Summary, conclusions and the theoretical commitments

Gregor Schöner
gregor.schoener@ini.rub.de

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

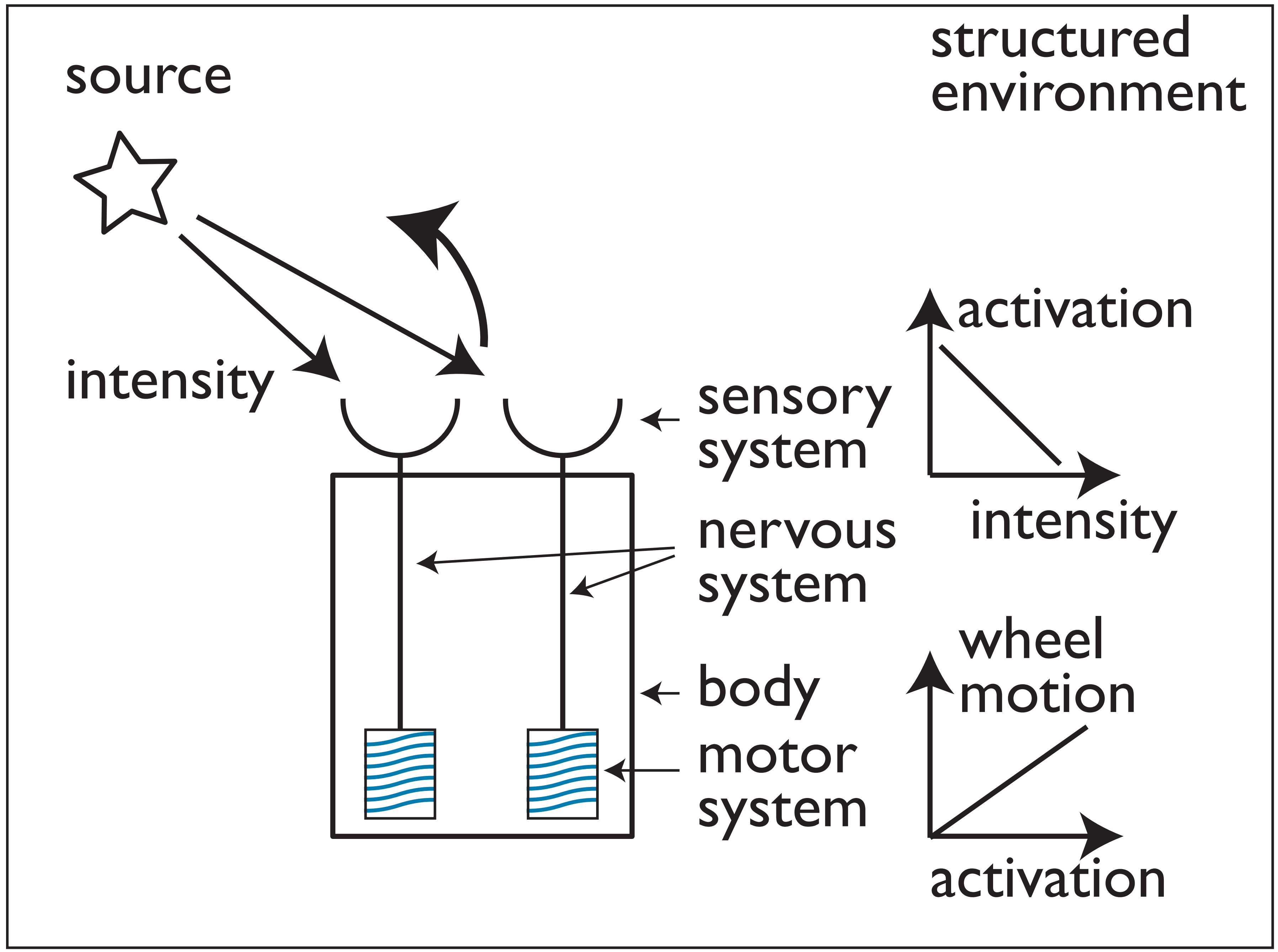
- graded state
- continuous time
- continuous/intermittent link to the sensory and motor surfaces
- from which discrete events and categorical behavior emerge
- in closed loop
- => states must be stable

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

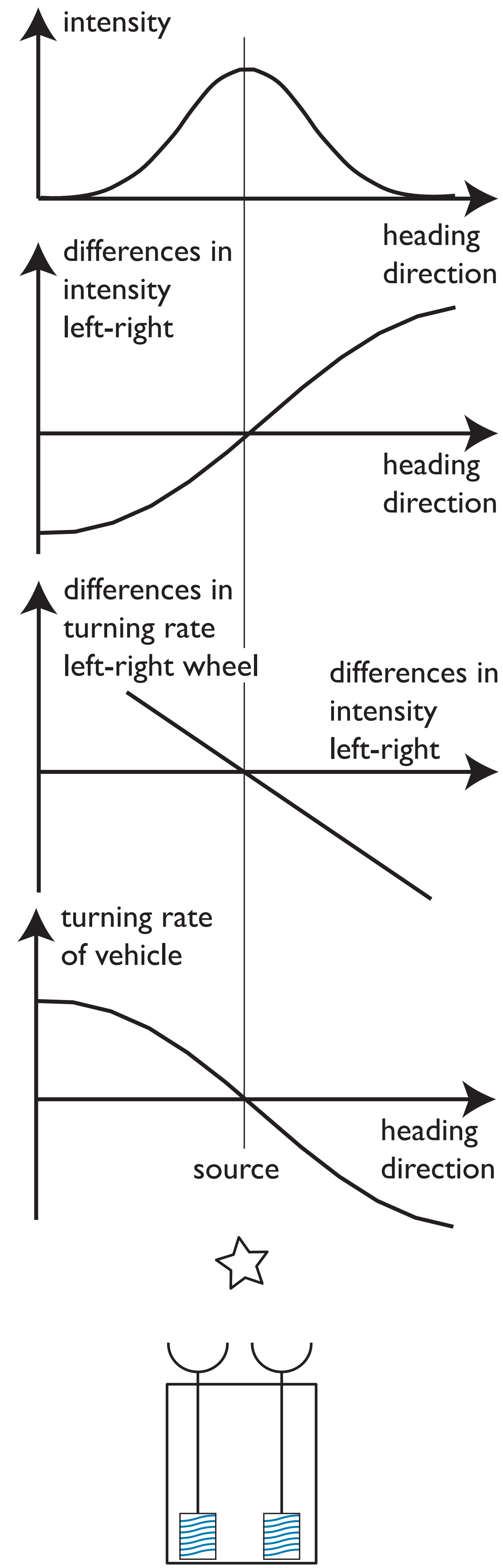
Five things needed to generate behavior

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



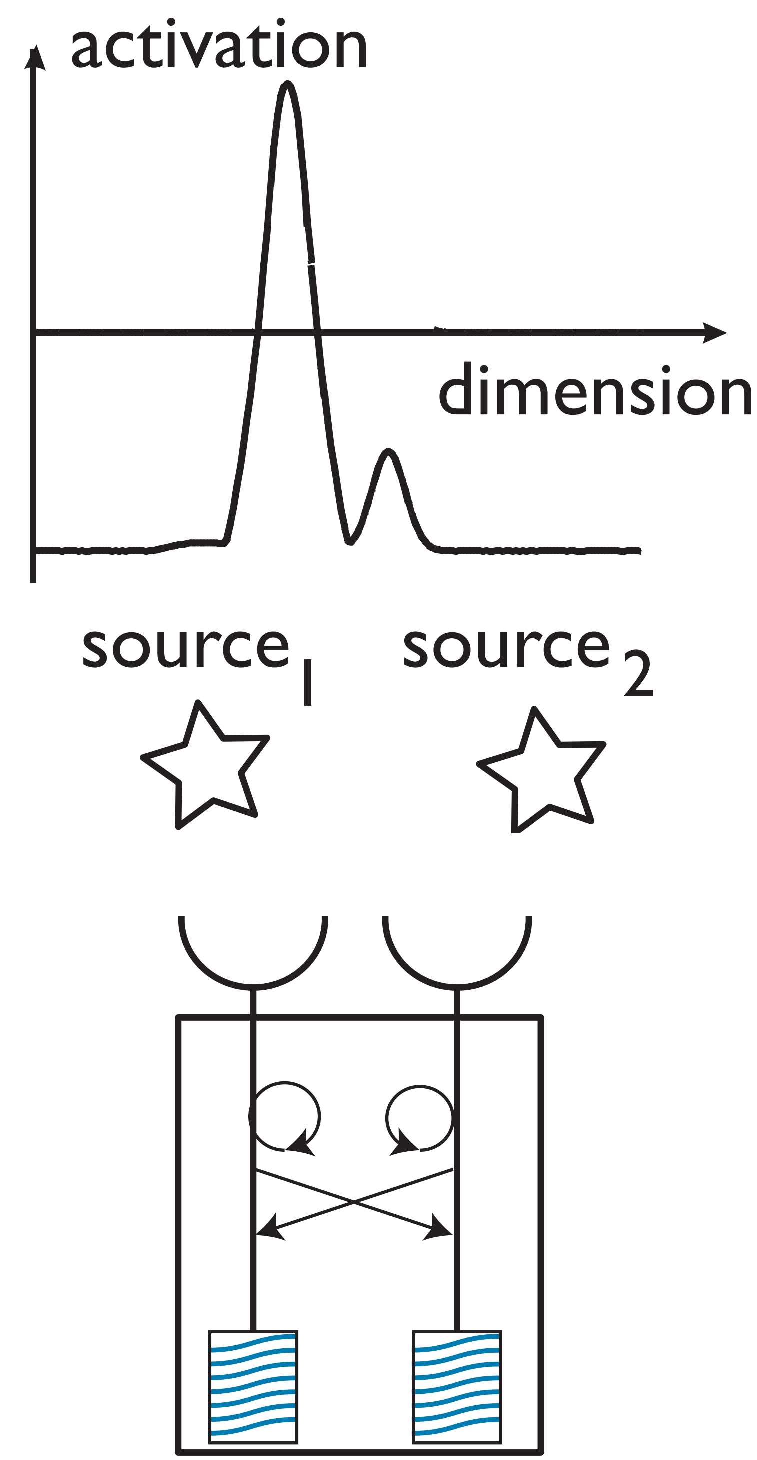
Emergent behavior: this is a dynamics

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



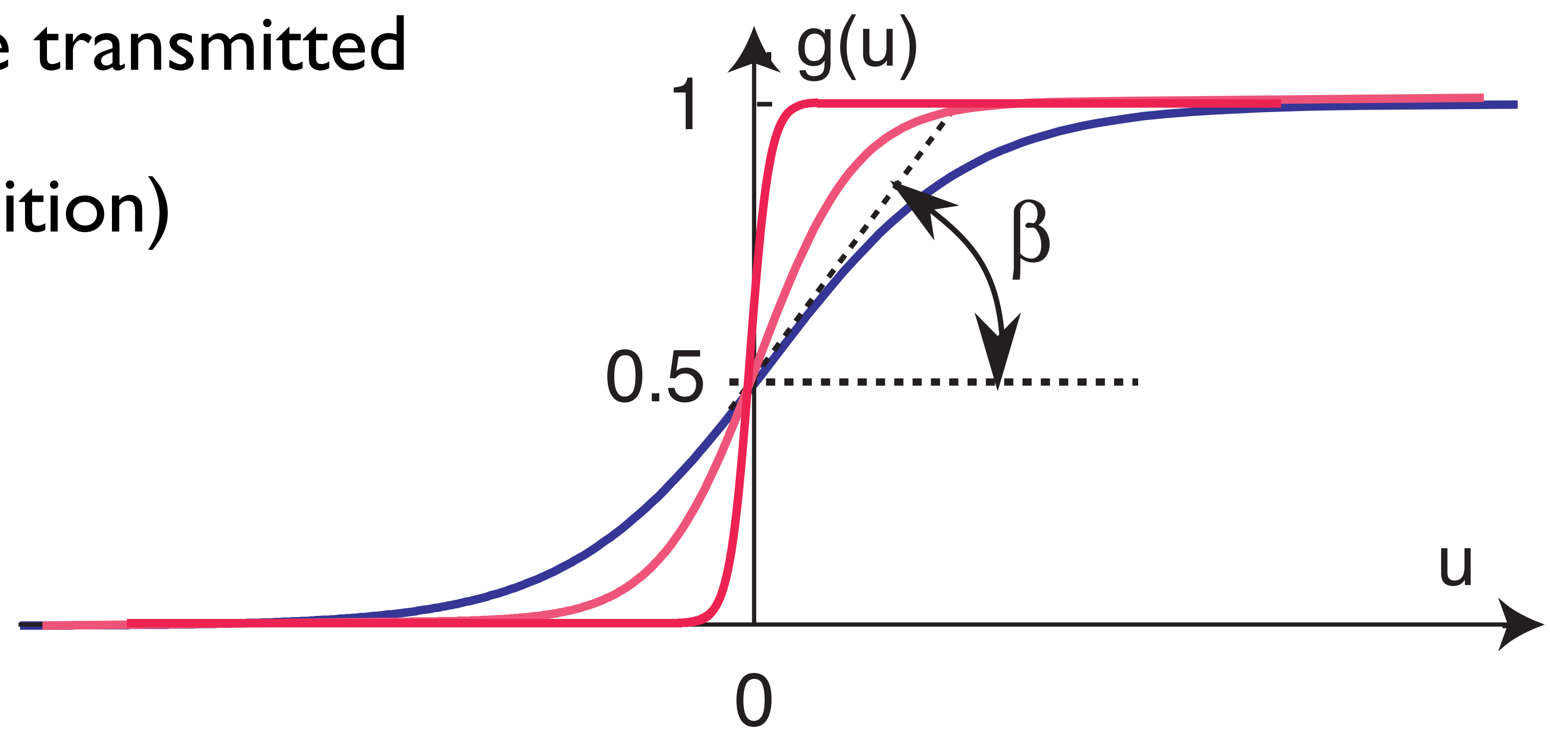
Emergent cognition from neural dynamics

- mental decisions, working memory..



What is “activation”?

- activation is an abstraction of the state of neurons, defined relative to sigmoidal threshold function
  - 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)

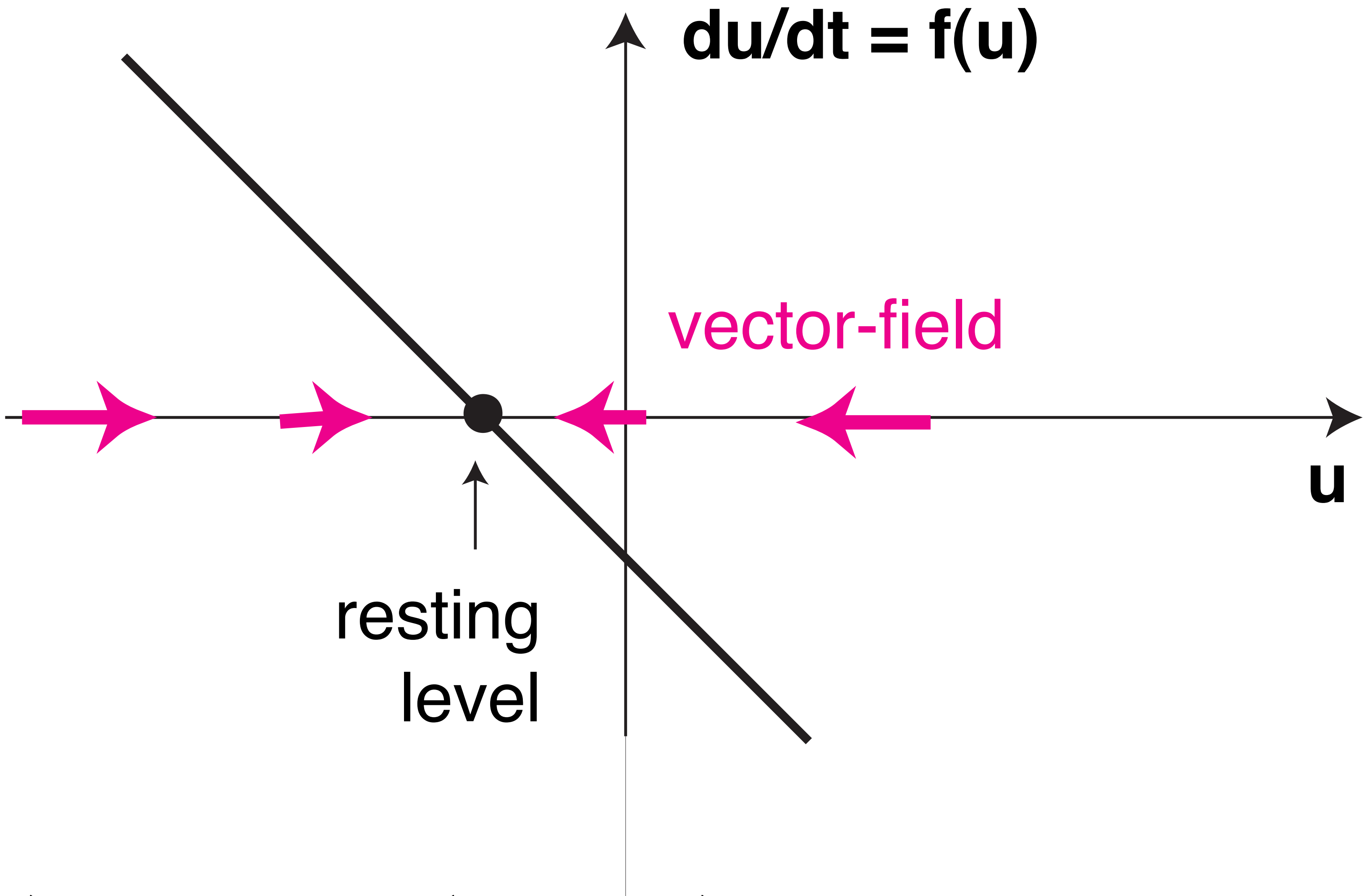


Activation dynamics

- activation evolves in continuous time
  - no evidence for a discretization of time, for spike timing to matter for behavior

Neural dynamics

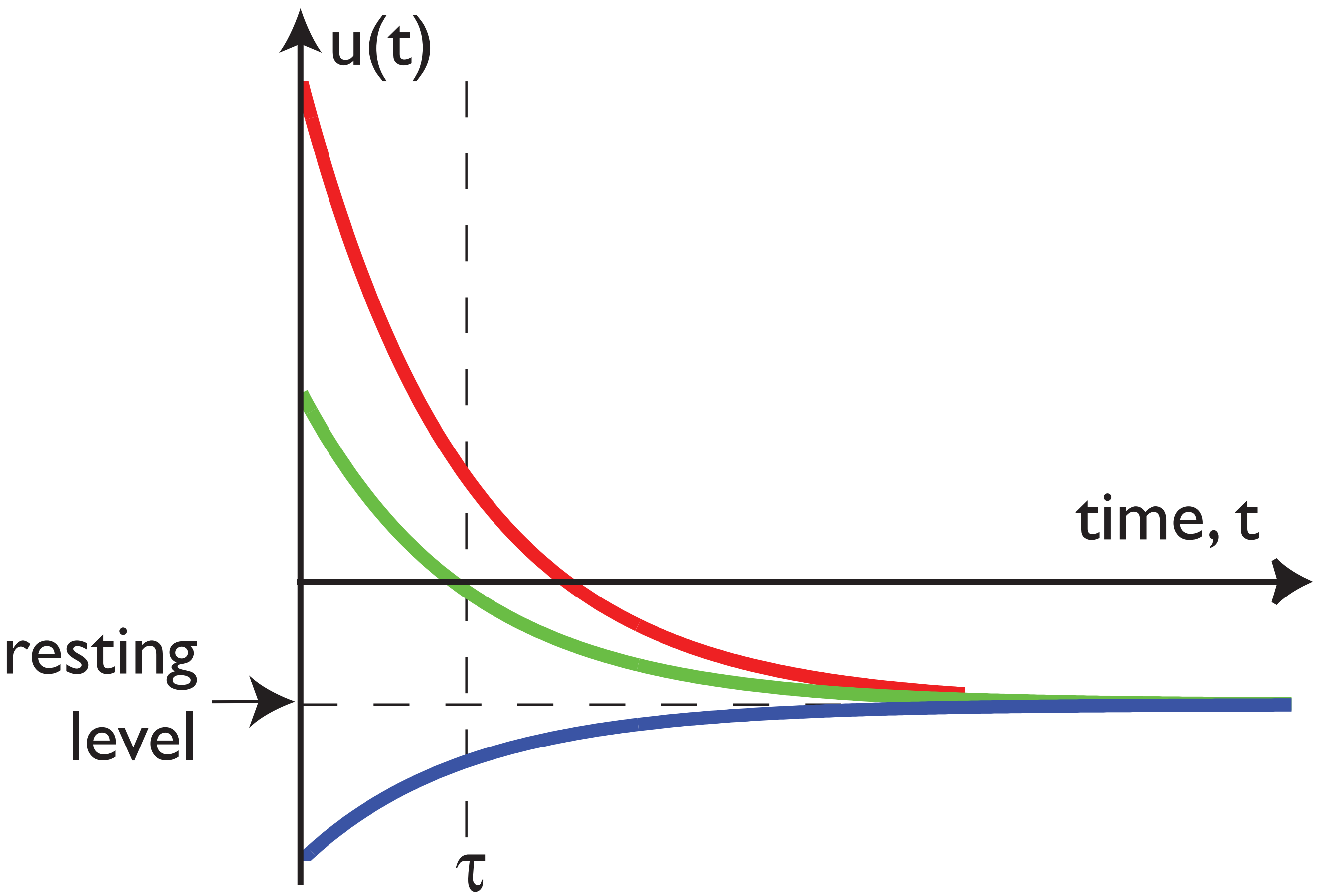
- stationary state=fixed point= constant solution
- stable fixed point: nearby solutions converge to the fixed point=attractor

