Summary

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Cognition in the wild…

- attention/gaze
- active perception/working memory
- action plans/decisions/ sequences
- goal orientation
- motor control
- background knowledge
- learning from experience

=> implied properties of the underlying neural processes

- graded state
- continuous time
- continuous/intermittent link to the sensory and motor surfaces
- from which discrete events and categorical behavior emerge
- in closed loop
- => states must be stable

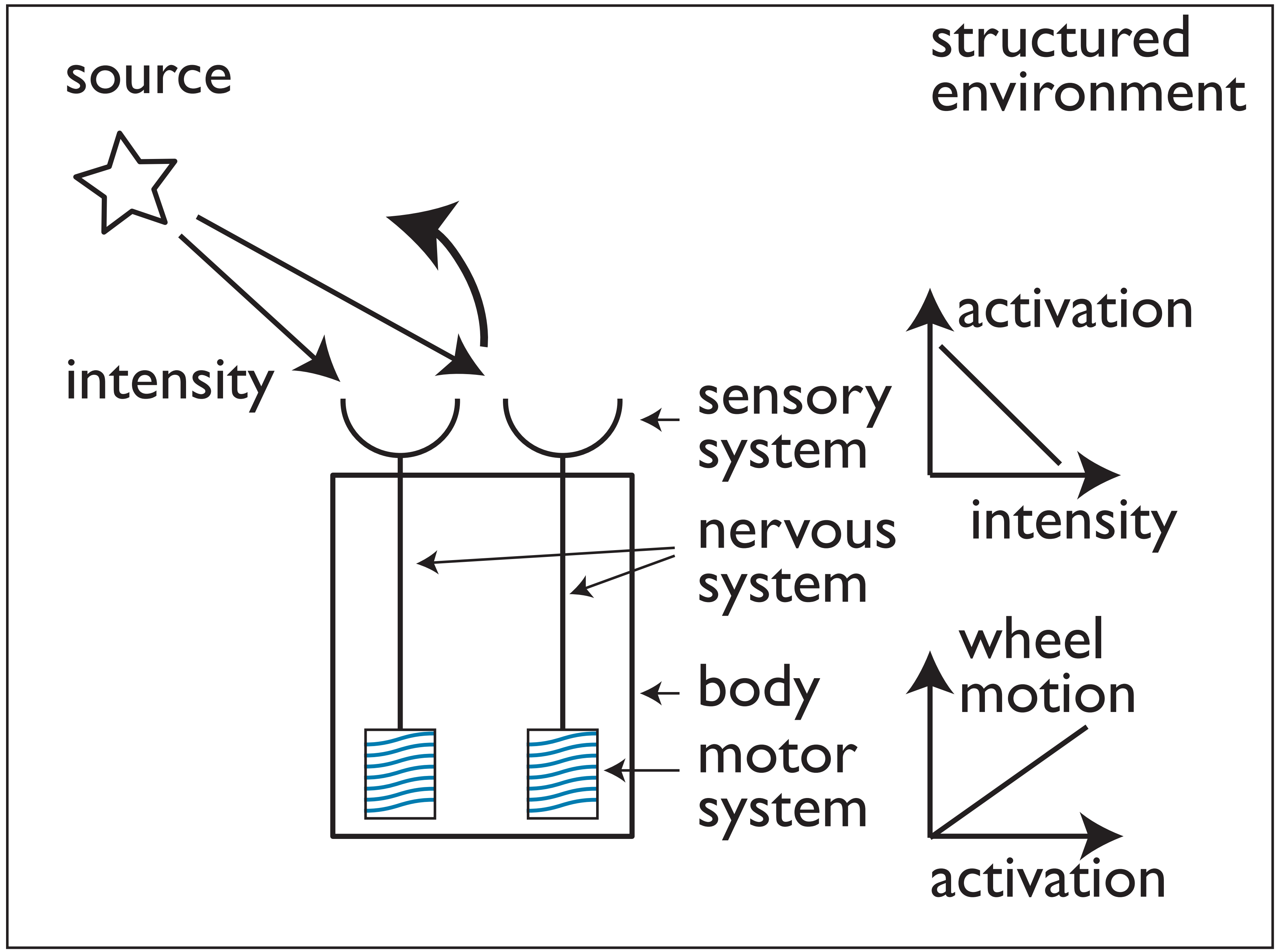
Embodiment hypothesis

- all cognition is like soccer playing = has the properties of embodied cognition
- => there is no particular boundary up to which cognition is embodied and beyond which it is computational/symbolic

Braitenberg

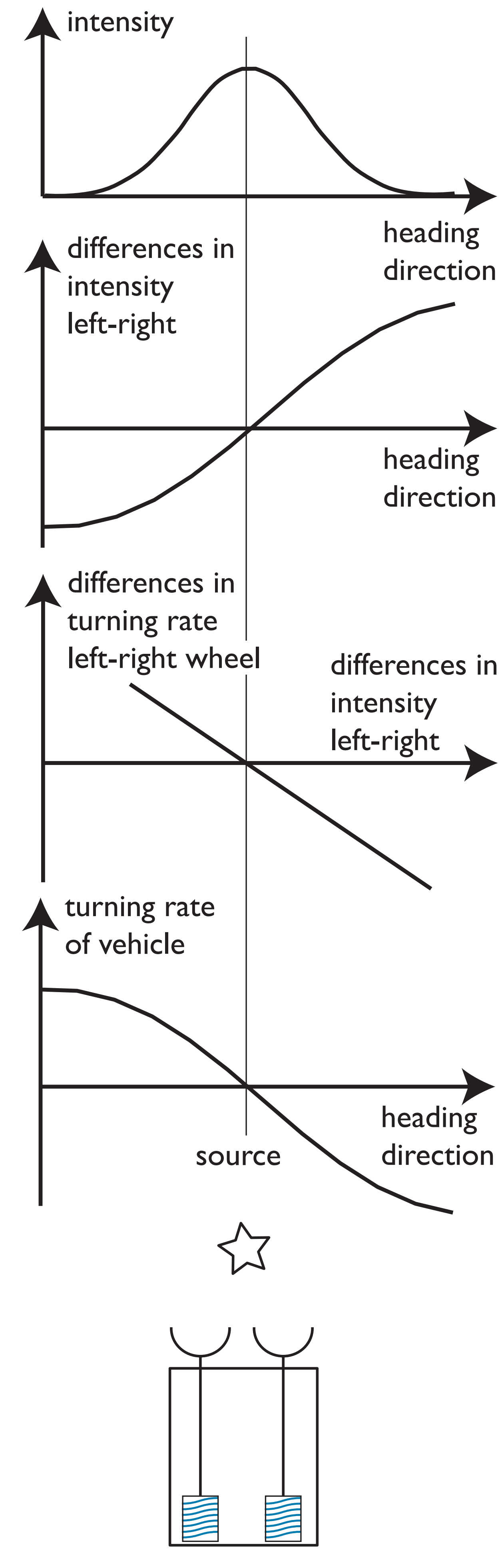
Five things needed to generate behavior

- sensors
- motors
- linked by a nervous system
- linked physically by a body
- an appropriately structured environment



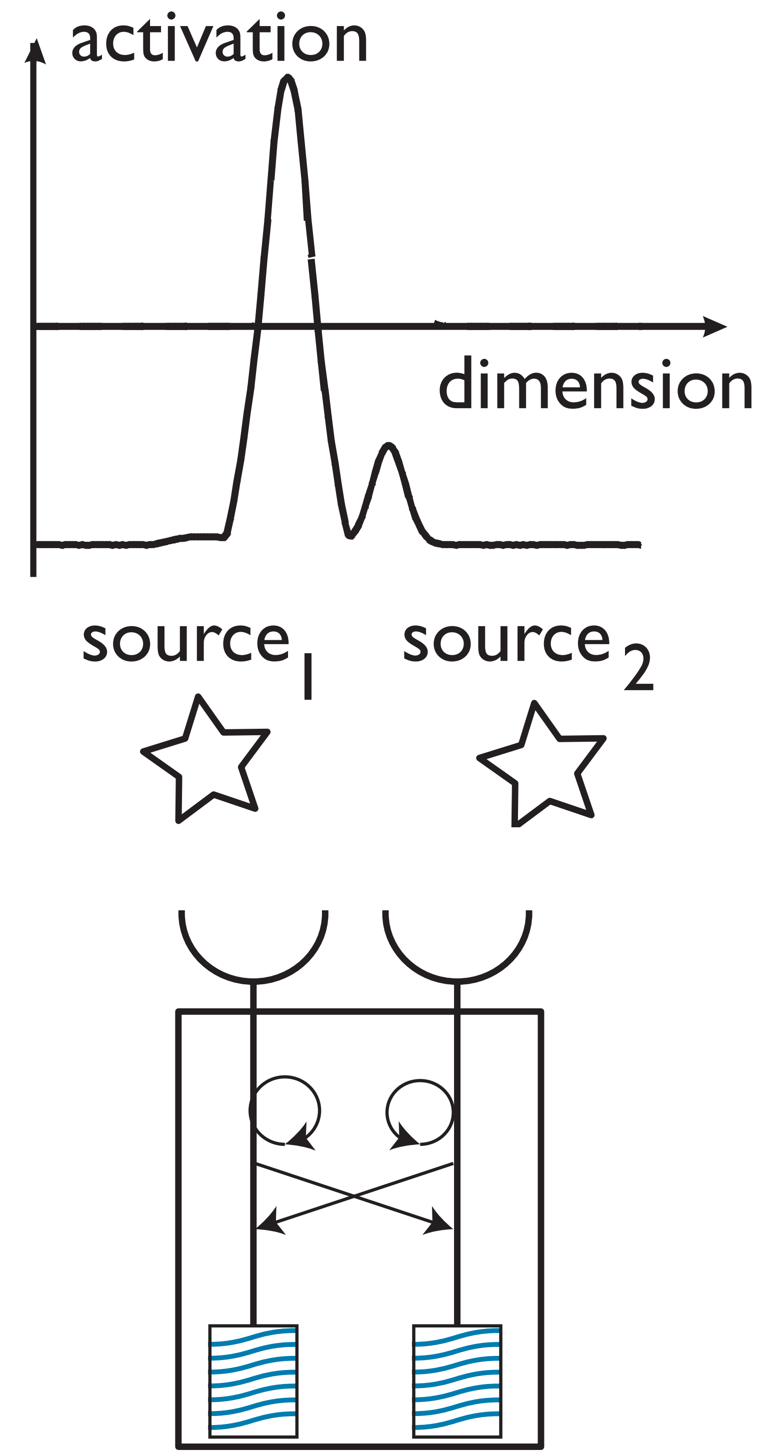
Emergent behavior: this is a dynamics

- feedforward nervous system
- + closed loop through environment
- => (behavioral) dynamics



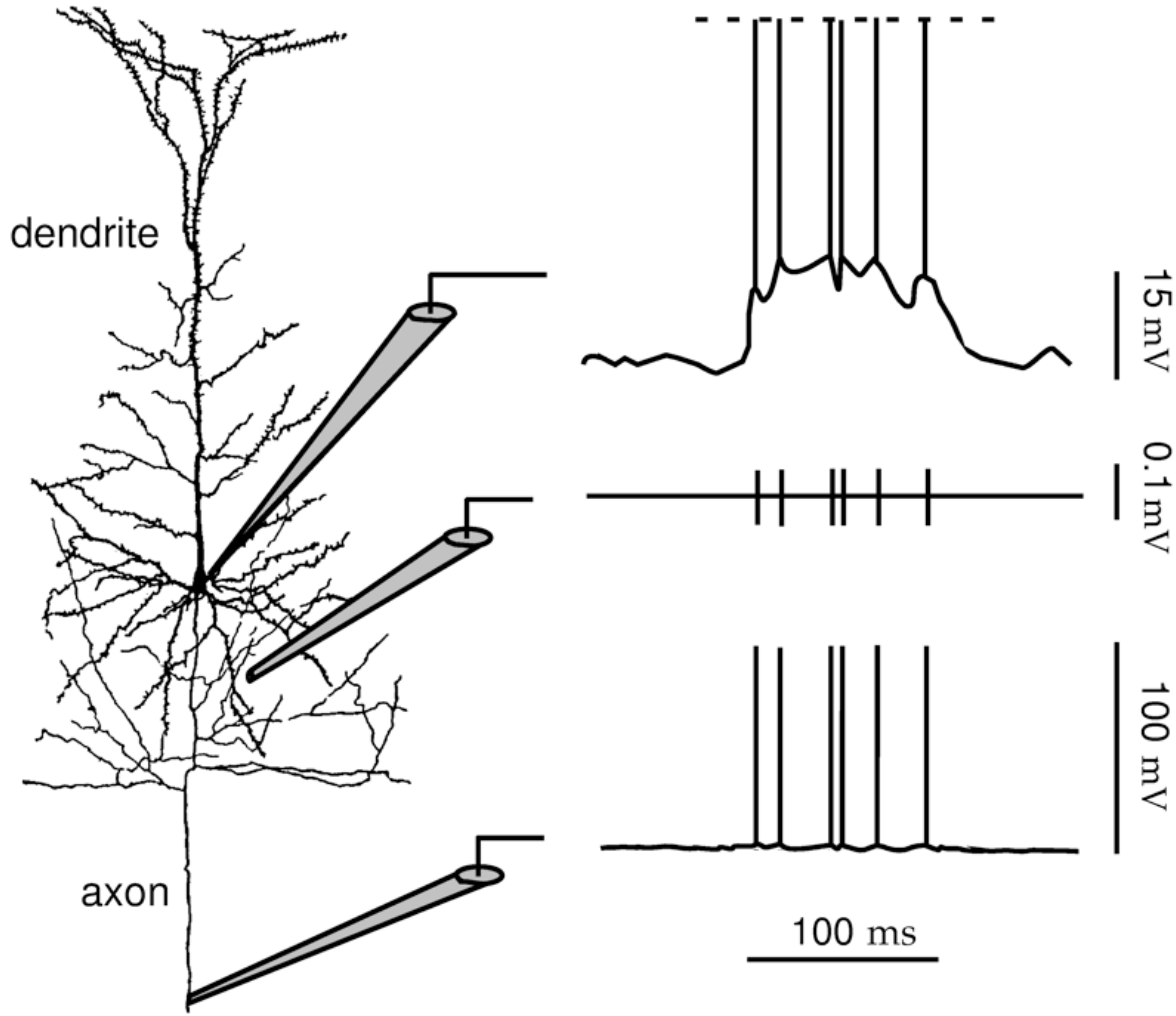
Emergent cognition from neural dynamics

- mental decisions, working memory..

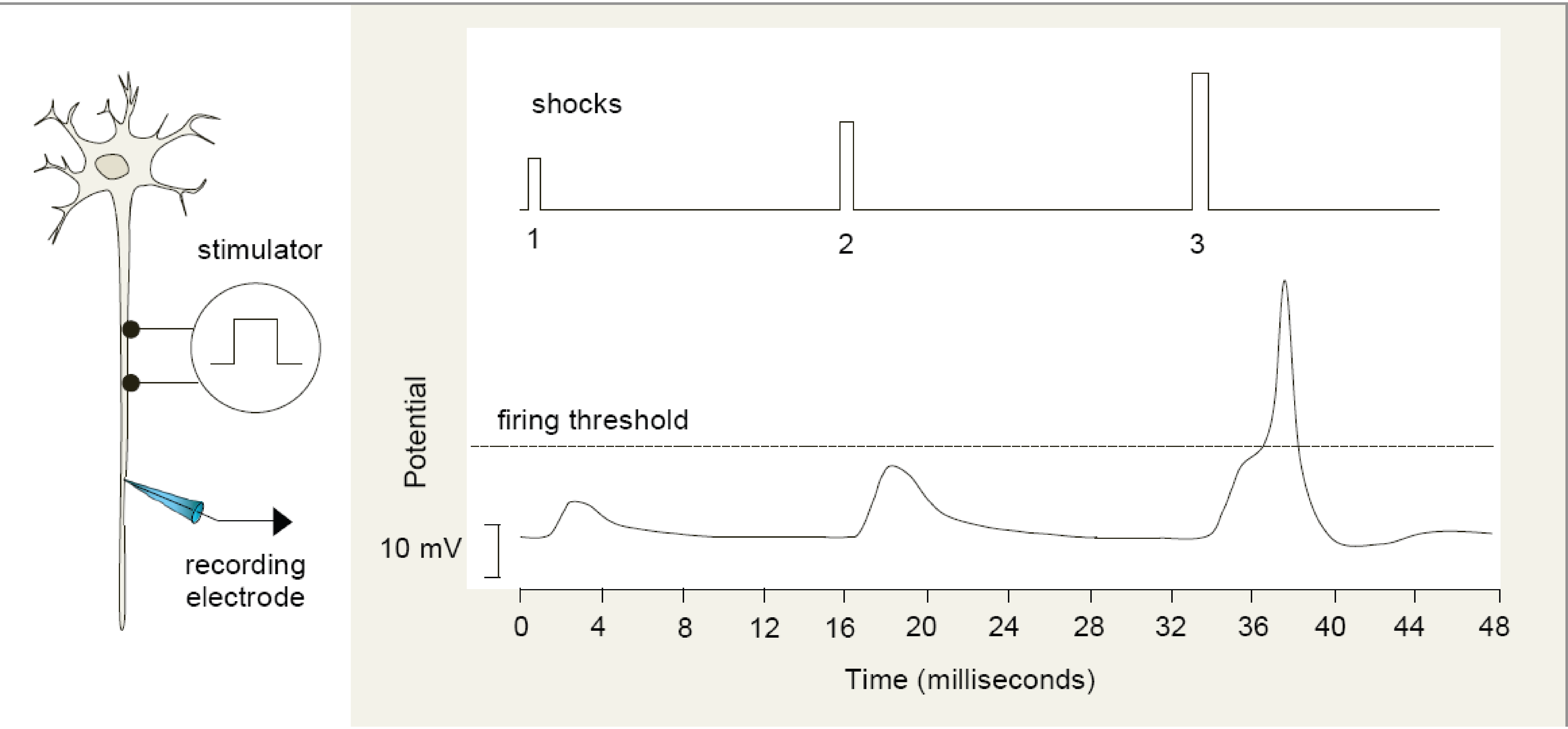


Neurons as input-output units

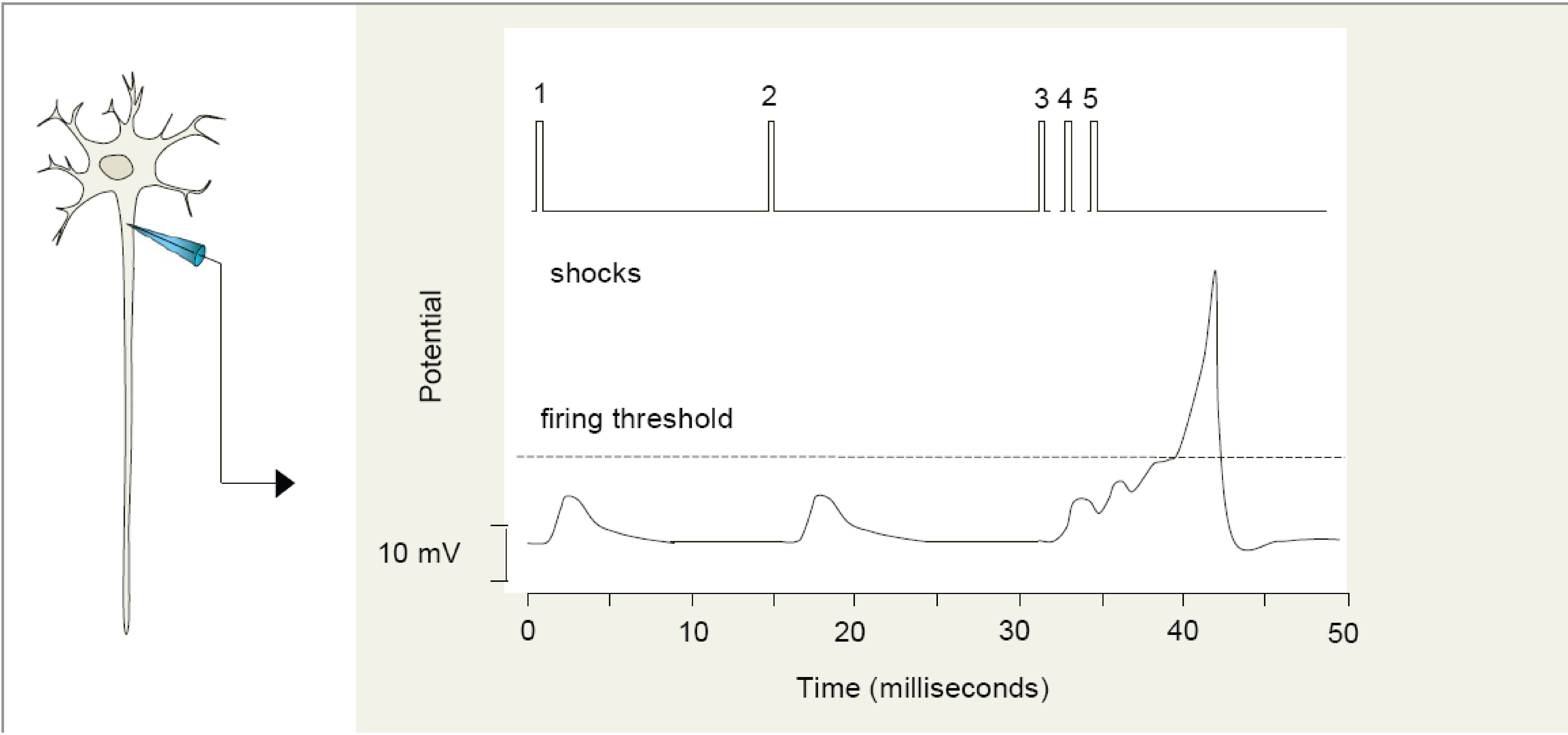
- inputs from dendrites
- spike formation at soma
- output at axon



