What is DFT?

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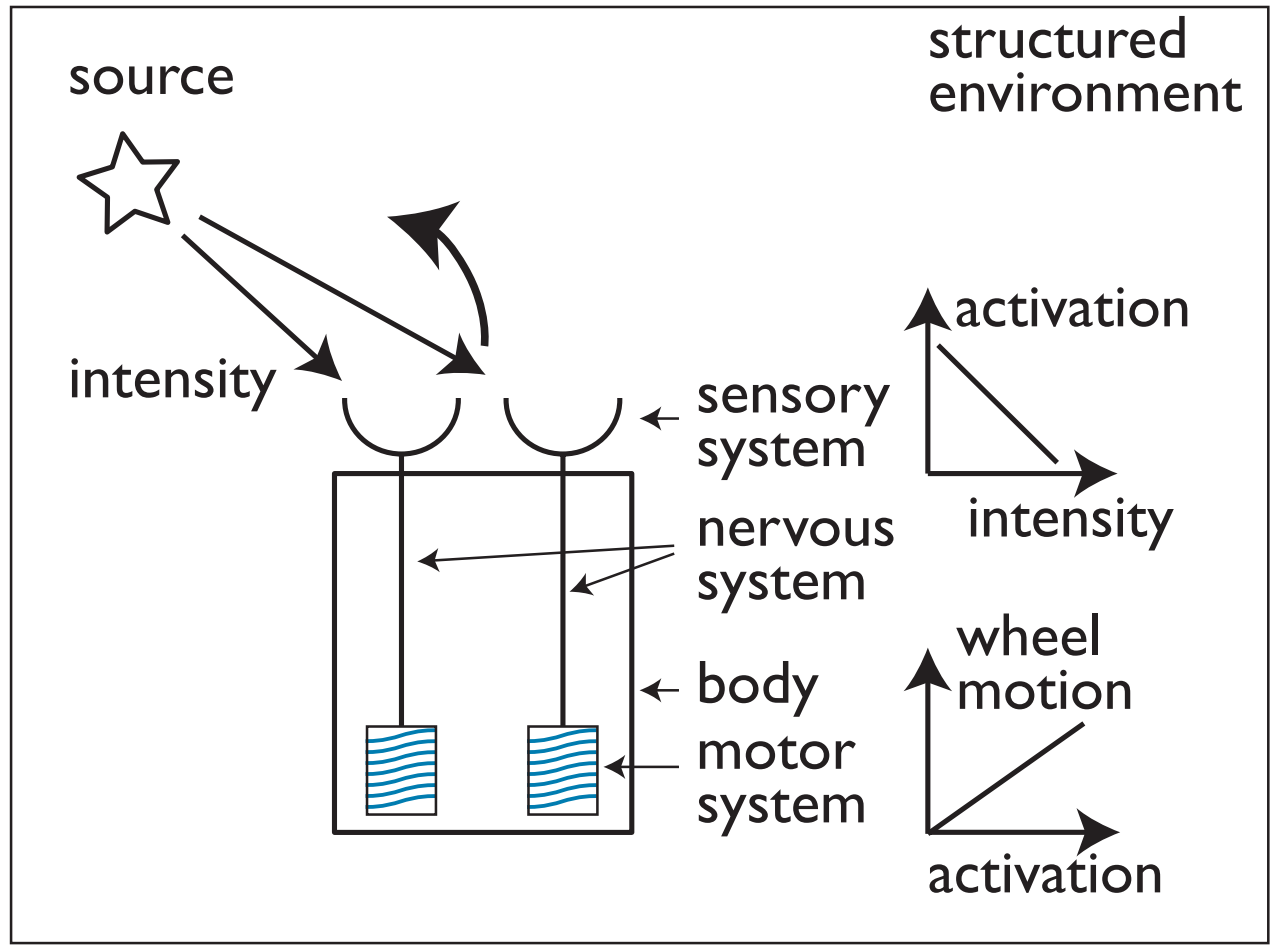
Theoretical commitment

- DFT is part of the grounded/embodied perspective on cognition…
- "thinking and acting are brought about by the embodied and situated brain that is shaped by evolution and development"
- this perspective this has important consequences for (neural) theory of cognition

Consequences for theory

- cognitive processes share properties with sensory-motor processes =>
- processes evolve continuously in time
- processes have continuous state
- processes may be coupled to sensory or motor systems
- processes may be in closed/recurrent loops
- => meaningful states have stability properties