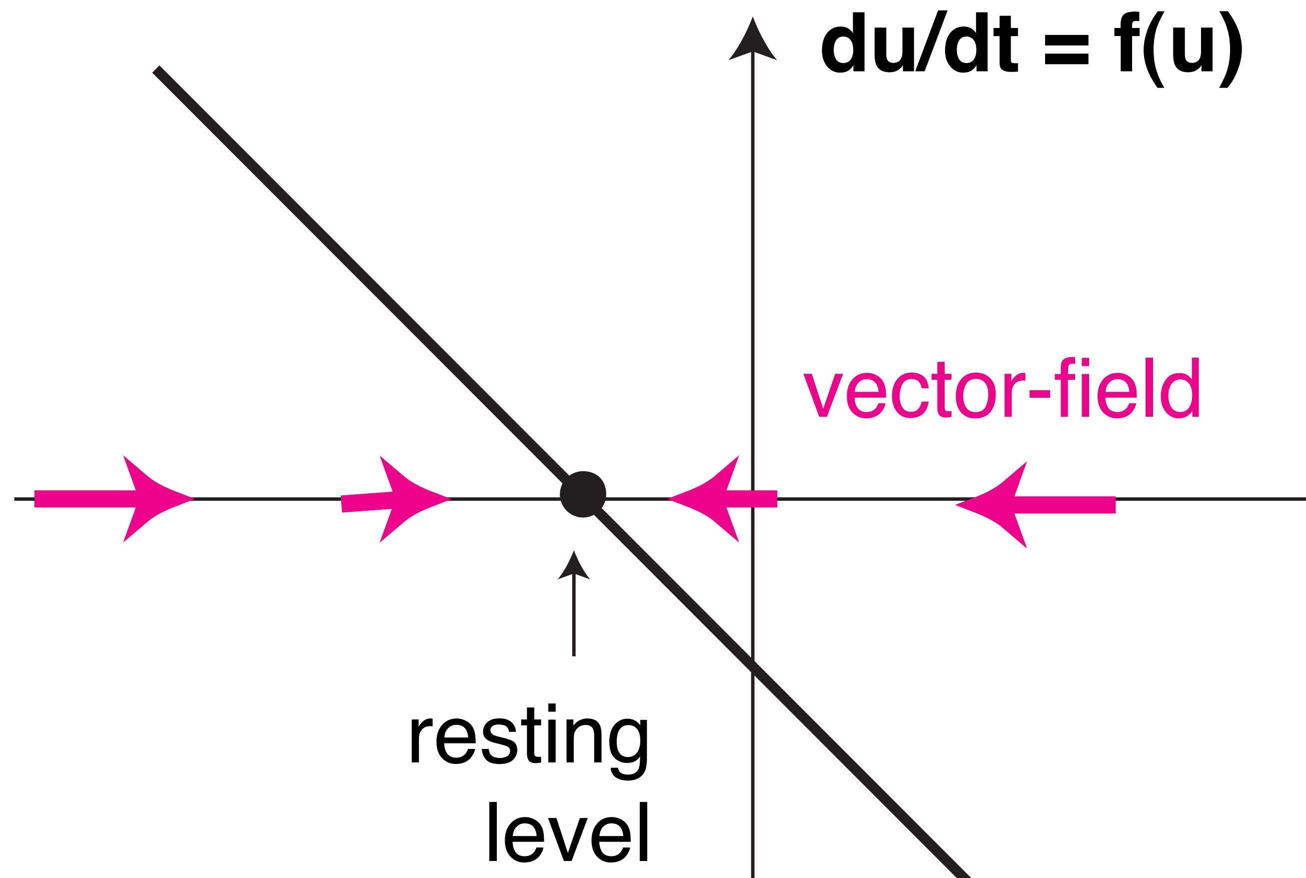


$$\frac{du(t)}{dt} = \dot{u}(t) = -u(t) + h \qquad (h < 0)$$

Neural dynamics

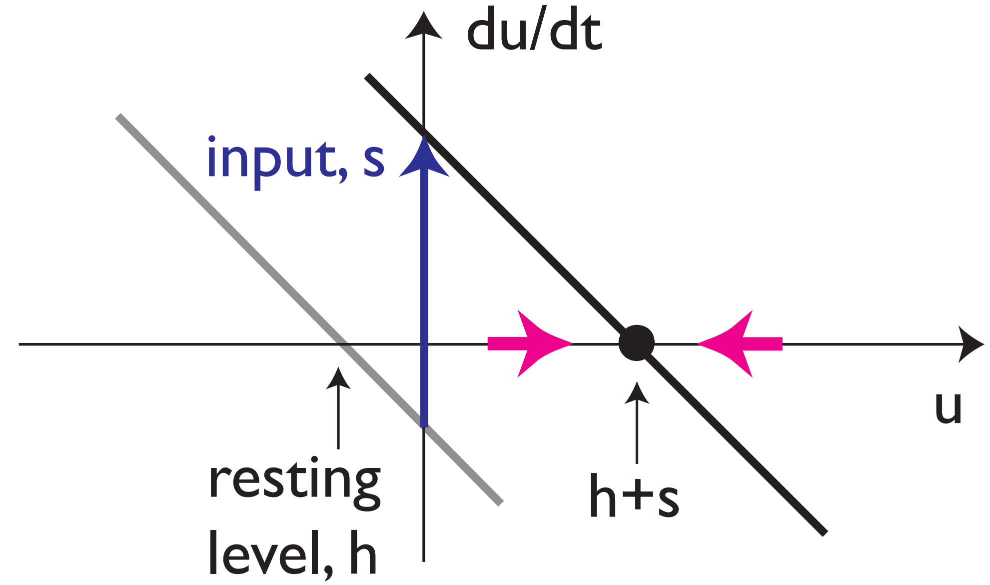
- attractor structures ensemble of solutions=flow



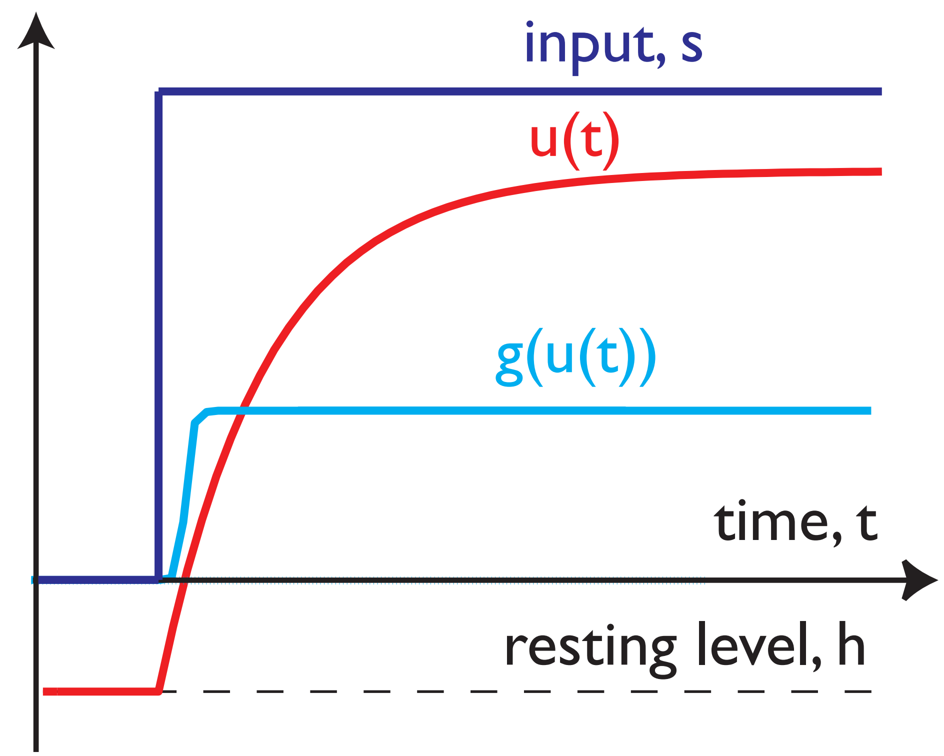


$$\tau \dot{u}(t) = -u(t) + h$$

Neuronal dynamics



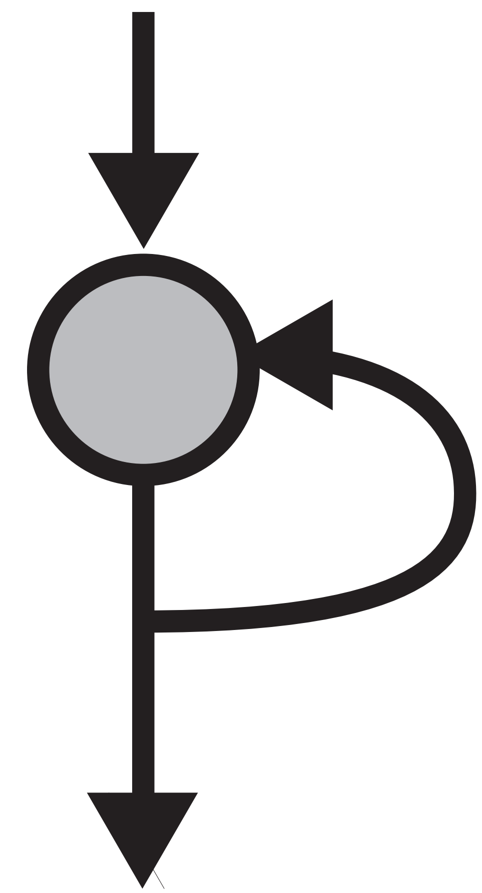
- inputs=contributions to the rate of change
  - positive: excitatory
  - negative: inhibitory
- => shifts the attractor
- activation tracks this shift (stability)



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

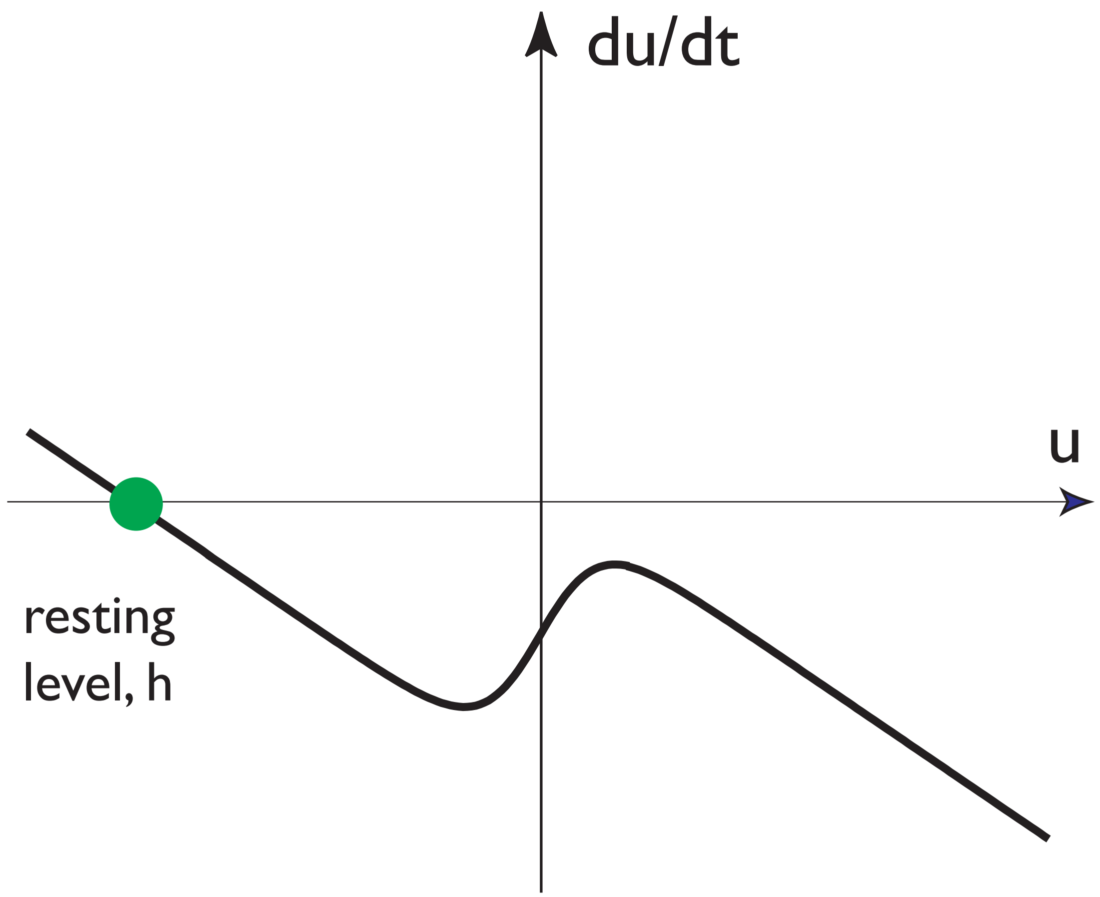
Neuronal dynamics with self-excitation

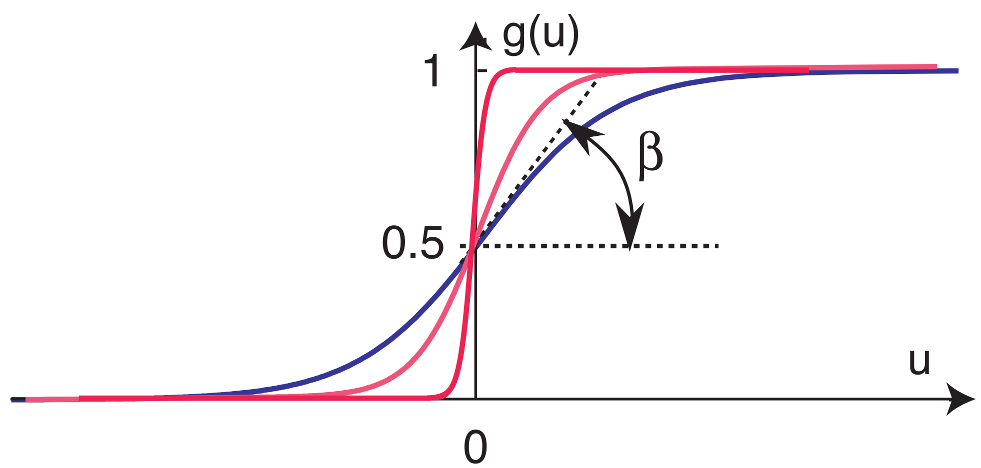
- single activation variable with self-excitation
- representing a small population with excitatory coupling



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

Neuronal dynamics with self-excitation



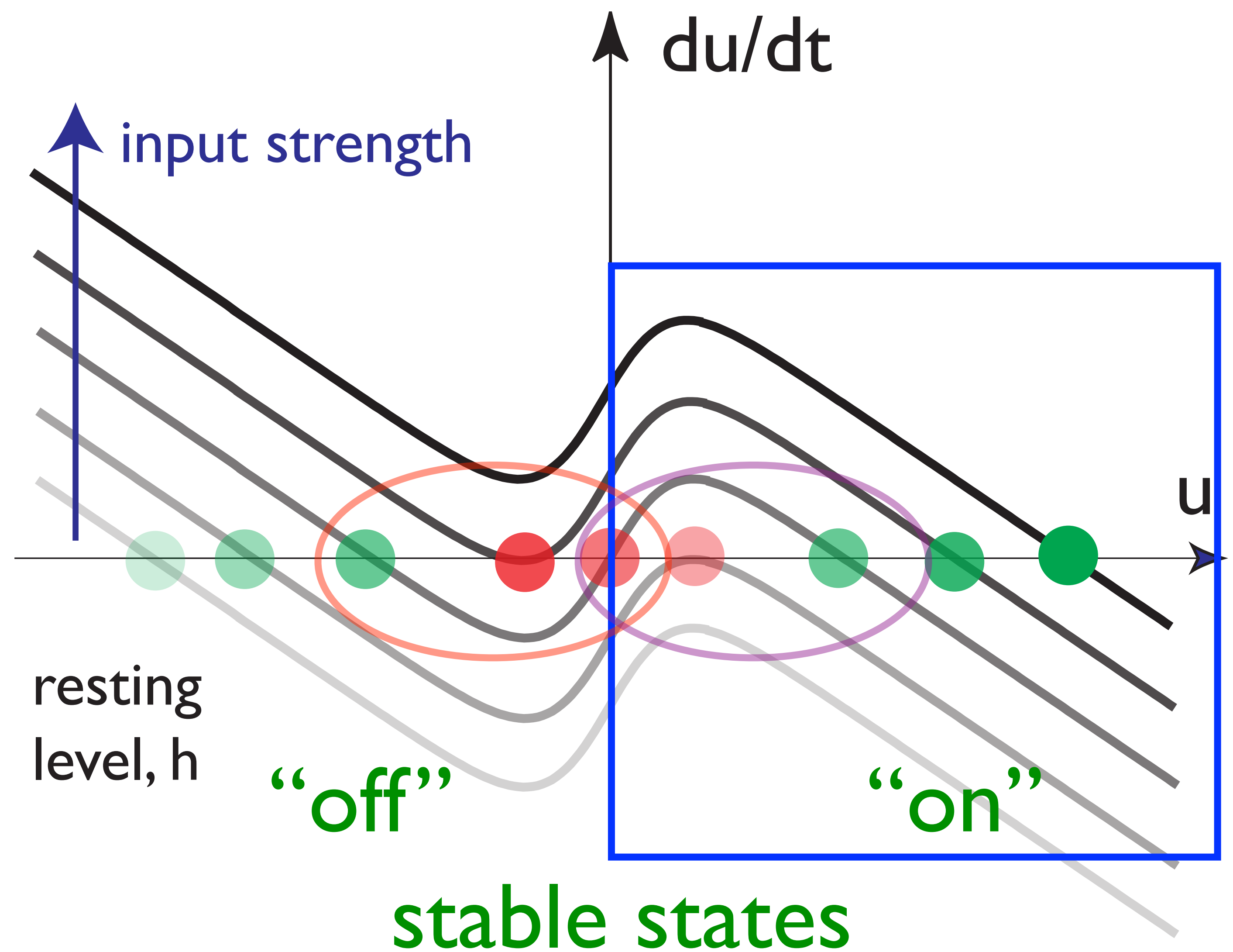


$$\tau \dot{u}(t) = -u(t) + h + S(t) + c\sigma(u(t))$$

Stability from neural dynamics

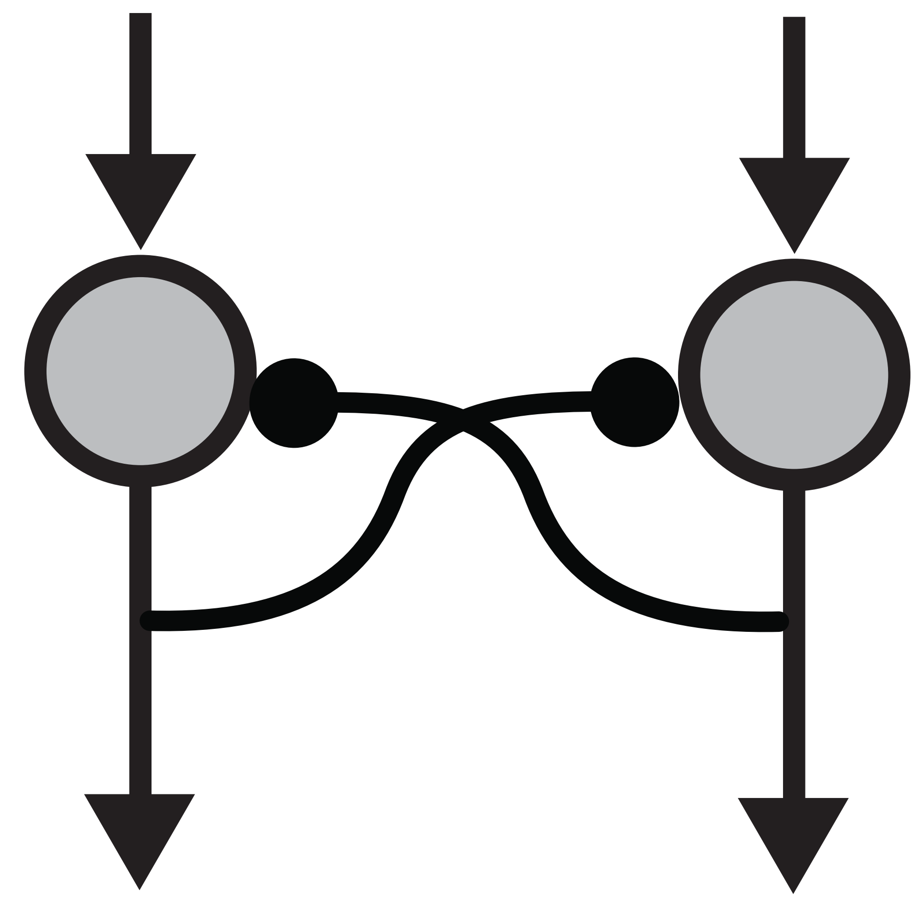
- autonomous activation from interaction
- $\dot{u}(t) = -u(t) + h + \text{input}(t) \boxed{+ \sigma(u(t))}$

- detection instability
- working memory
- reverse detection instability



Neuronal dynamics with competition

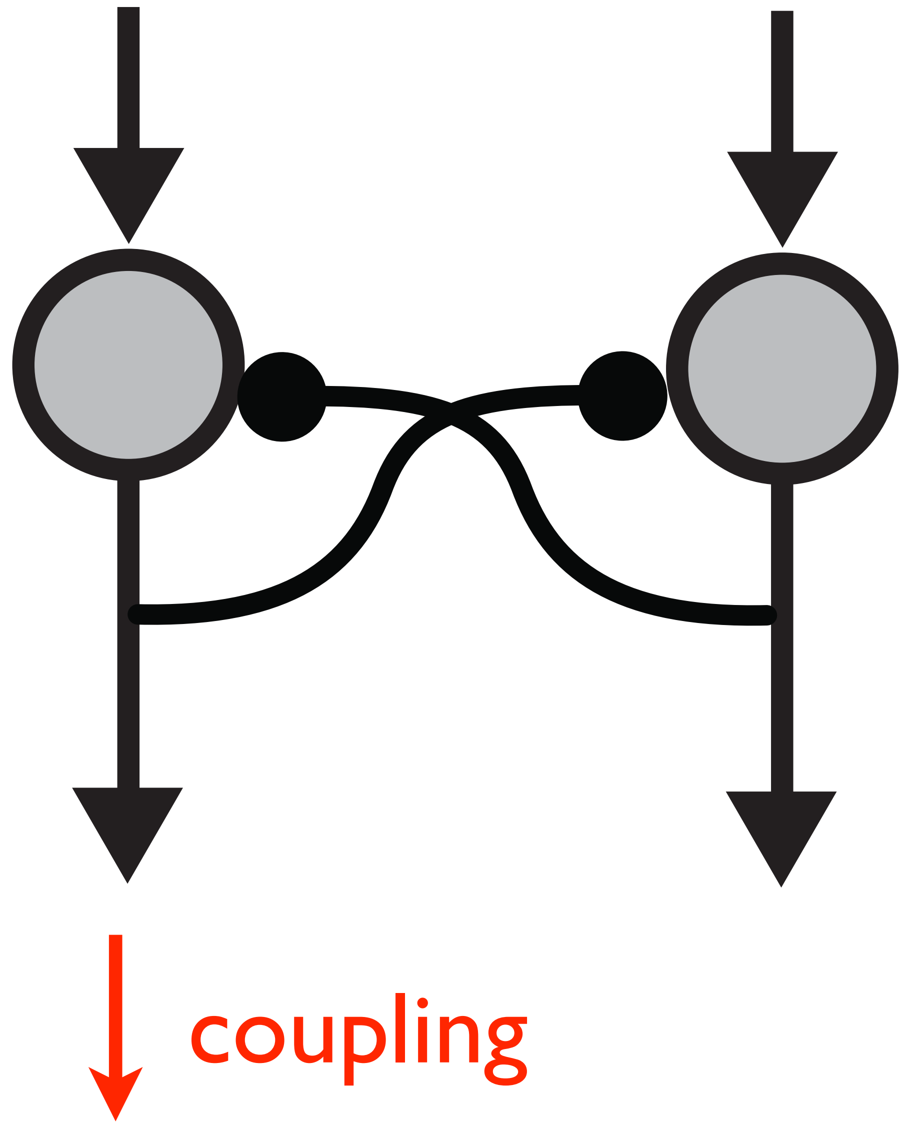
- two activation variables with reciprocal inhibitory coupling
- representing two small populations that are inhibitorily coupled



