# Moving embodied and situated cognition upwards using Dynamic Field Theory

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# Survey

(1) What is embodied and situated cognition and in which sense may we move it "upward"

(2) What is Dynamic Field Theory (DFT) and how does it generate cognitive function?

(3) What kind of embodied cognition emerges from DFT?

## (1) What is embodied and situated cognition and in which sense may we move it “upward”

# playing soccer

- see and recognize the ball and the other players
- select target, track it as well as the other players, all the while controlling gaze
- use working memory when players are out of view to predict where you need to look to update
- control own motion, initiate and control kick
- any time open to update
- get better at it
- background knowledge: goal of game, rules, how hard is the ball, how fast are players

# repairing a toaster

- visual exploration, recognizing screws, while keeping track of spatial arrangement of screws on the toaster (visual cognition, coordinate frames)
- finding tools, applying them to remembered locations, updated by current pose of toaster (working memory, scene represenation)
- manipulating cover, taking it off, recognizing spring, re-attaching it (goal-directed action plan)
- mounting cover back on, generating the correct action sequence (sequence generation)
- background knowledge: cover, screws, how hard to turn screw-driver

[image: mystery fandom theater 3000]

# => some elements of embodied, situated cognition

- active perception for a purpose
- perceptual objects grounded in space (Barsalou)
- using the world as a model, which requires memory and coordinate transforms
- and requires representations close to the sensory and motor surfaces, enabling continuous on-line updating
- behavioral history, learning
- back-ground knowledge (Searle)

# contrast to classical view of cognition

- cognition operates on symbols that are encapsulated and arbitrary, invariant under the sensory conditions through which they were instantiated ...
- .... very different concepts

# information processing view

- is like focussing only on penalty shooting:
  - given input information and priors
  - compute decision to kick left or right
  - initiate when computed to satisfaction...
- this is wrong even for penalty shooting
  - in which player updates plan as he runs
  - and motor control at kick matters greatly

# low-level vs. high-level cognition

- the distance of a representation from the sensory or motor surfaces as a measure for how "high-level" a particular act of cognition is
- this distance is indexed by the degree of invariance under changes on these two surfaces
  - e.g., long-term memory “higher” than working memory
  - e.g., thinking and language “higher” than reaching for an object

# hypothesis of embodiment

- the same principles that govern low-level cognition continue to work as the distance from the sensory-motor surfaces increases...

# the embodiment/situatedness program

- understanding cognition cannot be separated from understanding
  - the link of cognition to sensory and motor surfaces,
  - the immersion of embodied cognitive systems in real-time in structured environments, and
  - the context of a behavioral history on which cognition builds
- understanding of cognition must be based on neural principles

# neuronal principles

- the neural process of cognition are time continuous and autonomous, not paced by computational steps
- neurons code information somewhat rigidly as defined by their connectivity to sensory and motor surfaces
  - neurons send only simple messages

# which neural level of description?

- not: discrete individual neurons
  - no evidence the graininess of neural sampling in human behavior and cognition
- => population level
  - single cells may represent populations due to the tight coupling within population ensembles that induces correlations
  - recall: $10^4$ synapses per cortical neuron, many parameters represented in any given population...
  - => no need for redundancy to define population level

# which neural level of description?

- not: spikes
  - no behavioral signature exists of the discreteness of neuronal events
- => population dynamics: DFT

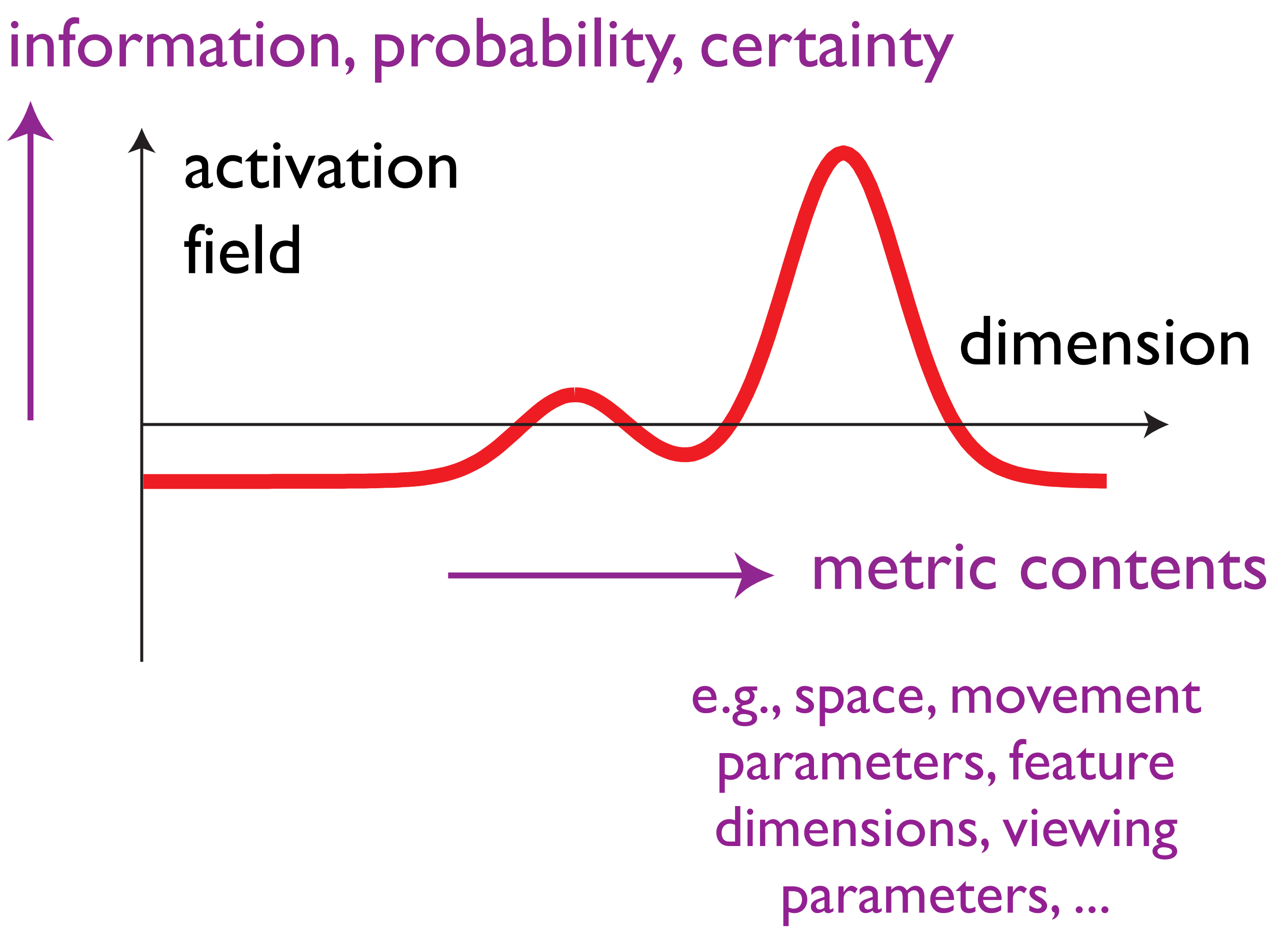
# Dynamic Field Theory as an interface

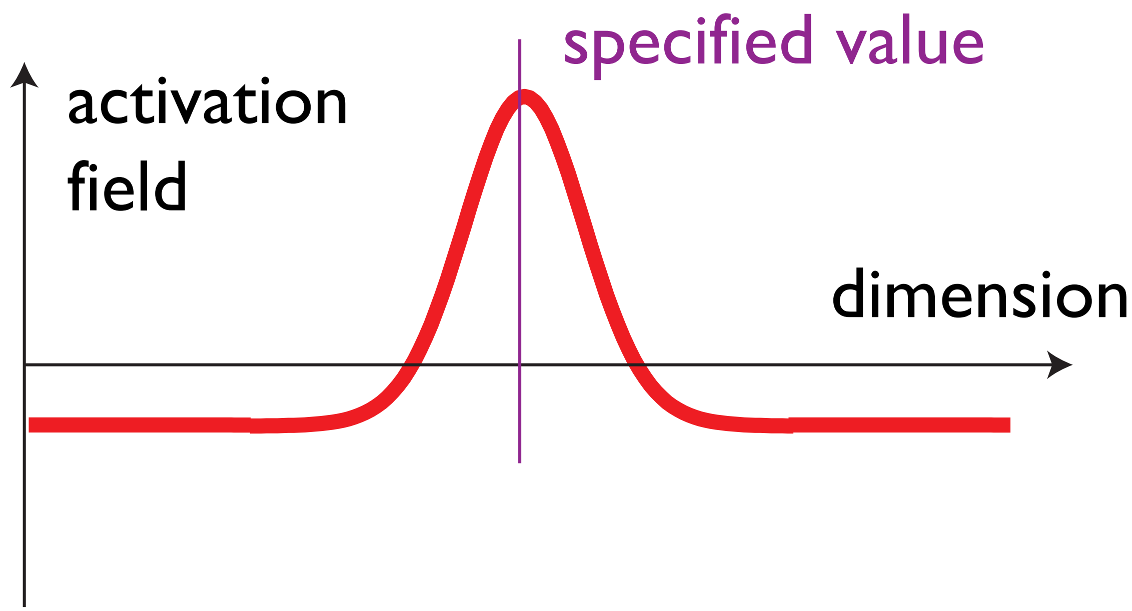
- between the microscopic neuronal dynamics
- and embodied cognition and behavior, including "higher-level" cognition

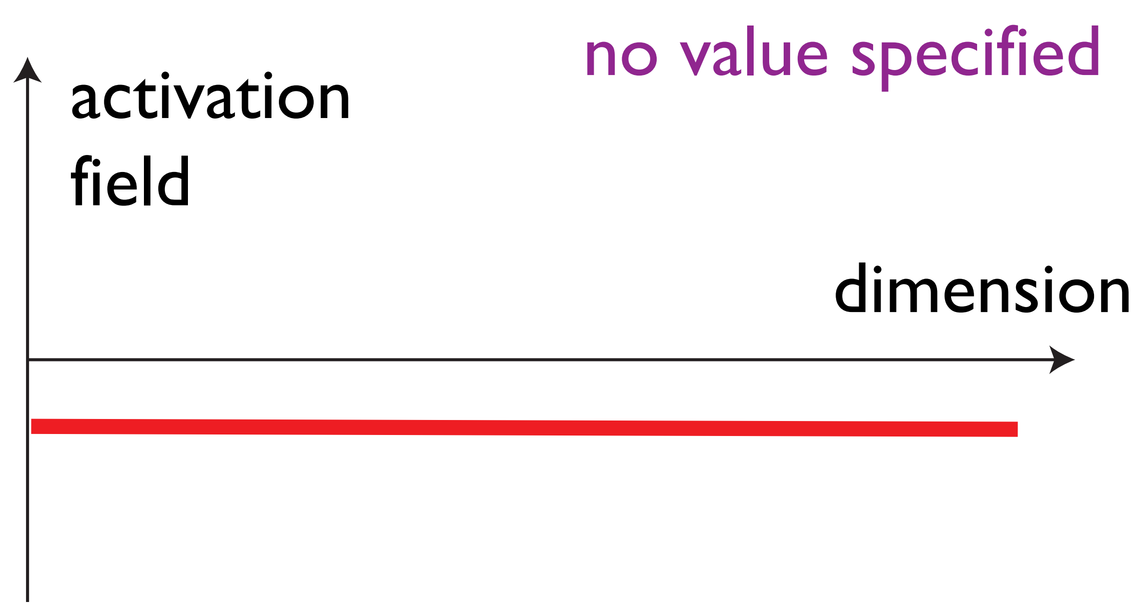
# (2) What is Dynamic Field Theory (DFT) and how does it generate cognitive function?

- activation fields over metric dimensions
- field dynamics
  - peaks as stable states (attractors)
  - instabilities generate different cognitive modes and functions
- memory traces
  - generate small changes which the instabilities of the field dynamics translate into macroscopic states

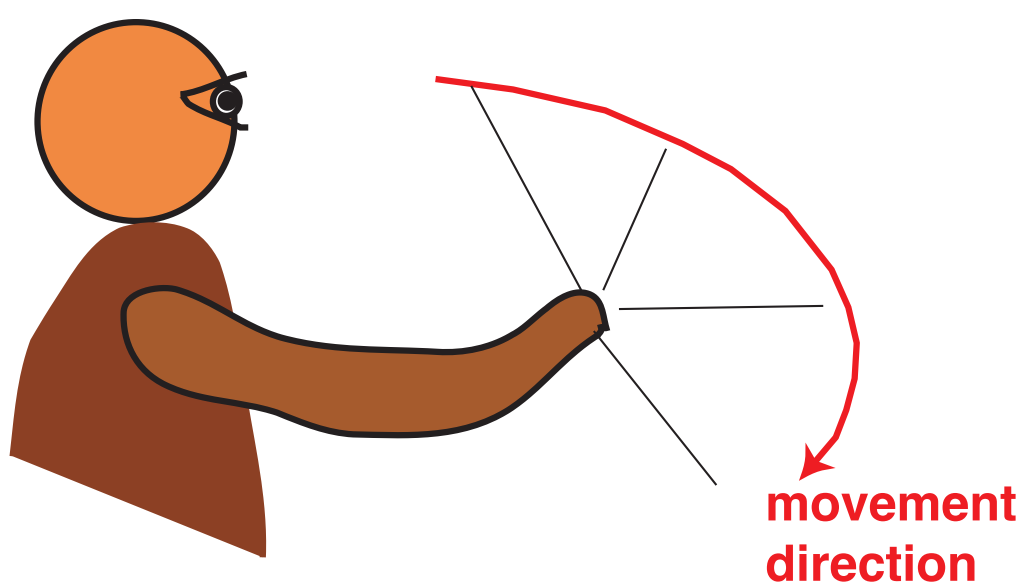
# activation fields

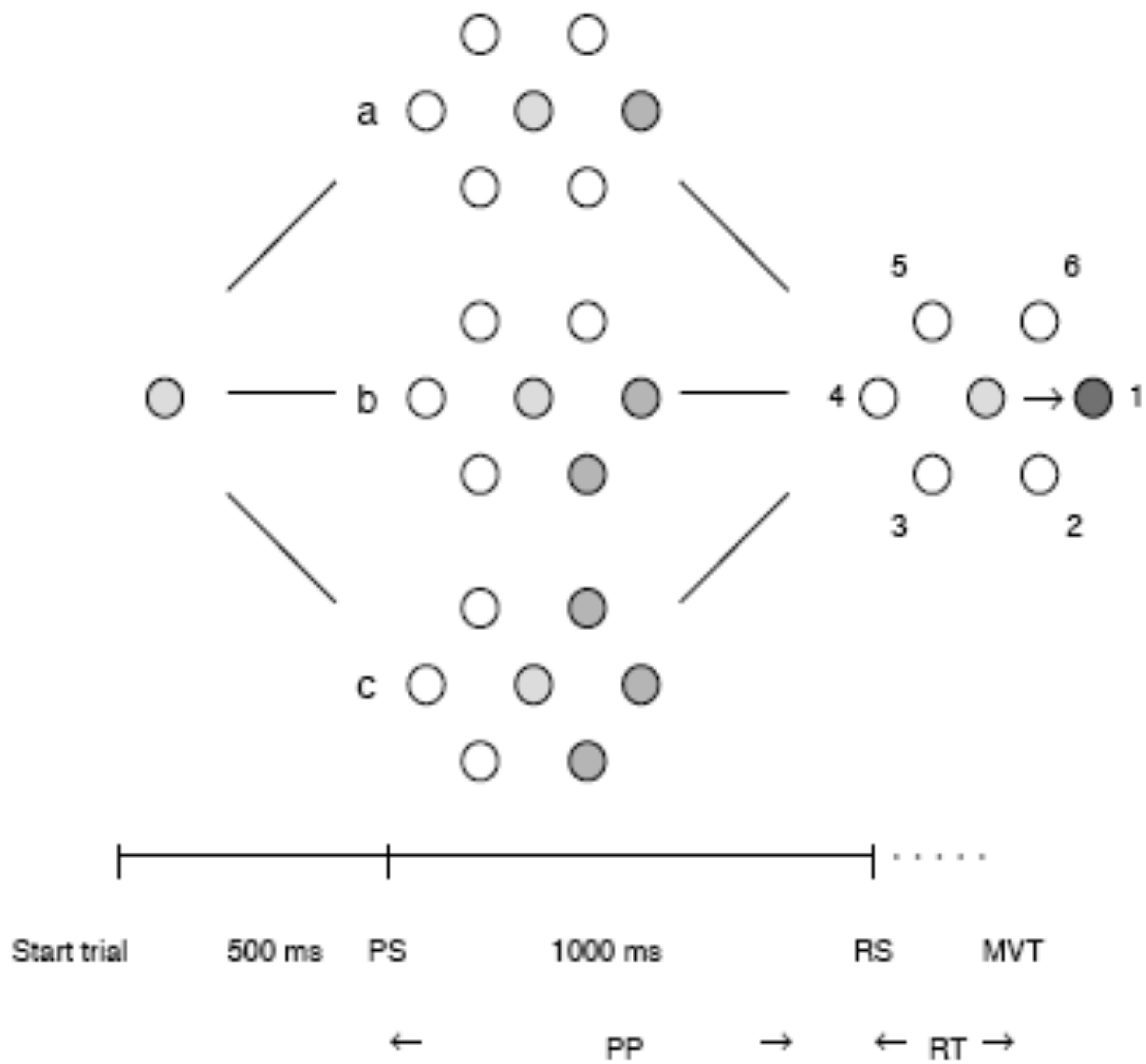


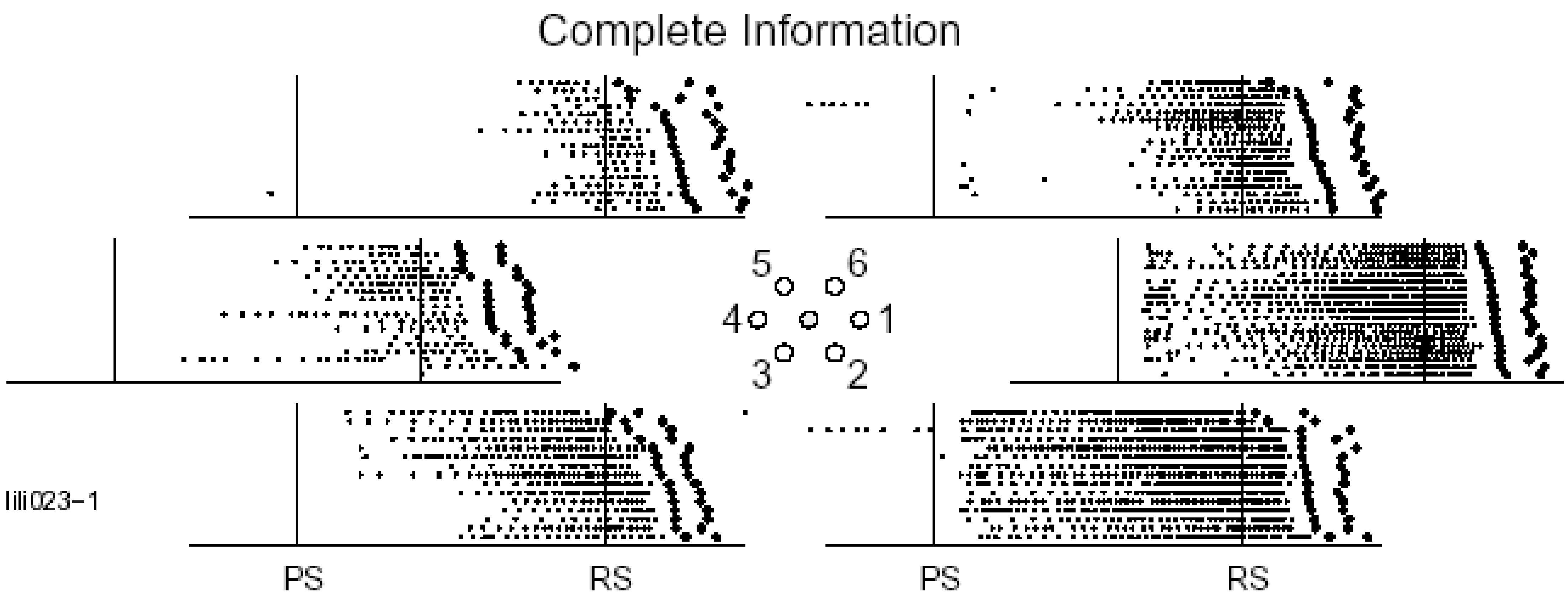
# example: movement planning



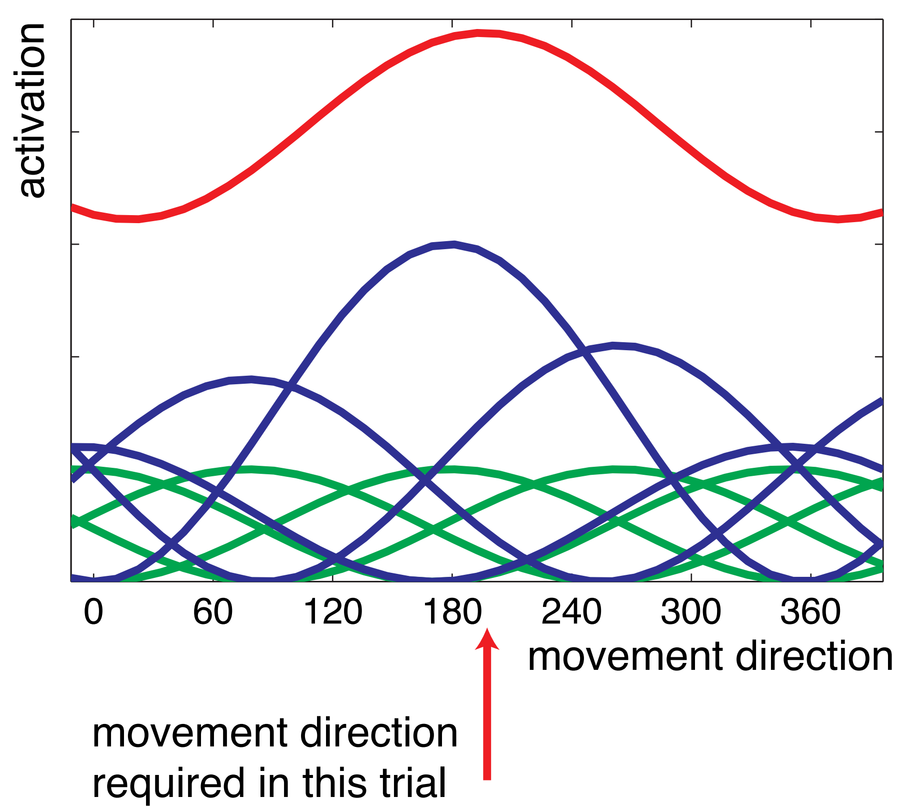

Bastian, Riehle, Schöner, 2003

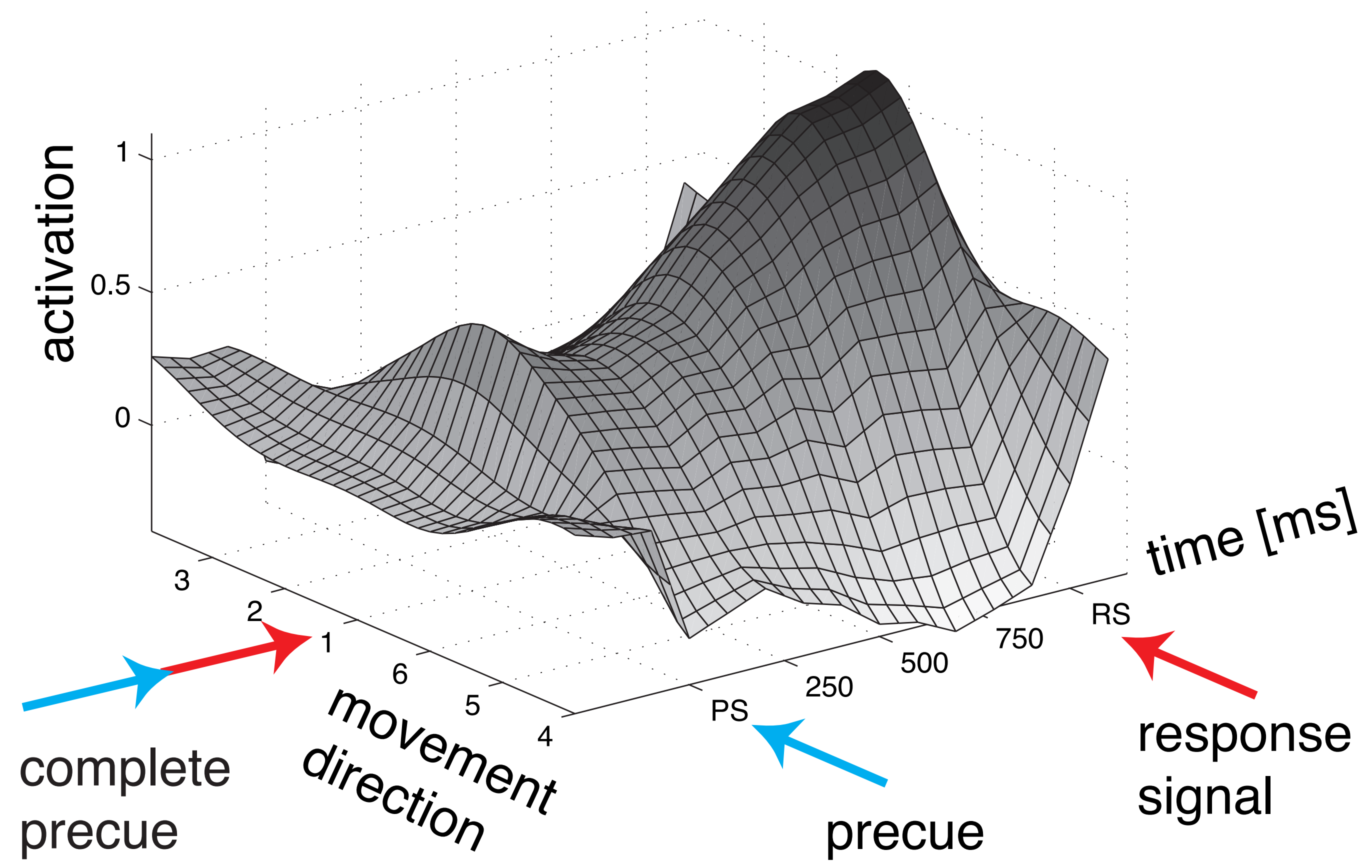
- tuning of cells in motor and premotor cortex to direction of end-effector movement path



# Distribution of Population Activation (DPA)

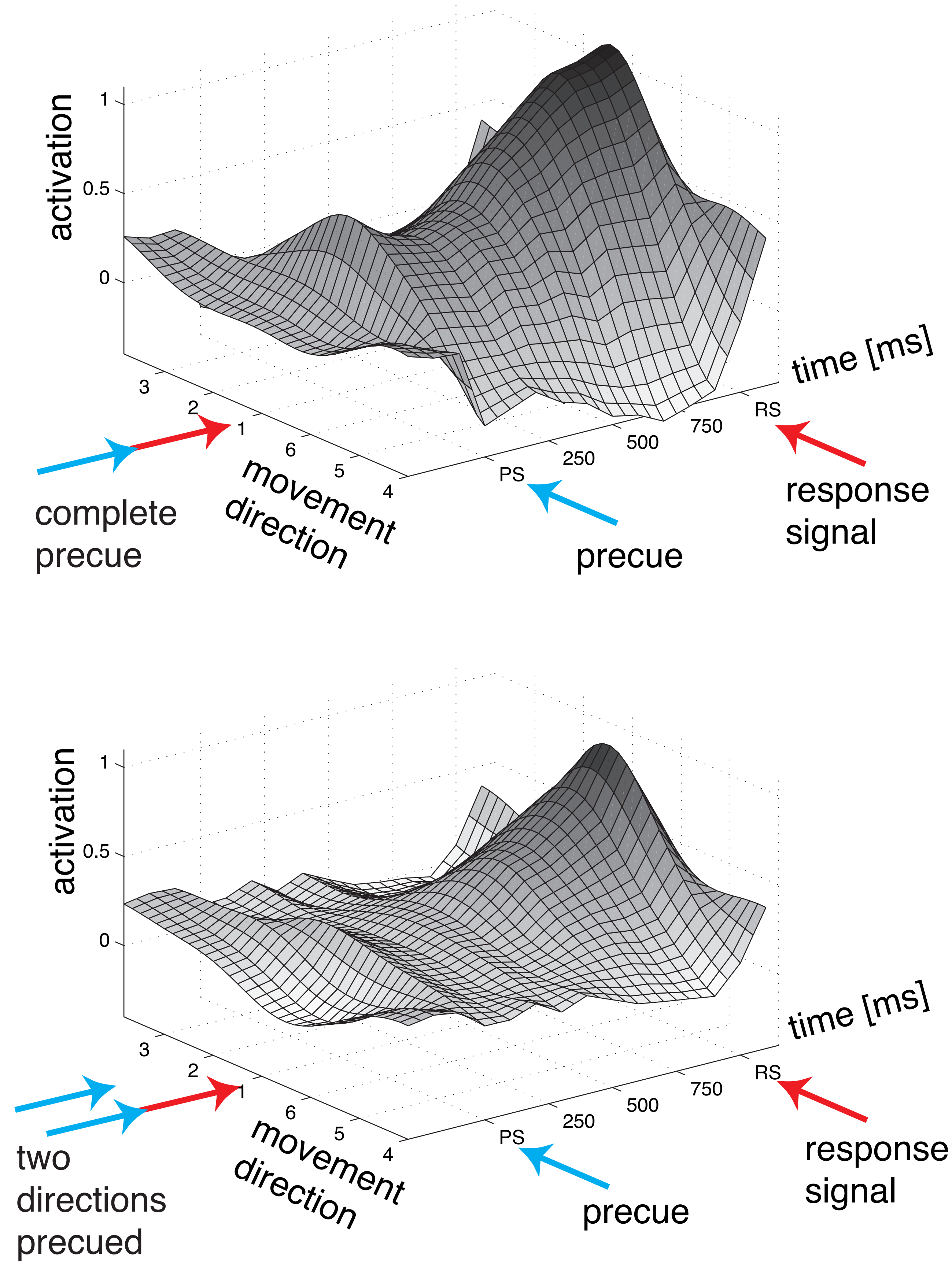
Distribution of population activation = $\sum_{\text{neurons}}$ tuning curve * current firing rate



