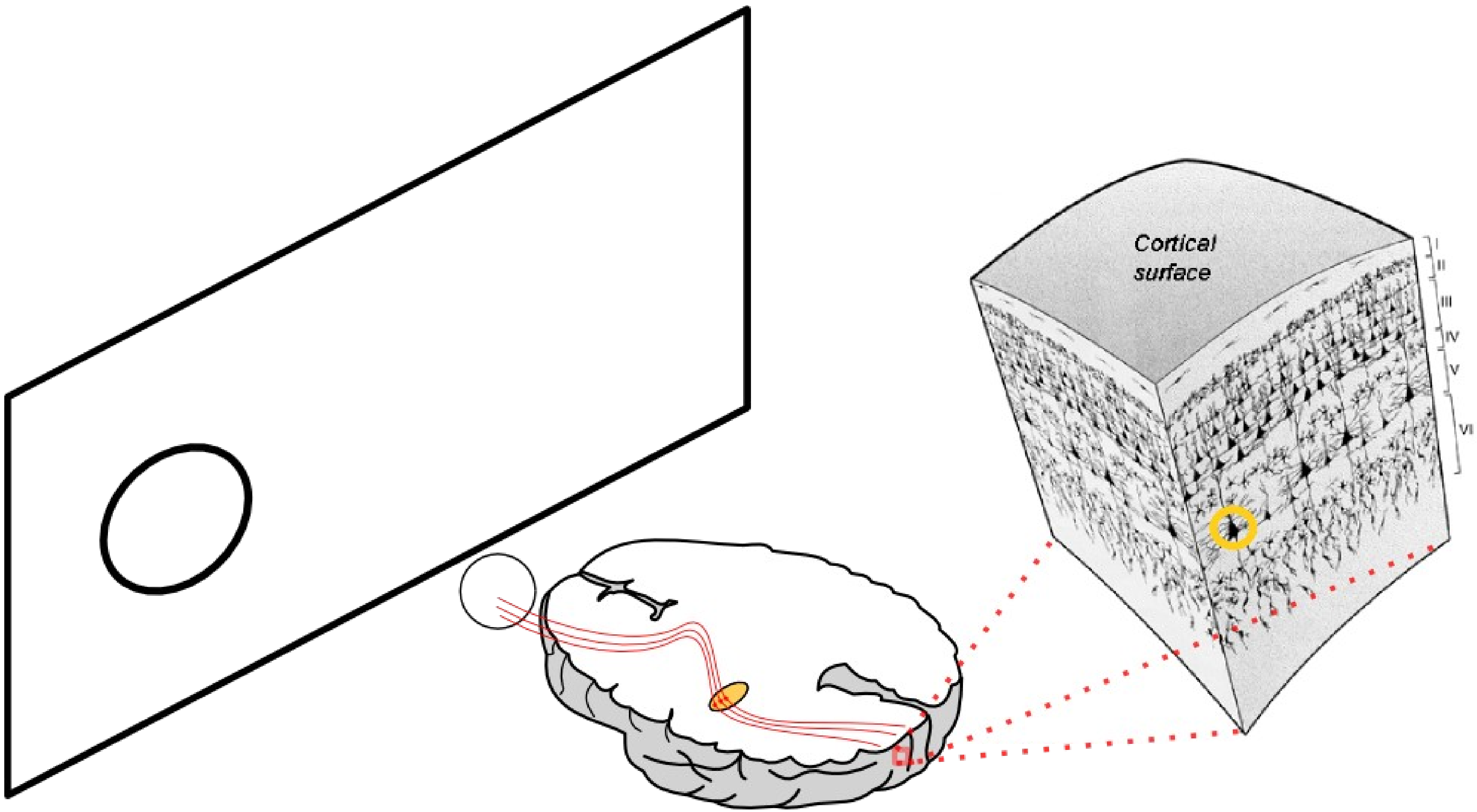
- Primary motor cortex of a monkey: arm-reaching task
  - sin, cos, $[\ .\ ]_+$ $f(s) = [r_0 + (r_{\max} - r_0)\cos(s - s_{\max})]_+ .$