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

Neuronal dynamics with competition

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



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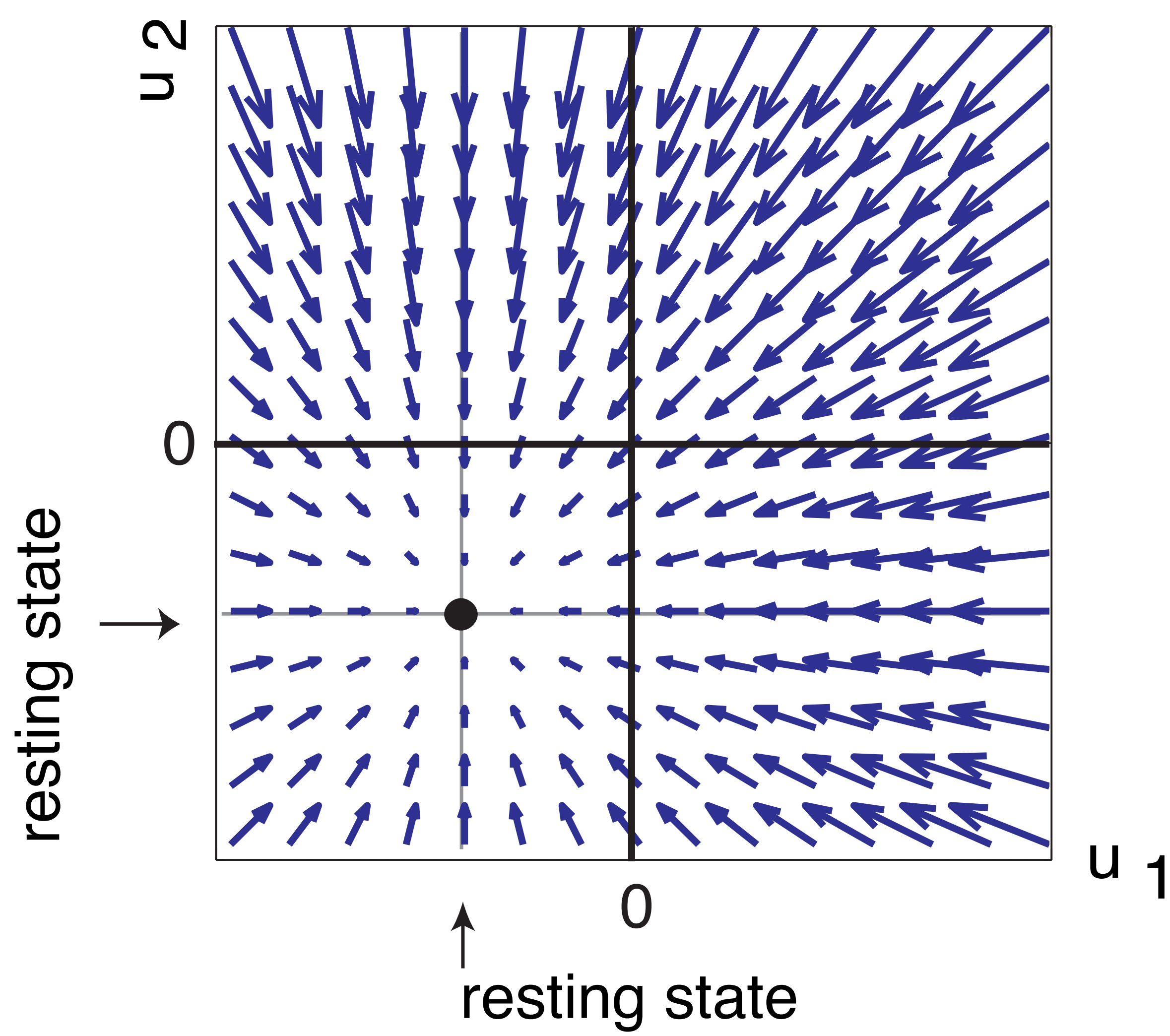
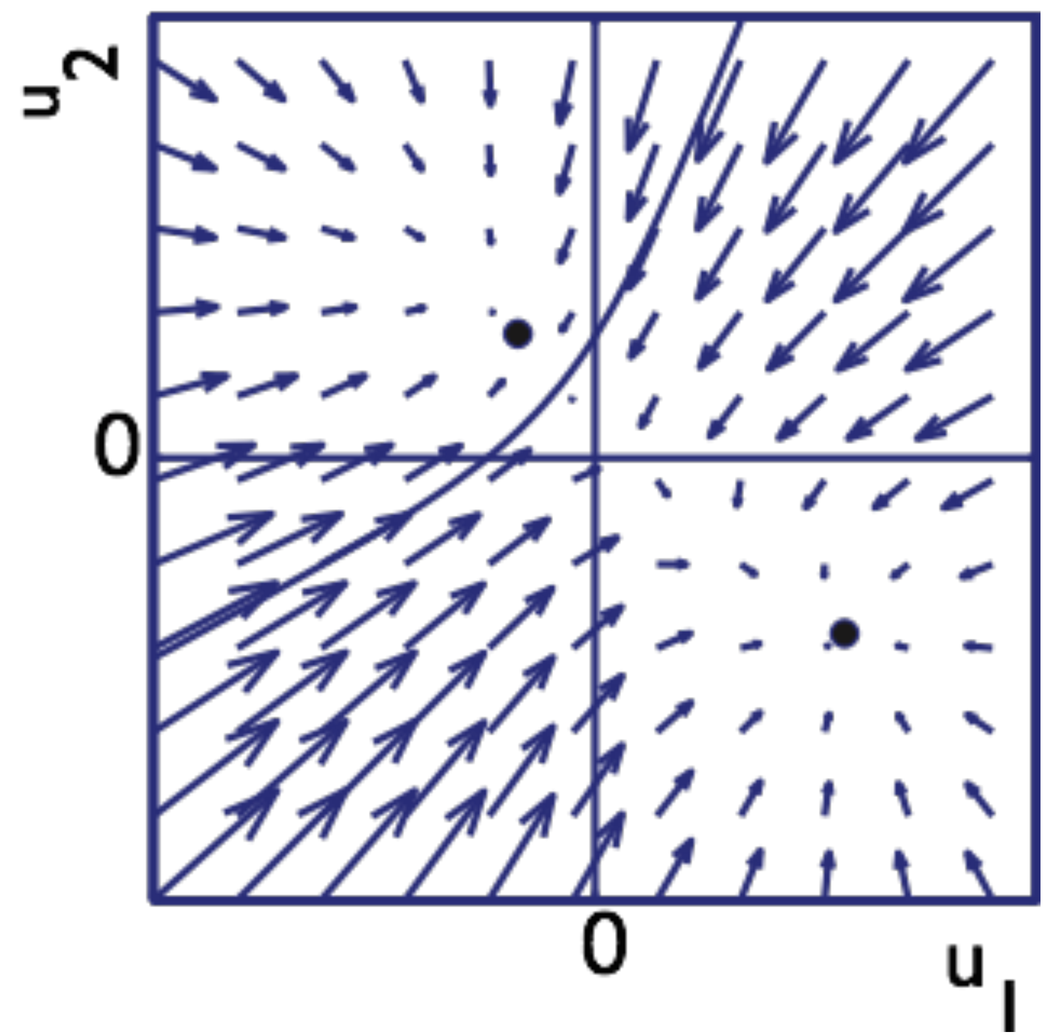
Neuronal dynamics with competition

=>biased competition

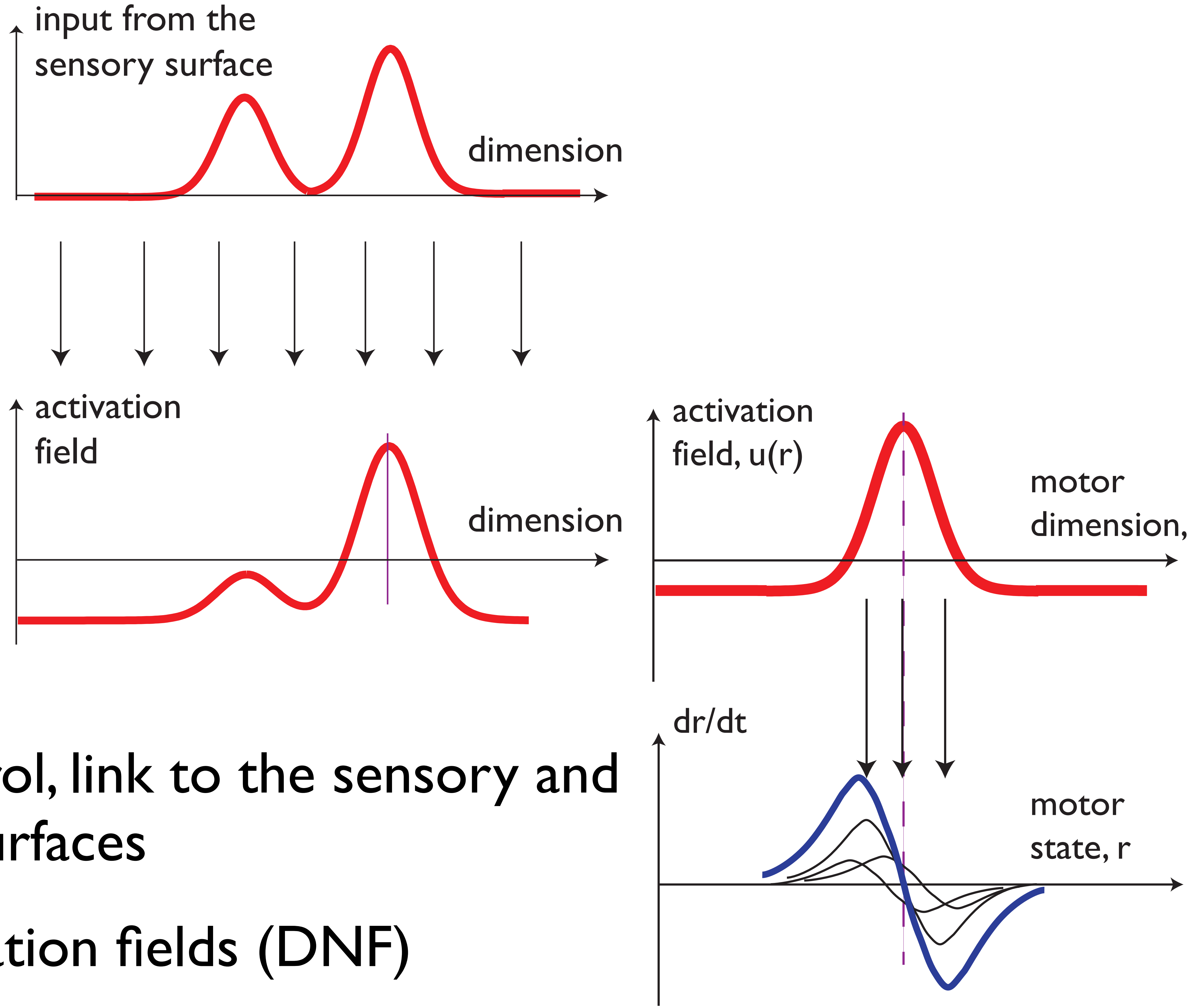
before input is presented



after input is presented

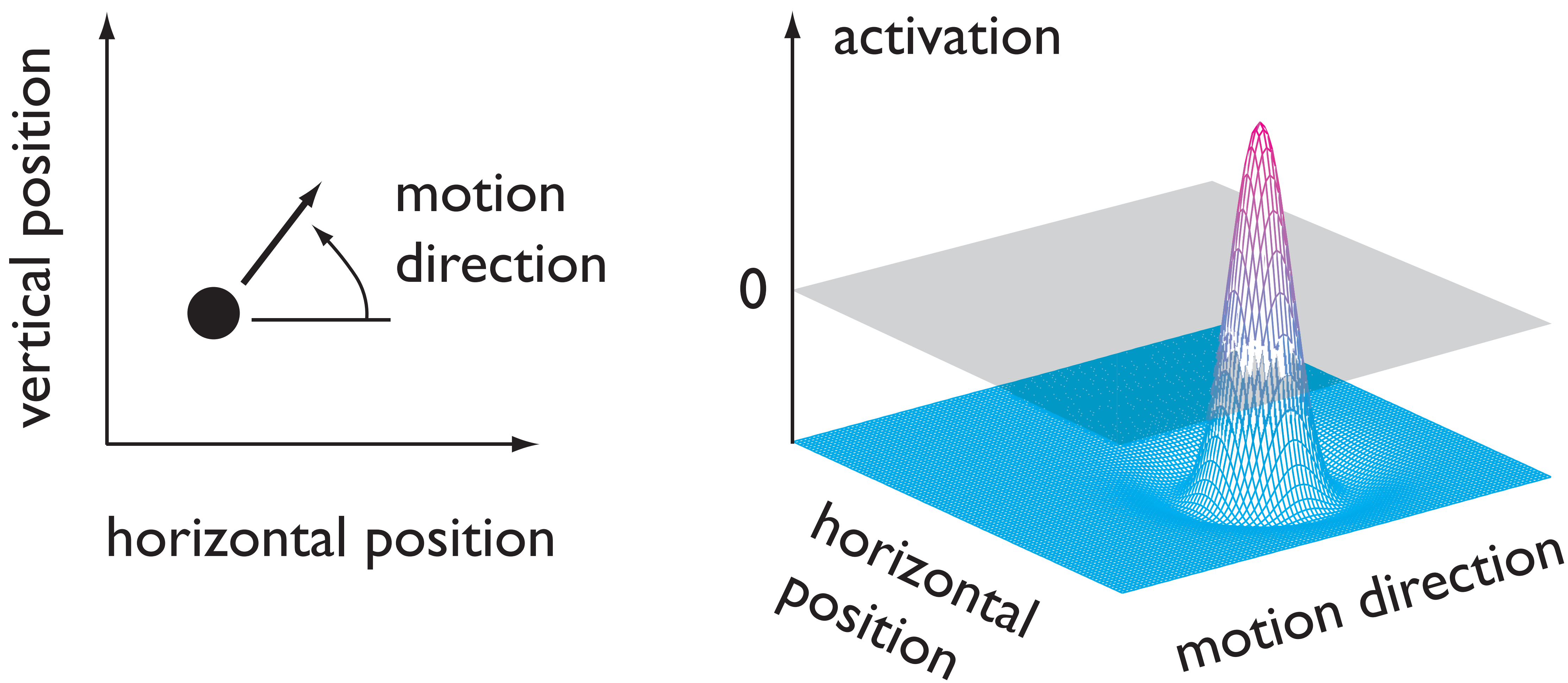


Neural fields

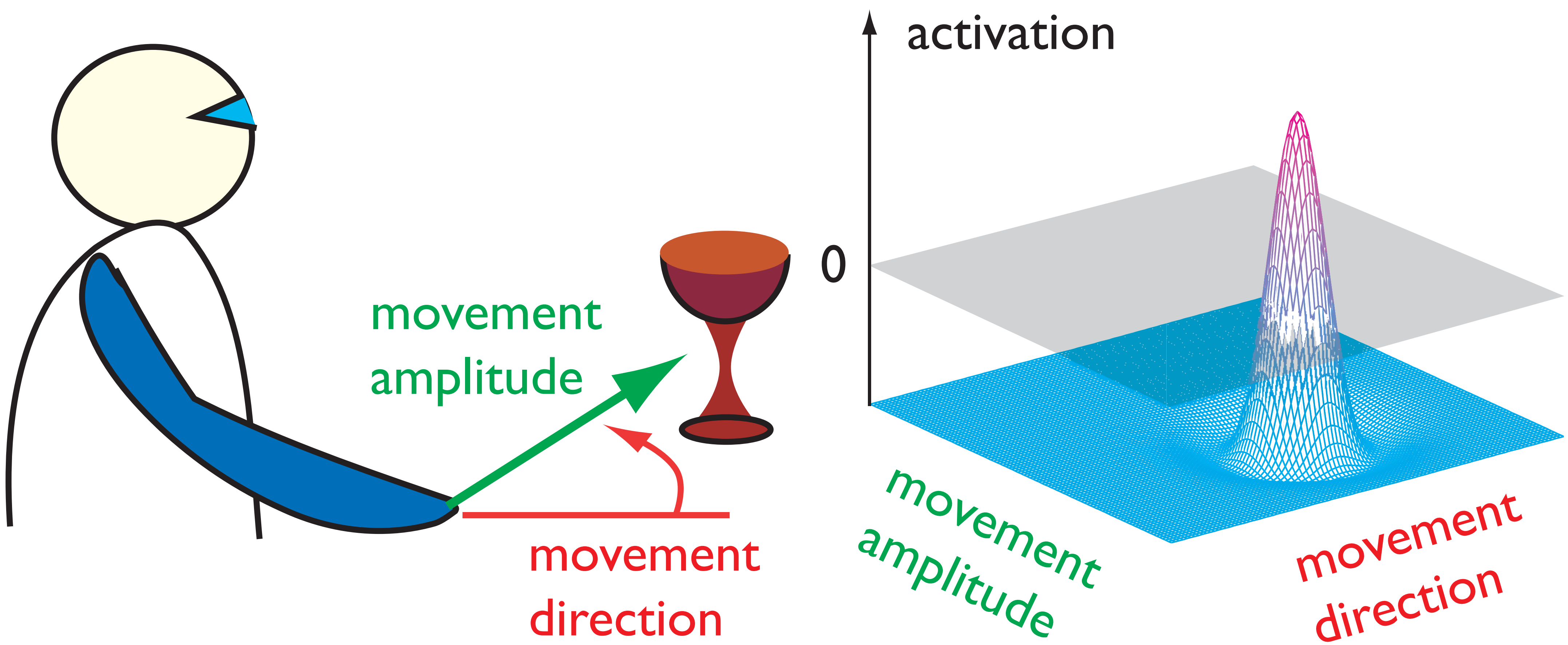


- for control, link to the sensory and motor surfaces
- => activation fields (DNF)

Example motion perception: space of possible percepts

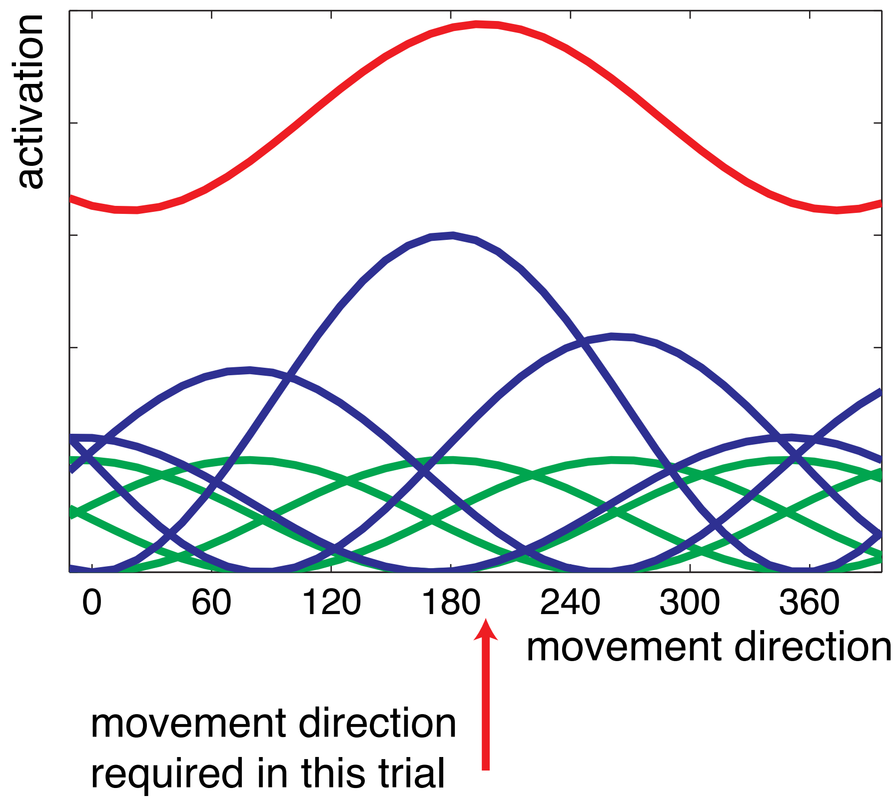


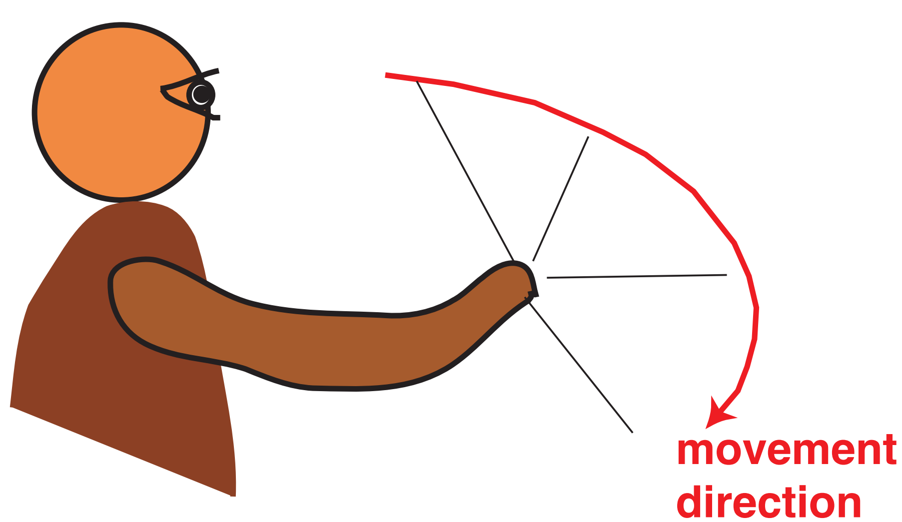
Example: movement planning: space of possible actions

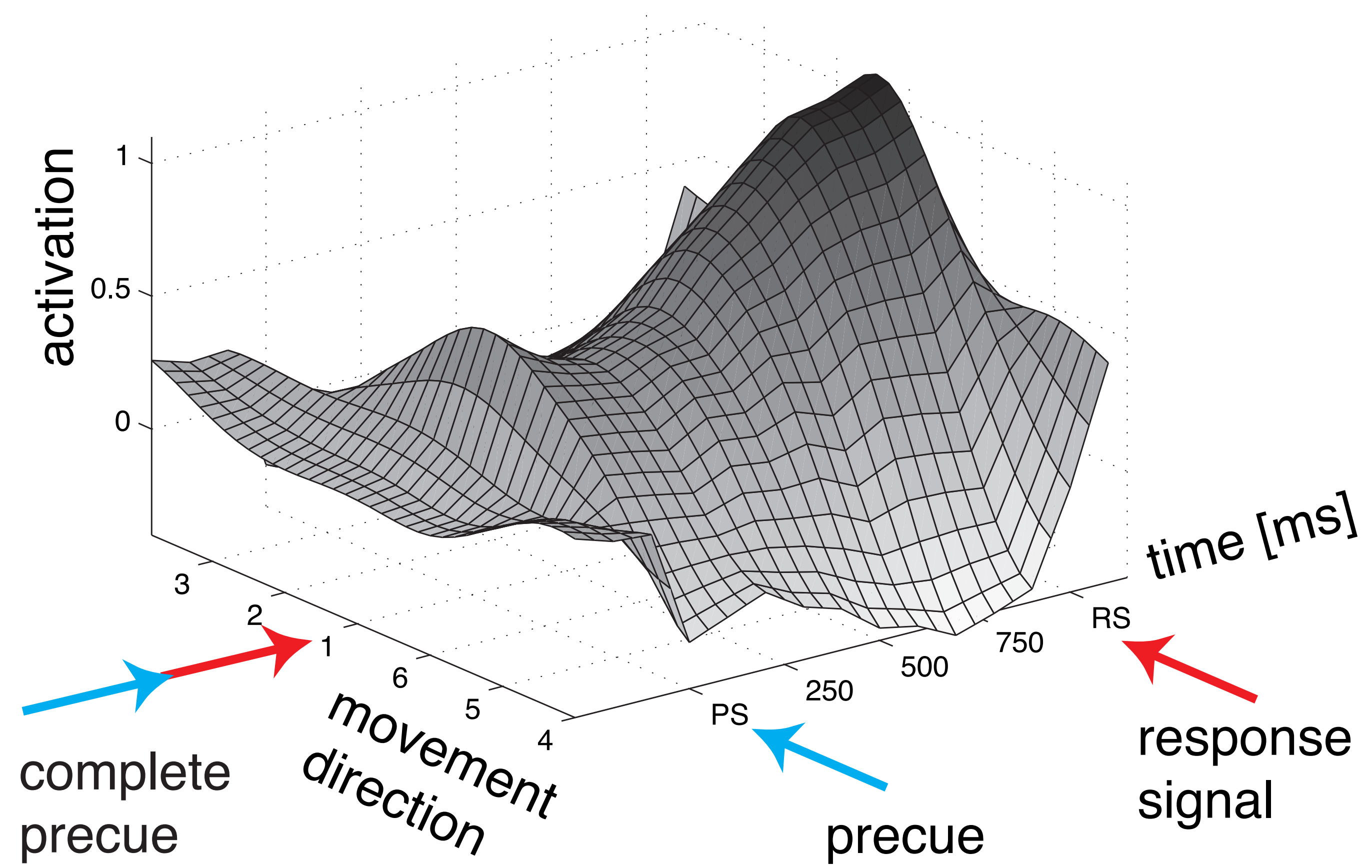


Distribution of Population Activation (DPA)