threshold behavior

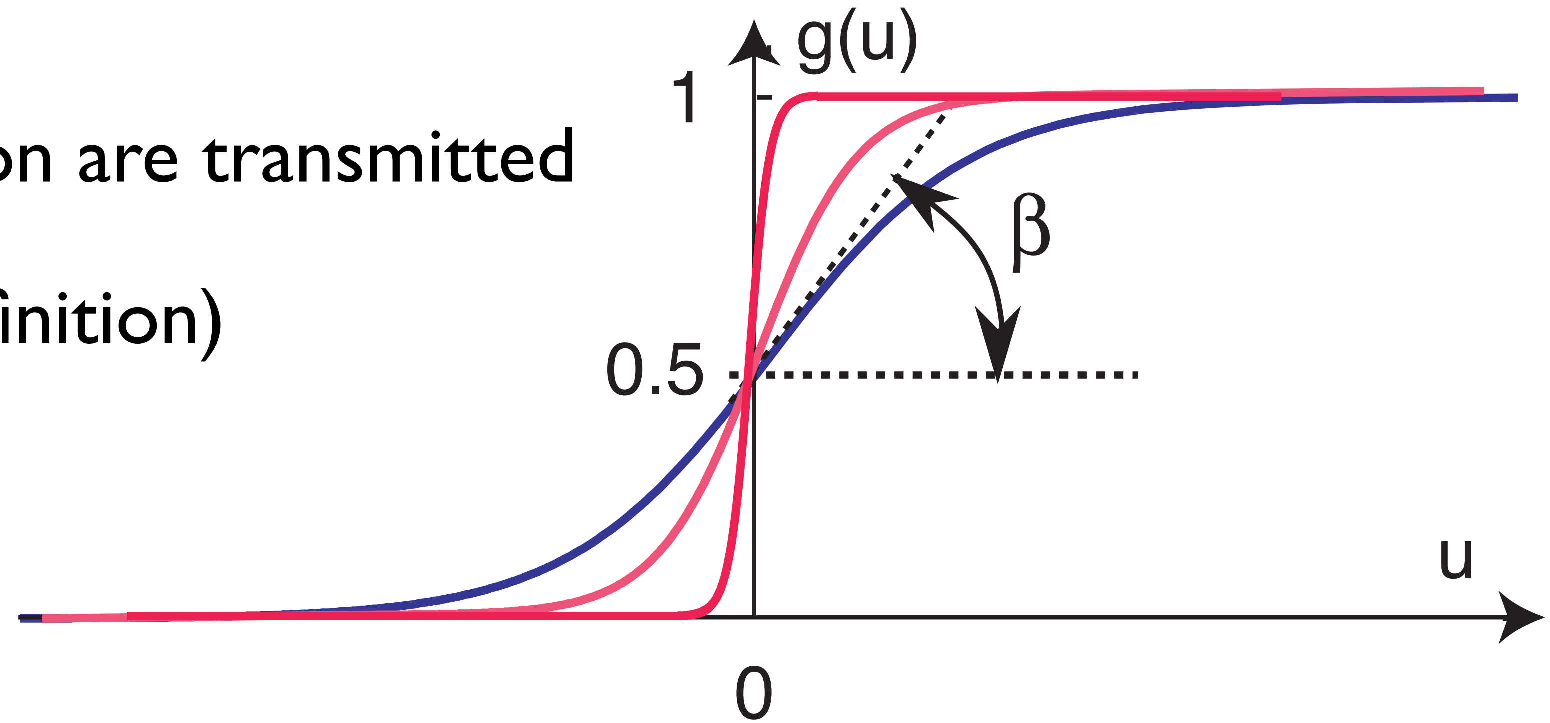


temporal summation



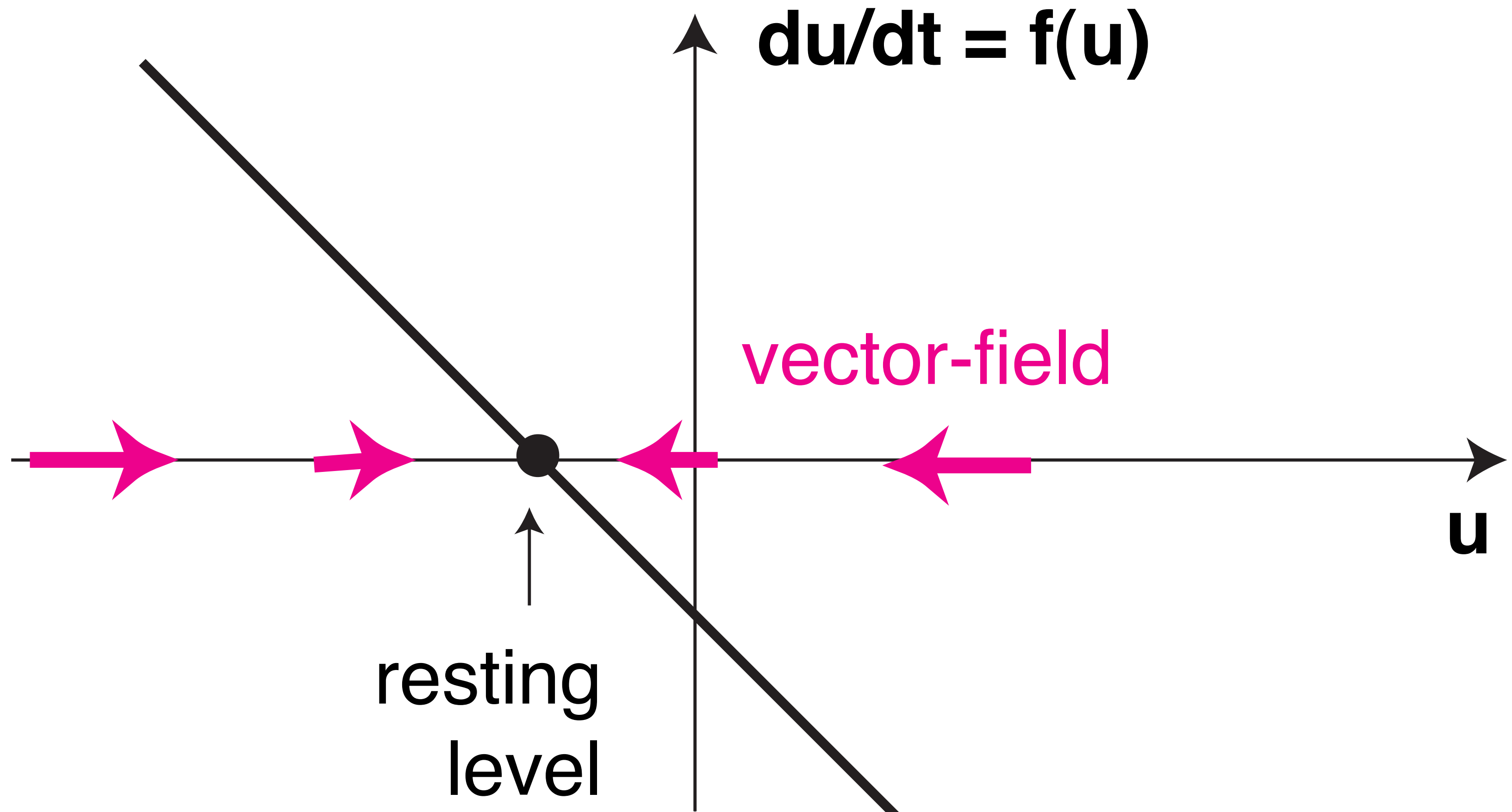
Neural dynamics

- replace spiking by a sigmoidal threshold function
- as an abstraction of the membrane potential
  - => low levels of activation are not transmitted (to other neural systems, to motor systems)
  - => high levels of activation are transmitted
  - threshold at zero (by definition)



Neural dynamics

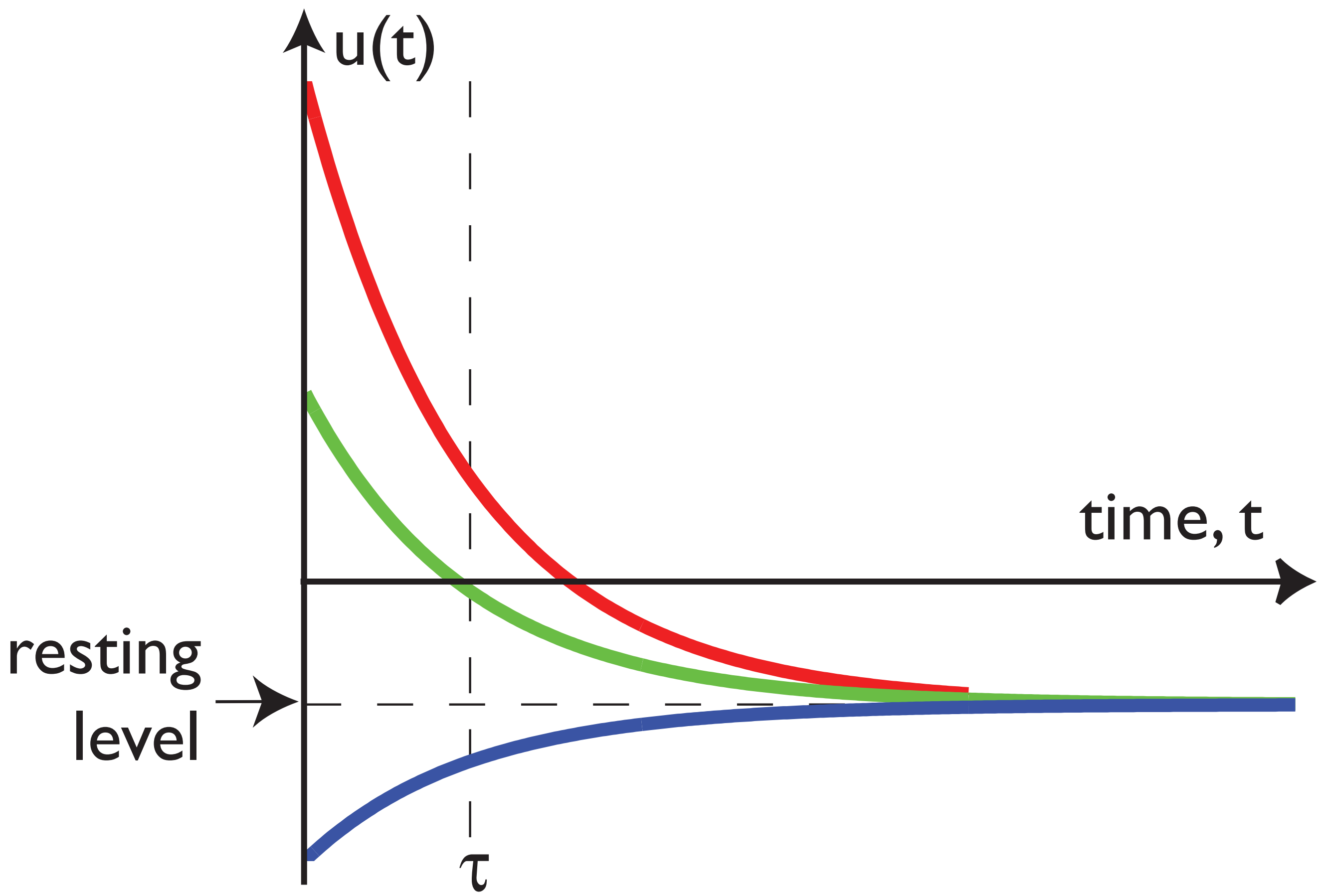
- stationary state=fixed point= constant solution
- stable fixed point: nearby solutions converge to the fixed point=attractor

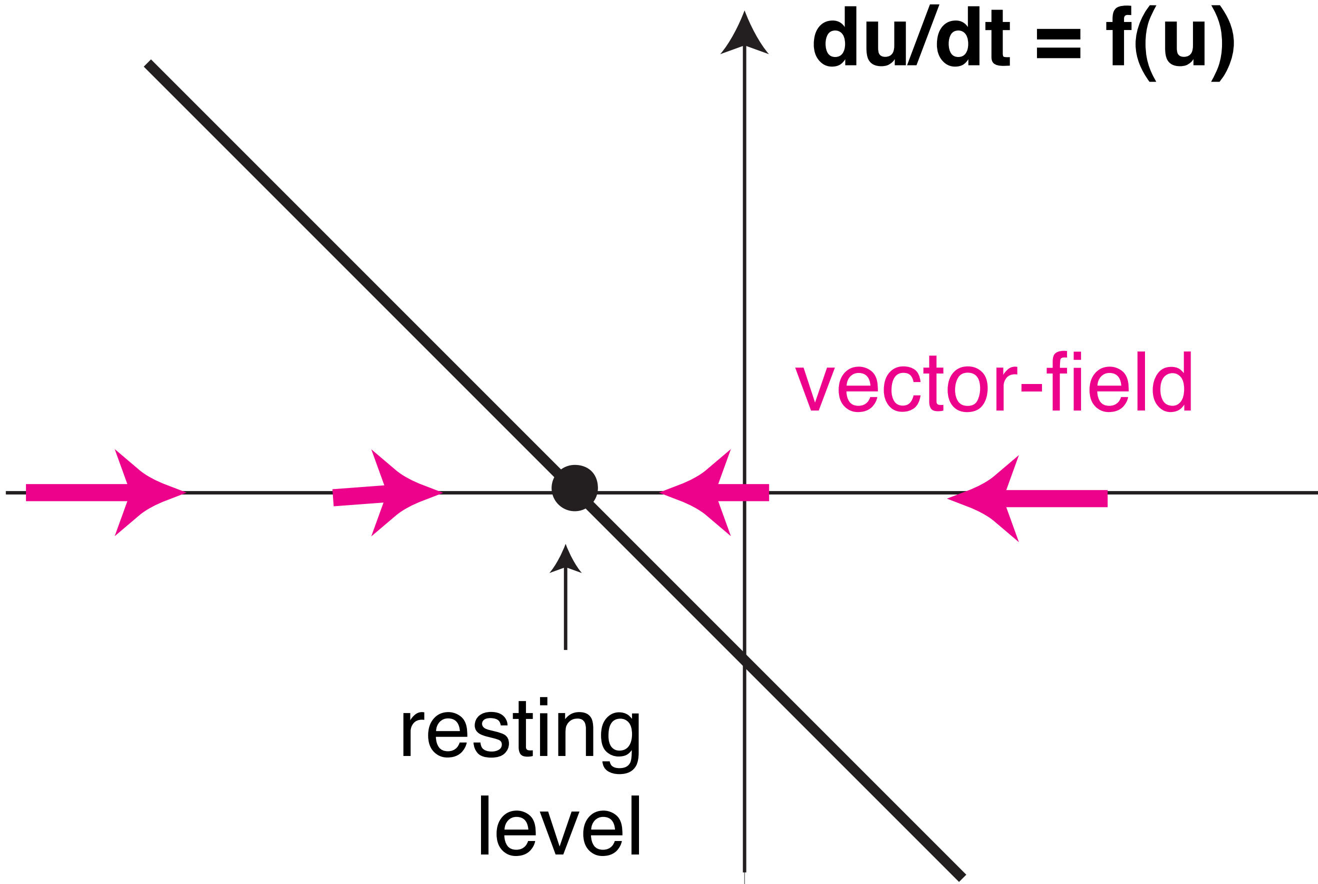


$$\frac{du(t)}{dt} = \dot{u}(t) = -u(t) + h \qquad (h < 0)$$

Neural dynamics

- attractor structures ensemble of solutions=flow

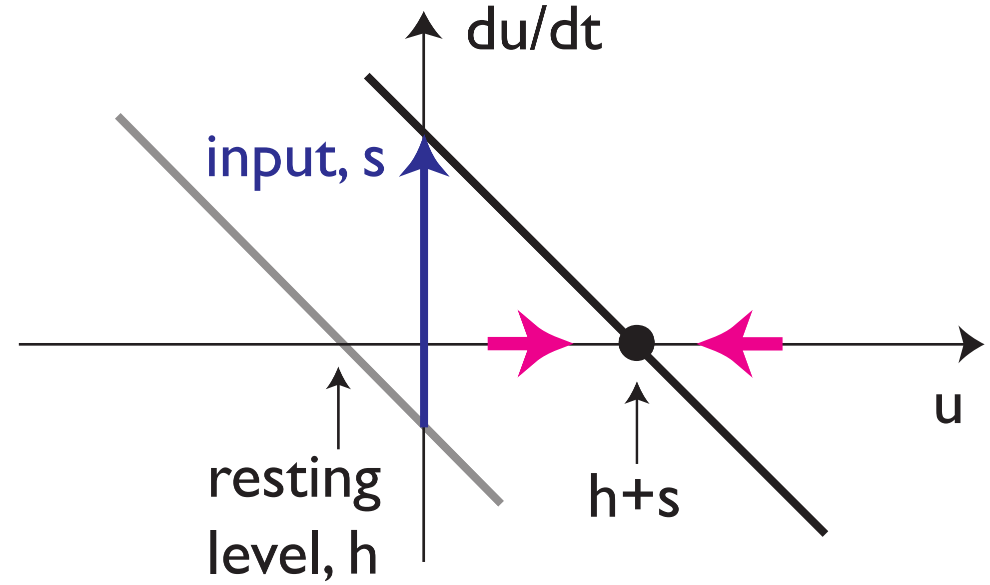


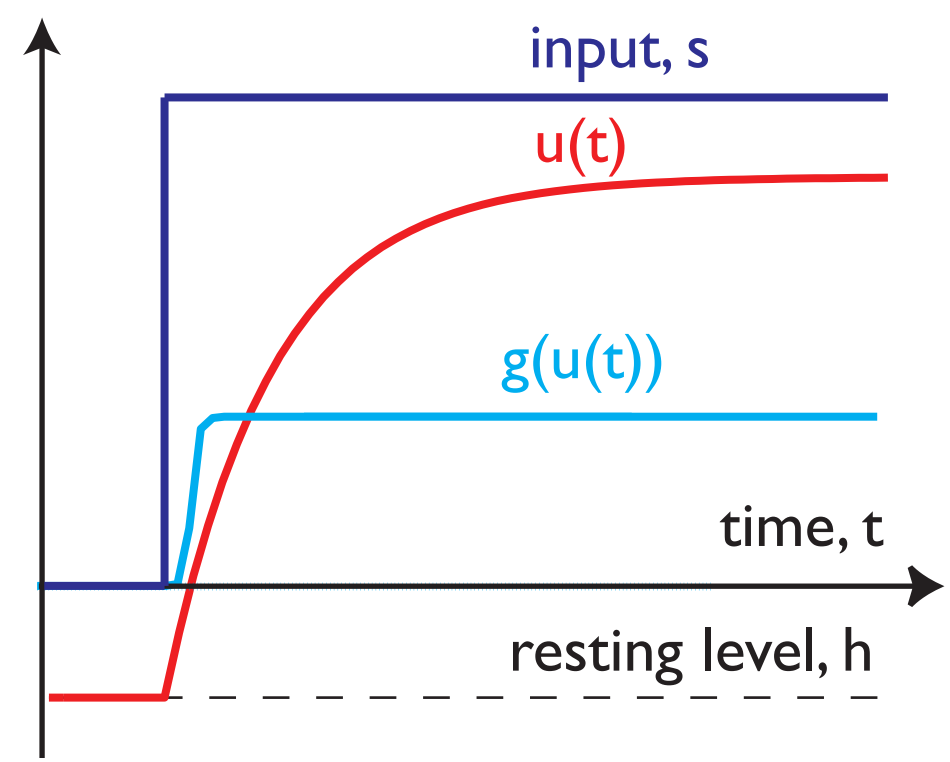


$$\tau \dot{u}(t) = -u(t) + h$$

Neuronal dynamics

- inputs=contributions to the rate of change
  - positive: excitatory
  - negative: inhibitory
- => shifts the attractor
- activation tracks this shift (stability)

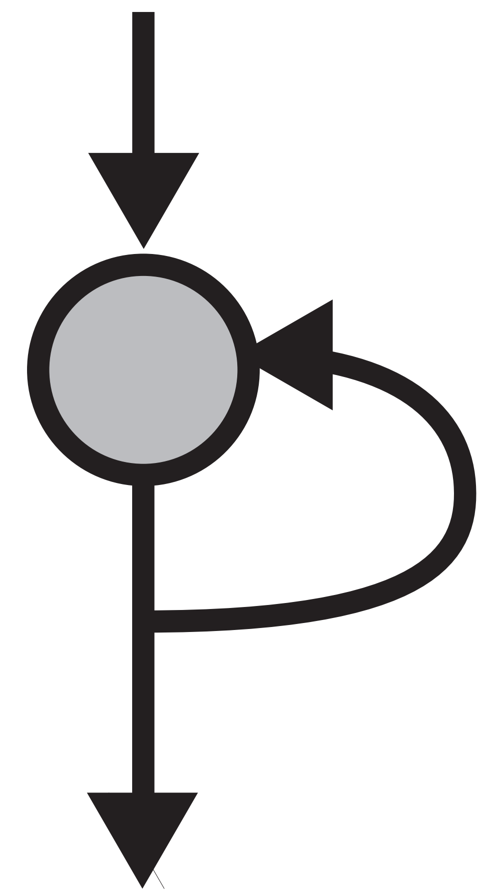




$$\tau\dot{u}(t) = -u(t) + h + \text{ inputs(t)}$$

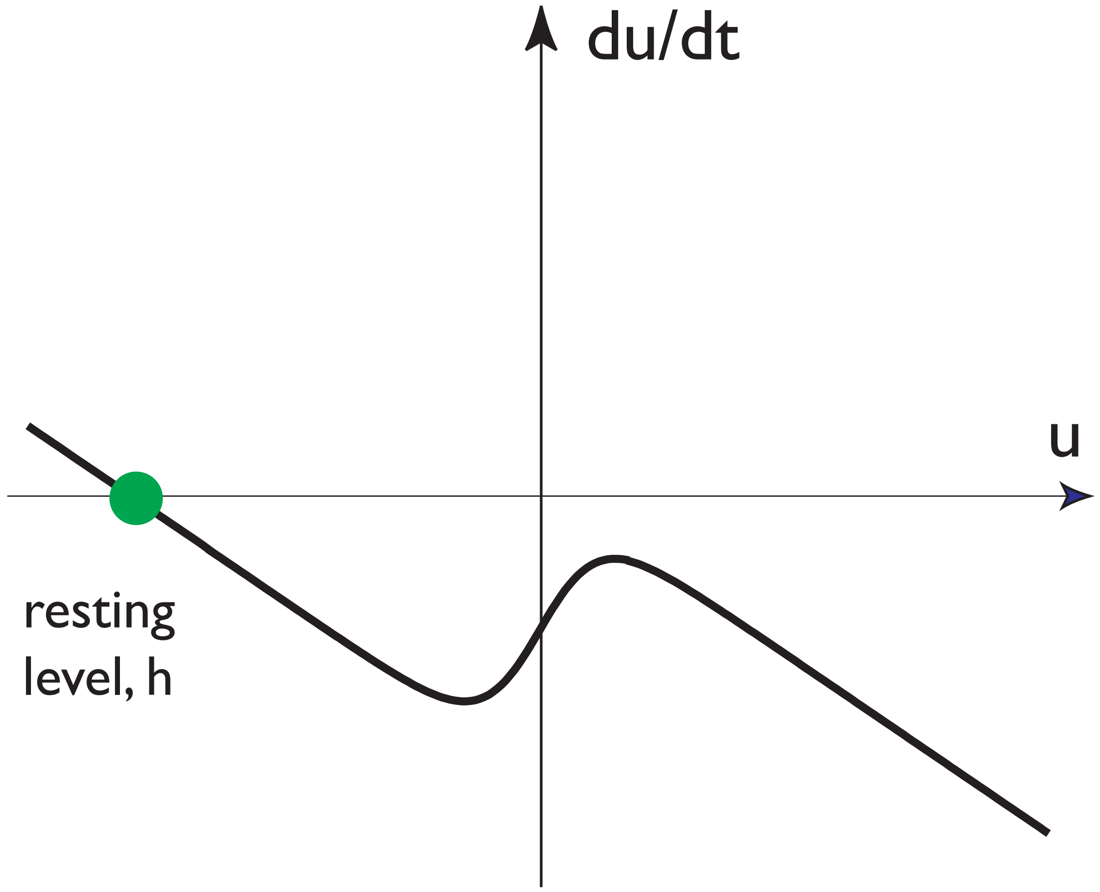
Neuronal dynamics with self-excitation

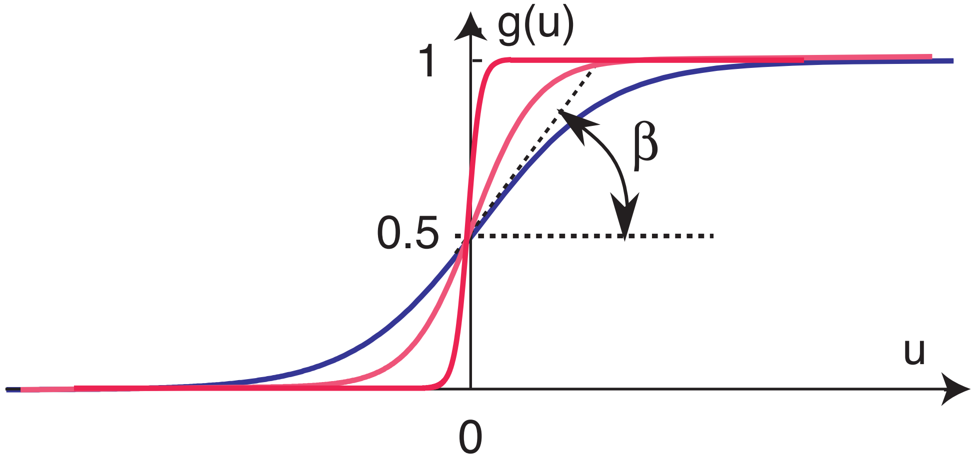
- single activation variable with self-excitation
- representing a small population with excitatory coupling