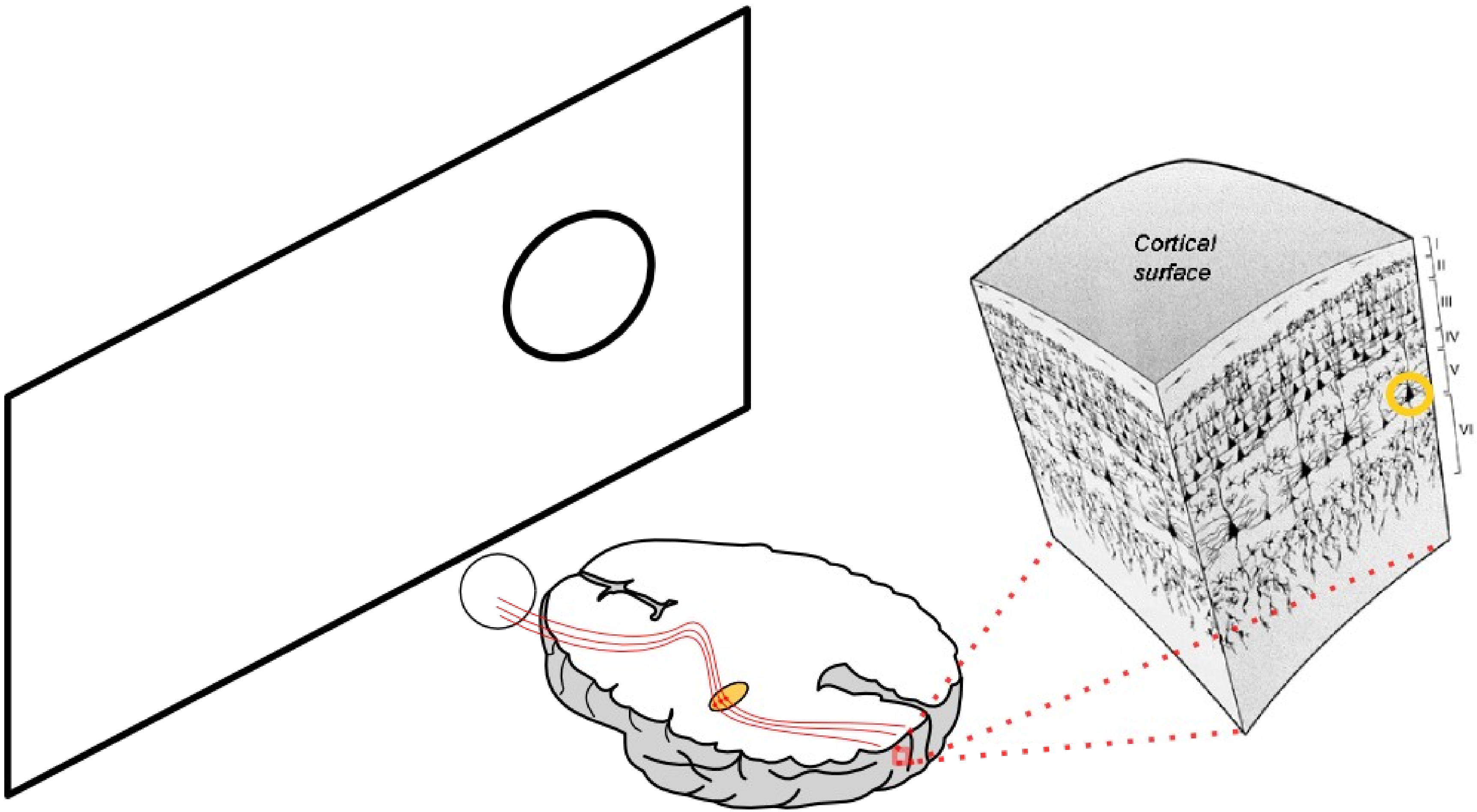
The Receptive Field concept



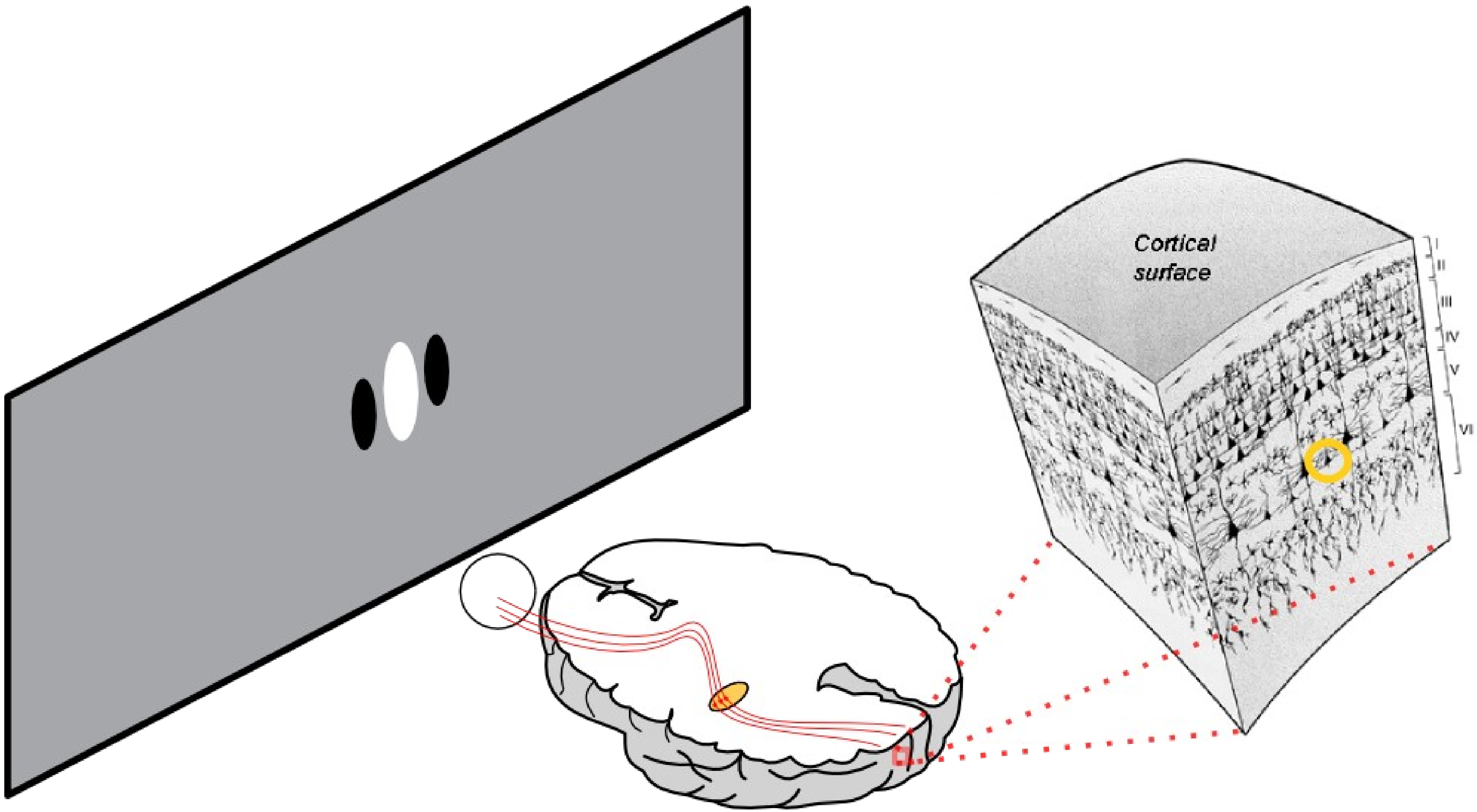
The Receptive Field concept



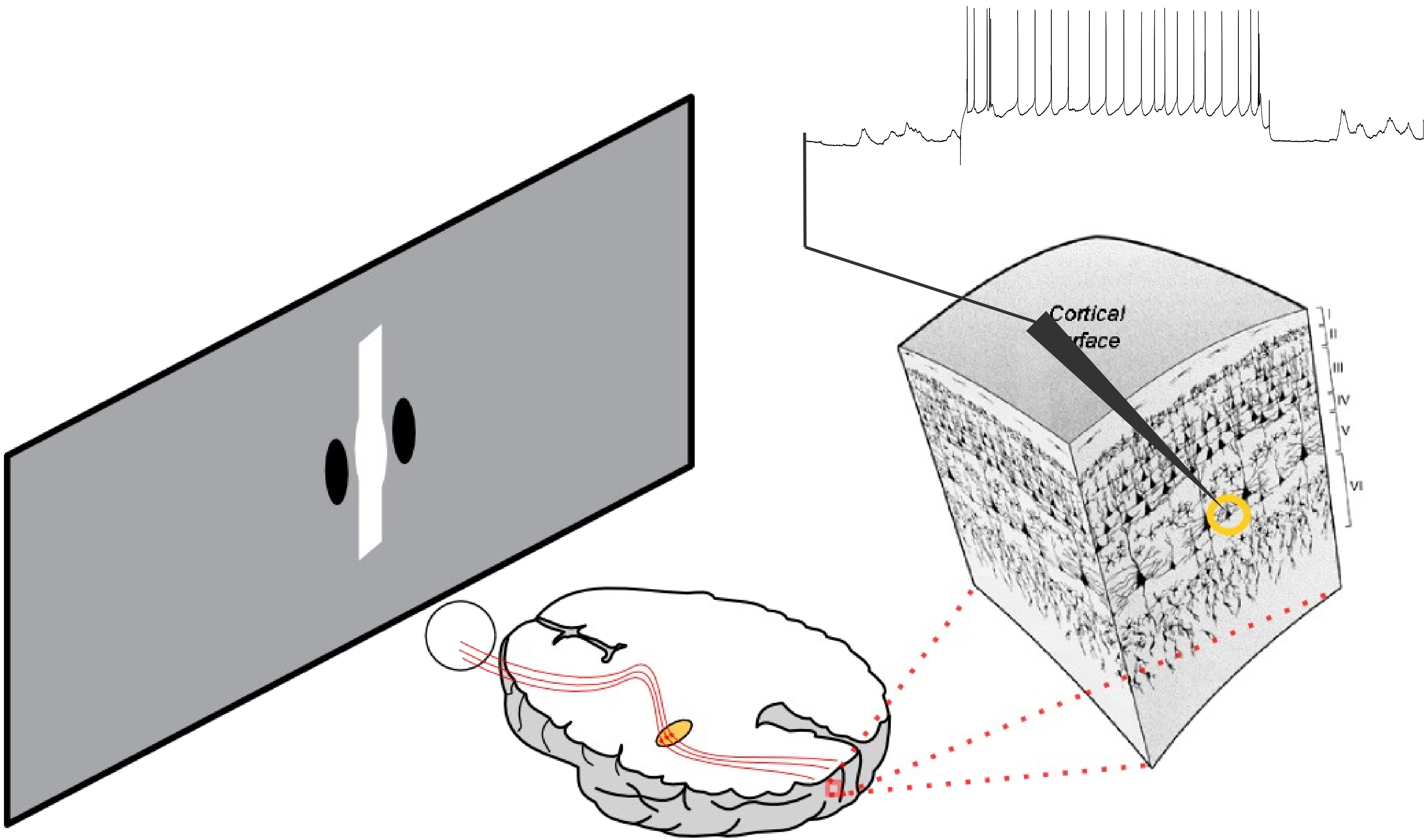
The Receptive Field concept



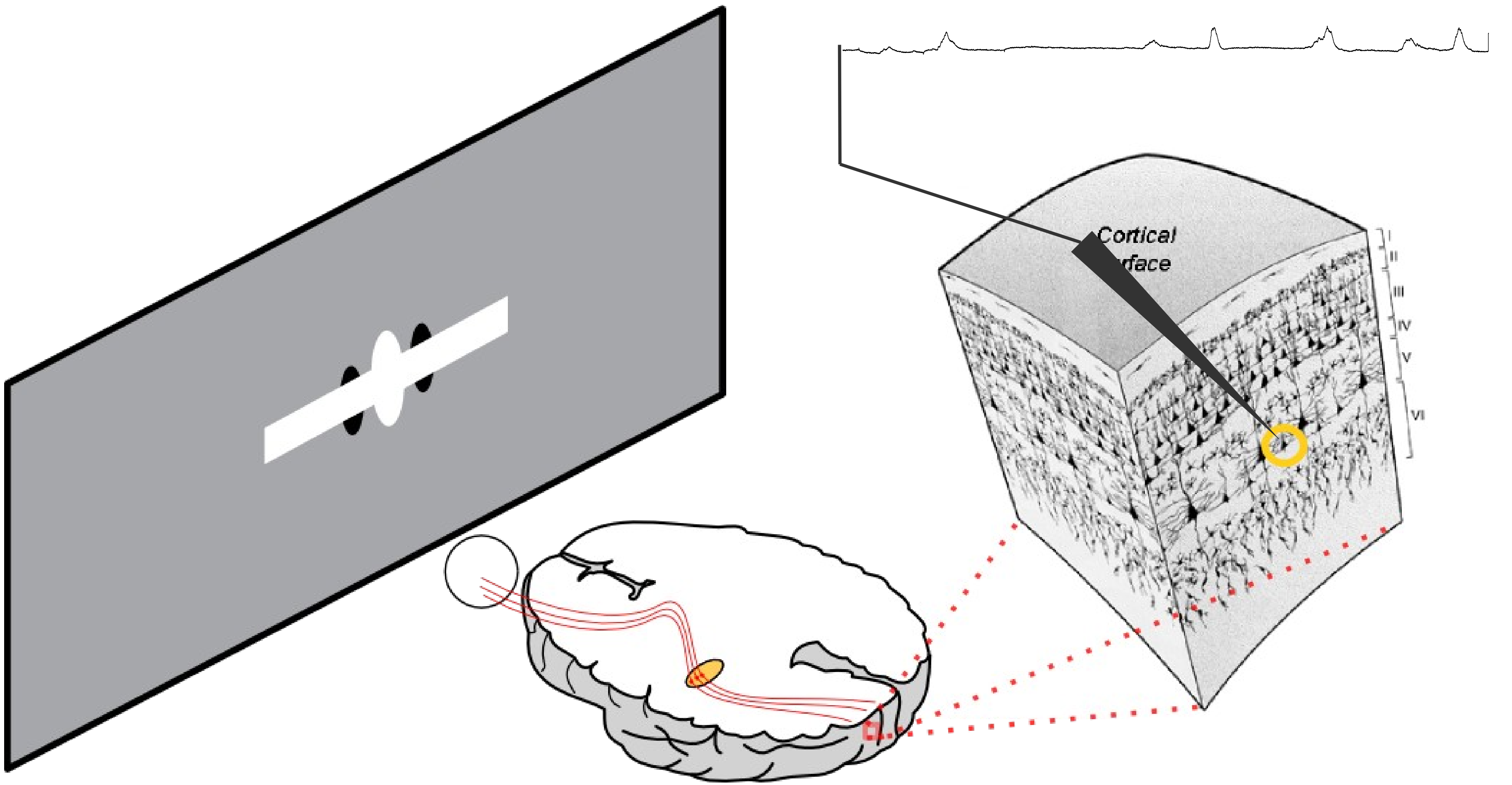
The Receptive Field concept



The Receptive Field concept