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



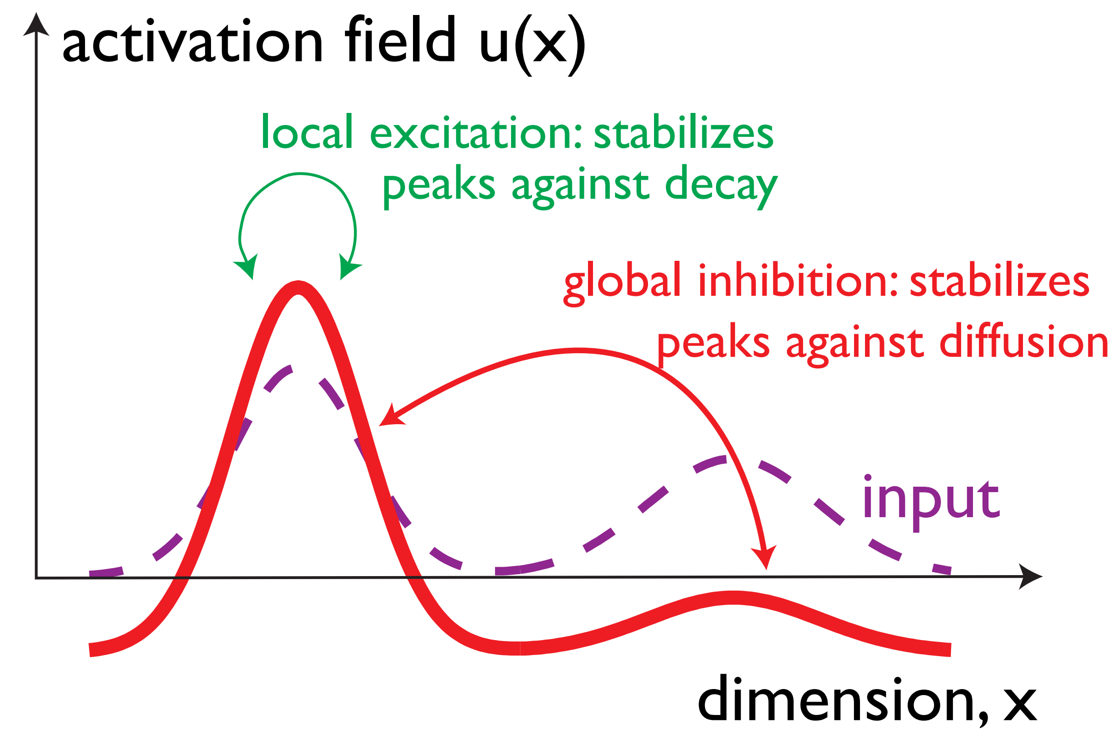


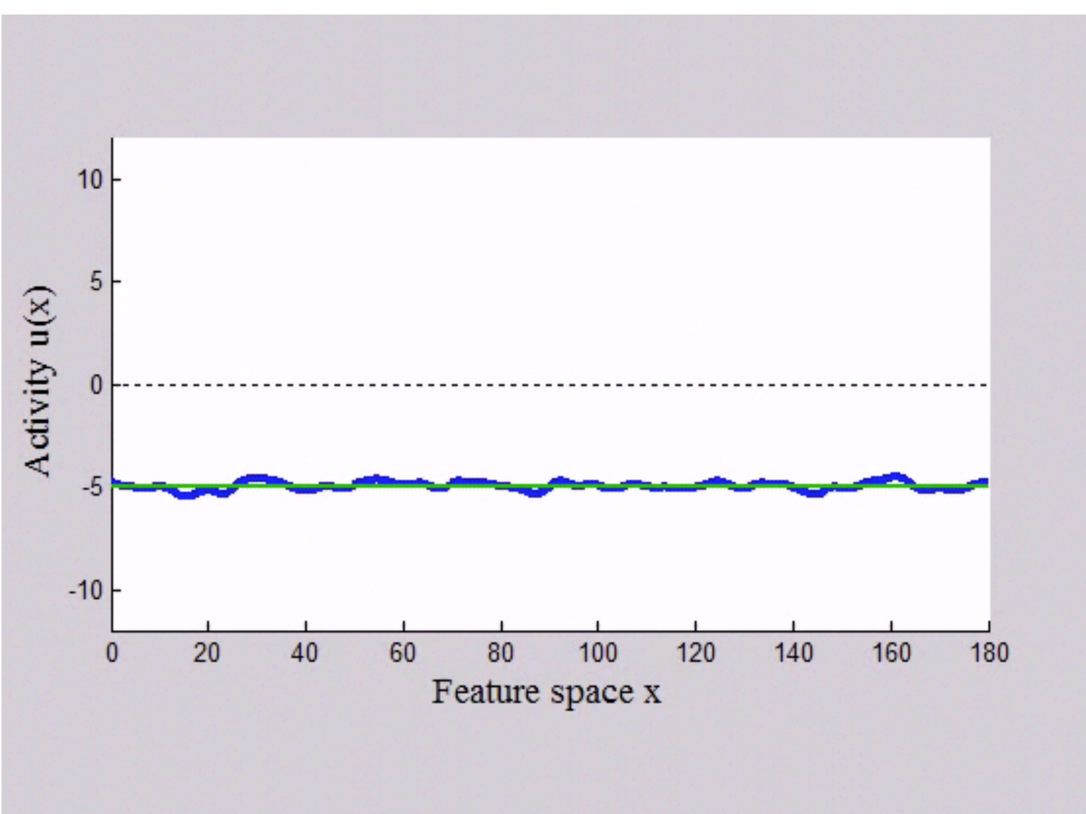


[Bastian, Riehle, Schöner, 2003]

Dynamic of neural fields

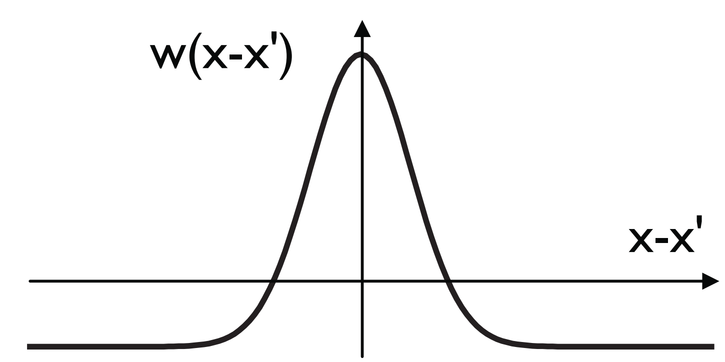
- peaks as attractors
- detection instability
- working memory
- selection