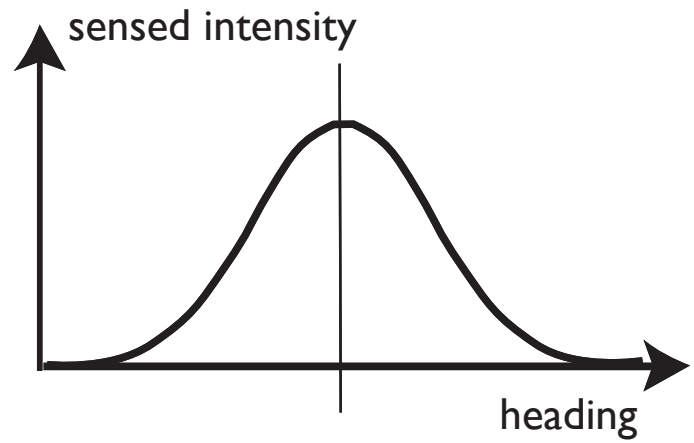
Stability ~ dynamical systems

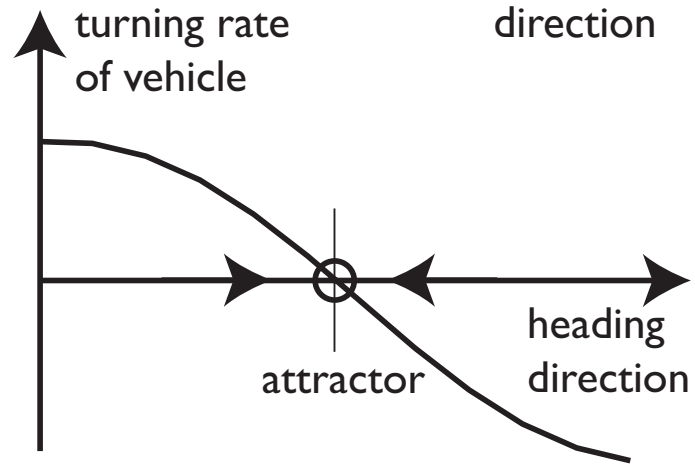


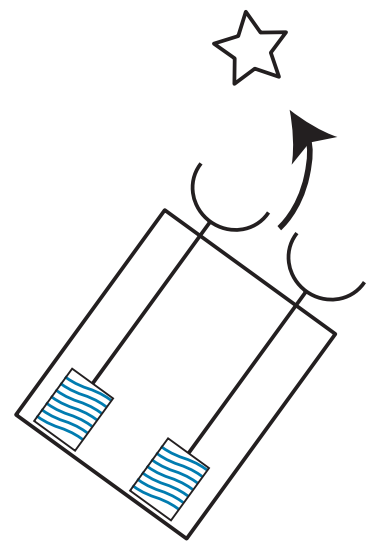
Braitenberg vehicle

Behavior emerges from a dynamical system

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

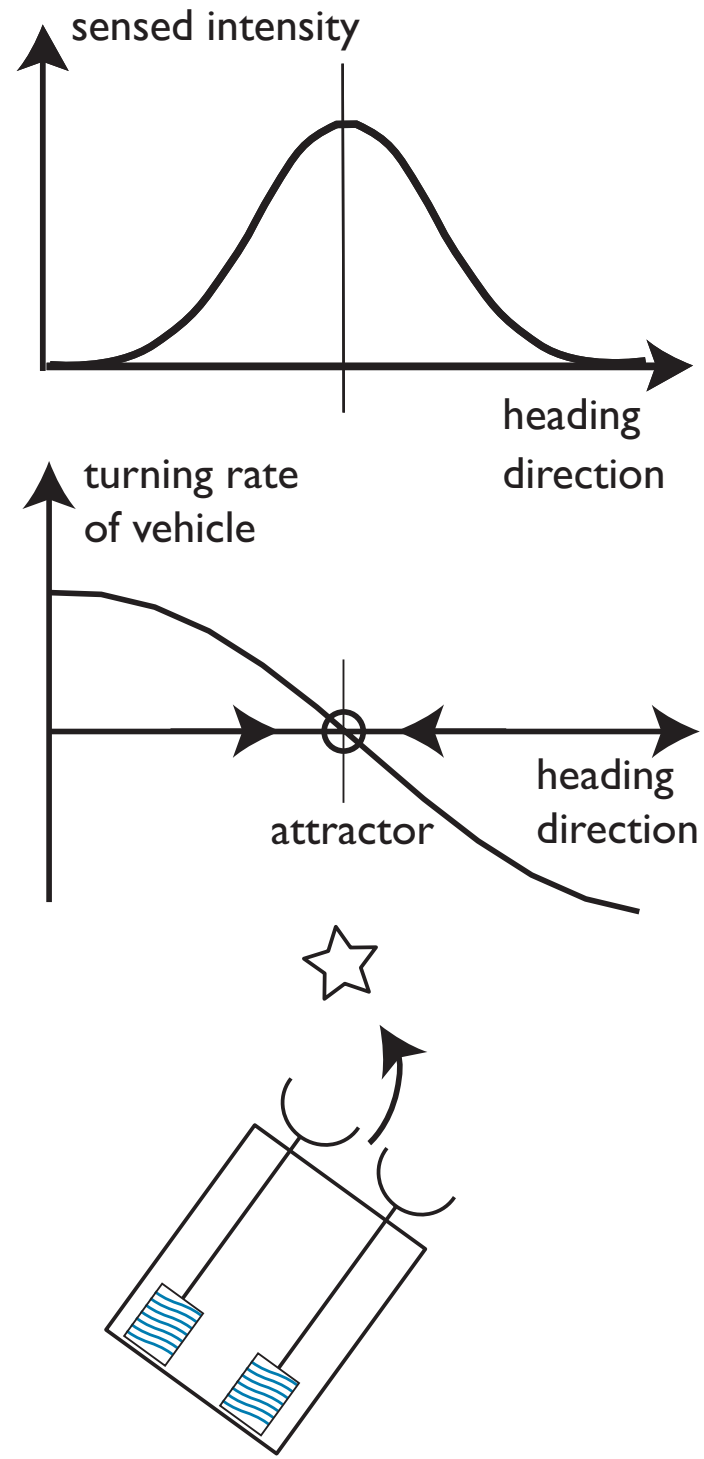






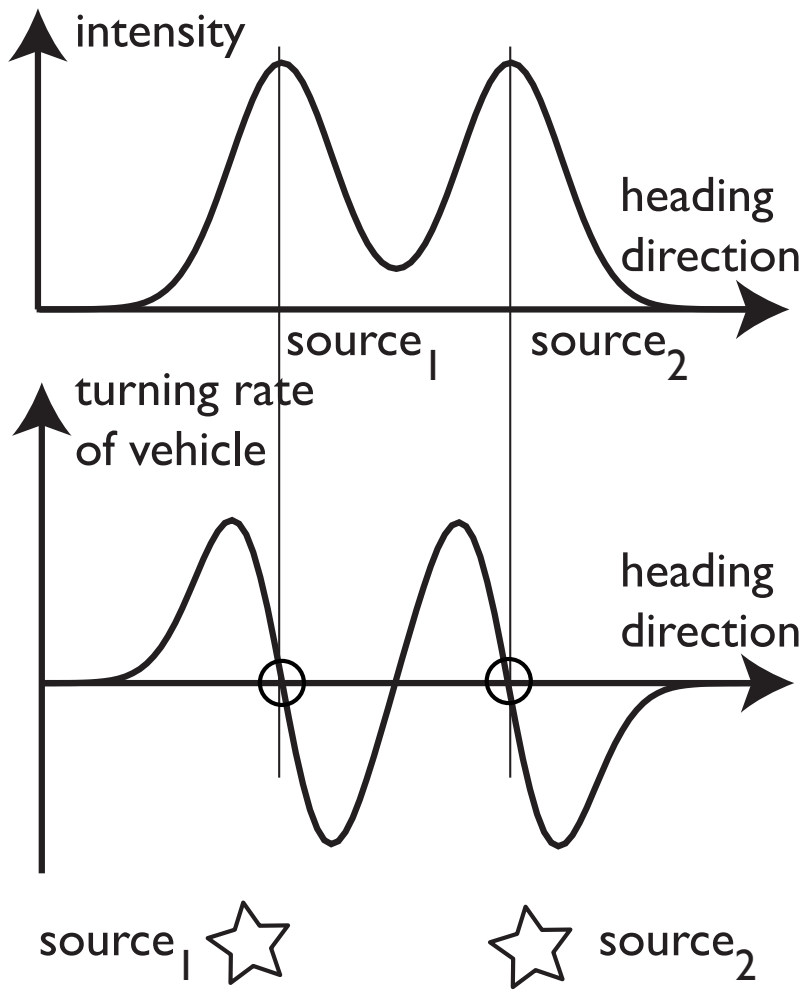
Attractor: Stability!