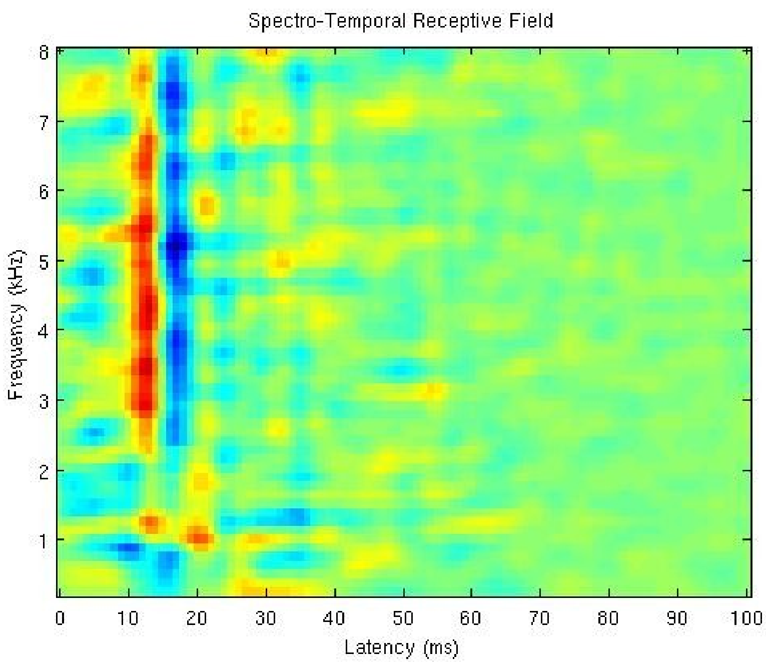


The Receptive Field concept

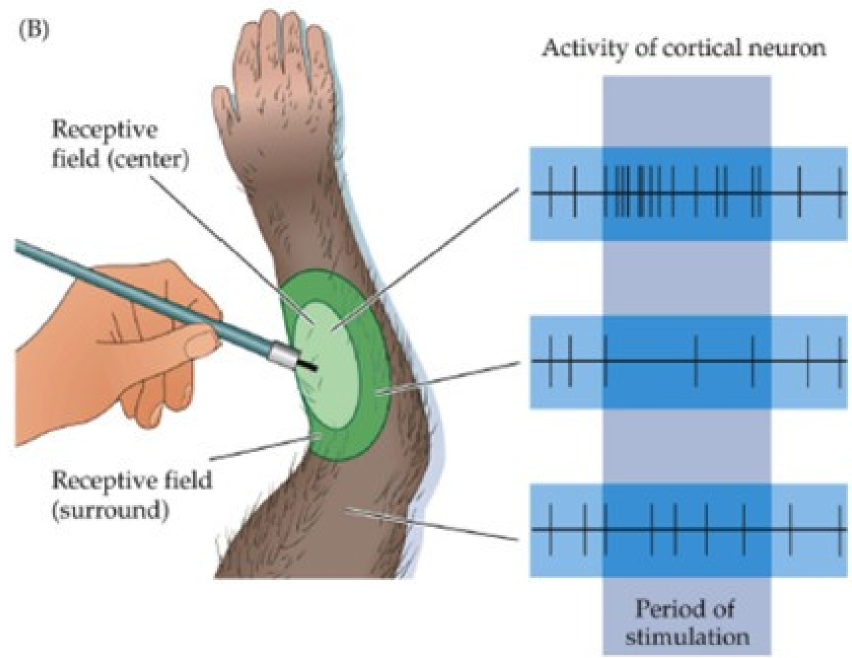


Receptive fields in other modalities

auditory receptive field



somato-sensory receptive field

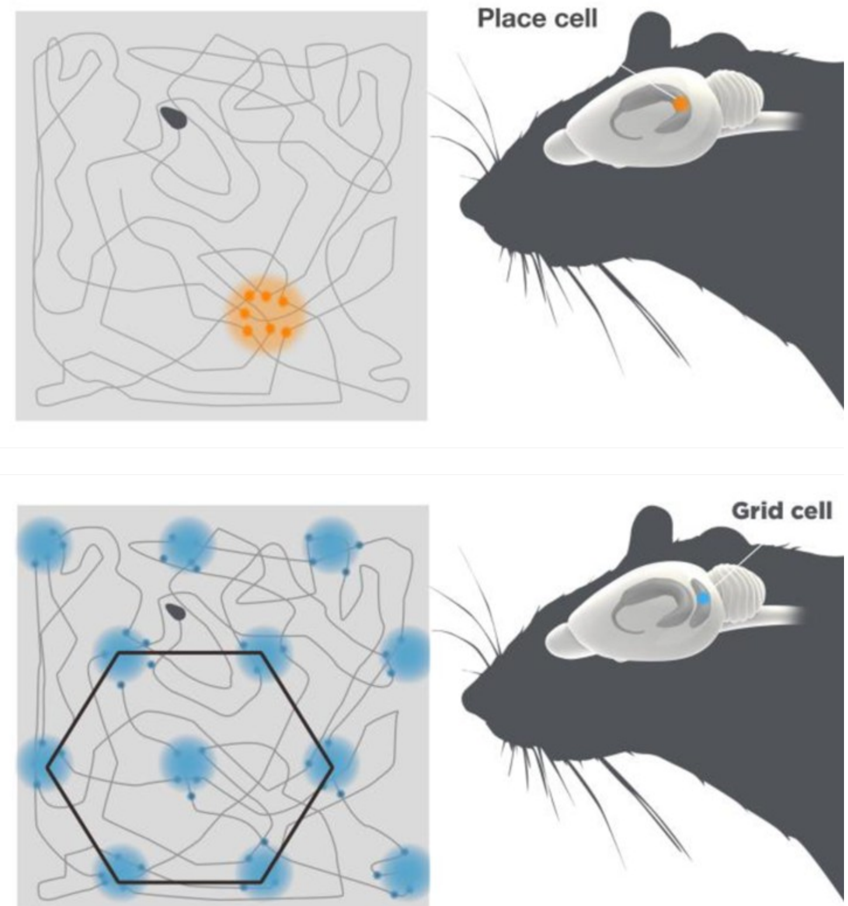


NEUROSCIENCE, Fourth Edition, Figure 1.13 (Part 2)