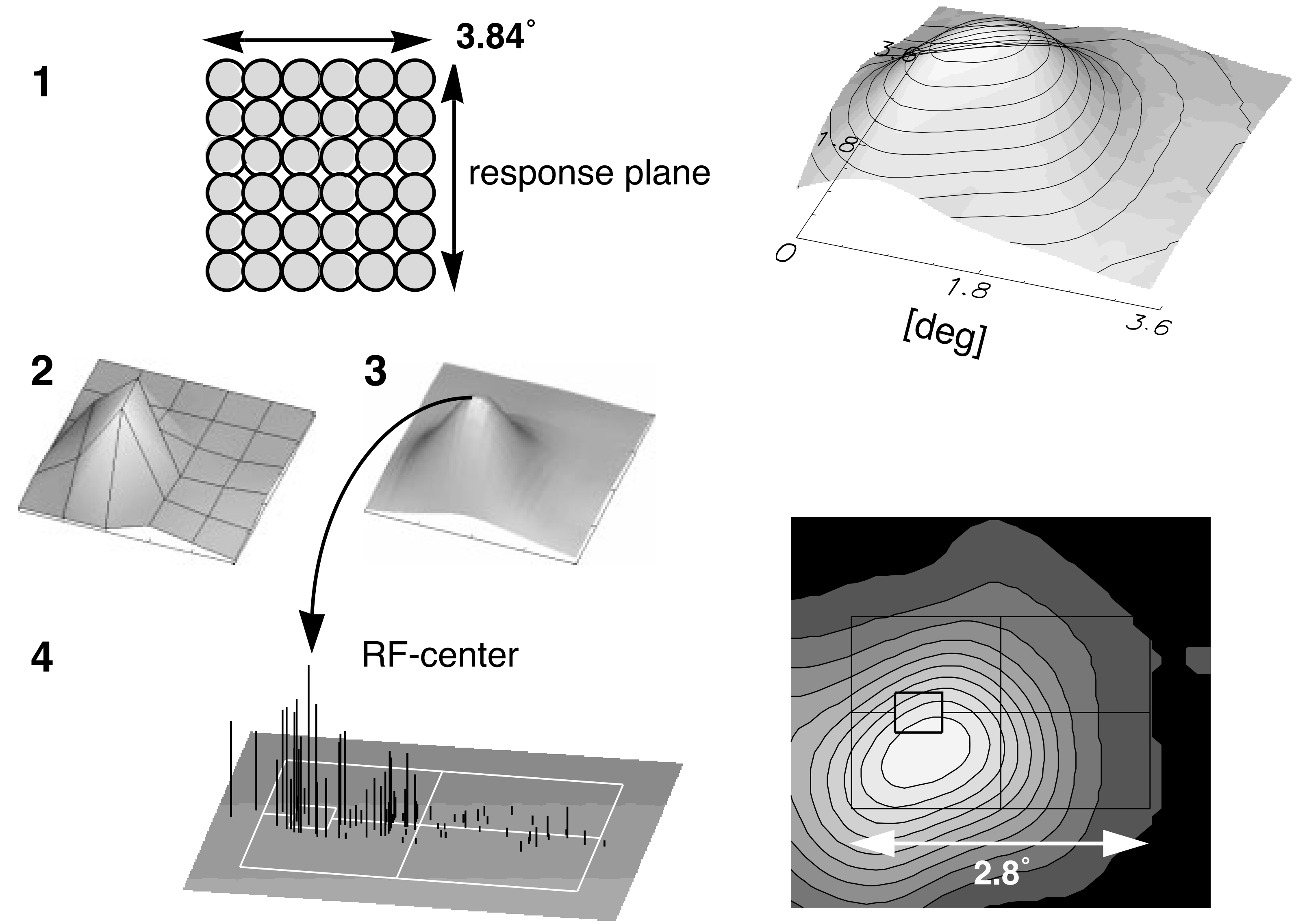

[Bastian, Riehle, Schöner, 2003]

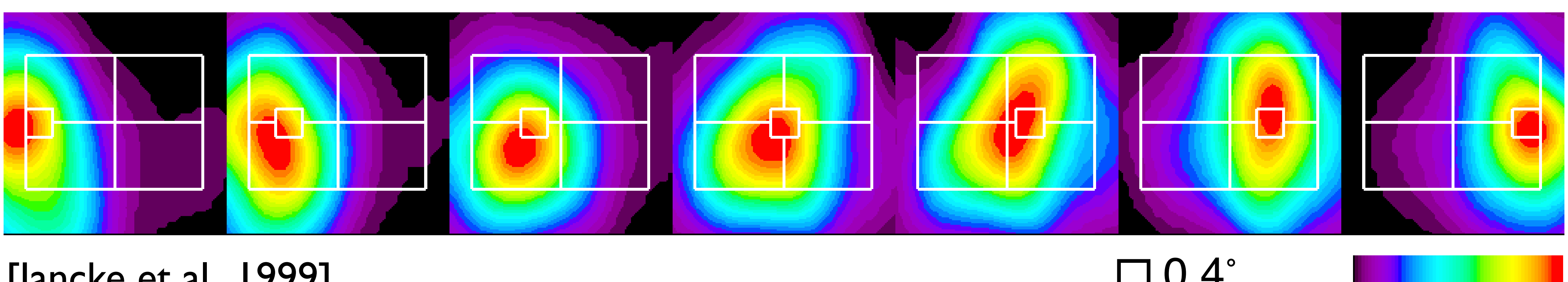
- look at temporal evolution of DPA
- or DPAs in new conditions, here: DPA reflects prior information



# example: visual space

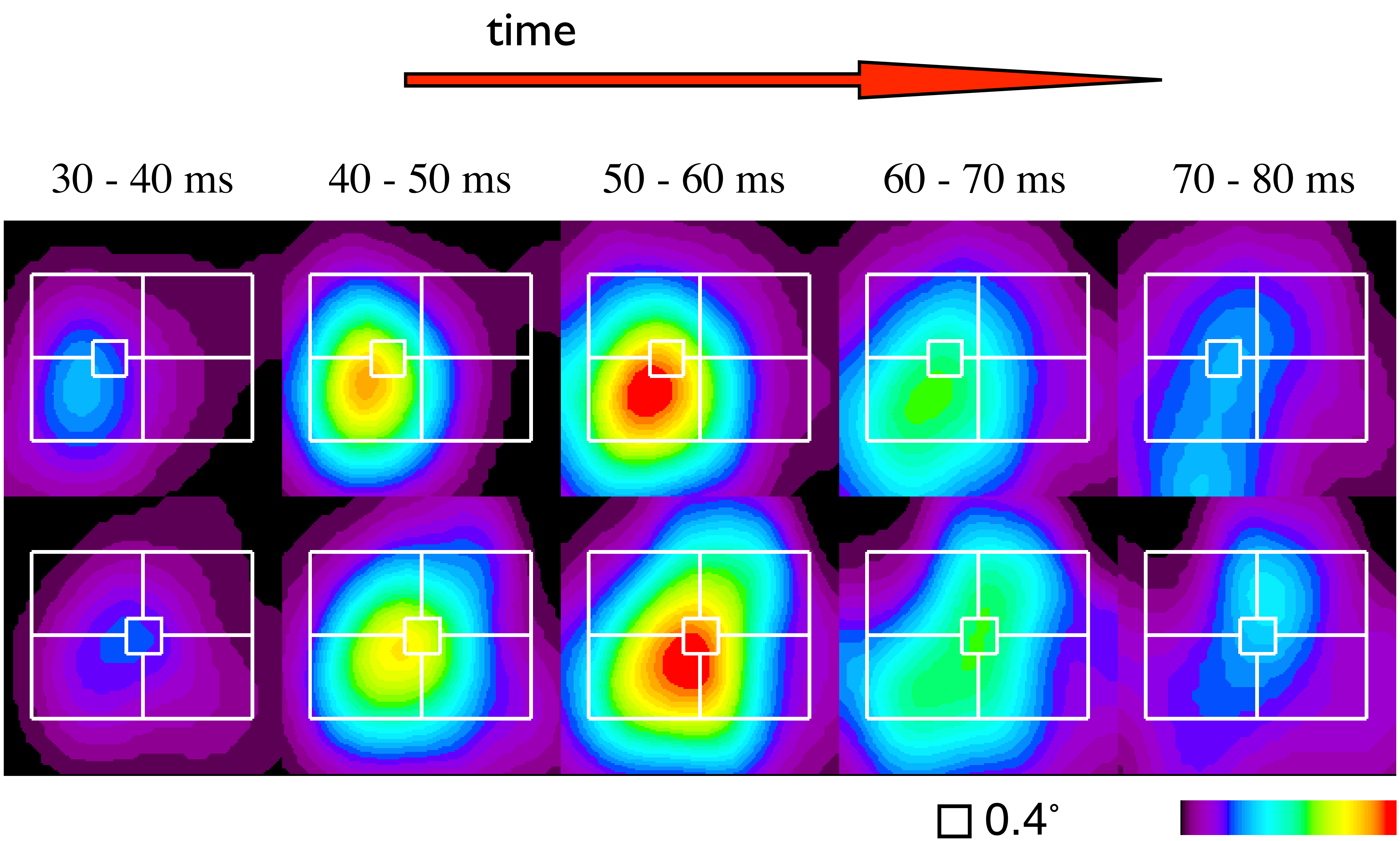
- in cat visual cortex A17 build DPA from receptive field profiles



[Jancke et al., 1999]

- temporal evolution of DPA of retinal location

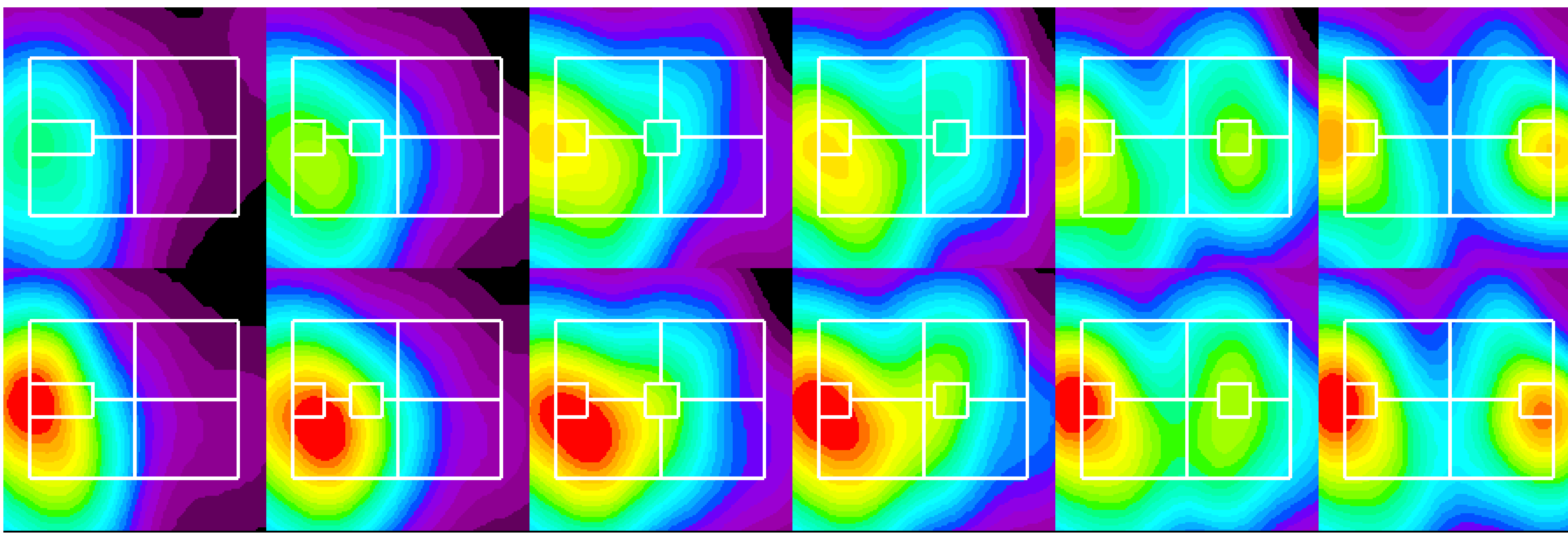



[Jancke et al., 1999]

## interaction betwen two stimulus locations

response to composite stimuli

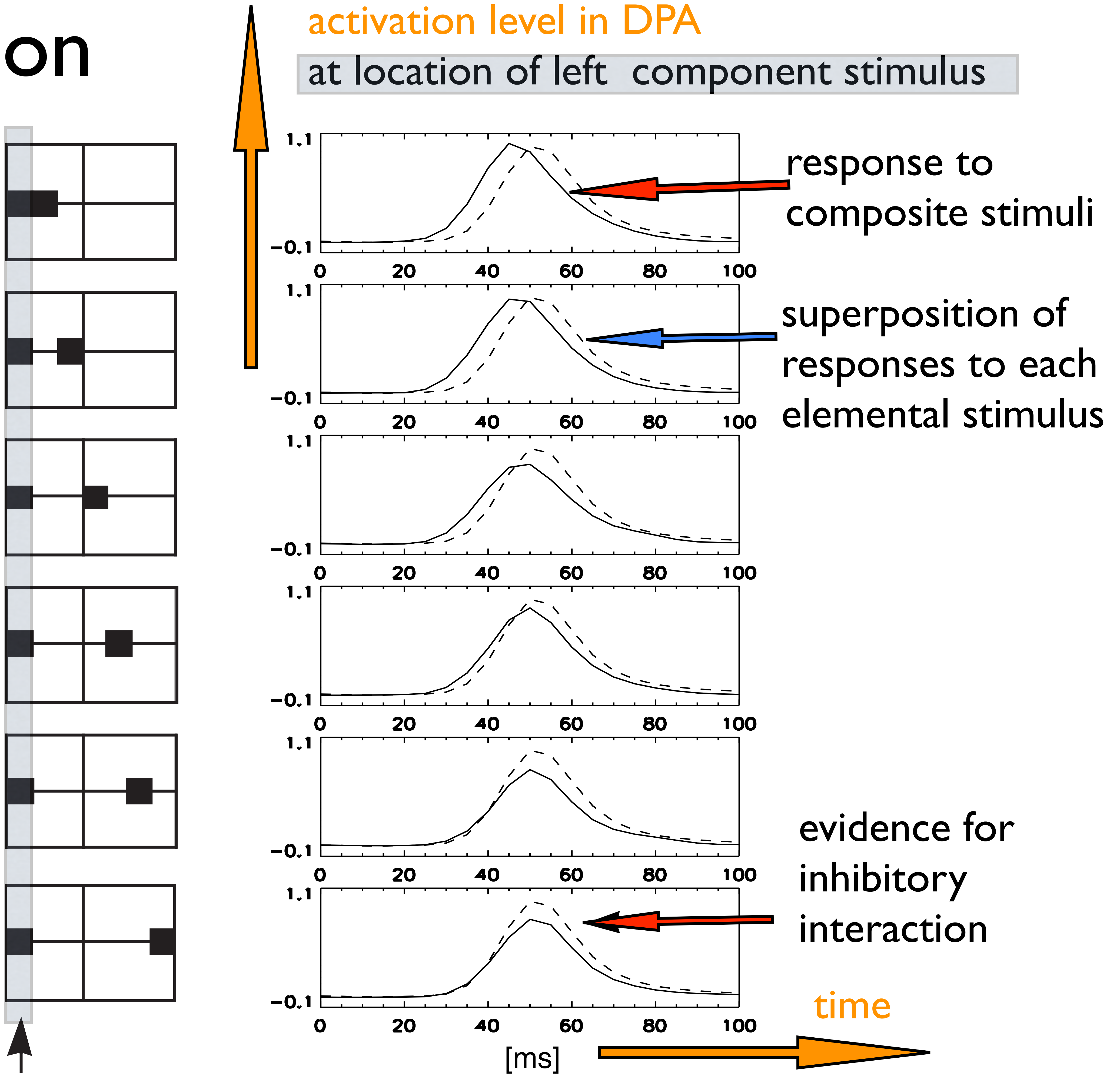
increasing distance between the two squares of light



superposition of responses to each elemental stimulus


[Jancke et al., 1999]

# interaction

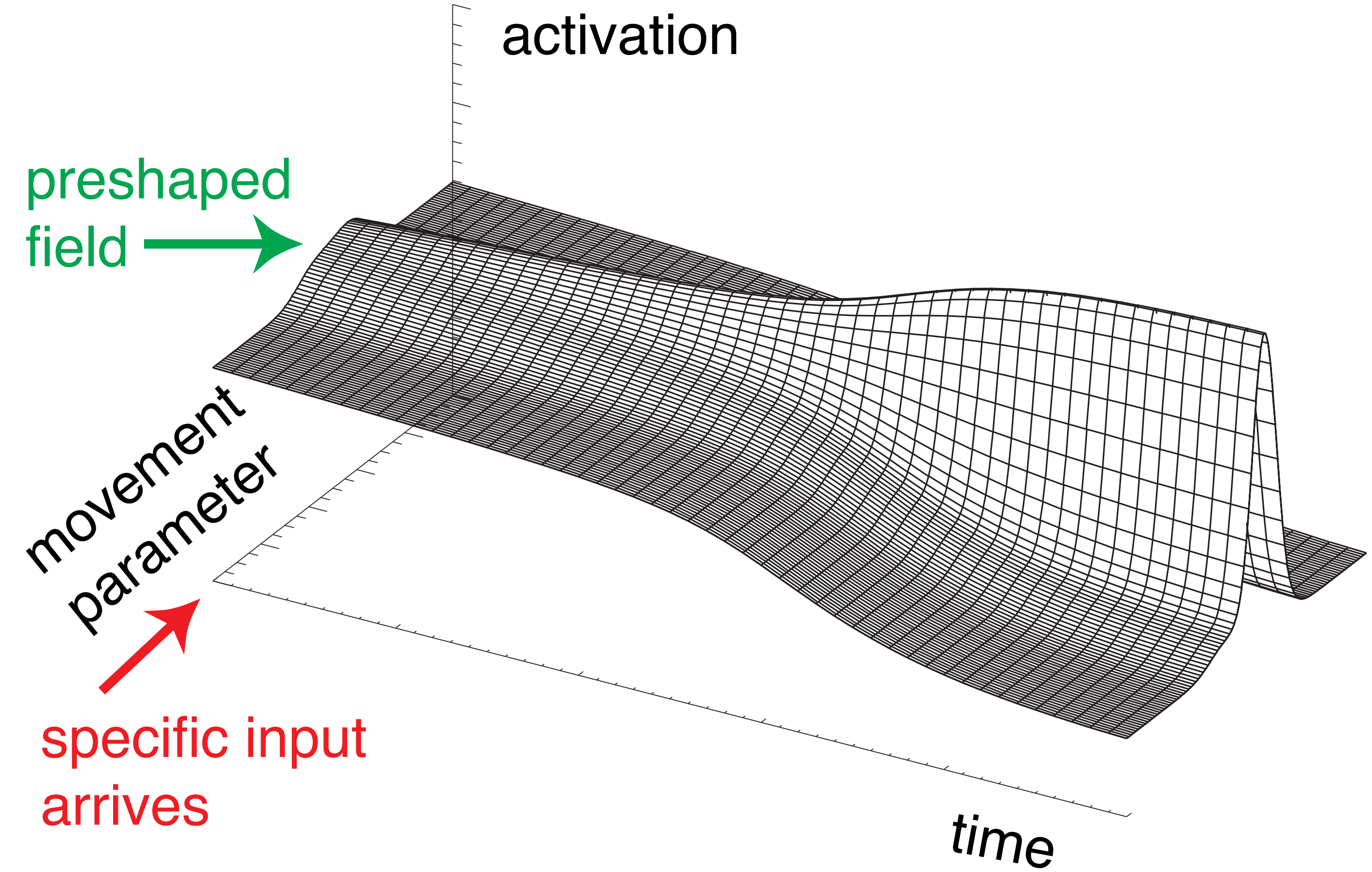


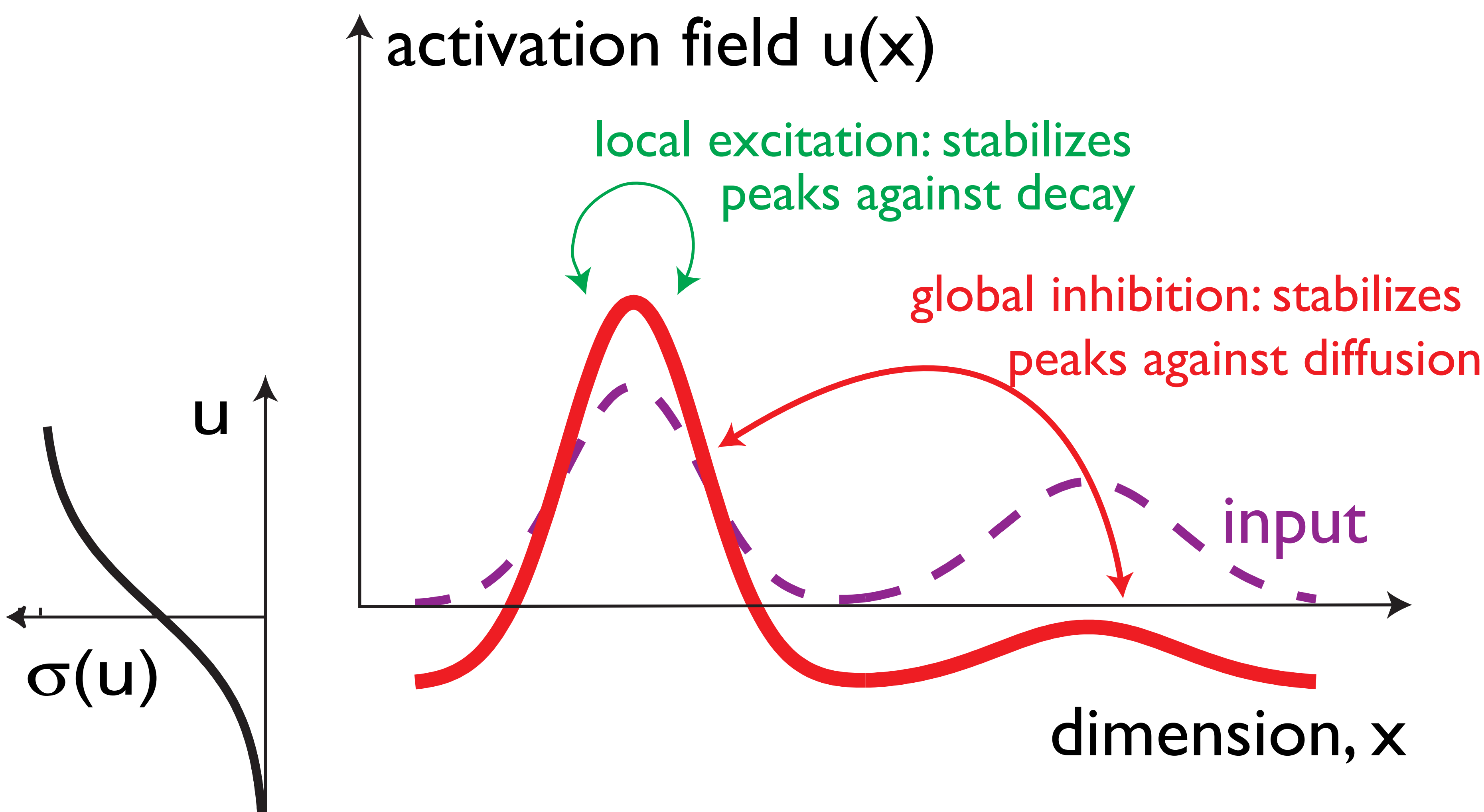

[Jancke et al., 1999]

# Distribution 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

the dynamics such activation fields is structured so that localized peaks emerge as attractor solutions



# illustration of DFT in 4 steps

- 1 layer Amari model
- 2 layer Amari model
- 3 layer model
- 2 layer 2D model

# Simplest model: 1 layer Amari

Amari equation

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

where

- time scale is $\tau$
- resting level is $h < 0$
- input is $S(x,t)$
- interaction kernel is

$$w(x-x') = w_i + w_e \exp\left[-\frac{(x-x')^2}{2\sigma_i^2}\right]$$

- sigmoidal nonlinearity is

$$\sigma(u) = \frac{1}{1+\exp[-\beta(u-u_0)]}$$

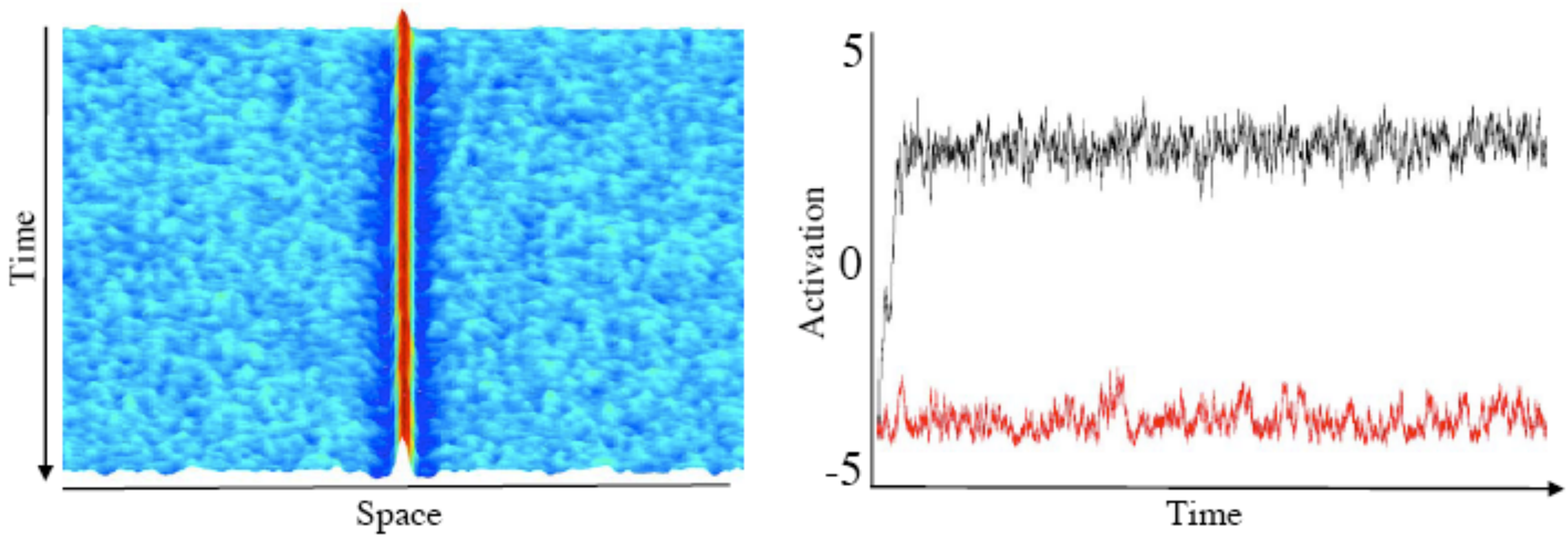
=> simulations

# solutions and instabilities

- input driven solution (sub-threshold) vs. self-stabilized solution (peak, supra-threshold)
- detection instability
- reverse detection instability
- selection
- selection instability
- memory instability
- detection instability from boost

