Background: Neural constraints

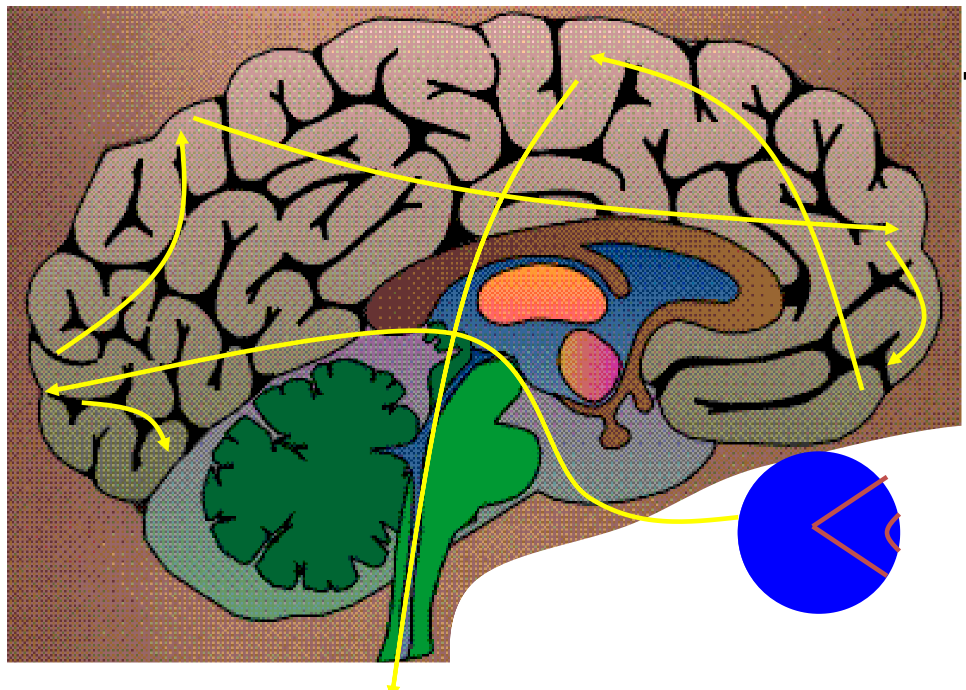
Gregor Schöner
dynamicfieldtheory.org

the brain

motor
cortex

frontal
cortex

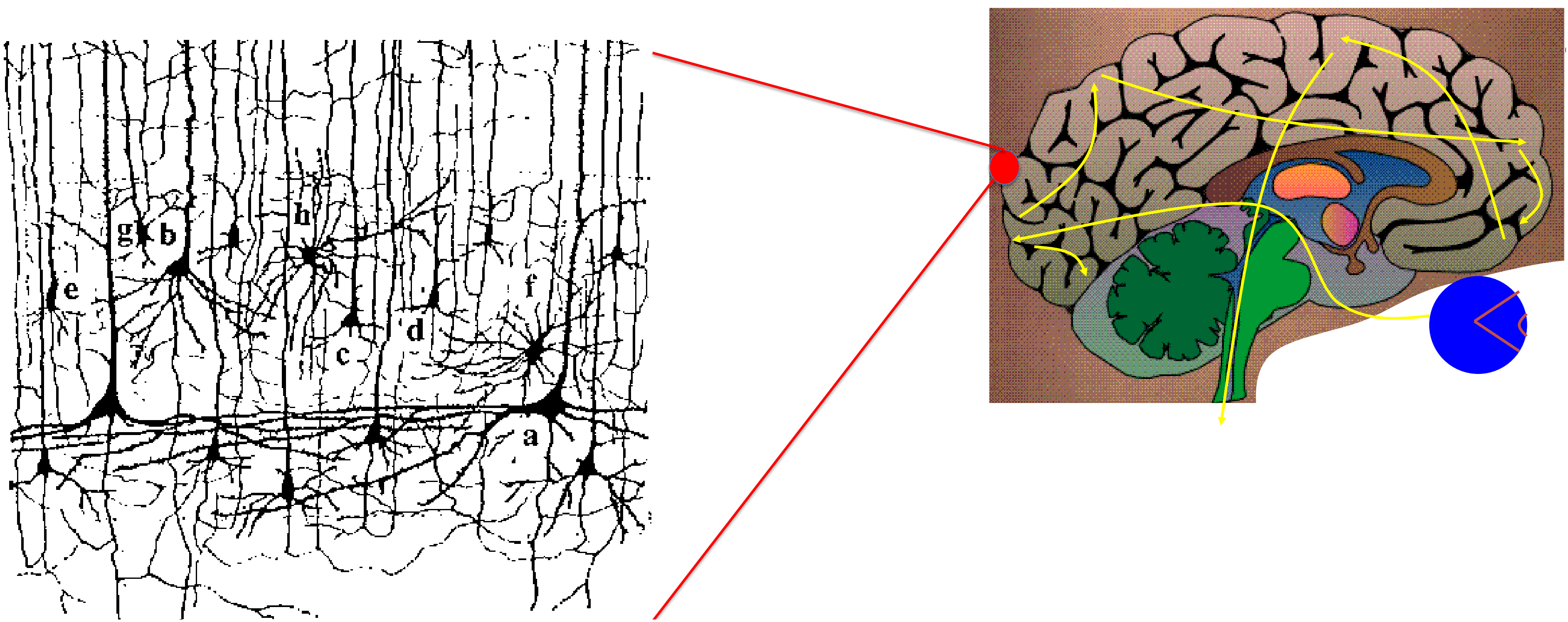
visual
cortex



to motor
output

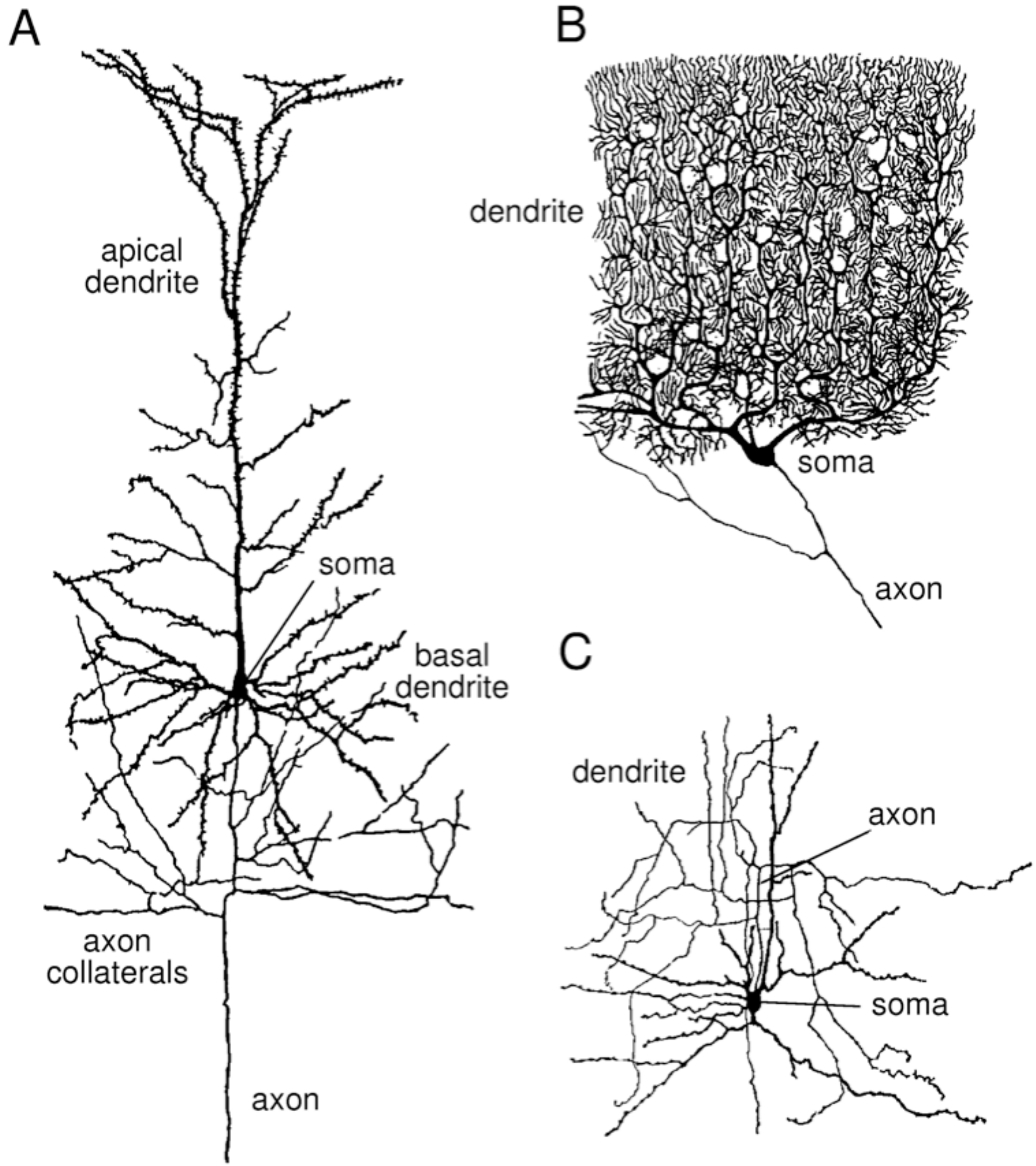
[from: Tresilian: Sensorimotor Control and Learning: An introduction to the behavioral neuroscience of action 2012]

neurons



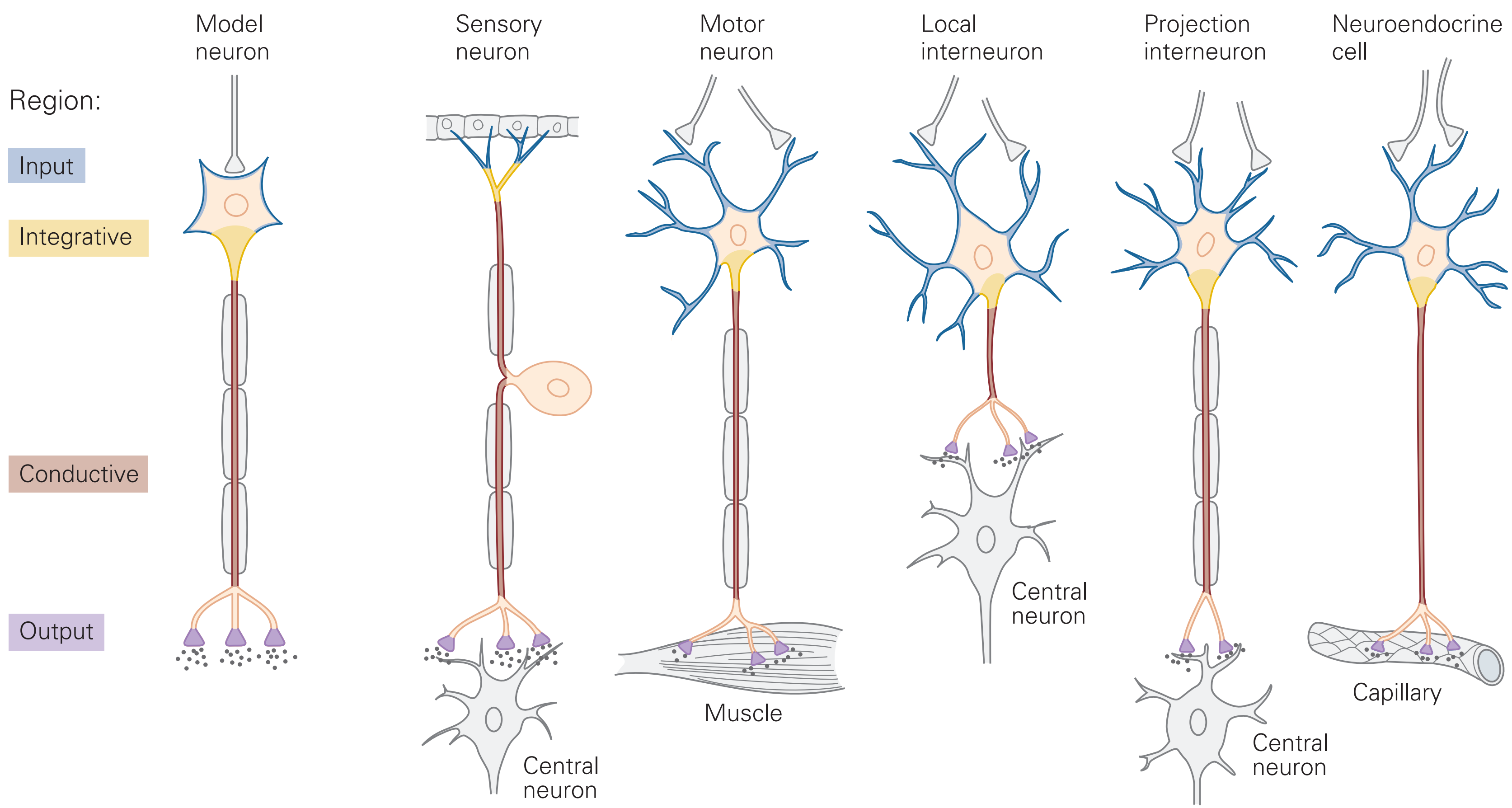
~10^11 with 10000 synapses each

neurons


A
apical
dendrite
soma
basal
dendrite
axon
collaterals
axon
B
dendrite
soma
axon
C
dendrite
axon
soma

neurons

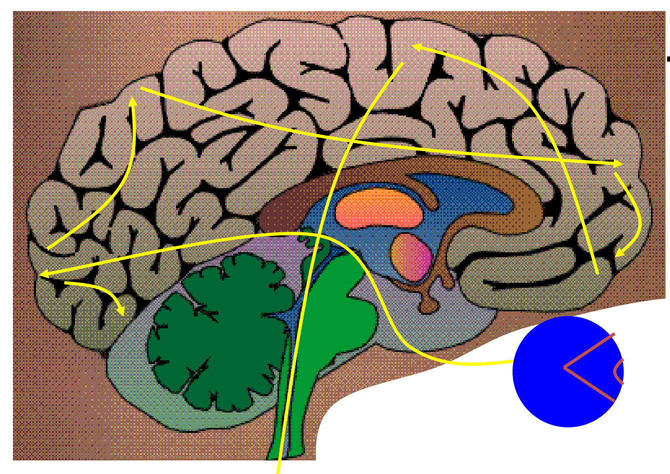
- four components of neurons



Functional analysis of the brain

- vary conditions “outside” the brain: stimulus, motor task, cognitive task and relate to neural activity: coding/ decoding, cognitive neuroscience

- or the reverse: vary neural substrate (lesioning, optogenetics, etc) and observe what happens to behavior/ competence: neuropsychology



[Tresilian, 2012]

Roadmap

Background: Neural constraints

- Neurophysics
- Sensors, actuators, rate code
- Receptive fields, tuning curves
- Maps
- Distributions of population representation
- Patterns of connectivity
- Synaptic dynamics