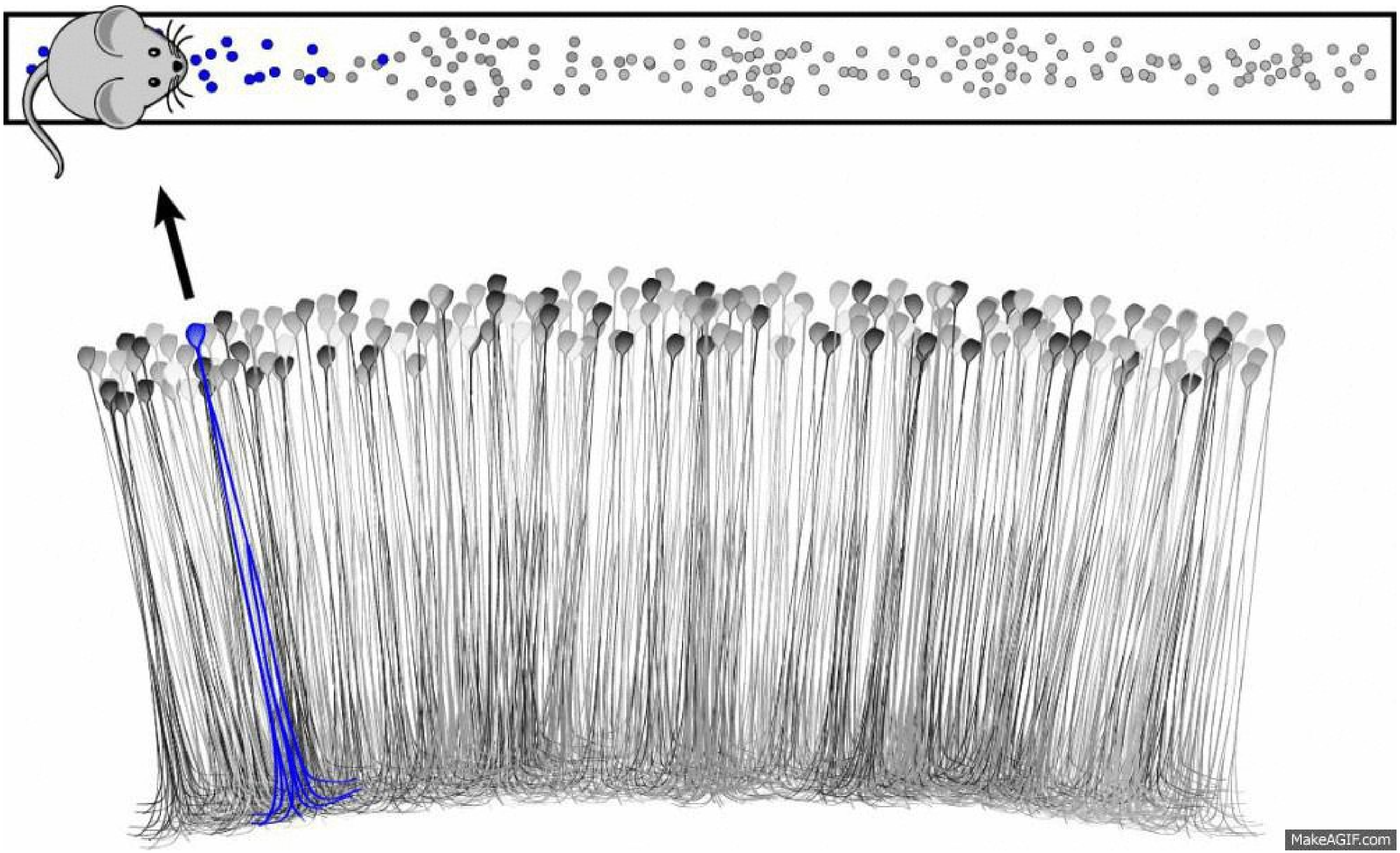
Neurons from different sensory modalities also respond to restricted ranges of the respective input space - i.e. have receptive fields.

Place/grid cells

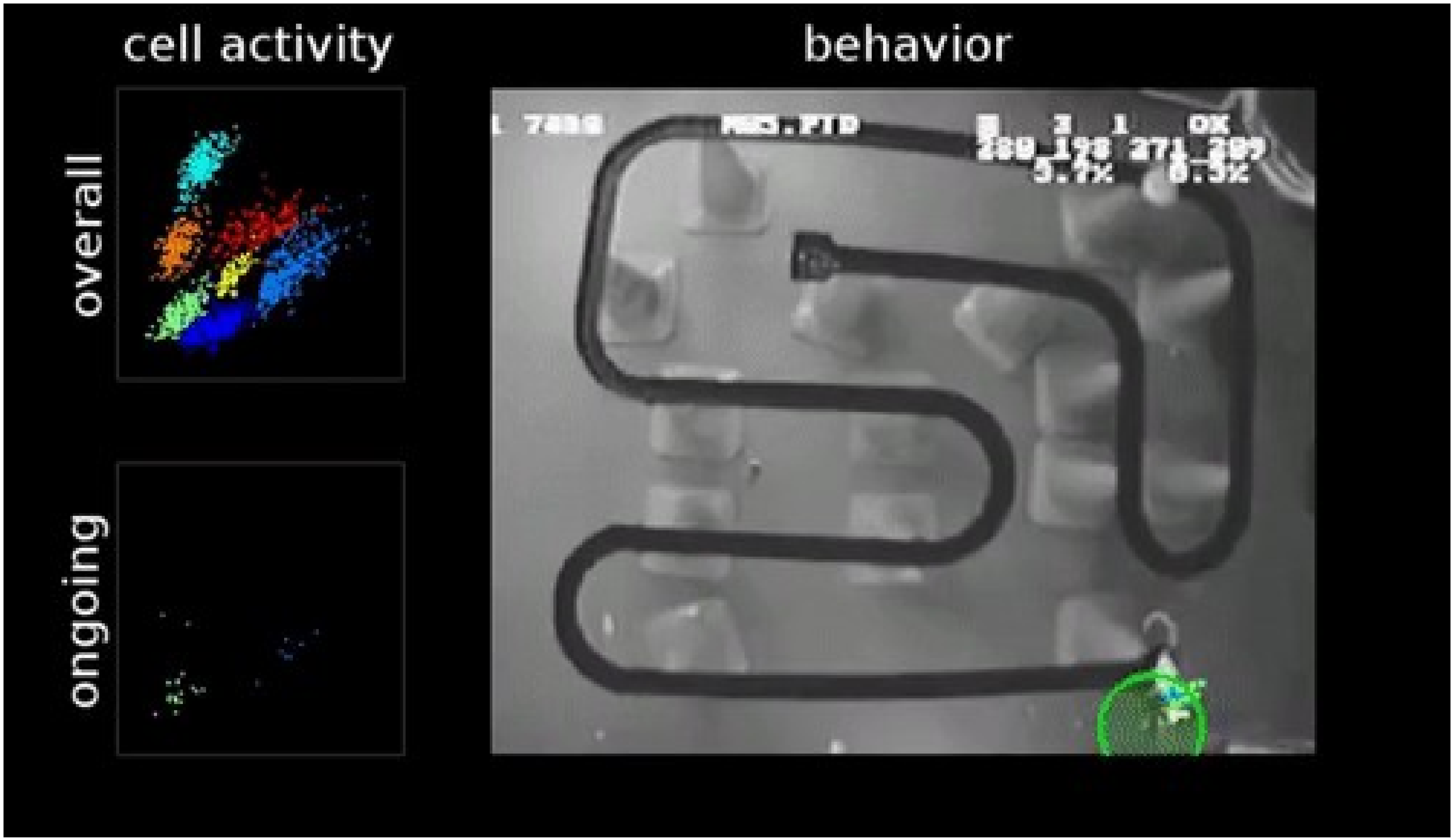
- Localized coding of the representation is not restricted only to sensory systems.
- Hippocampus and entorhinal cortex (EC) are centers of representation of physical space and navigation
- Hyppocmpus – place cells
- EC – grid cells