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

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



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

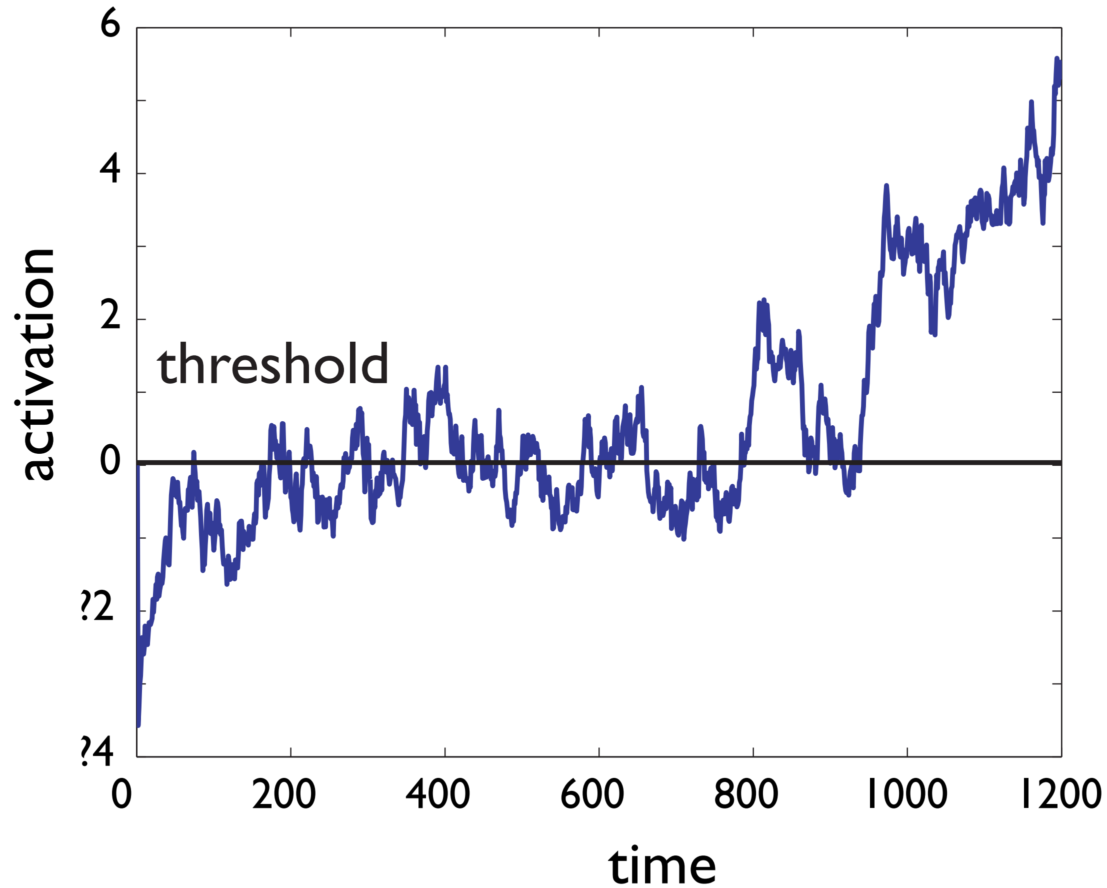
detection instability

reverse detection instability

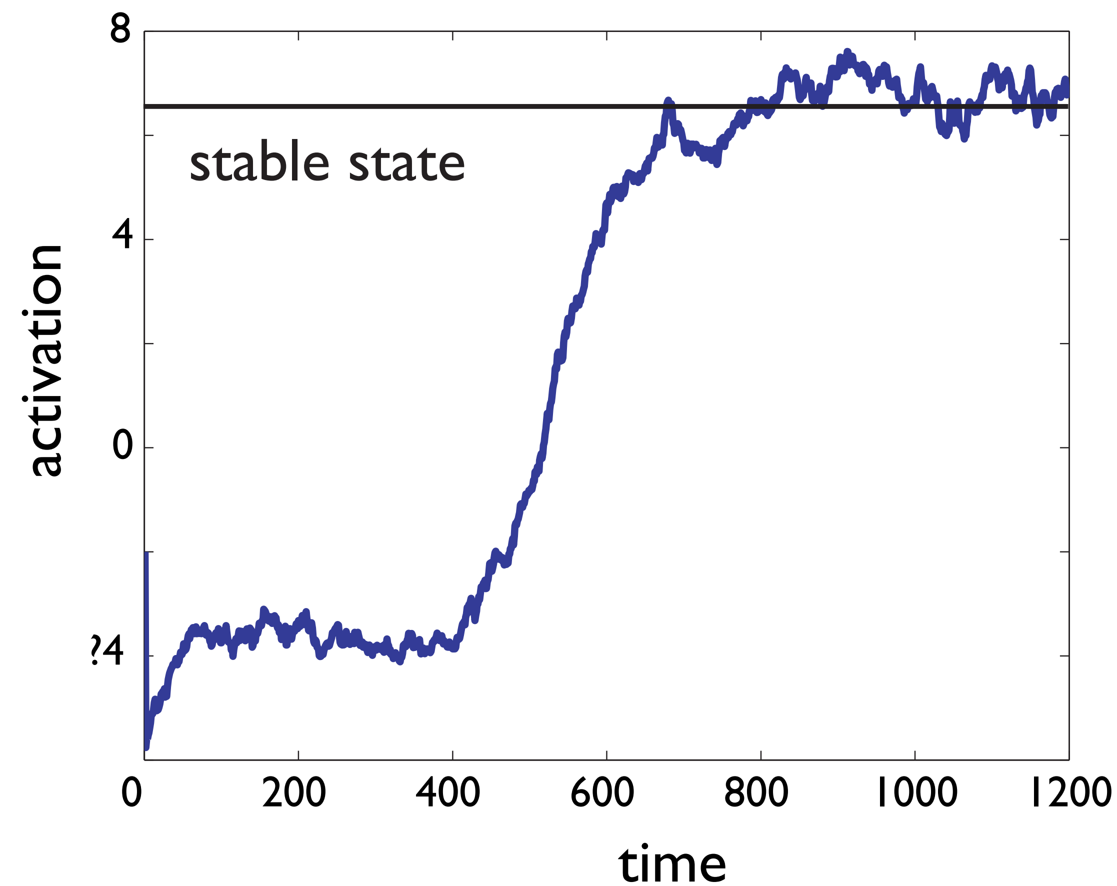
Noise is critical near instabilities

The detection instability stabilizes decisions

threshold piercing

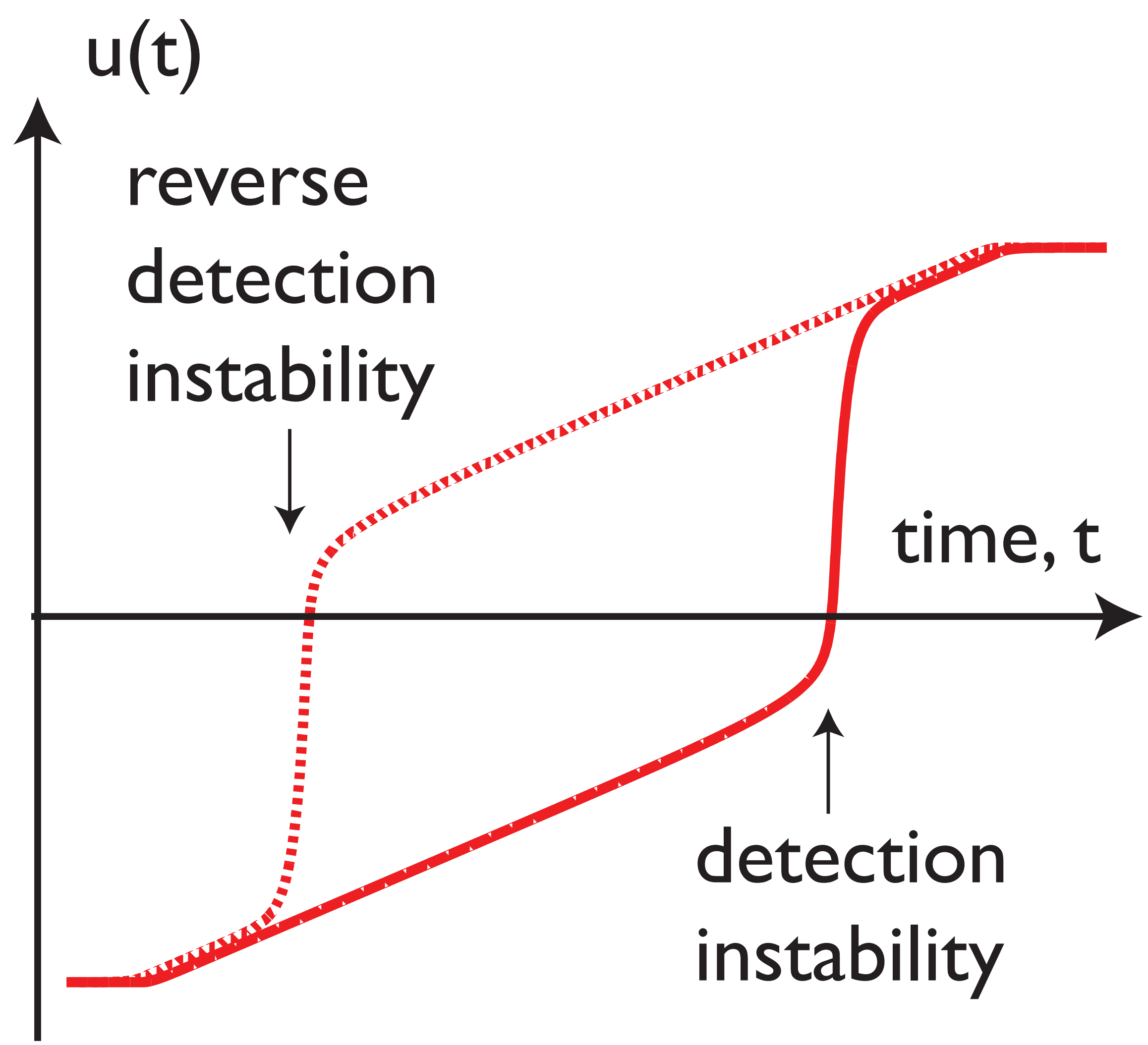


detection instability

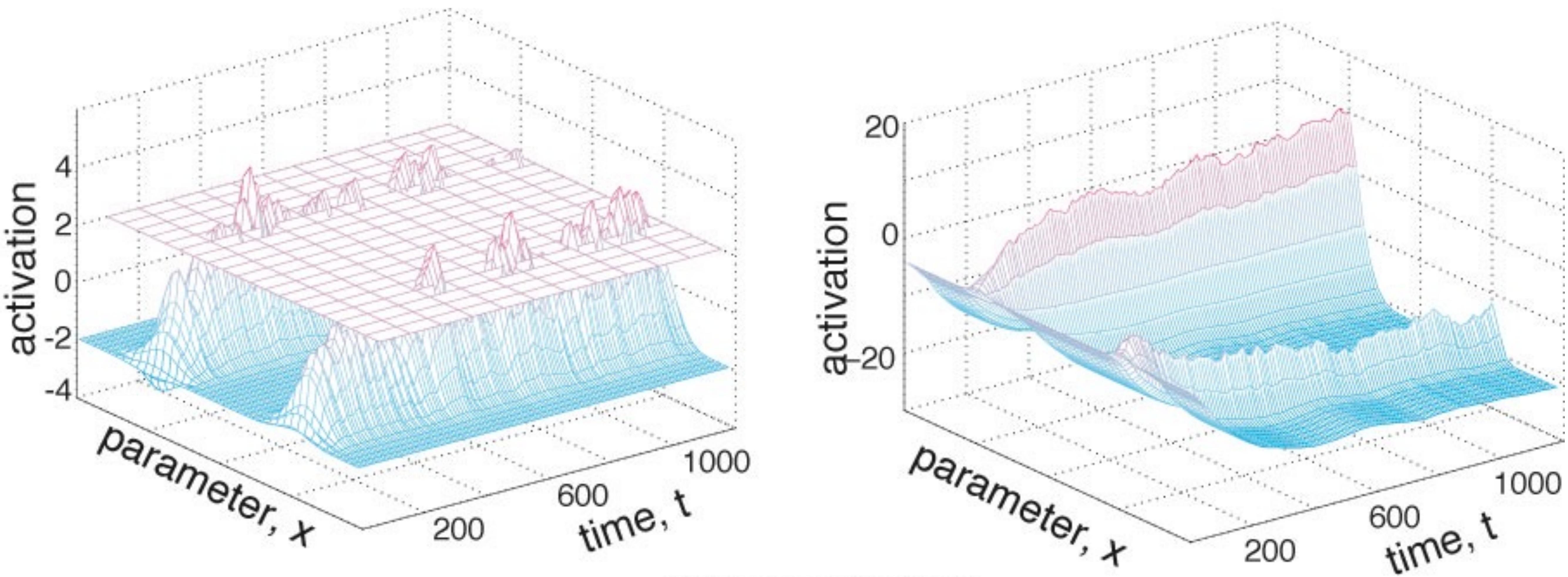


The detection instability leads to the emergence of events

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

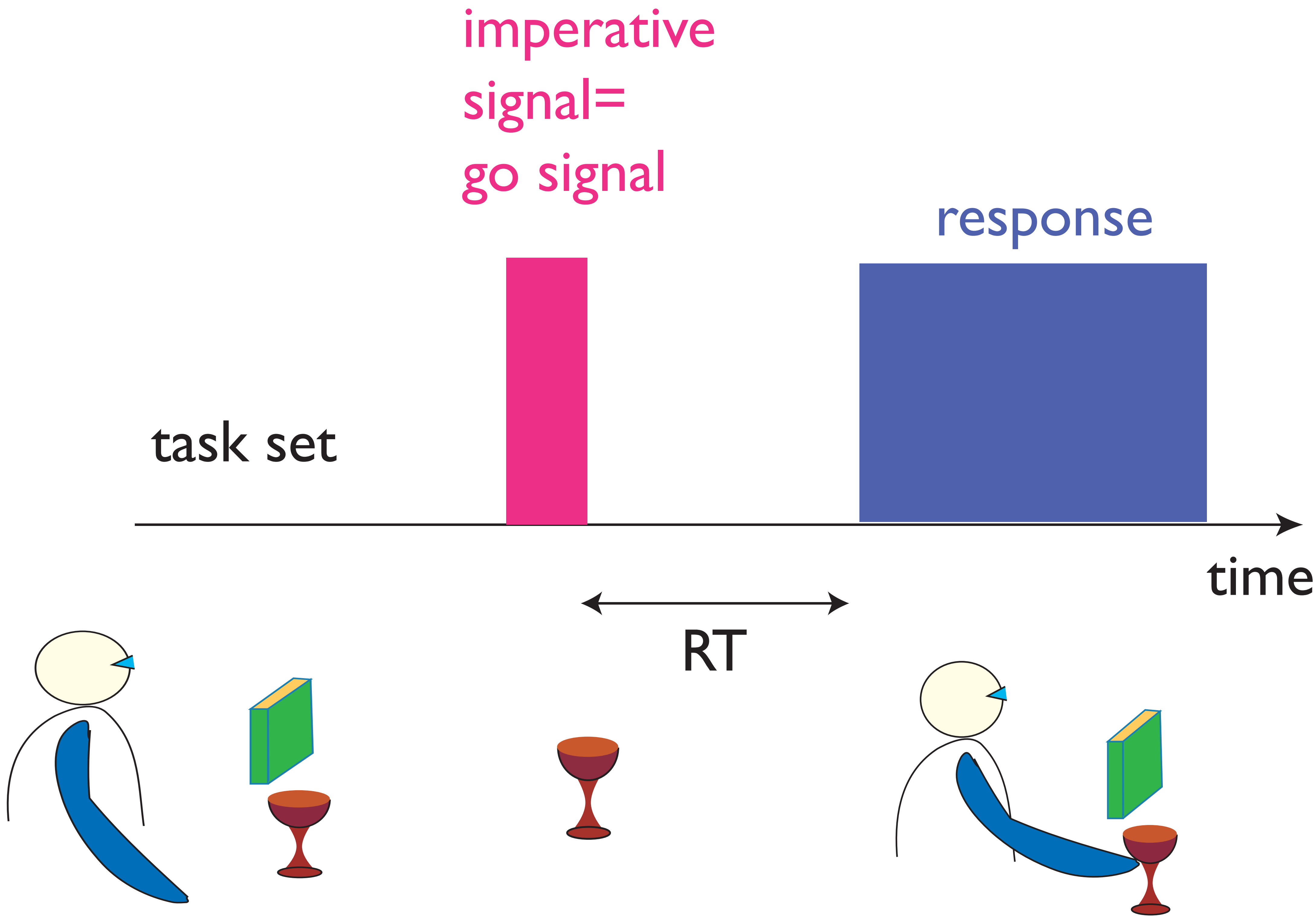


stabilizing selection decisions

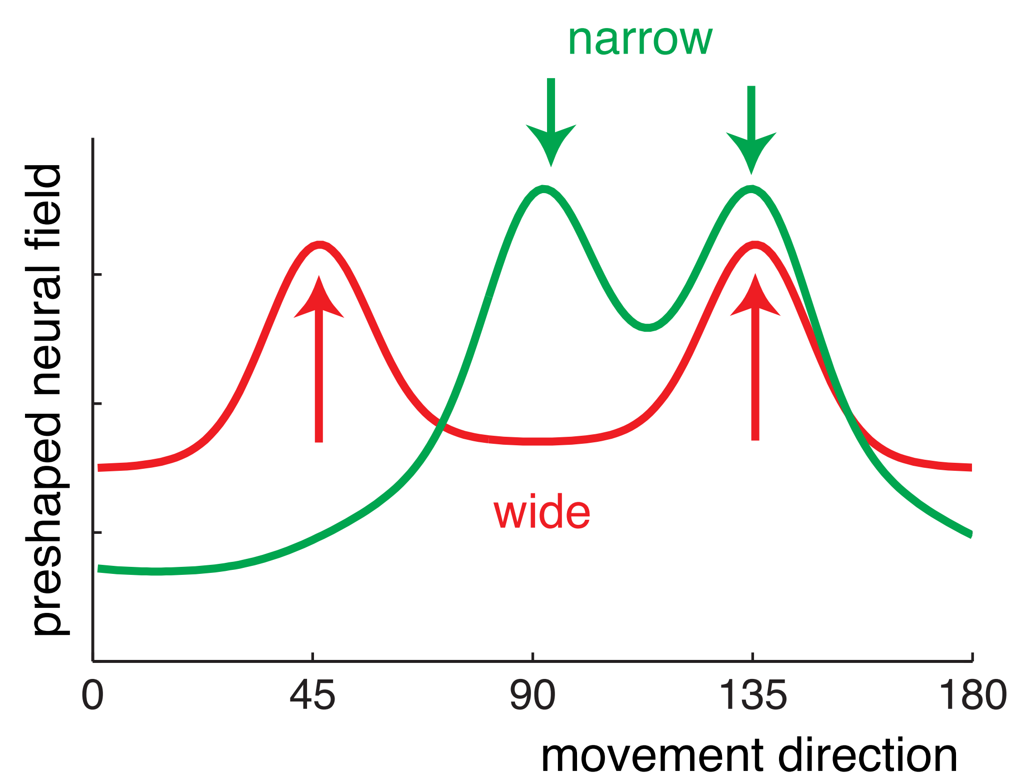


[Wilimzig, Schöner, 2006]

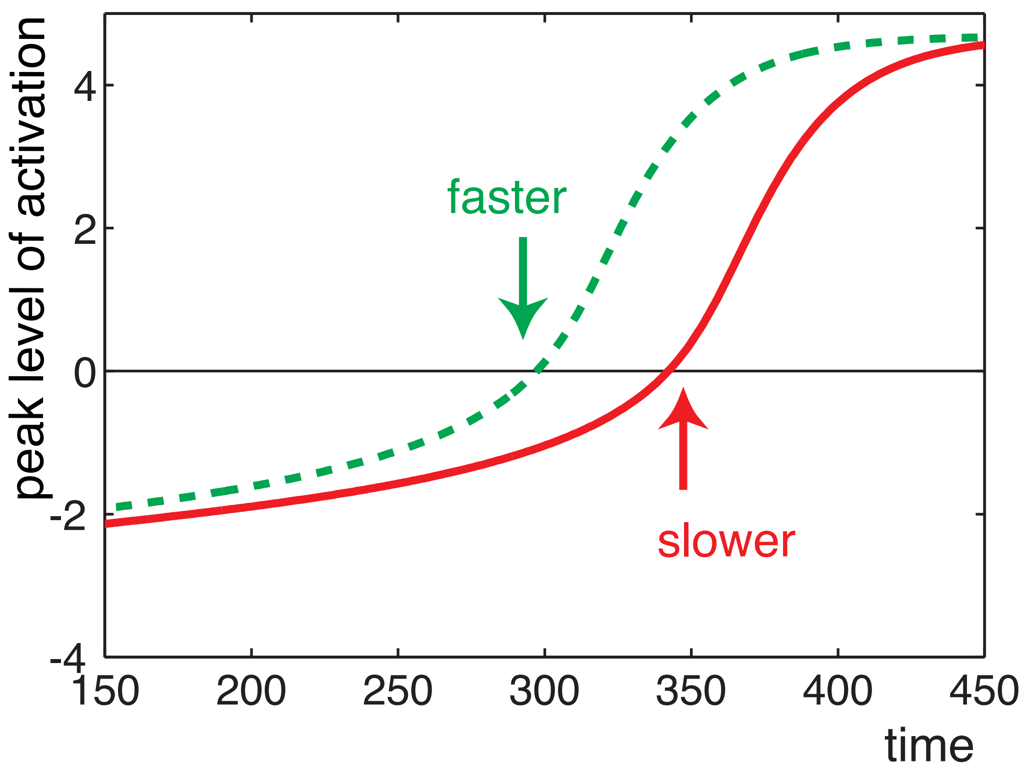
reaction time (RT) paradigm



metric effect



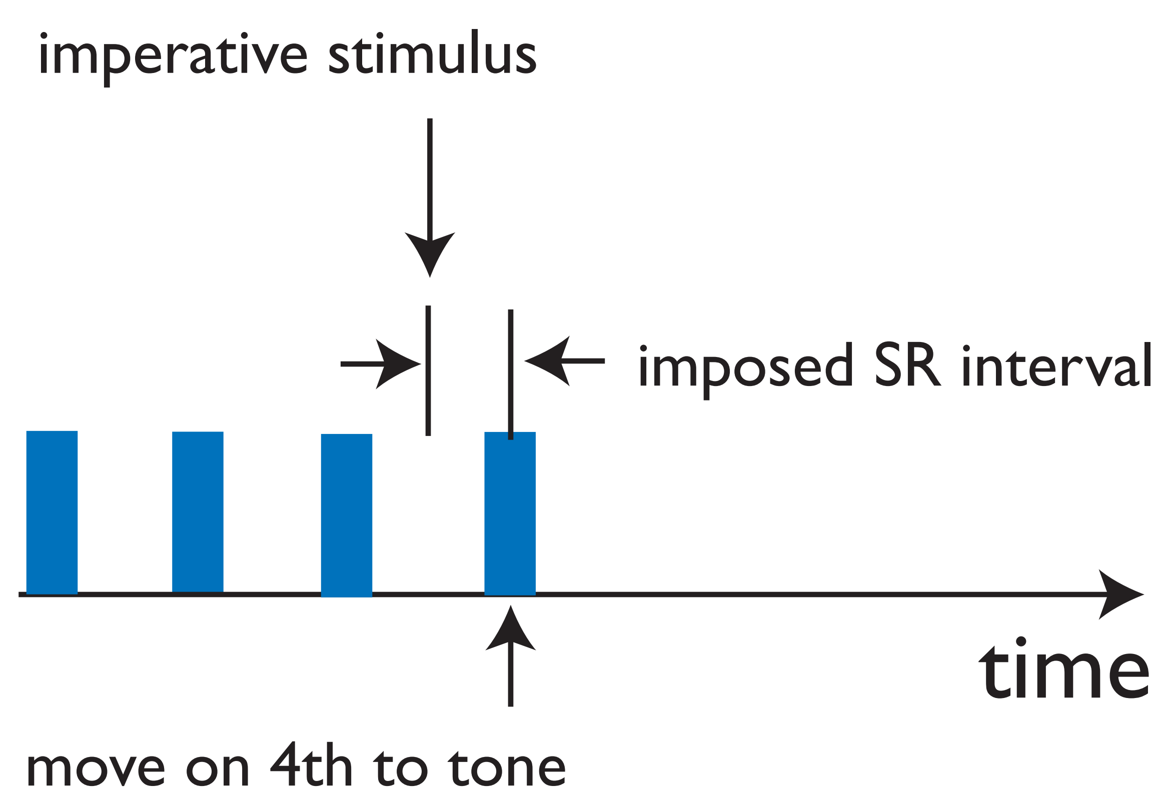
- predict faster response times for metrically close than for metrically far choices



[from Schöner, Kopecz, Erlhagen, 1997]

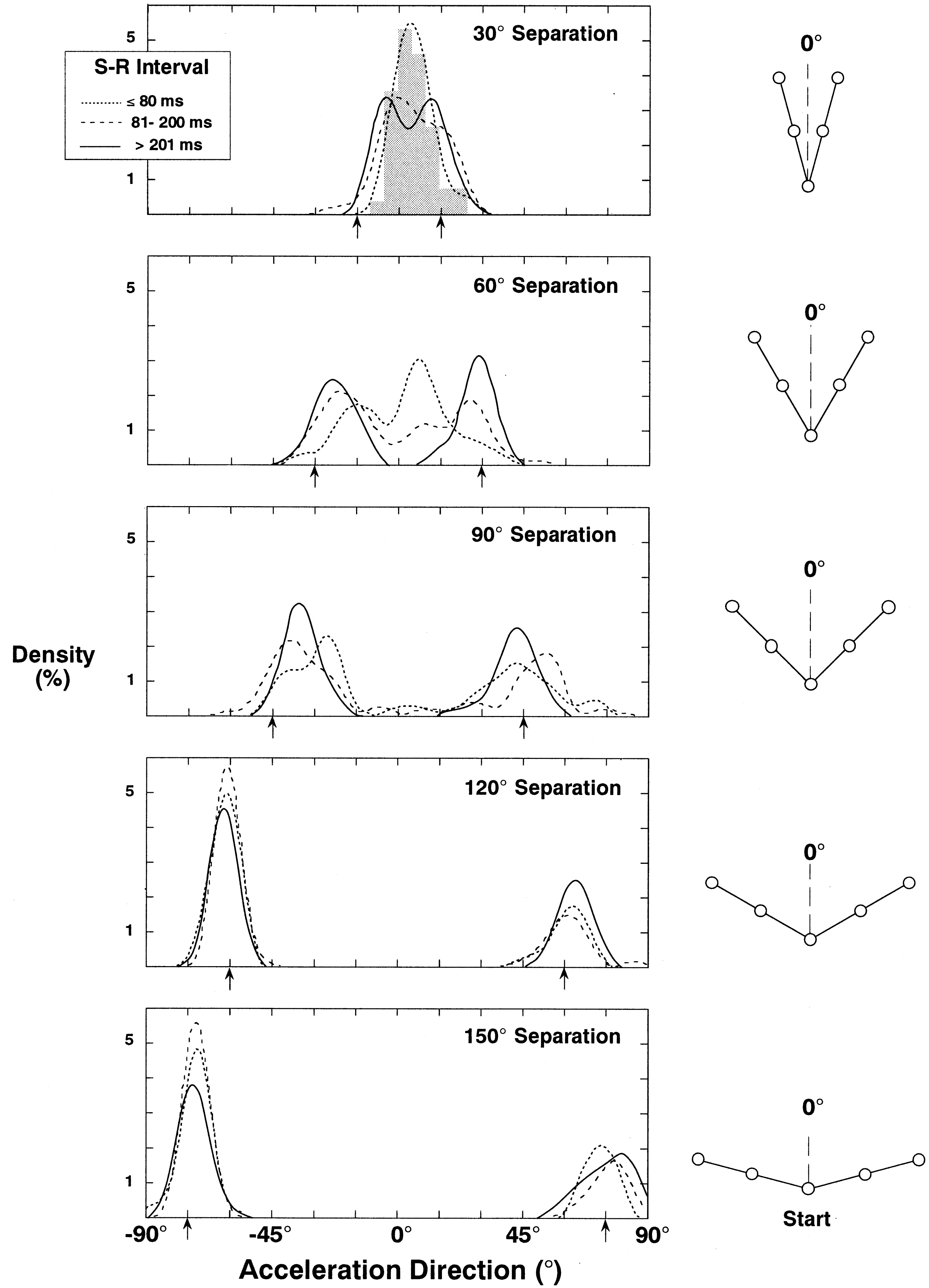
Time course of selection decisions: Behavioral evidence for the graded and continuous evolution of decision

timed movement
initiation paradigm



[Ghez and colleagues, 1988 to 1990's]

- infer width of preshape peaks in field

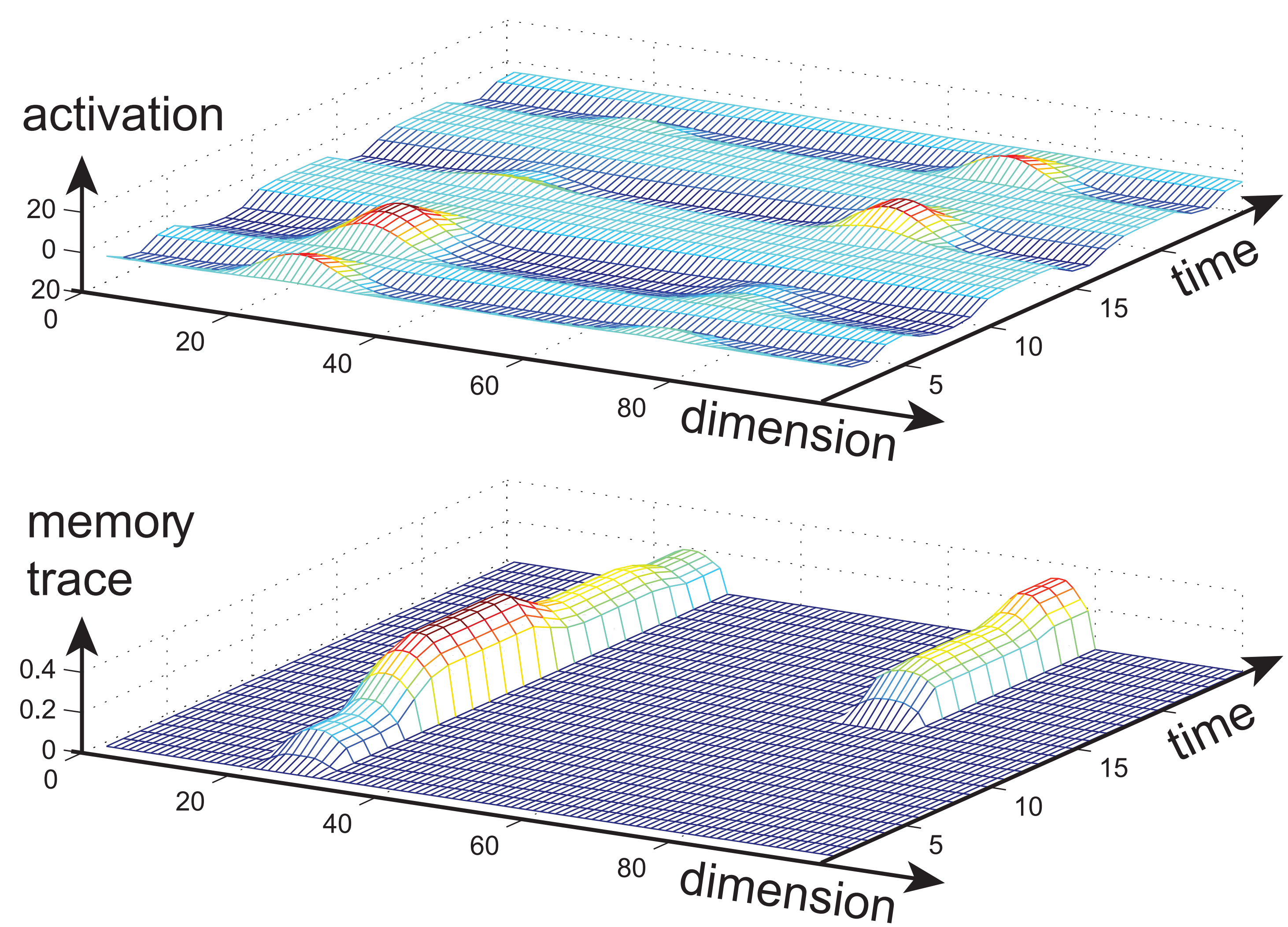


[Ghez et al 1997]

The memory trace

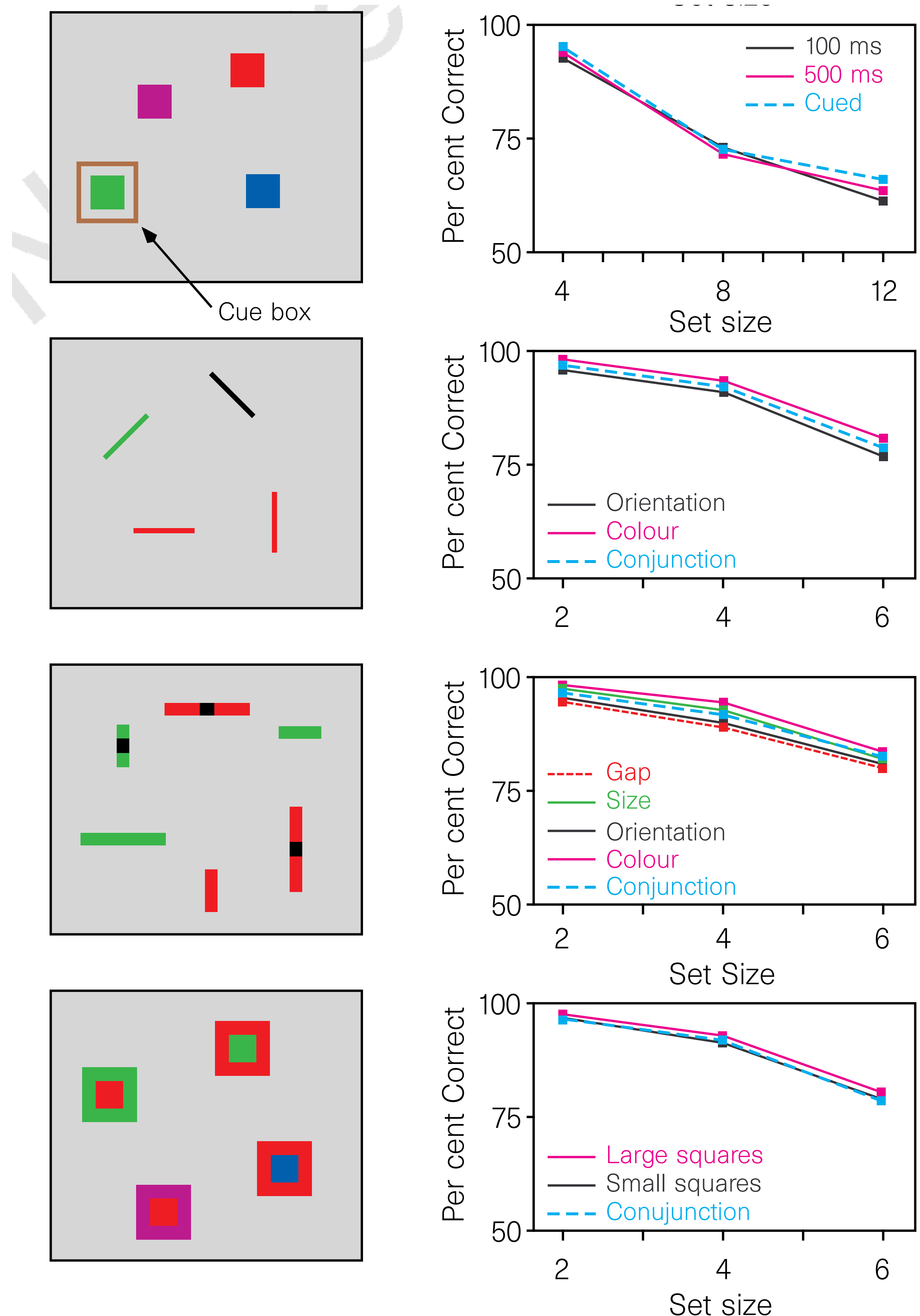
- activation leaves a trace that may influence the activation dynamics later… in a simplest form of learning, the "bias " term of NN