$$\tau \dot{u}(t) = -u(t) + h + s(t) + c\ \sigma(u(t))$$

Neuronal dynamics with self-excitation



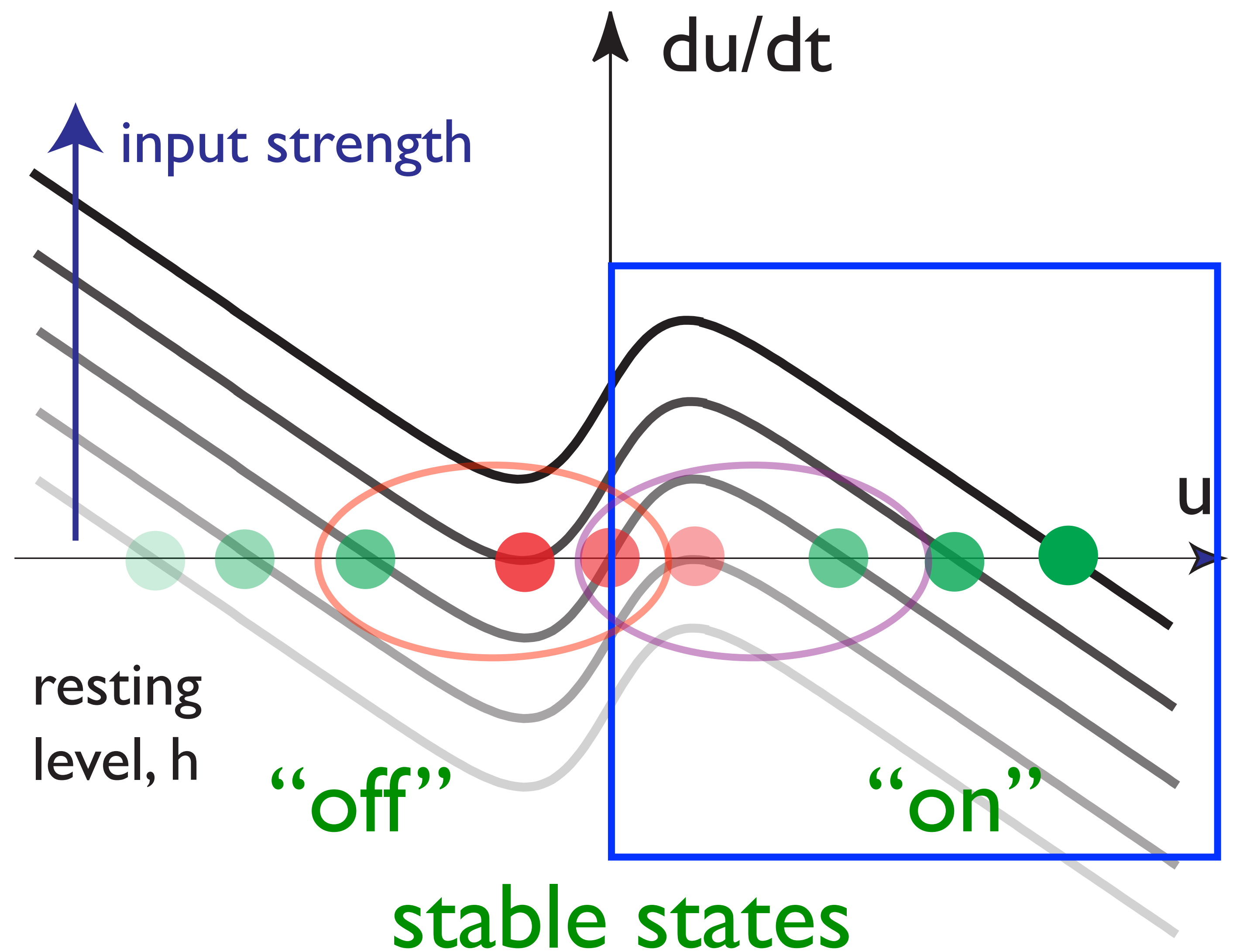


$$\tau \dot{u}(t) = -u(t) + h + S(t) + c\sigma(u(t))$$

Stability from neural dynamics

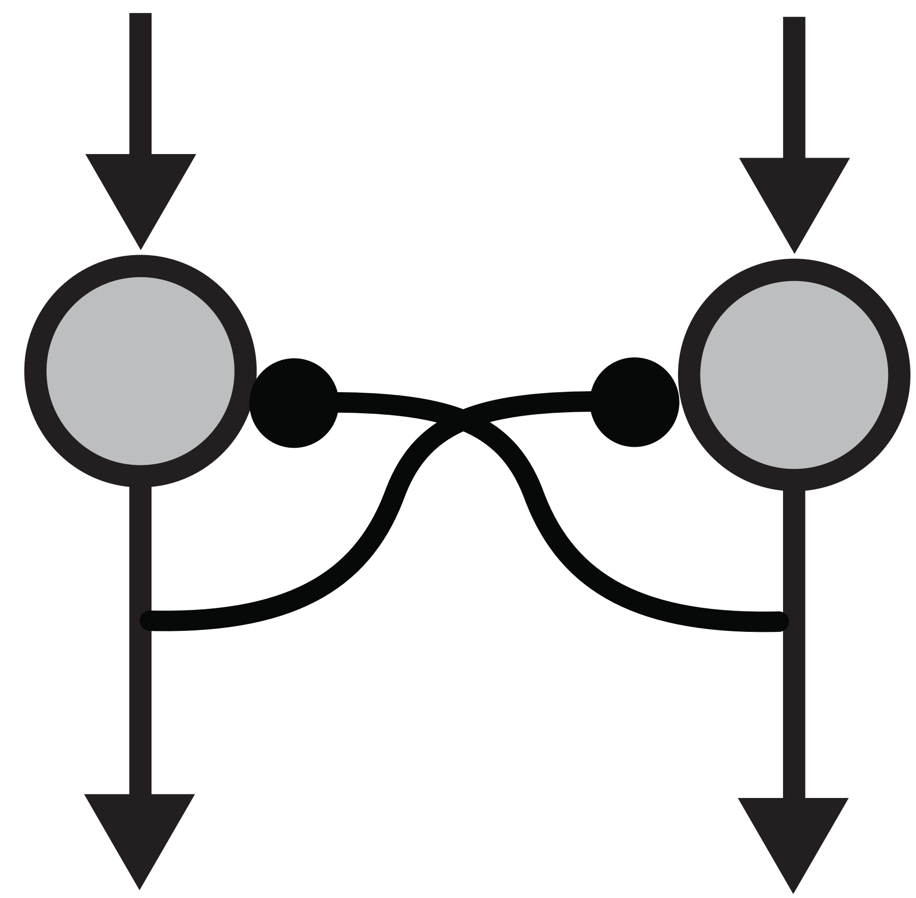
- autonomous activation from interaction
- $\dot{u}(t) = -u(t) + h + \text{input}(t) + \sigma(u(t))$

- detection instability
- working memory
- reverse detection instability



Neuronal dynamics with competition

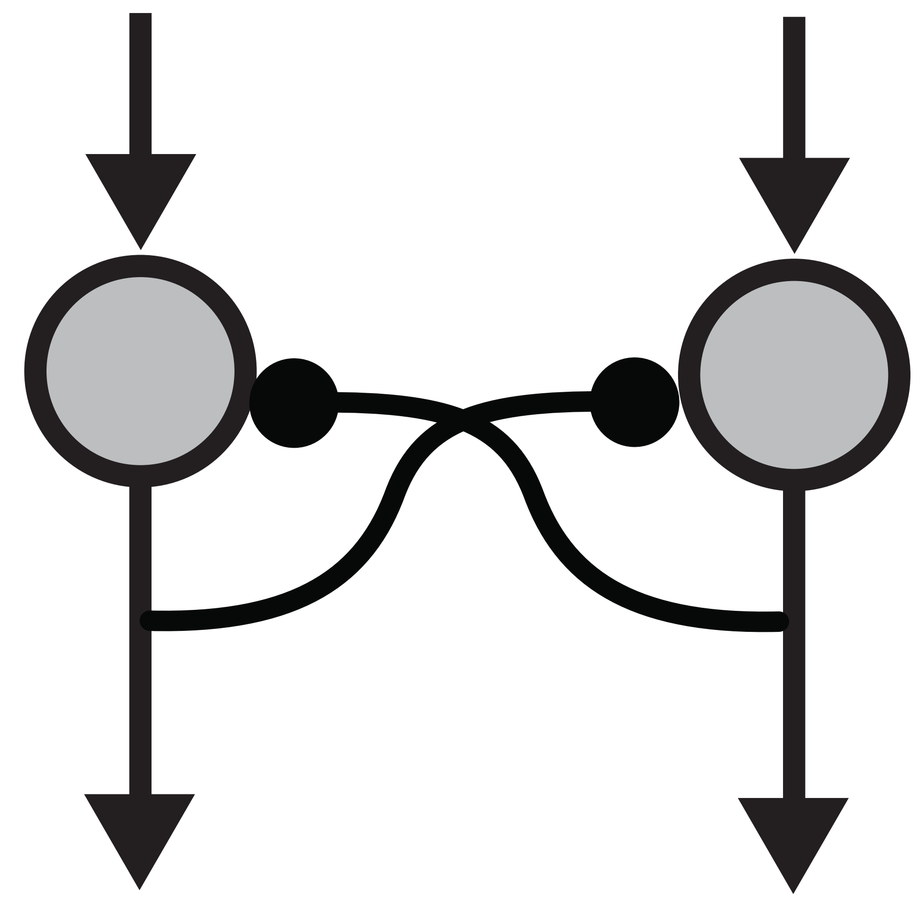
- two activation variables with reciprocal inhibitory coupling
- representing two small populations that are inhibitorily coupled



$$\tau\dot{u}_1(t) = -u_1(t) + h + s_1(t) - c_{12}\sigma(u_2(t))$$
$$\tau\dot{u}_2(t) = -u_2(t) + h + s_2(t) - c_{21}\sigma(u_1(t))$$

Neuronal dynamics with competition

- Coupling: the rate of change of one activation variable depends on the level of activation of the other activation variable



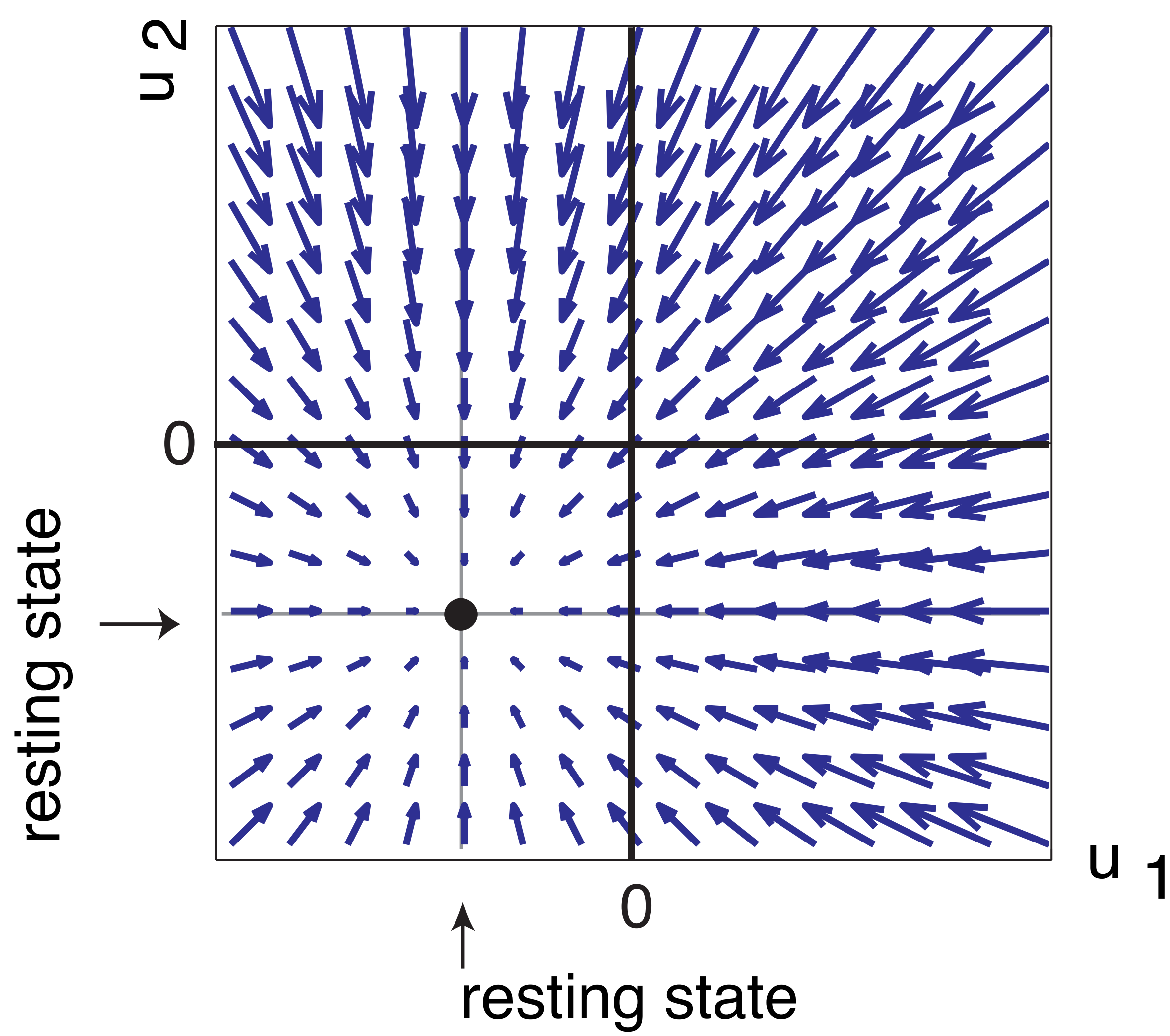
coupling

$$\tau \dot{u}_1(t) = -u_1(t) + h + s_1(t) - c_{12}\sigma(u_2(t))$$

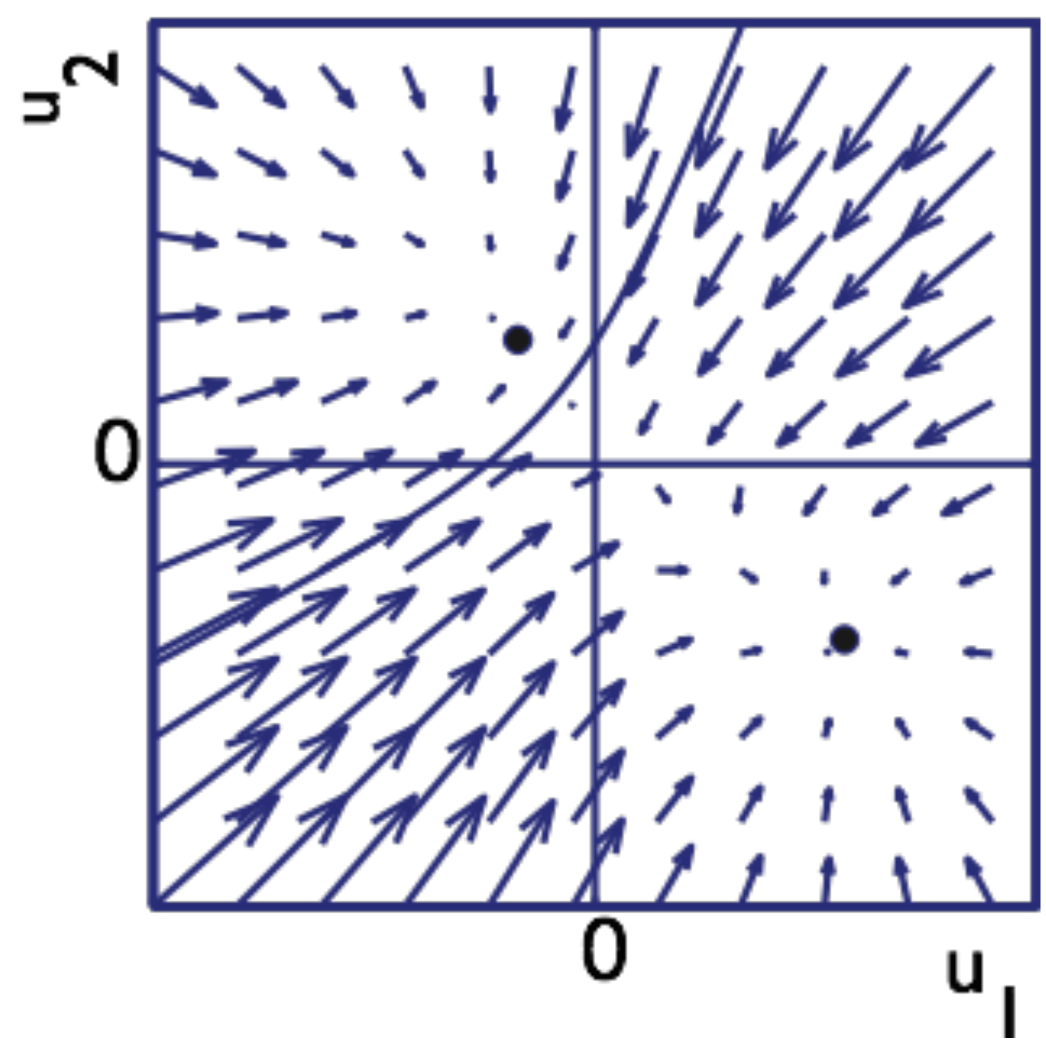
$$\tau \dot{u}_2(t) = -u_2(t) + h + s_2(t) - c_{21}\sigma(u_1(t))$$

Neuronal dynamics with competition
=>biased competition

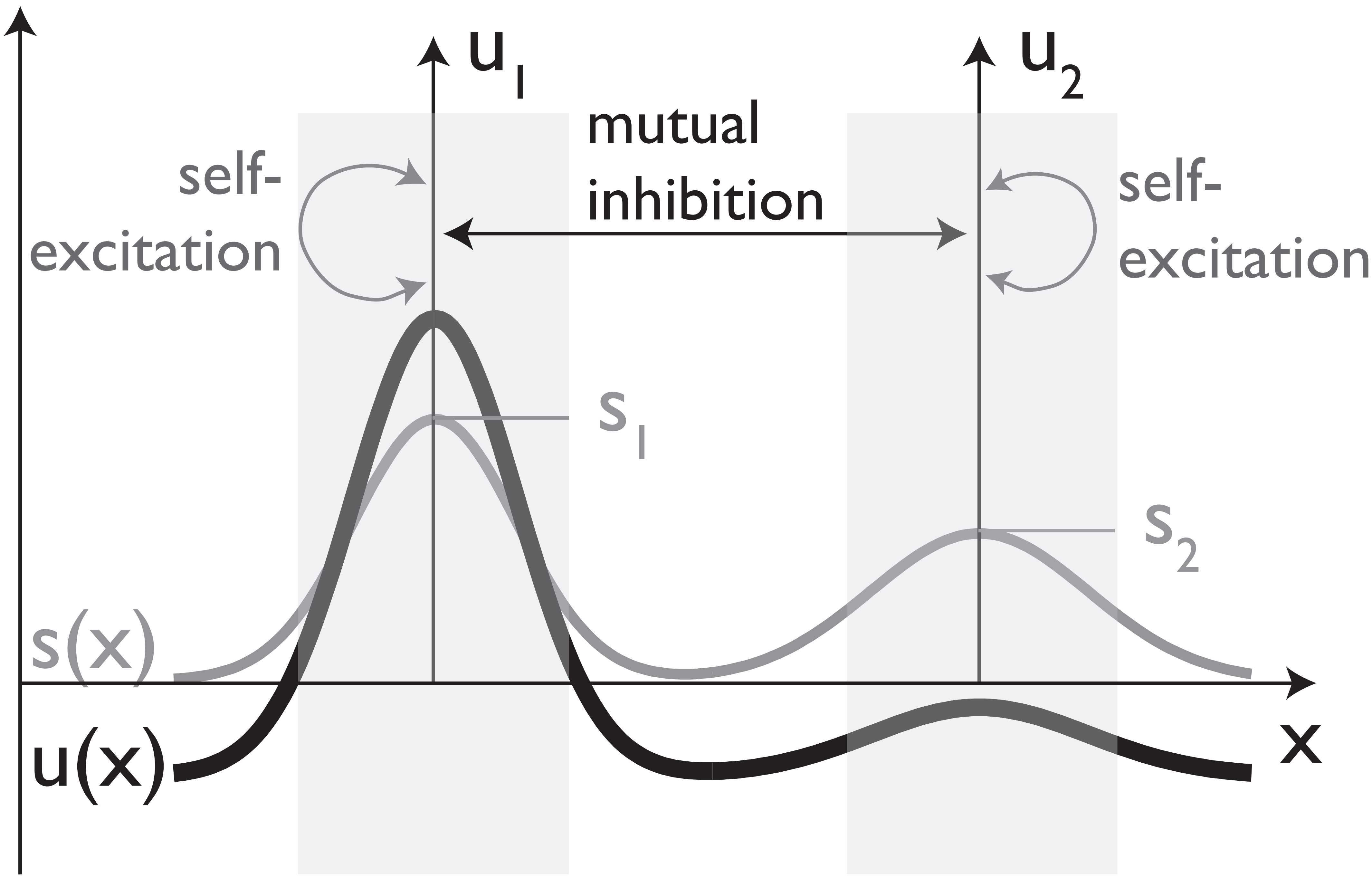
before input is presented



after input is presented



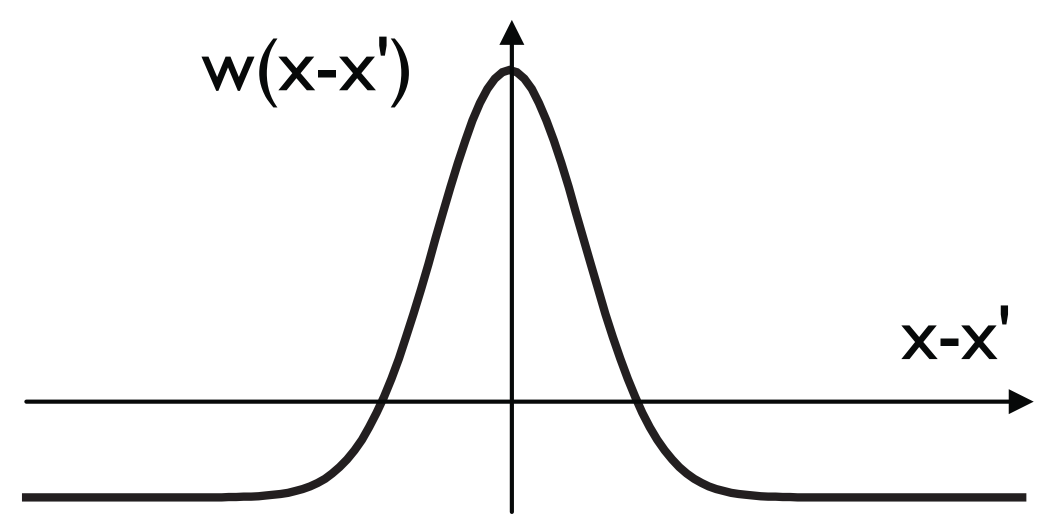
Neural fields



Neural fields

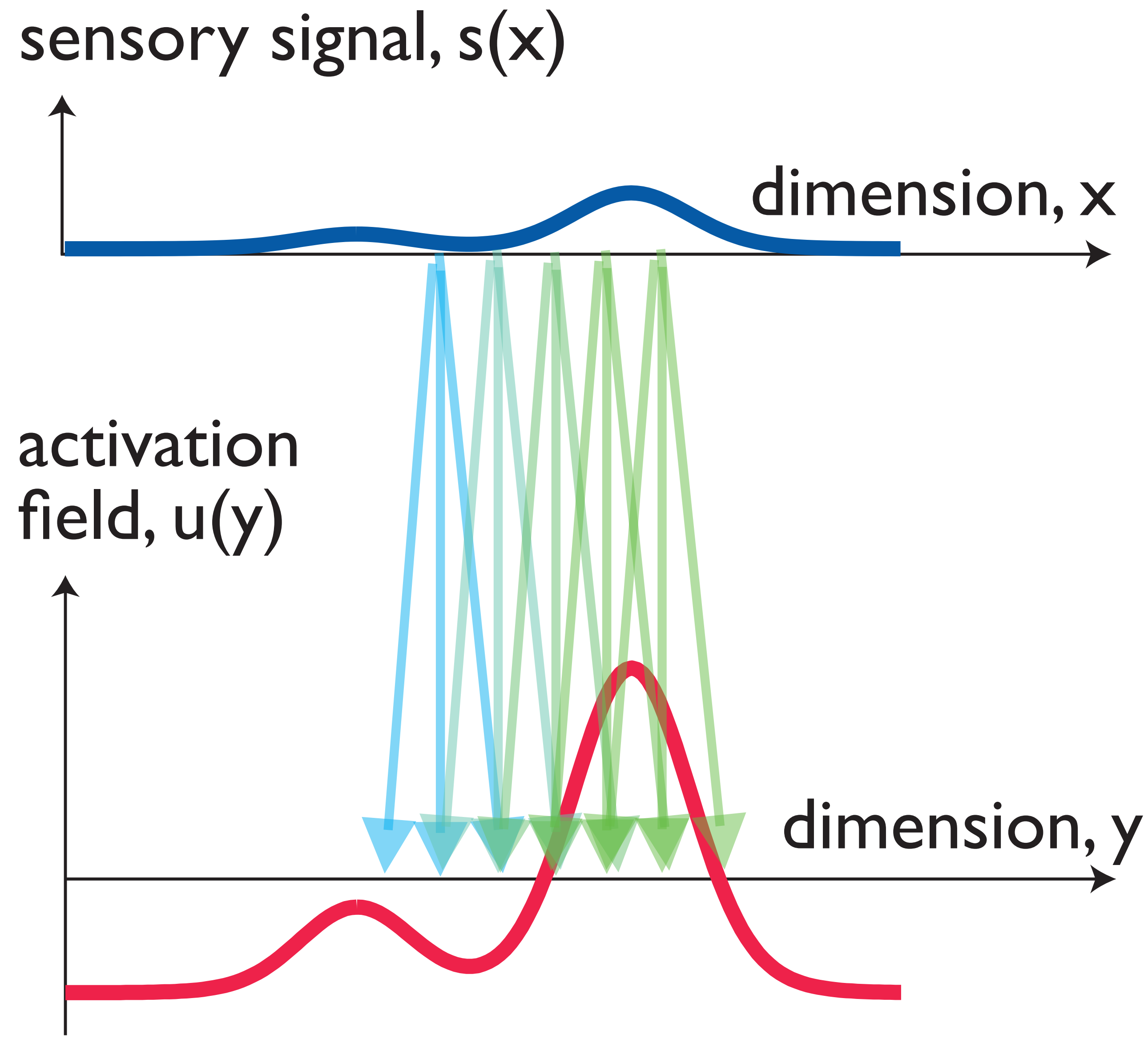
- … the same underlying math
- coupling among continuously many activation variables
- local excitatory coupling (“self-excitation”)
- global inhibitory coupling (“mutual inhibition”)