Place cells



Example of experiment



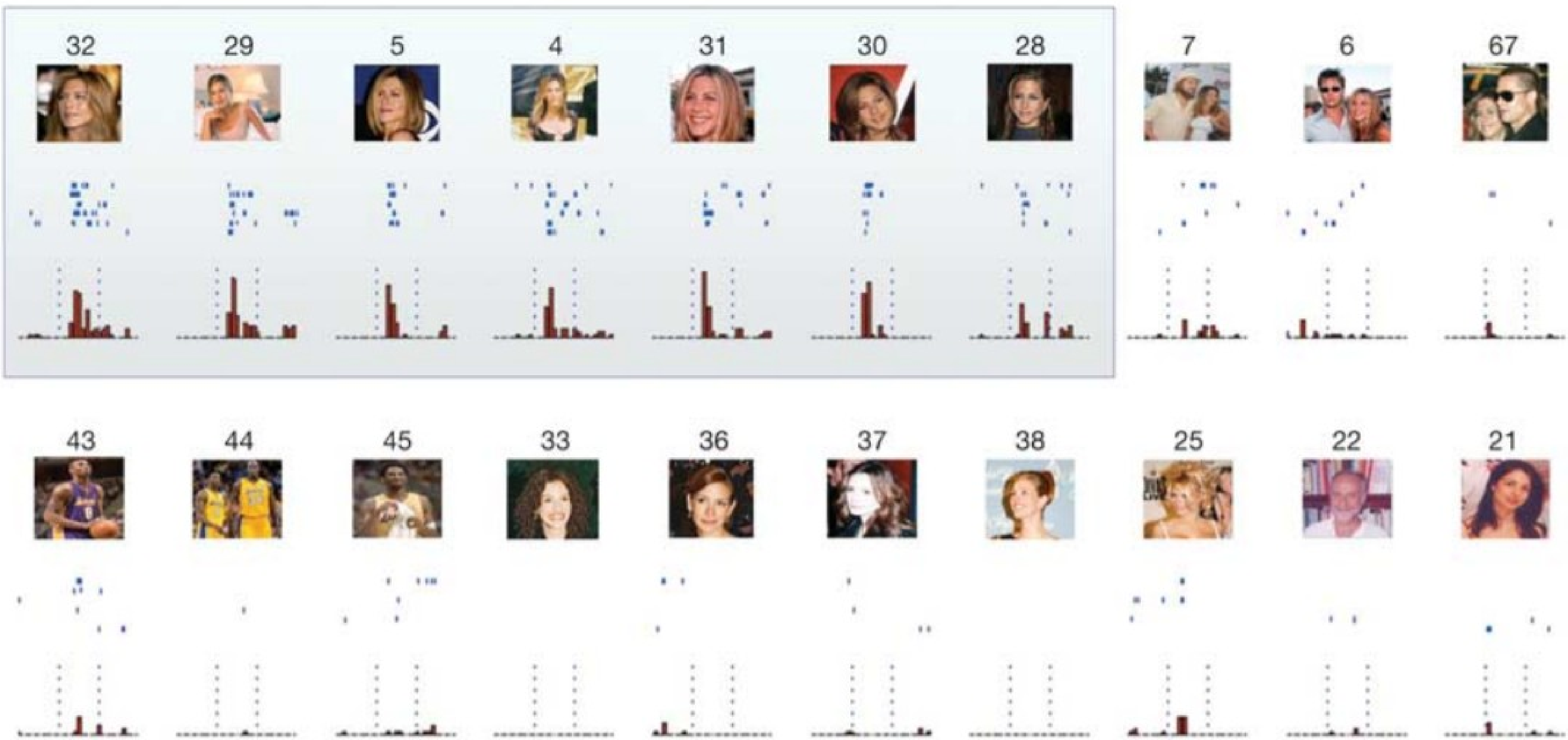
POPULATION CODE

Population coding

- Let us have feature F: how is it coded by a neural vector R?
- Local representation: <0, 0, .., 0, r_i, 0, .. 0>
  - “grandma” neuron, cardinal cells, ...

Jennifer Aniston Neuron

- Record from a cell in Inferior Temporal Cortex
- Present thousands of images of objects
- Order the images by the magnitude of the neurons' response:



What are the advantages/disadvantages of local representation

Population coding

- Let us have feature F: how is it coded by a neural vector R?
- Local representation: $<0, 0, .., 0, r_i, 0, .. 0>$
  - "grandma" neuron, cardinal cells, ...
- Fully distributed: $<r_1, r_2, .. r_n>$

What are the advantages/disadvantages of distributed coding

?

Population coding

- Let us have feature F: how is it coded by a neural vector R?
- Local representation: $<0, 0, .., 0, r_i, 0, .. 0>$
  - "grandma" neuron, cardinal cells, ...
- Fully distributed: $<r_1, r_2, .. r_n>$
- Sparsely distributed: $<0, 0, r_i, 0, 0, 0, r_j, 0, .. 0, r_k, 0, .. 0>$
  - Examples:
    - Highly selective tuning curves
    - Receptive fields
  - The neural selectivities have to span full range of possibilities

Decoding: population code

- Reasons
  - robustnest
    - cellular death
    - noise
  - precission
- Decoding

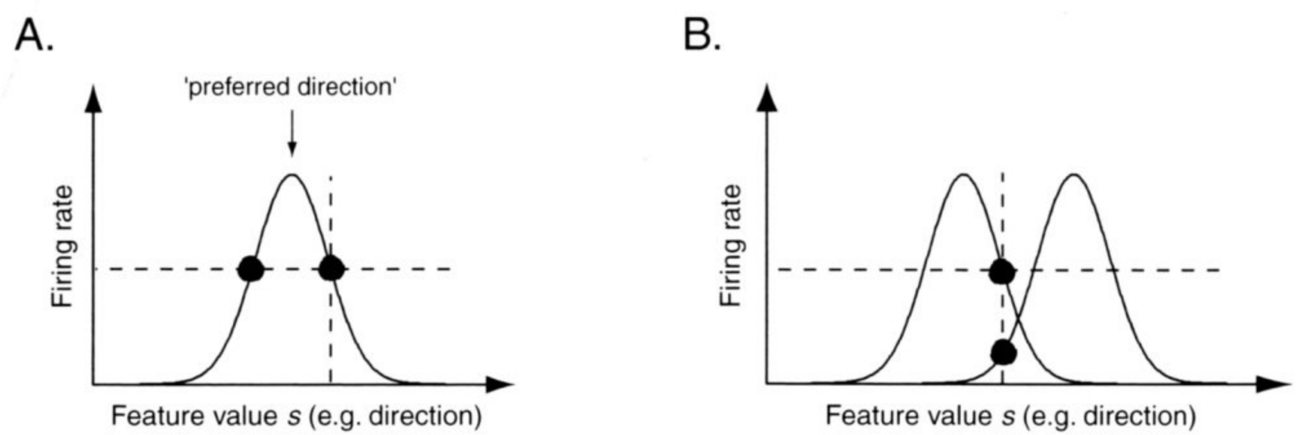
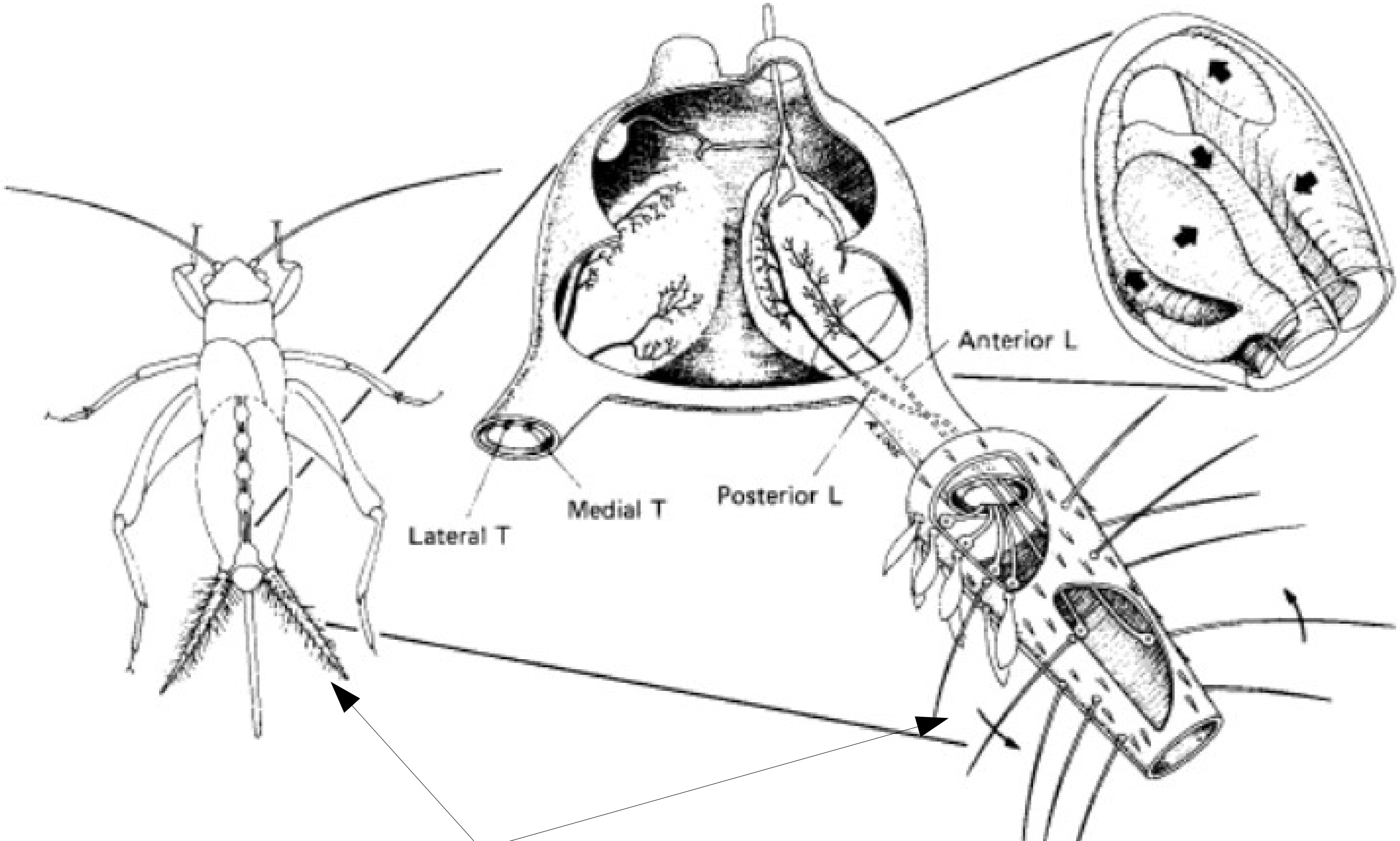