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



visual working memory

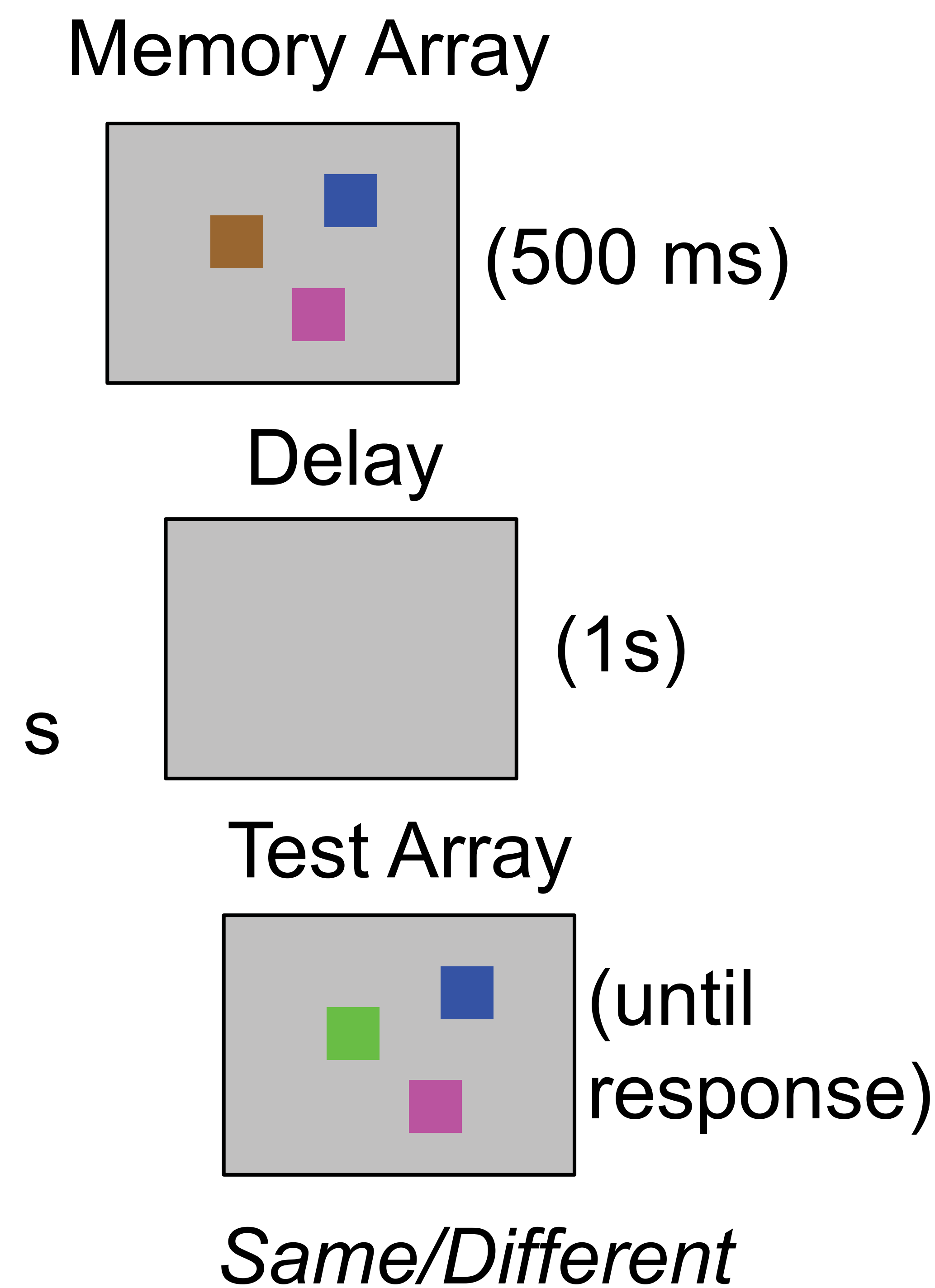
- has limited capacity
  - based on the number of objects…
  - about 4
- probed by change detection, free recall



[Luck, Vogel, 1997]

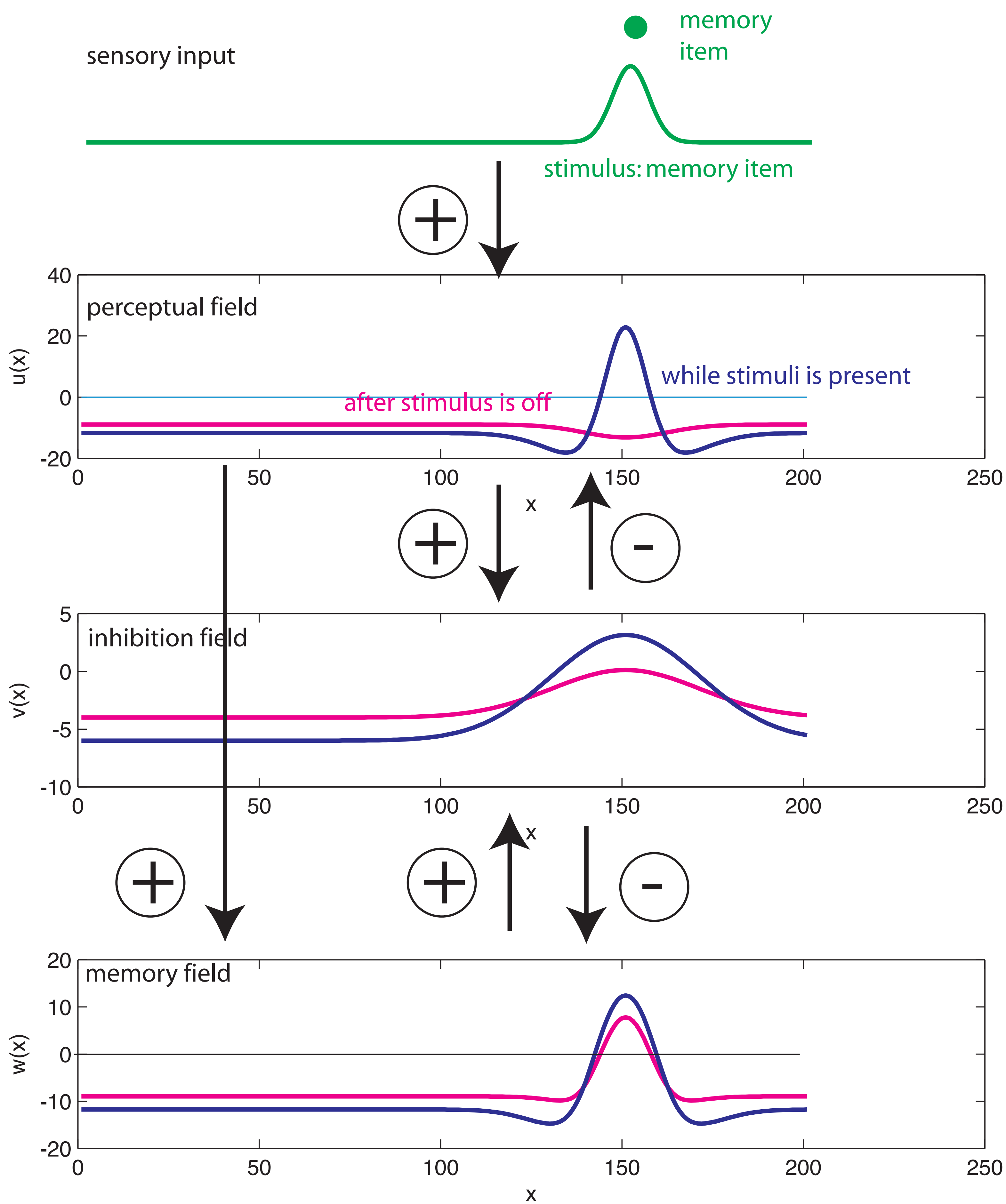
Change detection

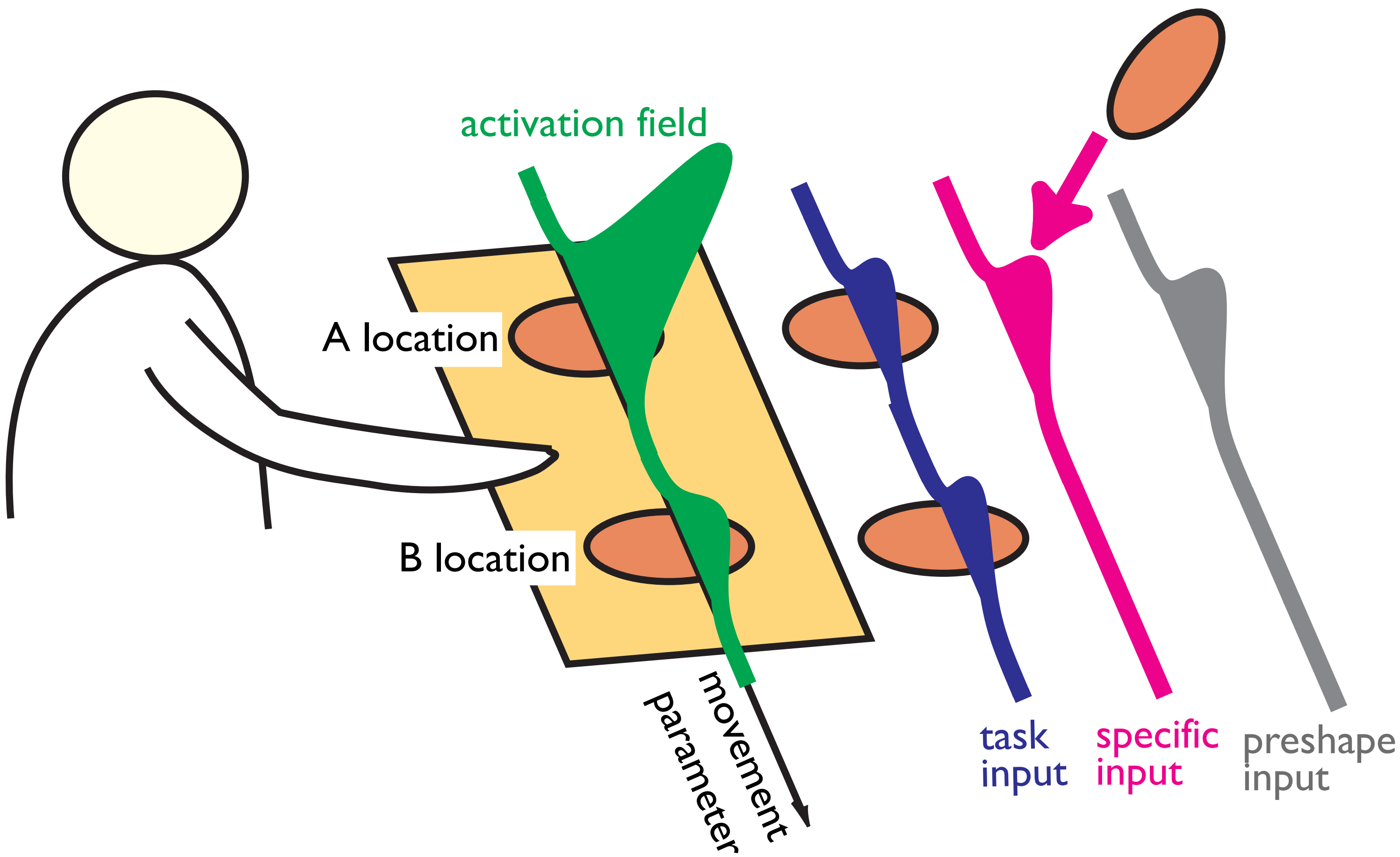
- the standard probe of working memory



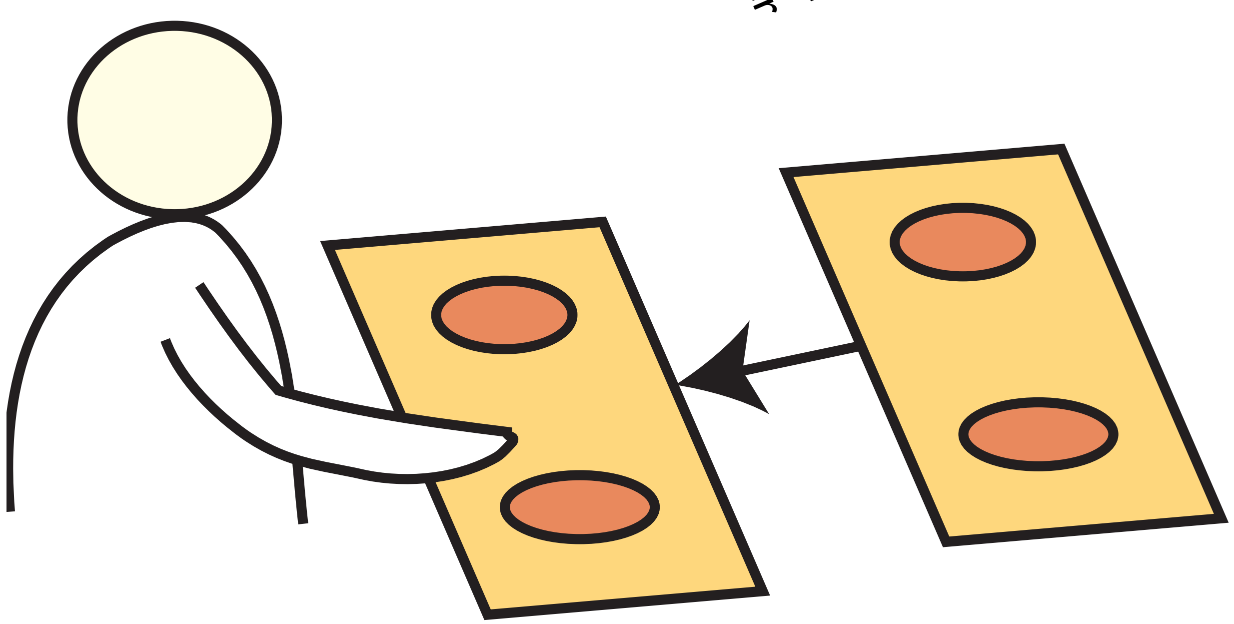
[Johnson, et al. 2009]

3 layer model





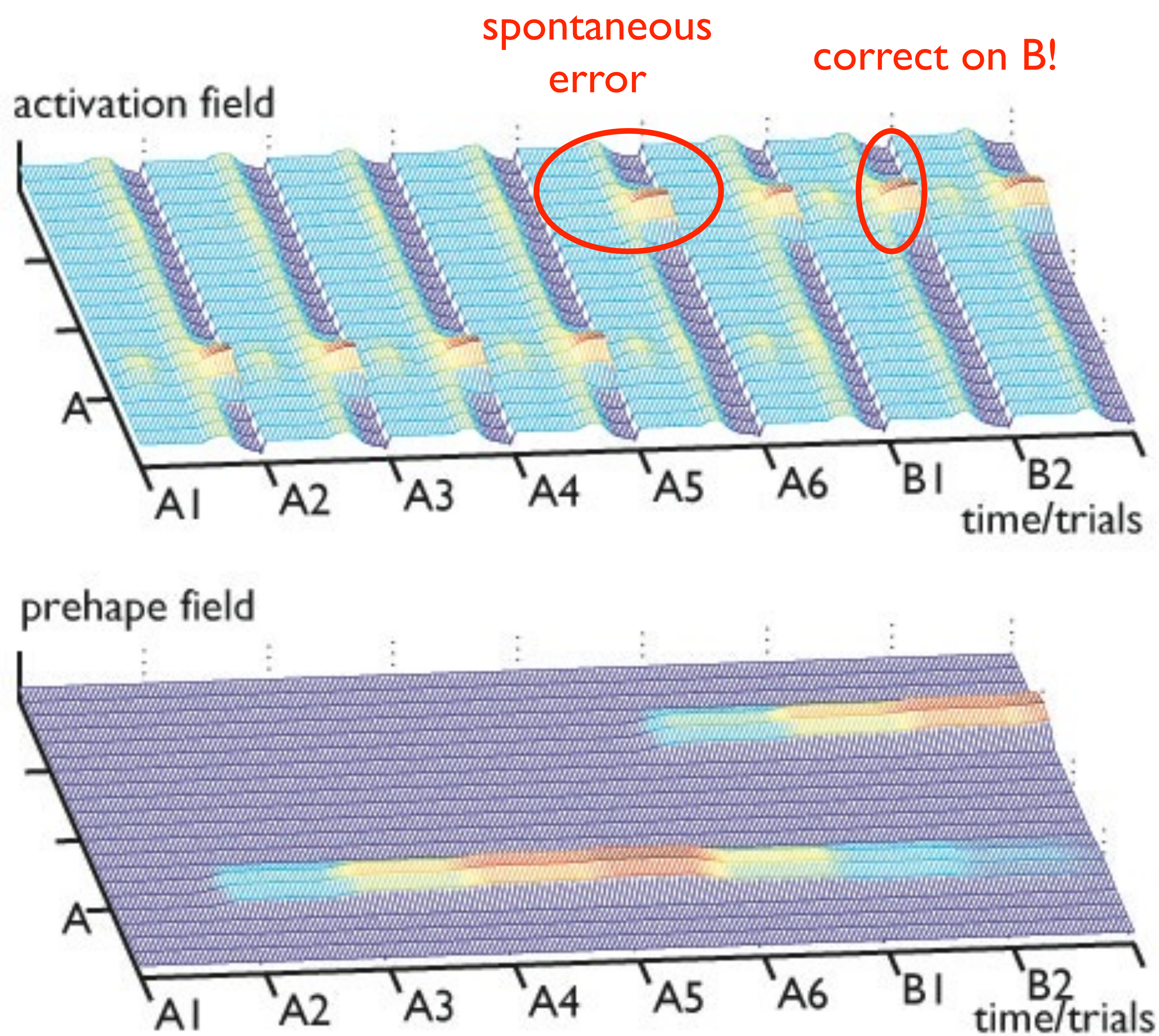
[Thelen, et al., BBS (2001)]



[Dinveva, Schöner, Dev. Science 2007]

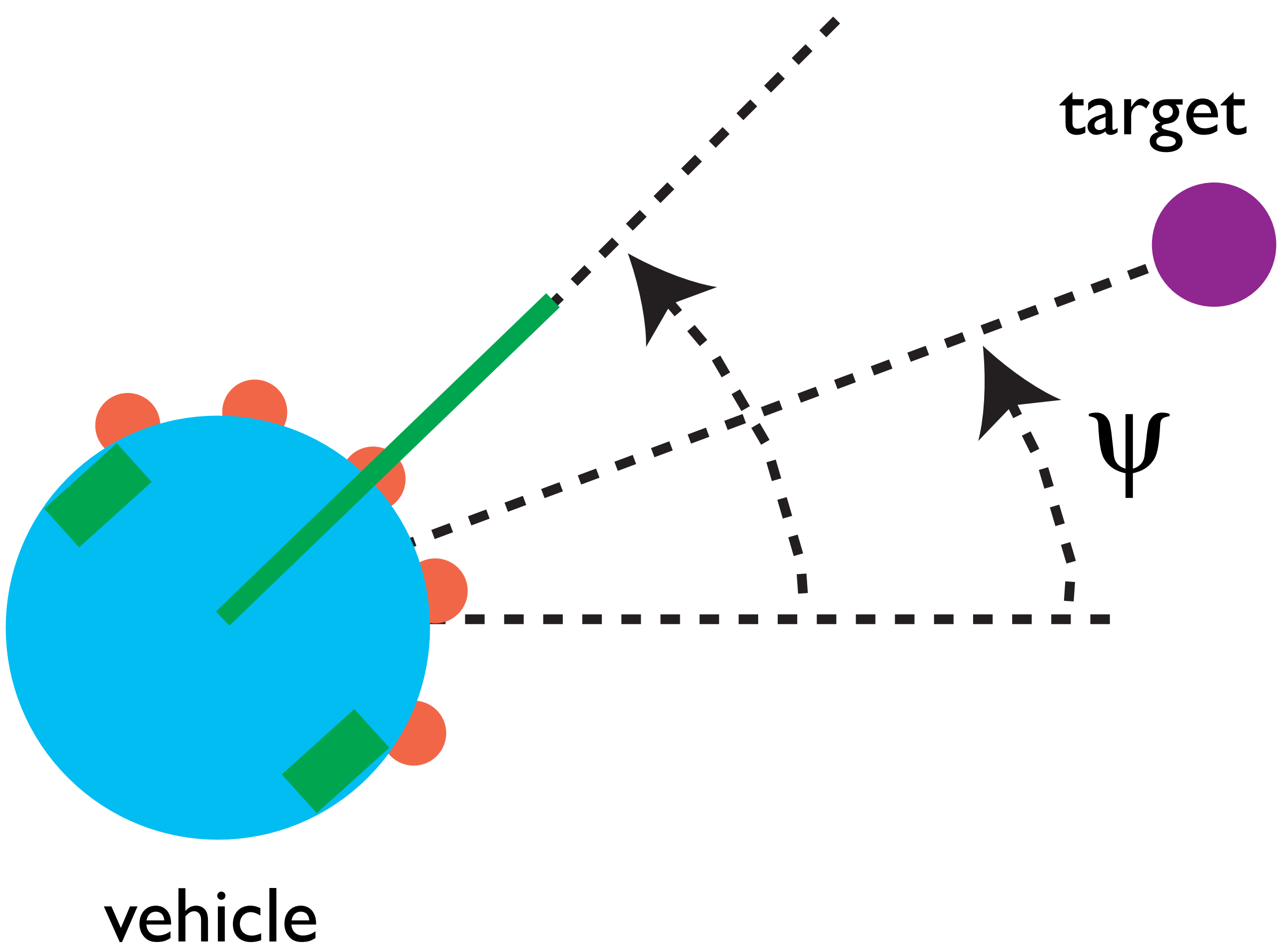
DFT of infant perseverative reaching

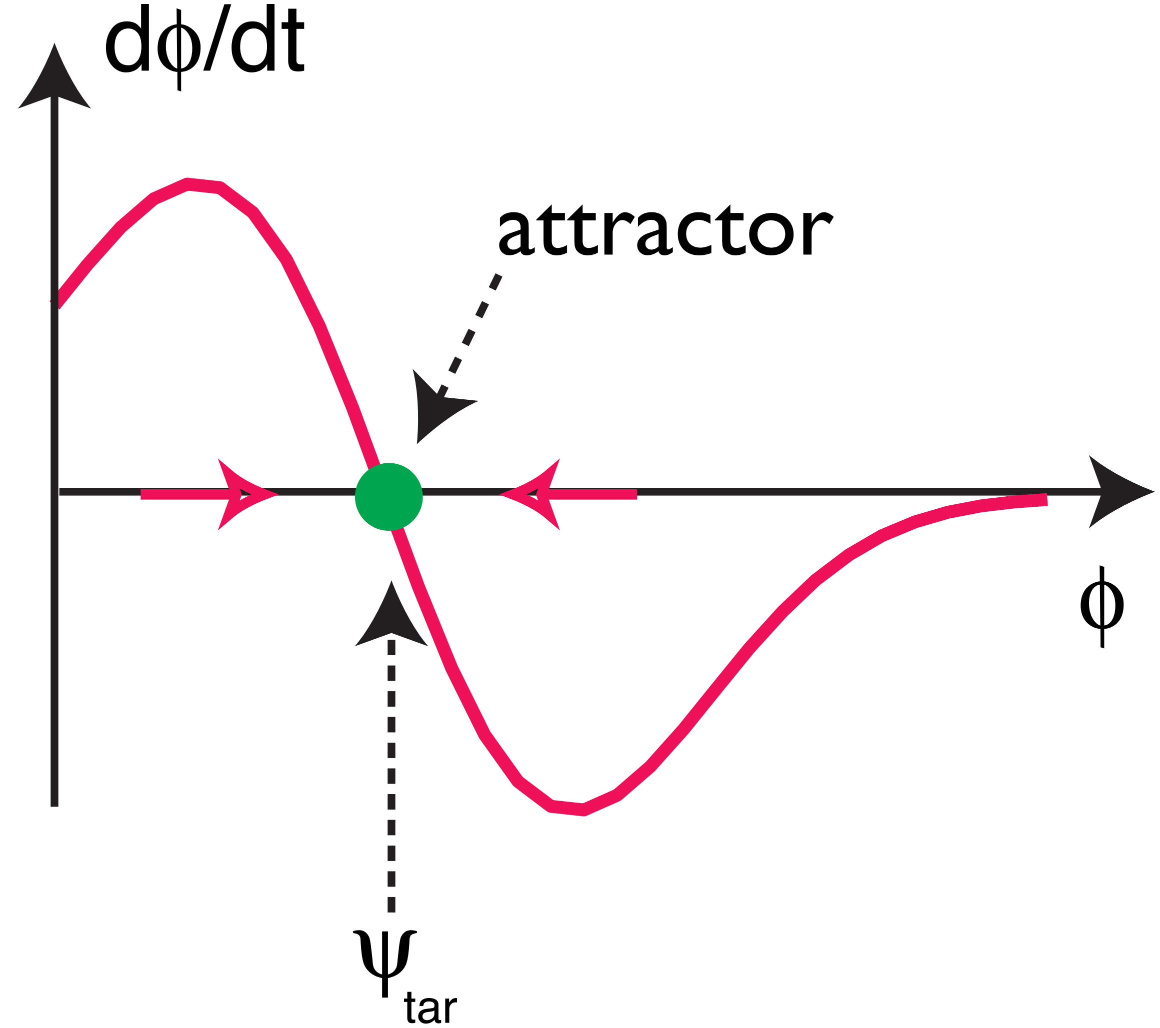
- that is because reaches to B on A trials leave memory trace at B