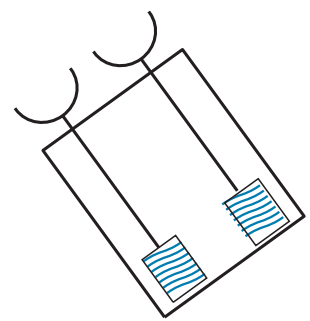
- recover orientation to source in response to disturbances of physical state
- recover orientation to source as environment changes or sensory information varies



Sensori-motor decisions

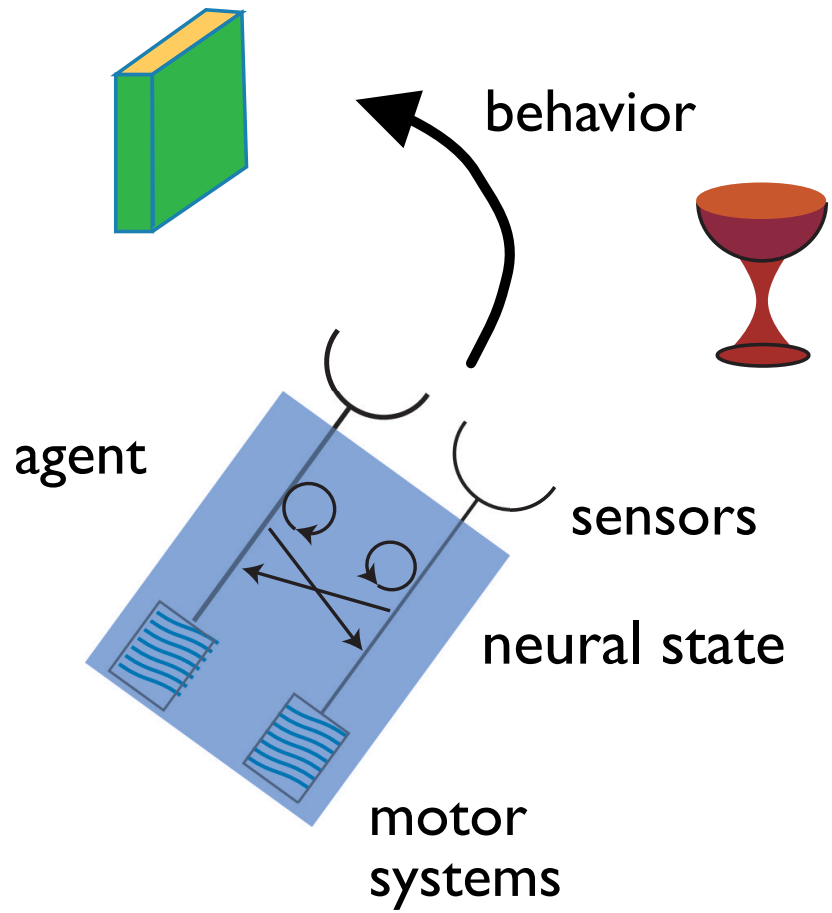
- two sources => selection … based on the initial heading
- in dynamical systems terms: bistability: two attractors
- each attractor stabilizes the selection decision





Cognitive decisions

- selection at the level of inner = neural state
- neural attractors… stabilize the selection decision
- based on recurrent neural dynamics



DFT as a neural theory of cognition

- what does that mean?
- a complete description of cognition on the basis of neural networks?
- thinking and action … are not reproducible => extensive description is not useful

Neural theory of cognition

- account for laws/constraints/regularities…
- links between such laws = explanation
- neural account: links neural laws/principles to behavioral laws
- neural process account: the link is causal, may actually generate behavior, e.g. on a robot

Which neural laws/principles?

- those of connectionism
  - activation = state of neural networks
  - sigmoidal threshold functions
  - functional significance of activation derives from connectivity
- two additional principles

DFT principle 1: Time/Autonomy

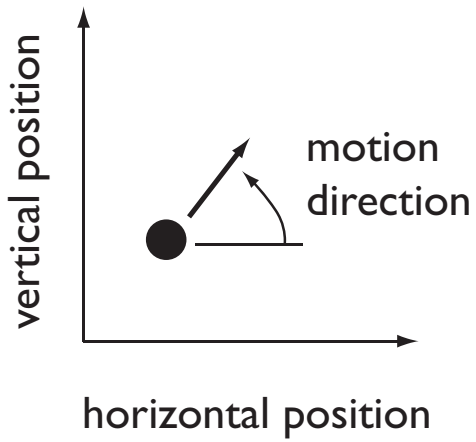
- conceptually, most current connectionist accounts are input driven: they react/responsibly to input
- thought and action are driven by the inner state of the mind/brain
- for inner states to do that, they must be stable: neural attractors
- attractors arise and disappear in dynamic instabilities => autonomous sequences of inner states
- stability and instabilities come from neural dynamics with strong recurrent interaction