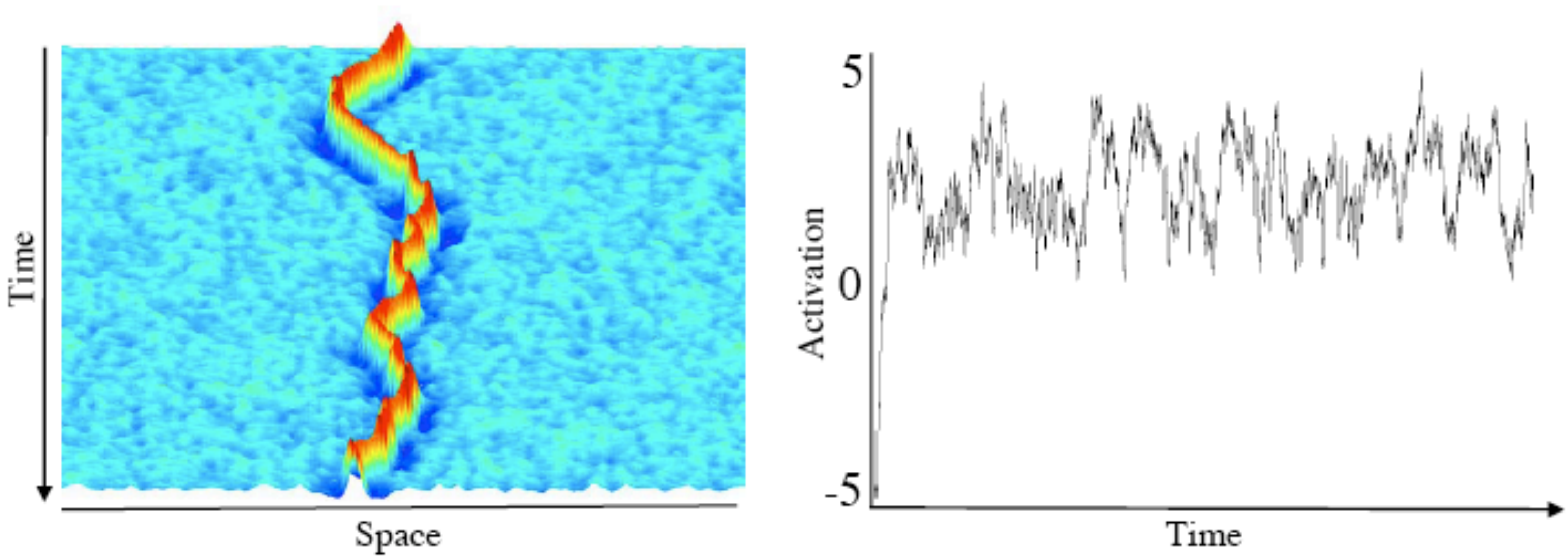
# functional significance of instabilities

- detection instability: stabilizes detection decisions



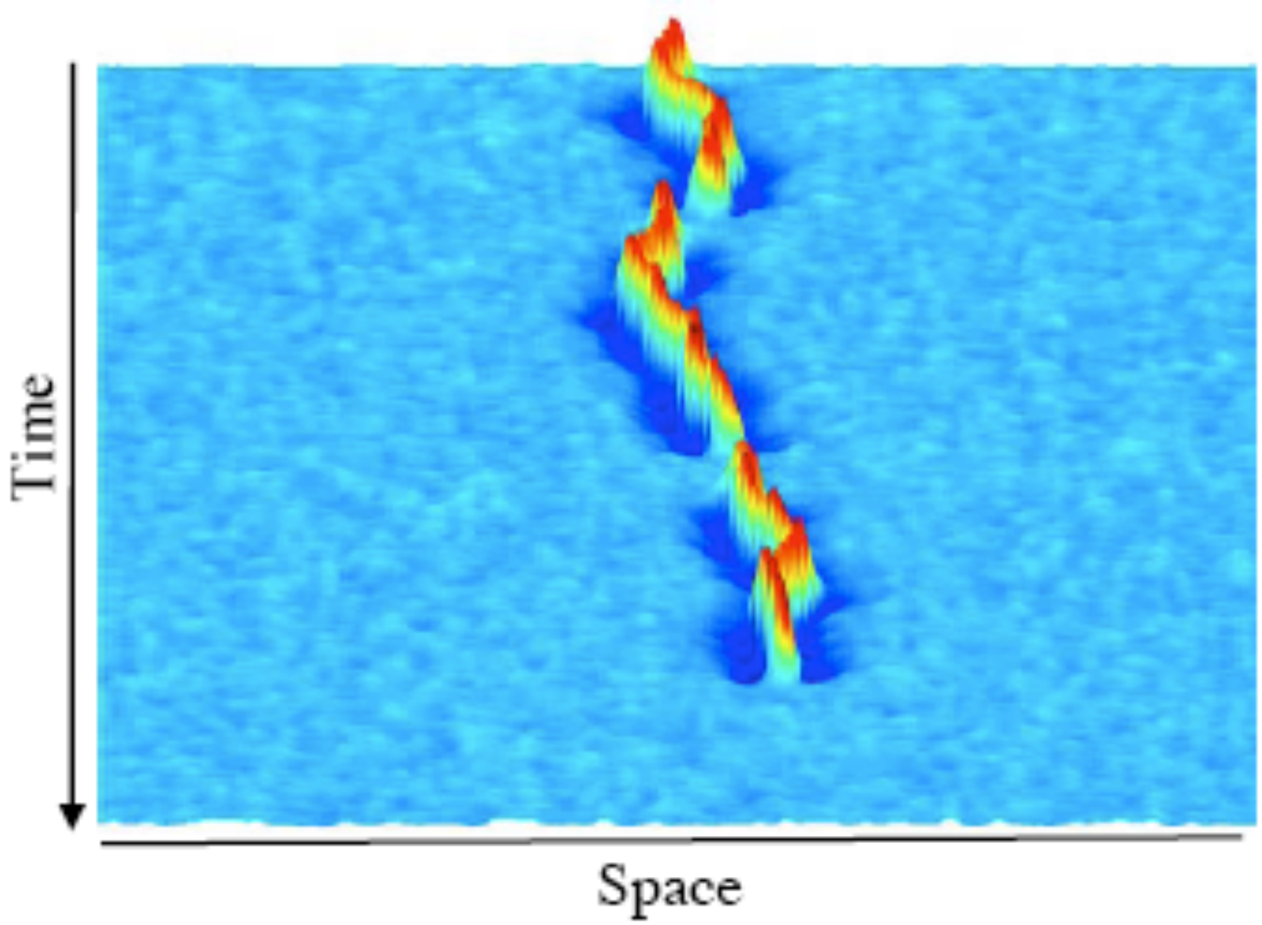

[figure: John Spencer]

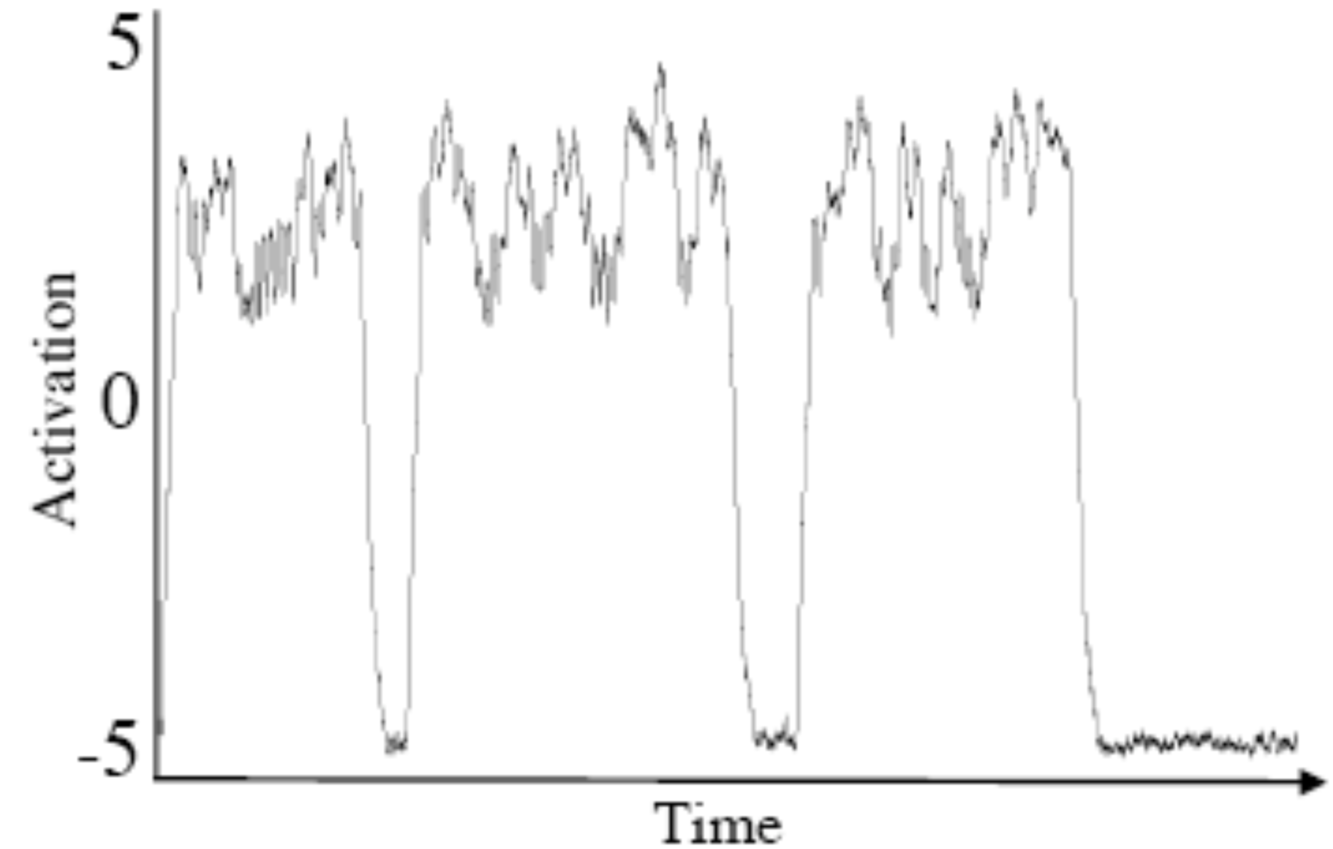
- stabilization against fluctuations in both amplitude and metric position of input: tracking




[figure: John Spencer]

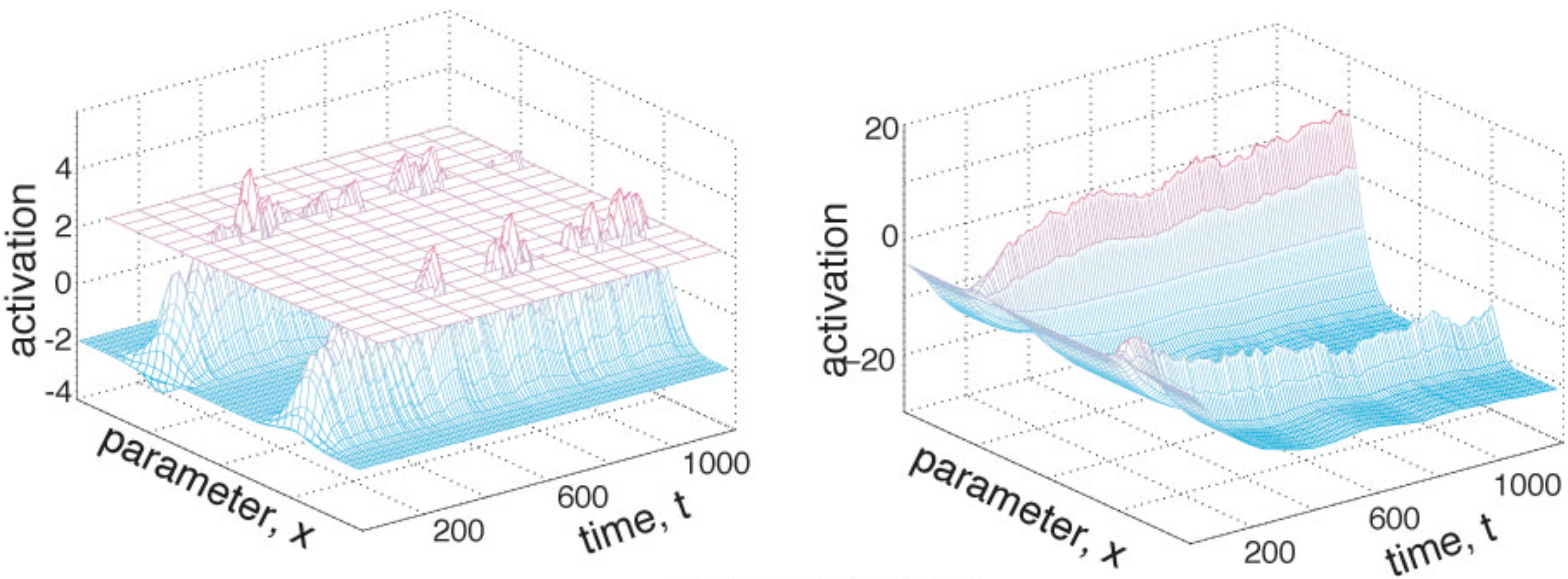
- tracking during occlusion of input



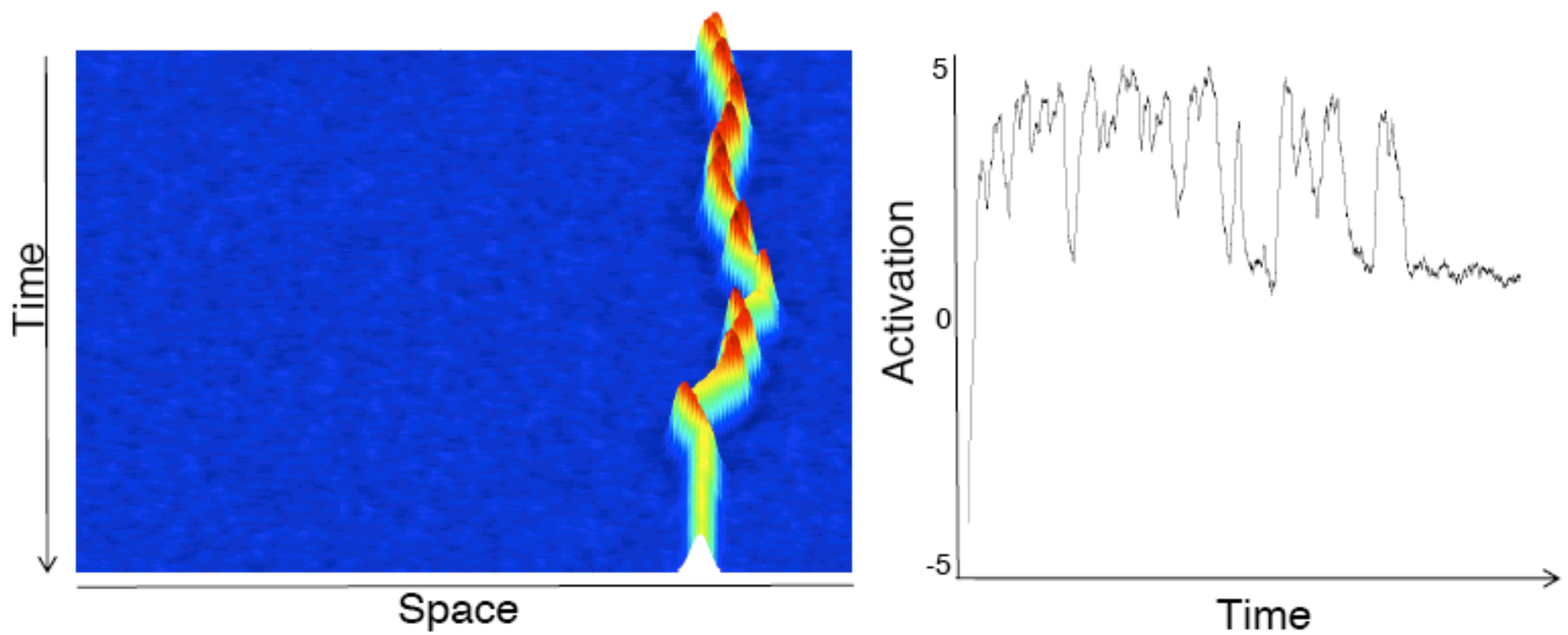

[figure: John Spencer]

- selection instability stabilizes selection decisions




[Wilimzig, Schöner, 2006]

- memory instability: stabilizes against long occlusions of input

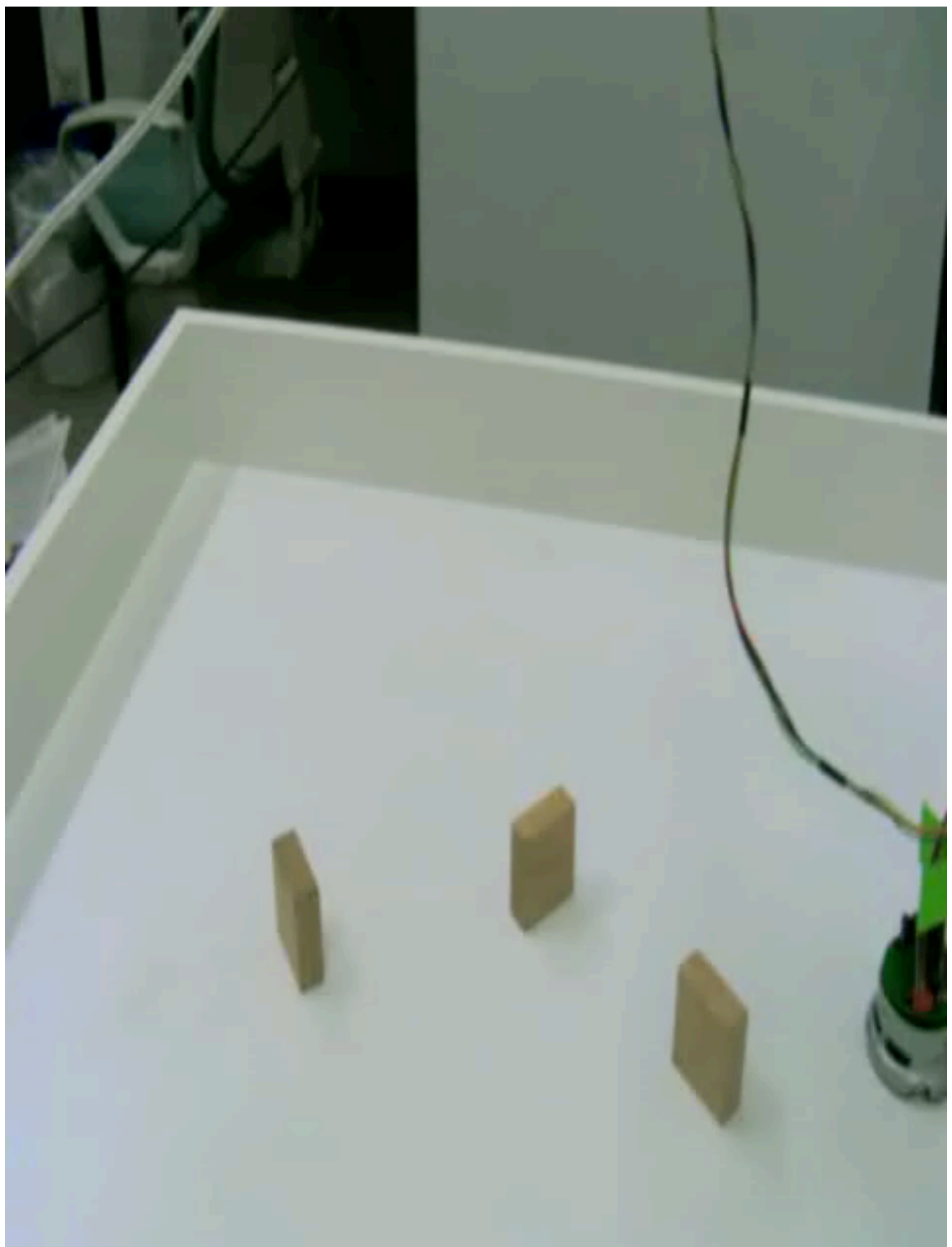



[figure: John Spencer]

# robotic demonstration of functional significance of sustained peaks

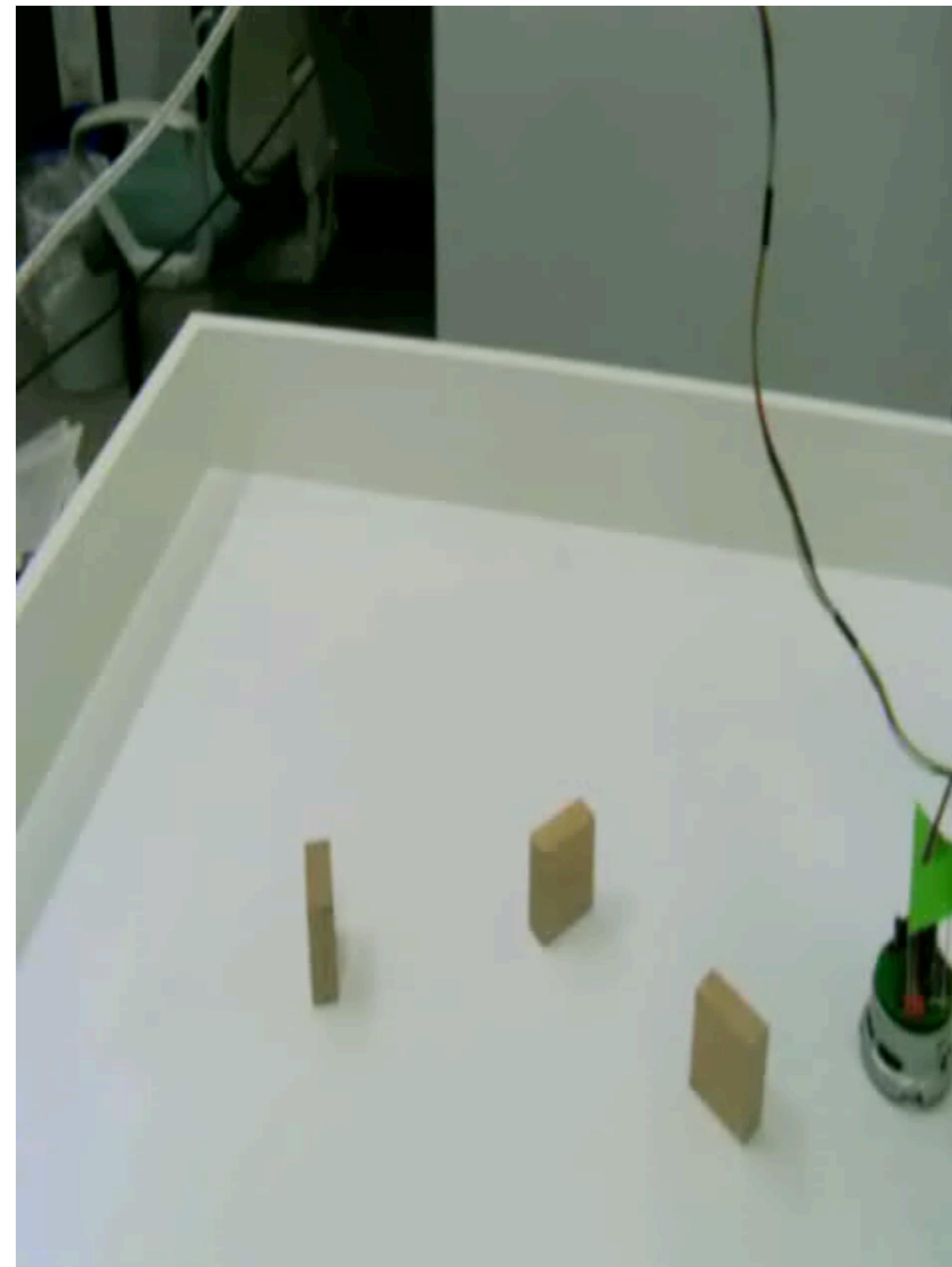
“young” robot: not sustained

target



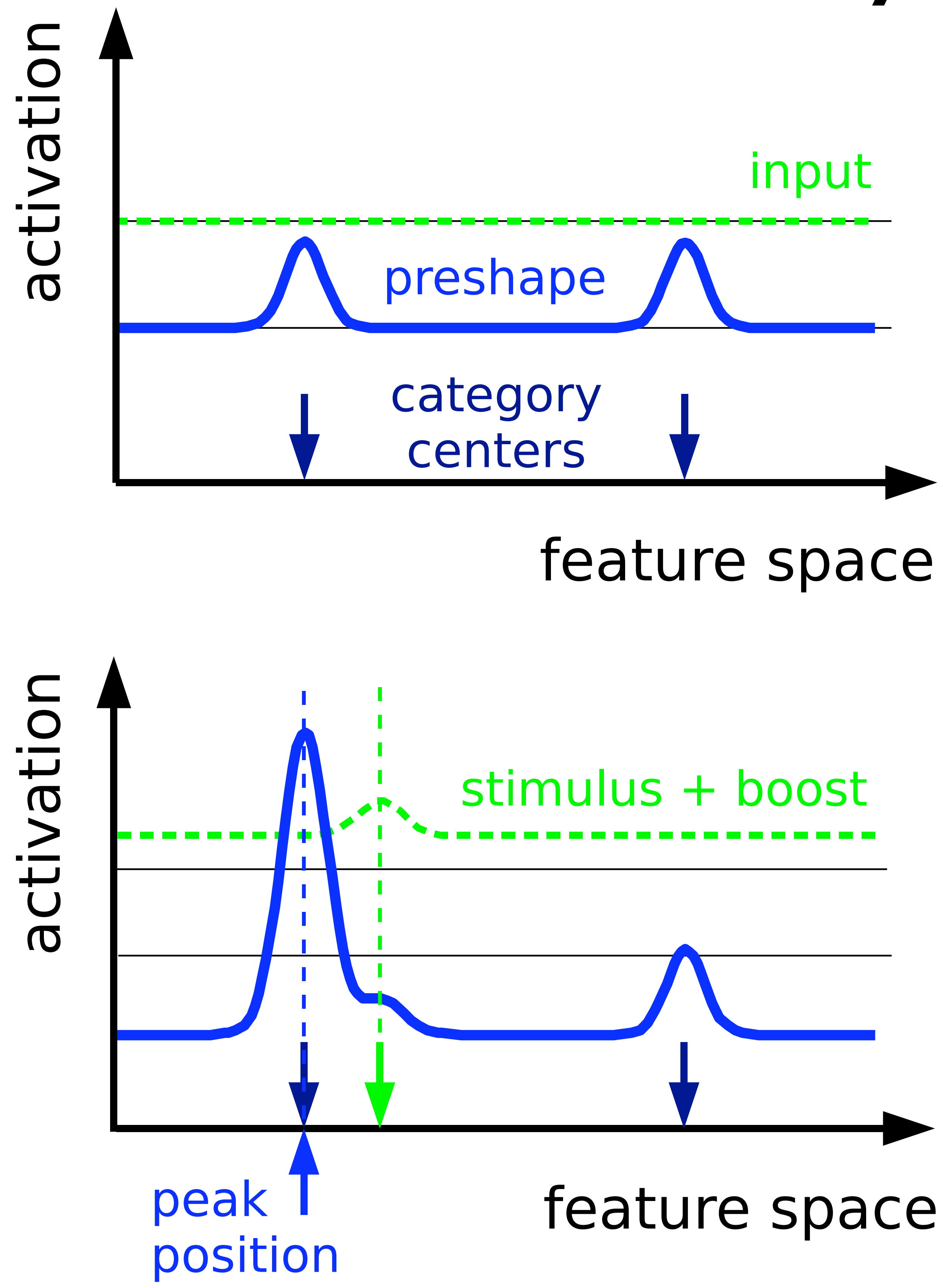
“old” robot: sustained

target



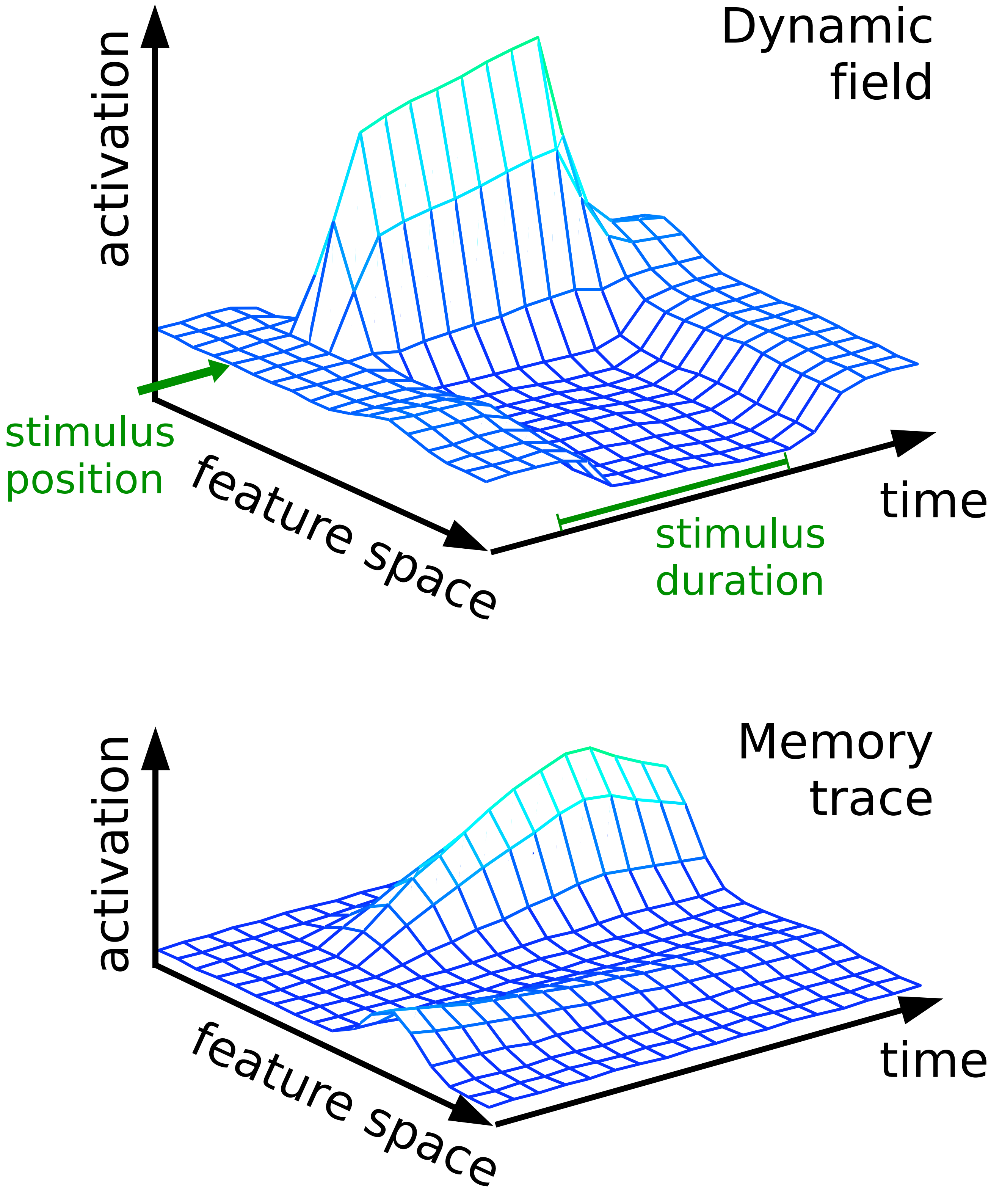
# boost-induced detection instability

- transforms graded patterns, learned inhomogeneities into macroscopic decisions: categorical states!