[Dinveva, Schöner, Dev. Science 2007]

From neural to behavioral dynamics





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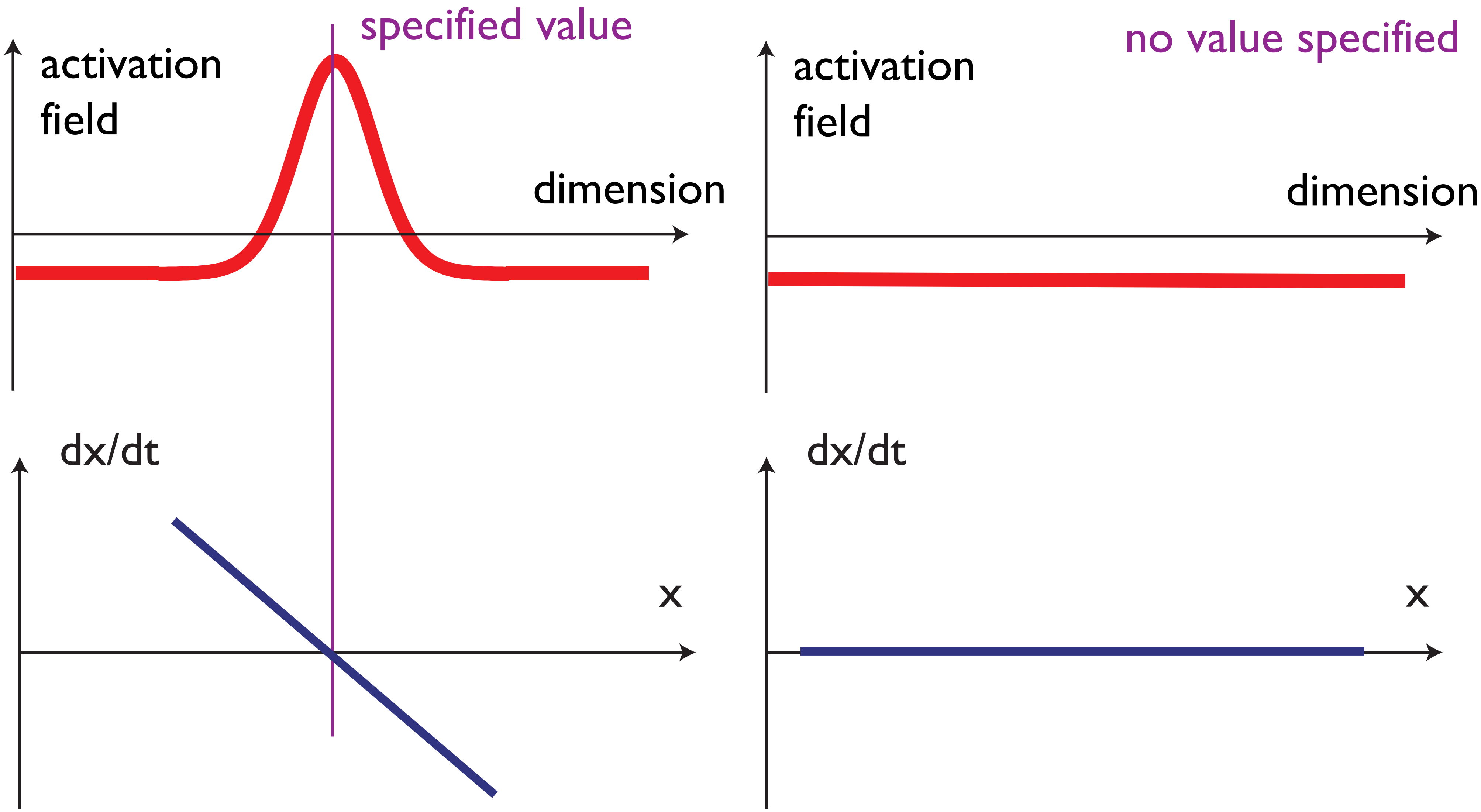
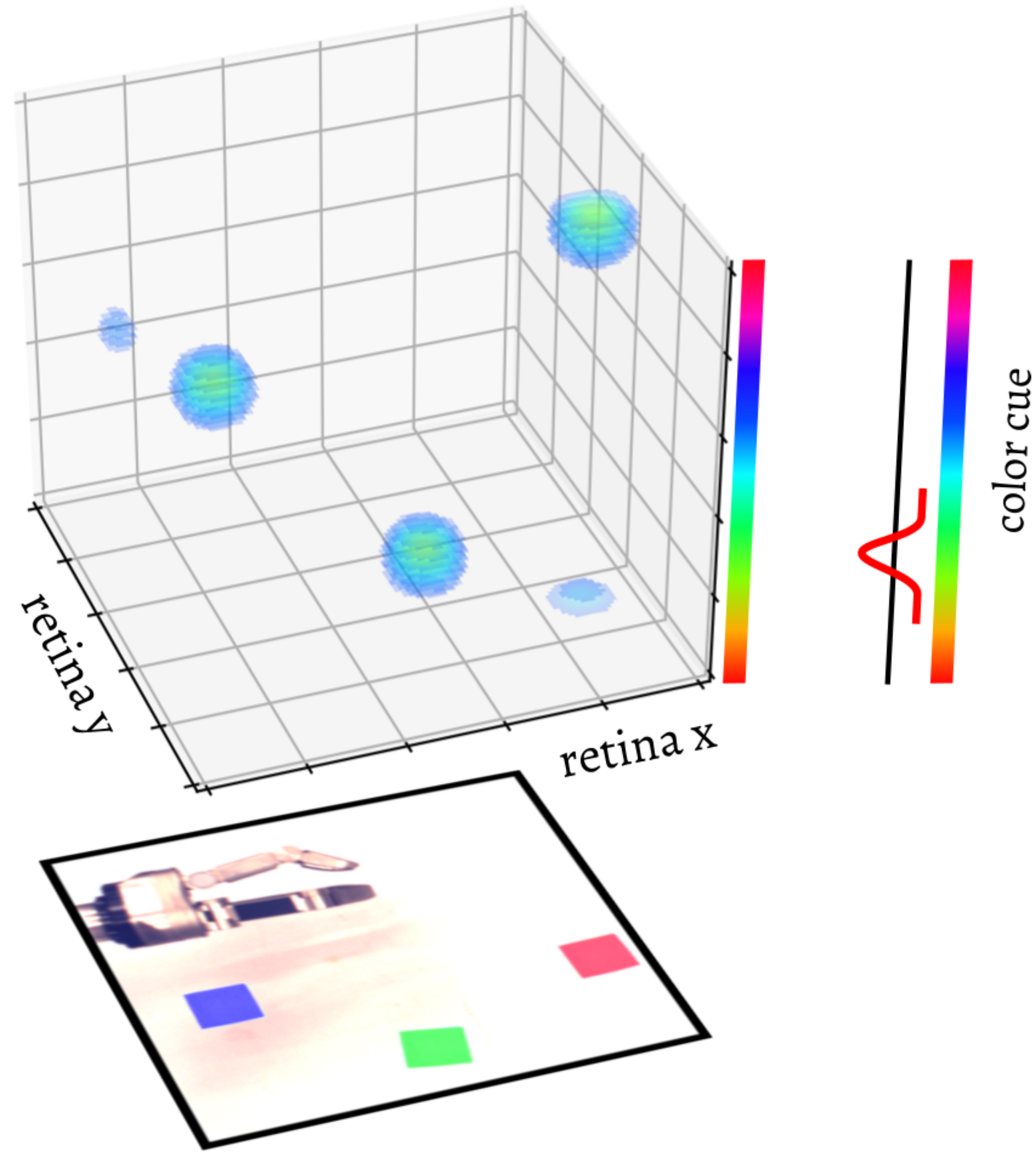


$$\dot{x} = -\int dx' \; g(u(x',t)) \; (x - x_{\text{peak}}) \qquad x_{\text{peak}} = \frac{\int dx \;\, x \; g(u(x,t))}{\int dx' \; g(u(x',t))}$$

=> $$\dot{x} = -\int dx' \; g(u(x',t)) \; (x - x')$$

New functions from higher-dimensional fields

- visual search:
- any action / thought directed at an object
- requires bring the object into the attentional foreground…



[Tekülve, 2020]

New functio dimensi

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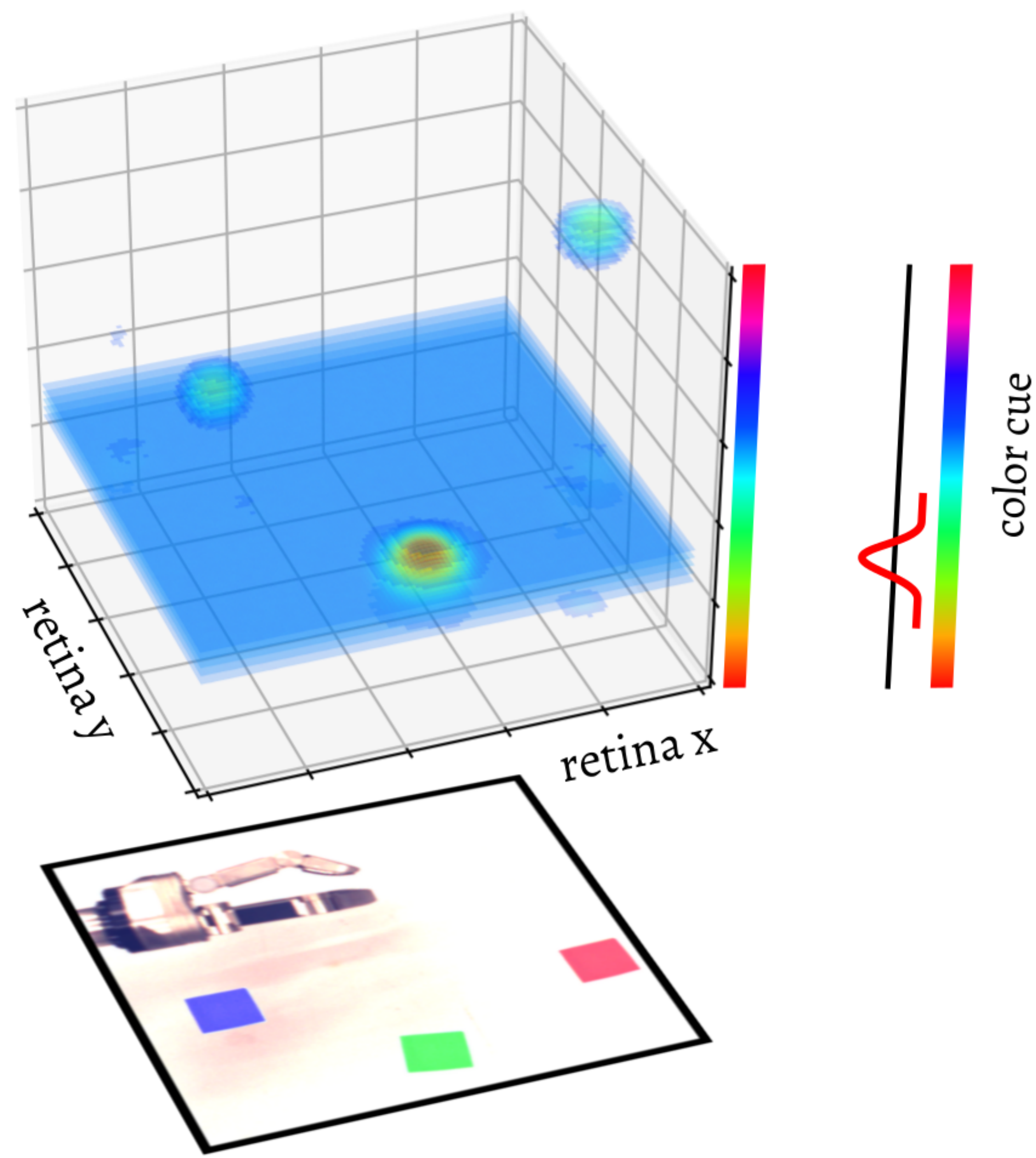

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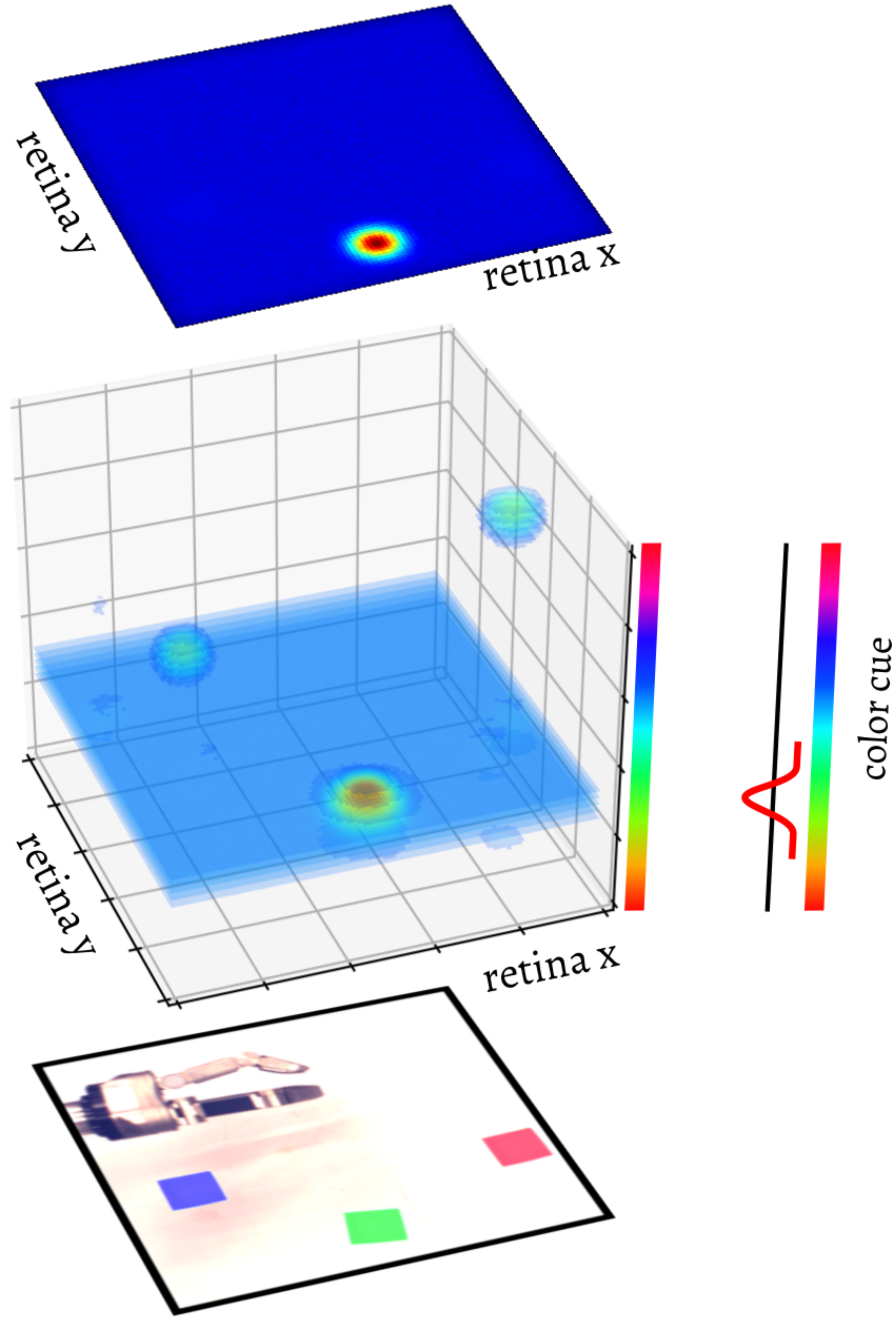
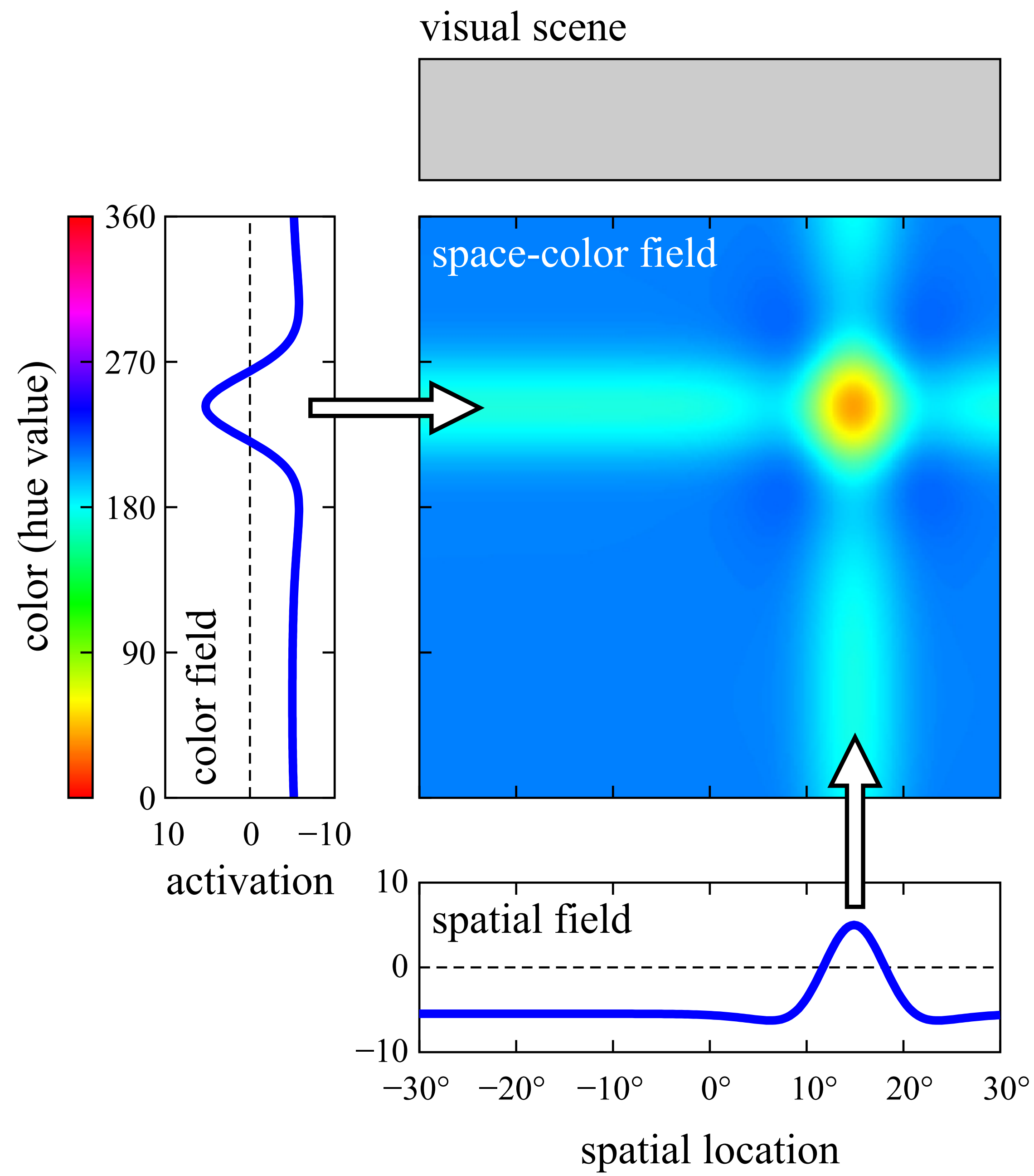


[Tekülve, 2020]

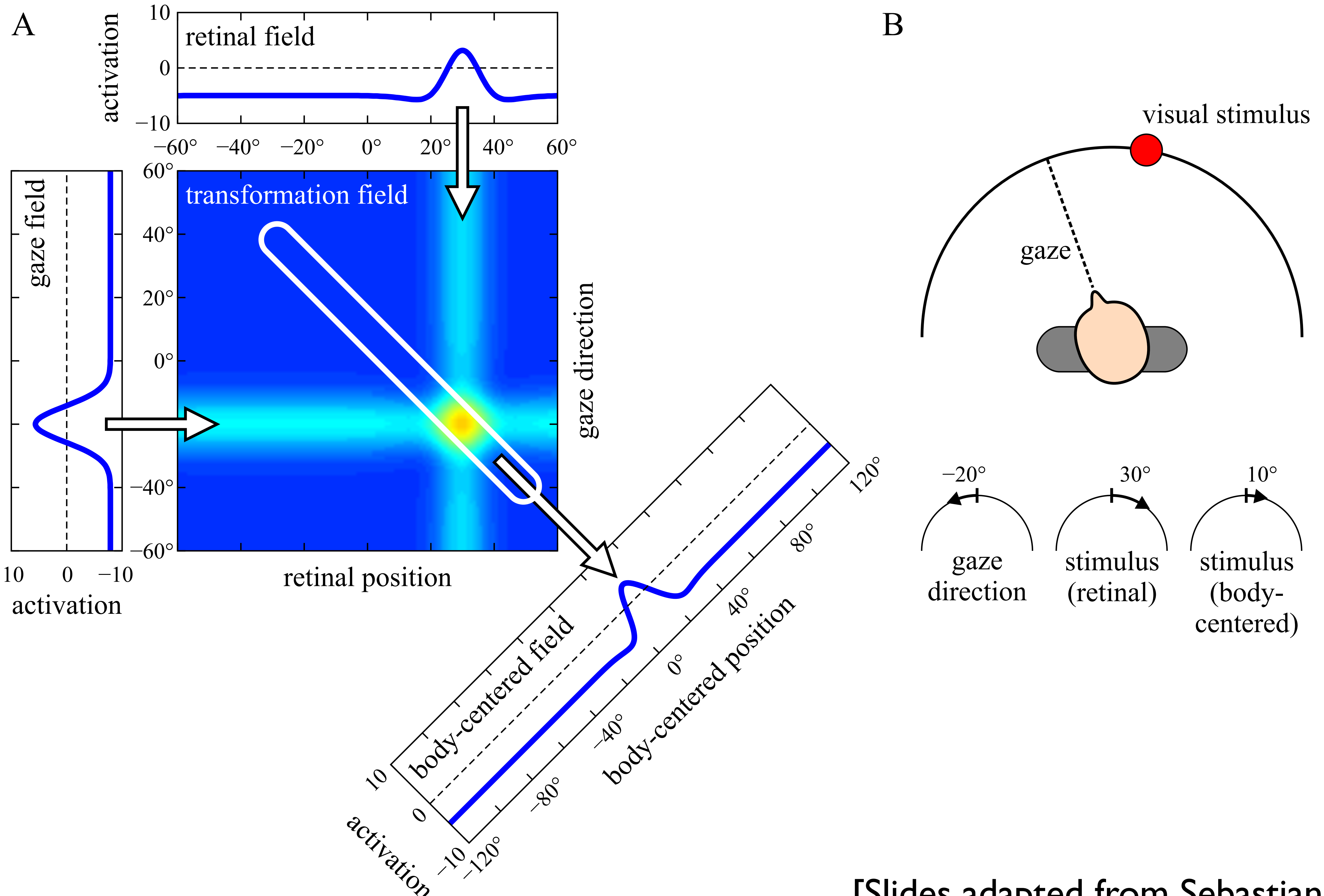
New functions from higher-dimensional fields