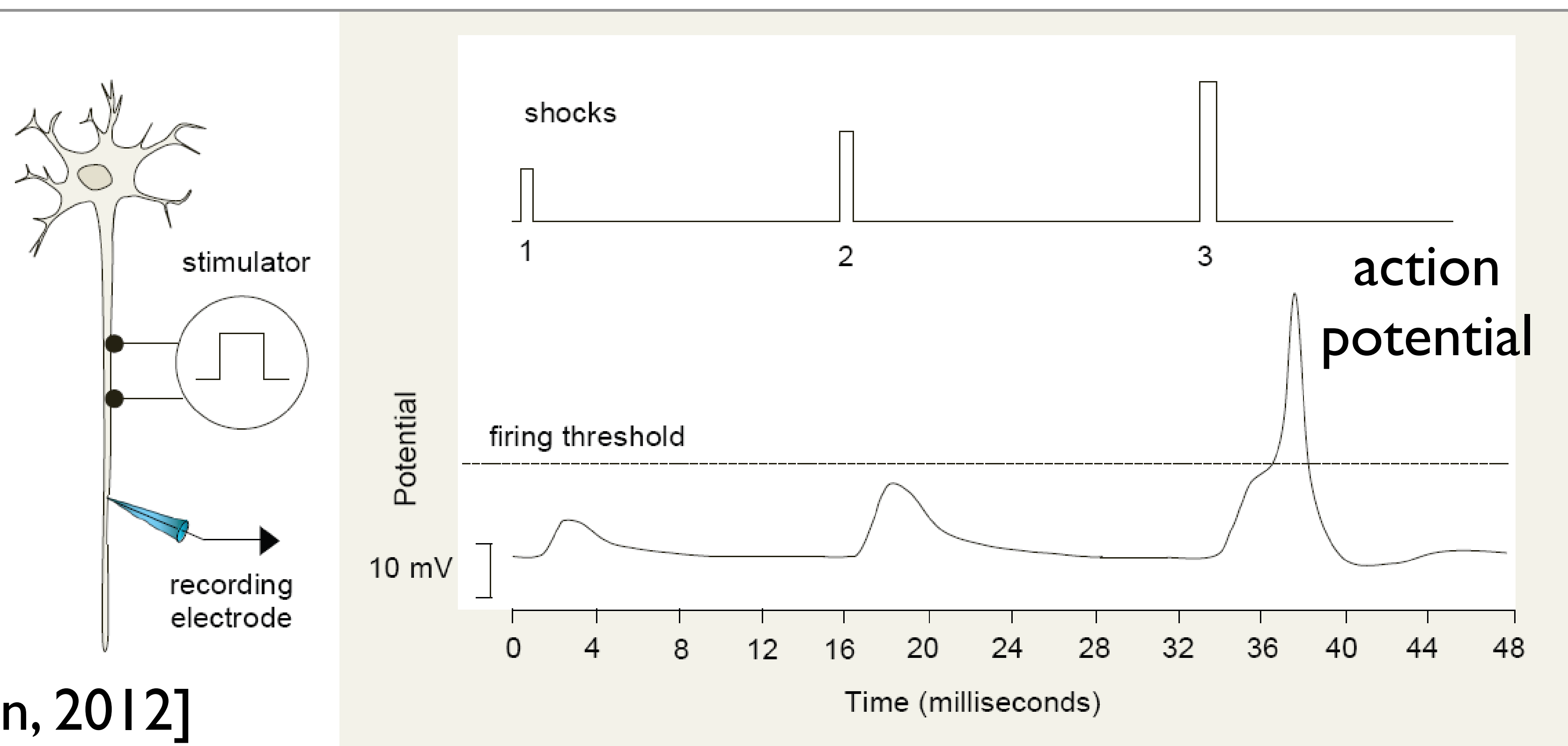
Neuro-physics

- membrane potential, $u(t)$, evolves as a dynamical system

$$\tau \dot{u}(t) = -u(t) + h + \mathrm{input}(t)$$

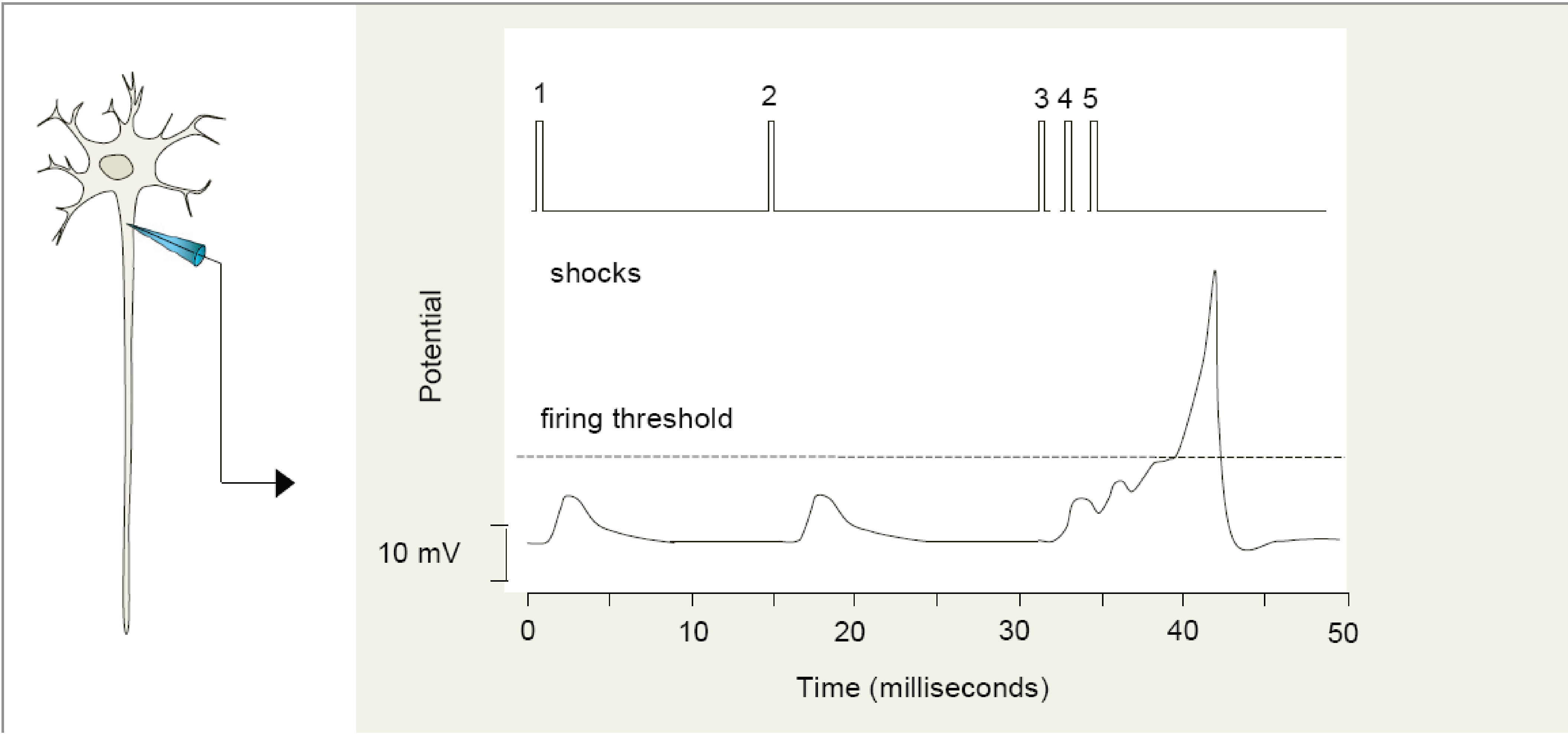
$\tau \approx 10$ ms time scale

- only when membrane potential exceeds a threshold is activation transmitted to downstream neurons



[from: Tresilian, 2012]

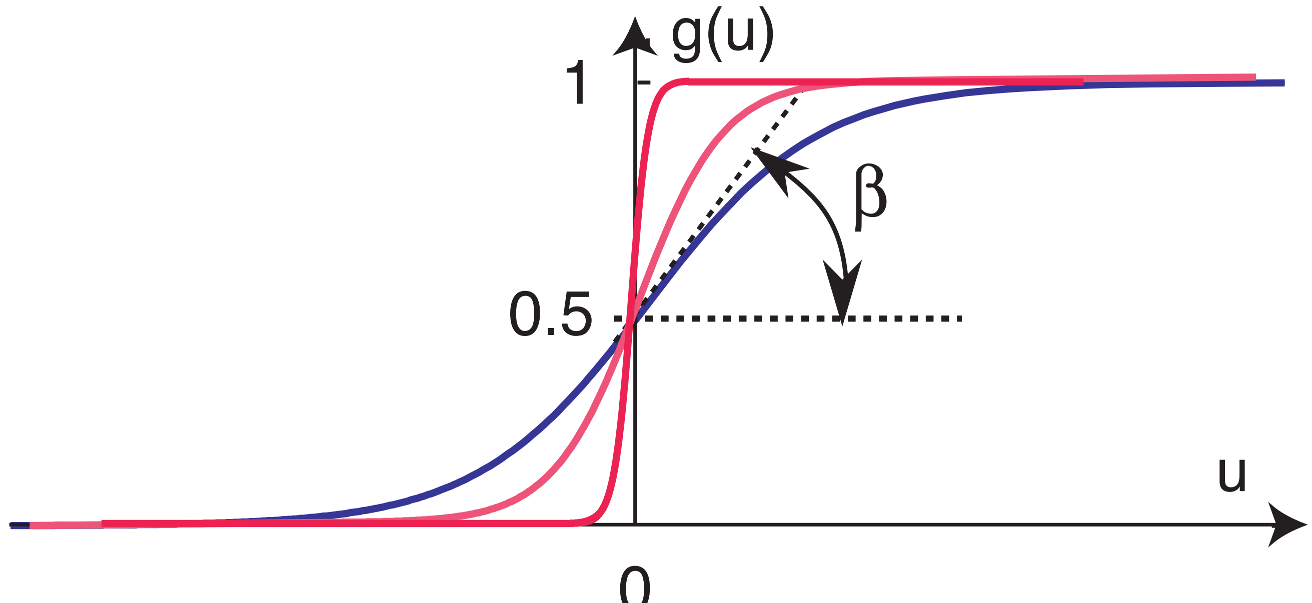
temporal summation



[from: Tresilian, 2012]

Neural dynamics

- replace spiking mechanism by sigmoid:
  - low levels of activation: not transmitted to downstream systems
  - high levels of activation: transmitted to downstream systems
- abstracting from biophysical details ~ population level membrane potential



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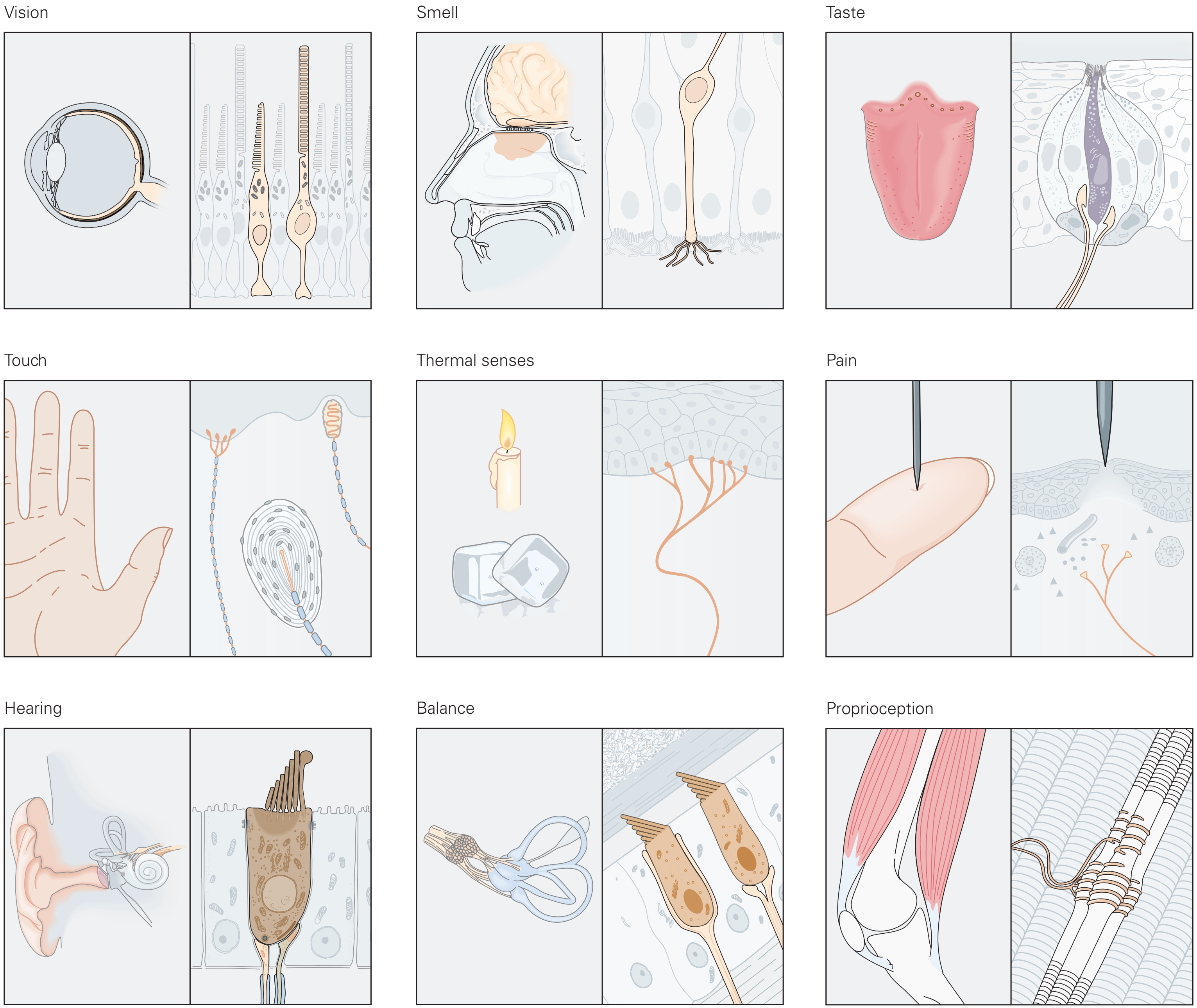
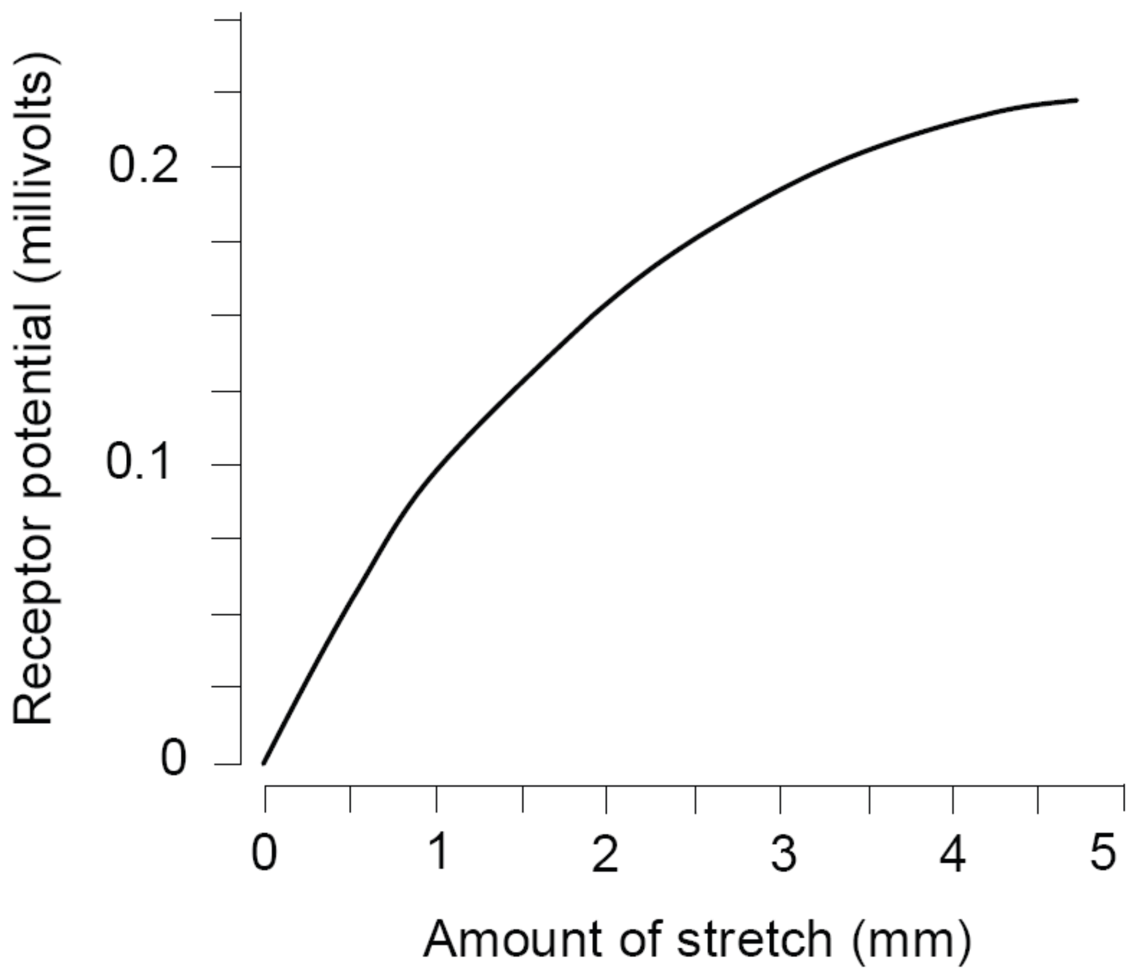
Sensor cells



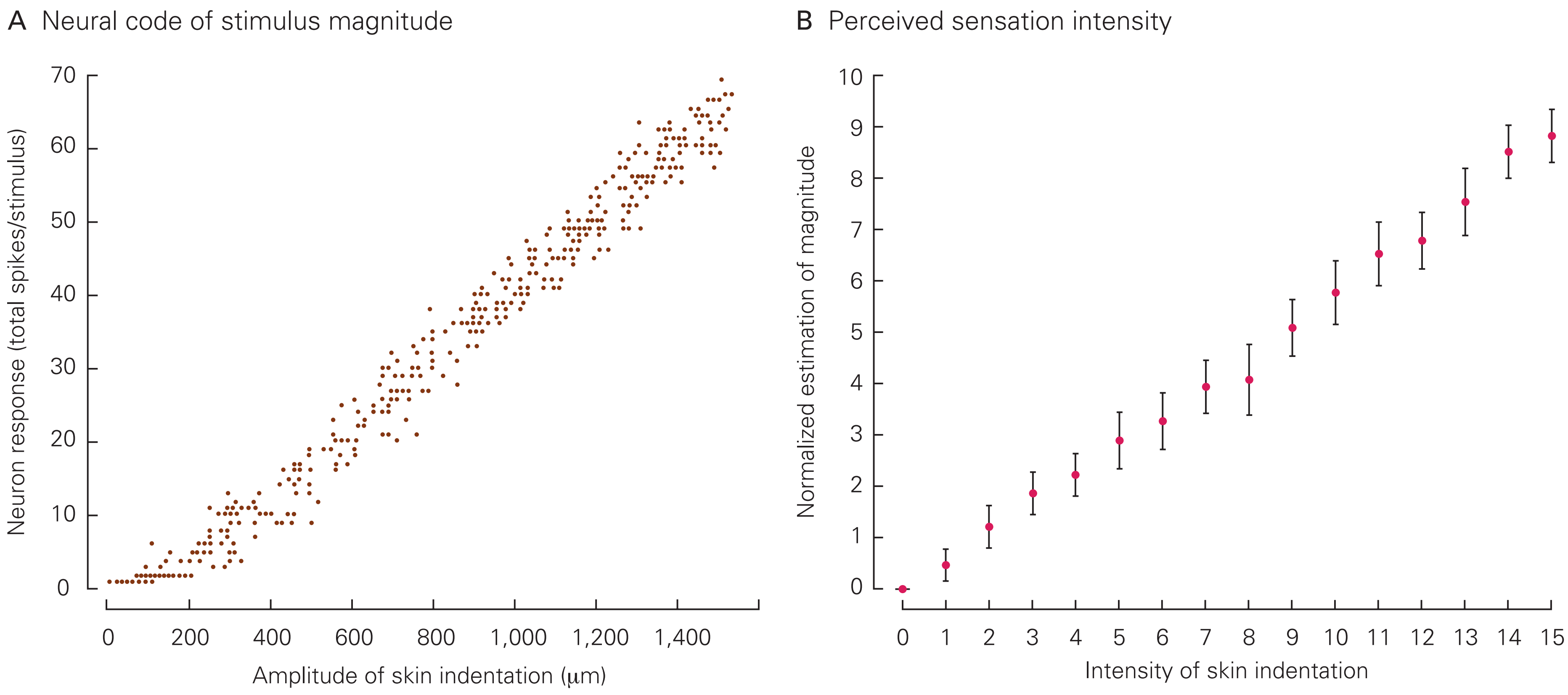
[from: Tresilian, 2012]

Sensor characteristic



[from: Tresilian, 2012]