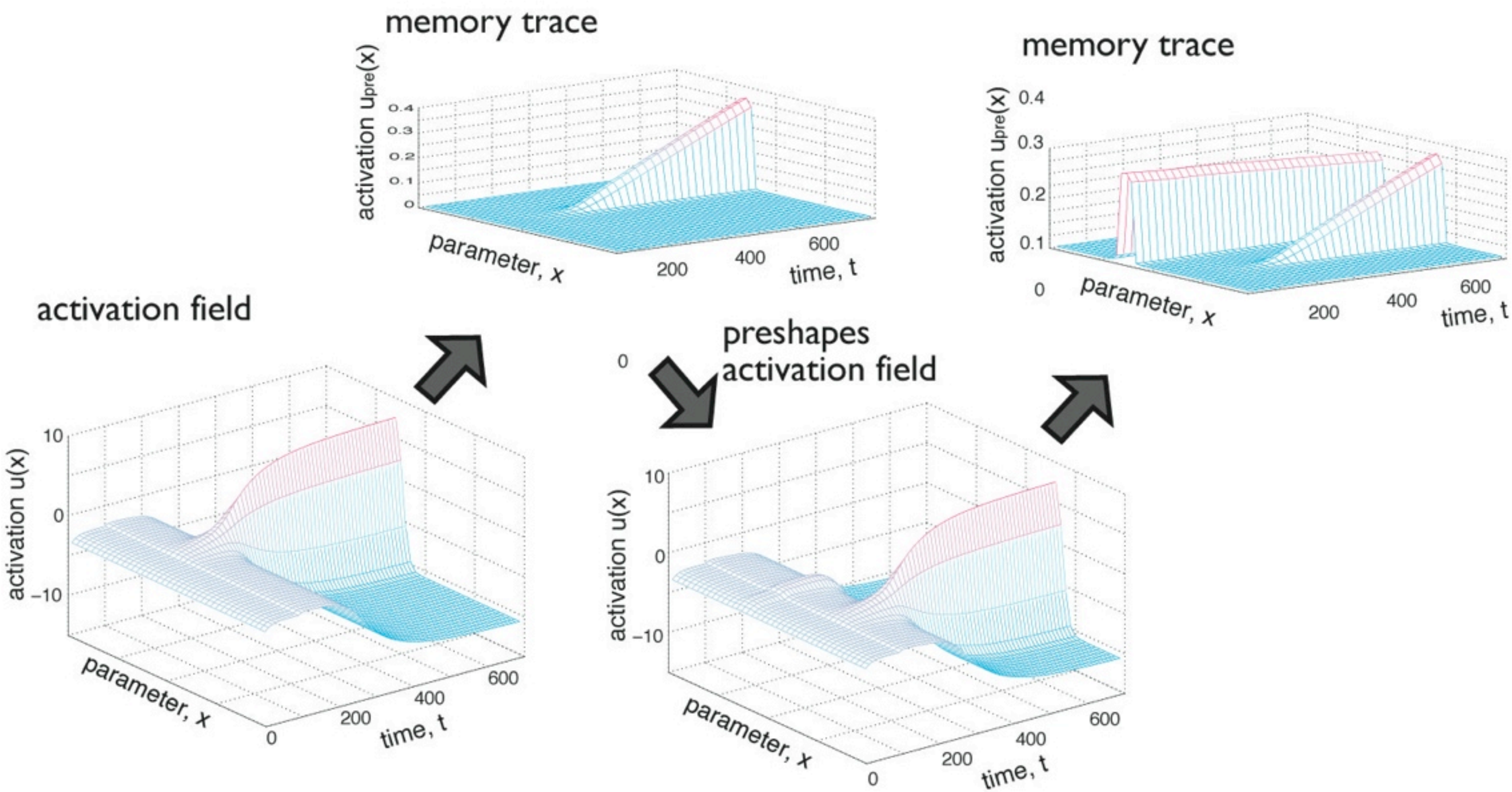


# how does preshape arise?

- from learning, e.g., a memory trace
- or hebbian learning

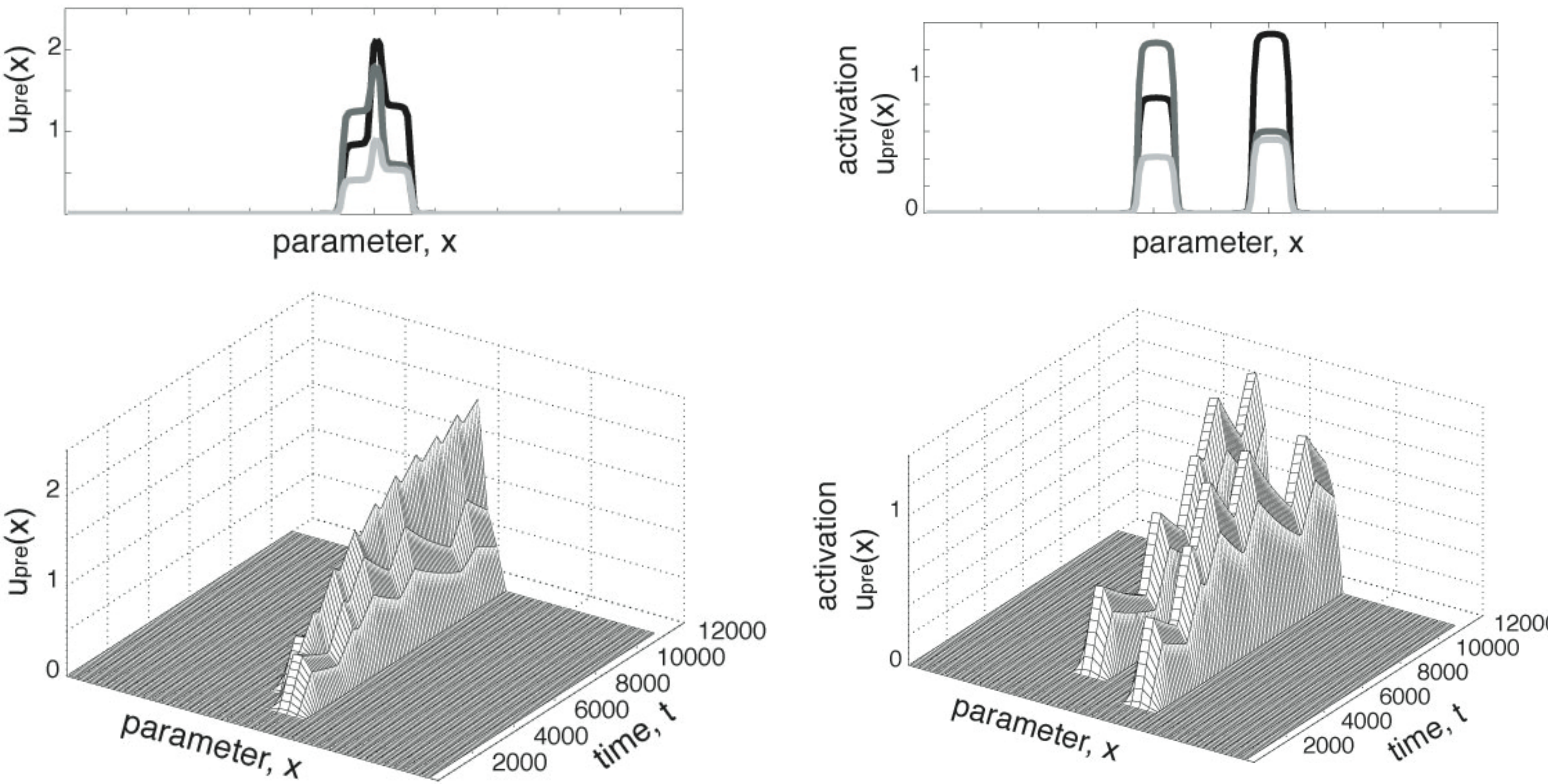


# preshaping fields through a memory trace of prior activation




Wilimzig, Schöner 2006

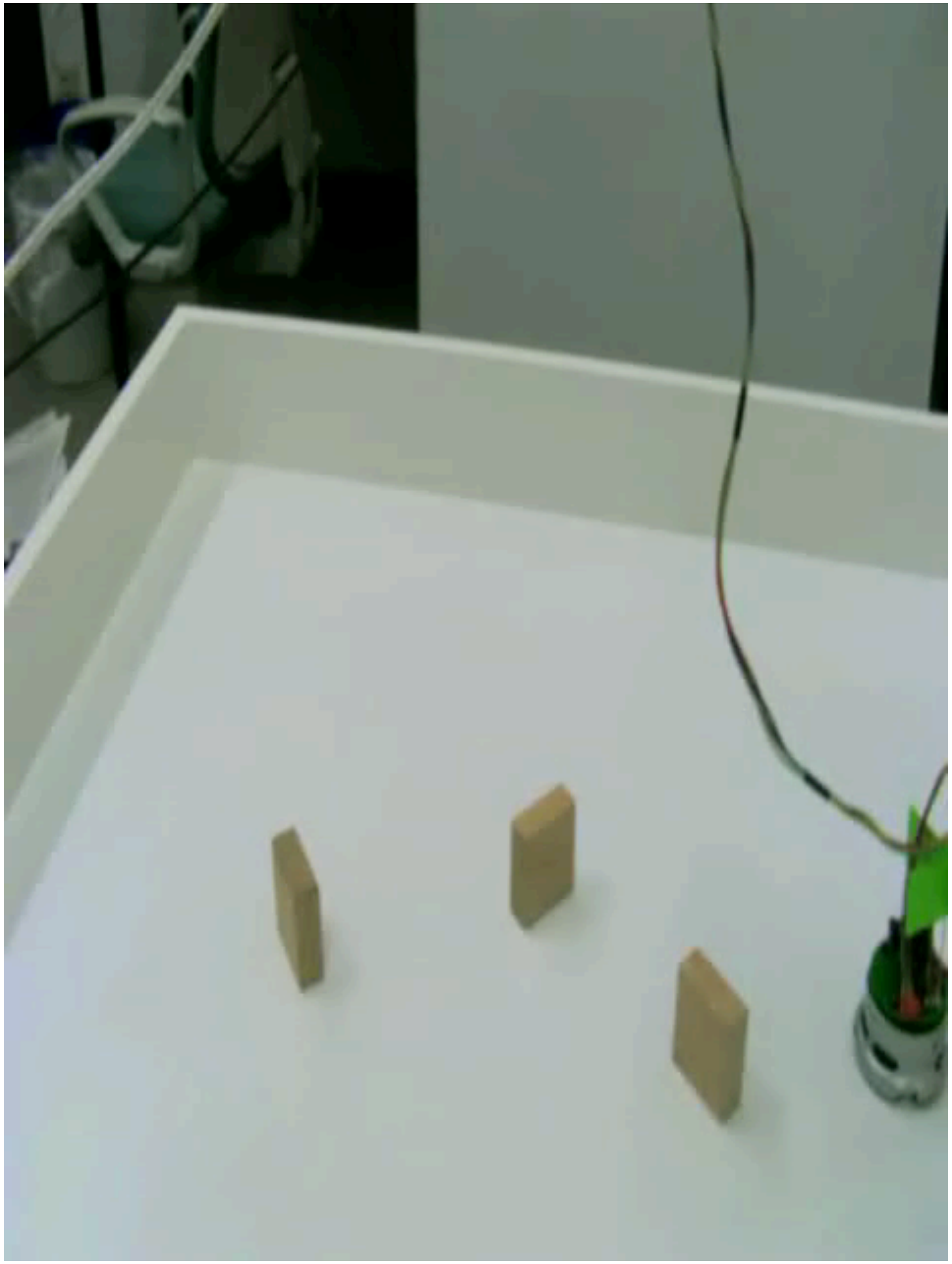
# leads to categories




Wilimzig, Schöner 2006

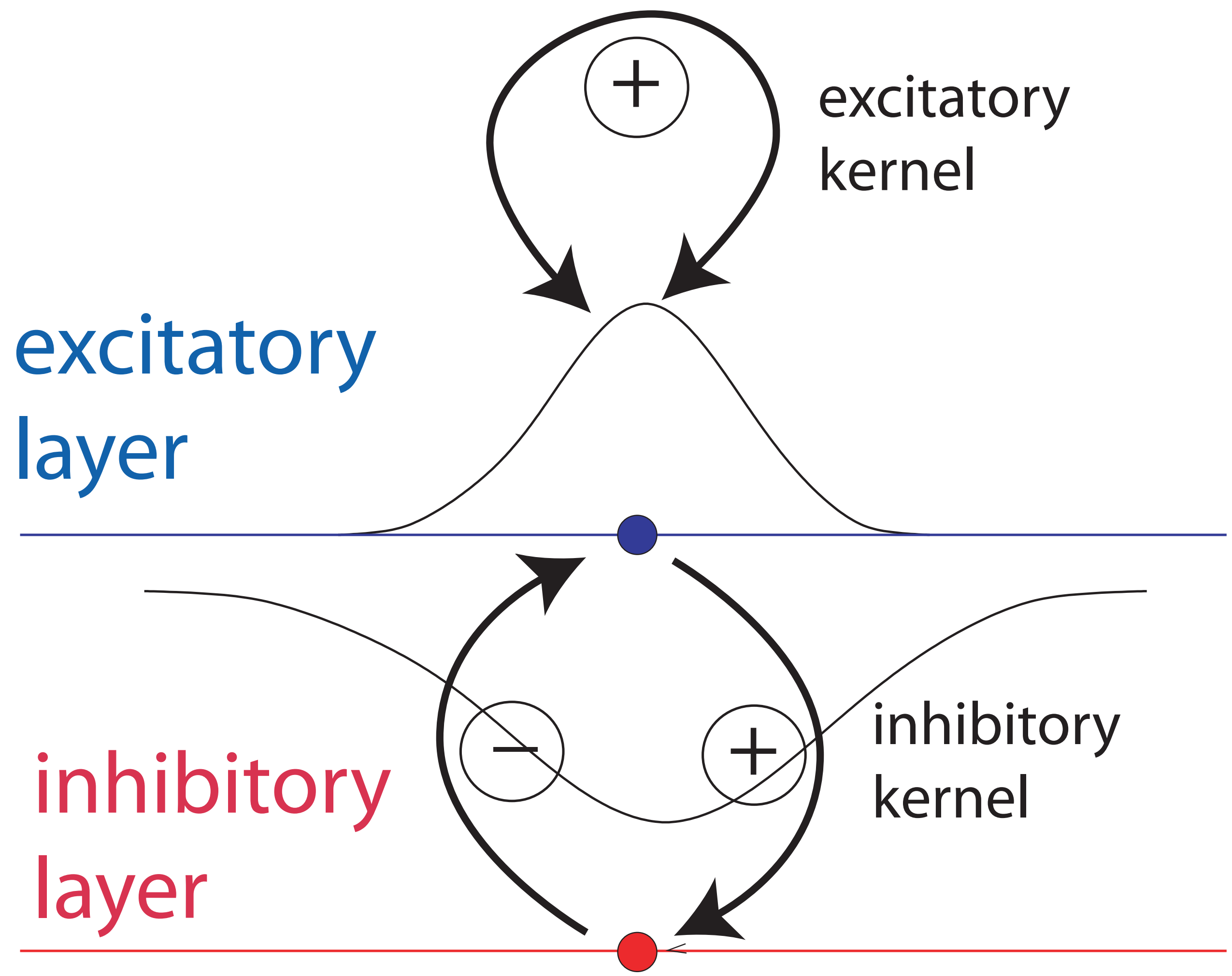
# habit formation stabilizes behavior

target



# 2 layer Amari fields

- to comply with Dale's law
- and account for difference in time course of excitation (early) and inhibition (late)




[figure: Wilimzig, Schneider, Schöner, Neural Networks, 2006]

# 2 layer Amari model

$$
\begin{aligned}
\tau \dot{u}(x,t) &= -u(x,t) + h_u + S(x,t) + \int dx'\; c_{\mathrm{uu}}(x-x')\;\sigma(u(x',t)) \\
&- \int dx'\; c_{\mathrm{uv}}(x-x')\;\sigma(v(x',t)) \\
\tau \dot{v}(x,t) &= -v(x,t) + h_v + \int dx'\; c_{\mathrm{vu}}(x-x')\;\sigma(u(x',t))
\end{aligned}
$$

$$
c_{ij}(x-x') = c_{i,j,\mathrm{strength}}\;\exp\left[-\frac{(x-x')^2}{2\sigma_{ij}^2}\right].
\qquad
\sigma(u) = \frac{1}{1+\exp[-\beta\;u]}.
$$

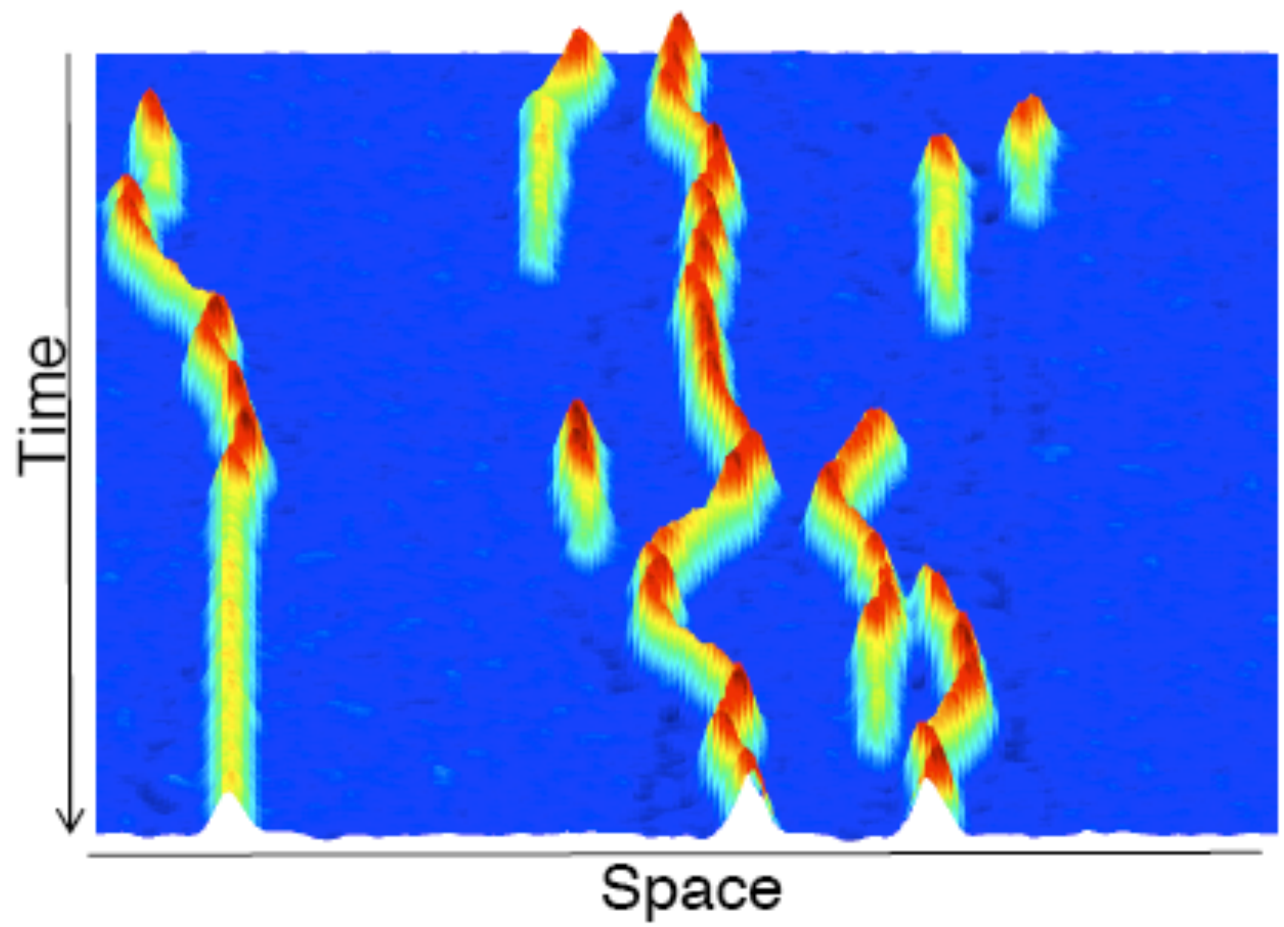
=> simulations

# solutions and instabilities

- selection vs. multi-peak mode
- capacity limit for sustained multi-peak solution

# functional significance

- multi-item working memory and tracking ...

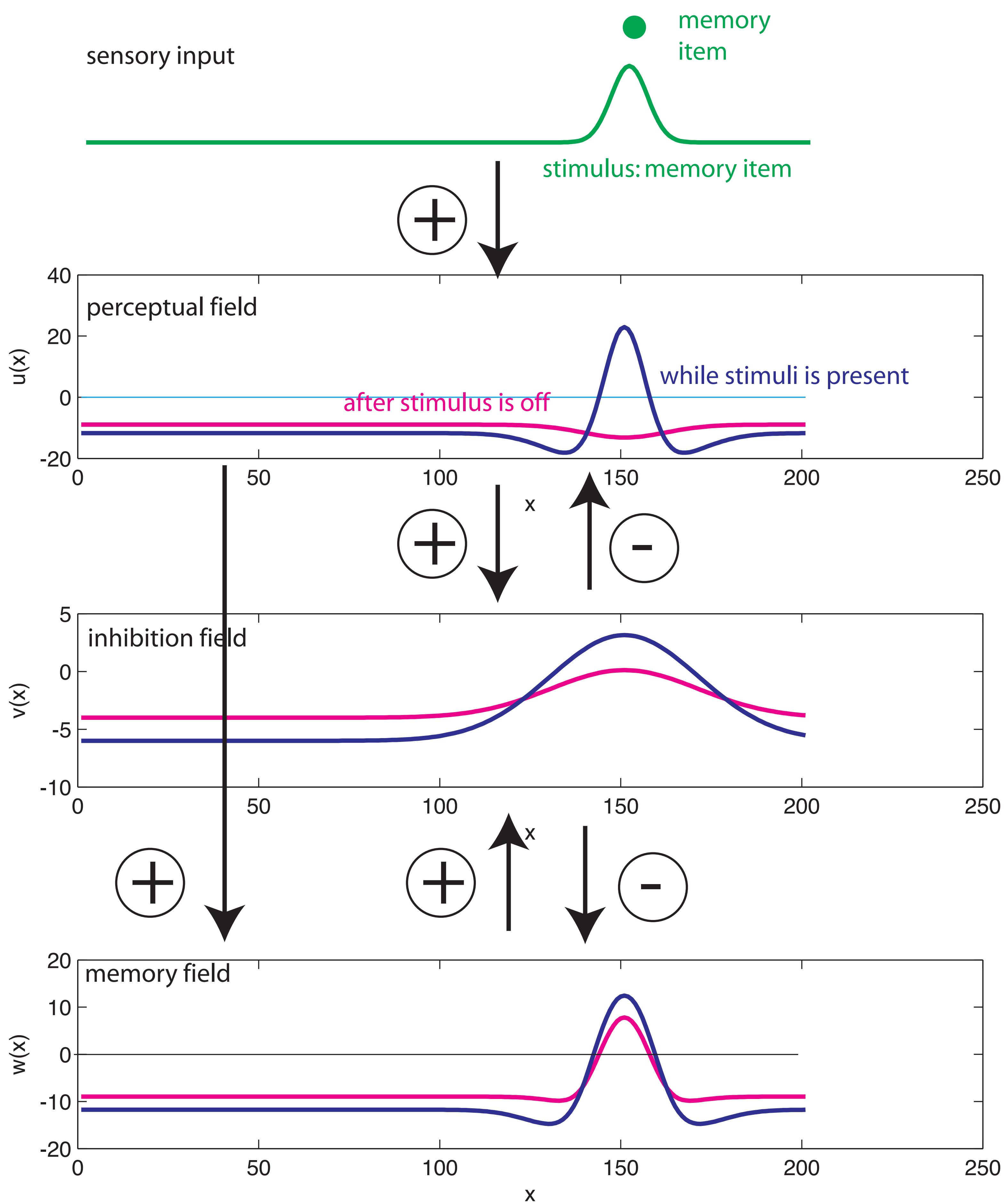



[figure: John Spencer]

# 3 layer model

- to accomodate separation between perceptual and memory function
- and to thus account for how memories arise from percepts, how percepts may detect change and update memories...