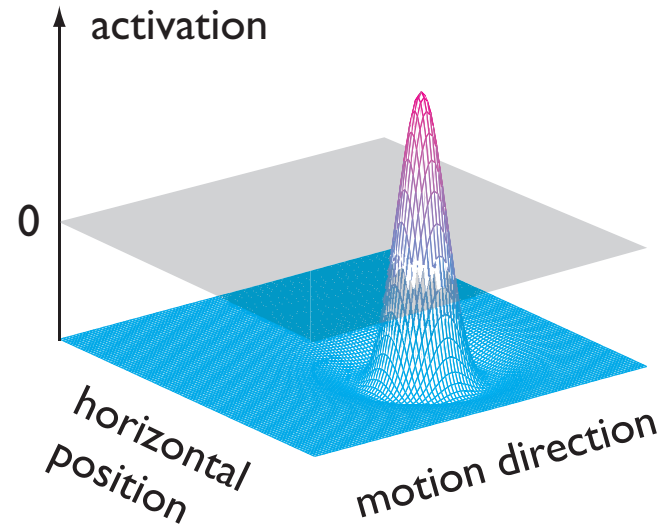
DFT principle 2: Space

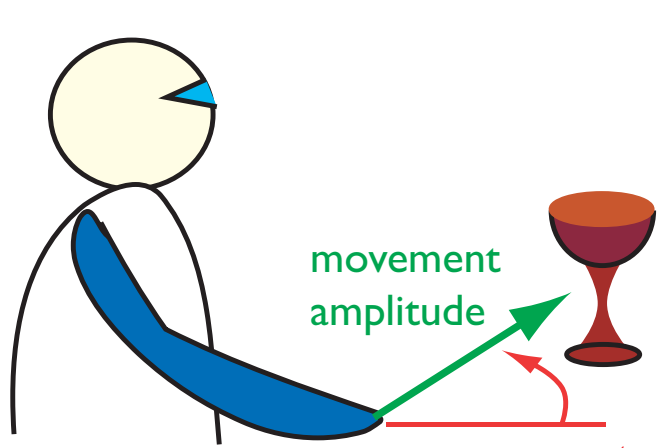
- neural attractors are embedded in low-dimensional continuous spaces ~ neural fields
- when these share dimensions => flexible binding
- basis for productivity, compositionality, systematicity => grounded higher cognition

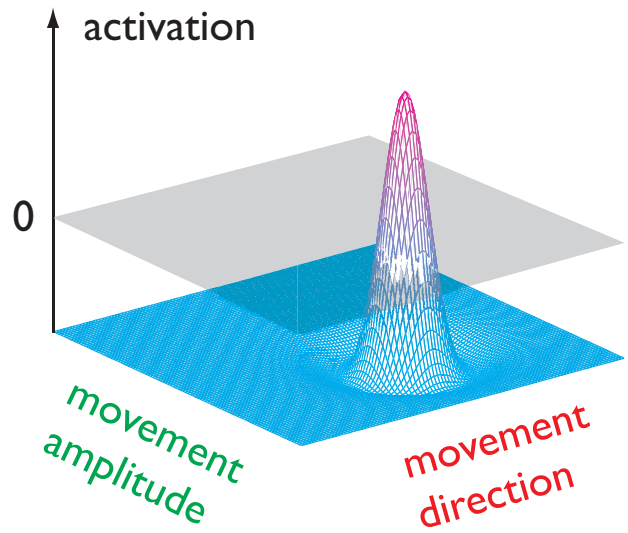
Space

- activation in neural populations carries functional meaning
- activation: $u(x, t)$ where x spans low-dimensional spaces







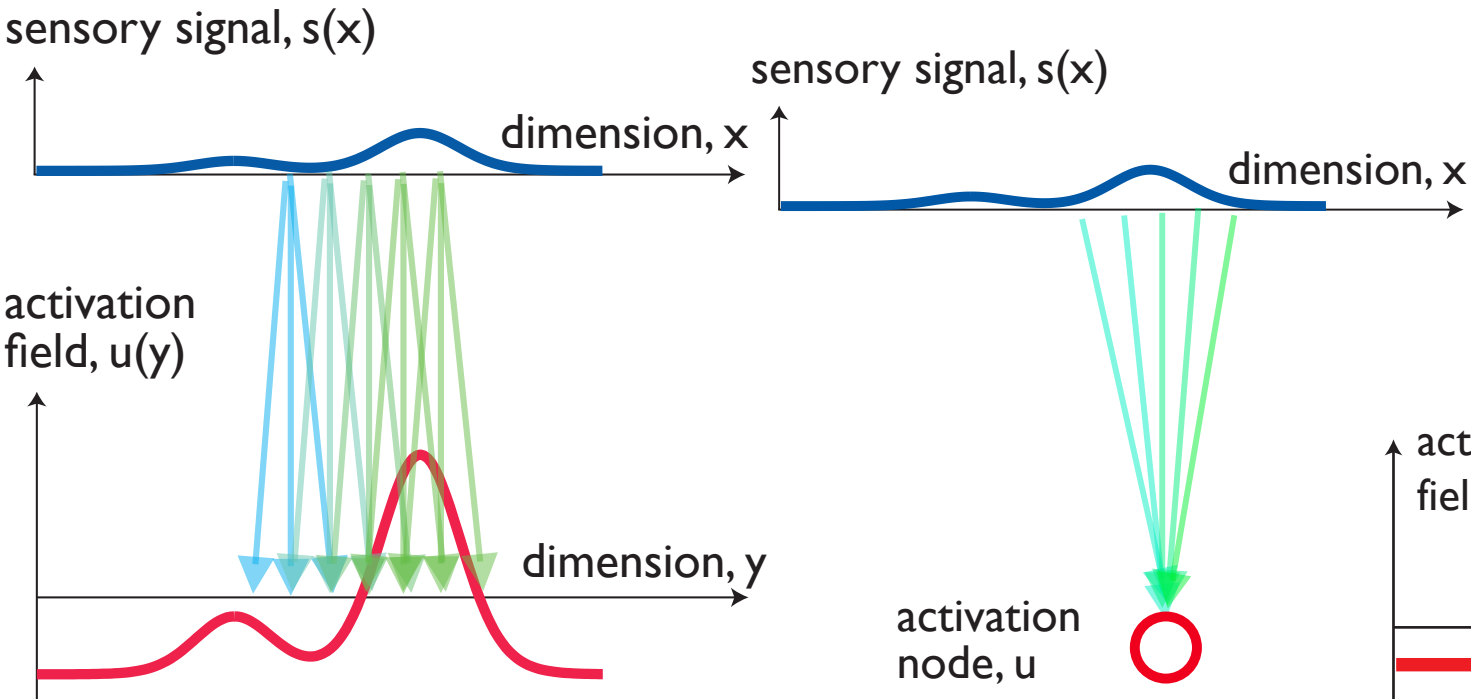


[Schöner TopiCS 2019]