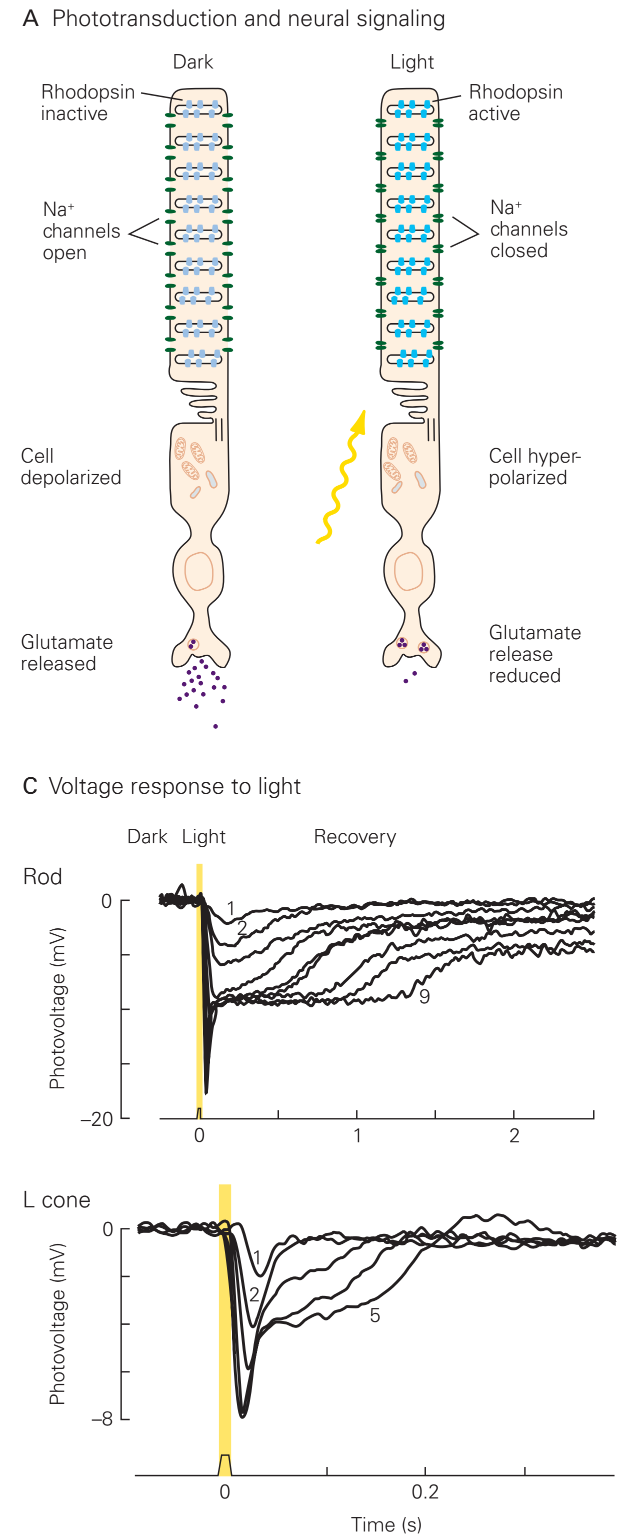
Sensor characteristic



[from: Tresilian, 2012]

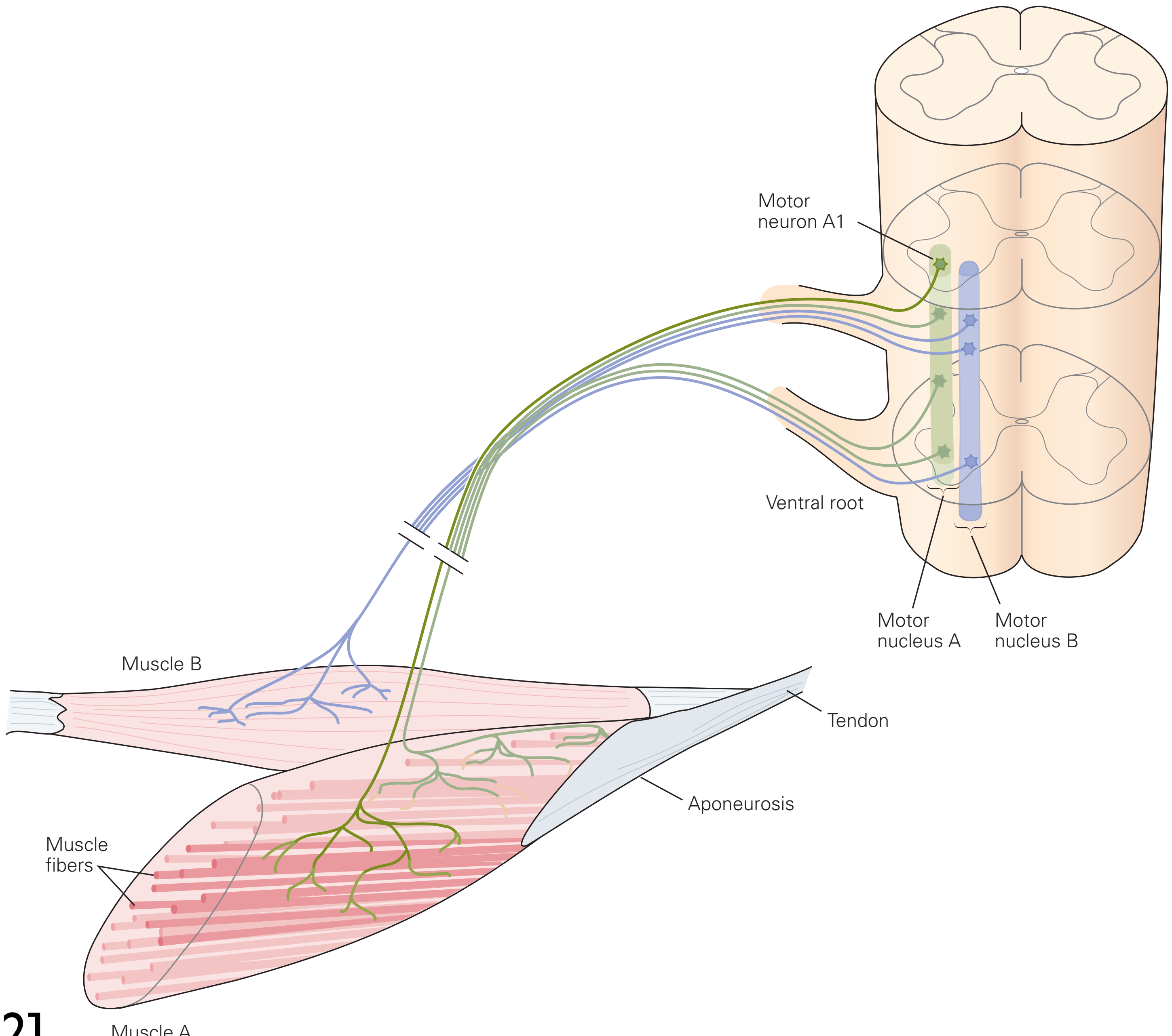
Sensor characteristic

- photoreceptors



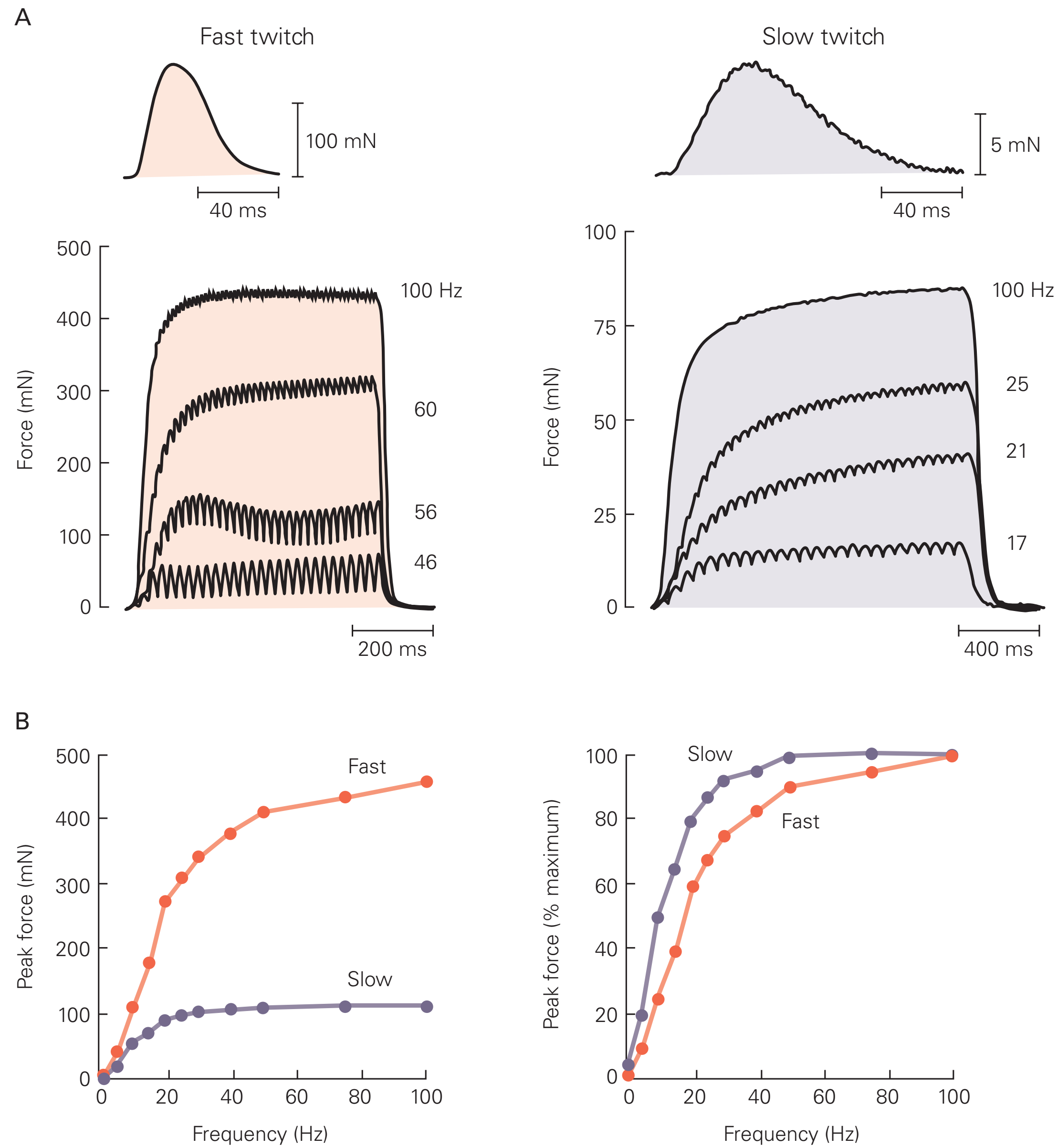
[from: Tresilian, 2012]

Motor neurons



[from: Tresilian, 2012]

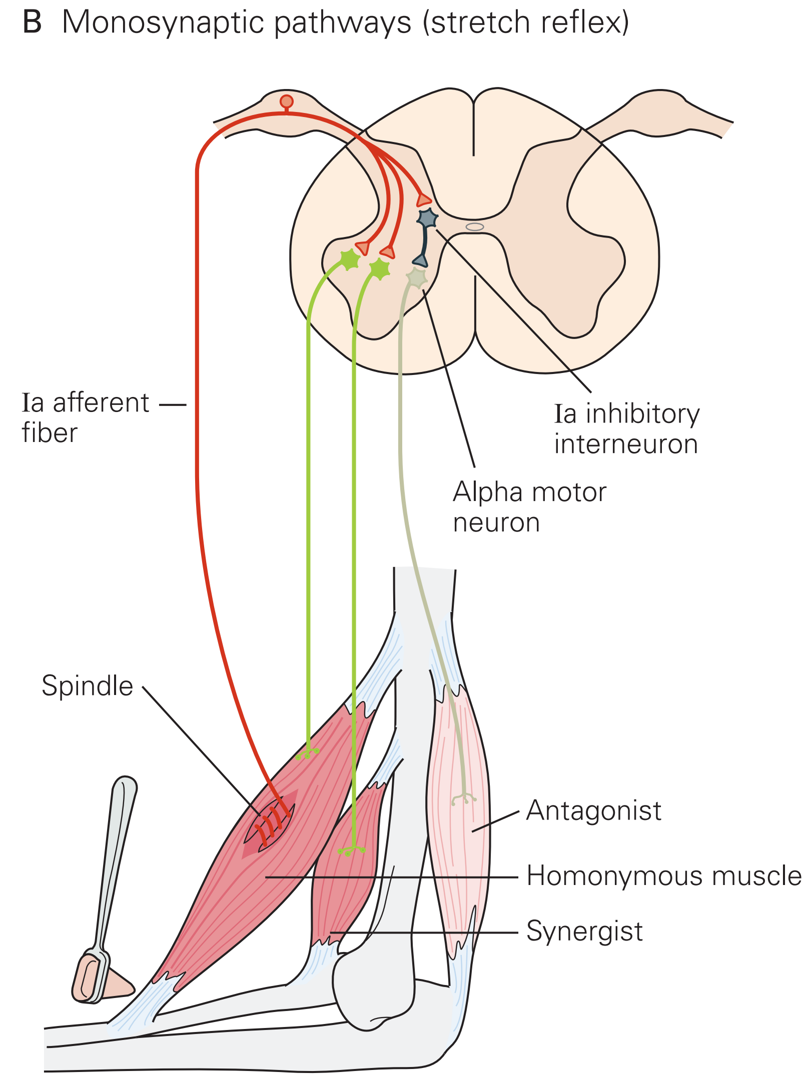
Motor neurons



[from: Tresilian, 2012]

Peripheral neural circuits

- stretch reflex



[from: Tresilian, 2012]

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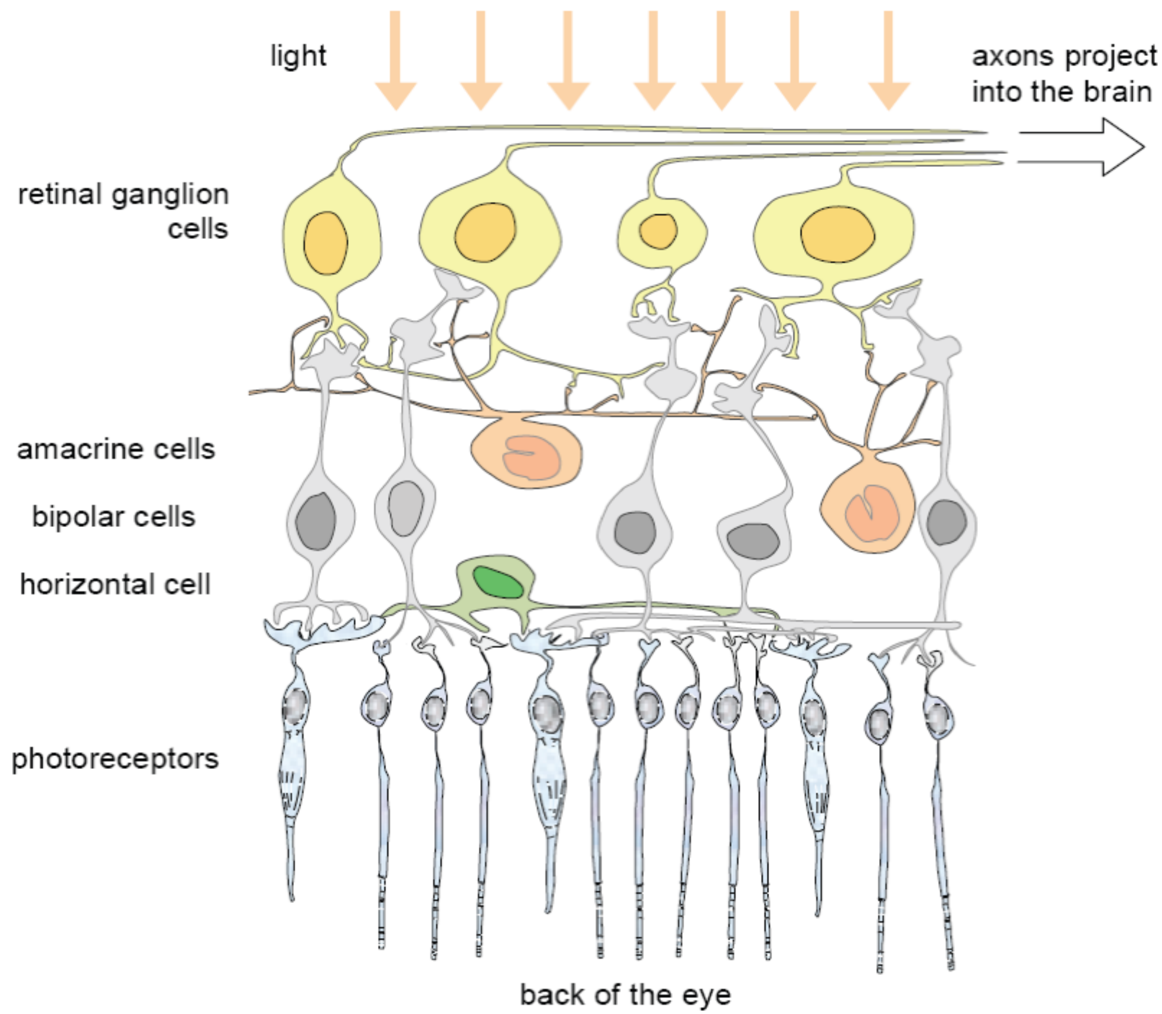
Sensory networks