# 3 layer model



# 3 layer model

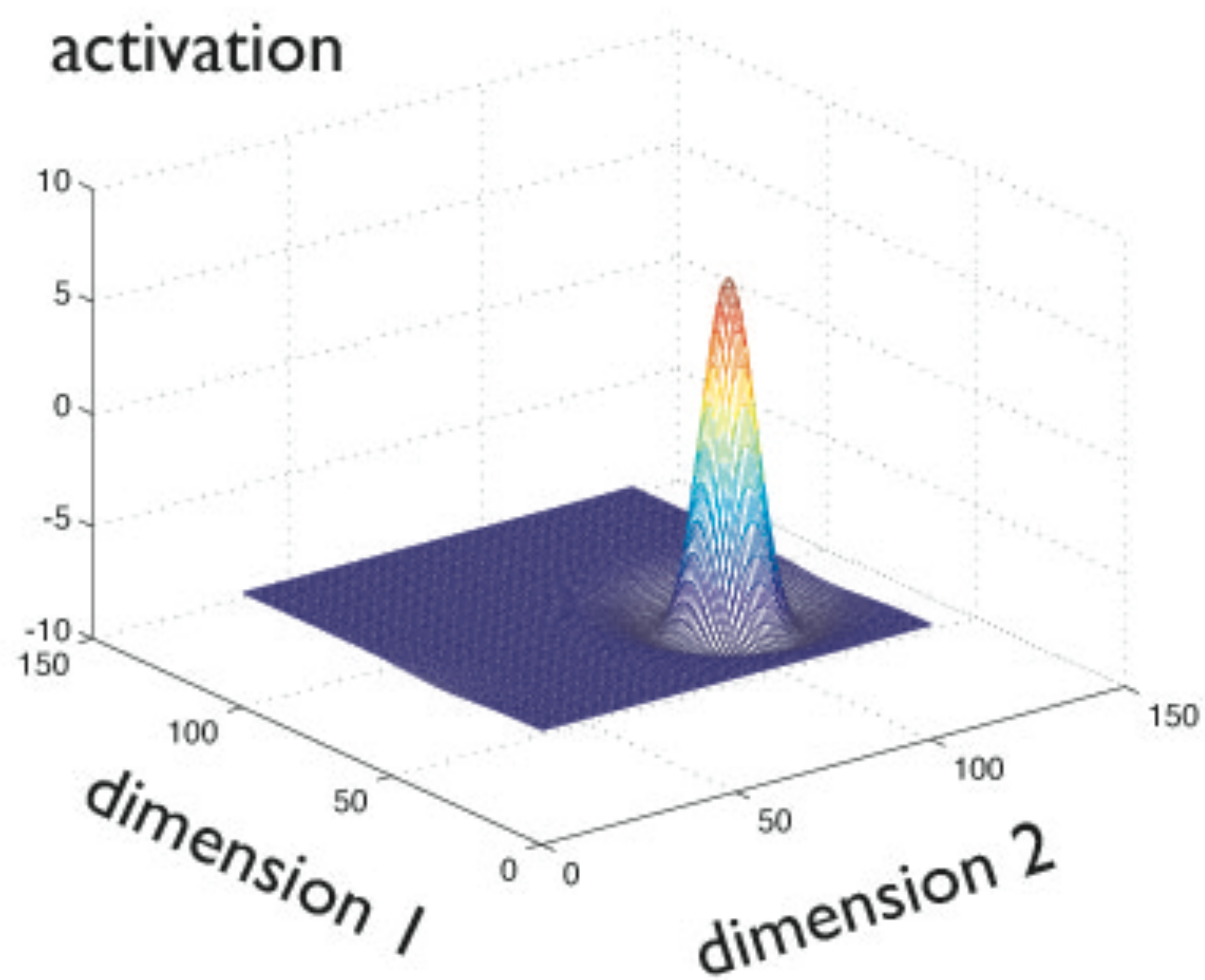
$$
\begin{aligned}
\tau \dot{u}(x,t) &= -u(x,t) + h_u + S(x,t) + \int dx'\, c_{\mathrm{uu}}(x-x')\, \sigma(u(x',t)) \\
&- \int dx'\, c_{\mathrm{uv}}(x-x')\, \sigma(v(x',t)) + \int dx'\, c_{\mathrm{uw}}(x-x')\, \sigma(w(x',t)) \\
\tau \dot{v}(x,t) &= -v(x,t) + h_v \\
&+ \int dx'\, c_{\mathrm{vu}}(x-x')\, \sigma(u(x',t)) + \int dx'\, c_{\mathrm{vw}}(x-x')\, \sigma(w(x',t)) \\
\tau \dot{w}(x,t) &= -w(x,t) + h_w + \int dx'\, c_{\mathrm{ww}}(x-x')\, \sigma(w(x',t)) \\
&- \int dx'\, c_{\mathrm{wv}}(x-x')\, \sigma(v(x',t)) + \int dx'\, c_{\mathrm{wu}}(x-x')\, \sigma(u(x',t))
\end{aligned}
$$

=> simulations

# solutions and instabilities

- emergent working memory
- change detection and updating of working memory

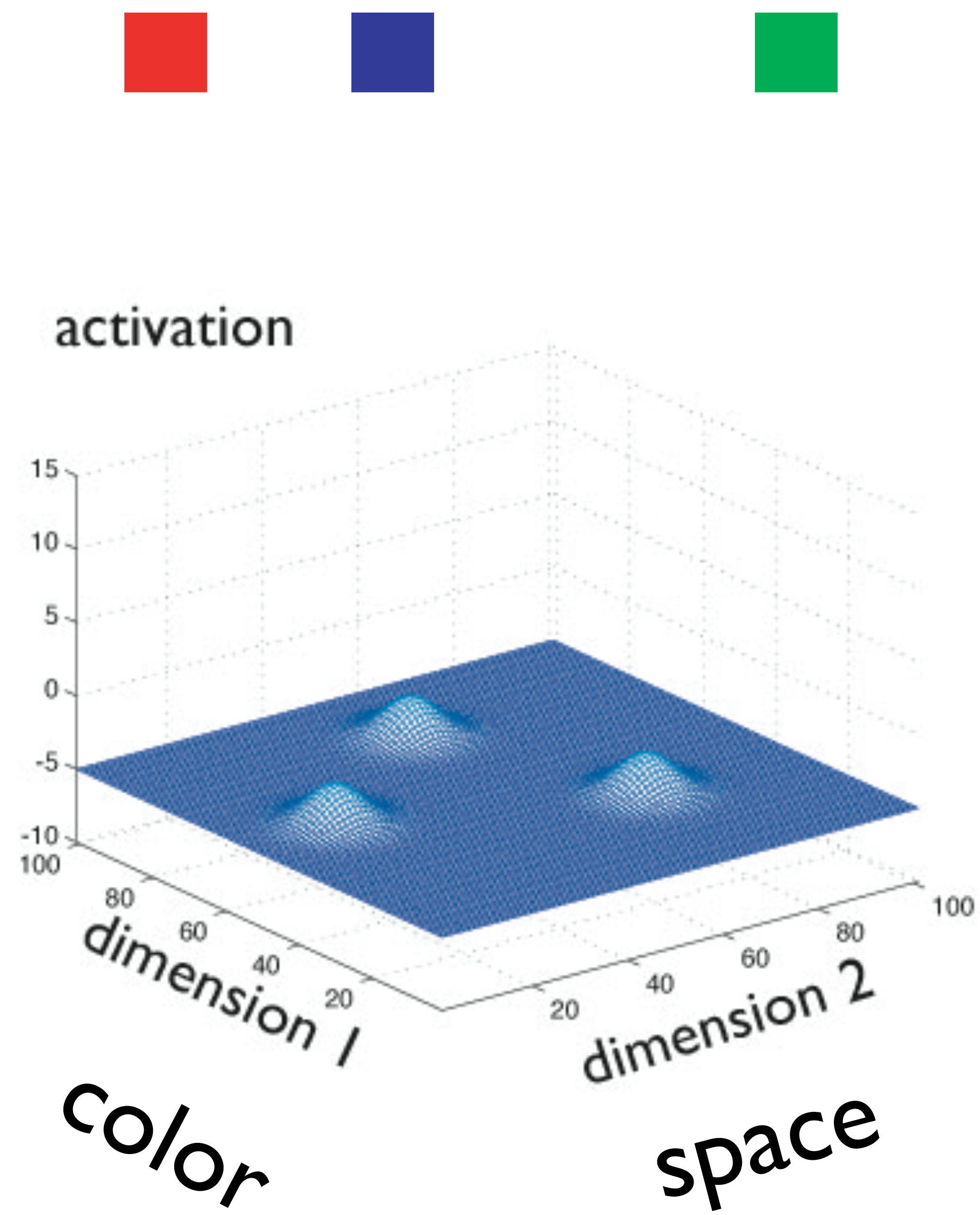
# 2layer 2D field



=> simulations

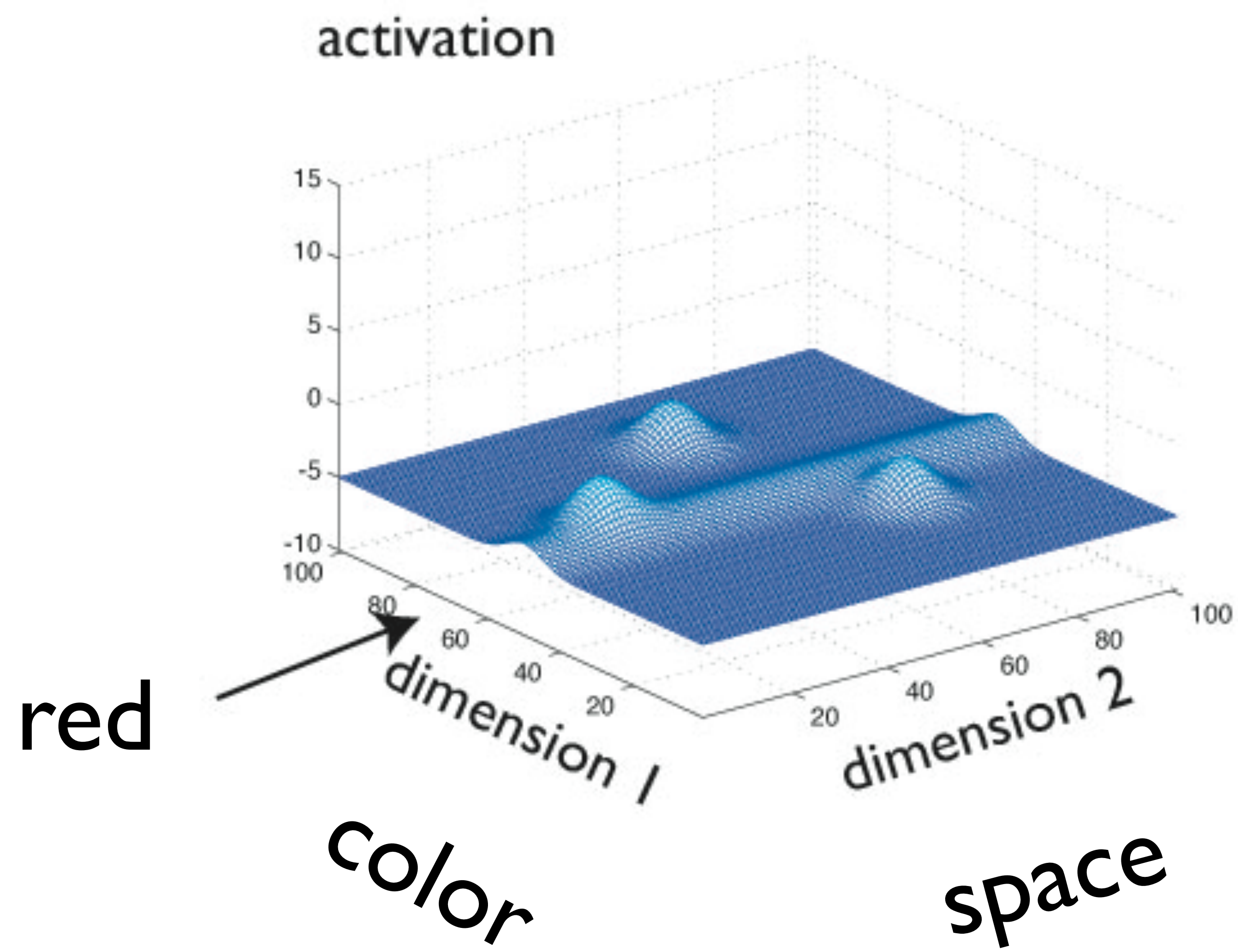
# functional significance: dimensional cuing

- e.g., three inputs at three locations with three different colors
- answer: "where is the red square"



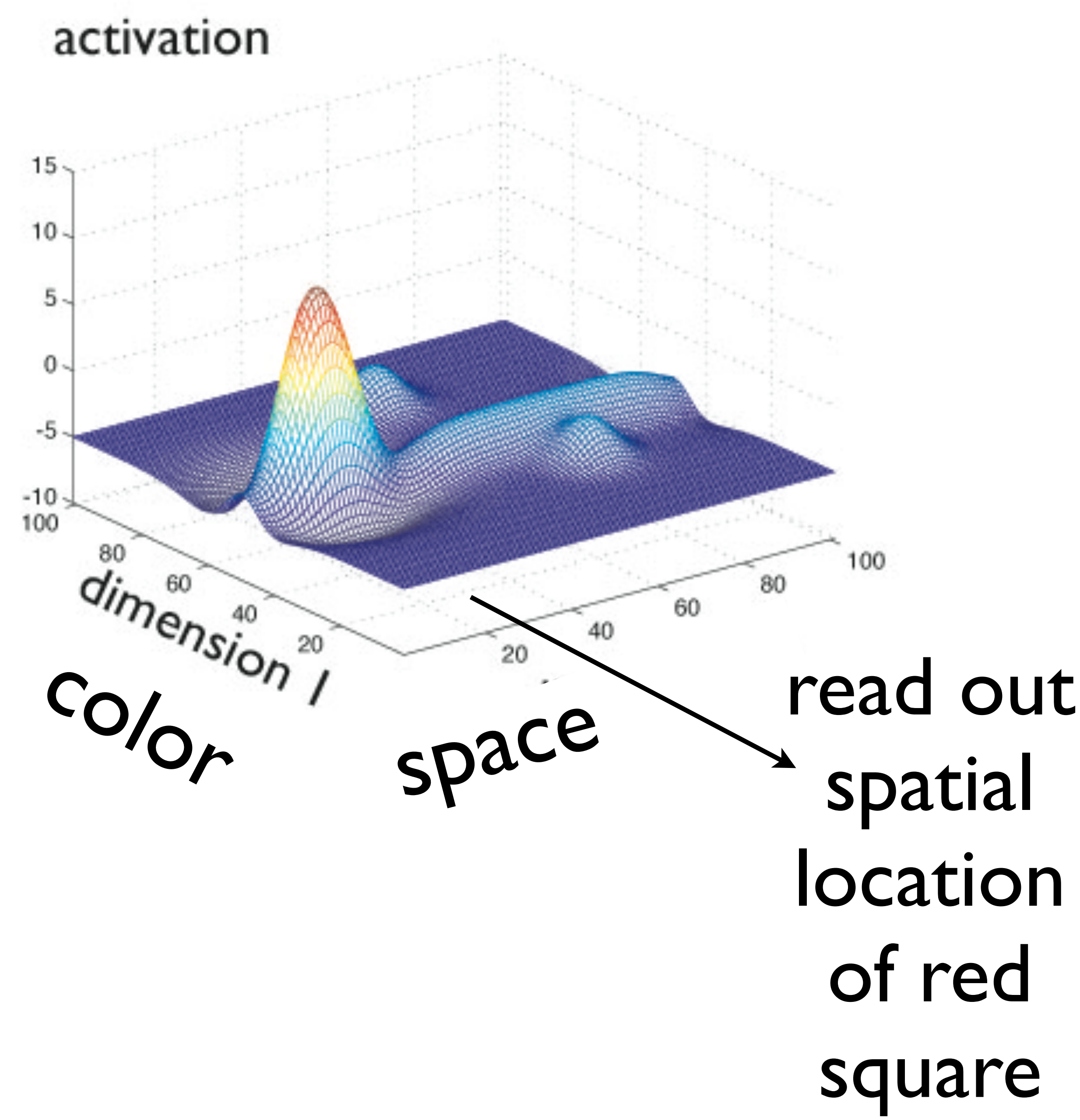
# dimensional cuing

- supply ridge input along the cued color dimension



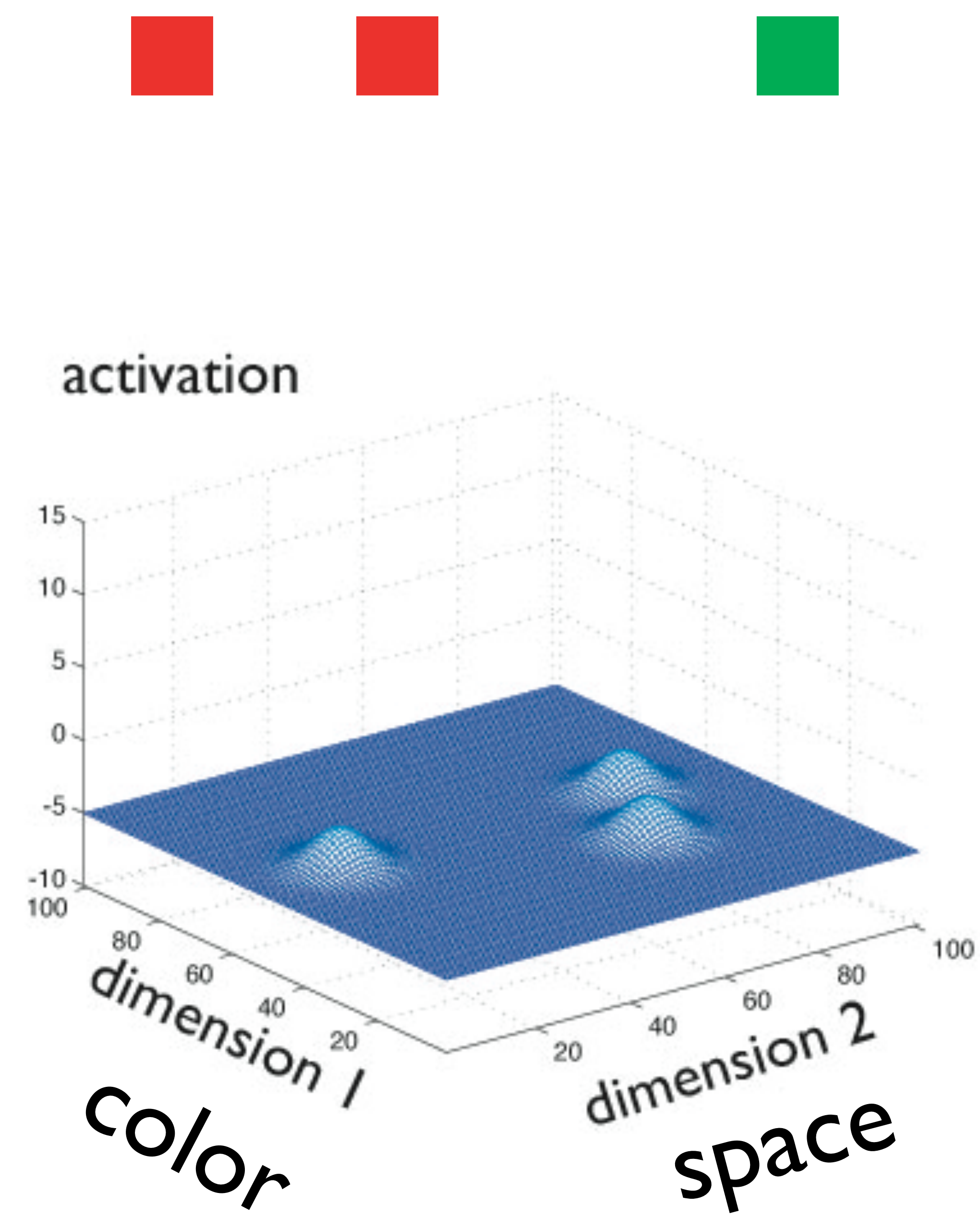
# dimensional cuing

- peak comes up where stimulus input and cue overlap
- read out spatial location at which peak is located



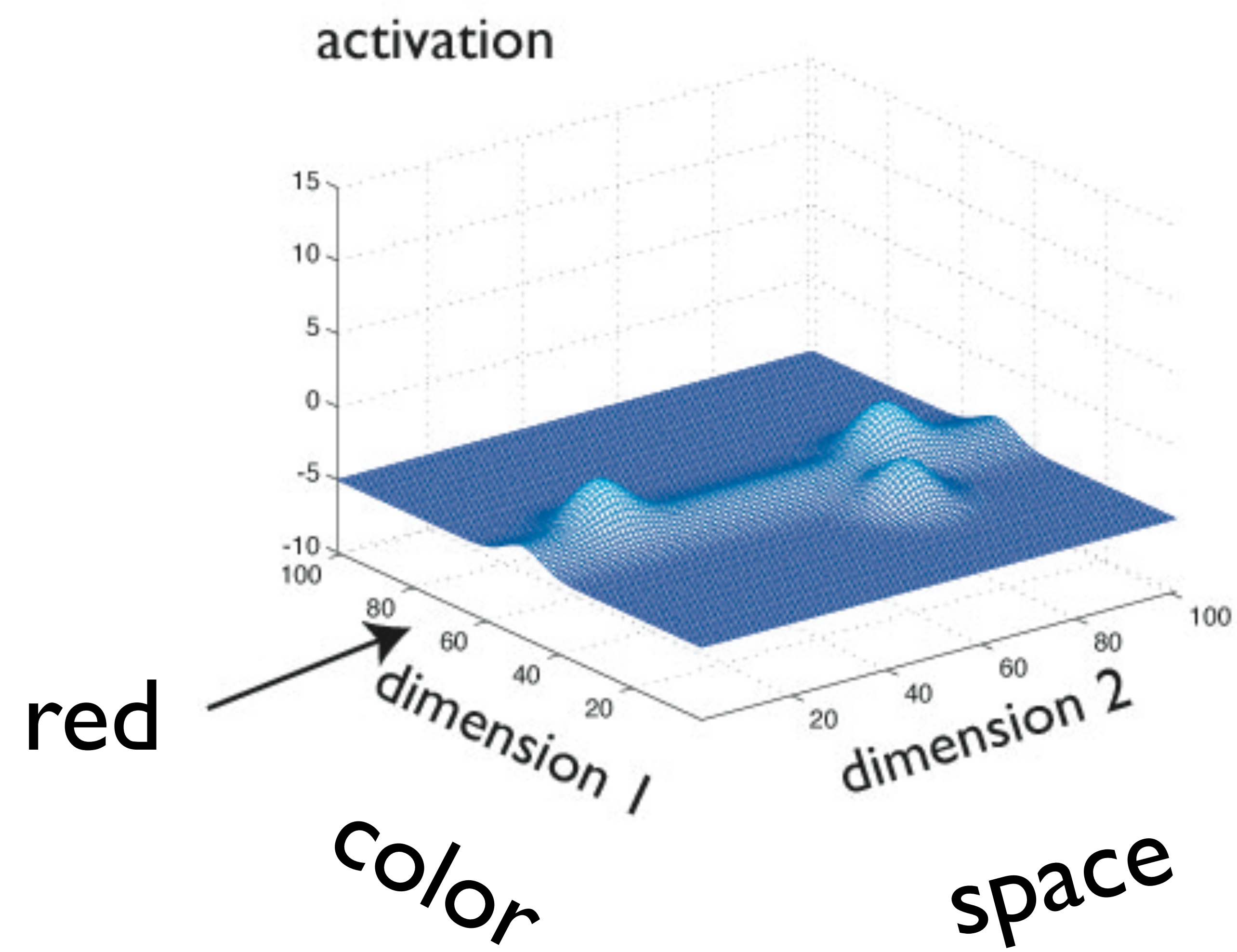
# dimensional cuing

- three colored objects including two red ones
- answer: "where are the red ones"?



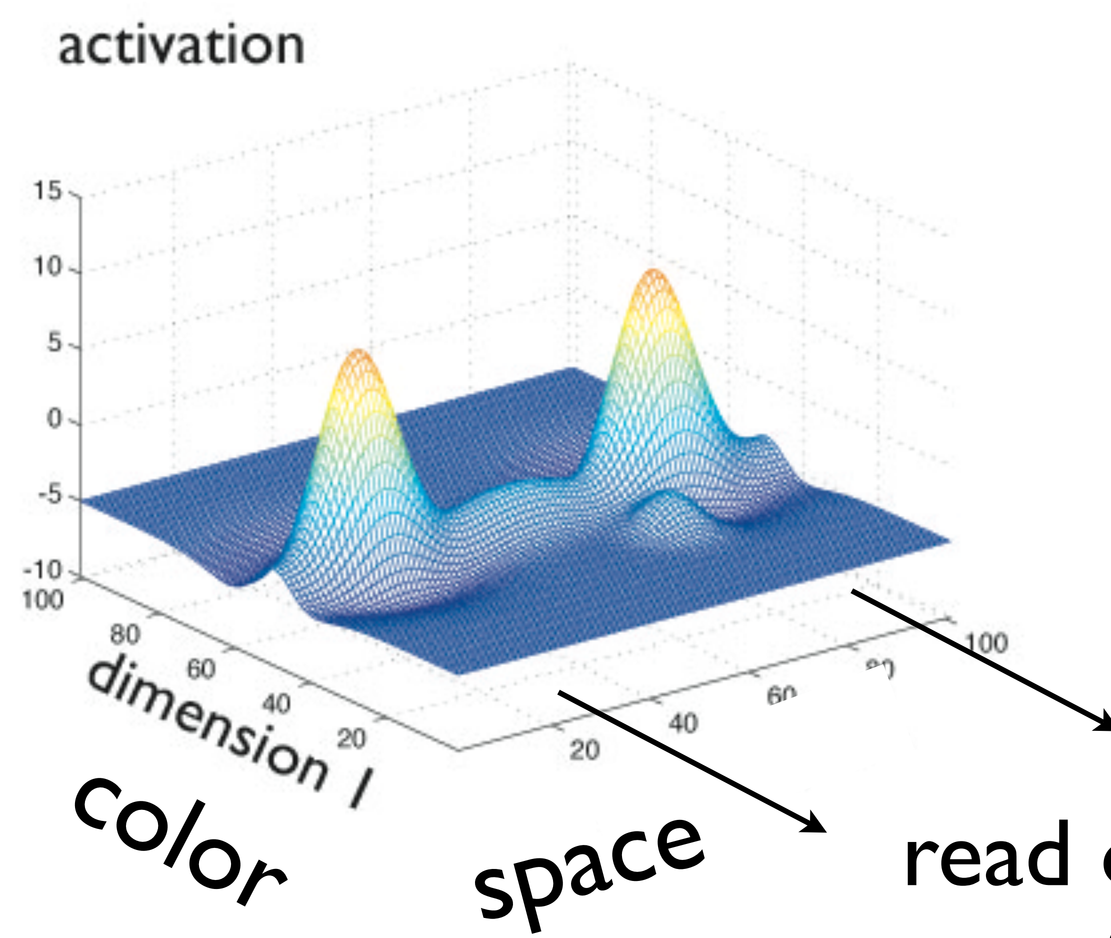
# dimensional cuing

- same idea: cue at read through ridge input



# dimensional cuing

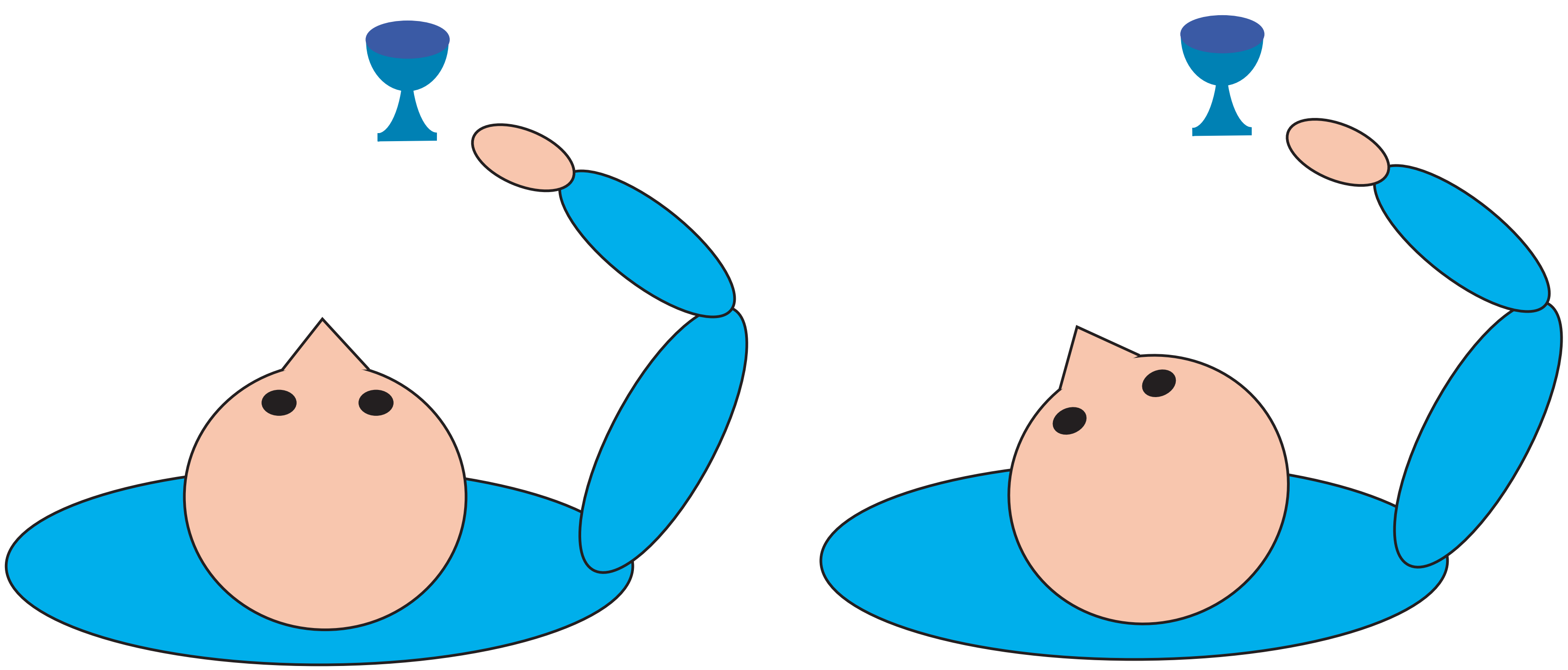
- => both red squares generate peaks
- and their locations can be read out




read out spatial locations of red squares

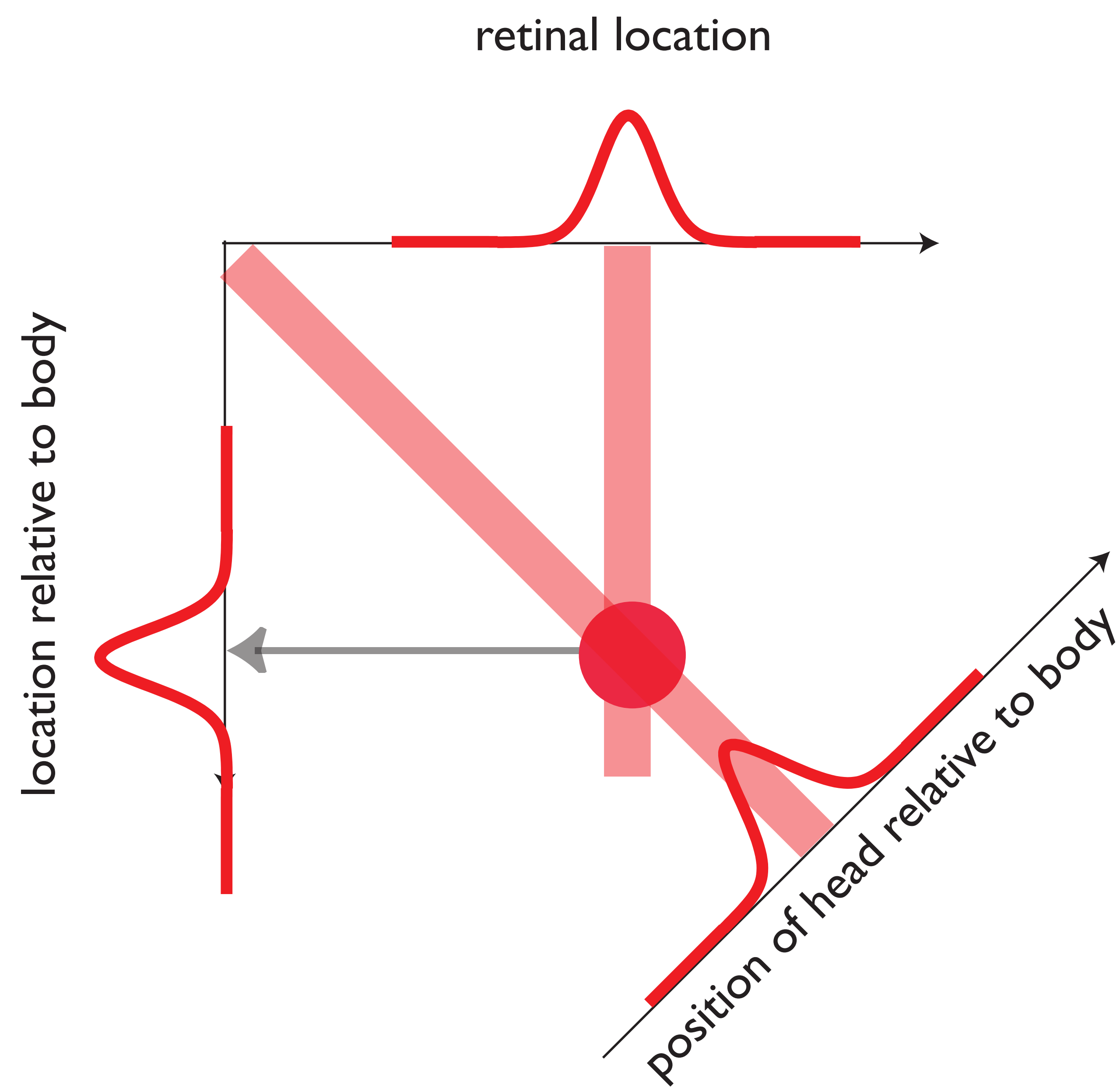
# functional significance: coordinate transformations