$$\tau \dot{u}(x,t) = -u(x,t) + h + s(x,t) + \int dx' w(x-x')\ \sigma(u(x',t))$$

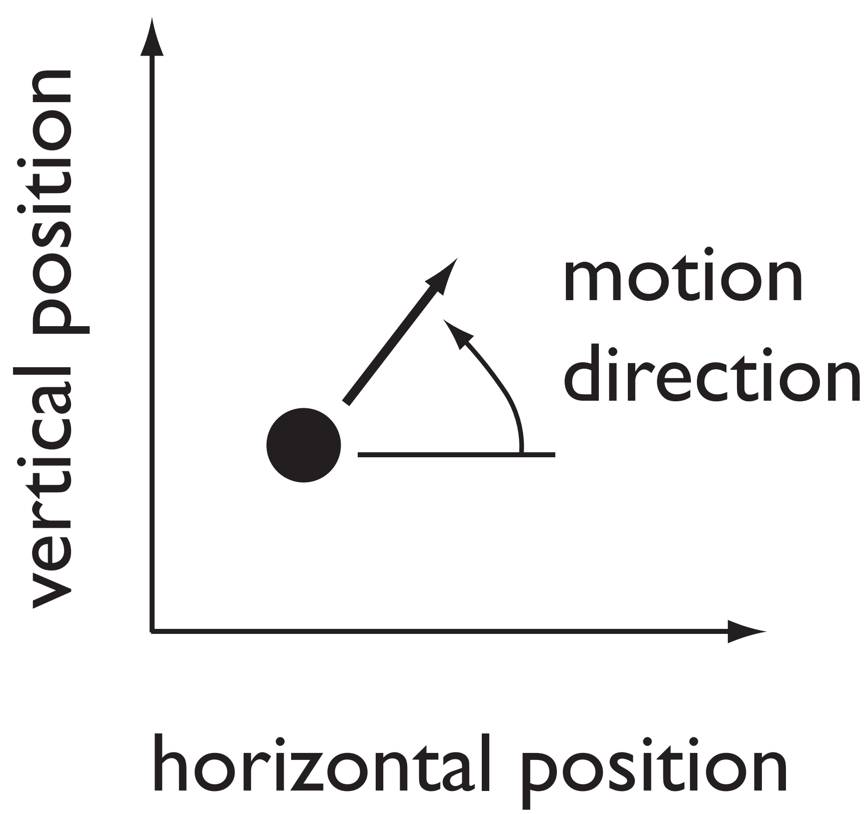


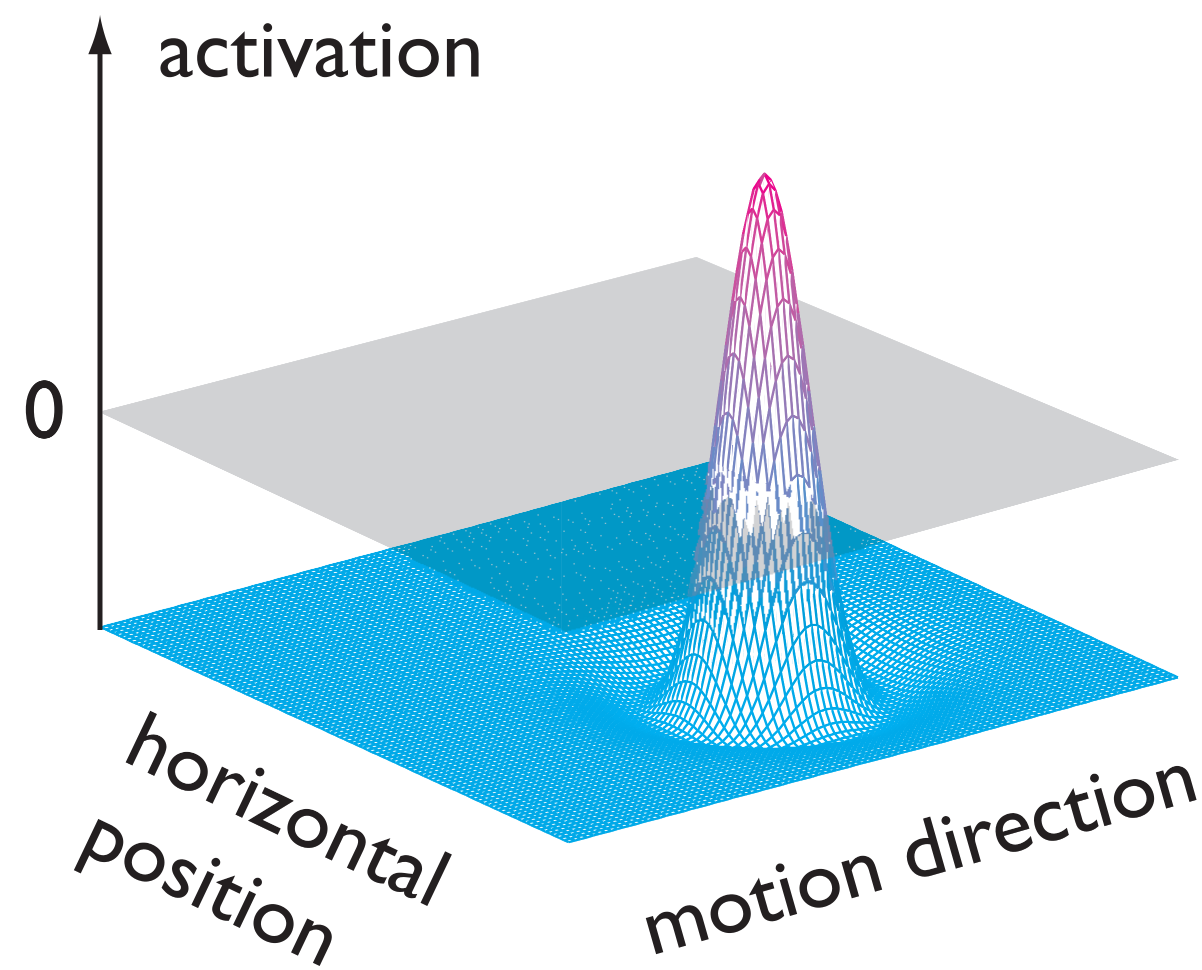
Neural fields

- forward connectivity thus generates a map from sensory surface to feature dimension
- neglect the sampling by individual neurons => activation fields



Example motion perception: space of possible percepts



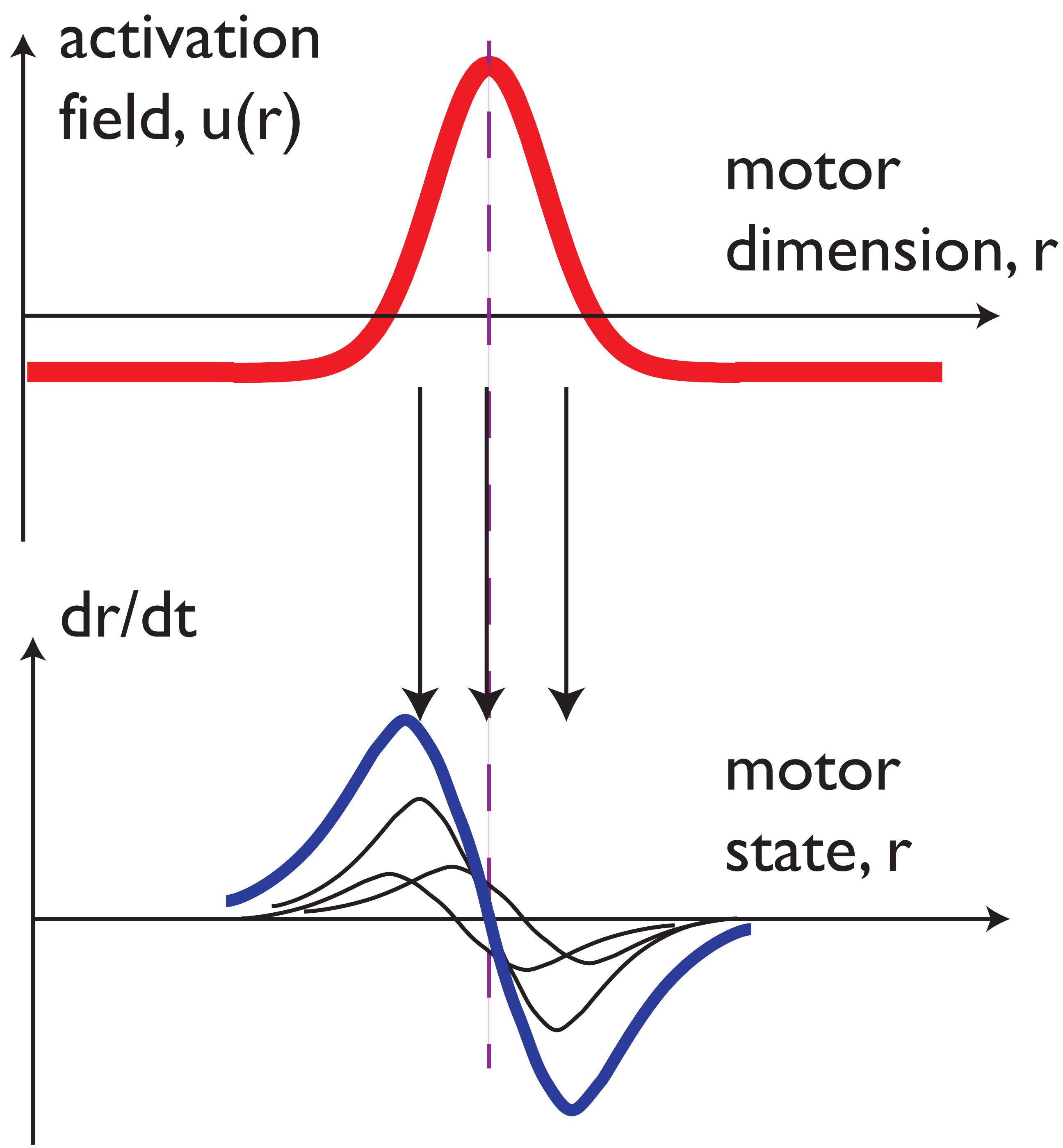


Neural fields

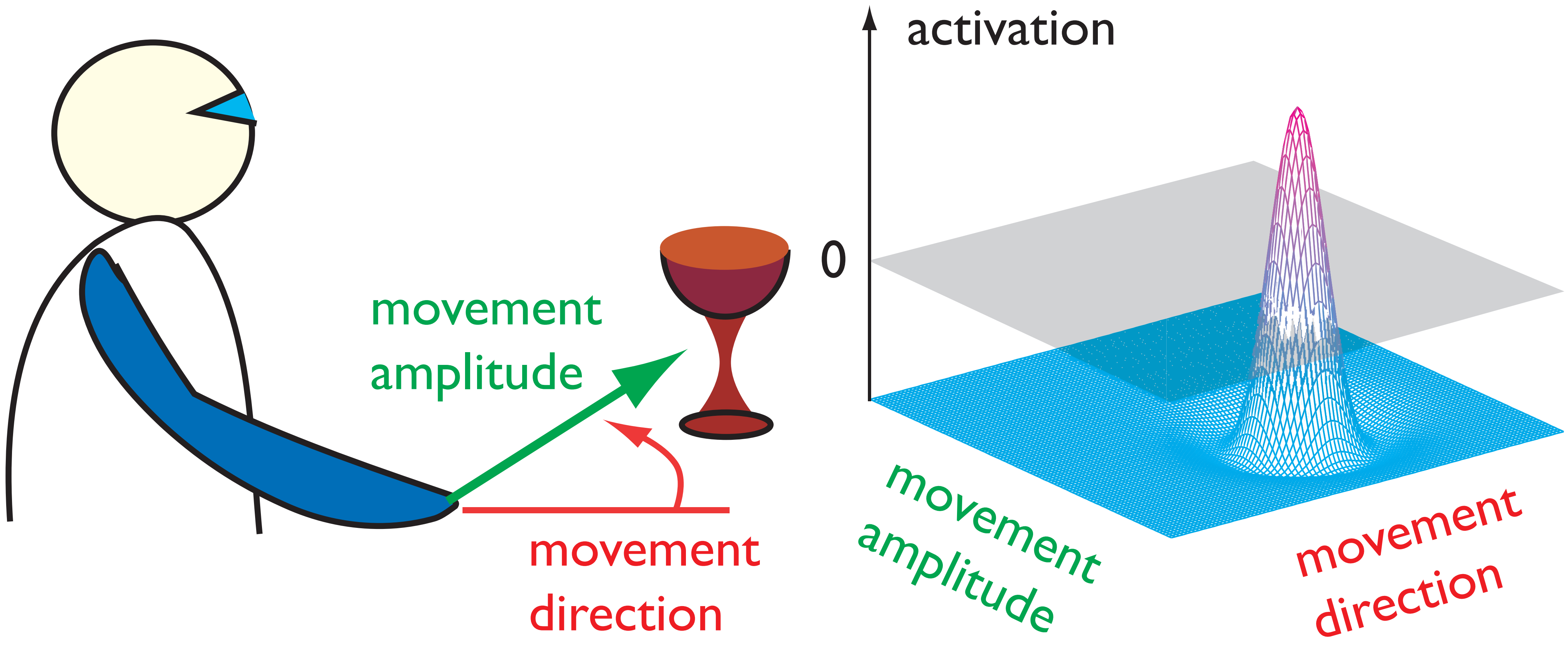
gous notion for
rd connectivity to
r surfaces…

lly involves
ioral dynamics)

through neural oscillators
eripheral reflex loops)



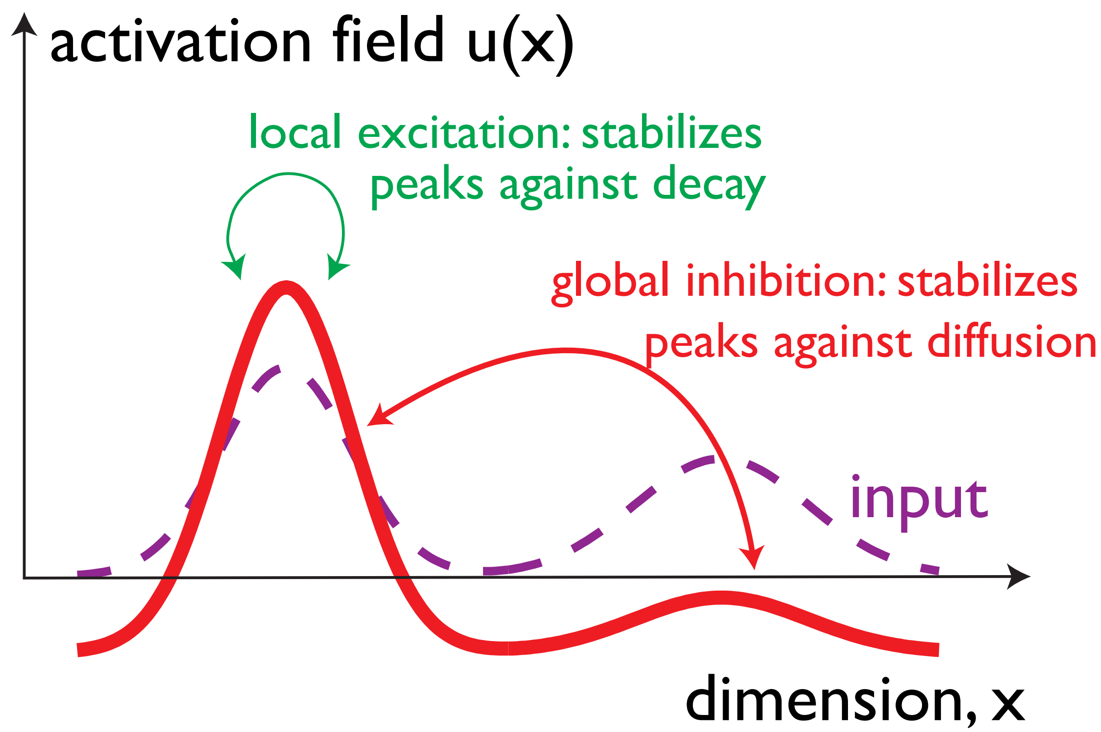
Example: movement planning: space of possible actions

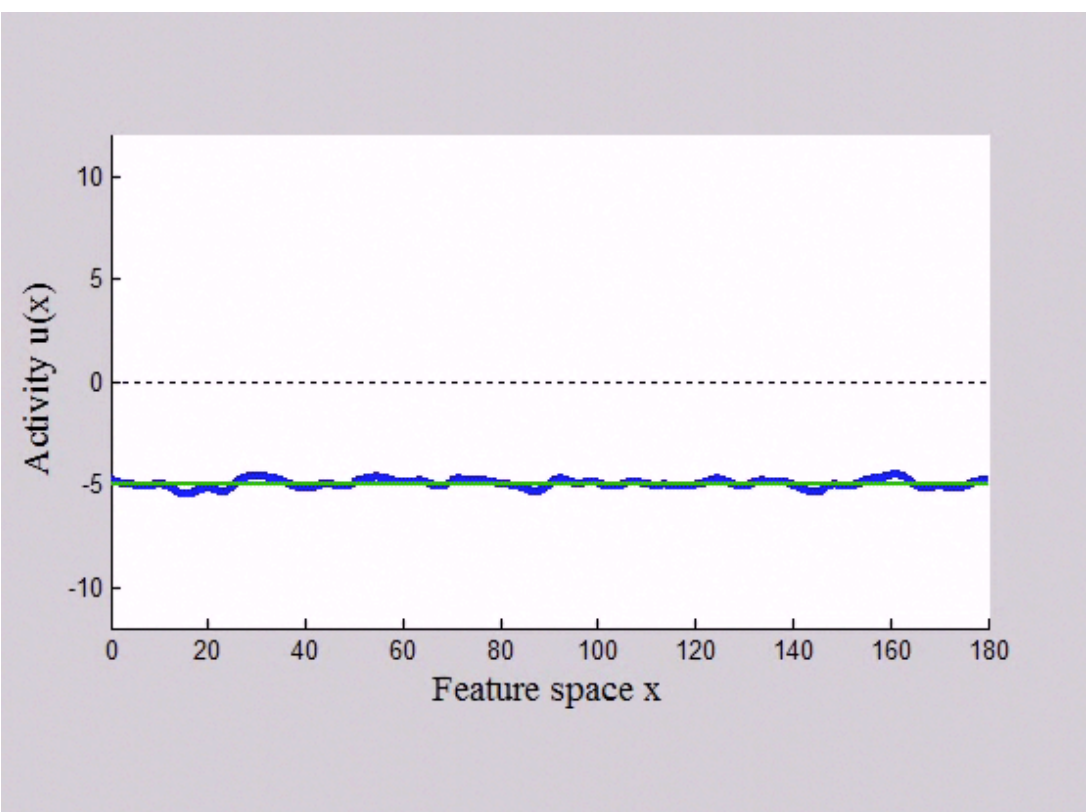


Detection

Dynamic of neural fields

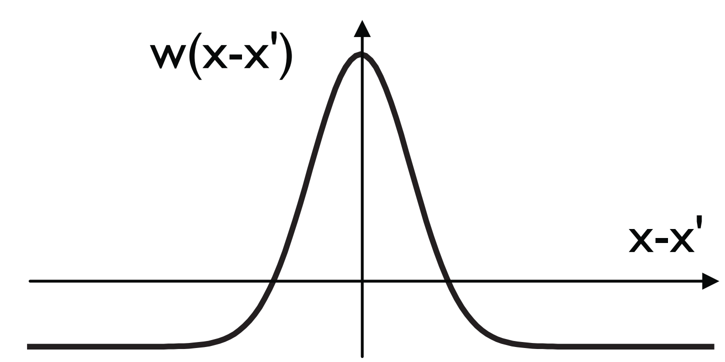
- peaks as attractors
- detection instability
- working memory
- selection





$$\tau \dot{u}(x,t) = -u(x,t) + h + s(x,t)$$

$$+ \int dx' w(x-x')\ g(u(x',t))$$



Attractors and their instabilities

- input driven solution (sub-threshold)
- self-stabilized solution (peak, supra-threshold)
- selection / selection instability
- working memory / memory instability
- boost-driven detection instability