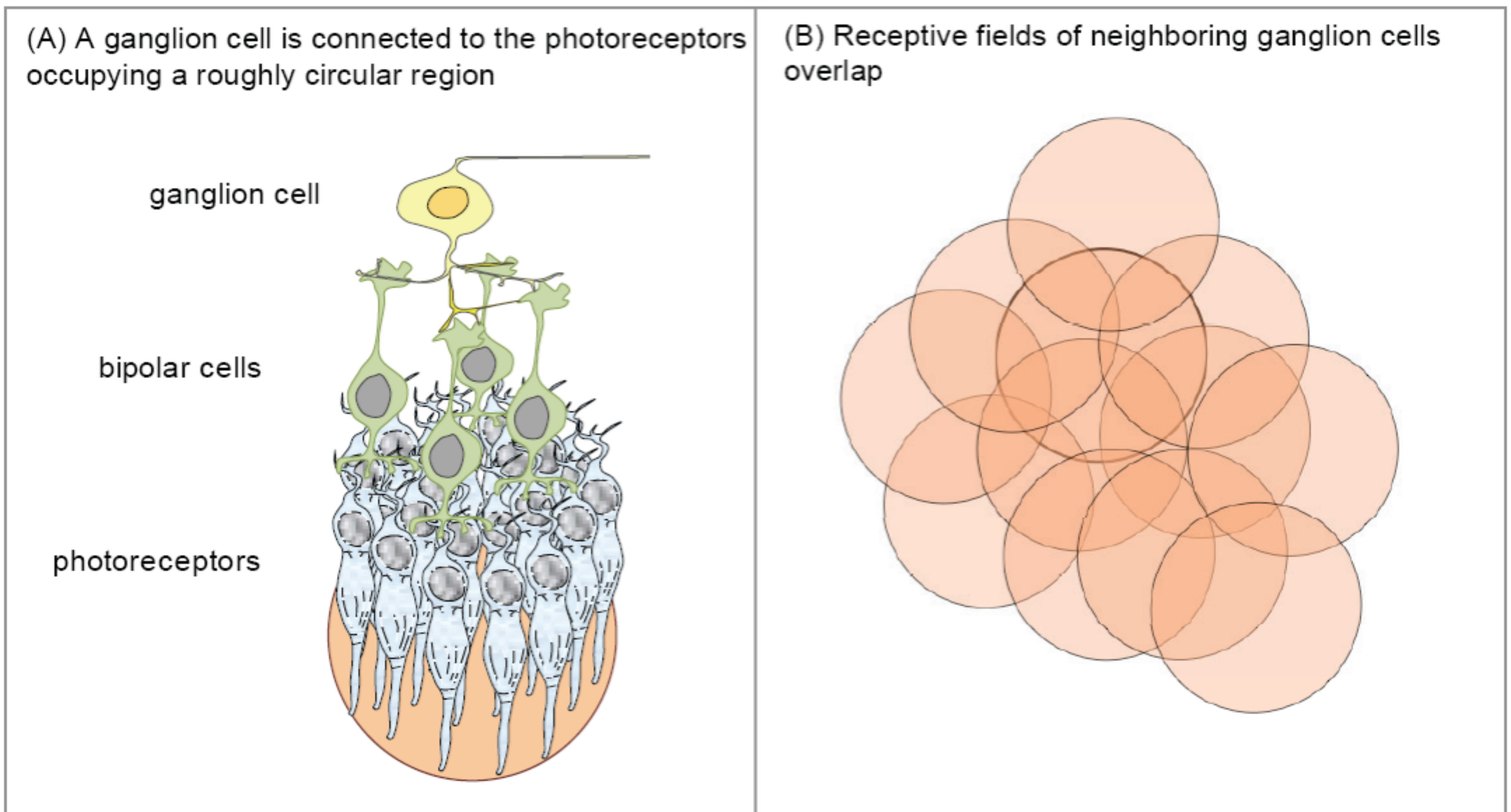
- retinal network



[from: Tresilian, 2012]

Sensory networks

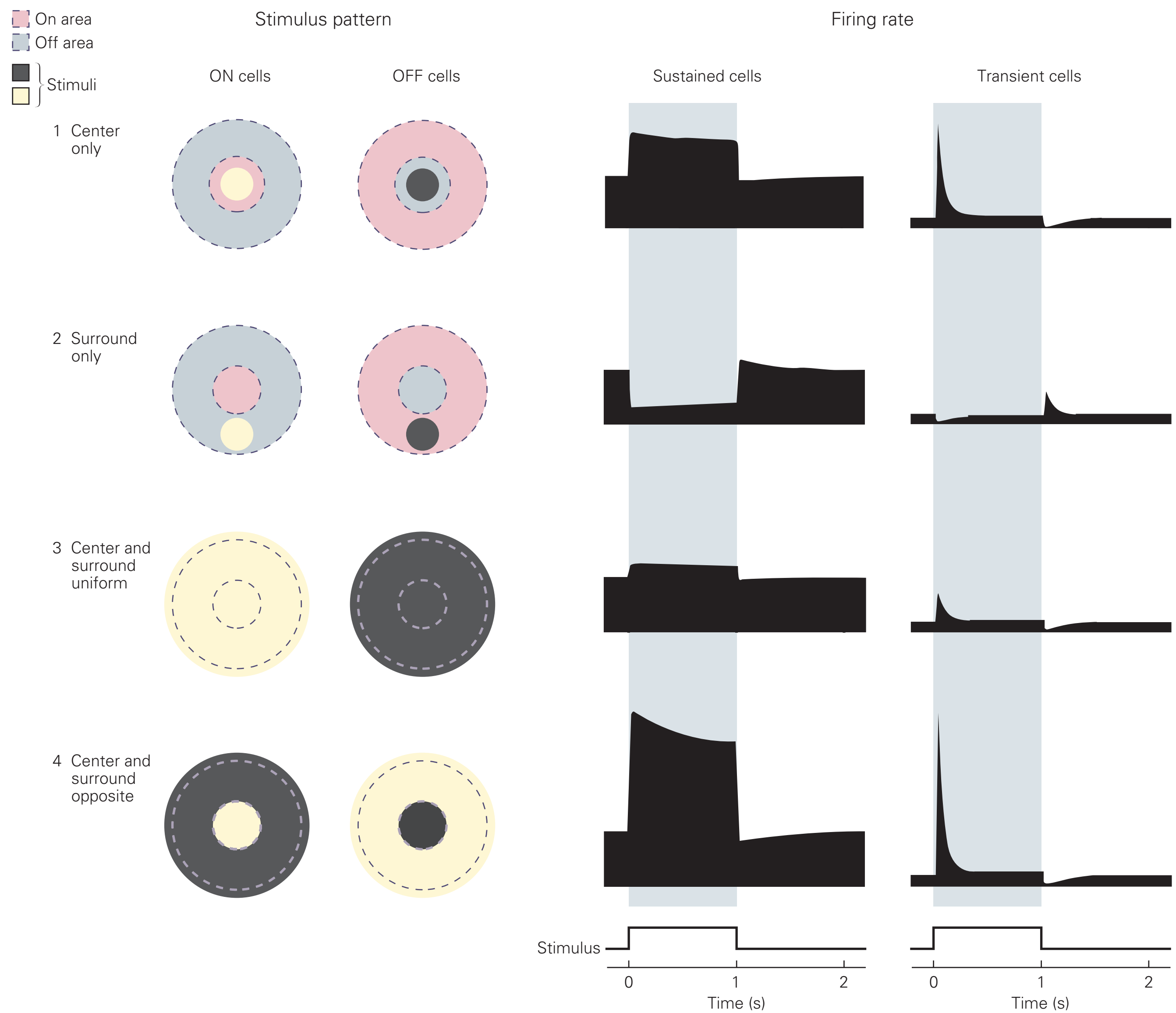
- receptive fields



[from: Tresilian, 2012]

Sensory networks

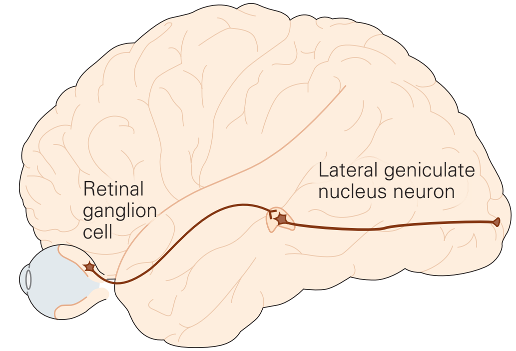
- space-time structure of receptive fields
- retinal ganglion cells

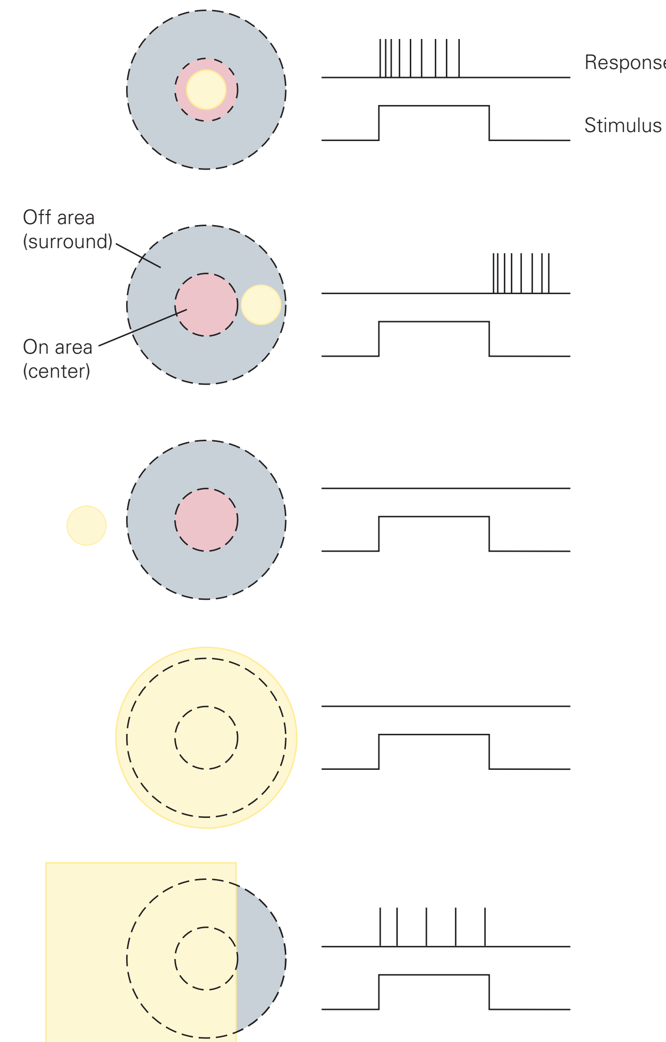


[from: Tresilian, 2012]

Sensory networks

- LGN

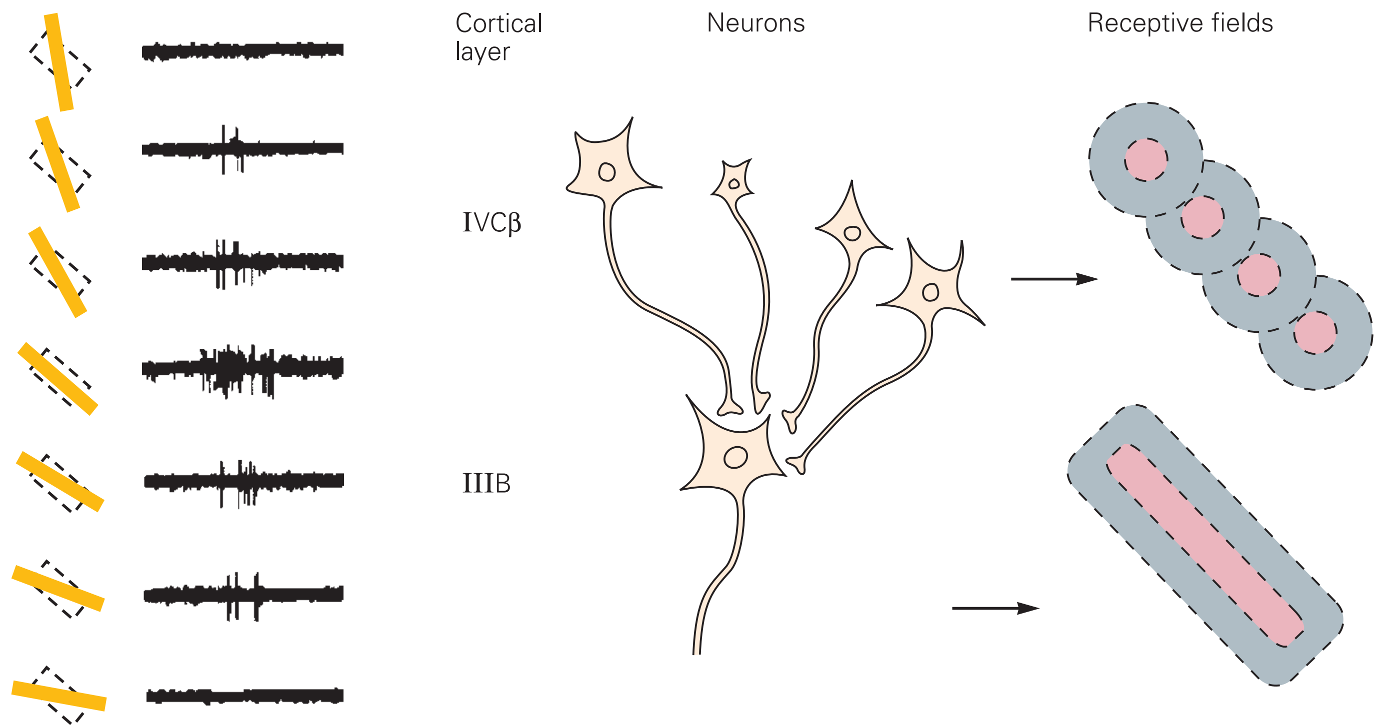




[from: Tresilian, 2012]

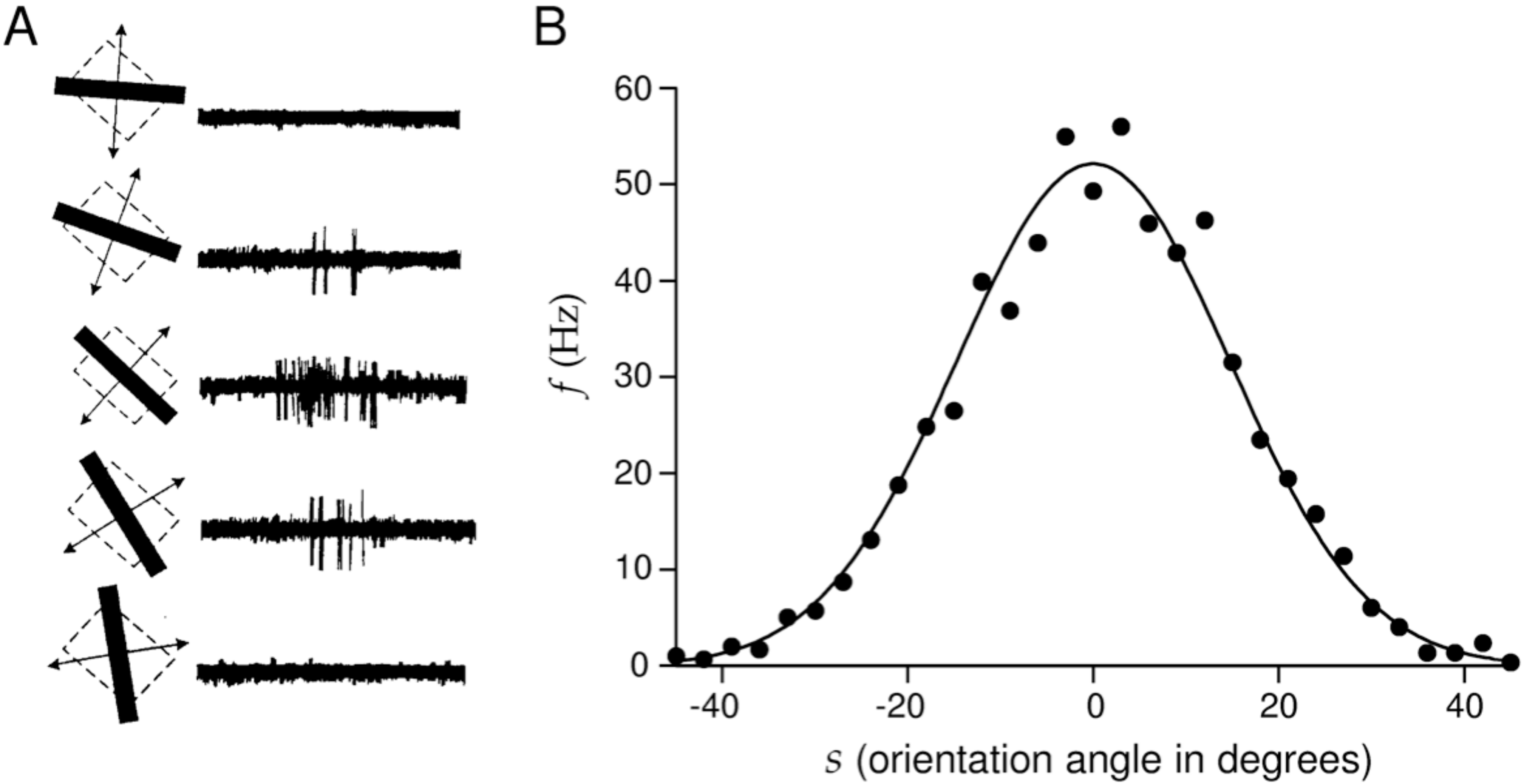
Sensory networks

- tuning curves in primary visual cortex

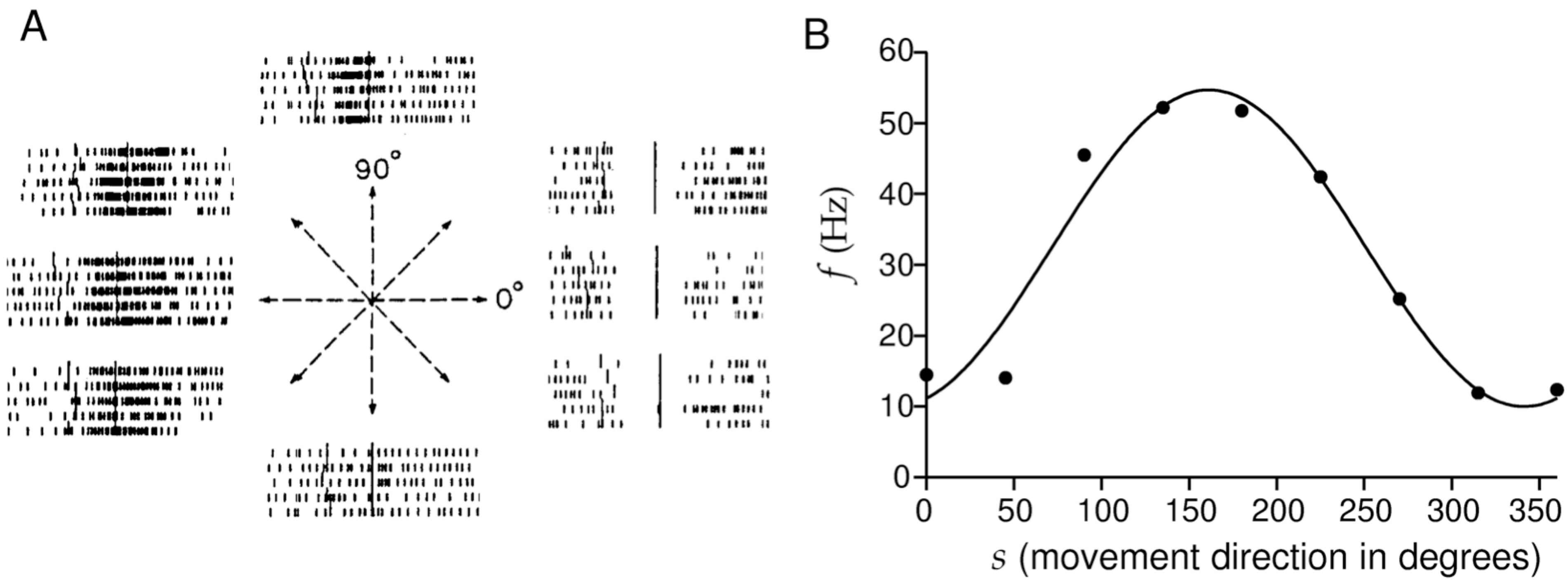


[from: Tresilian, 2012]