- e.g., transform visual target from retinal representation to body-centered representation for reaching



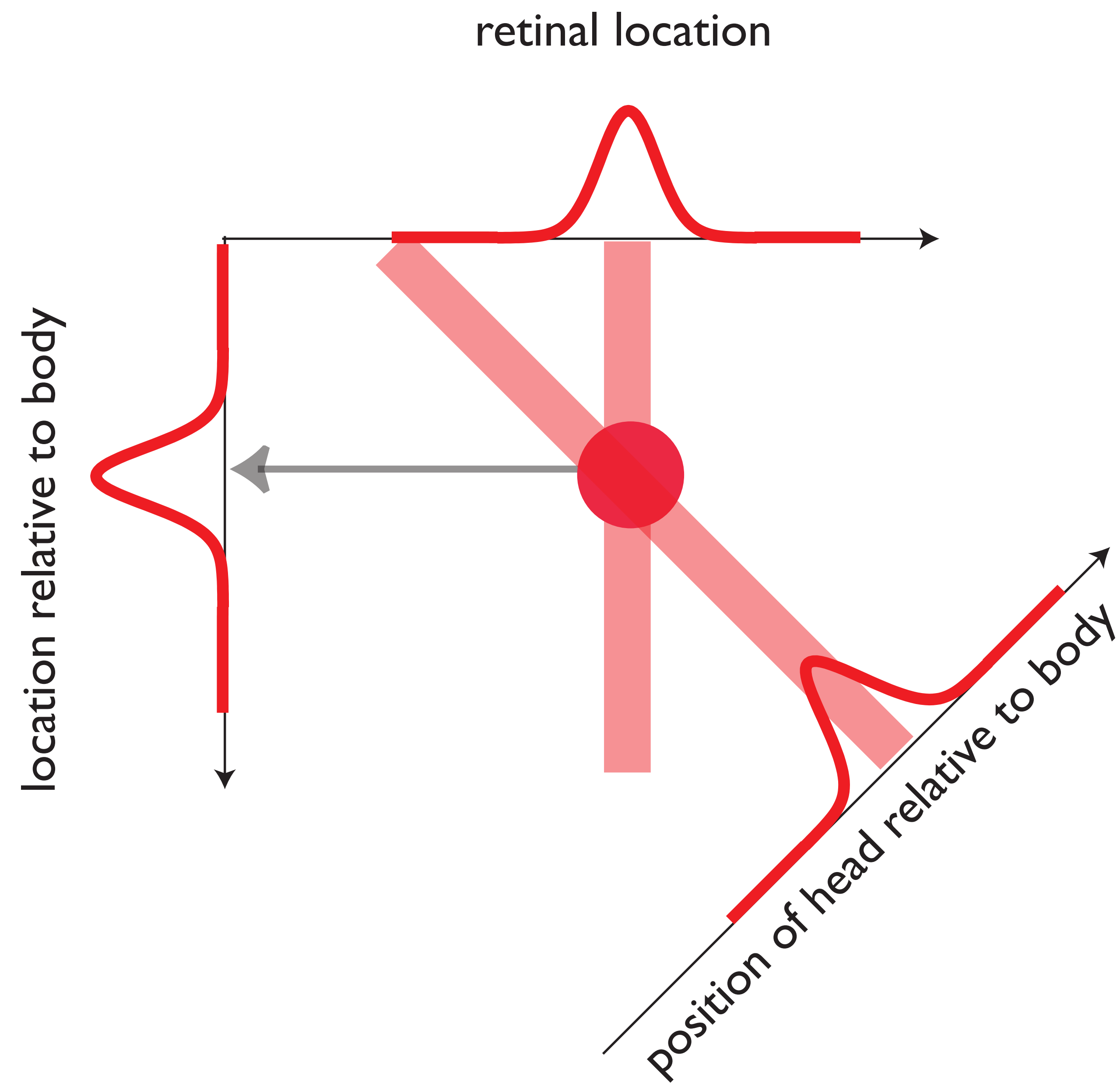
# coordinate transformations

- 2D field enables representation of associated retinal location and head position
- => project to extract body related location



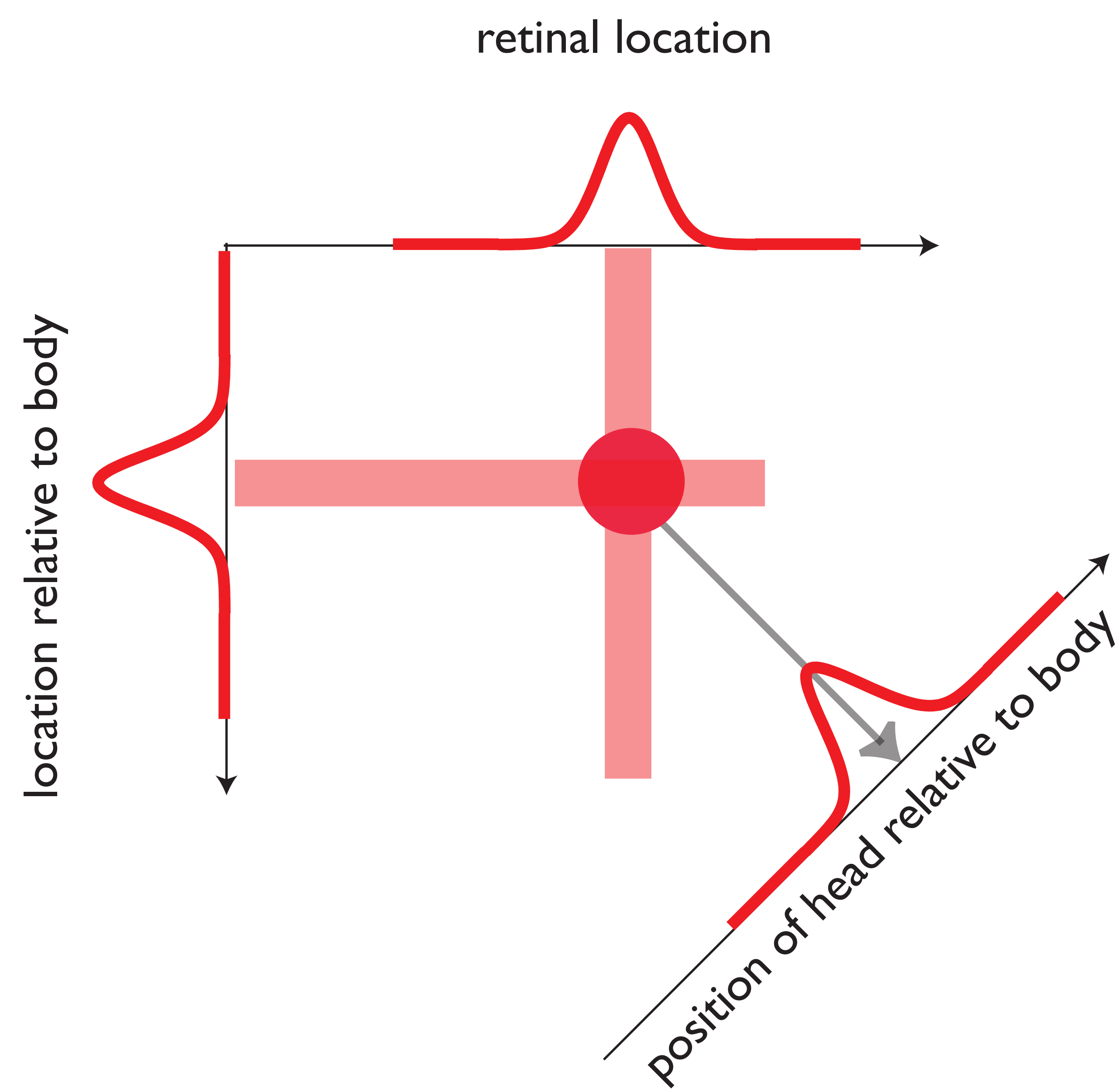
# coordinate transformations

- peak in body relative coordinates tracks changes of head position



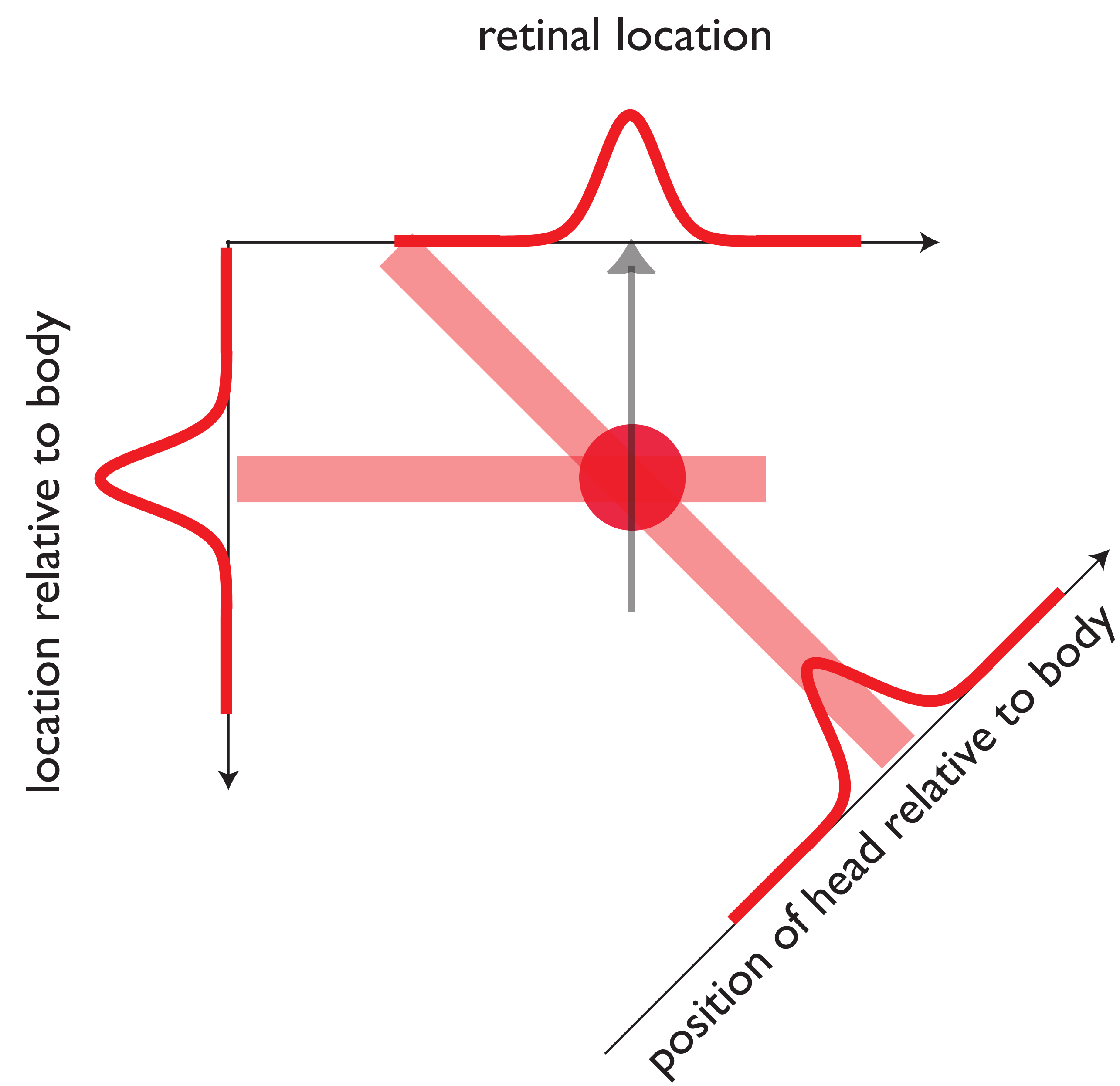
# coordinate transformations

- use same 2D field to reciprocally estimate head position from retinal position and position relative to body (e.g., while holding object in hand)



# coordinate transformations

- or predict retinal position from location of object relative to body and head position

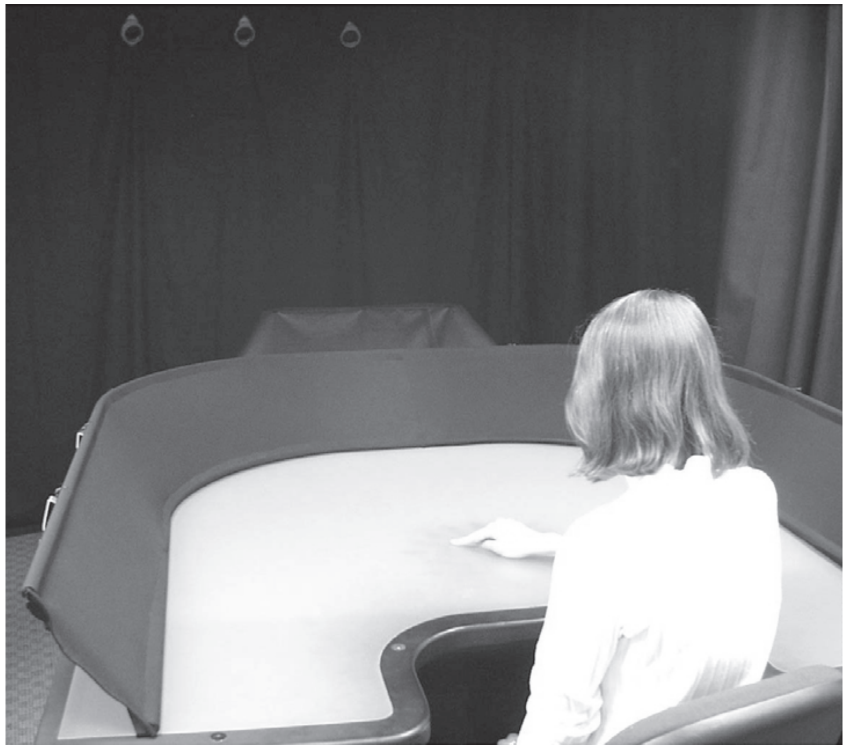


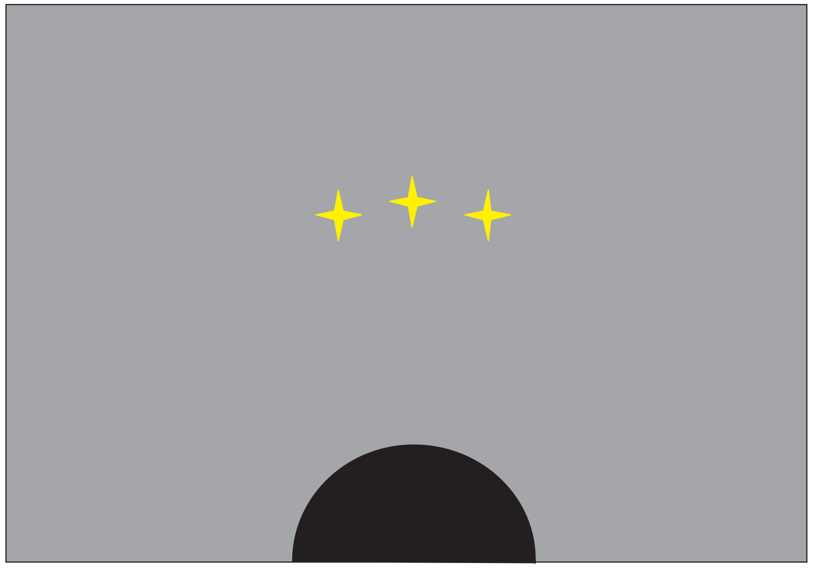

=> ongoing research project Sebasian Schneegans

# (3) What kind of embodied cognition emerges from DFT?

# DFT of spatial memory

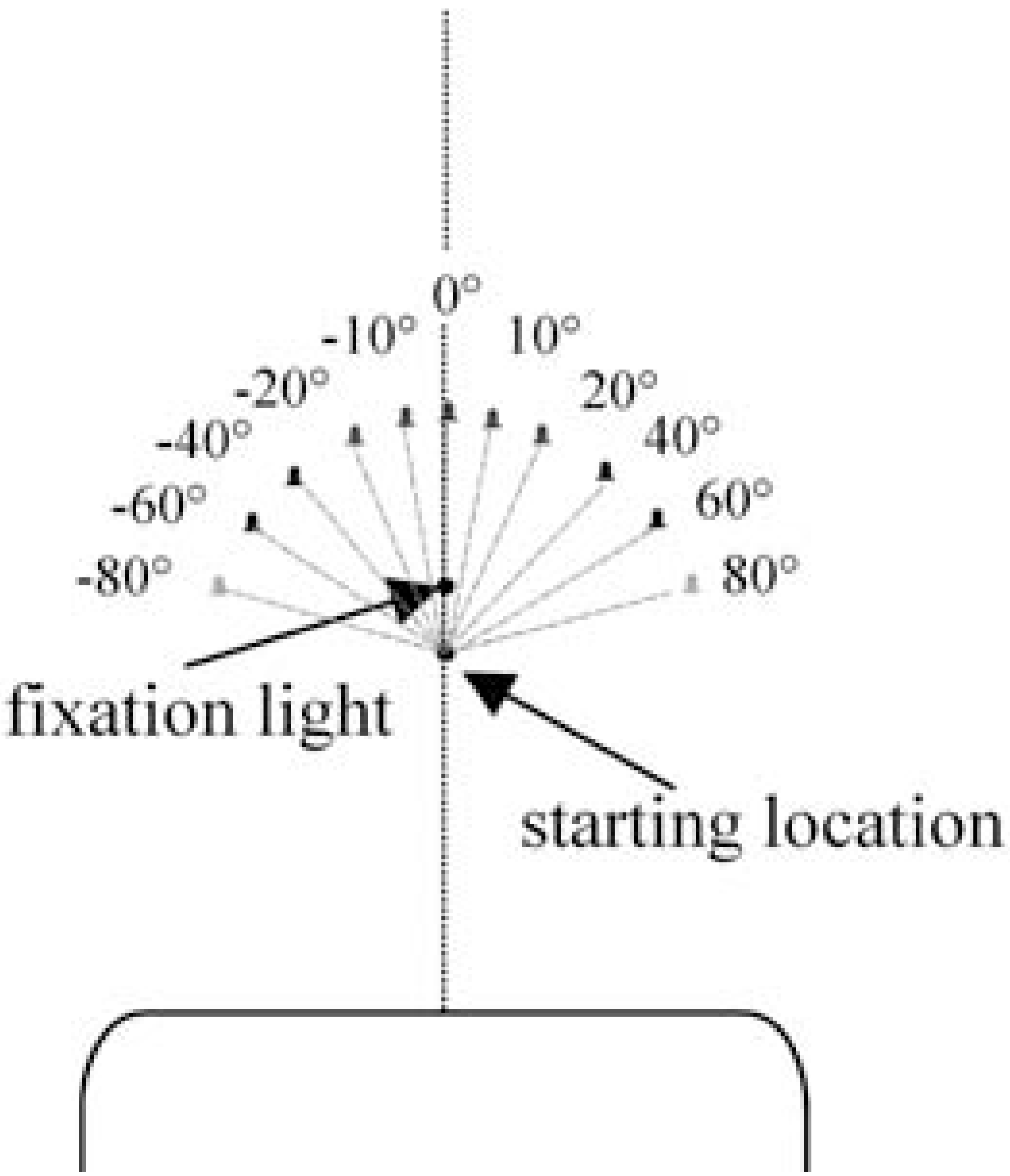
- space ship task of John Spencer lab





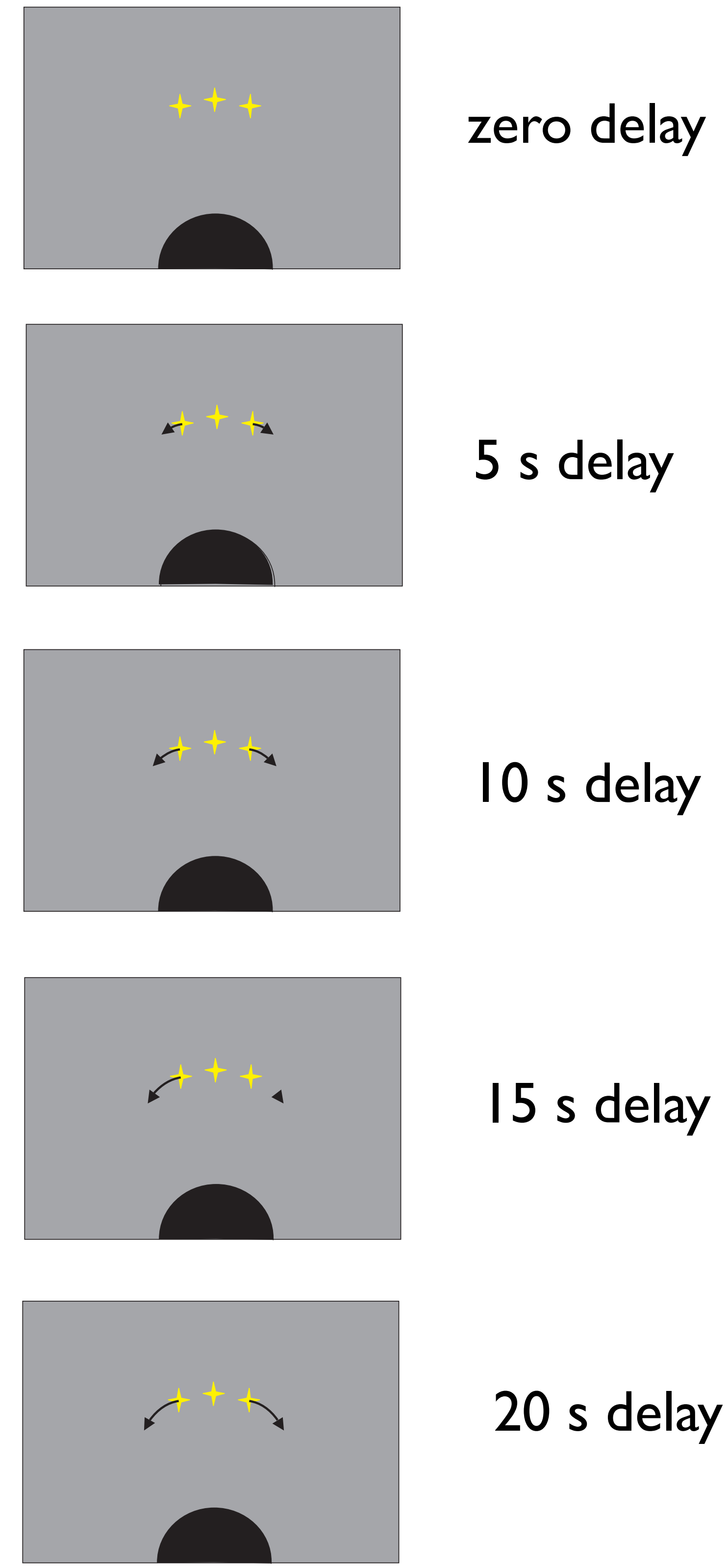
# spatial memory

- repulsion from perceptual boundaries, e.g., midline



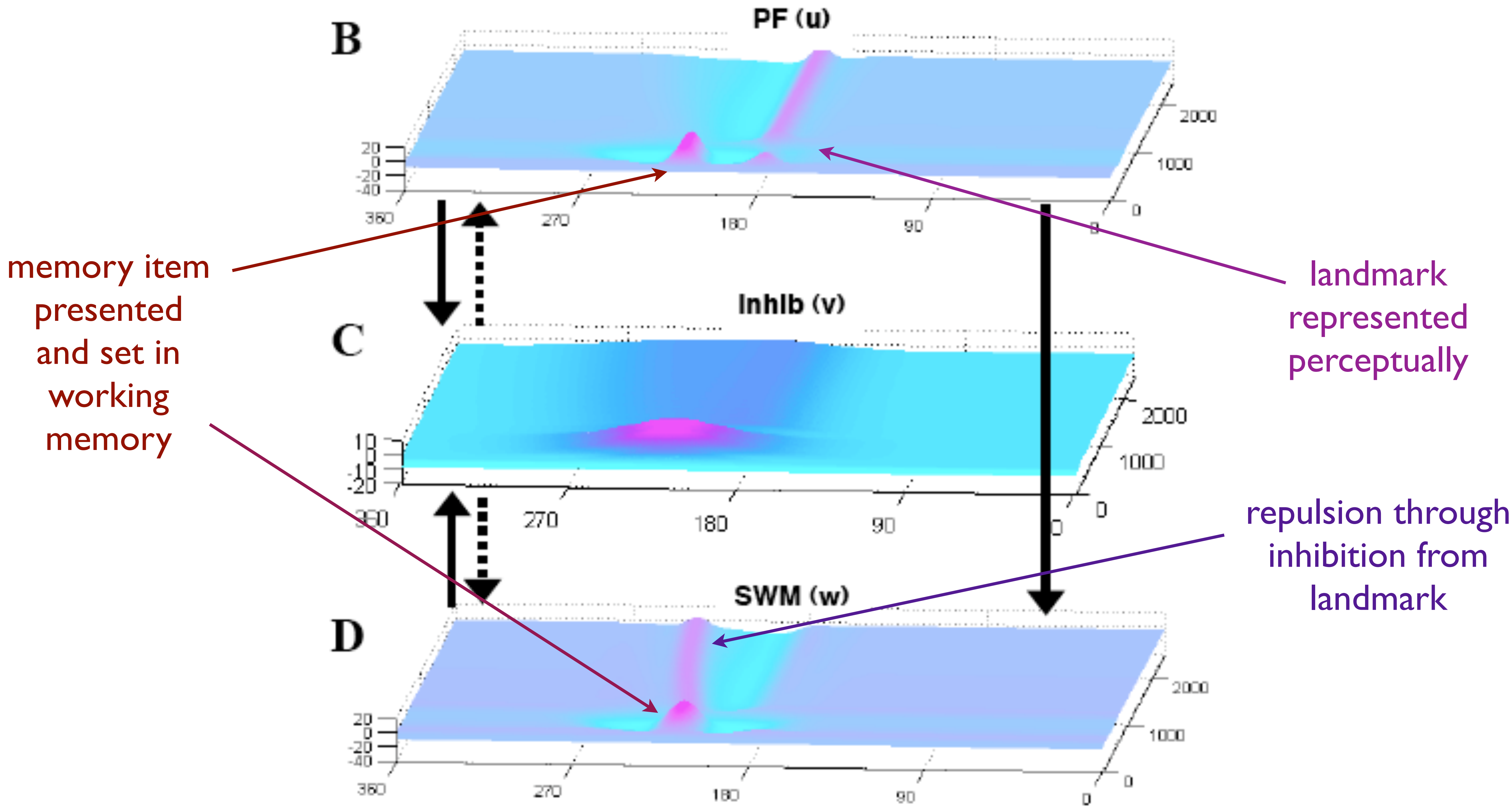

Spencer, Hund, Cog. Psych. (2003)