- peaks at intersections of ridges: bind two dimensions



[Slides adapted from Sebastian Schneegans,
see Schneegans, Lins, Spencer, Chapter 5 of Dynamic Field Theory-A Primer, OUP, 2015]

New functions from higher-dimensional fields: coordinate transforms

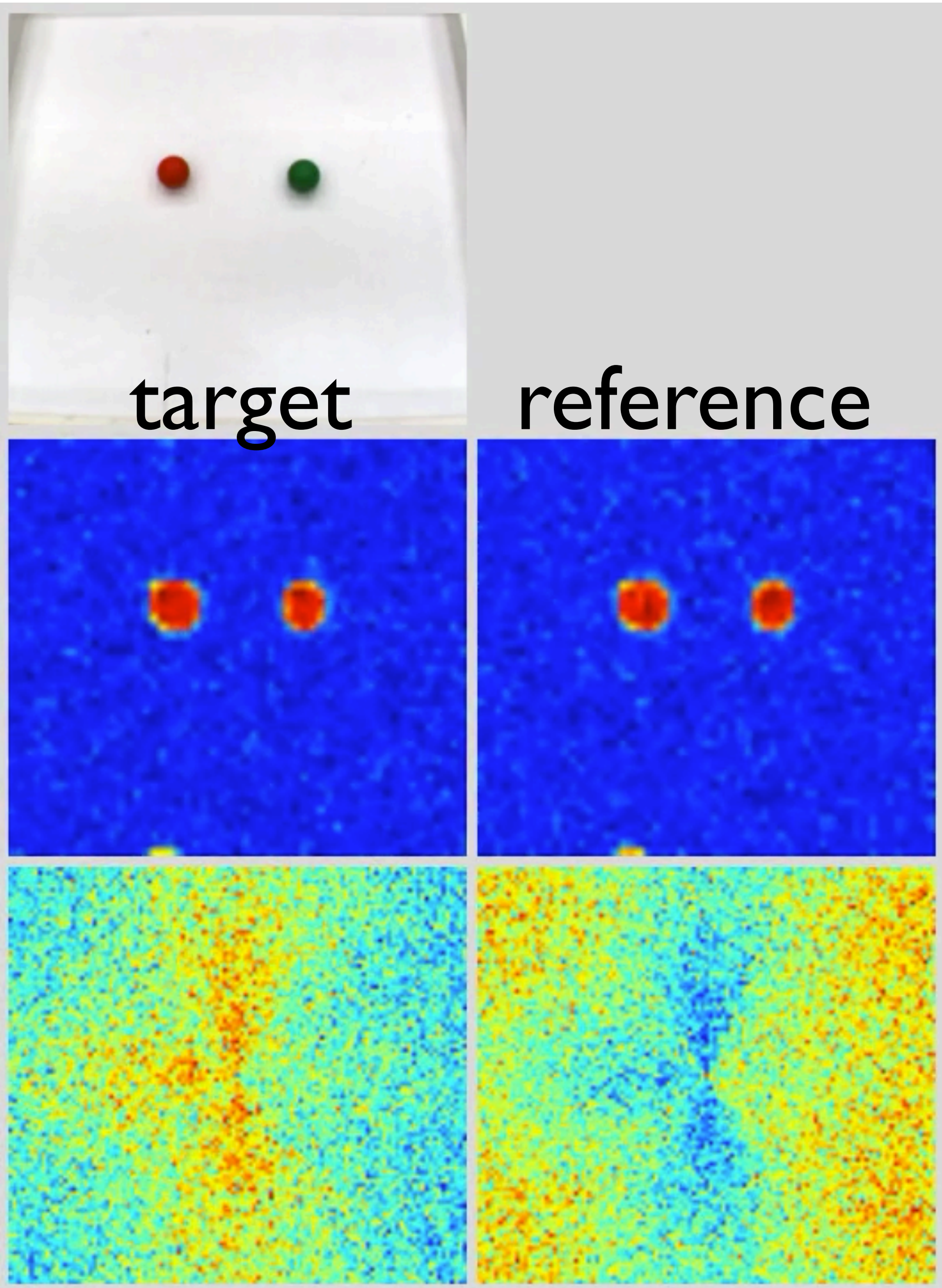


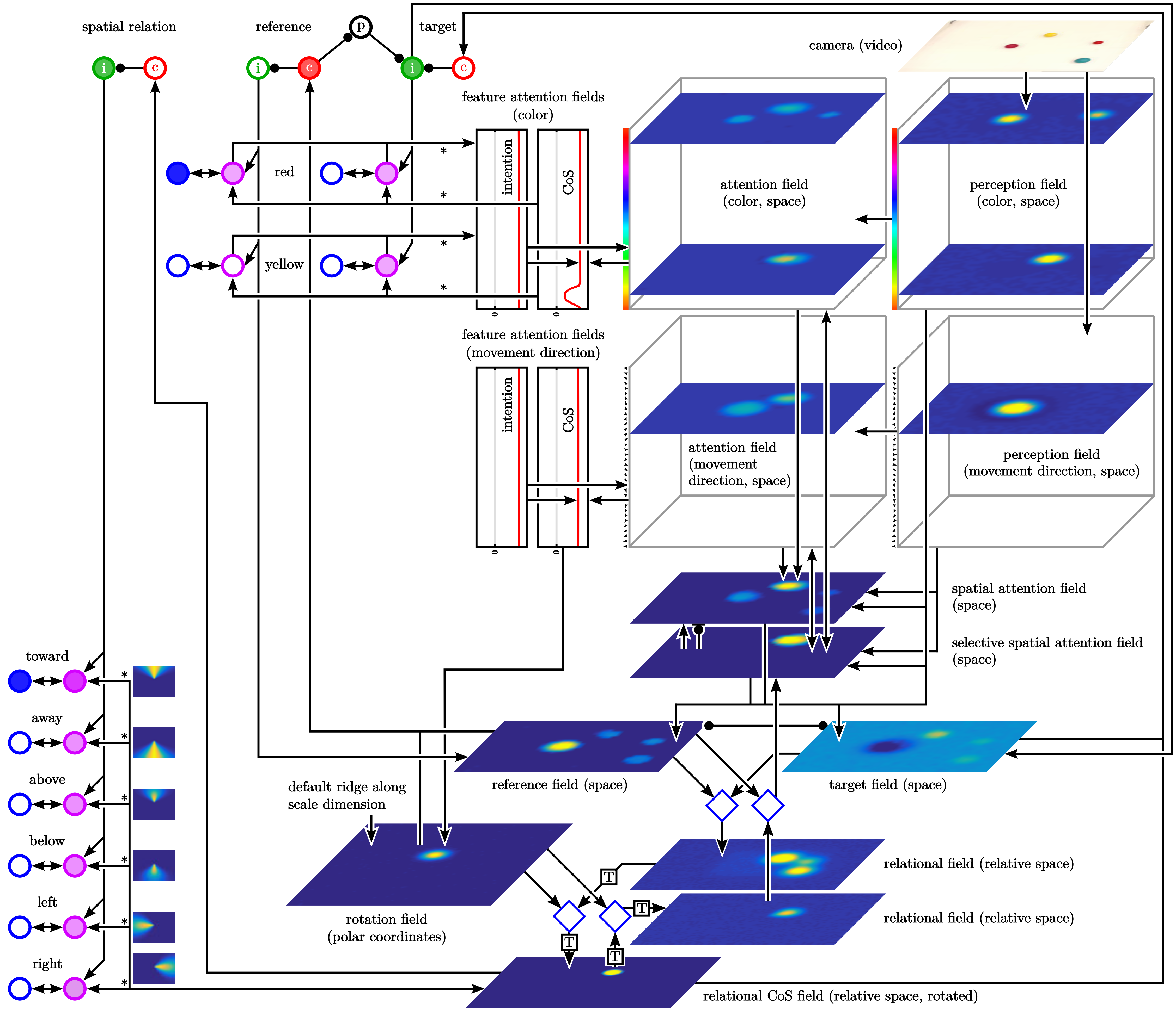
[Slides adapted from Sebastian Schneegans, see Schneegans, Chapter 7 of Dynamic Field Theory-A Primer, OUP, 2015]

Relational thinking

- Perceptual grounding = bringing the target object into the attentional foreground

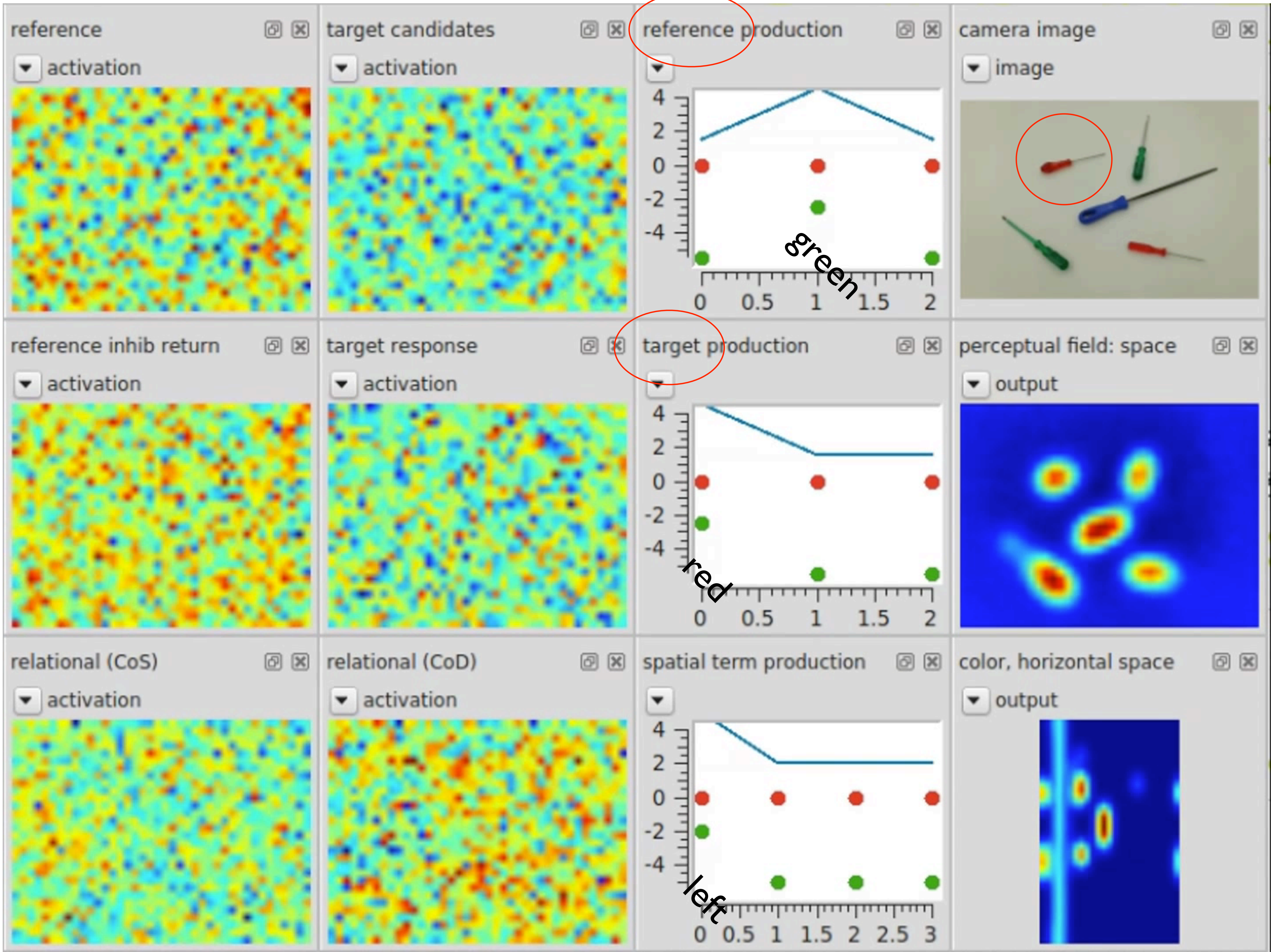
[Lipinski, Sandamirskaya, Schöner 2009
… Richter, Lins, Schöner, *Topics* 2017]





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

“red to the left of green”

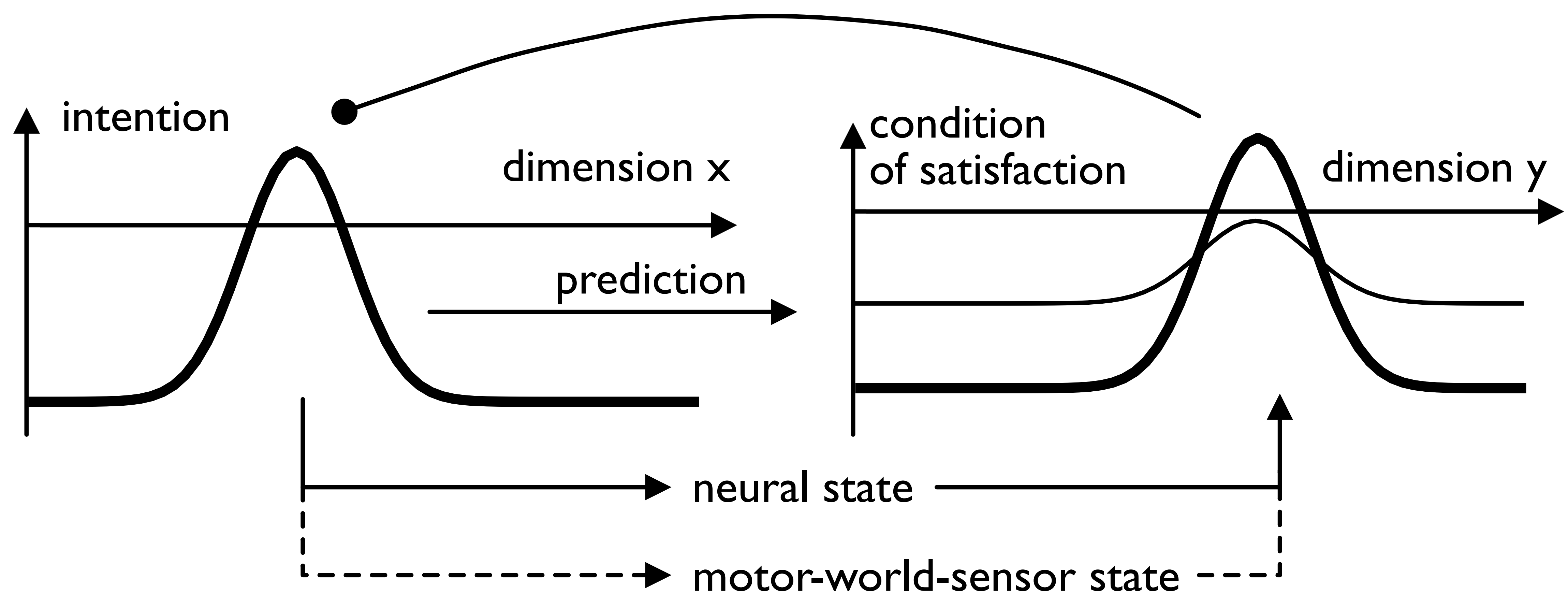


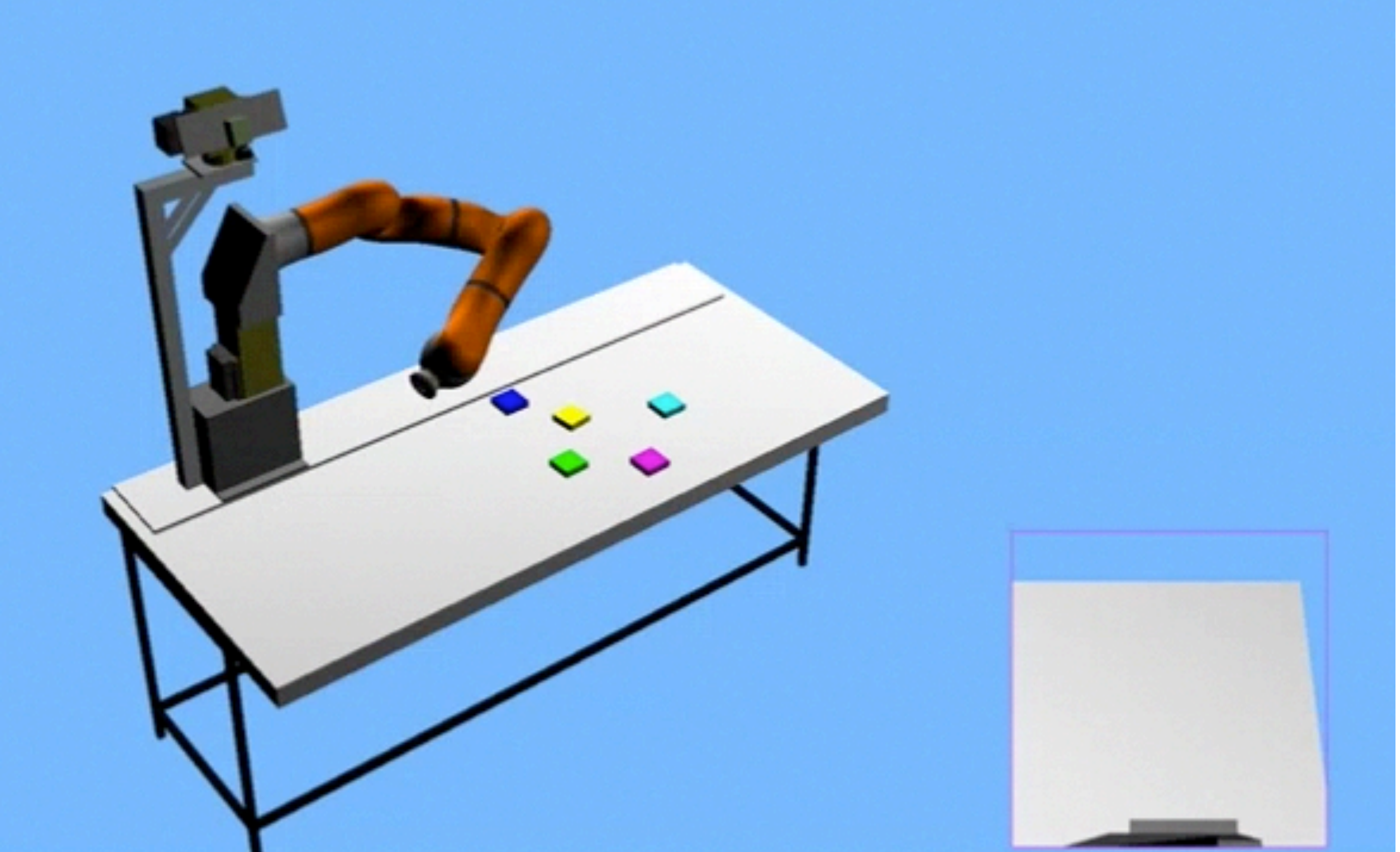
Sequential behaviors or mental acts

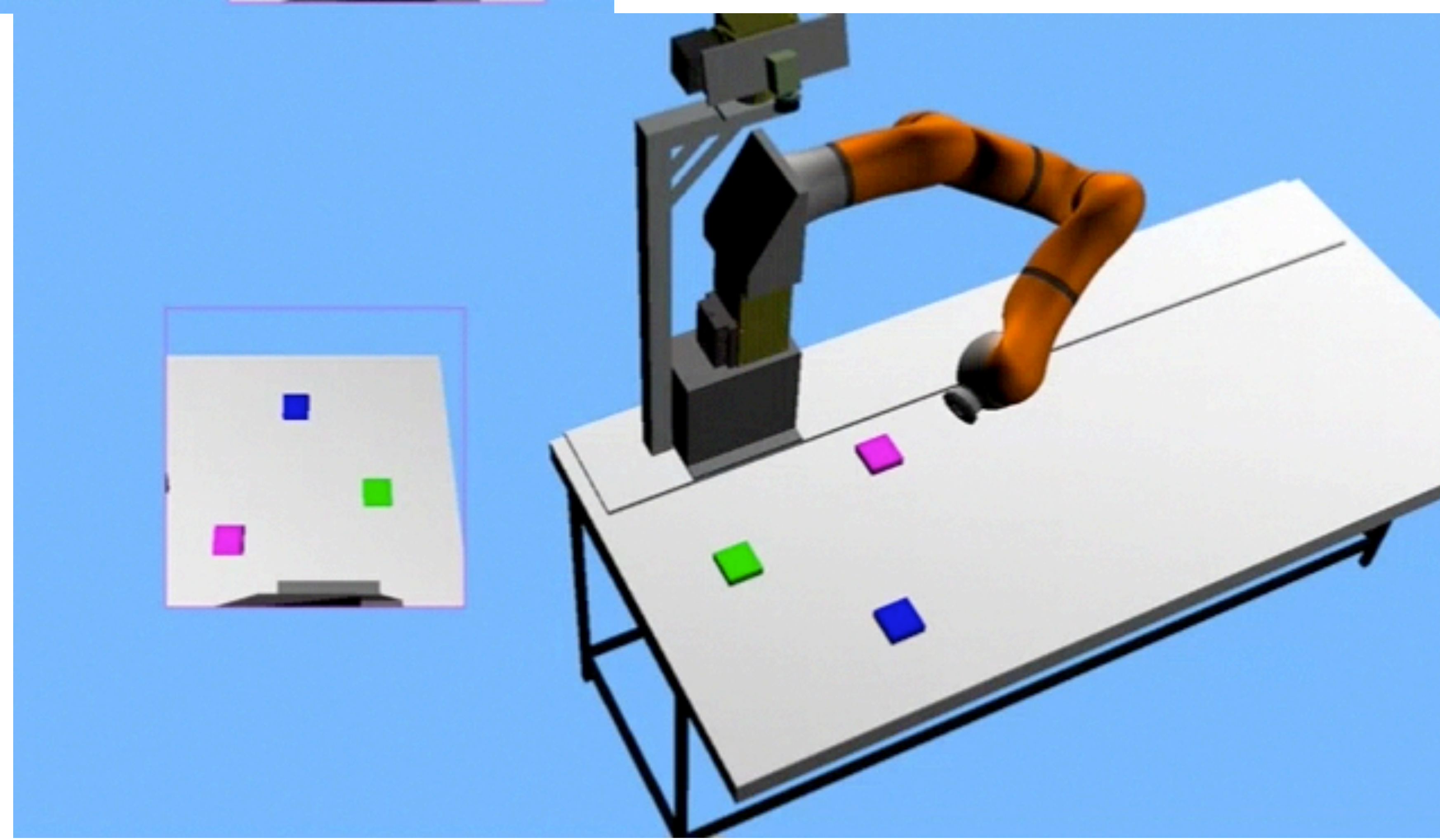
- behaviors/mental states are attractors
- that resist change…
- to induce change in sequential behavior/thinking: induce an instability

Conclusion

- 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

- … any fun?