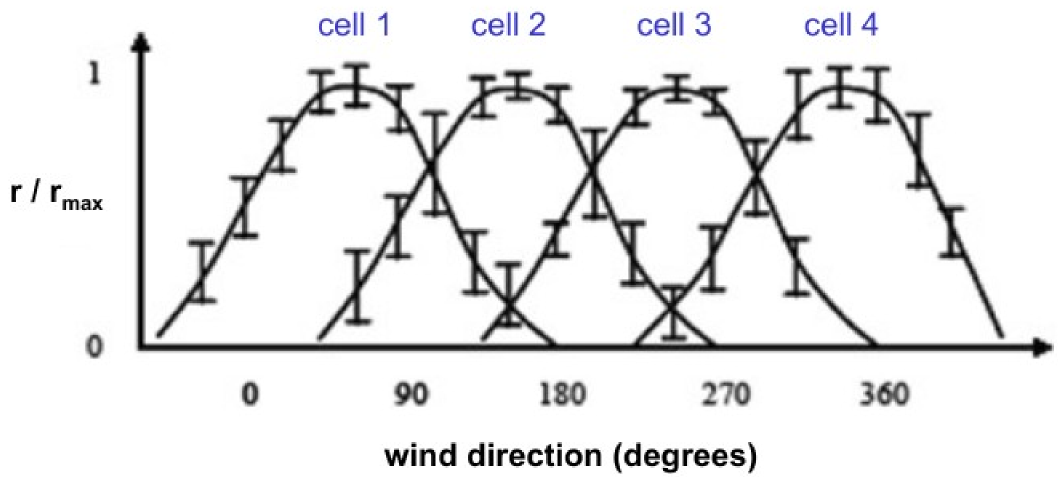
Fig. 5.13 Gaussian tuning curves representing the firing rate of a neuron as a function of a stimulus feature. (A) A single neuron cannot unambiguously decode the stimulus feature from the firing rate. (B) A second neuron with shifted tuning curve can resolve the ambiguity.

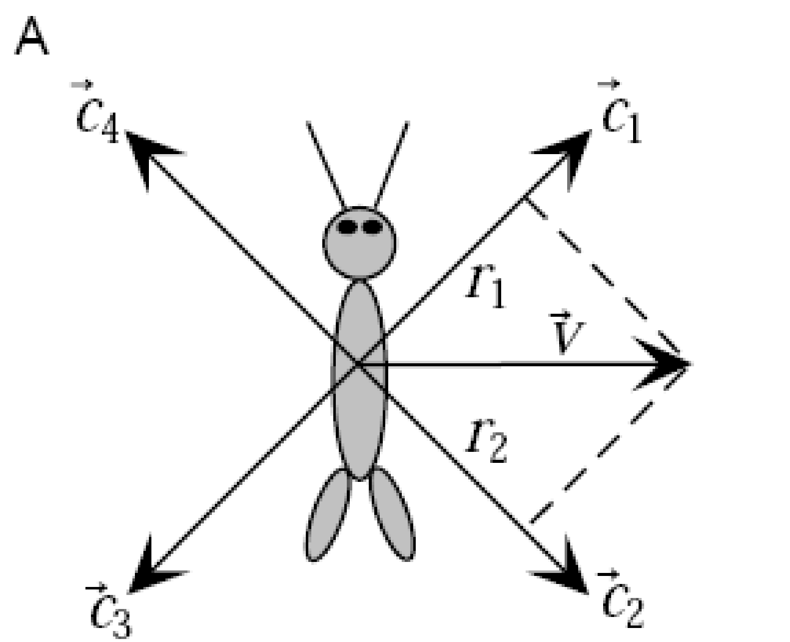
Population coding: CRICKET



Crickets have two appendages ‘cerci‘, that are covered with hair that are deflected by the air, reporting wind’s direction. All interneurons in cricket’s neural system respond to limited range of wind directions. This means interneurons encode wind direction as a population.

Population coding: CRICKET



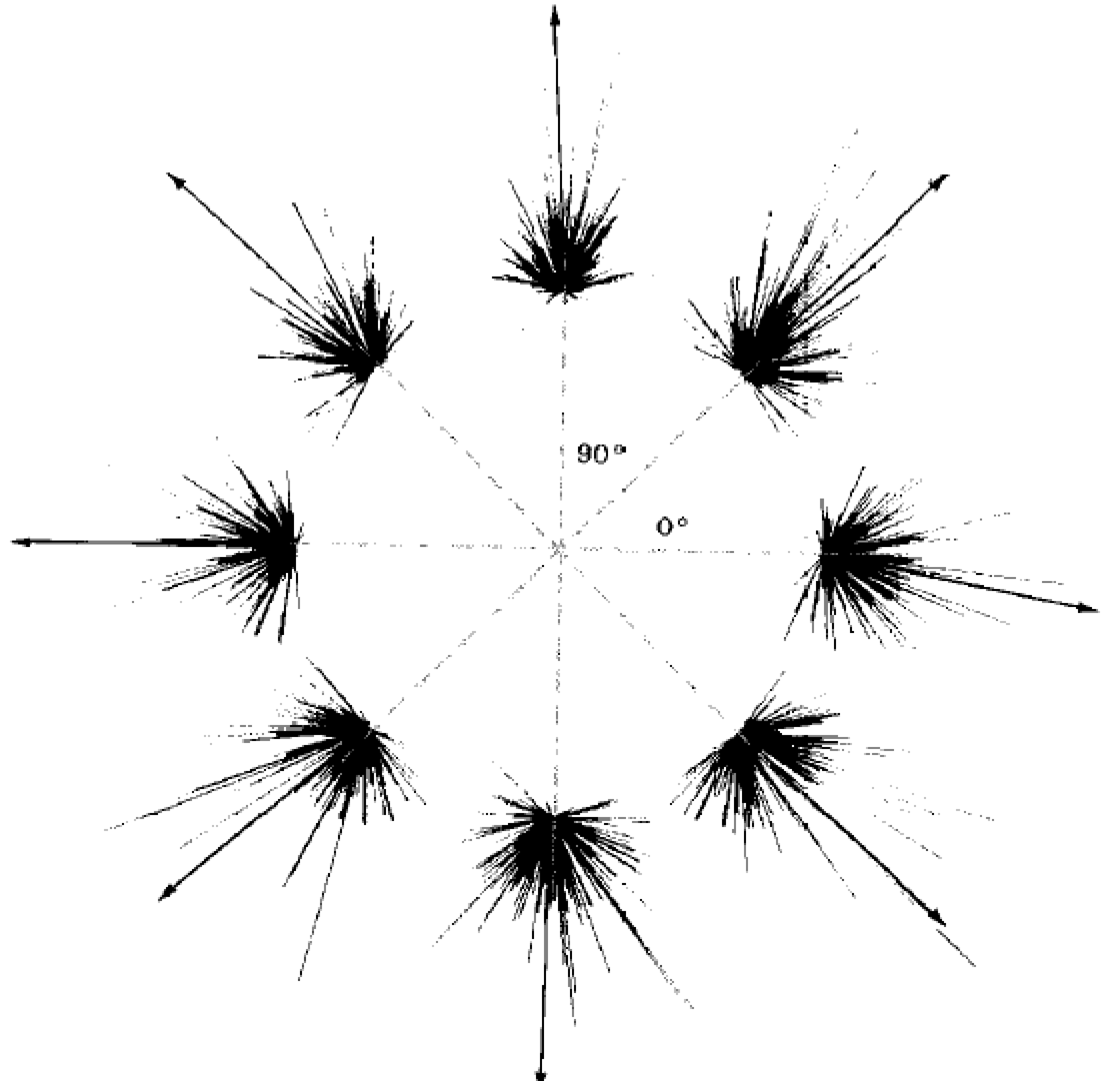


Crickets have many more than 4 direction sensitive neurons.