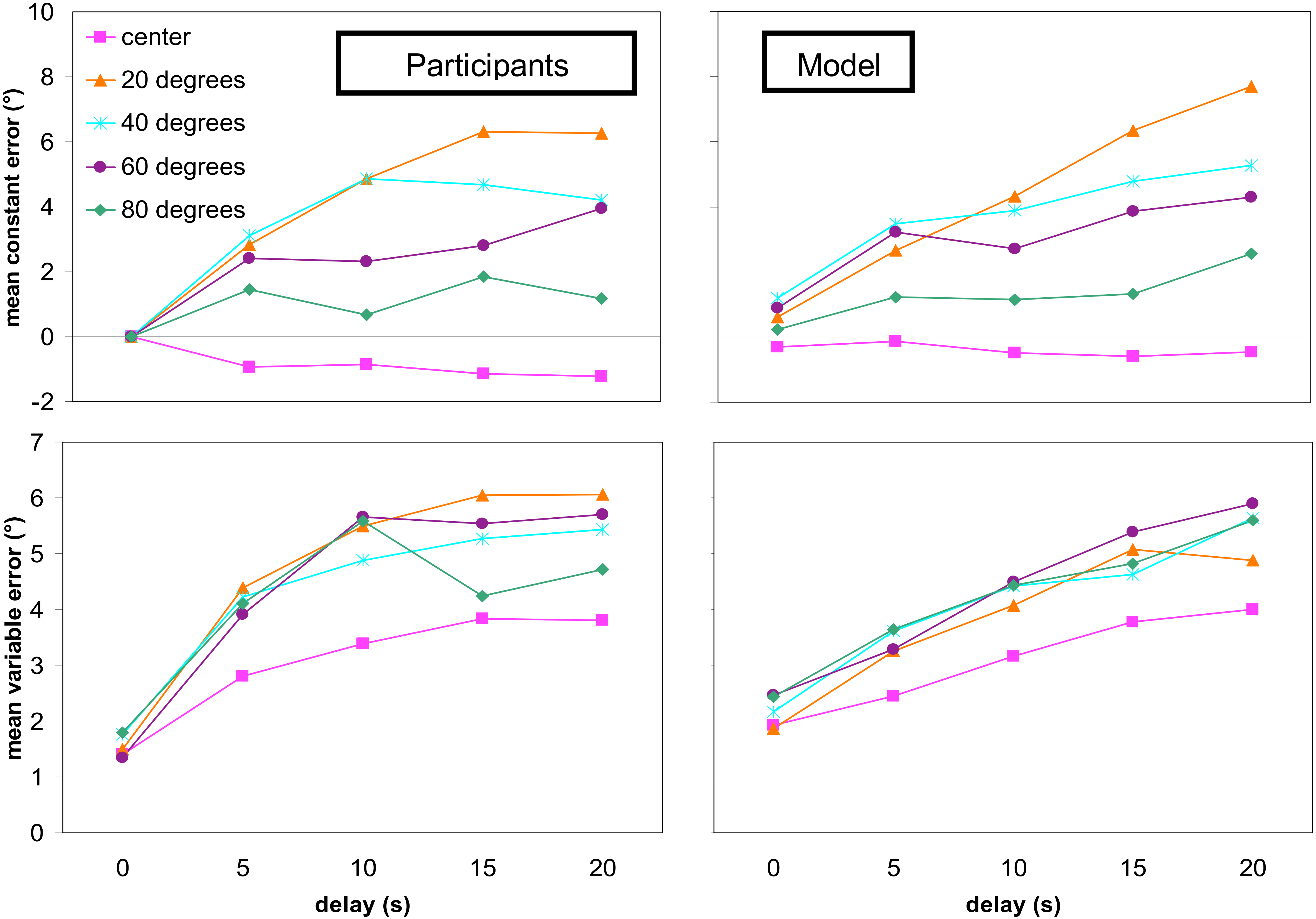
Results 6 years olds




Spencer, Hund, JEP:G (2002)

# Landmarks repel working memory

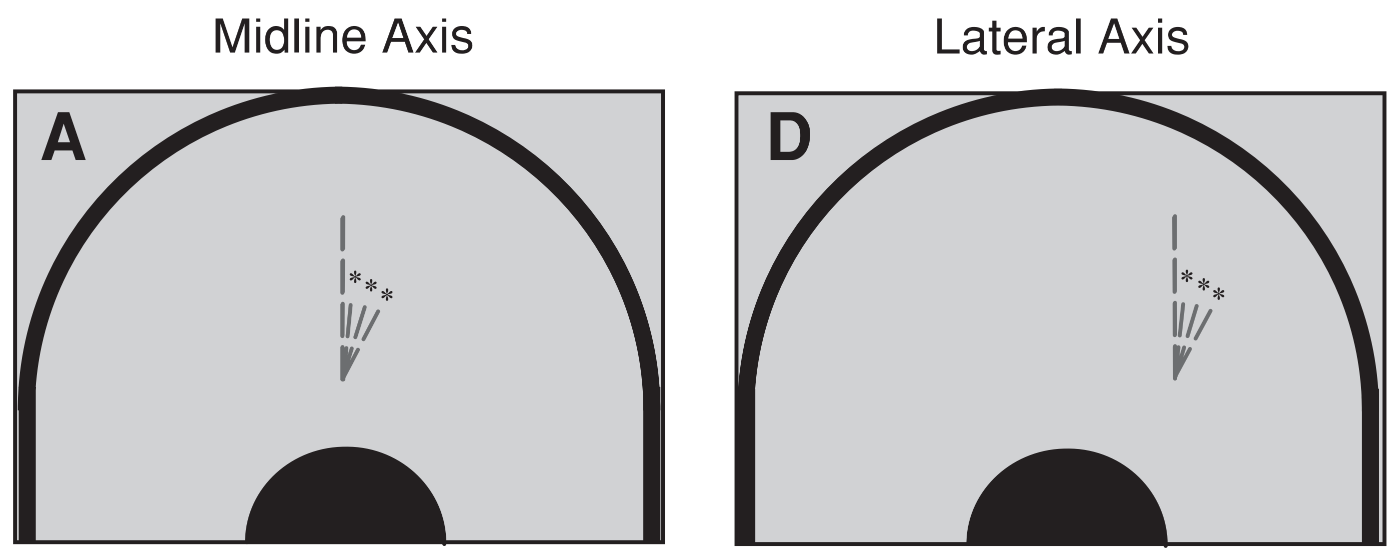


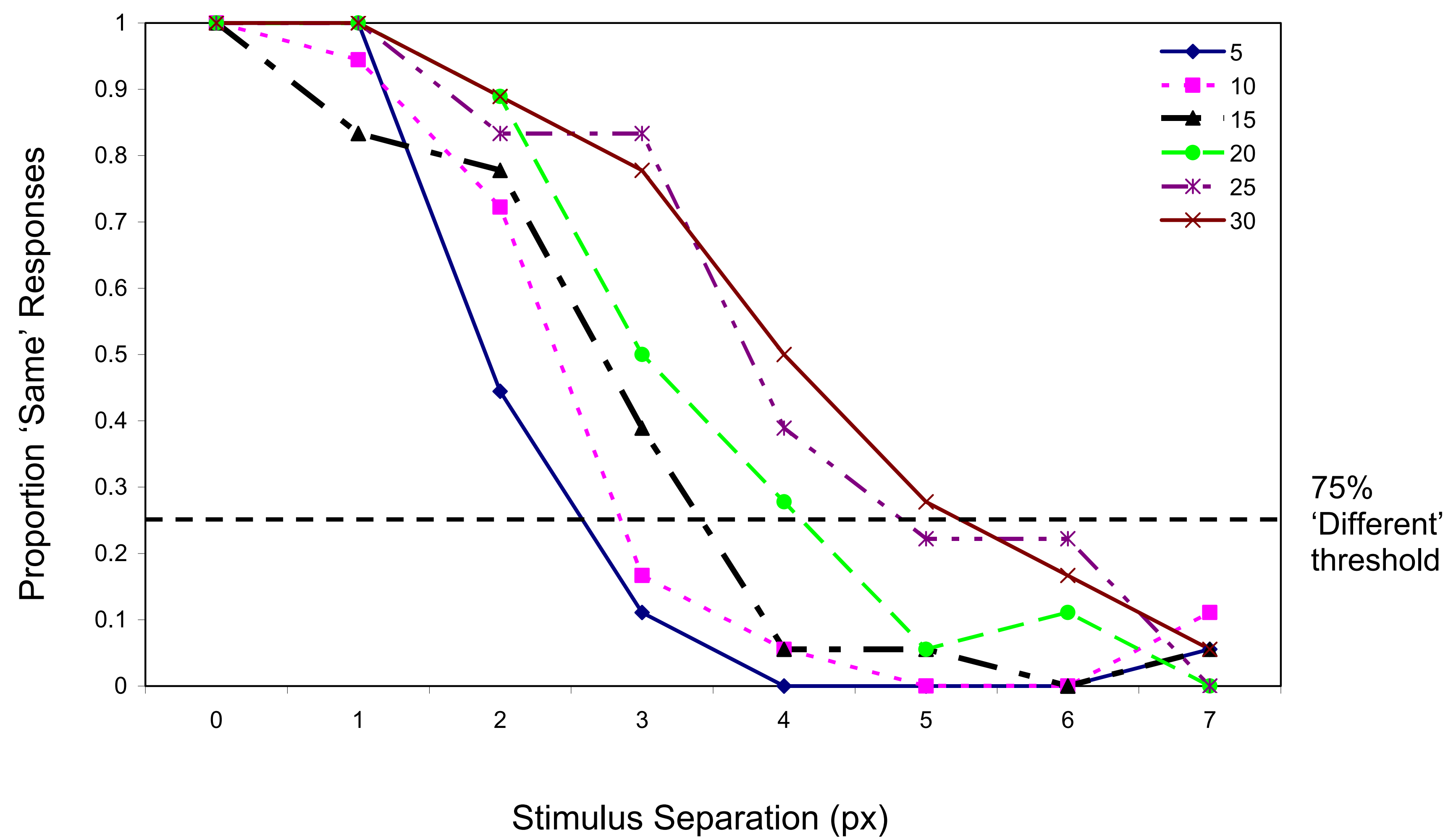



Spencer, Schöner, Cog. Sci. 2006

# change detection in space

- = spatial discrimination
- first non-trivial prediction: discrimination is improved near perceptual boundaries

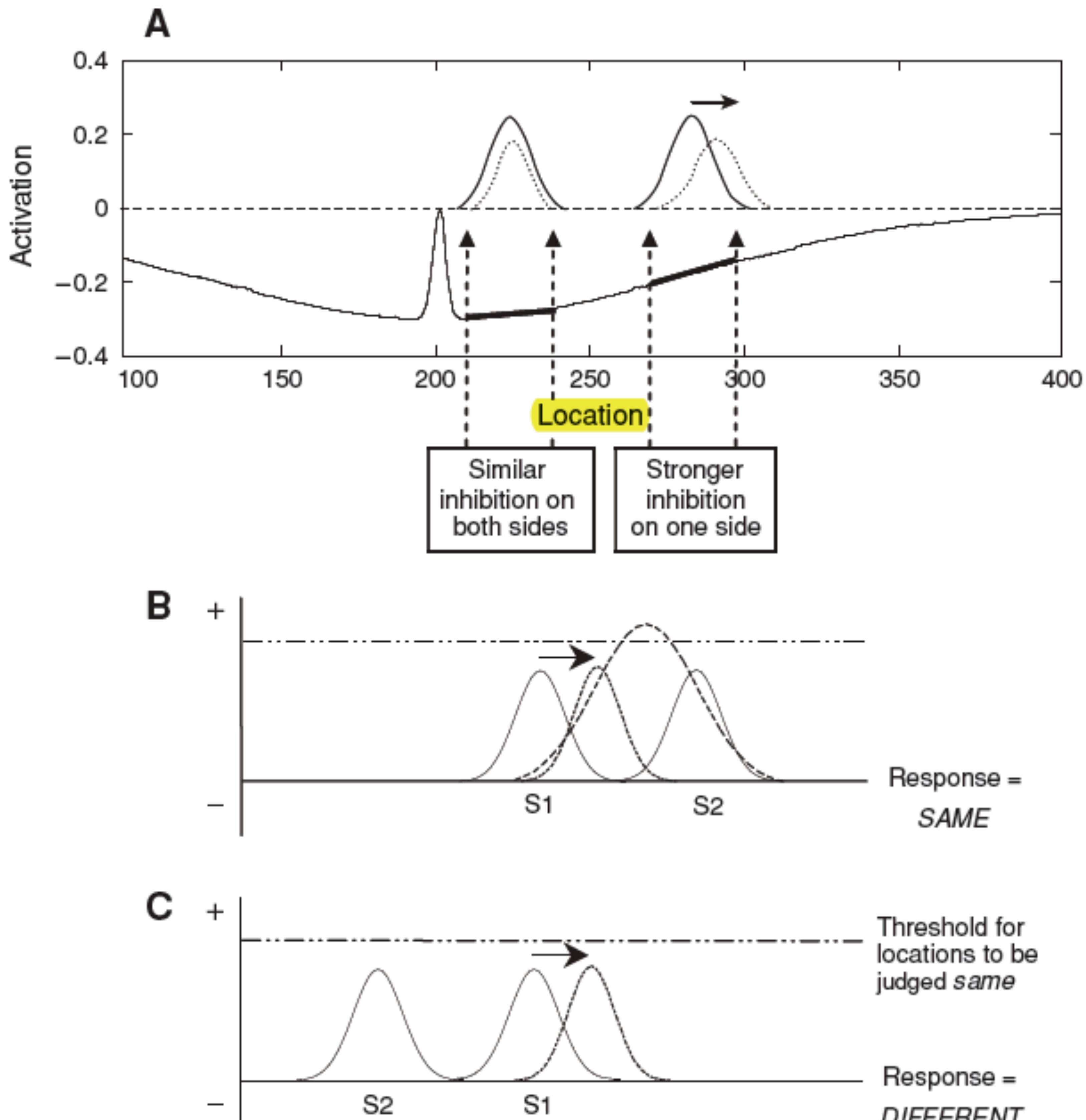



Simmering, Spencer, Schöner: Perc & Psychophysics (2006)

# change detection in space

- combine drift of working memory and change detection: predict interaction with presentation order

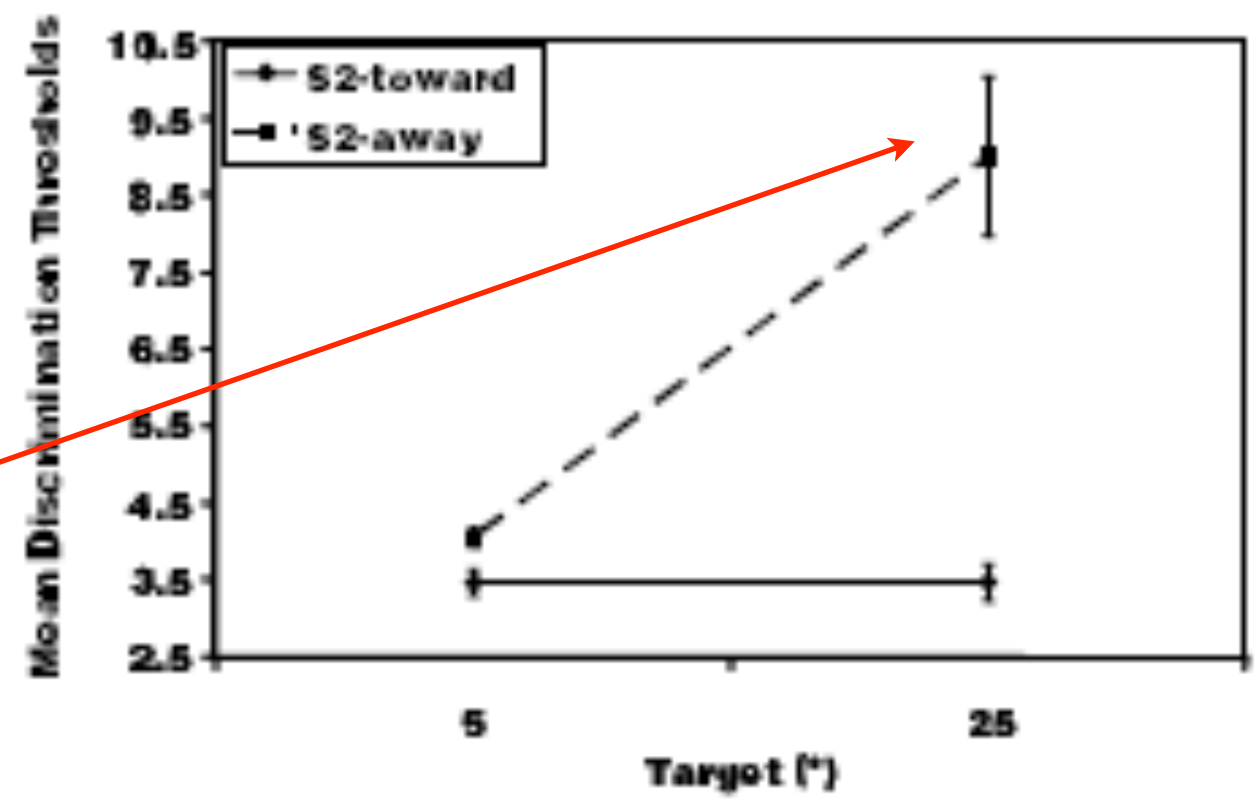



Simmering, Spencer, Schöner: Perc & Psychophysics (2006)

# Change detection: space

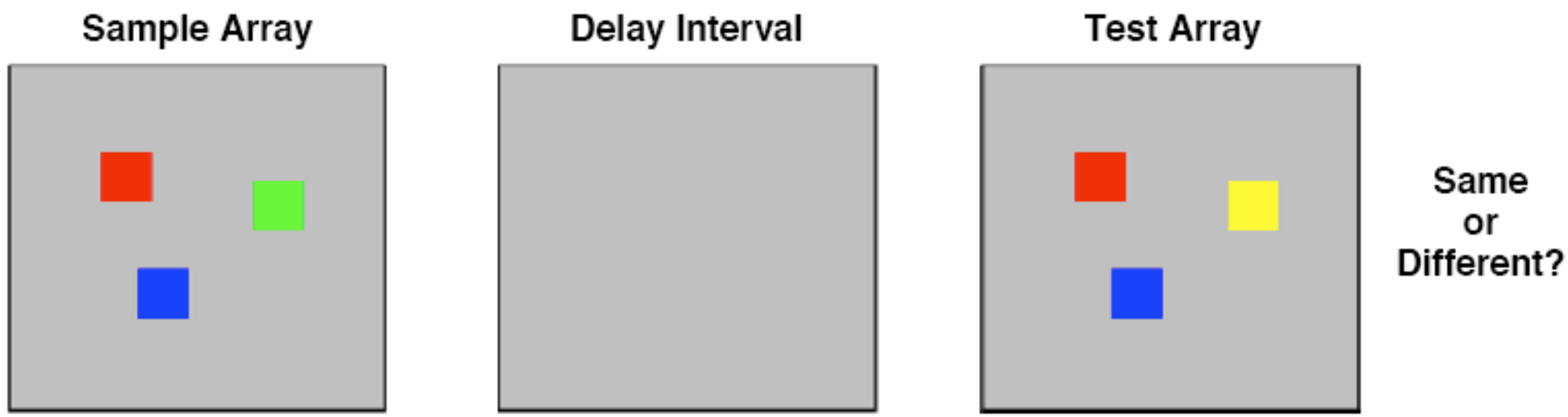
- confirmed experimentally

in the presence of drift (that is, at 25 deg), discrimination is worse when the second stimulus is presented away from the landmark



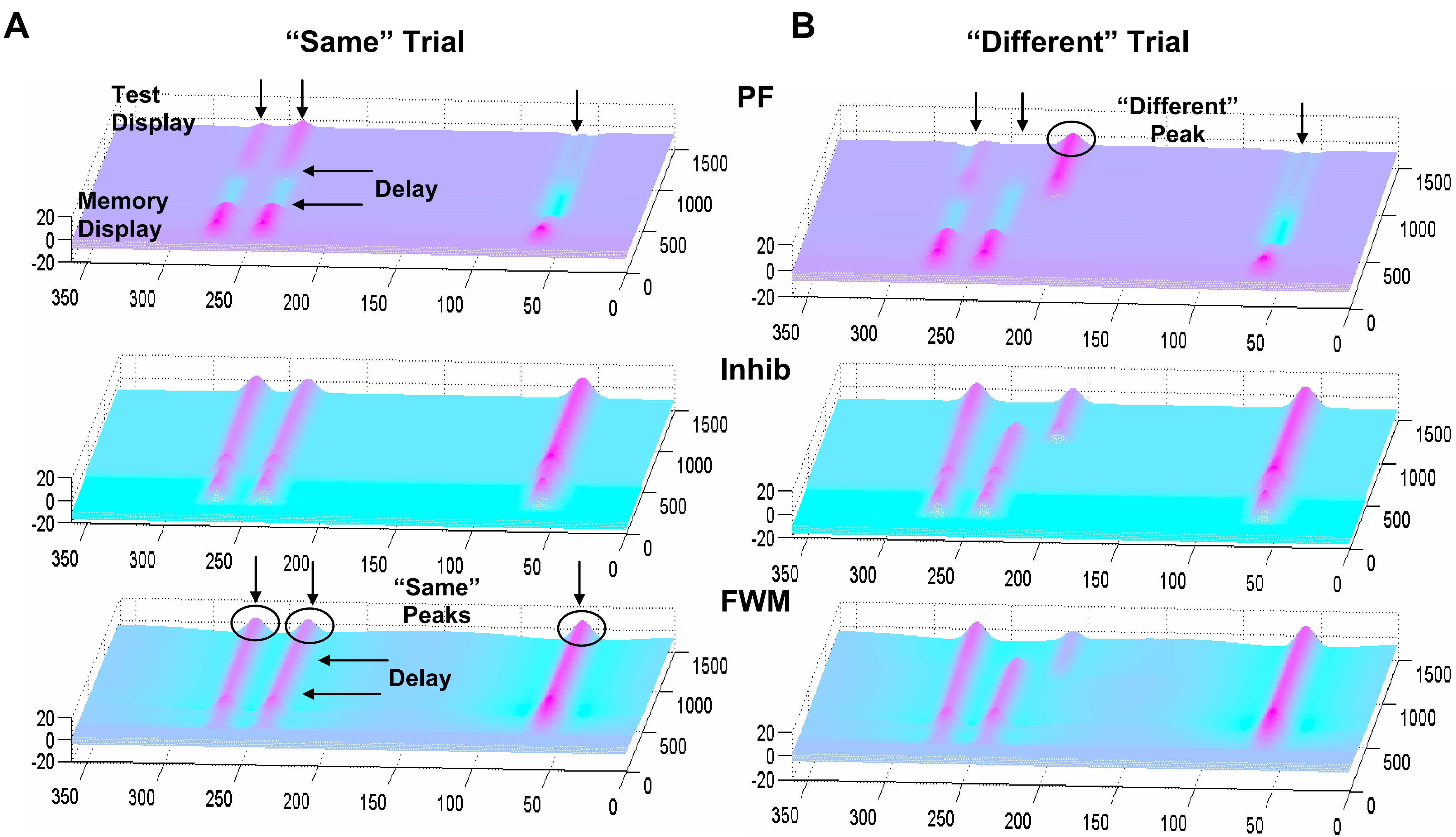

Simmering, Spencer, Schöner: Cognitive Science 2006

# change detection for color




Johnson, Spencer, Luck, Schöner, 2008

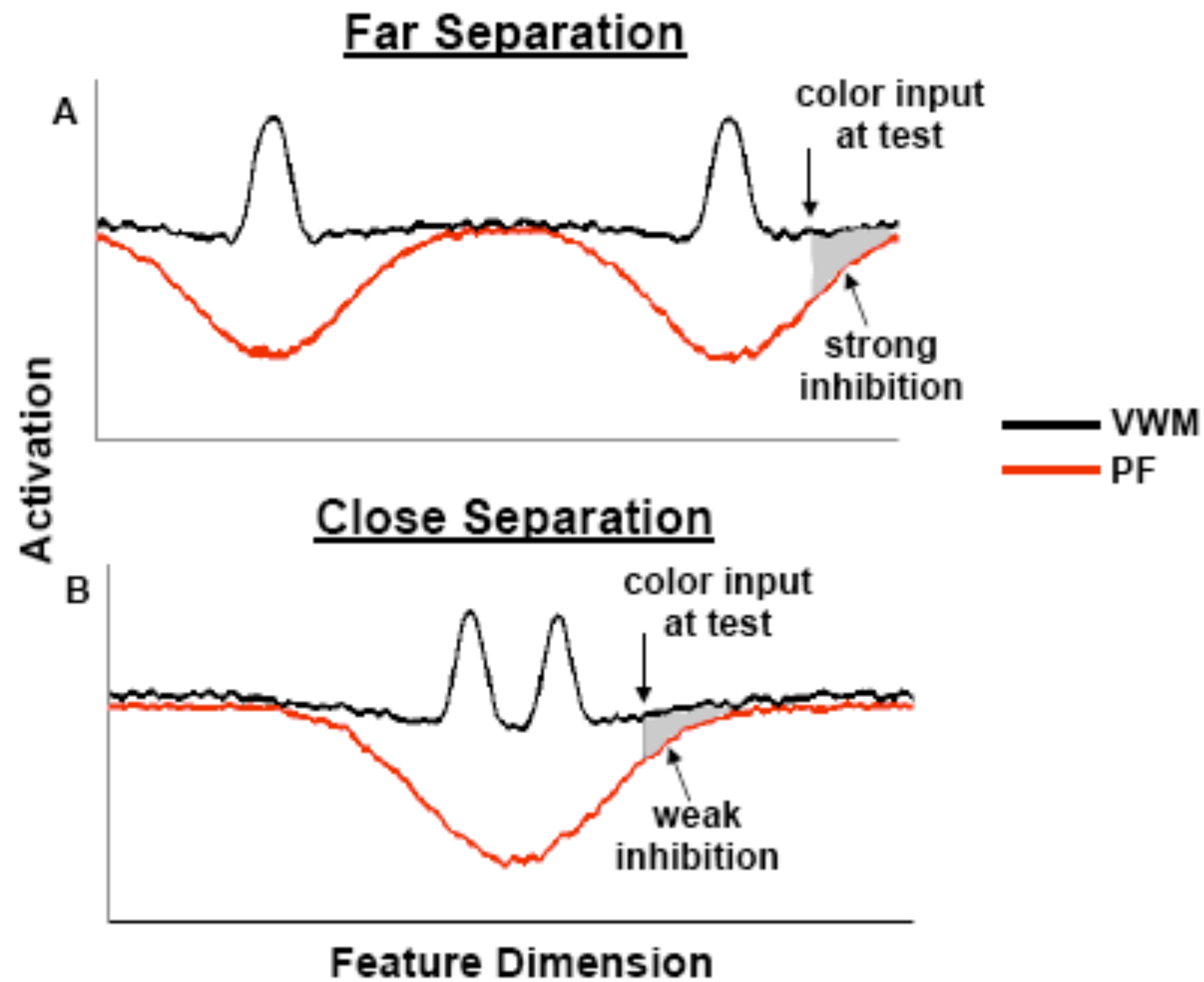
# DFT model of change detection




Johnson, Spencer, Schöner, 2007

# behavioral signatures of DFT

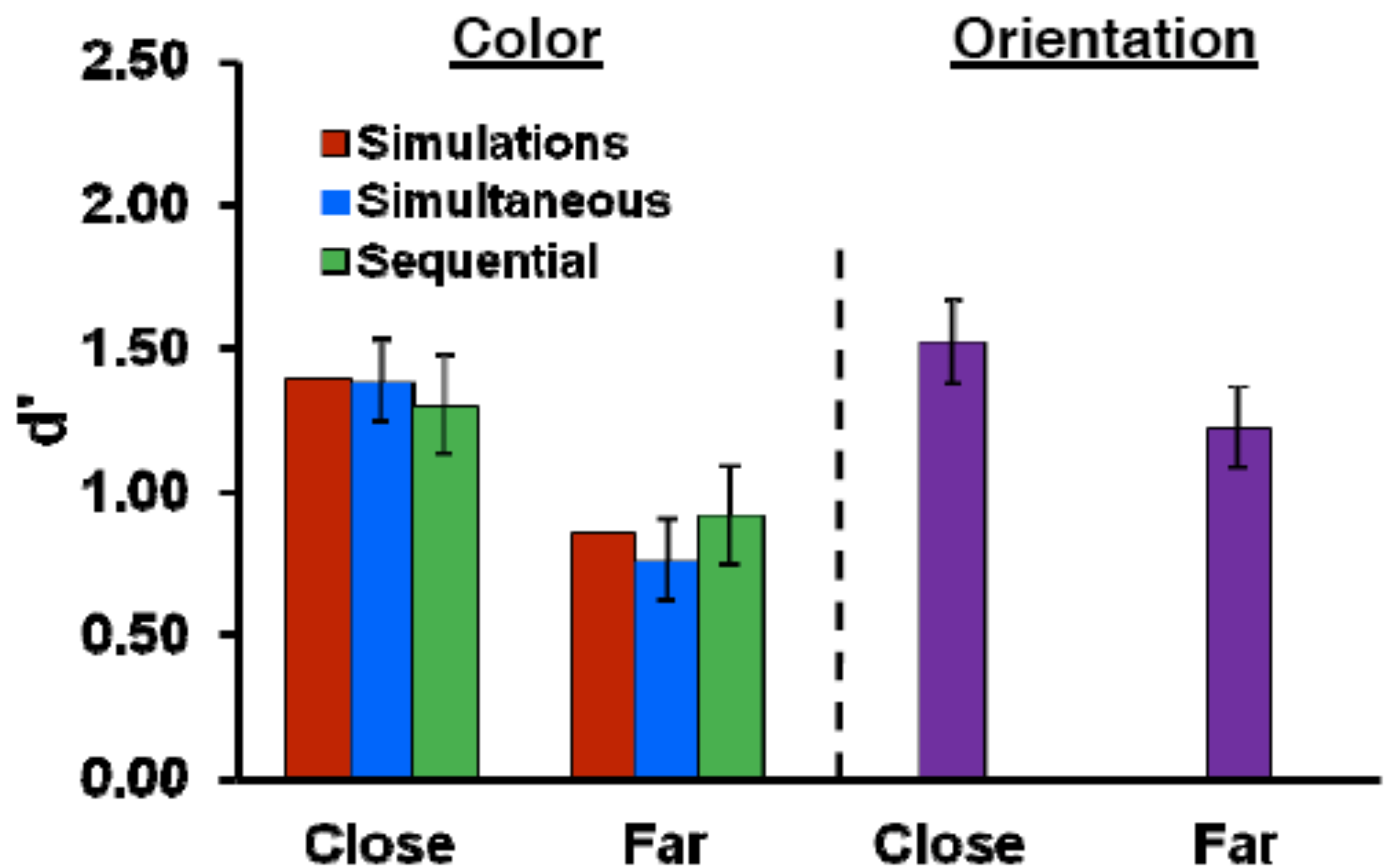
- at close metric separation, there is less inhibition in perceptual layer, leading to reduced threshold for change detection for metrically close items!