Hubel, Wiesel: Tuning curve in macaque primary visual cortex



Tuning curve in macaque primary motor cortex



[Georgopoulos et al, 1990]

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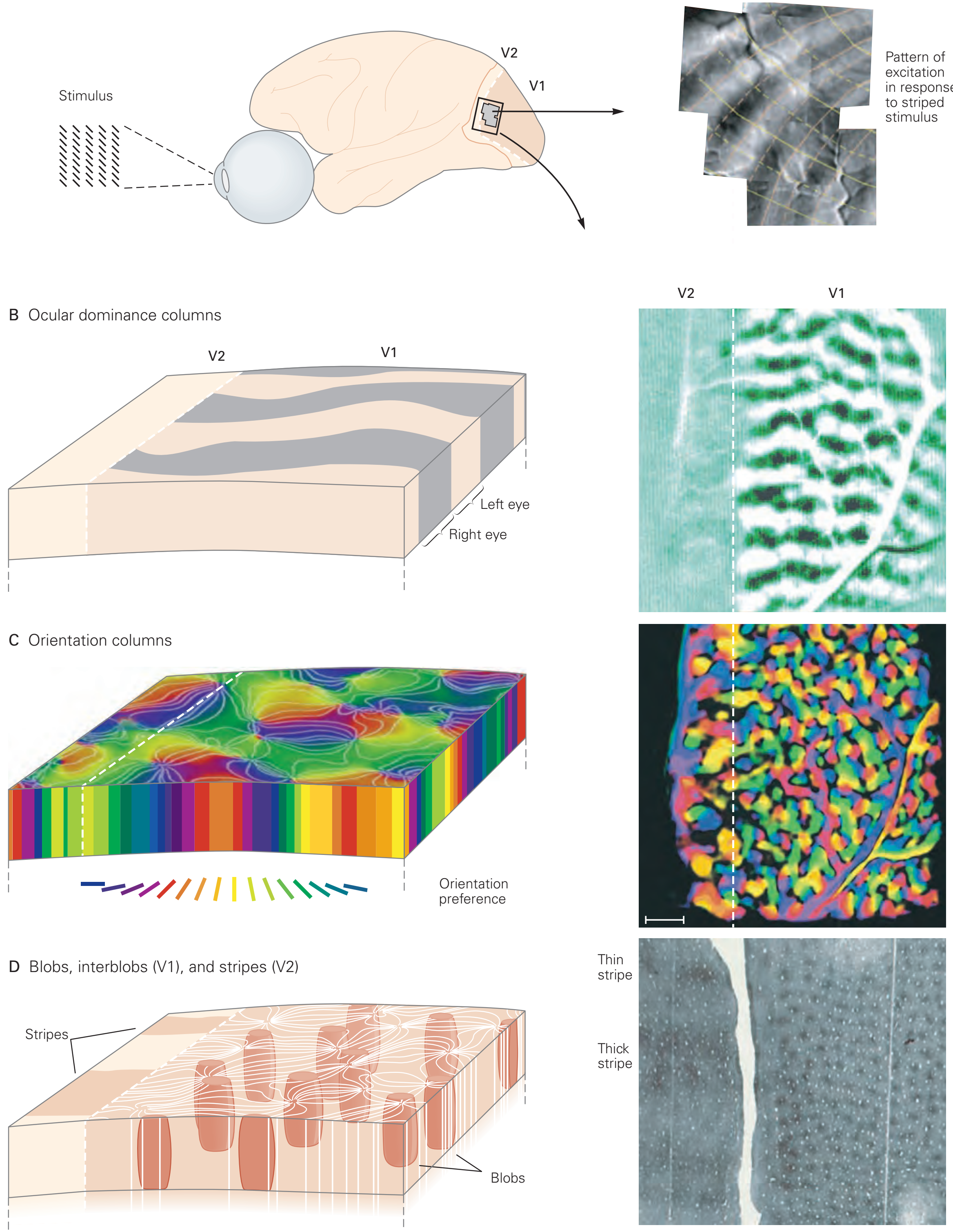
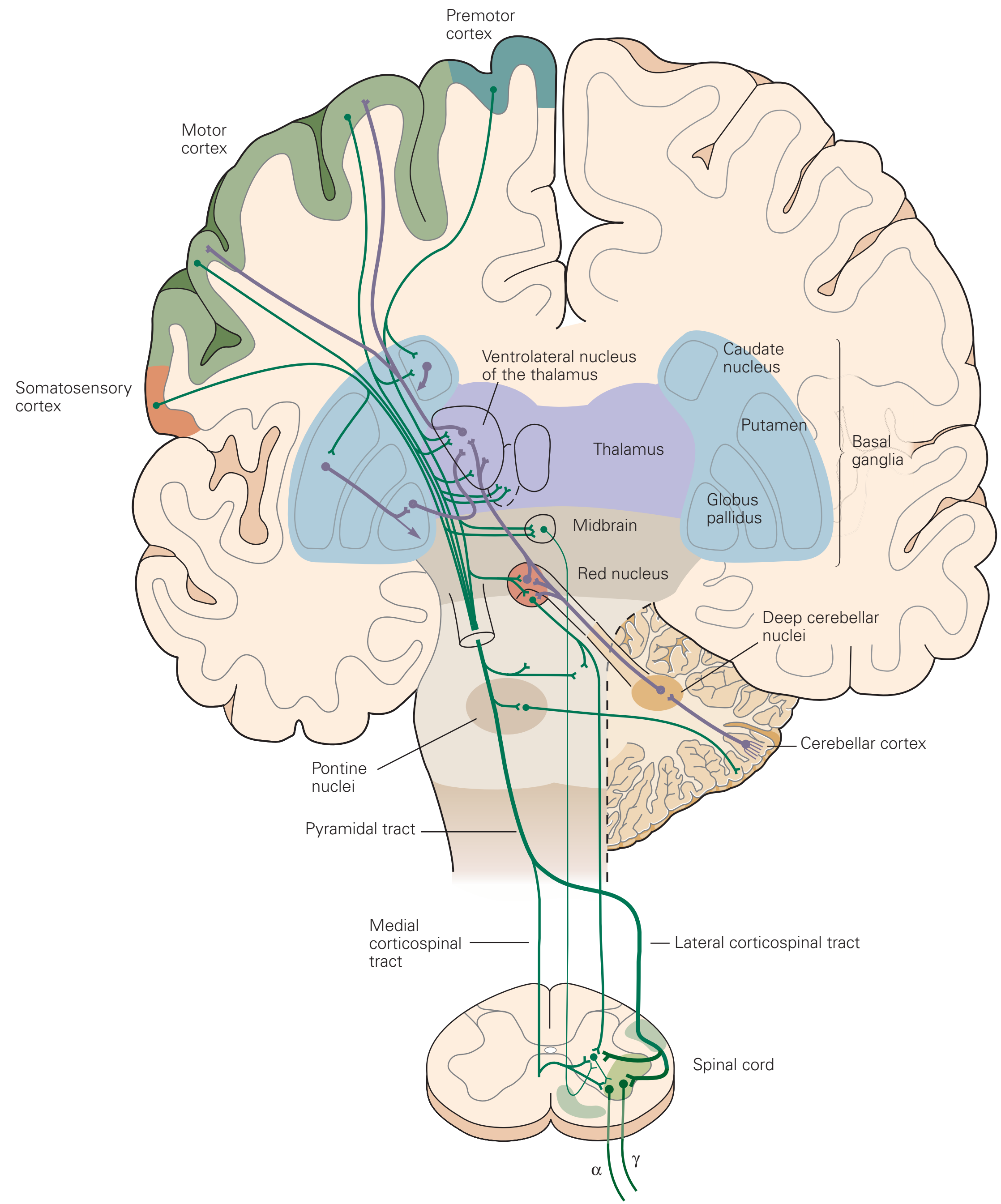
Neural maps

- tuning curves studied systematically across the cortical surface
- => feature maps
- topography



[from: Charles D. Gilbert, Aniruddha Das, Chapter 21 of Kandel et al 2021]

Motor networks



[from: Tresilian, 2012]

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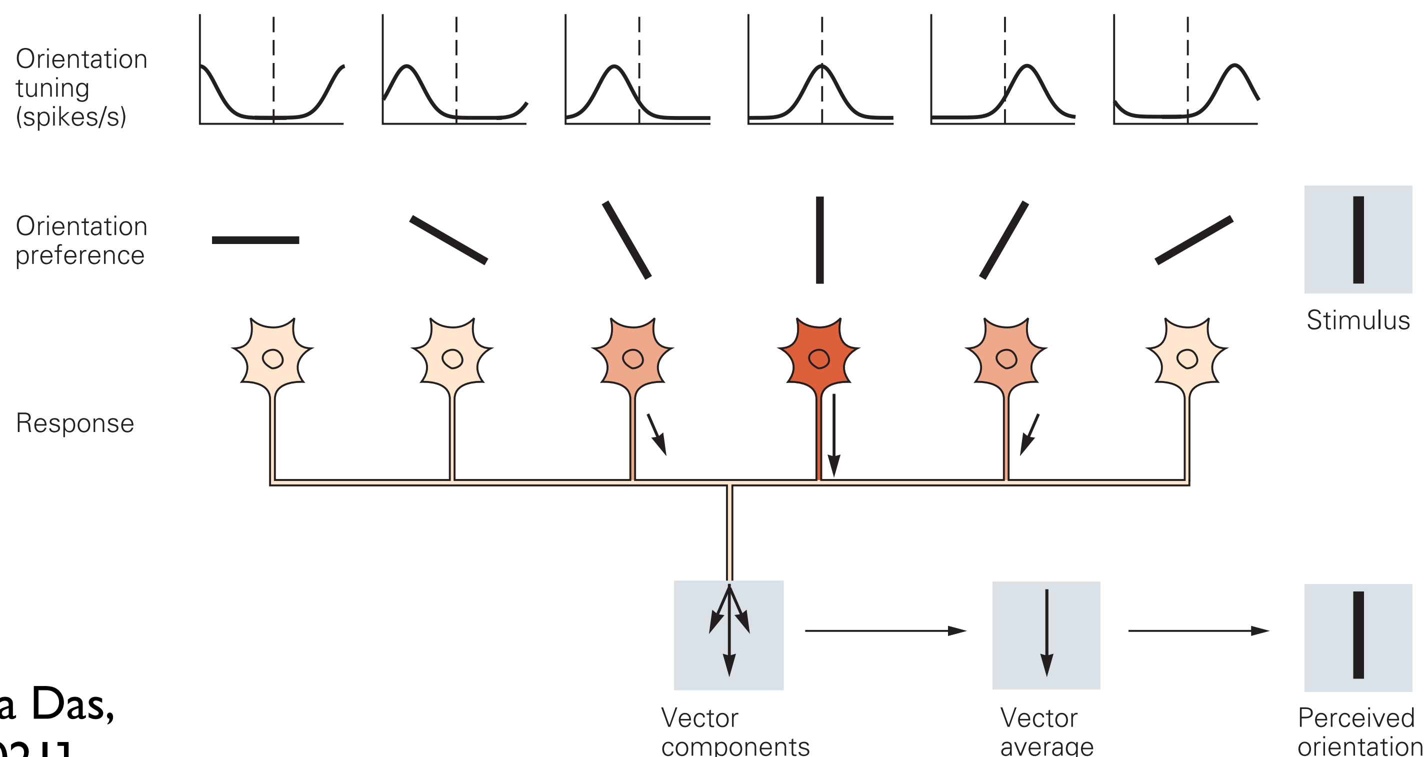
Population code

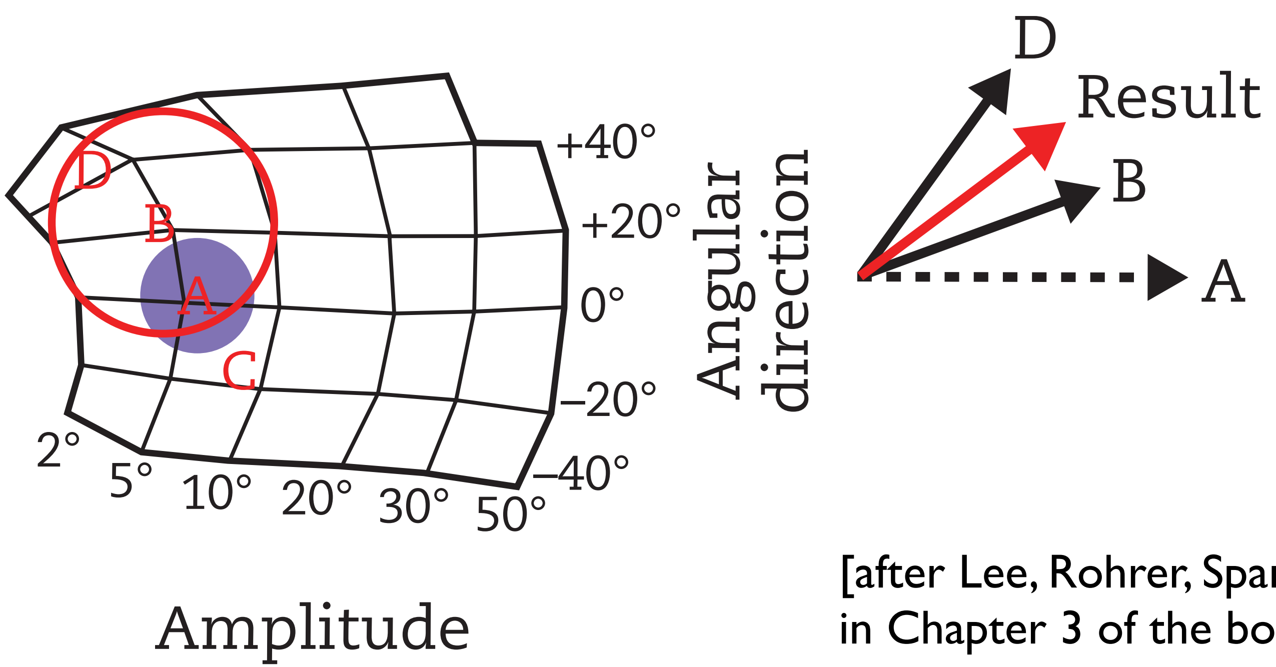
- notion that all activated neurons contribute to feature representation according to their tuning curves



[Charles D. Gilbert, Aniruddha Das, Chapter 21 of Kandel et al 2021]

Experimental evidence for population representations

- Lee, Rohrer, Sparks: use the topographic map of saccadic endpoint in superior colliculus
- to reversibly deactivate portions of the population: observe predicted deviations of saccadic endpoints



[after Lee, Rohrer, Sparks: Nature (1988) in Chapter 3 of the book]