Why?

Population coding: monkey motor cortex

- Hand direction



Population coding – cortical functional organization

- One neuron often codes multiple features
- More neurons code more "dense" space
  - e.g., why do we recognize more easily human faces vs. dog faces
  - Kohonen network metaphor

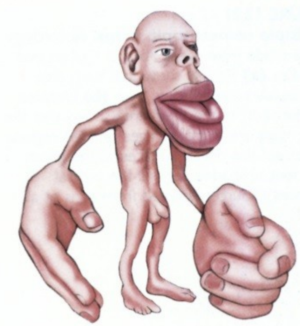


FIGURE 12.19
The homunculus.

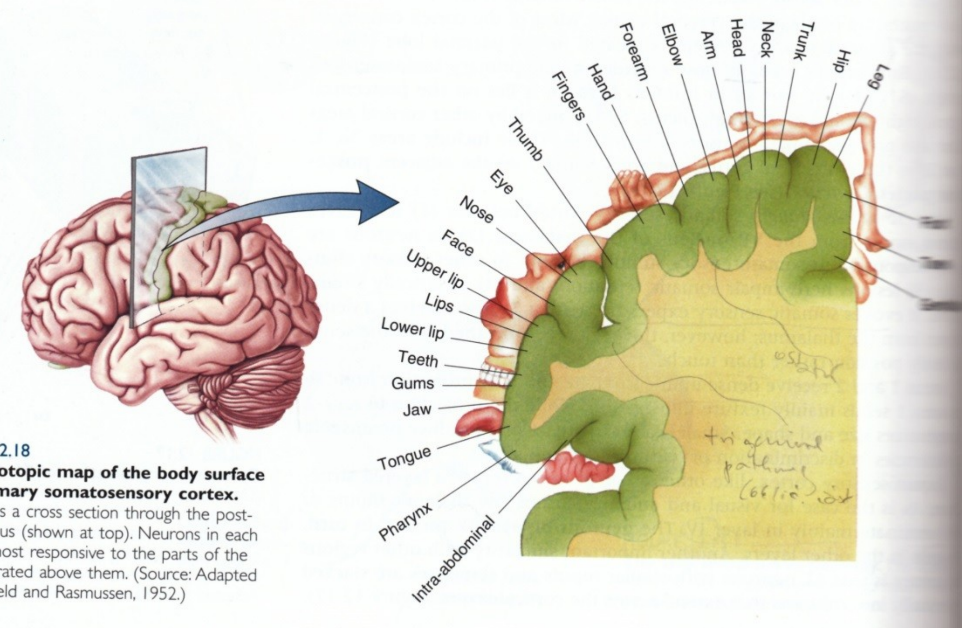
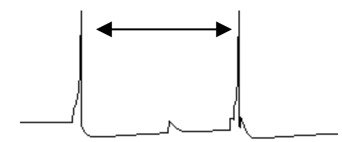


FIGURE 12.18
A somatotopic map of the body surface onto primary somatosensory cortex. This map is a cross section through the post-central gyrus (shown at top). Neurons in each area are most responsive to the parts of the body illustrated above them. (Source: Adapted from Penfield and Rasmussen, 1952.)

TEMPORAL CODING

Information coding

- Temporal distance between spikes
- Synchronization?
- The beginning of a spike pattern?
- …



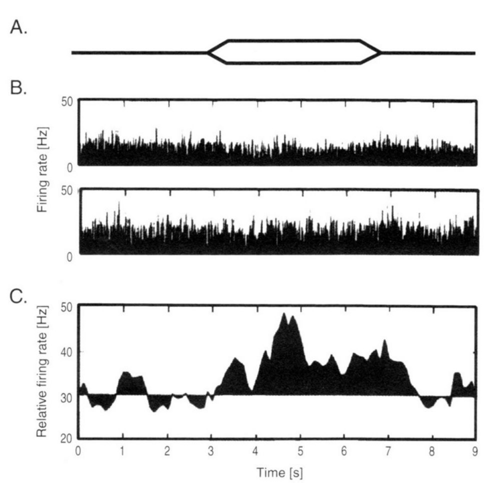


Fig. 5.3 An example of the response of some neurons in the primary auditory cortex that do not show significant variations in response to the onset of a 4 kHz tone with the amplitude envelope shown in (A). (B) Average firing rates in 5 ms bins of two different neurons. (C) Spike-triggered average rate that indicates some correlation between the firing of the two neurons that is significantly correlated to the presentation of the stimulus [from DeCharms and Merzenich, *Science* 381: 610–13 (1996)].

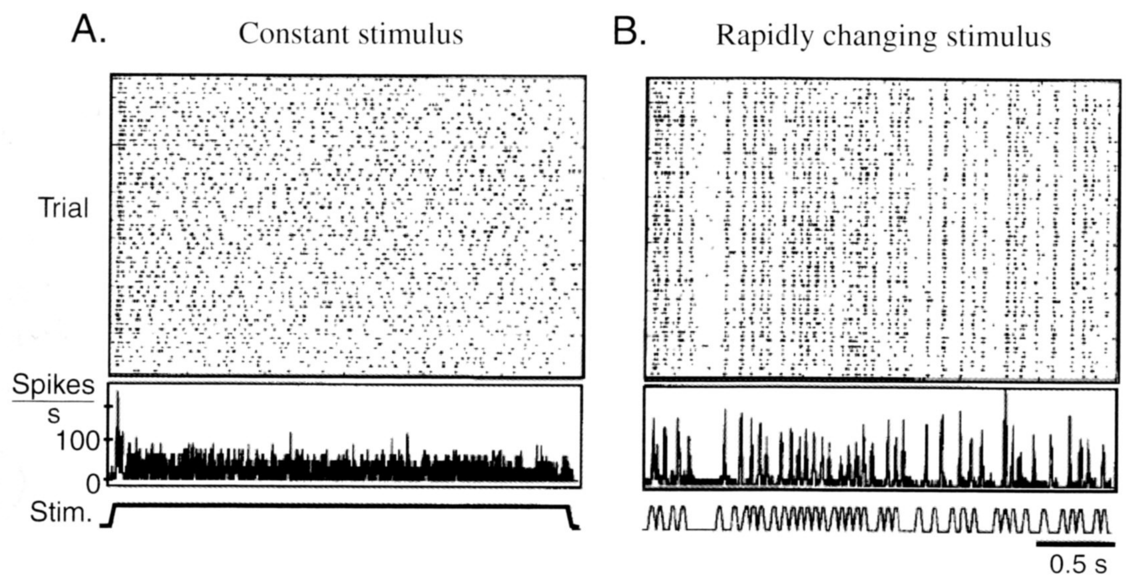
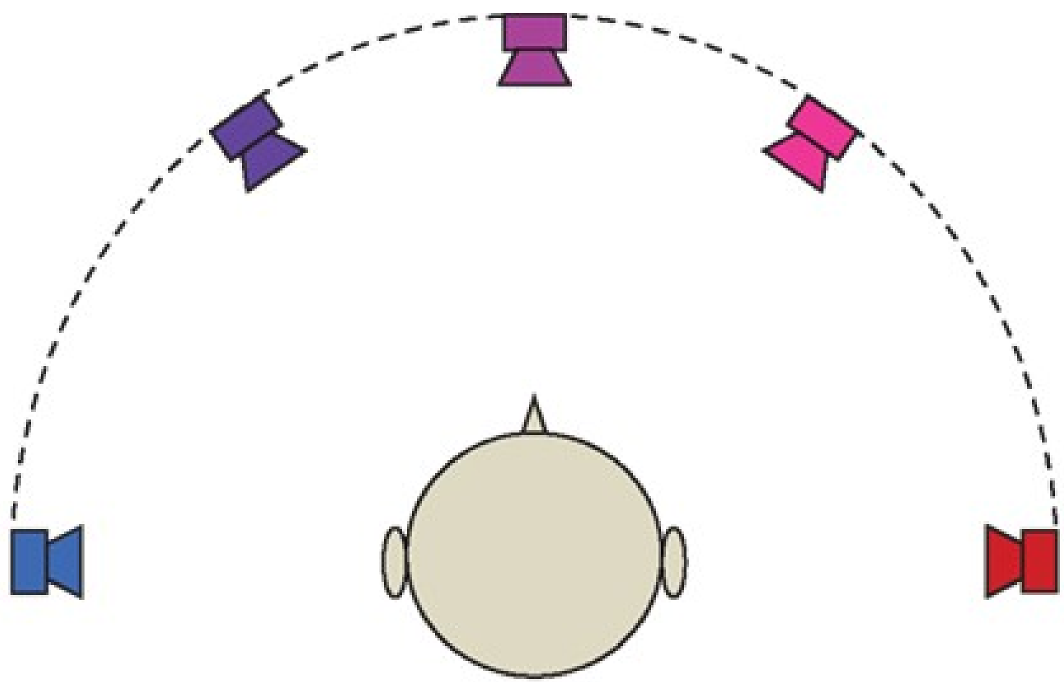