Johnson, Spencer, Luck, Schöner, 2008

# Experimental confirmation

- better change detection when items are metrically close!
- true also for orientation discrimination

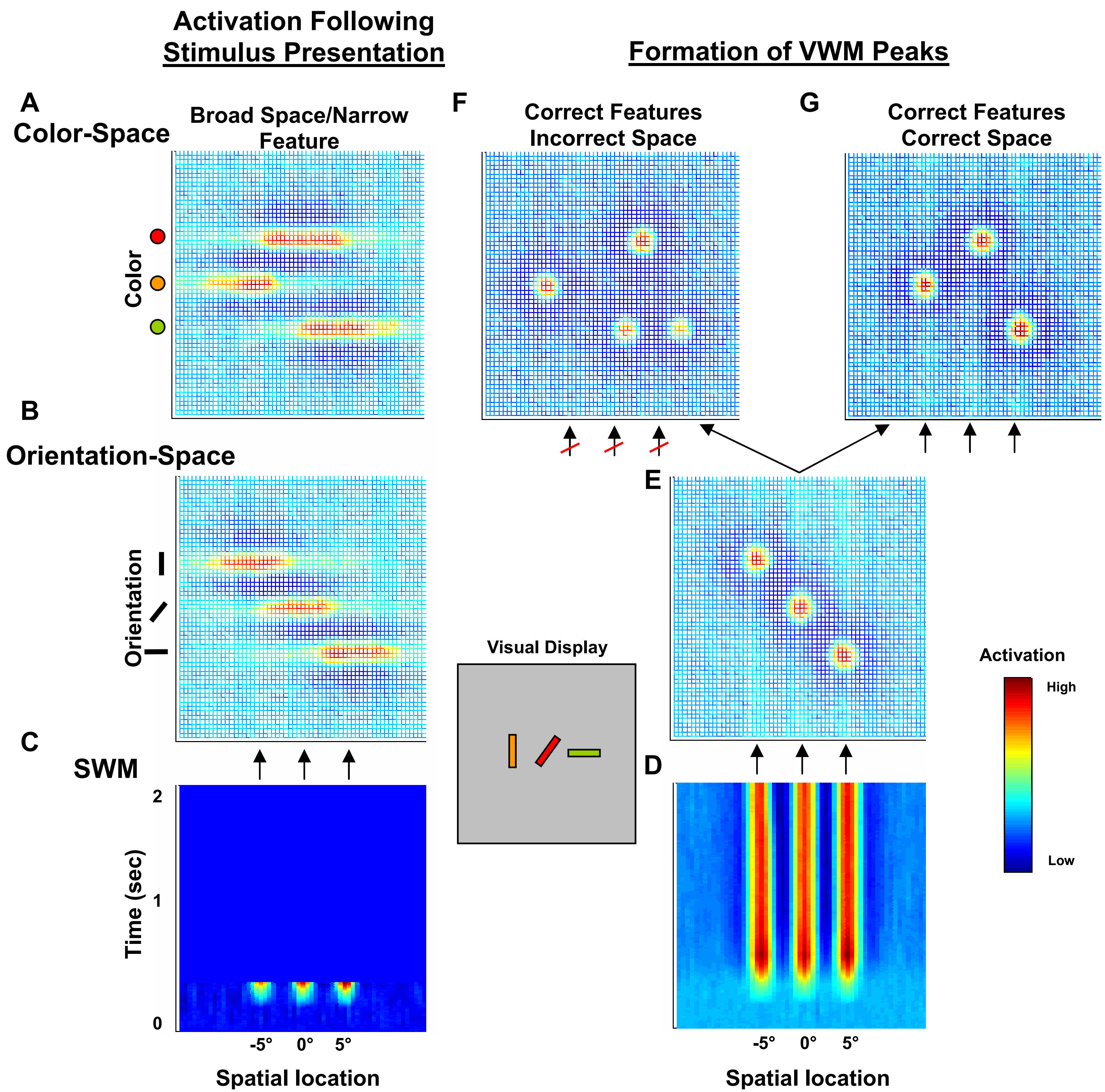



Johnson, Spencer, Luck, Schöner, 2008

# DFT account for feature binding

- use space as a way to link items (peaks) across different feature dimensions

# DFT of feature binding

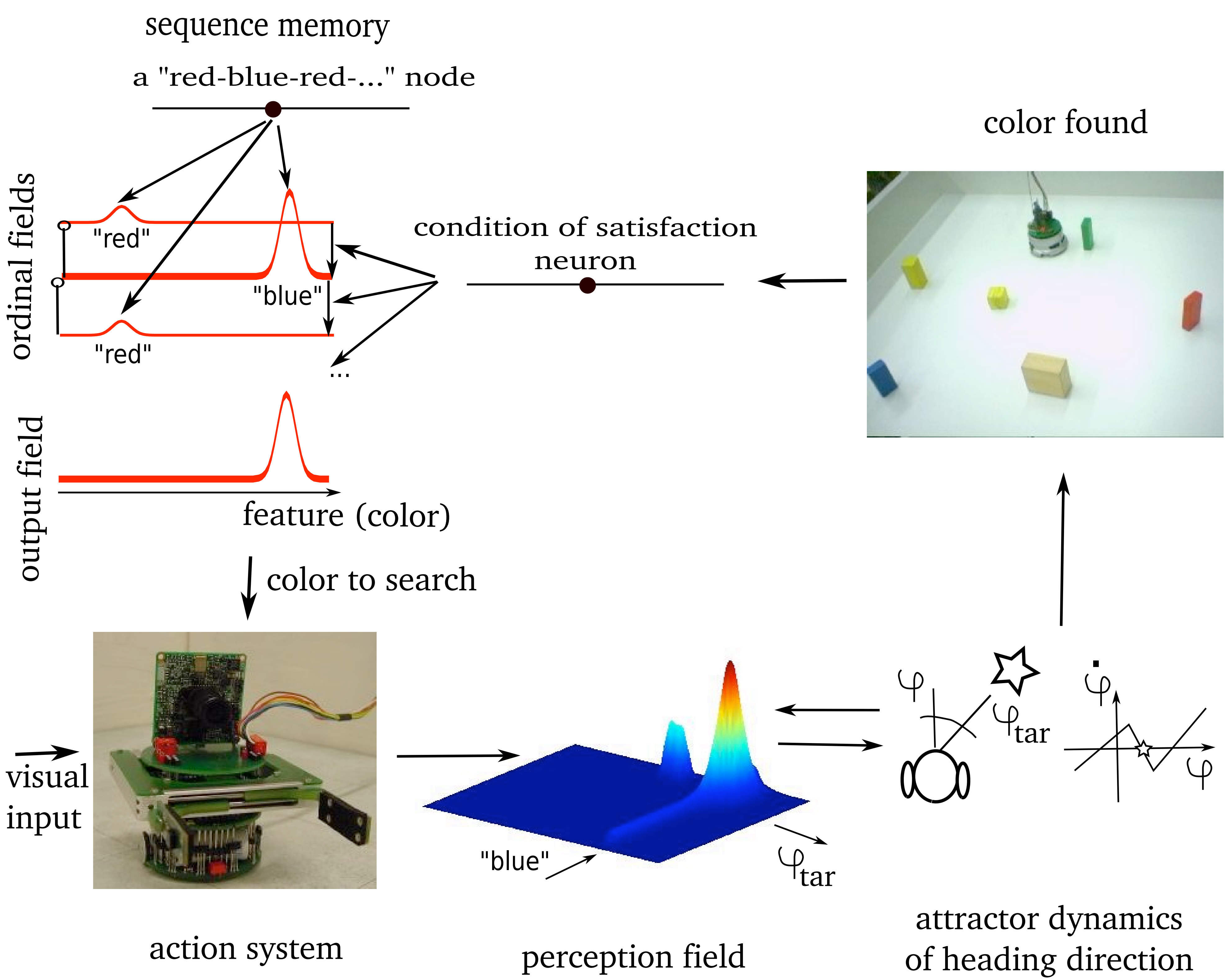



Johnson, Spencer, Schöner, 2007

# sequence generation

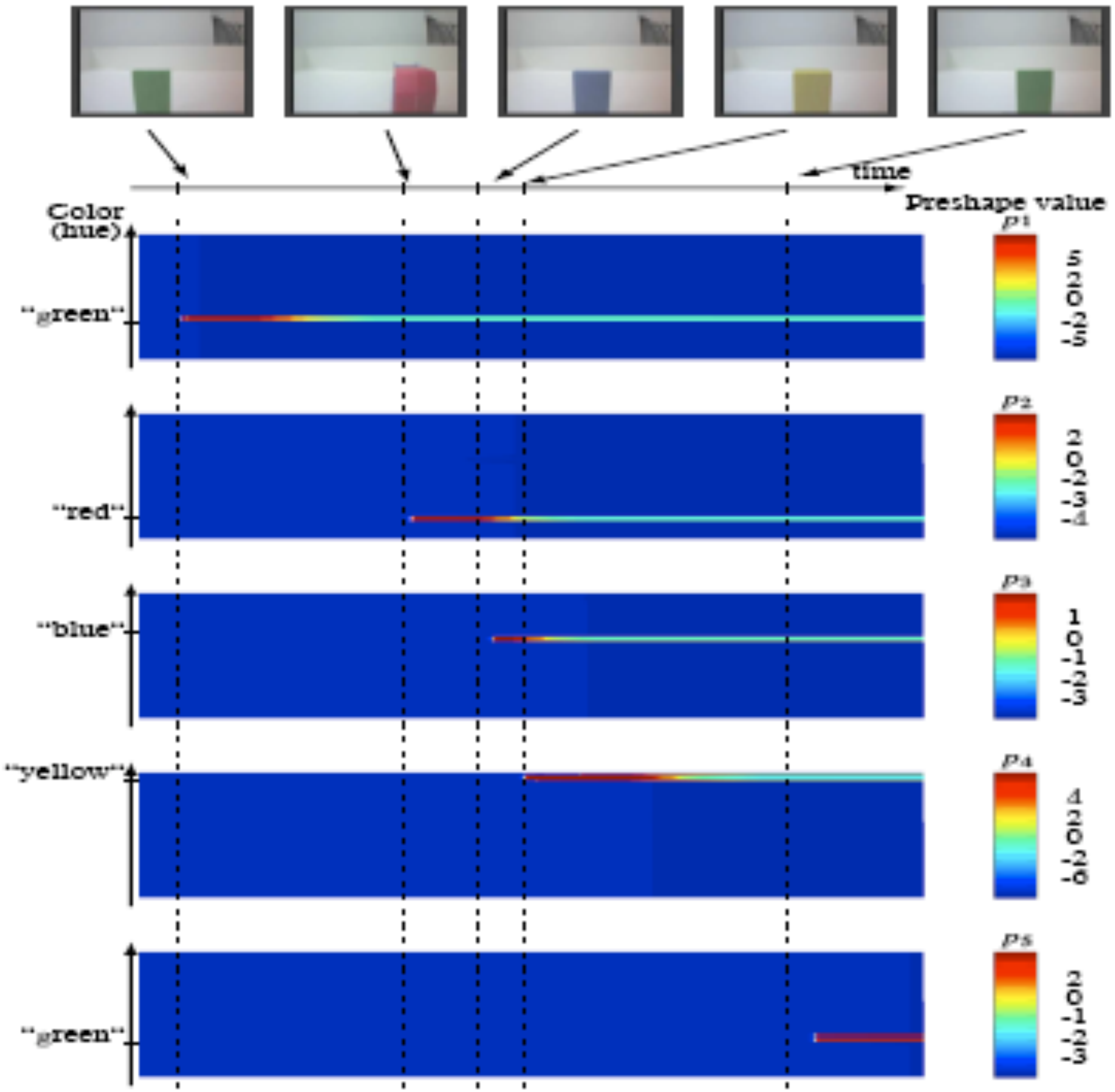
- exemplary sequence generation task: robot is shown a sequence of colors
- and must then search for objects of those colors in the order shown
- irrespective how long each step takes

# architecture



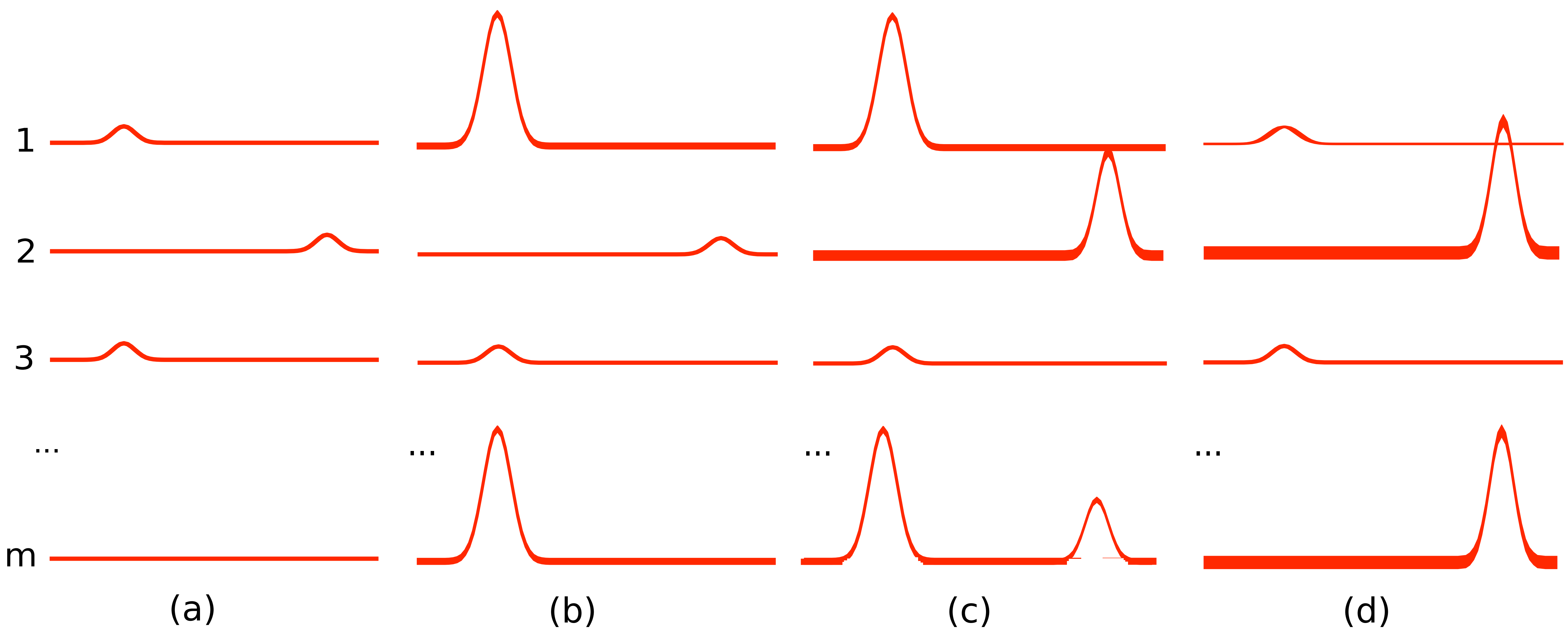

[Sandamirskaya, Schöner, 2008]

# teaching the sequence



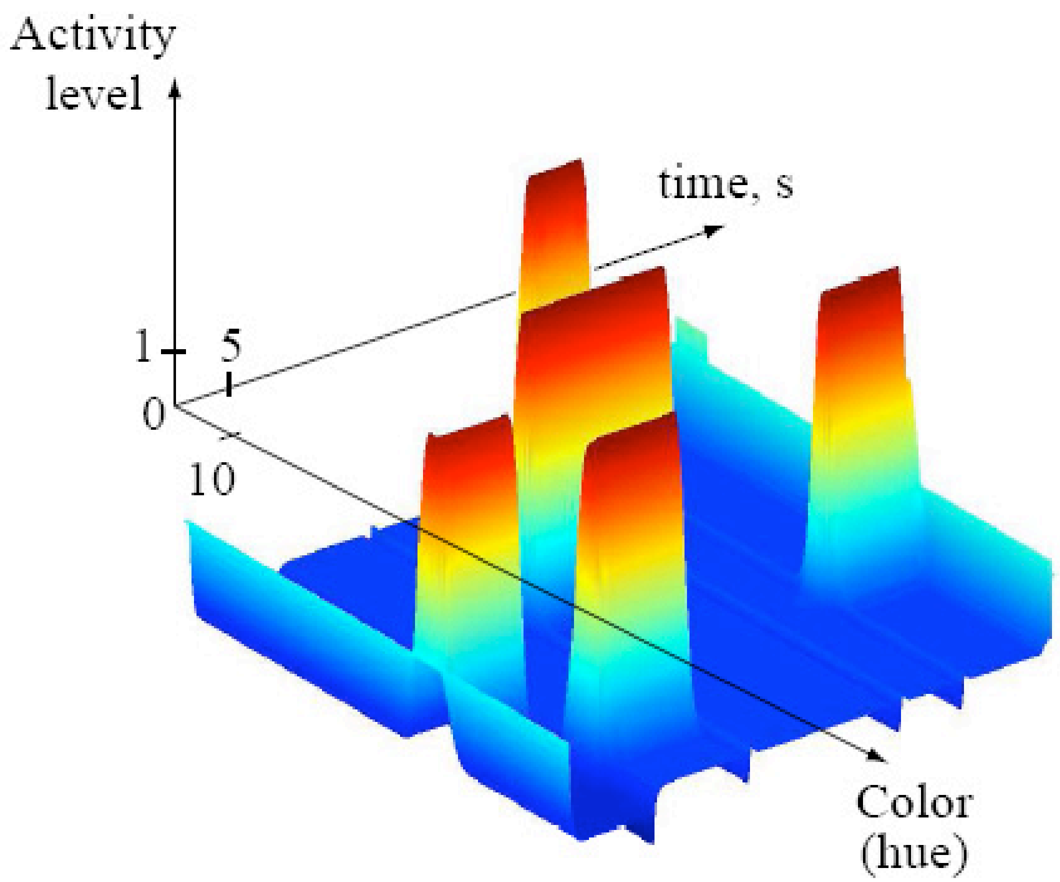

[Sandamirskaya, Schöner, 2008]

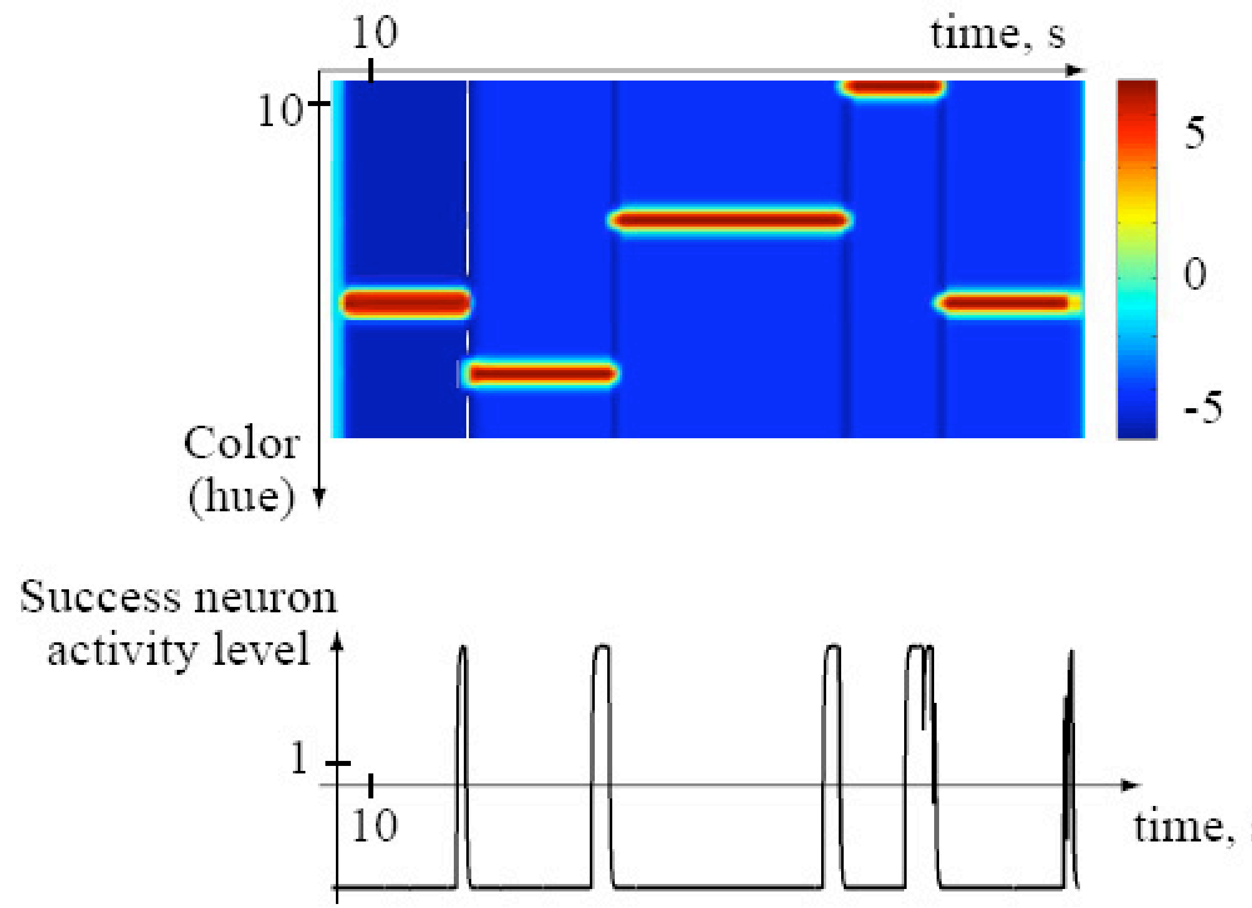
# discrete times at which sequence advances emerge from instabalities




[Sandamirskaya, Schöner, 2008]

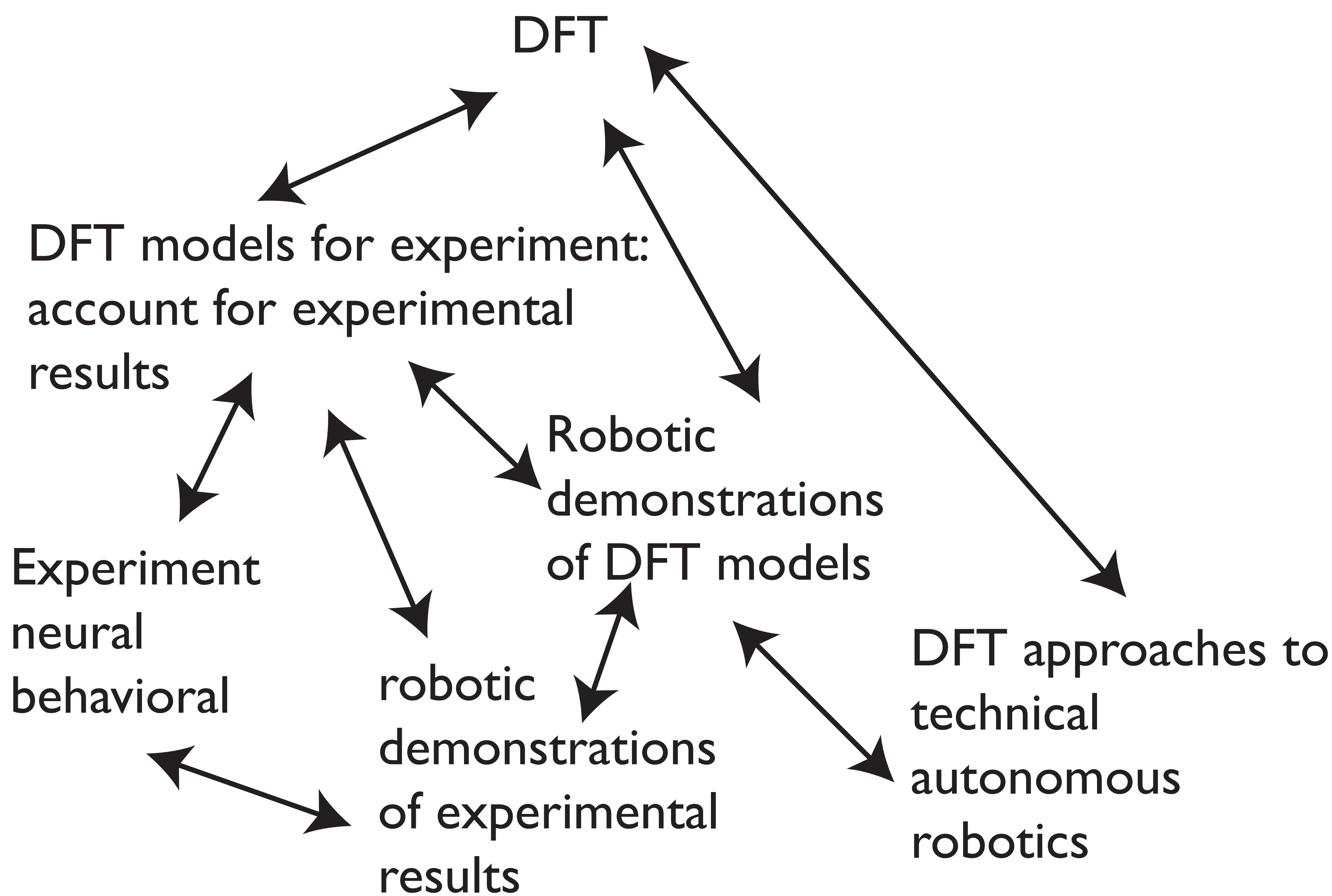
# result: generating a sequence that takes variable amounts of time




[Sandamirskaya, Schöner, 2008]

# different ways DFT can be used



# conclusion

- embodiment/situatedness program: moving toward higher cognition using DFT
  - linked to the sensory and motor surfaces, but not dominated by inputs
  - sensitive to structured environments and behavioral history through simple learning mechanisms