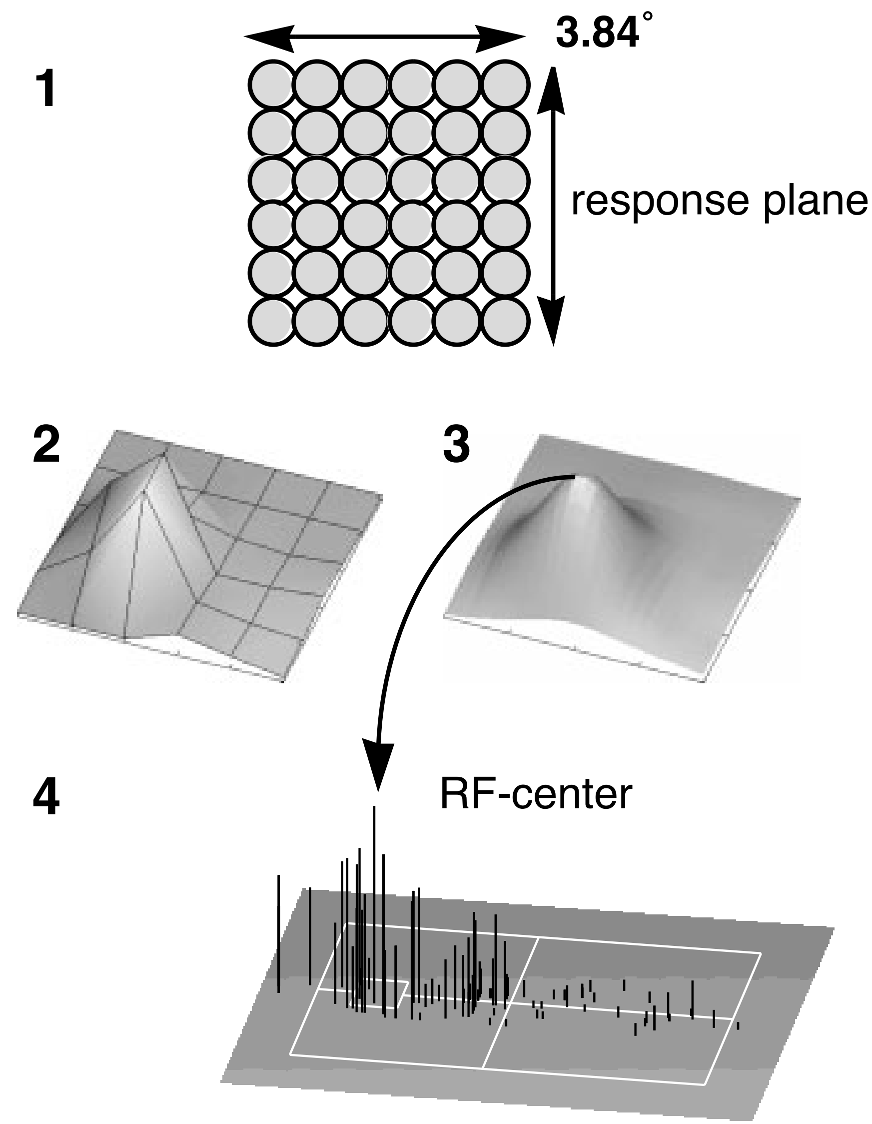
Population representation in the visual system

- Example 1: Jancke et al: A17 in the cat, population representation of retinal location

Jancke, Erlhagen, Dinse, Akhavan, Giese, Steinhage, Schöner JNeurosci 19:9016 (99)

Distribution of Population Activation (DPA)

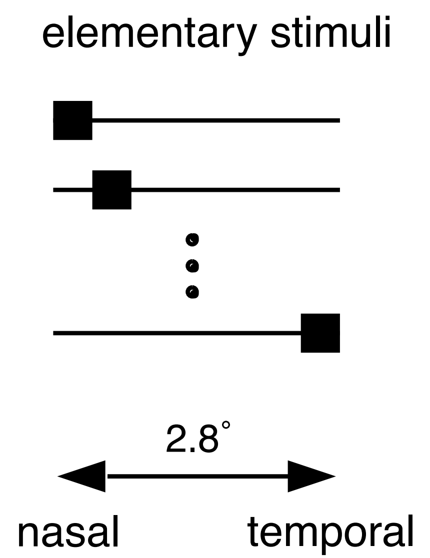
- determine tuning to retinal location for each cell
- superpose tuning curves weighted by current firing rate: distribution of population activation DPA representing retinal location

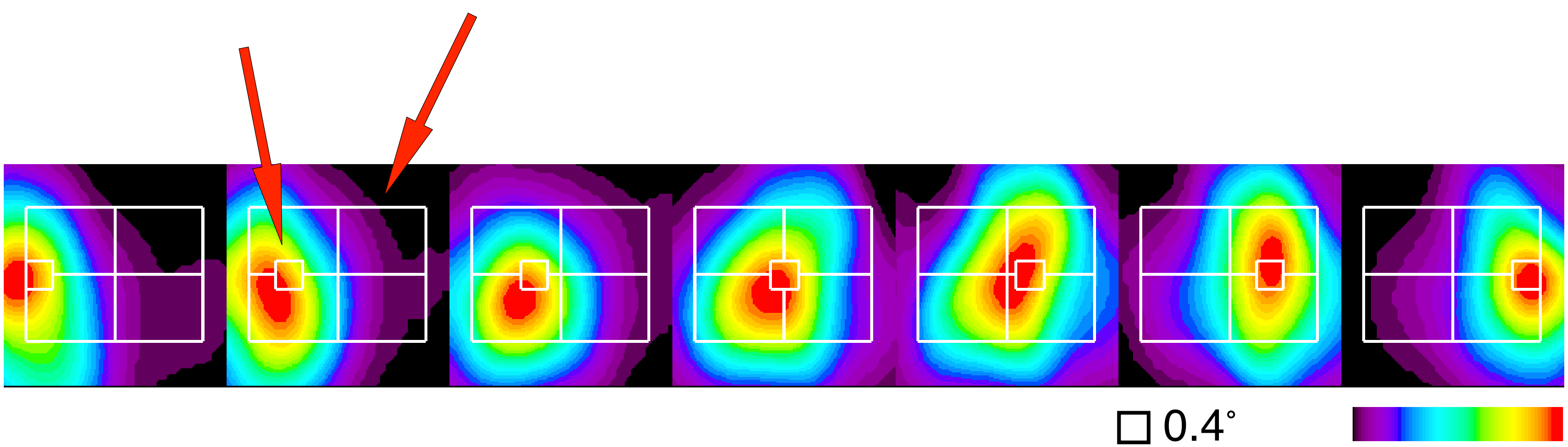


[Jancke, Erlhagen, Dinse, Akhavan, Giese, Steinhage, Schöner JNsci 19:9016 (99)]

Neural grounding of DFT: sensory

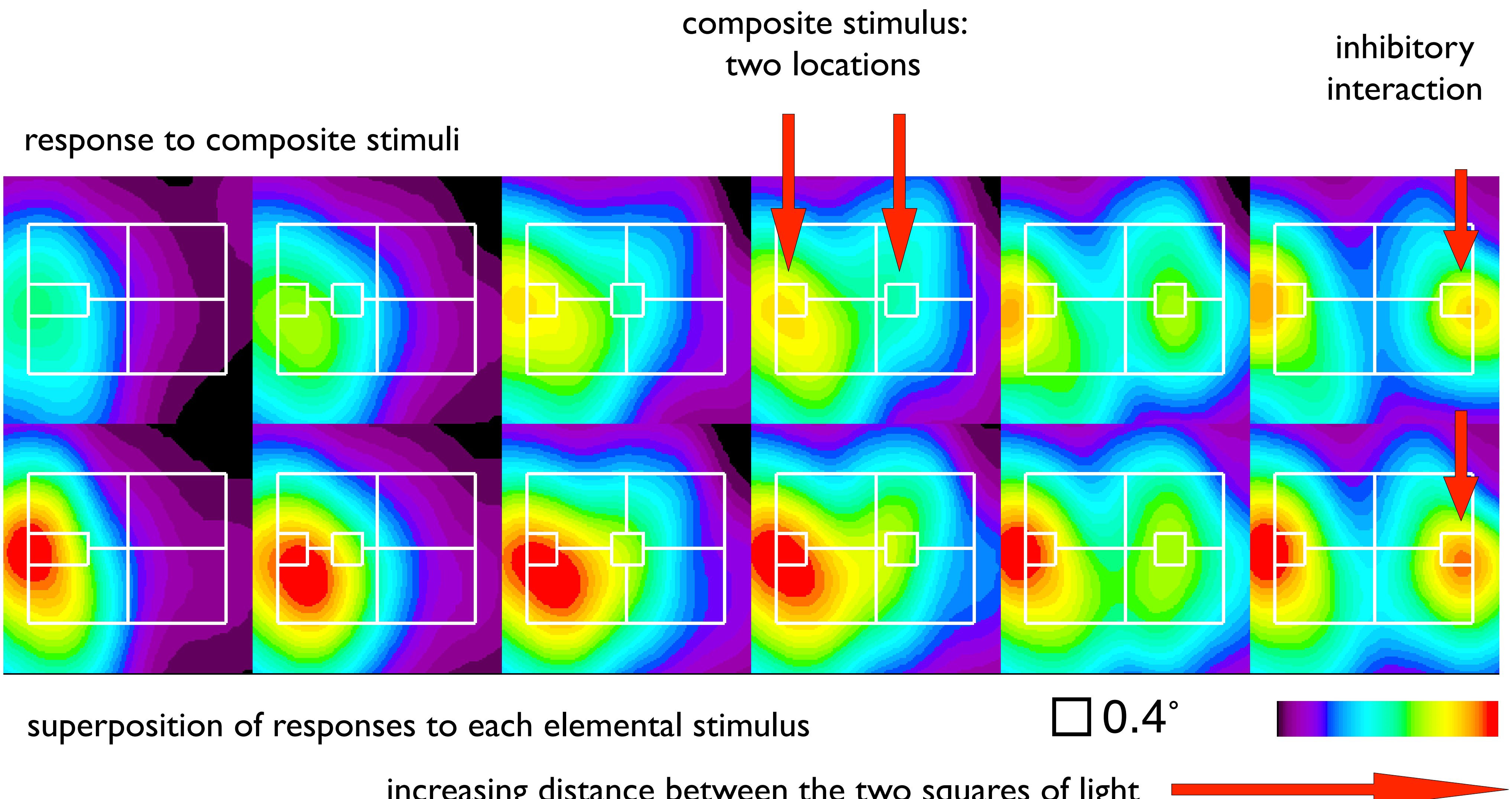
- DPA of stimuli presented to all neurons



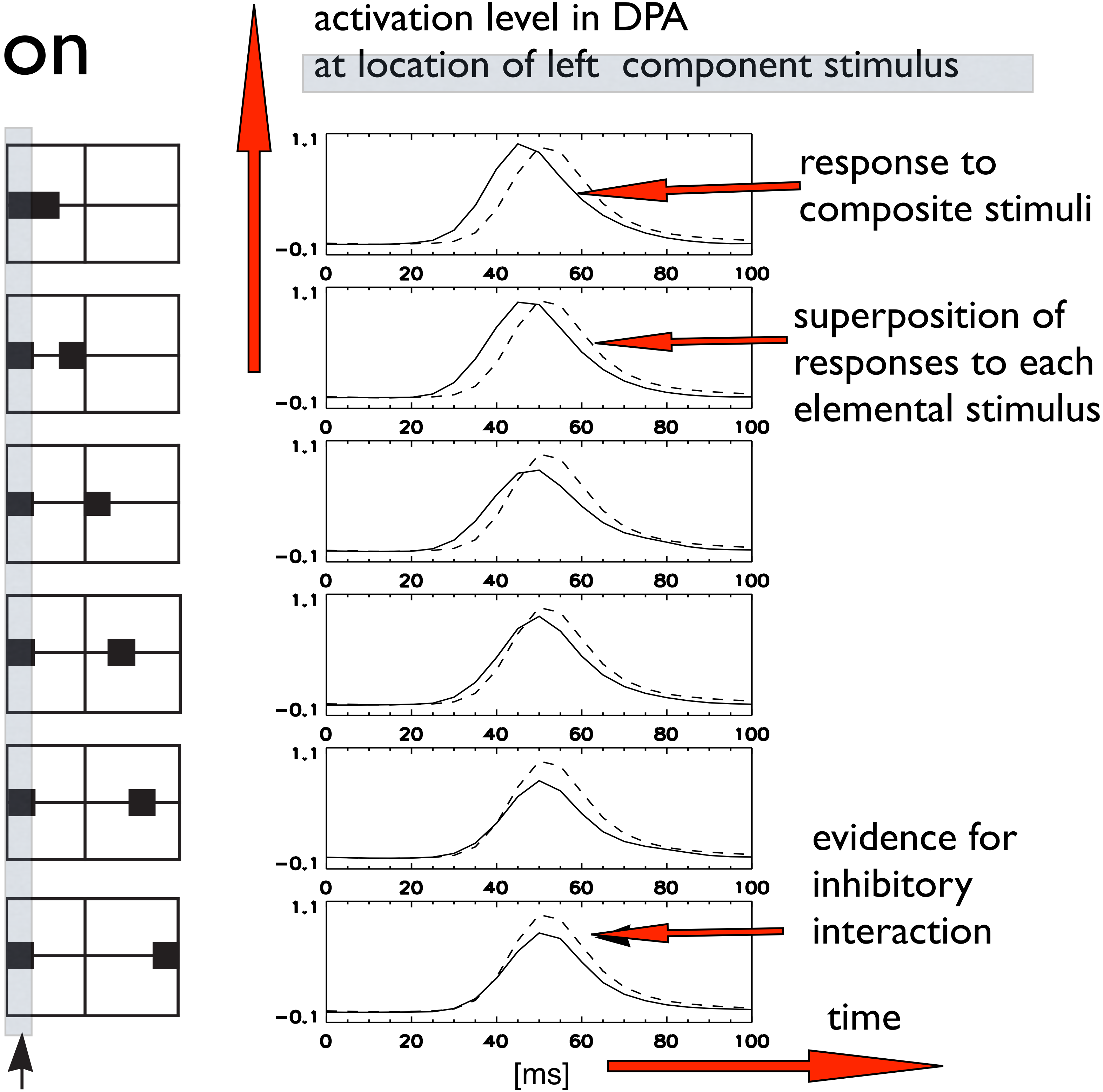


Neural grounding of DFT: sensory

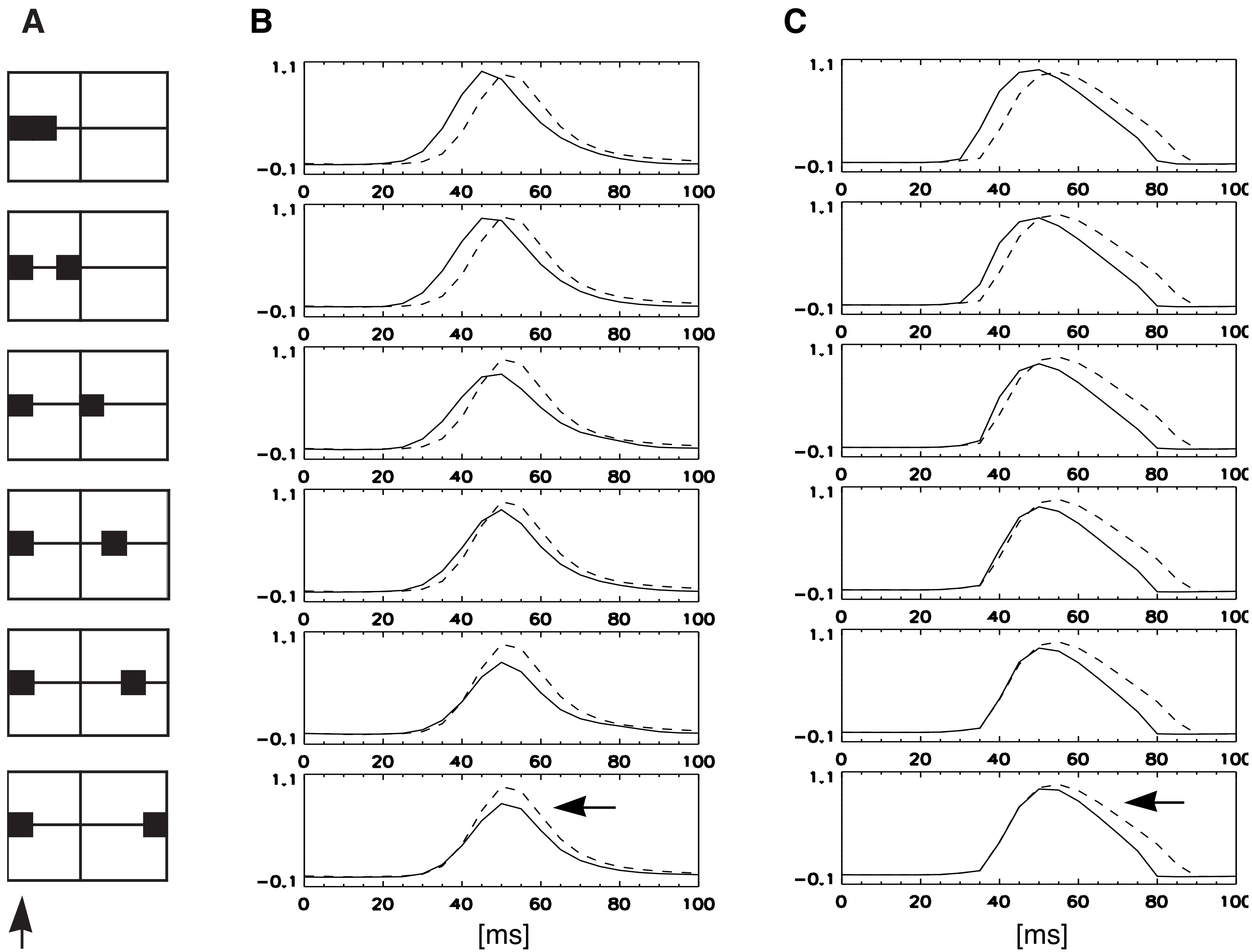
- => observe interaction in DPA



interaction



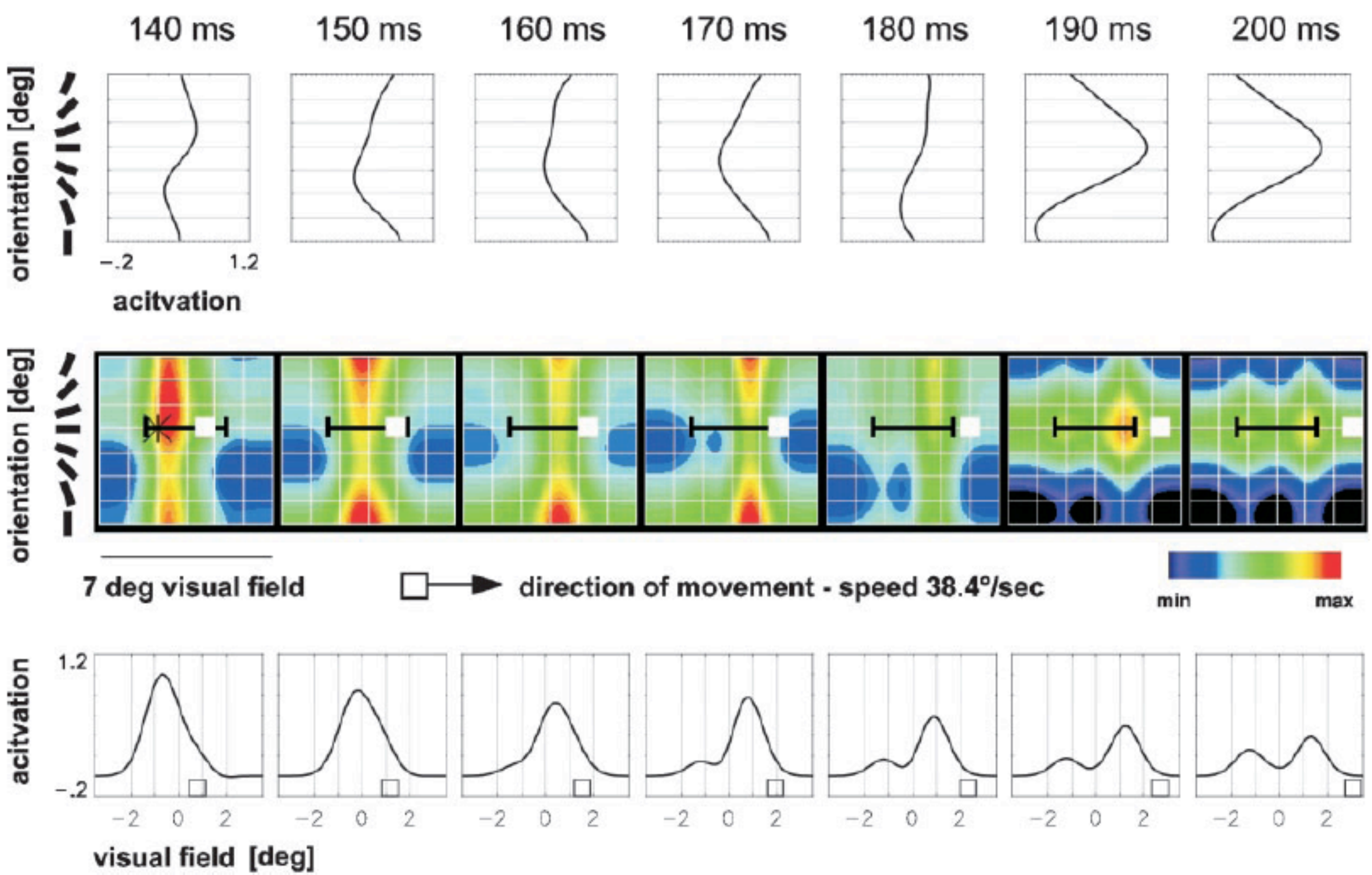
model by dynamic field:



stimulus experiment DFT model

Neural grounding of DFT: sensory

- DPA of orientation and (1D) retinal location

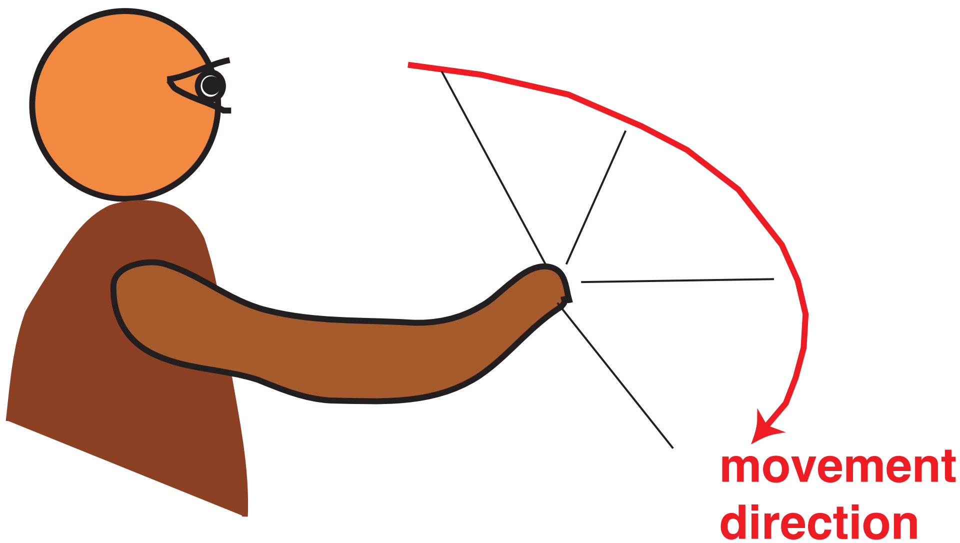


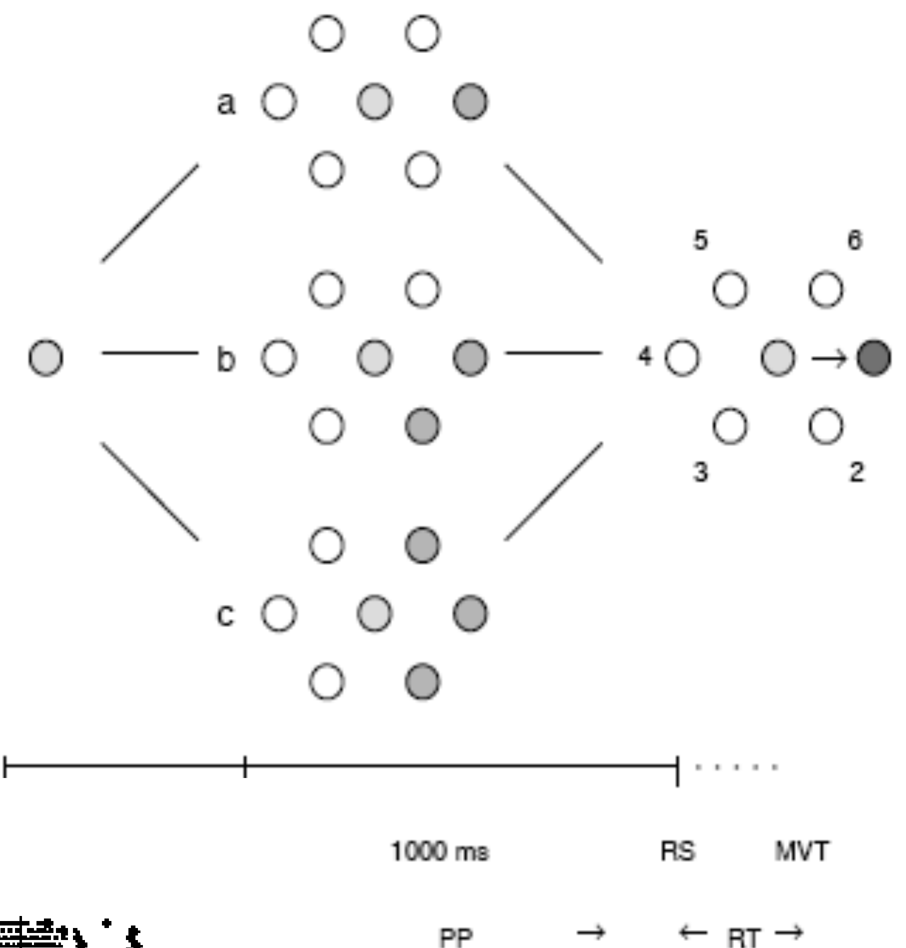
[Jancke, JNeursci (2000)]

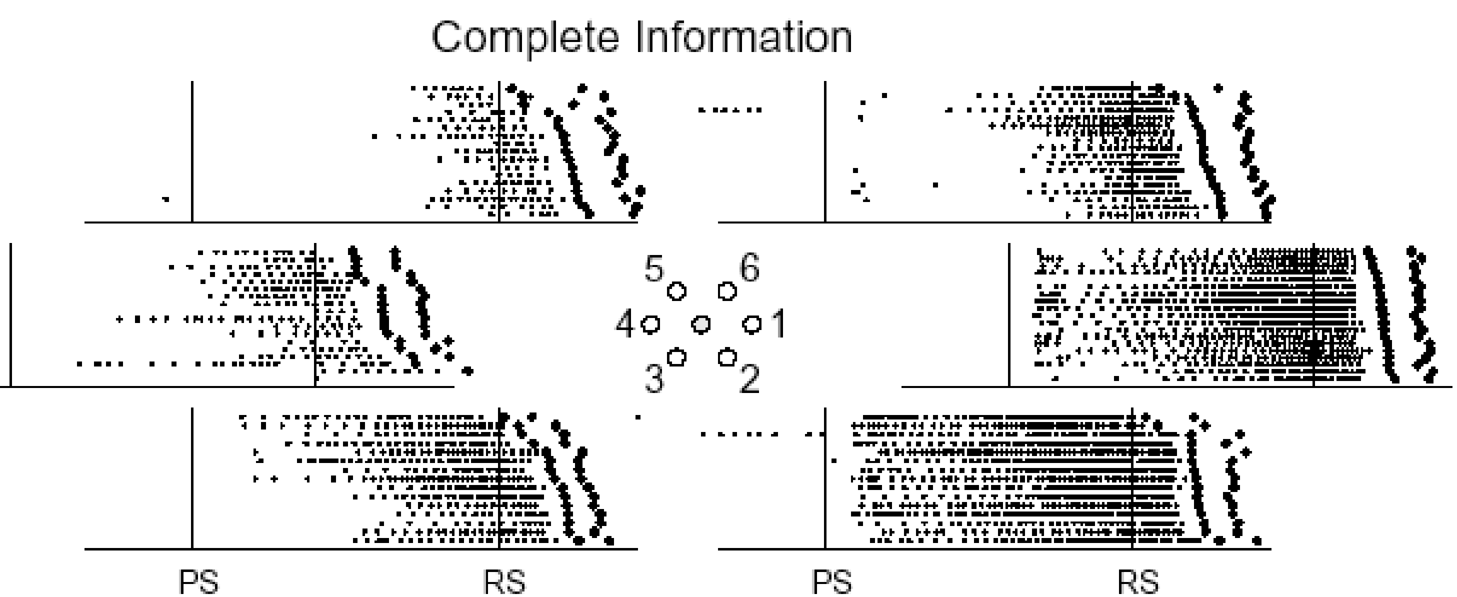
Population representation motor system

- motor and pre-motor cortex (macaque)
- in behaving animal

[Bastian, Riehle, Schöner, Euro J Neuro 2003]

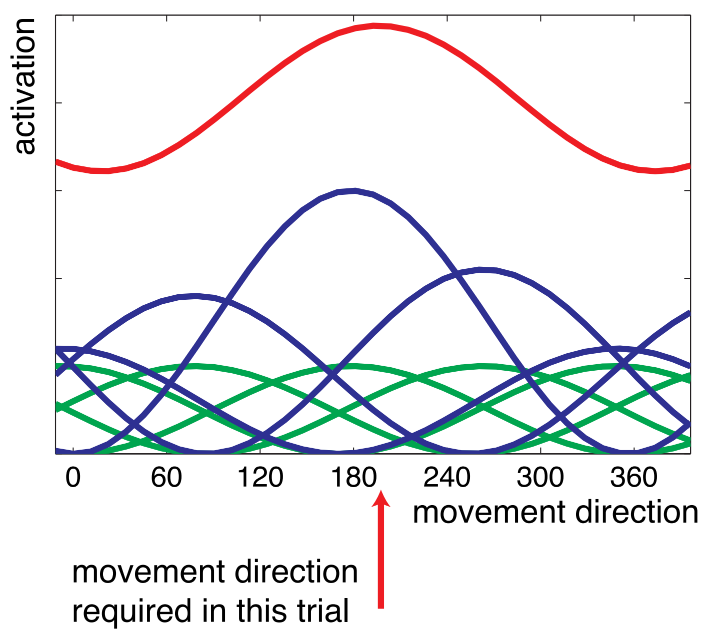

movement
direction

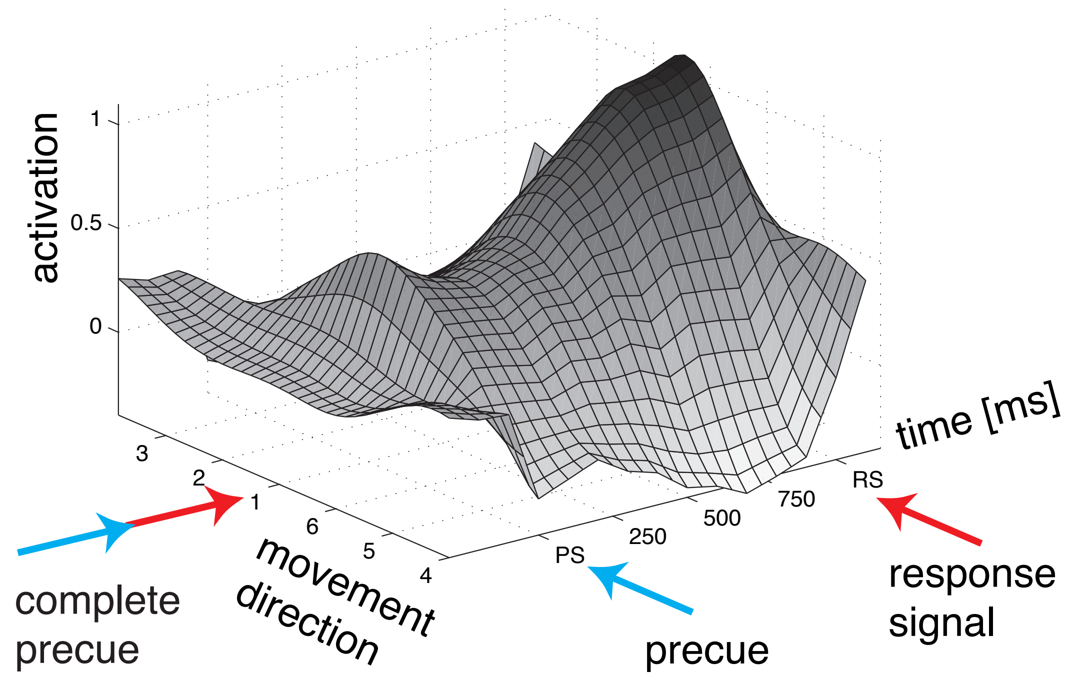

a
b
c
5
6
4
1
3
2
1000 ms
RS
MVT
PP
RT


Complete Information
5
6
4
1
3
2
PS
RS
PS
RS

Distribution of Population Activation (DPA)

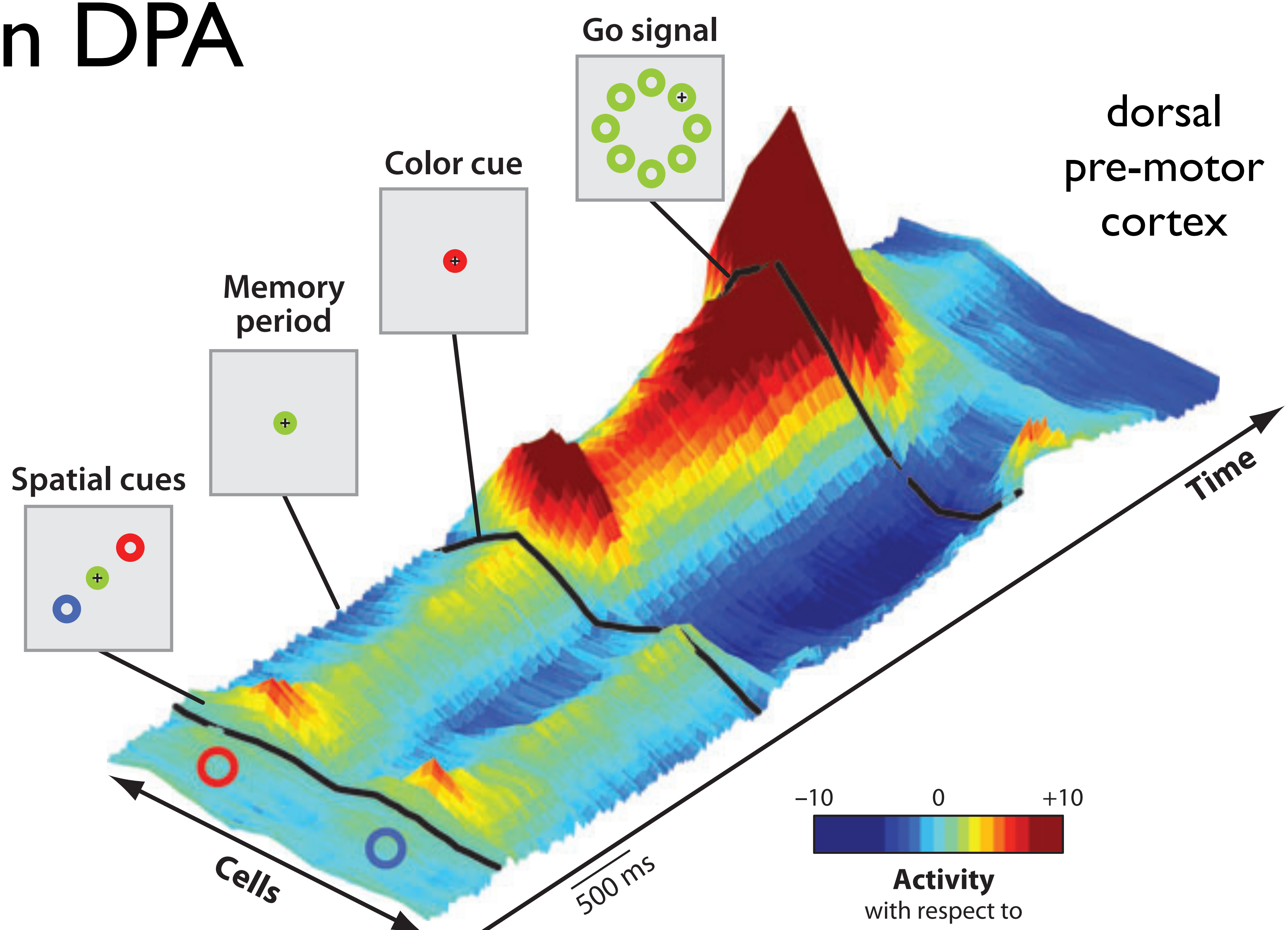
Distribution of population activation =
$\sum_{\text{neurons}}$ tuning curve * current firing rate





[Bastian, Riehle, Schöner, 2003]