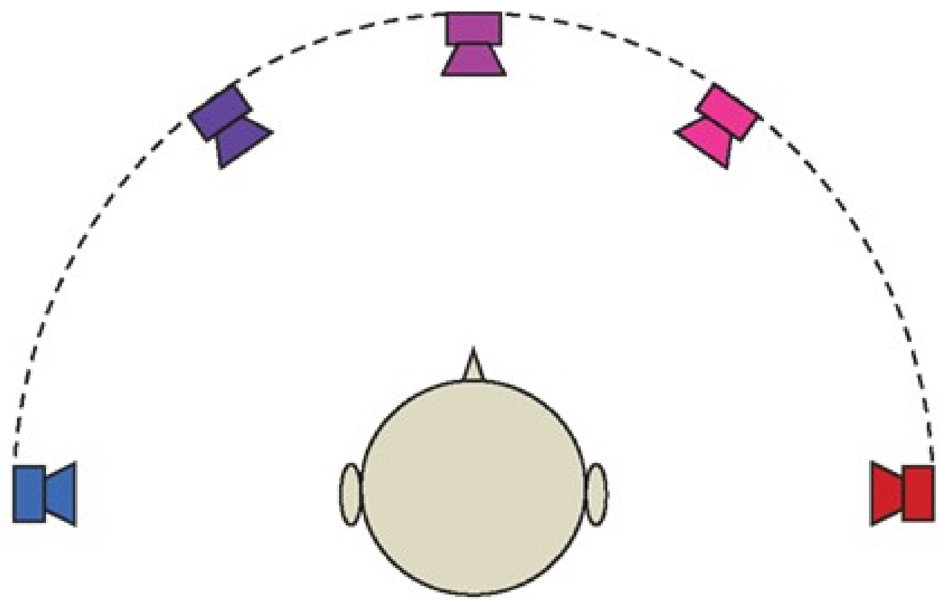
Fig. 5.5 Spike trains (top) and average response over trials (middle) of an MT neuron to a visual stimulus with either constant velocity (A) or altering velocity (B) as indicated in the bottom graph [adapted from Buračas *et al.*, *Neuron* 20: 959–69 (1998)].

Sound localization

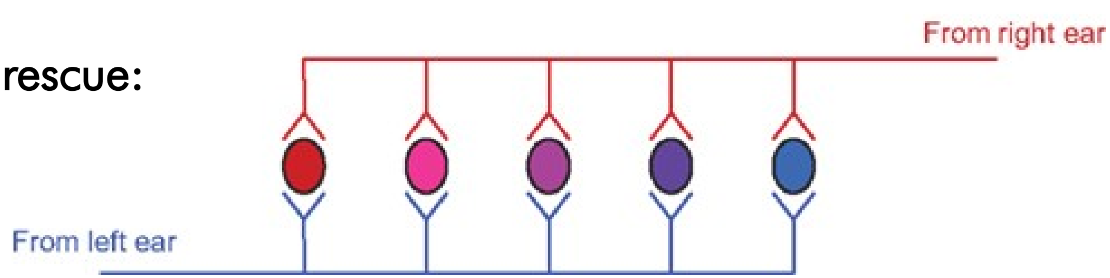
Sound takes different amount of time to arrive to the two different ears depending on the position of the sound source – inter aural delays. We an use this information to perform sound localization.



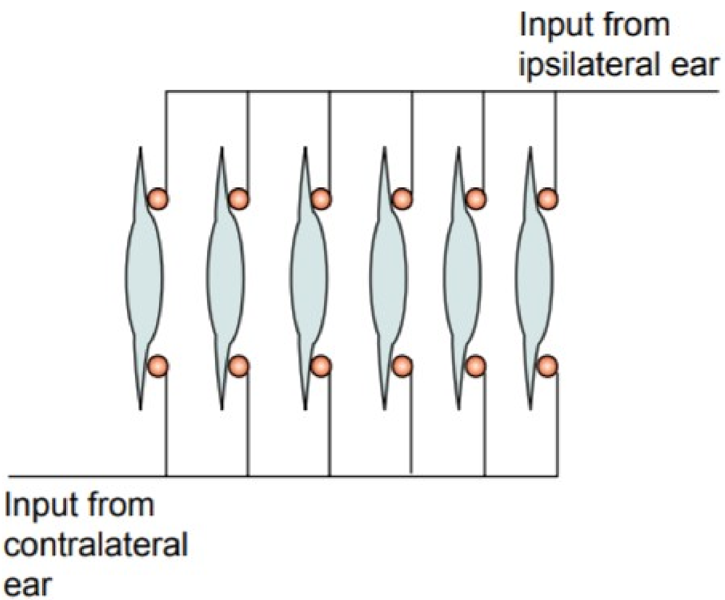
But how to implement this in neural substrate?

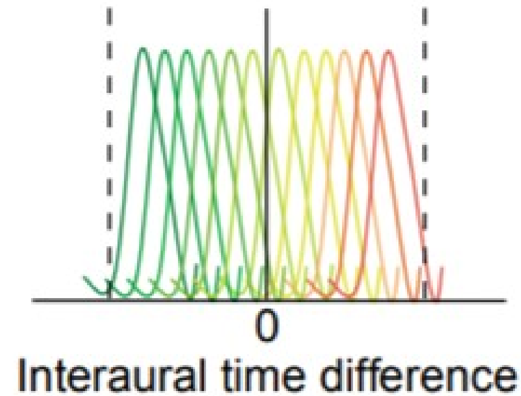


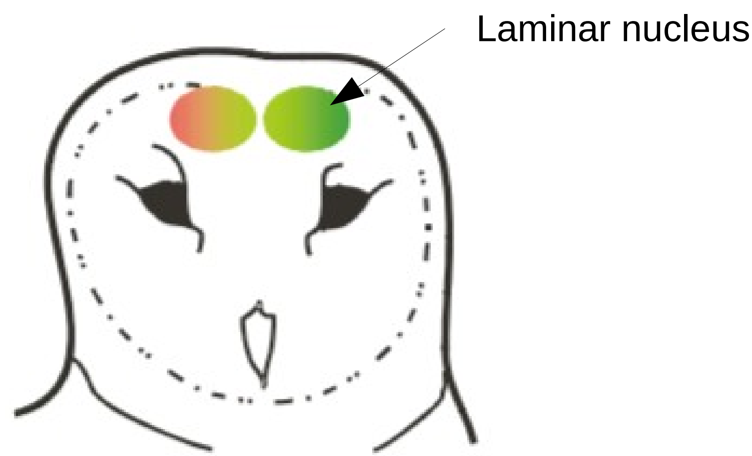
Delay lines to the rescue:



Delay lines in birds







- Delay-lines were identified in birds
- In laminar nucleus
- Systematic mapping of inter-aural delays along cortical surface
- The mapping is consistent with logic of delay-lines.
- Bio-physics of these neurons optimized for coincidence detection.