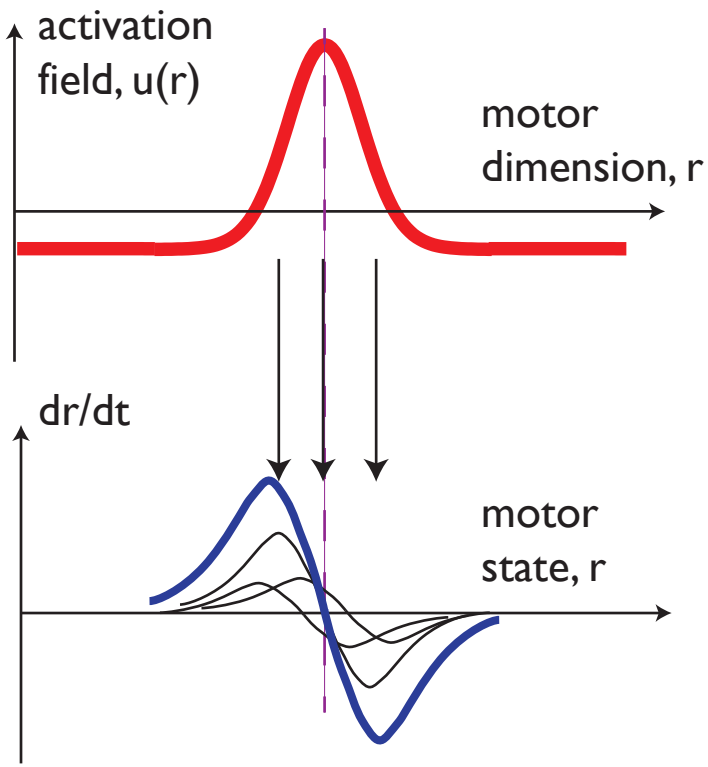
Spaces come from forward connectivity

from sensory surfaces

to motor surfaces



motor space

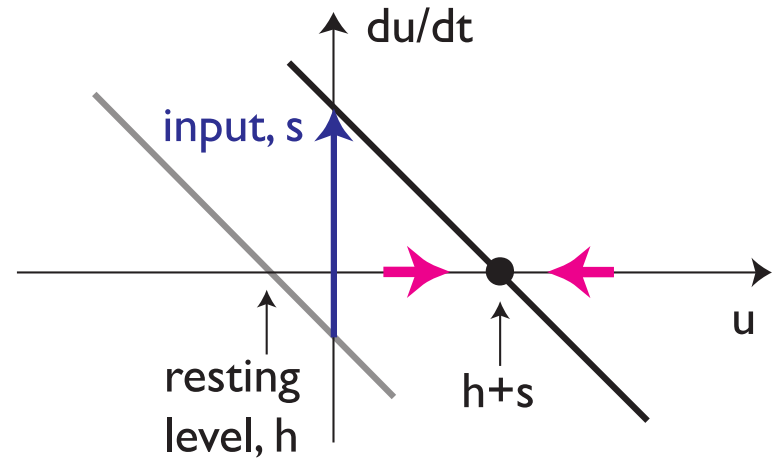


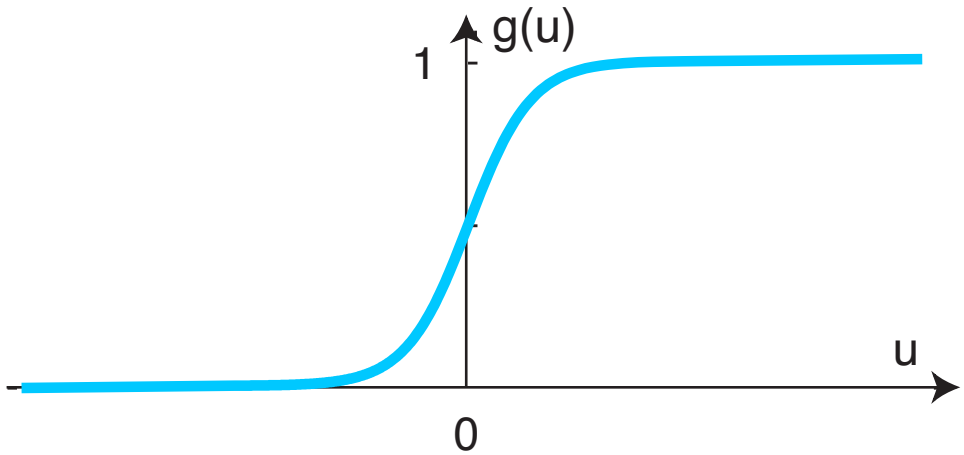
feature space

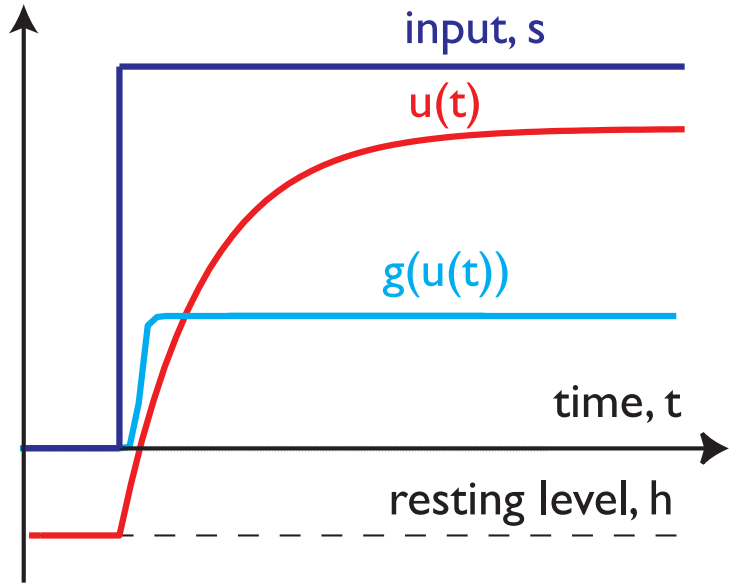
concepts

Time/Autonomy

- Neural dynamics $\tau \dot{u}(x,t) = -u(x,t) + h + s(x,t)$
- inherited from the membrane dynamics of neurons
  $\tau \approx 10$ msec
- this is input-driven