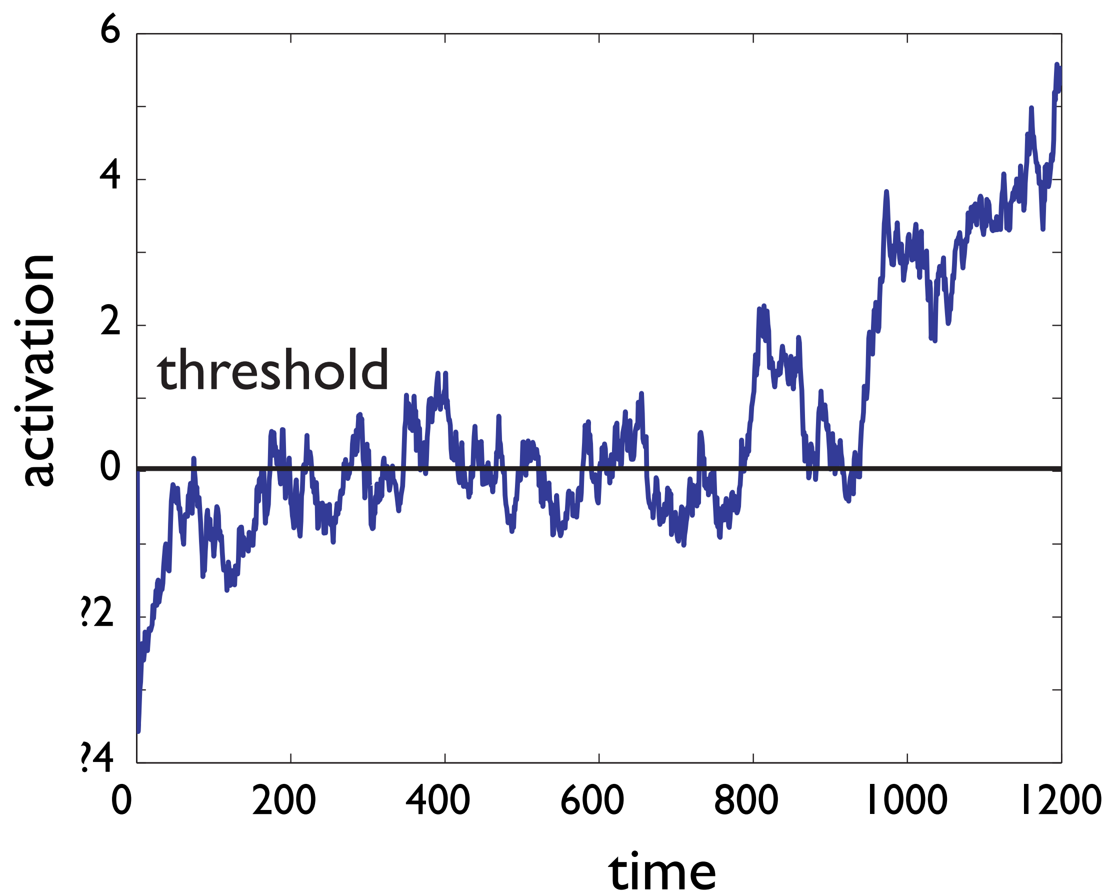
↓ detection instability

↑ reverse detection instability

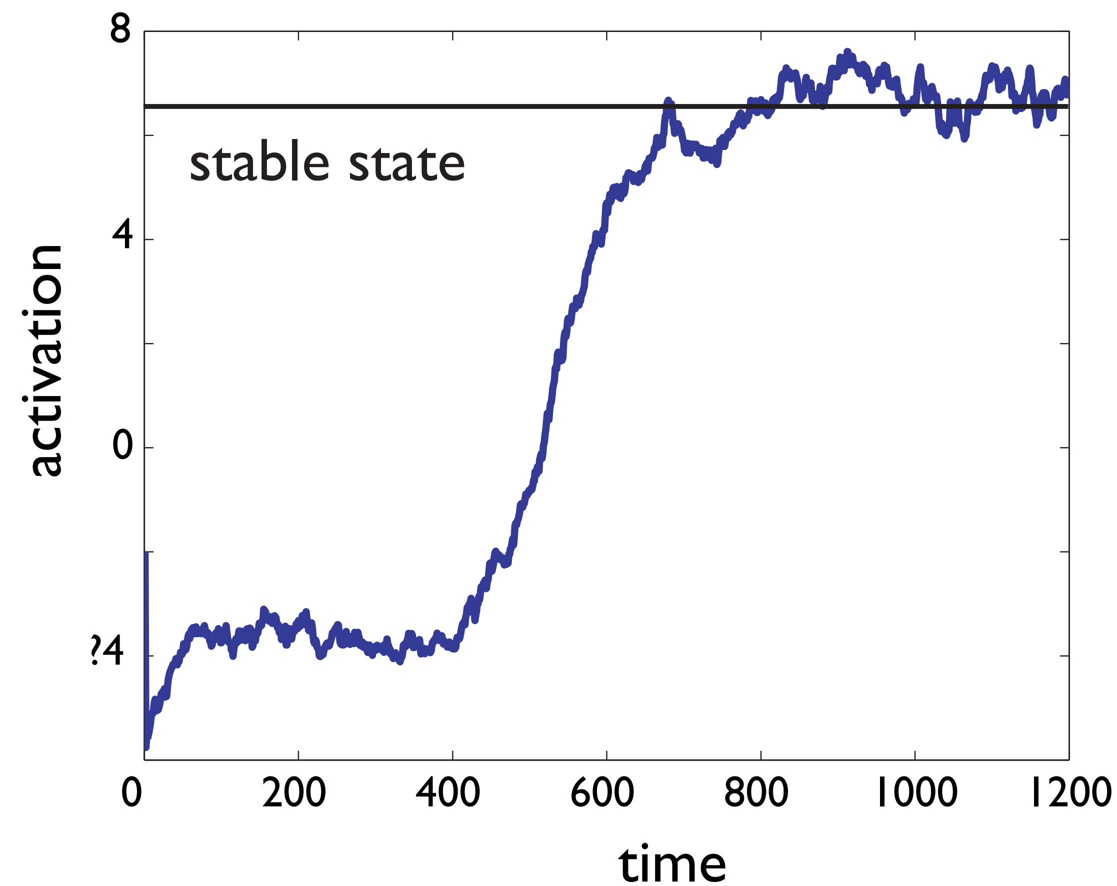
Noise is critical near instabilities

The detection instability stabilizes decisions

threshold piercing

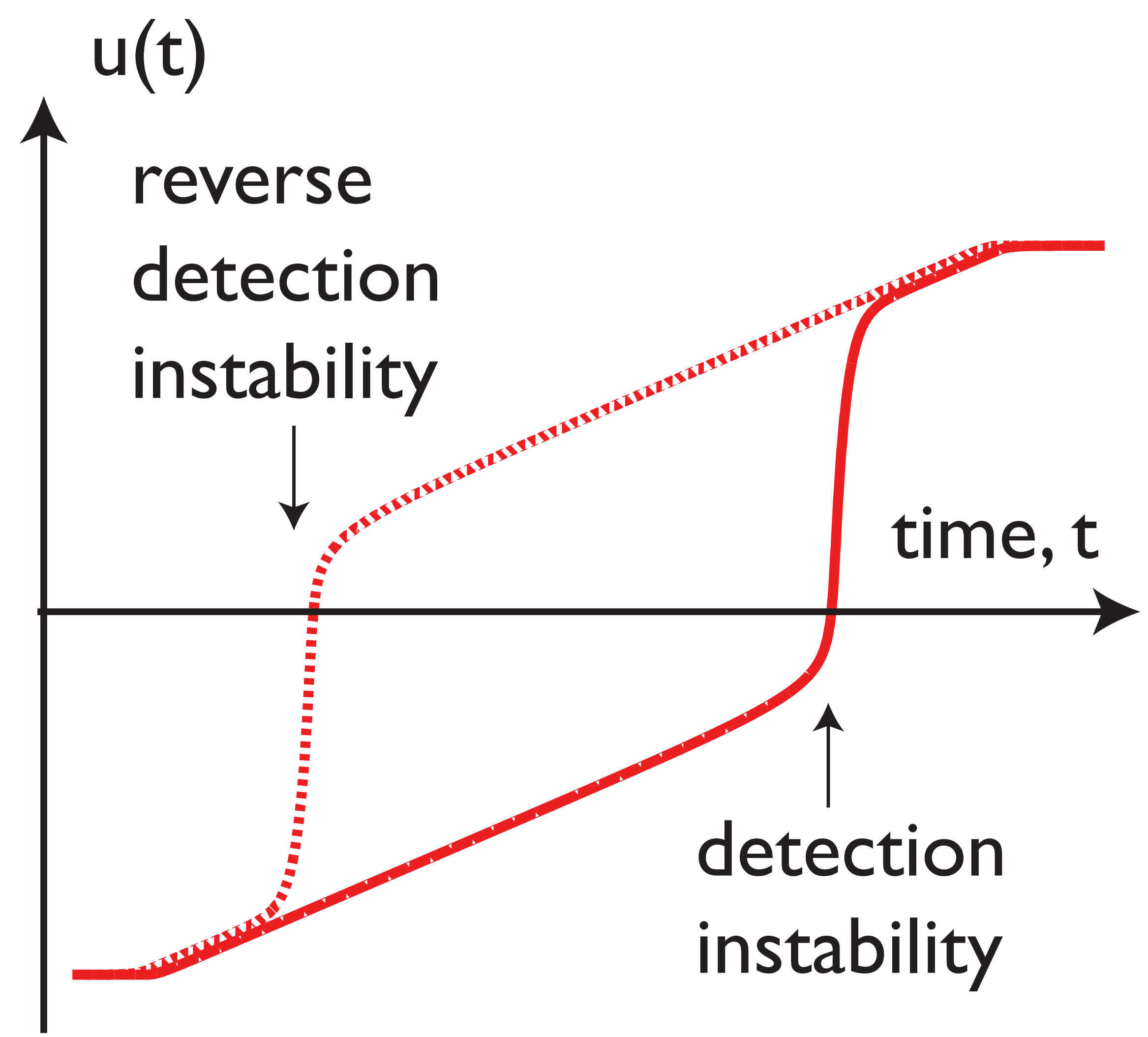


detection instability

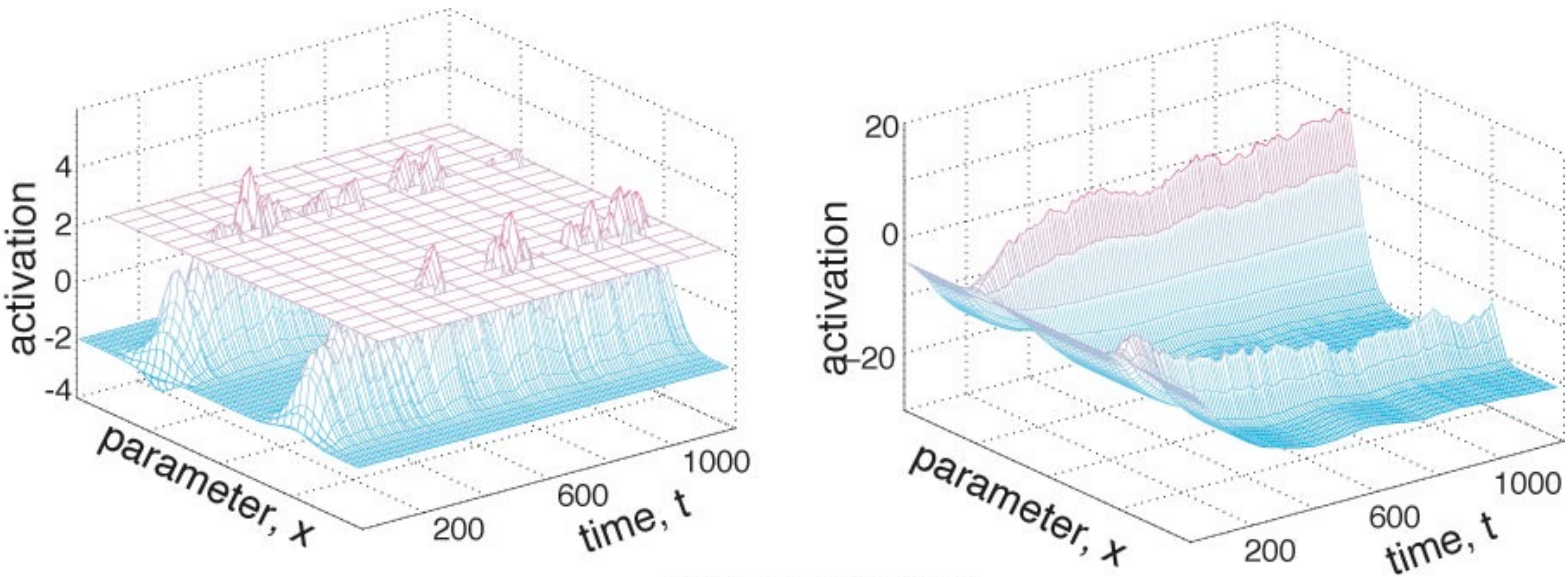


The detection instability leads to the emergence of events

- the detection instability explains how a time-continuous neuronal dynamics may create macroscopic events at discrete moments in time

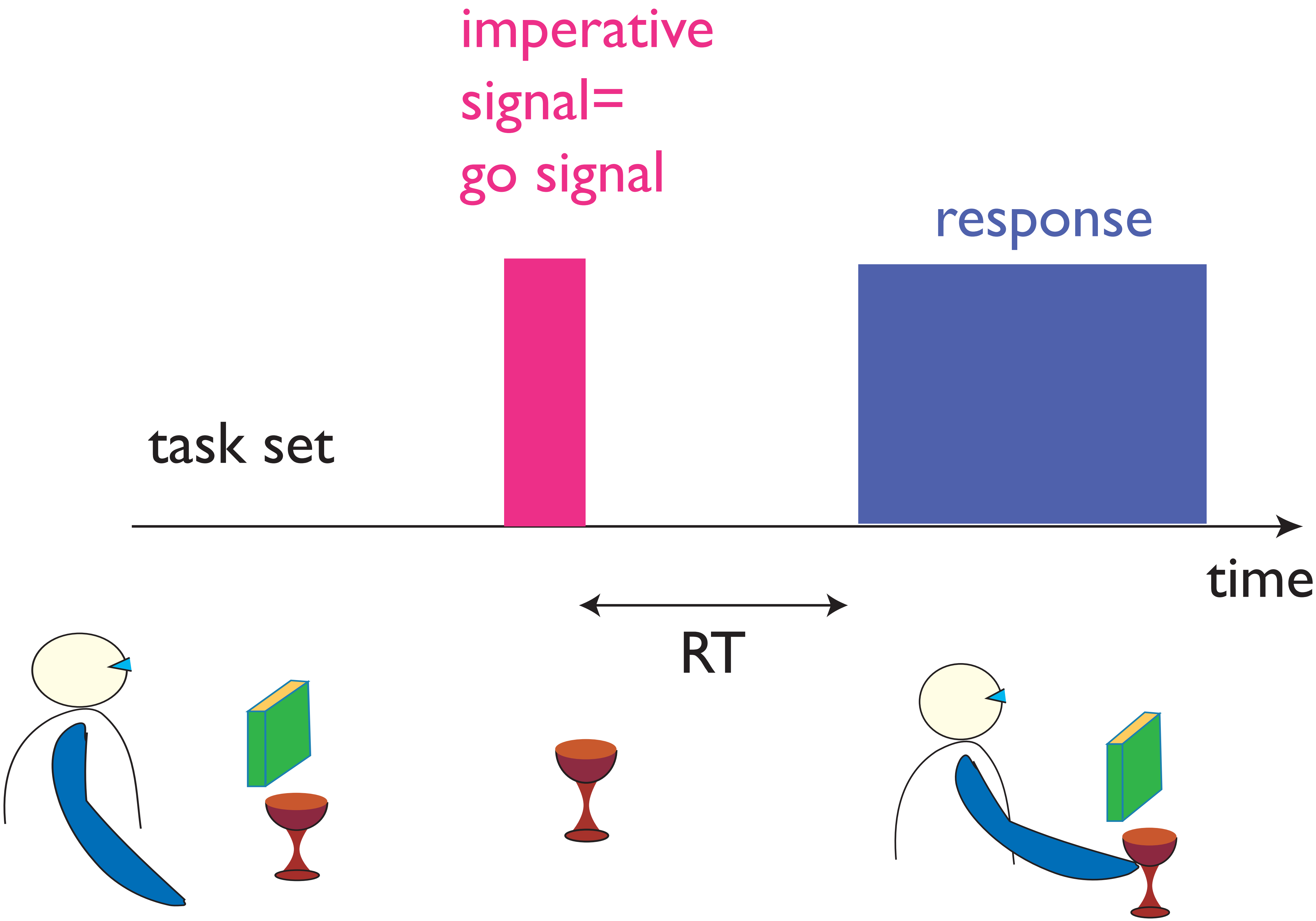


Selection decisions are stable



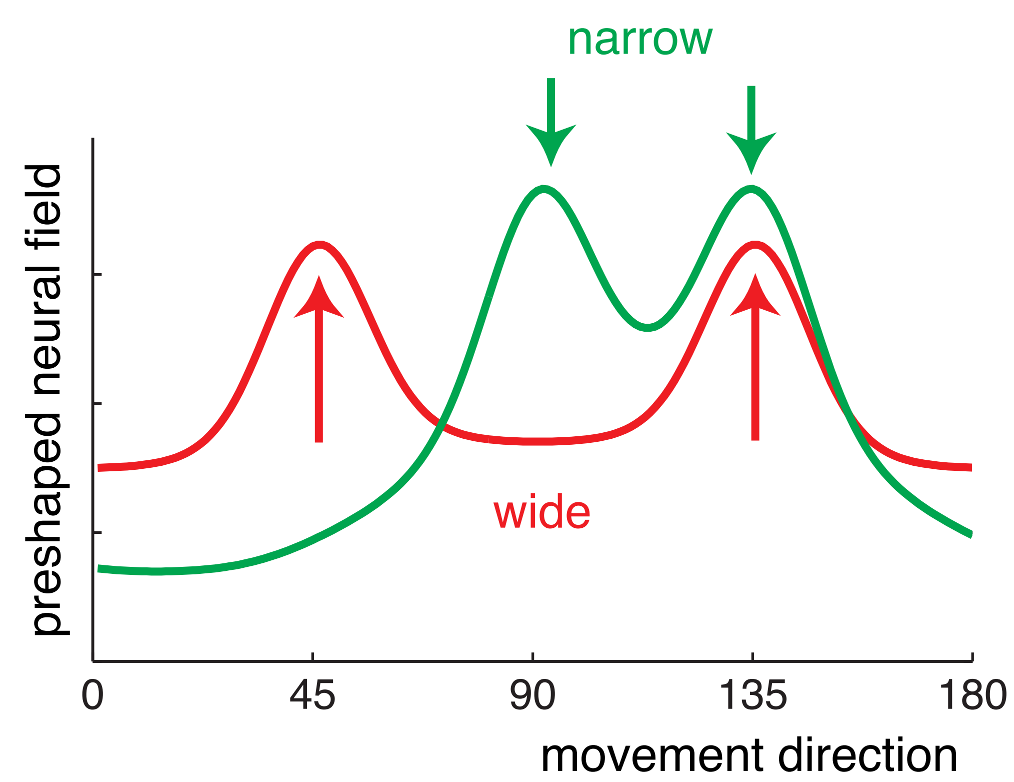
[Wilimzig, Schöner, 2006]

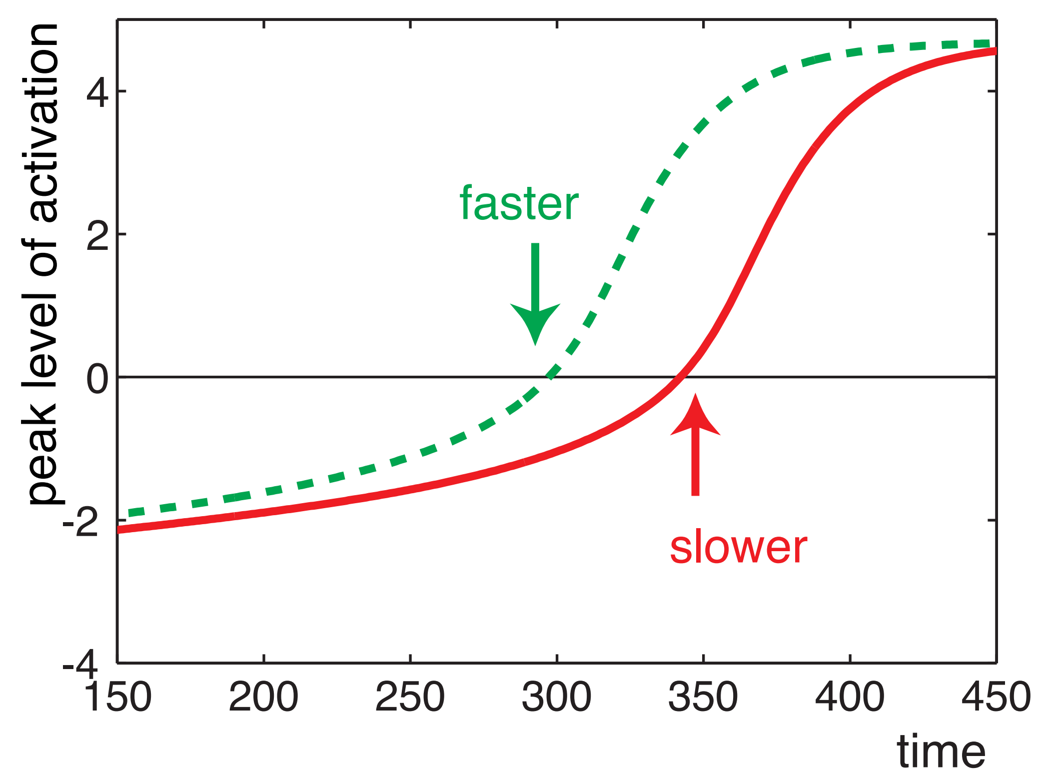
reaction time (RT) paradigm



metric effect

- predict faster response times for metrically close than for metrically far choices