Decision making in DPA



dorsal pre-motor cortex

[Cisek, Kalaska 2005]

Distributions of Population Activation (DPA)

- neurons are not localized within DPA!
- cortical neurons really are sensitive to many dimensions
  - motor: arm configuration, force direction
  - visual: many feature dimensions such as spatial frequency, orientation, direction...
- => DPA is a projection from that high-dimensional space onto a single dimension

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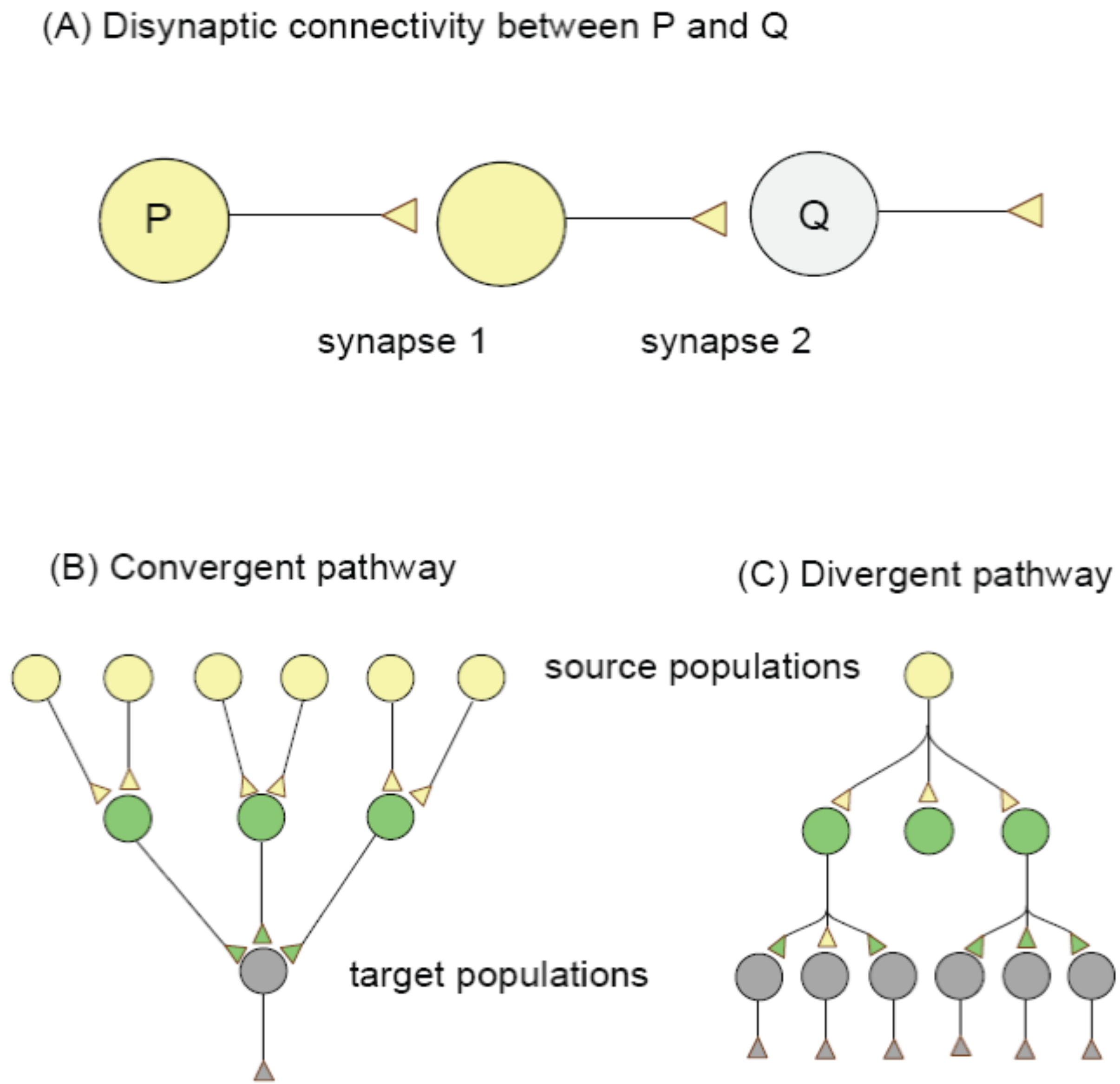
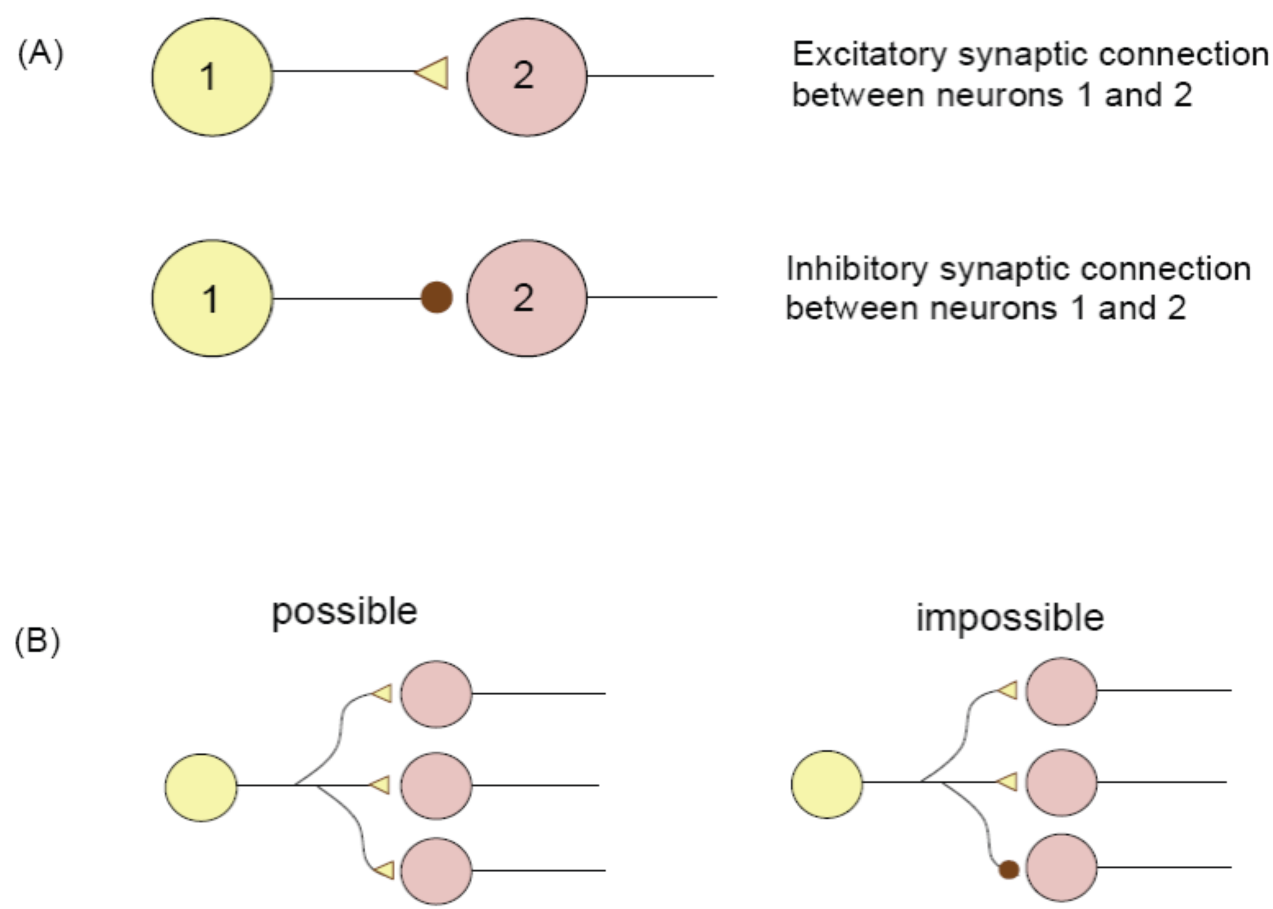
Forward connectivity



[from: Tresilian, 2012]

Dale’s law

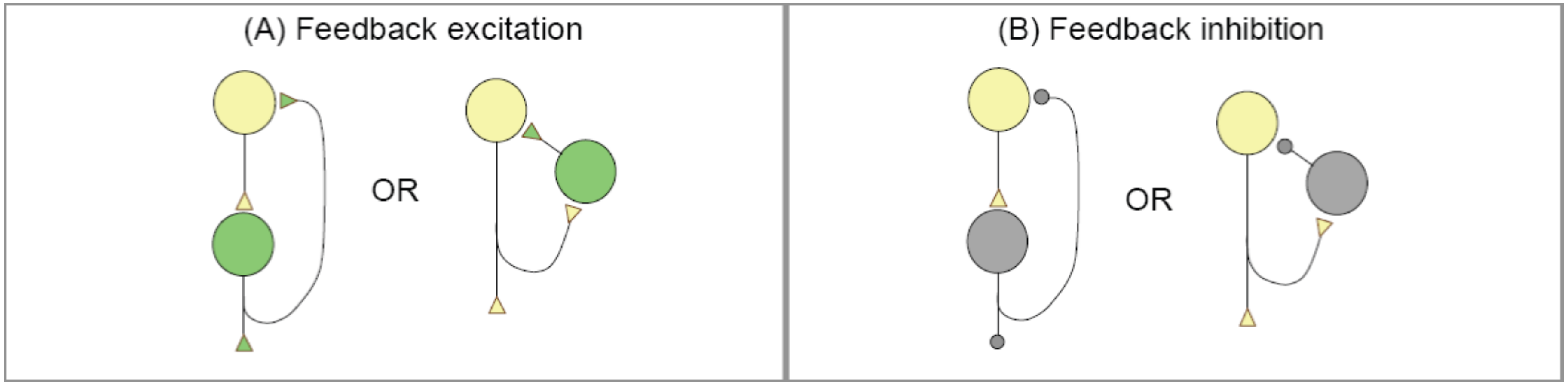
- all synaptic connections coming from a given neuron are of the same type



[from: Tresilian, 2012]

Patterns of connectivity

- recurrent connectivity



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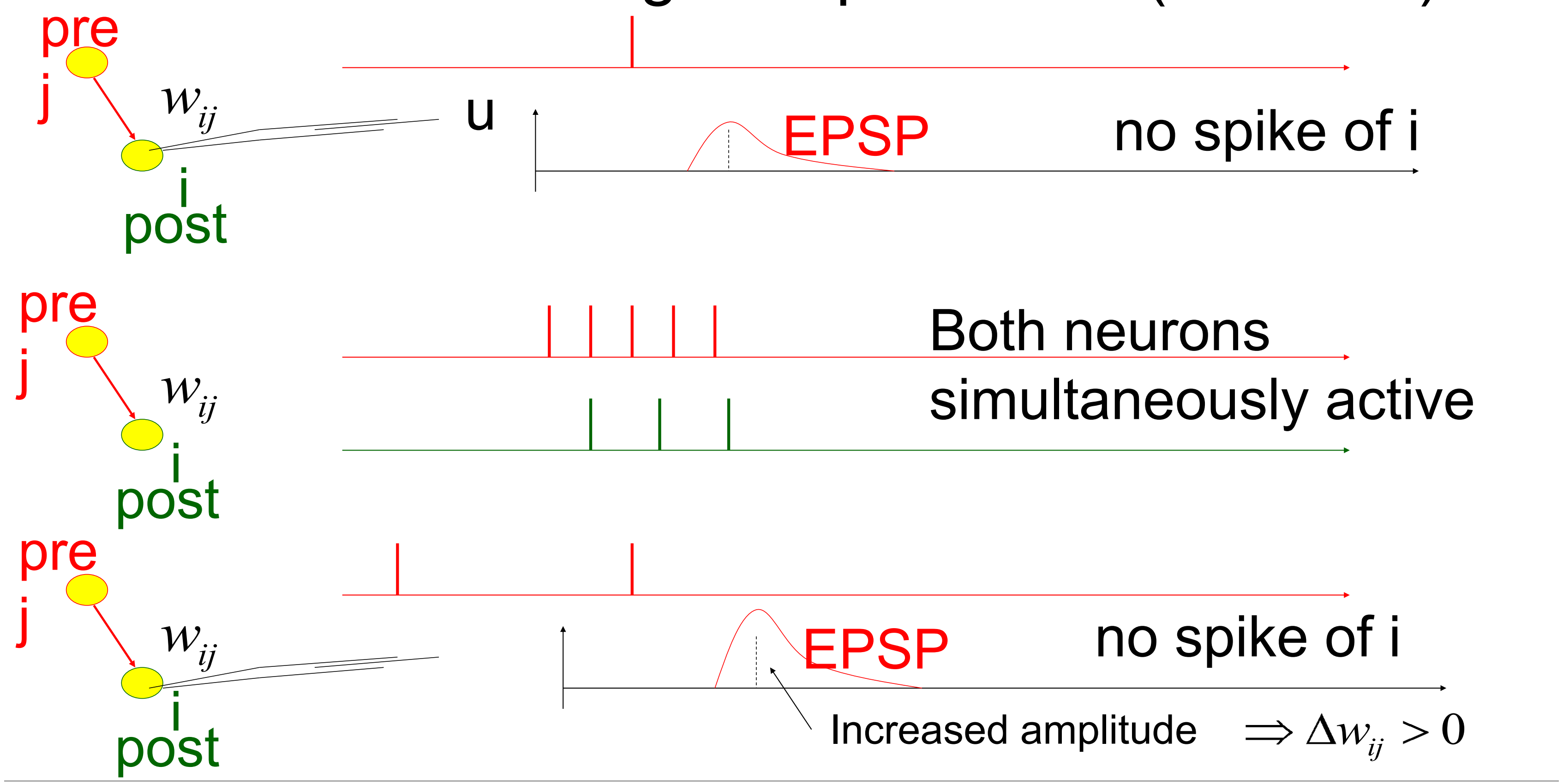
Learning by synaptic plasticity

- synaptic strengths change as a function of pre/post synaptic neural state

Hebbian Learning in experiments (schematic)

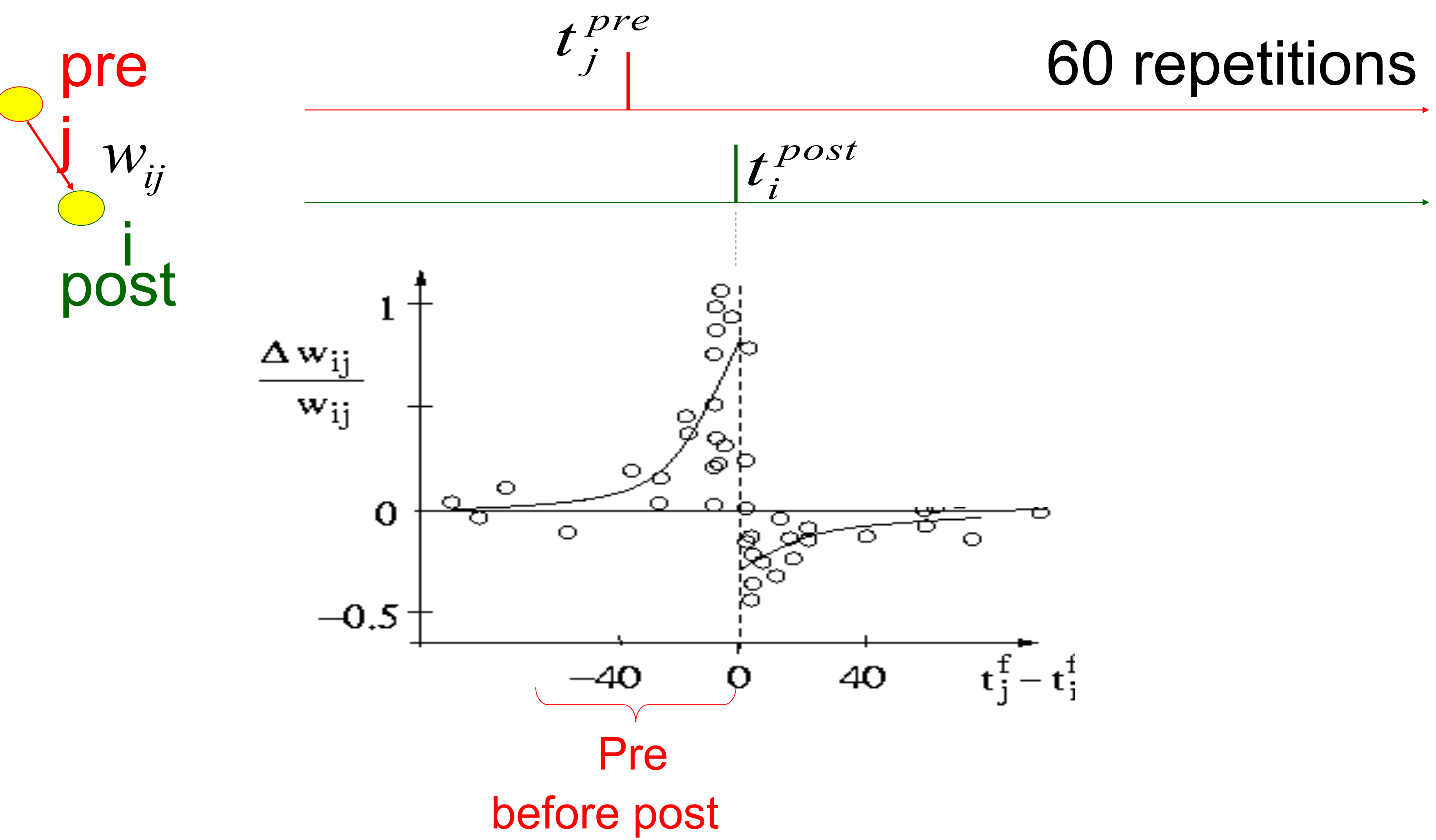


[Gerstner et al, 2014]

Learning by plasticity

- spike-time dependent plasticity
  - strengthening of synapses in which pre-synaptic spike precedes post-synaptic spike
  - weakening synapses when the temporal order is the reverse…

Spike-time dependent plasticity



[Gerstner et al, 2014]

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