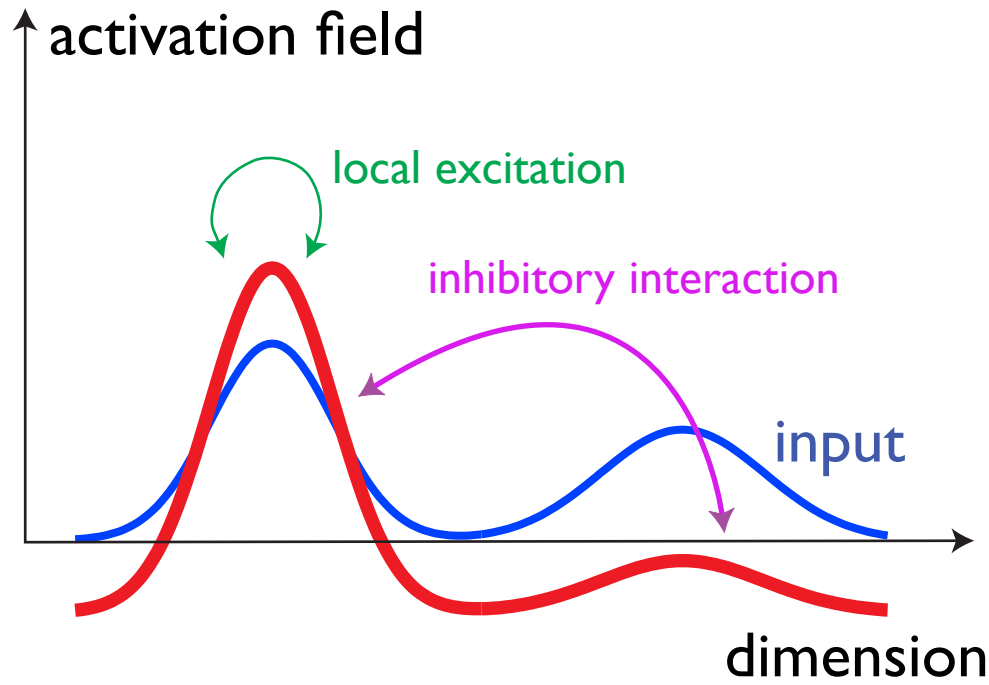


…beyond input driven activation

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

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

- strong recurrent connectivity within populations = interaction
- excitatory for neighbors in space
- inhibitory for activation at a spatial distance