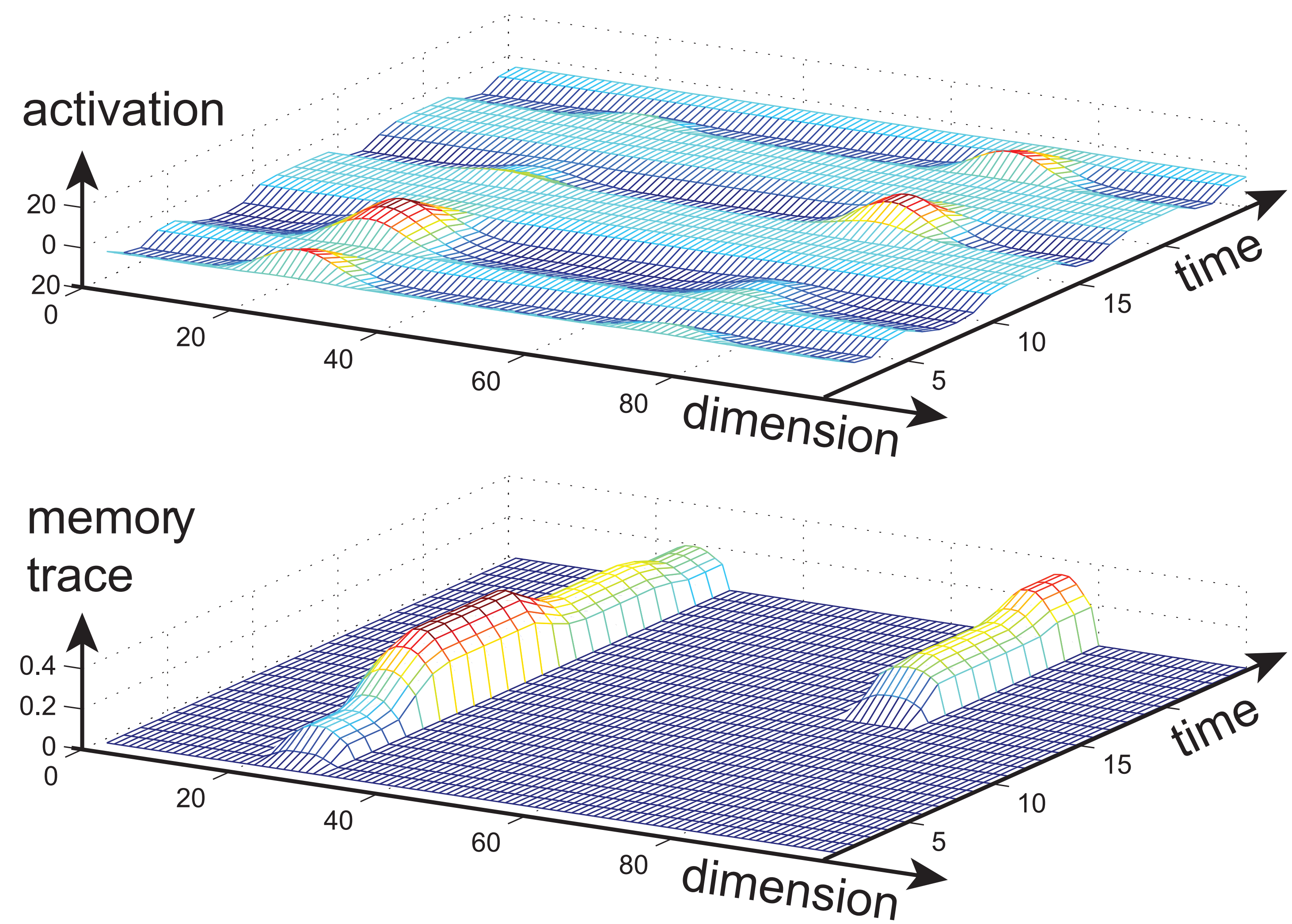


[from Schöner, Kopecz, Erlhagen, 1997]

The memory trace

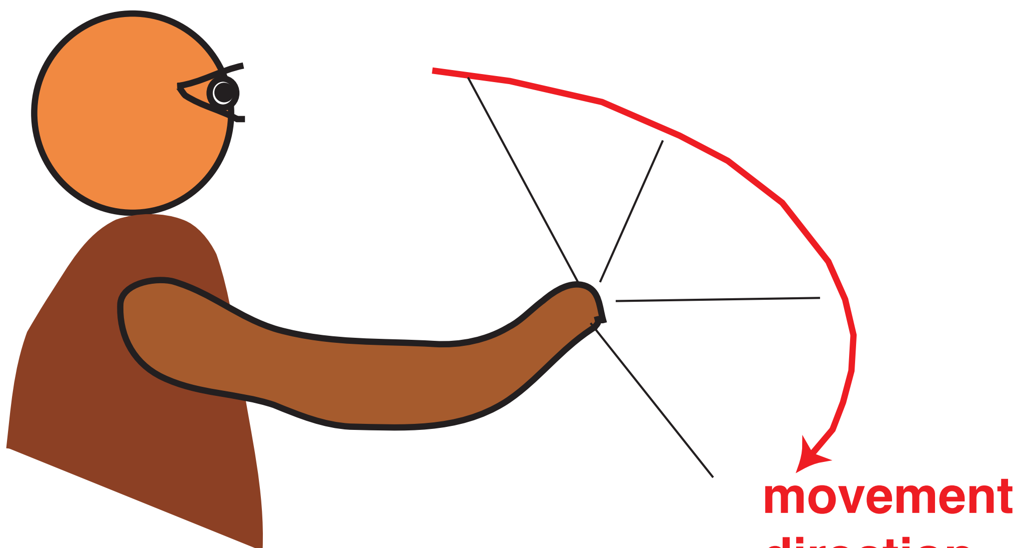
- activation leaves a trace that may influence the activation dynamics later… in a simplest form of learning, the "bias " term of NN

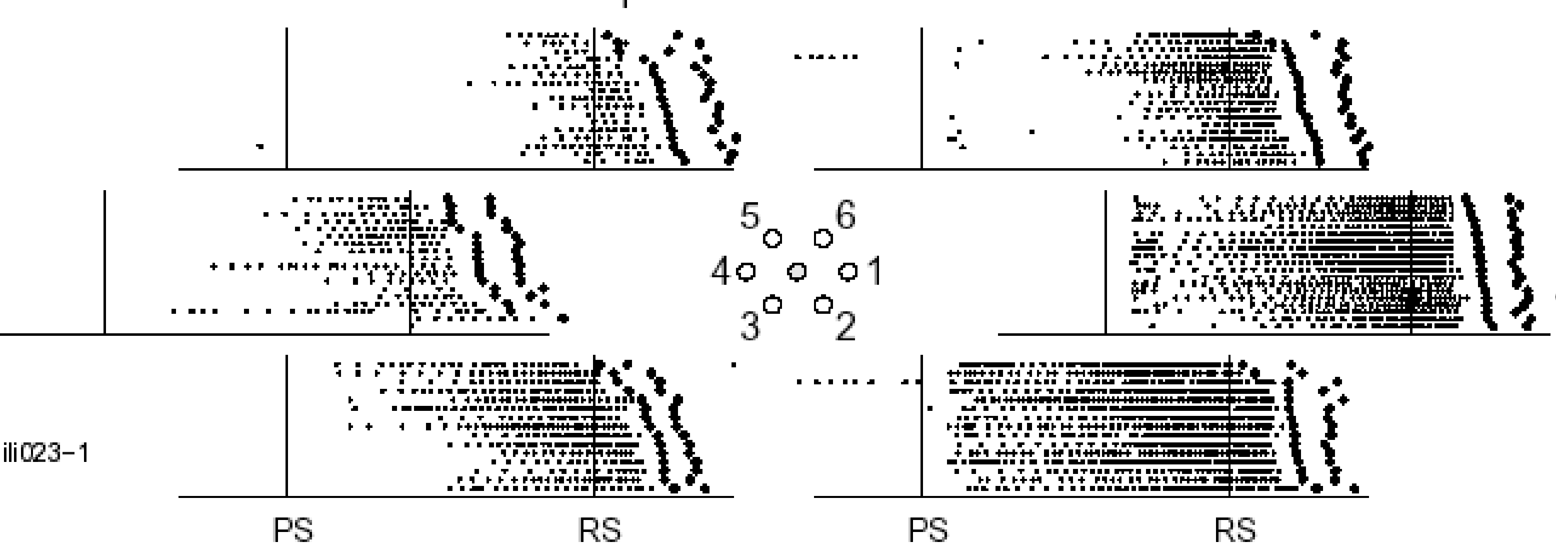
- powerful in DFT because the detection instability may amplify the induced into peaks of activation

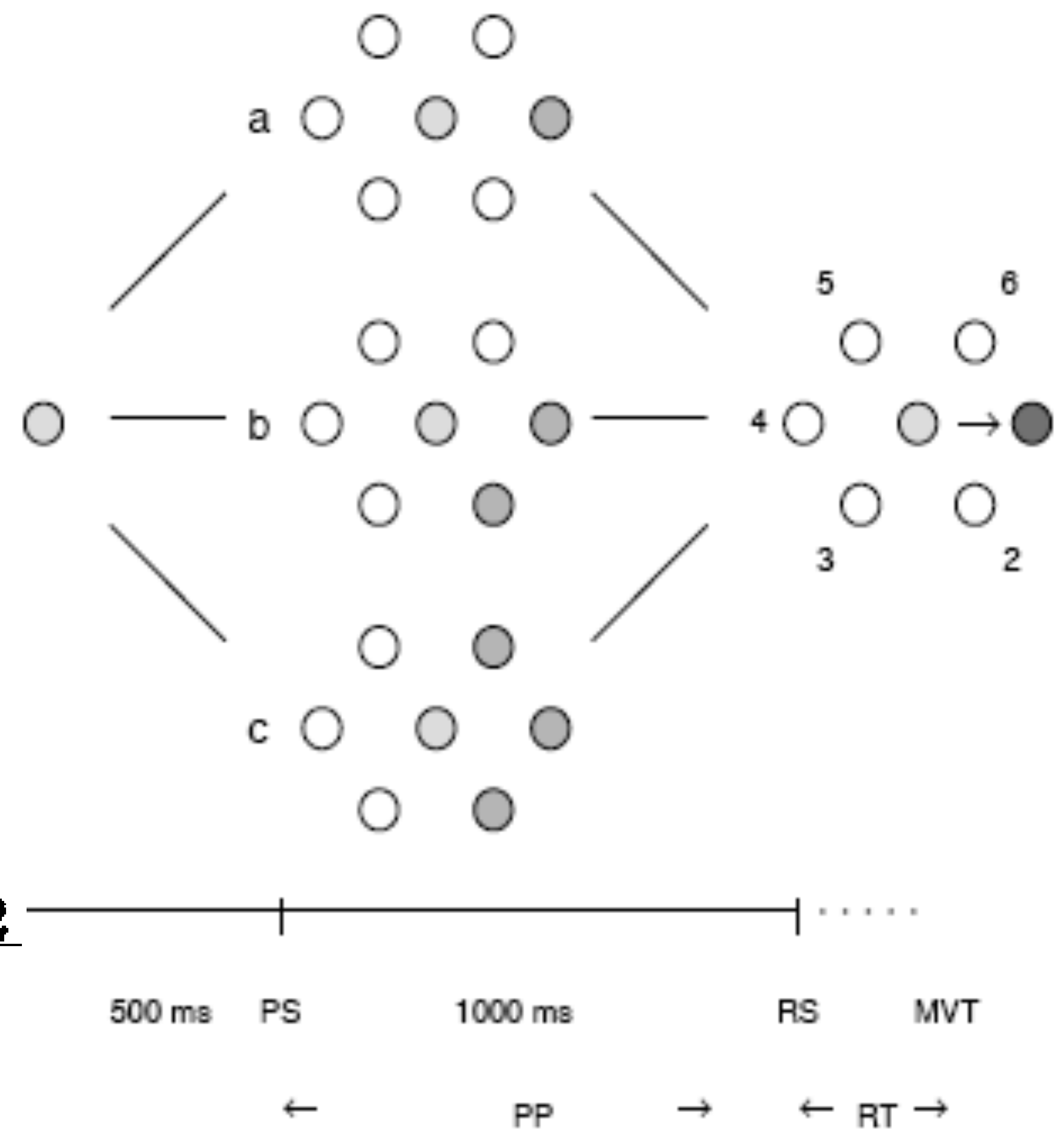


Neural grounding

Tuning of neurons



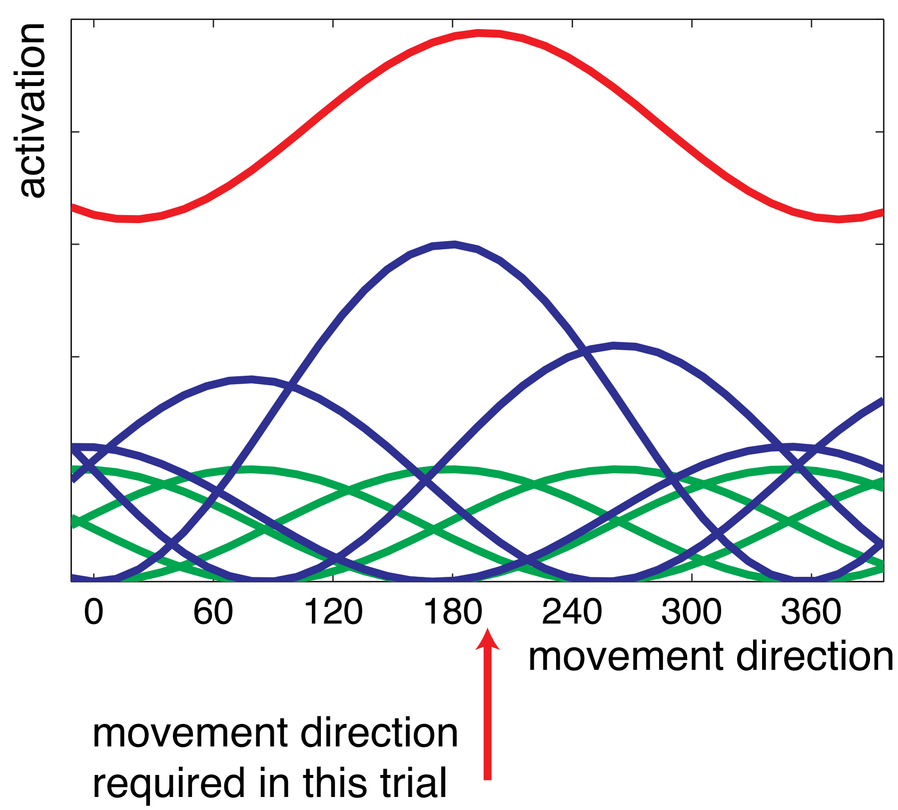


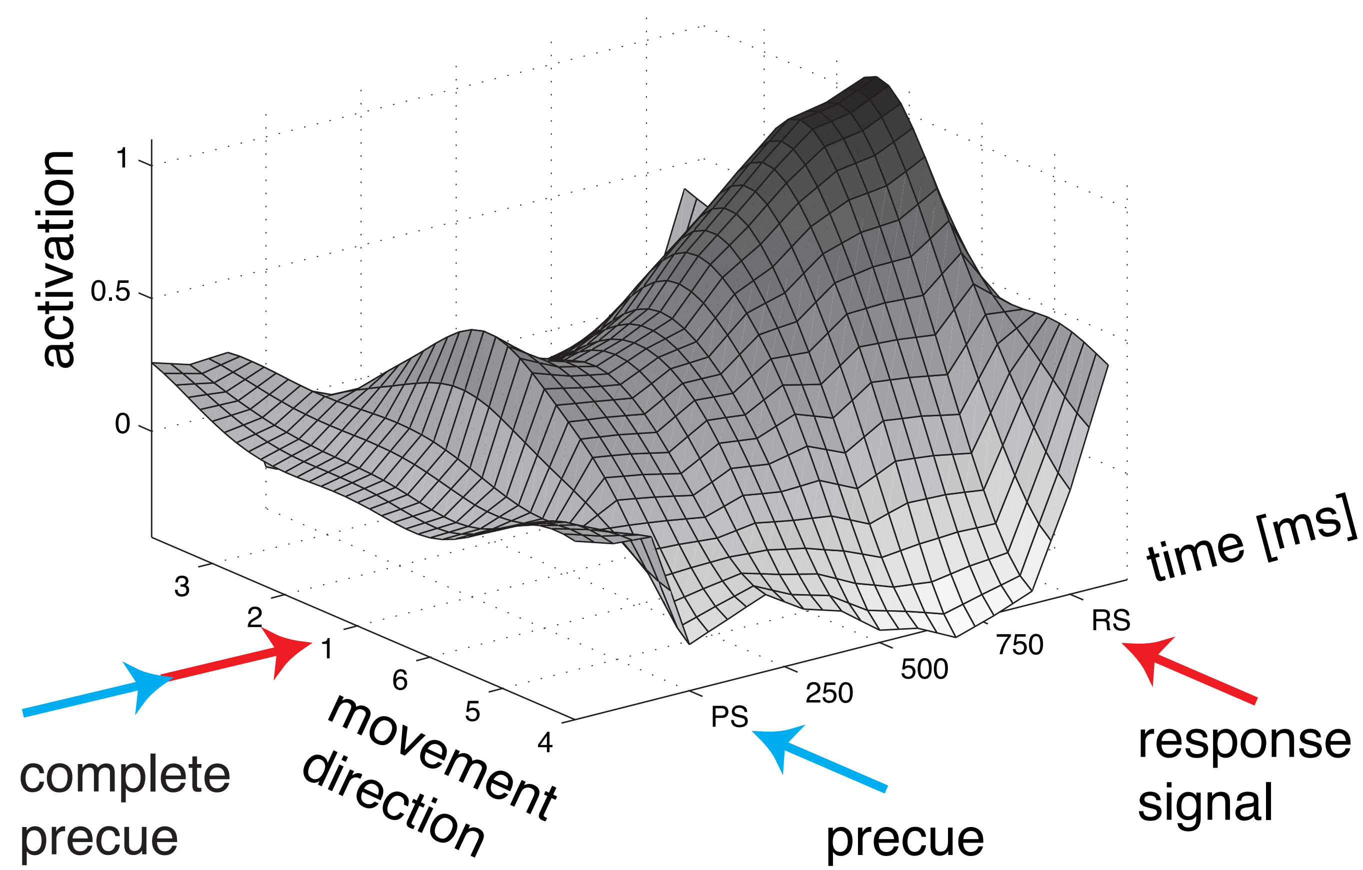


Bastian, Riehle, Schöner, 2003

Distribution of Population Activation (DPA) <=> neural field

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

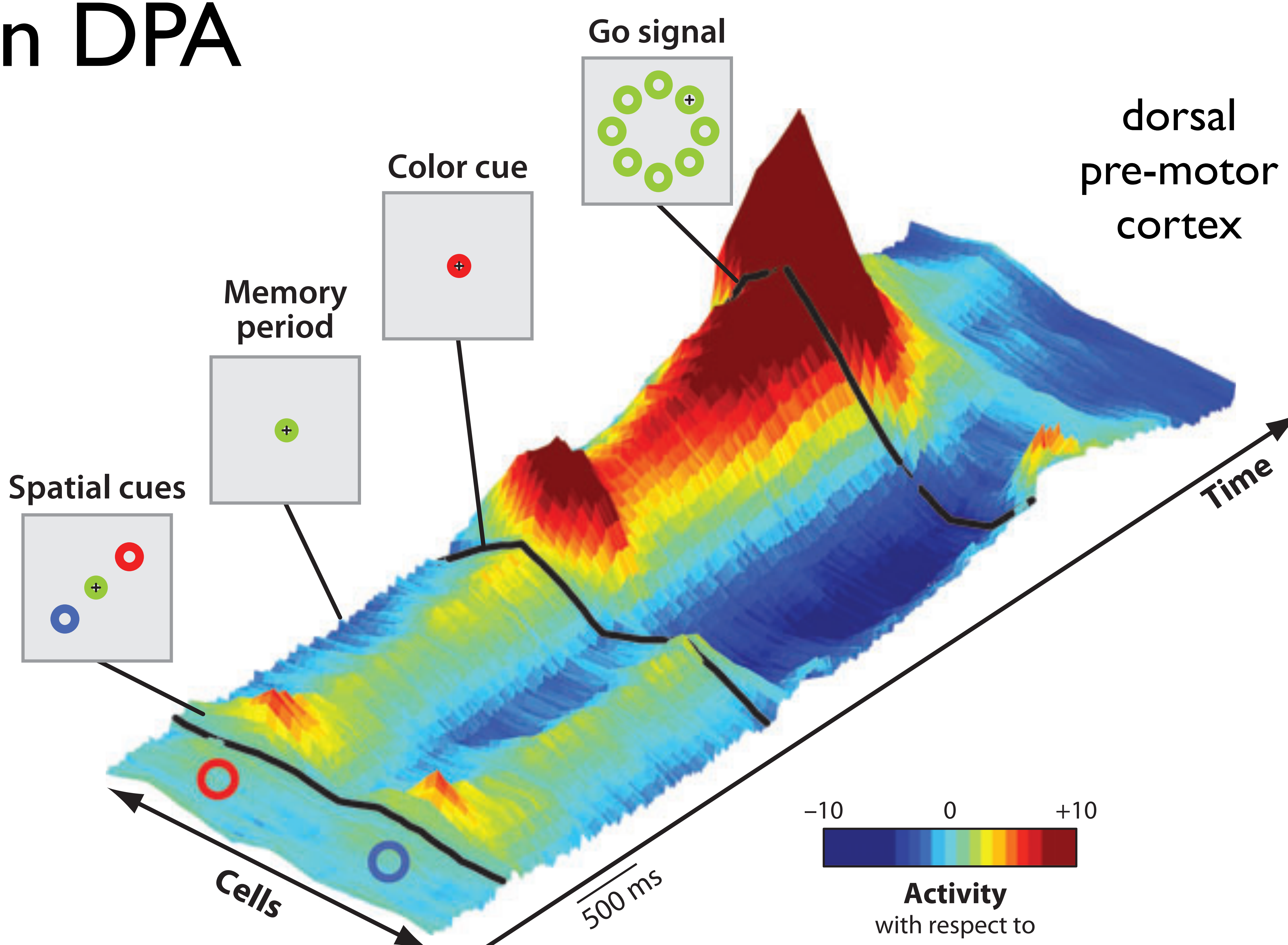




- note: neurons are not localized within DPA!