…beyond input driven activation

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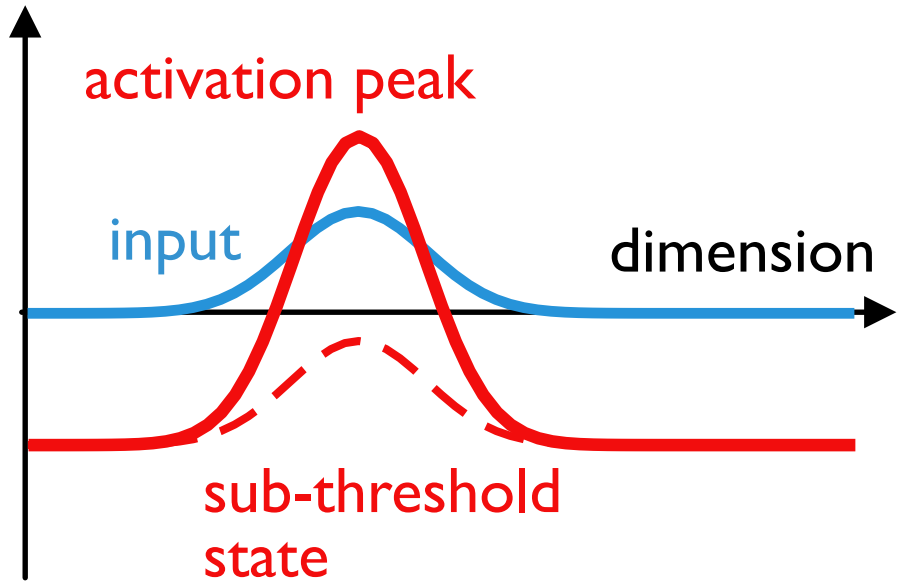
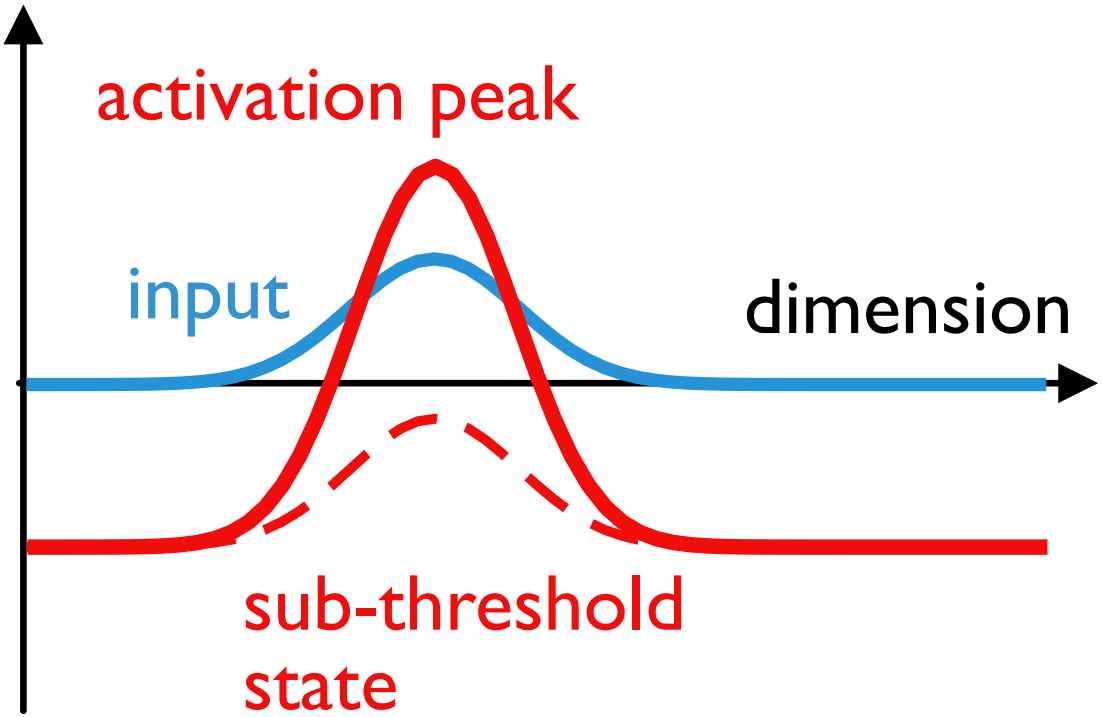
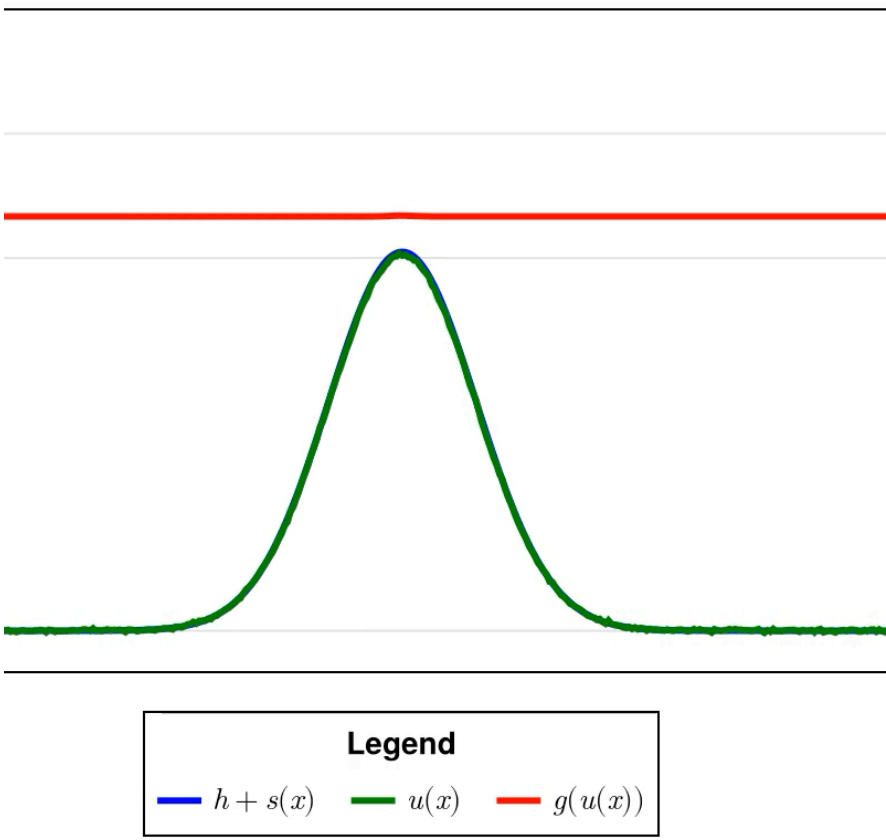
- strong recurrent connectivity within populations = interaction
- excitatory for neighbors in space
- inhibitory for activation at a spatial distance
- => peak attractors