[Bastian, Riehle, Schöner, 2003]

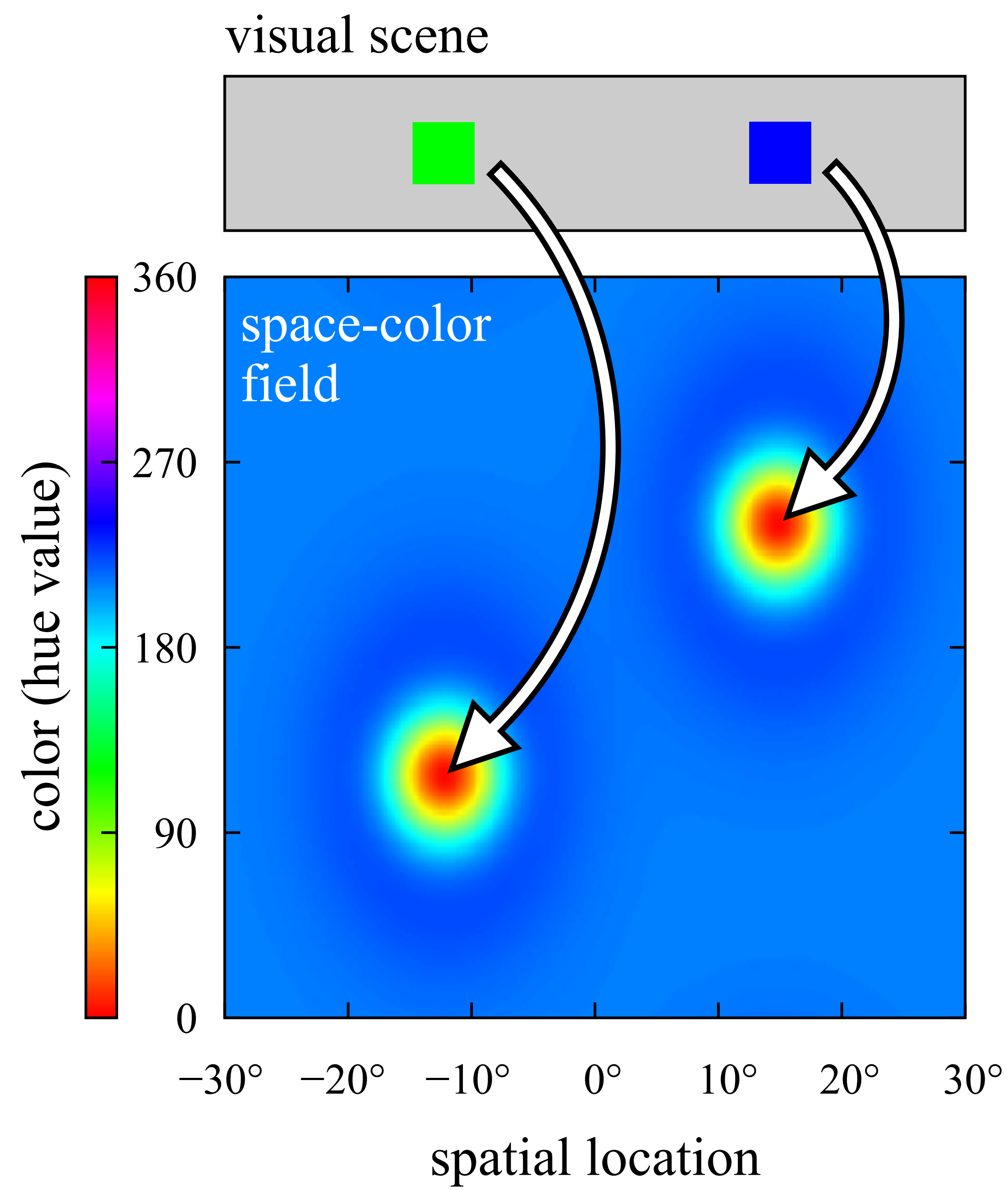
Decision making in DPA



[Cisek, Kalaska 2005]

Joint representations

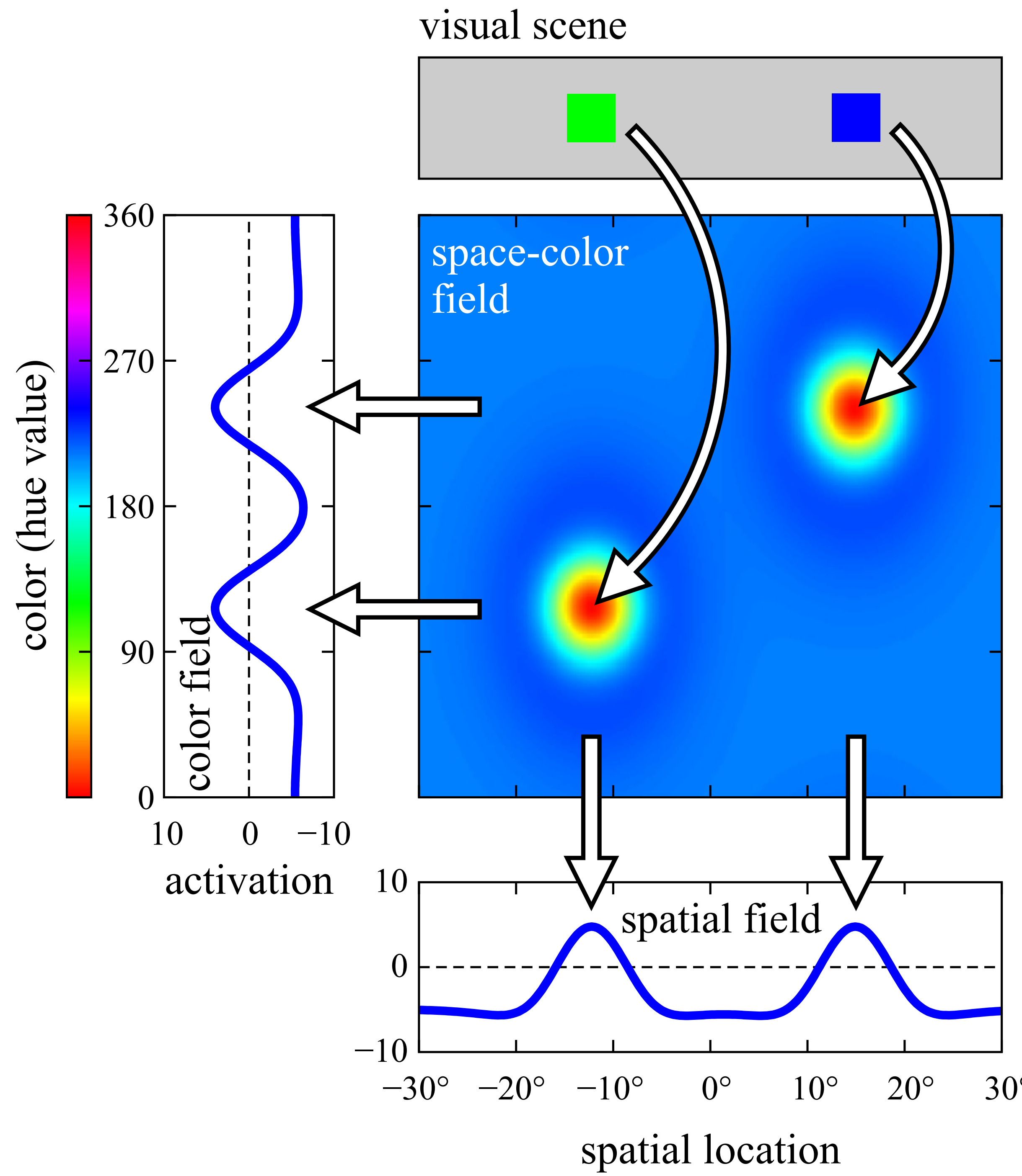
- “anatomical” binding
- example: a joint representation of color and visual space “binds” these two dimensions



[Schneegans et al., Ch 5 of *DFT Primer,* 2016]

Extract the bound features

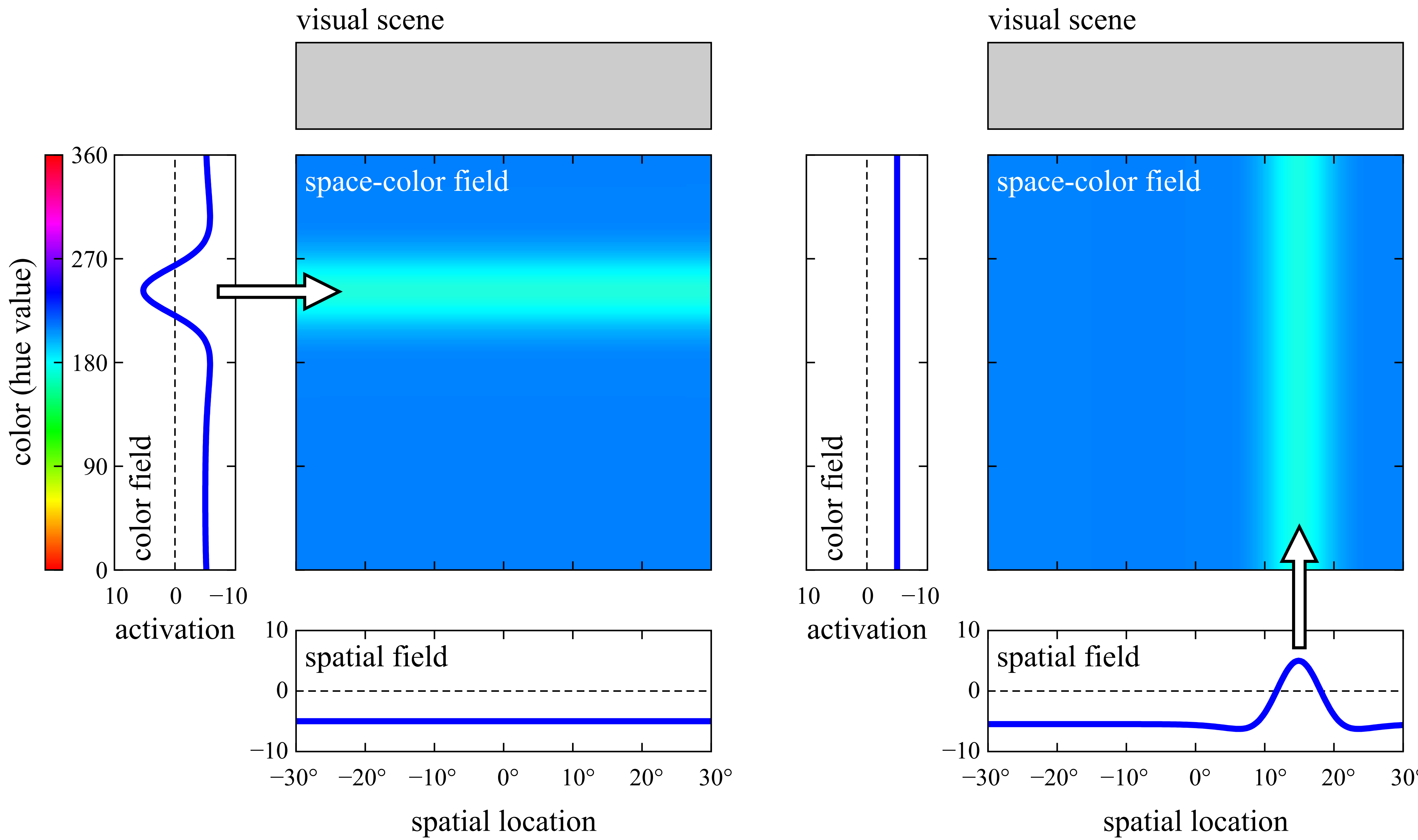
- project to lower-dimensional fields
- by summing along the marginalized dimensions
- (or by taking the soft-max)



[Schneegans et al.,Ch 5 of *DFT Primer*, 2016]

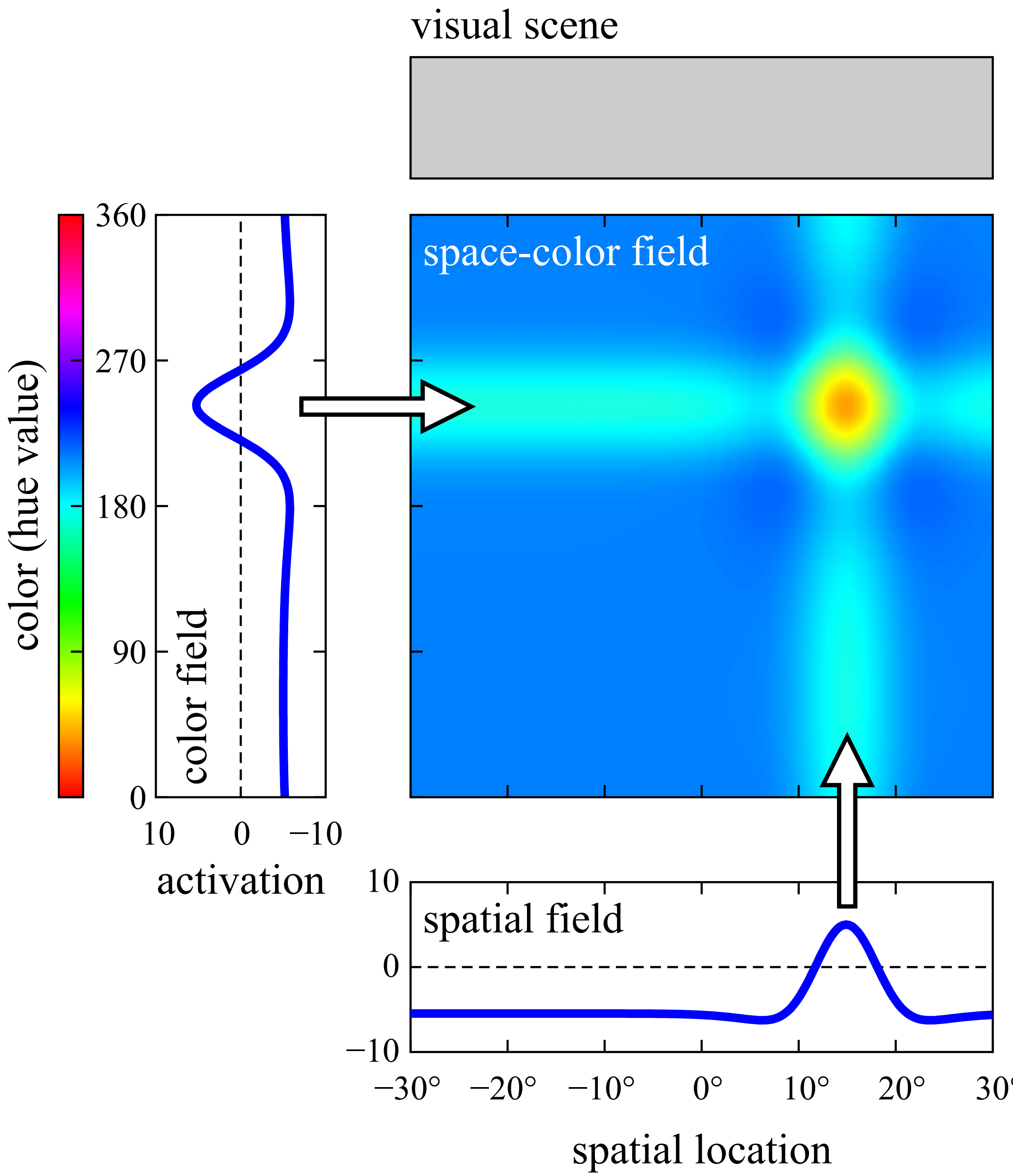
Assemble bound representations

- project lower-dimension field onto higher-dimensional field as "ridge input"



[Schneegans et al.,Ch 5 of *DFT Primer*, 2016]

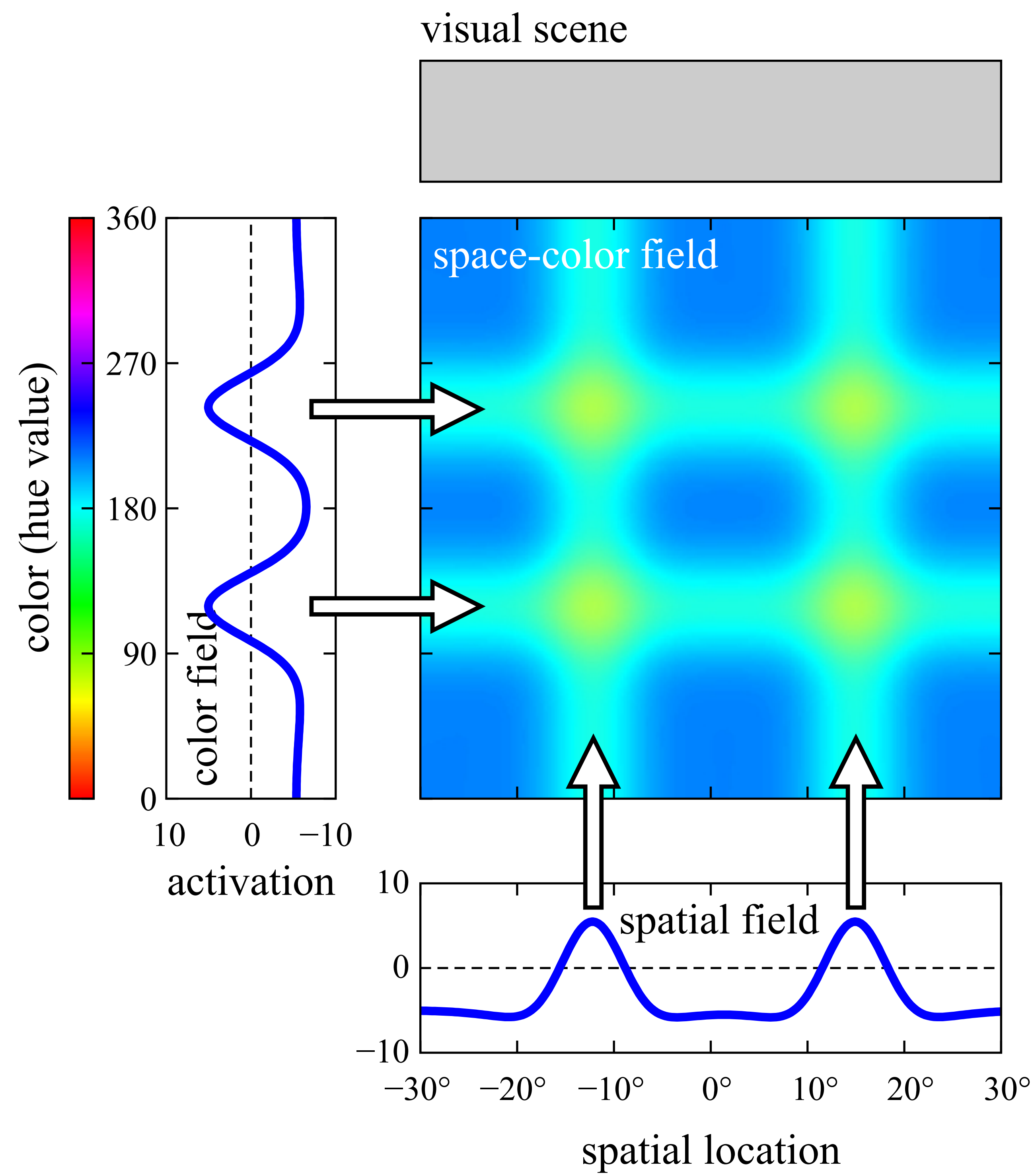
Assemble bound representations



[Schneegans et al.,Ch 5 of *DFT Primer,* 2016]

Assemble bound representations

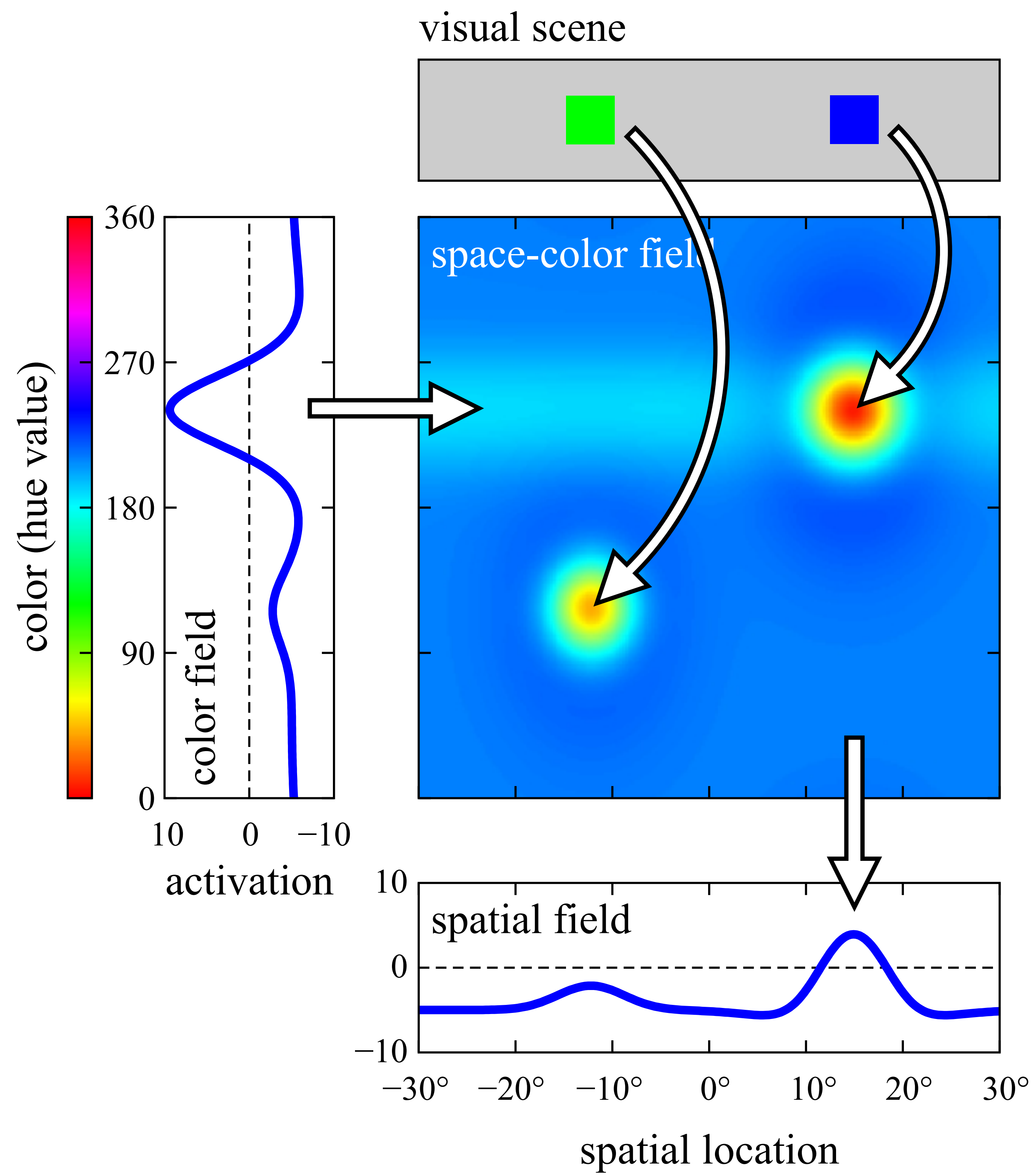
- binding problem: multiple ridges along lower-dimensional space lead to a correspondence problem
- => assemble one object at a time…
- => sequentiality bottle-neck!



[Schneegans et al.,Ch 5 of *DFT Primer*, 2016]

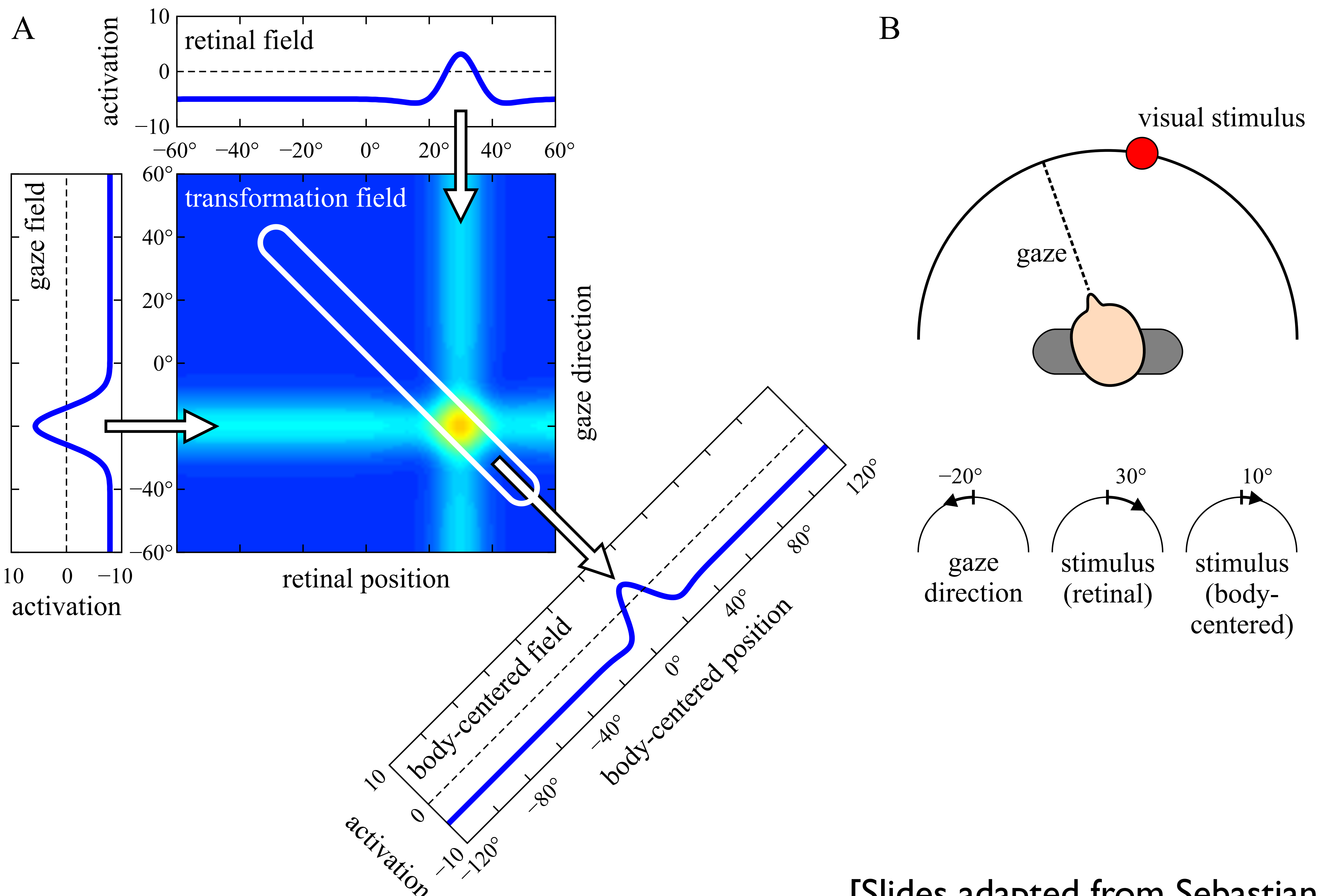
Search

- ridge input along one dimension extracts from bound representation matching objects
- other dimensions of those objects can then be extracted
- e.g. visual search



[Schneegans et al.,Ch 5 of *DFT Primer*, 2016]

Coordinate transforms

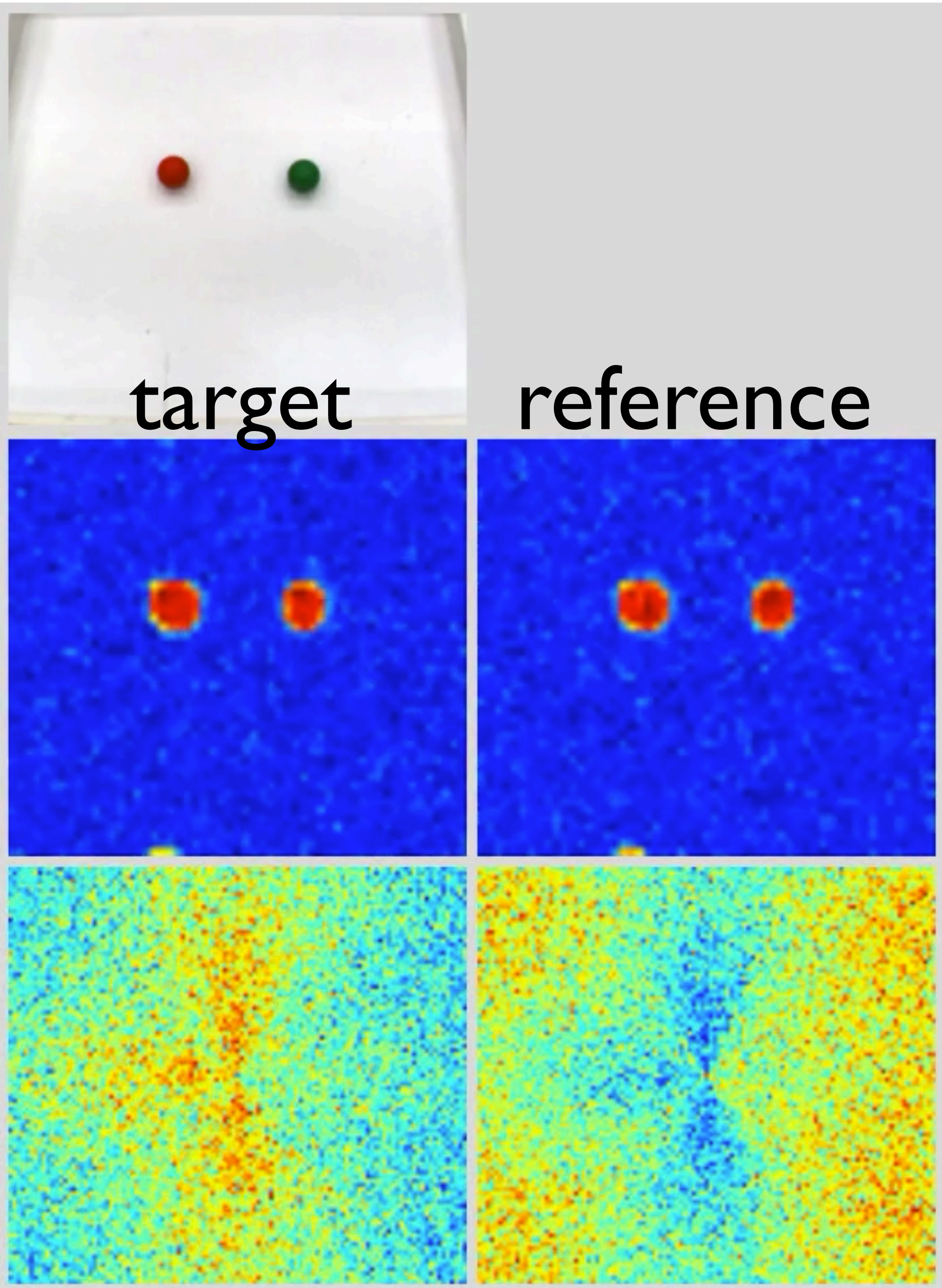


[Slides adapted from Sebastian Schneegans,
see Schneegans, Chapter 7 of Dynamic Field Theory-A Primer, OUP, 2015]

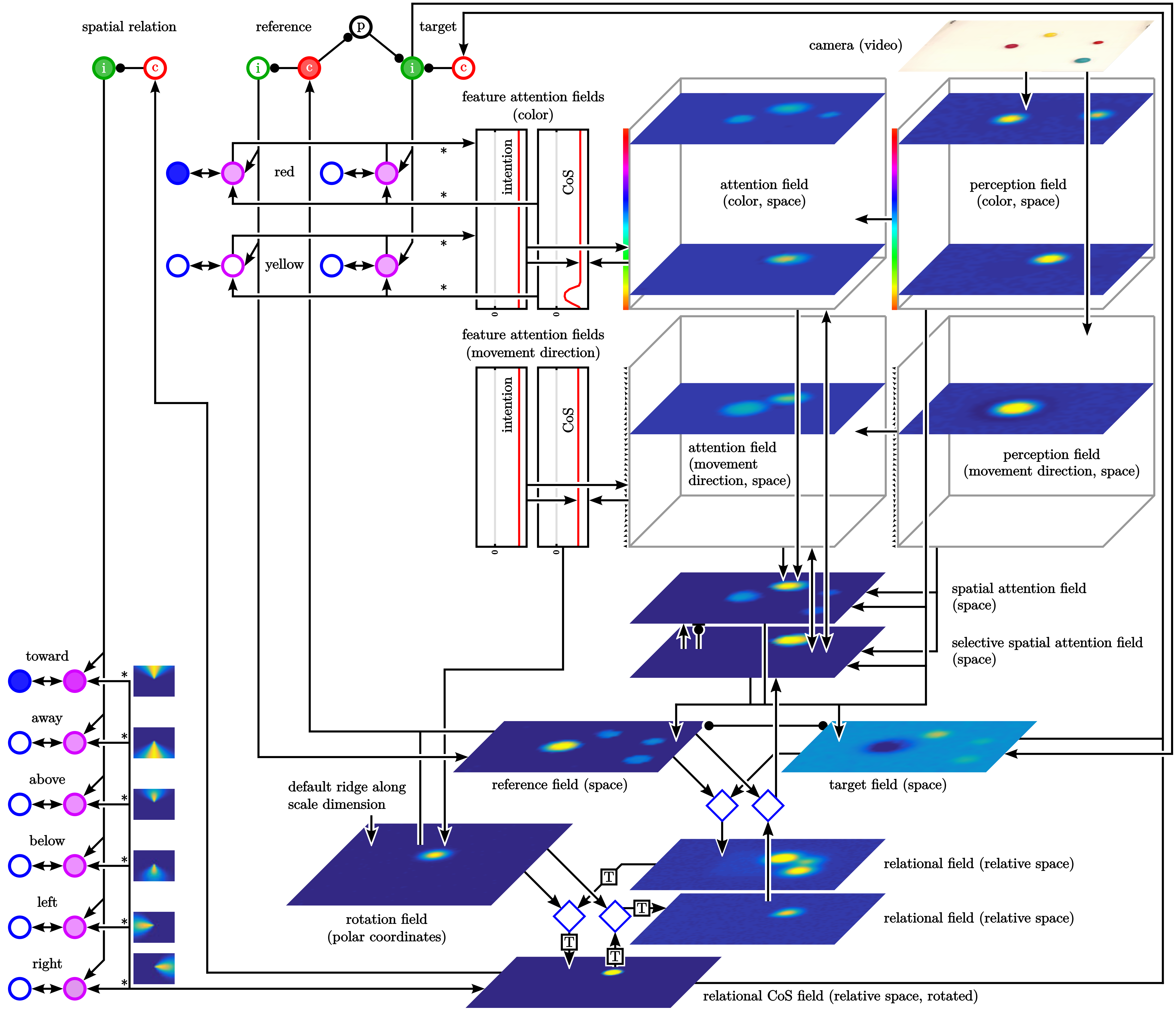
Perceptual grounding of concepts

- Perceptual grounding of a relation: bringing the target object into the attentional foreground

"red to the left of green"

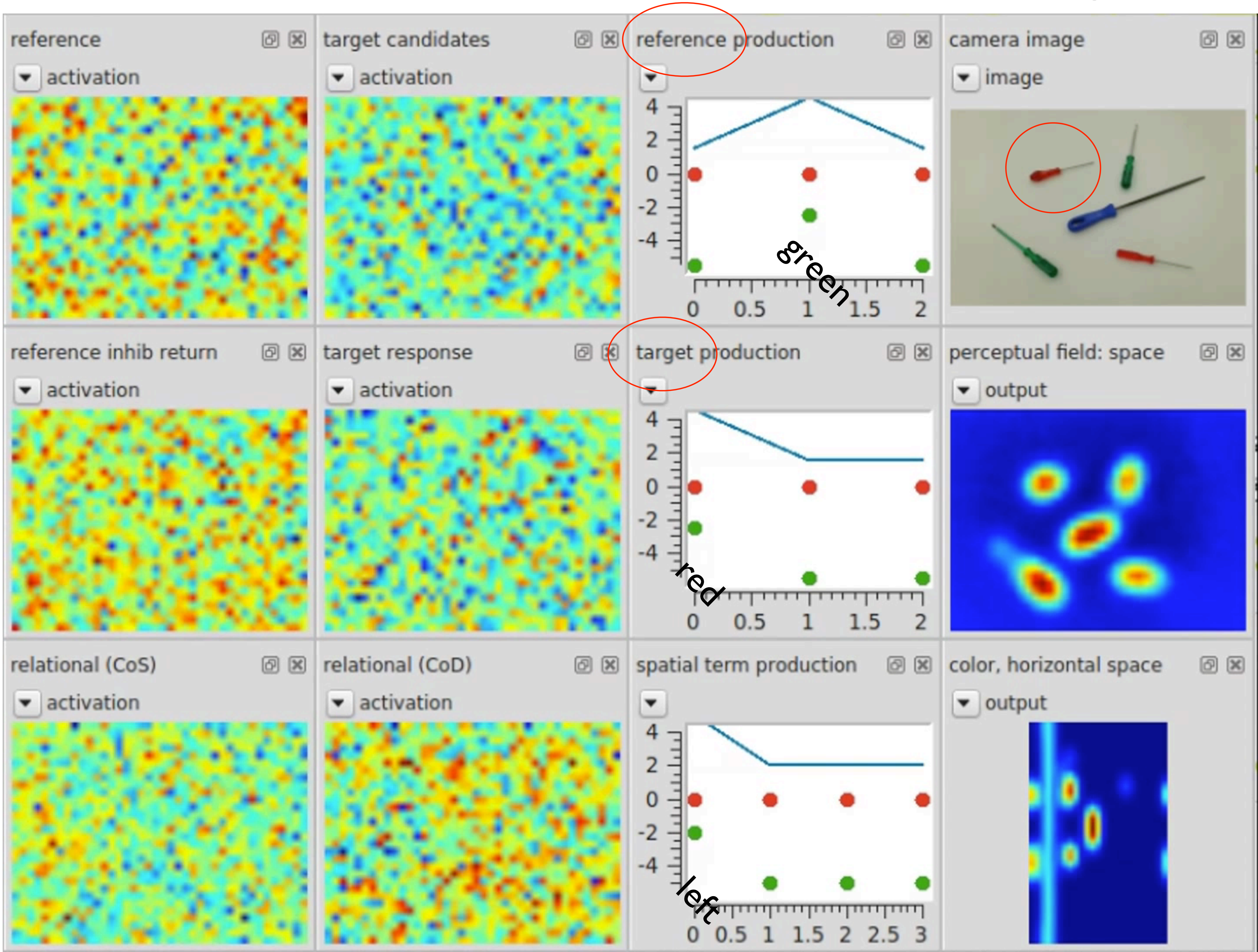


[Lipinski, Sandamirskaya, Schöner 2009
… Richter, Lins, Schöner, *Topics* 2017]



[Richter, Lins, Schöner, ToPiC (2017)]

“red to the left of green”

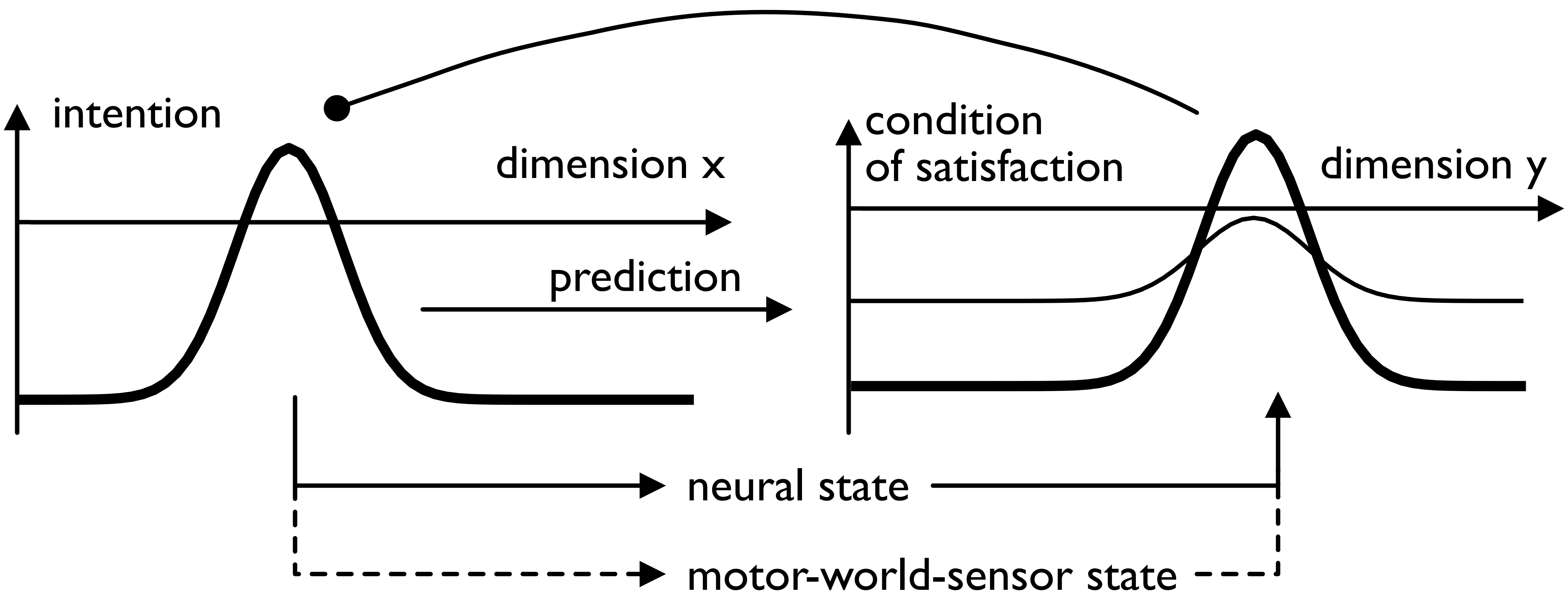


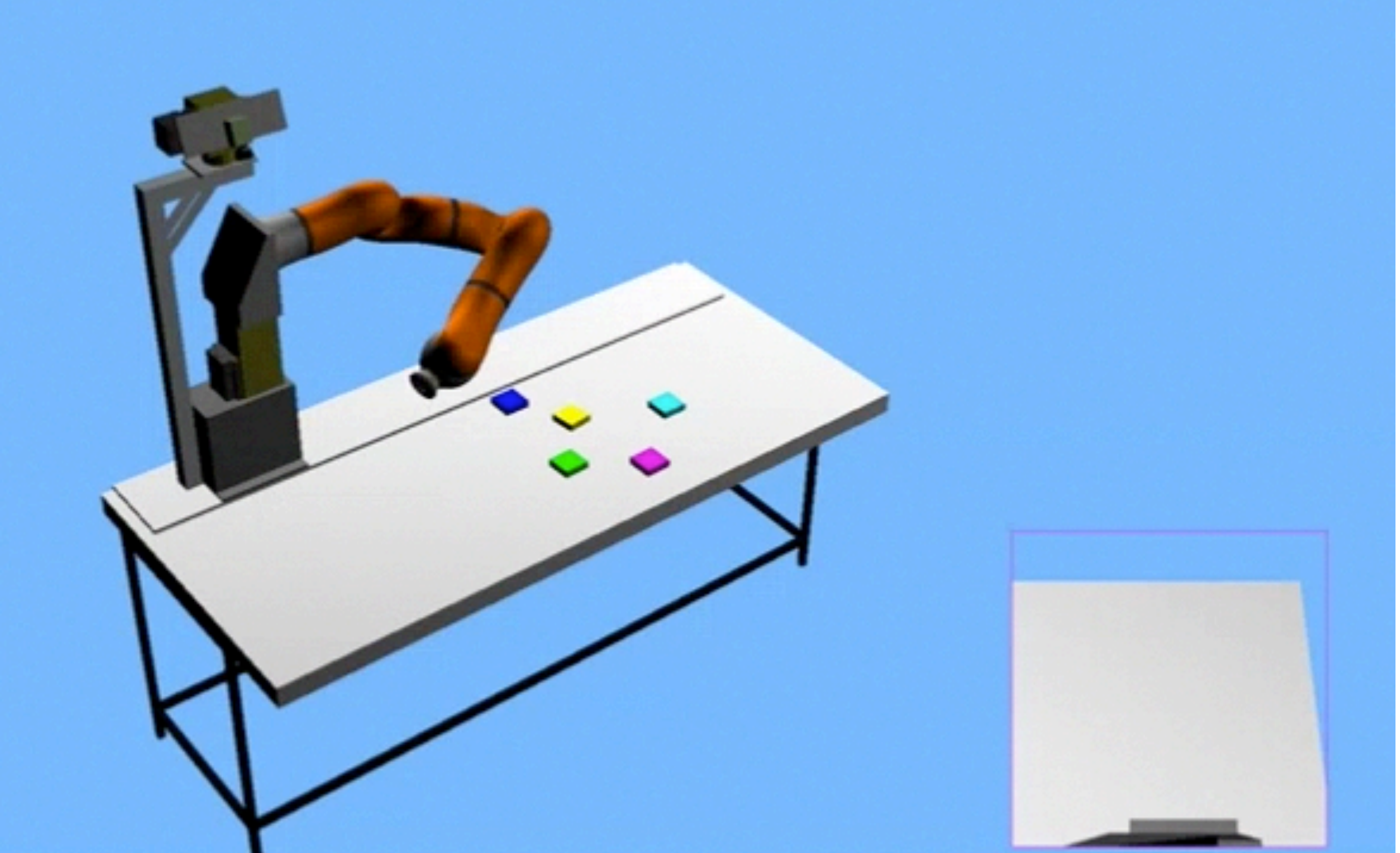
Sequential behaviors or mental acts

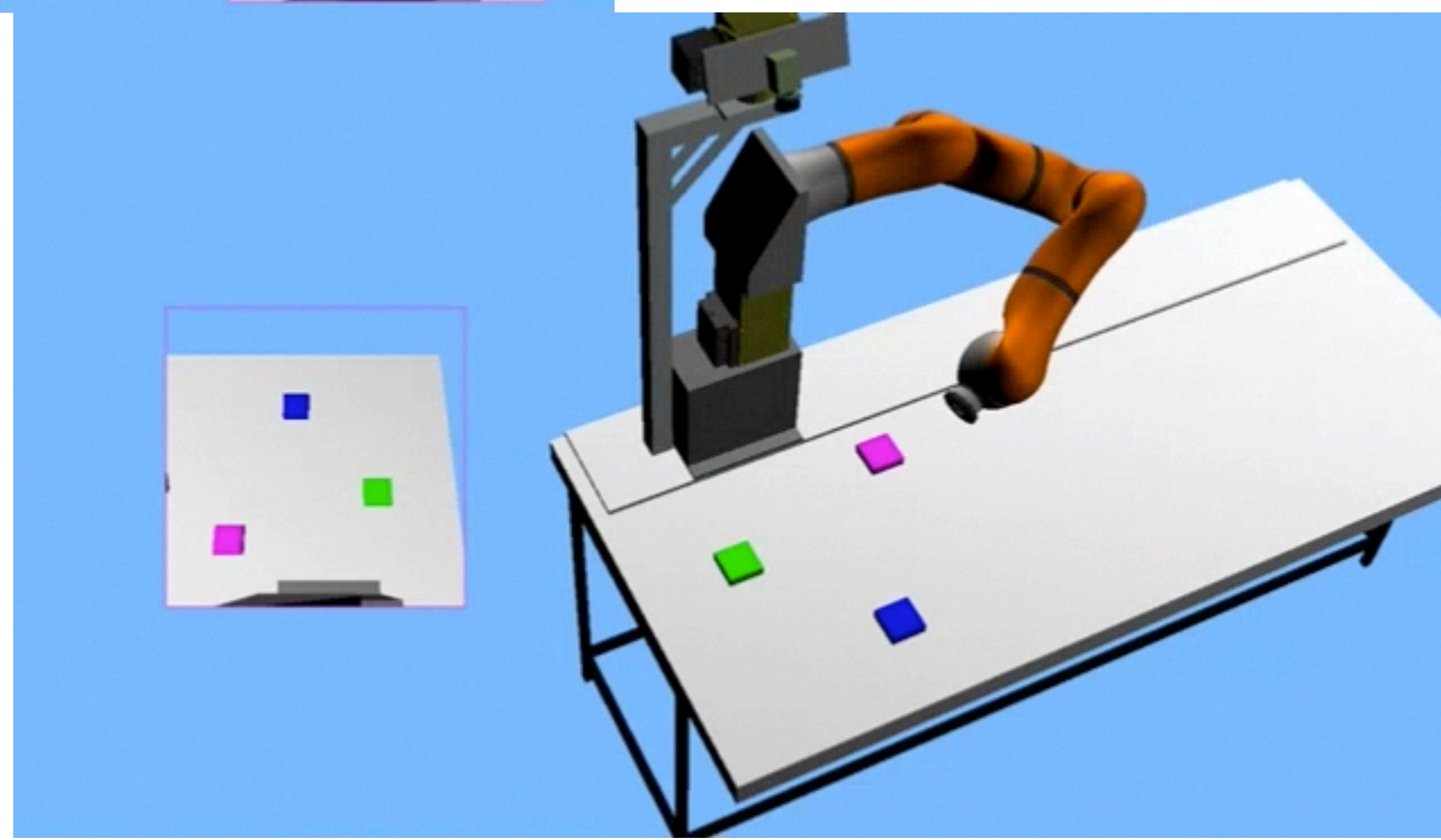
- behaviors/mental states are attractors
- that resist change…
- to induce change in sequential behavior/ thinking: induce an instability

Sequence generation

- the CoS organizes the transition away from on ongoing behavior/mental state
- based on a signal from perception or from an inner state of a neural architecture that is predicted to be indicative of successful completion of the behavior/ mental act







What skills do you learn?

- academic skills
  - read and understand scientific texts
  - write technical texts, using mathematical concepts and illustrations

What skills do you learn?

- mathematical skills
  - conceptual understanding of dynamical systems
  - capacity to read differential equations and illustrate them
  - perform "mental simulation" of differential equations
  - use numerical simulation to test ideas about an equation

What skills do you learn?

- interdisciplinary skills
  - handle concepts from a different discipline
  - handle things that you don’t understand
  - sharpen sense of what you understand and what not