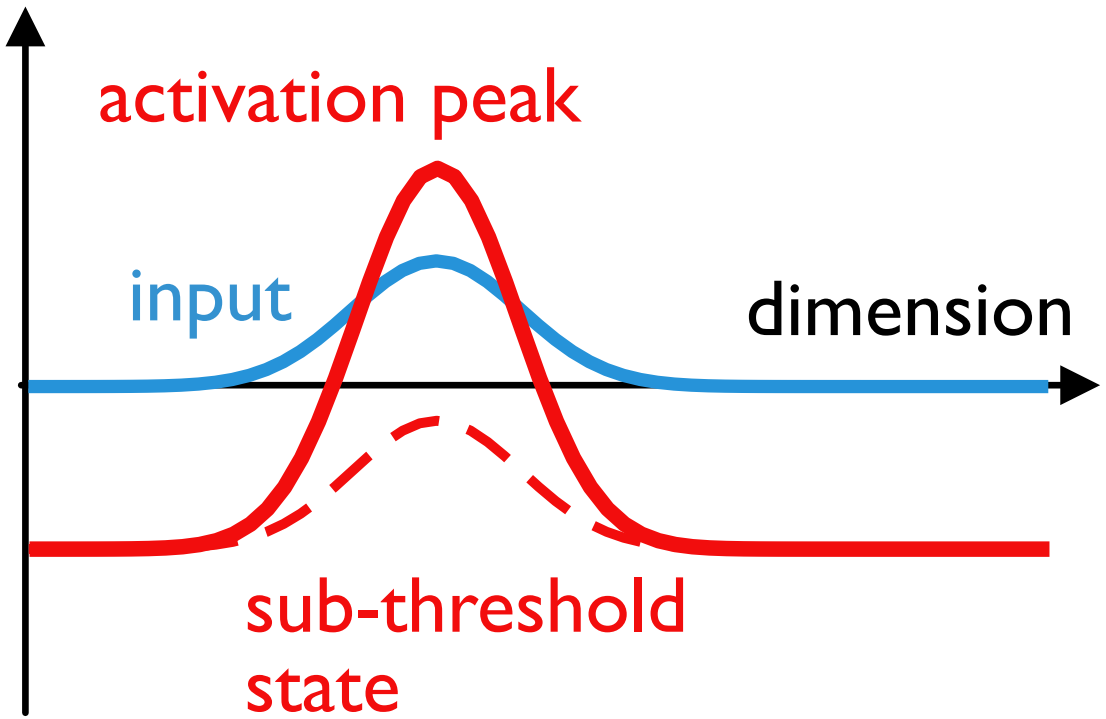


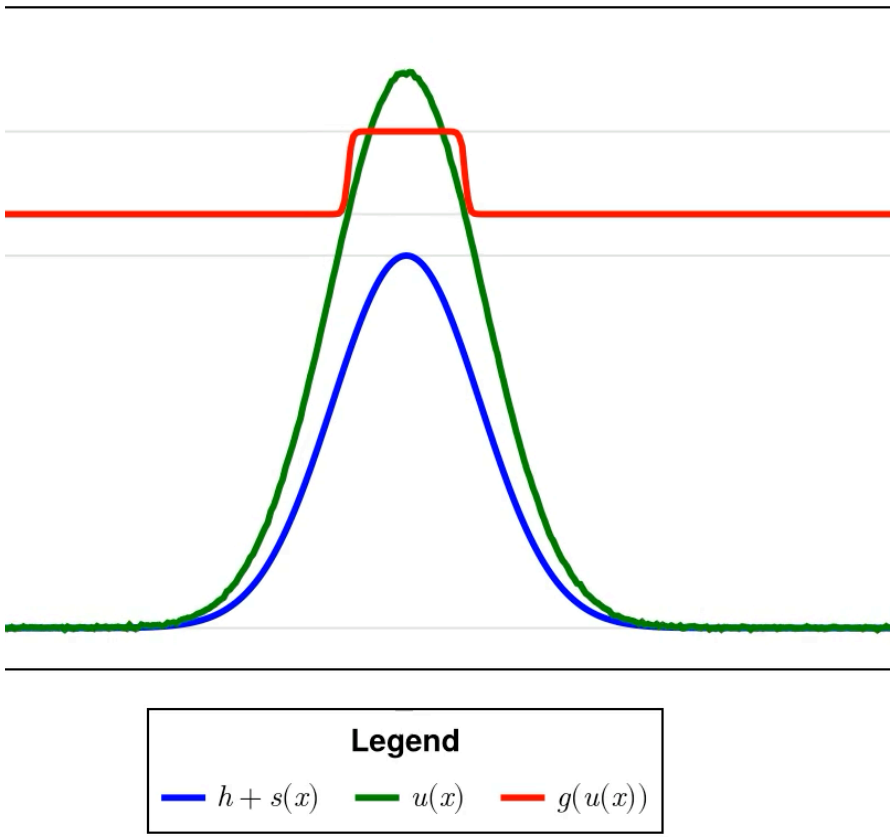
- bistable => gap between peak and sub-threshold activation pattern
- detection instability: peak arises



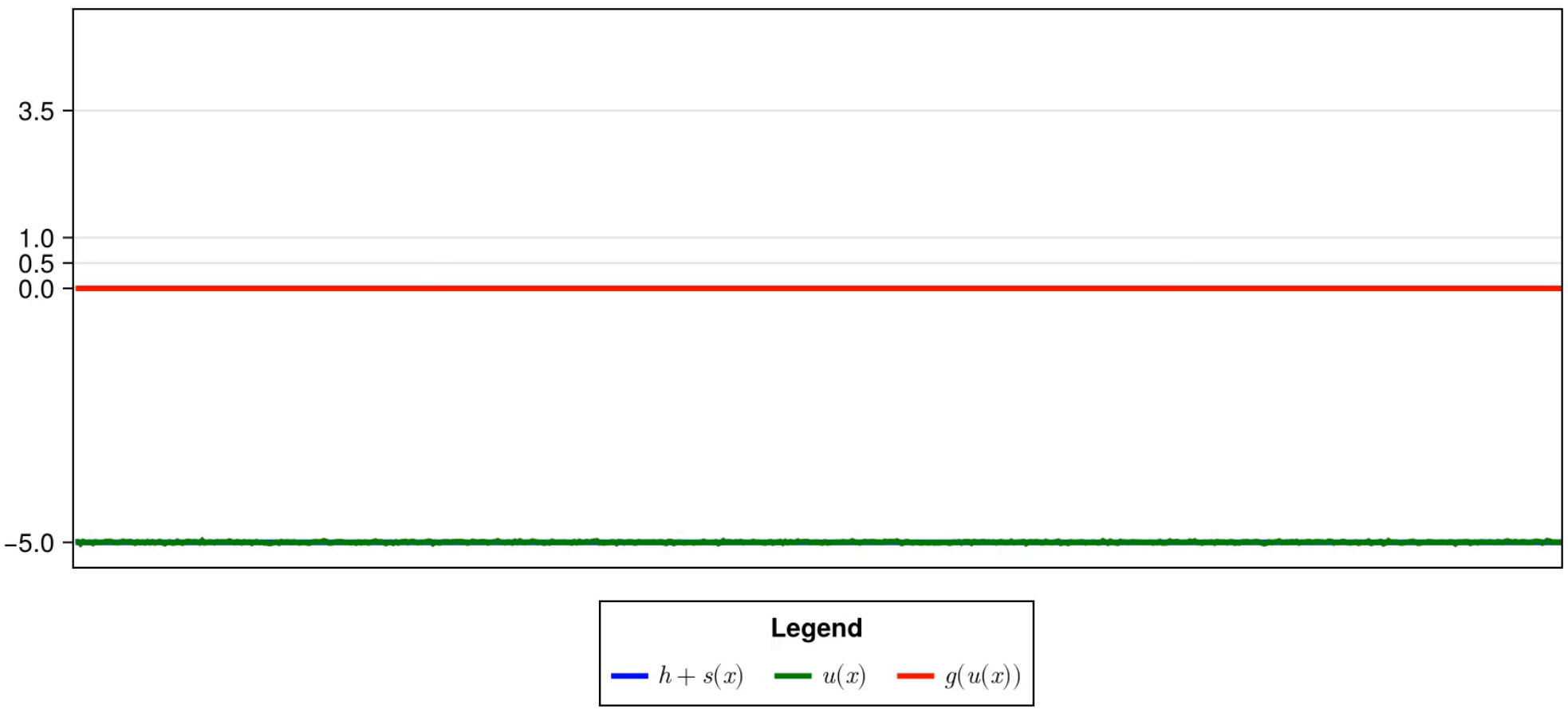


- peaks disappear in the reverse detection instability

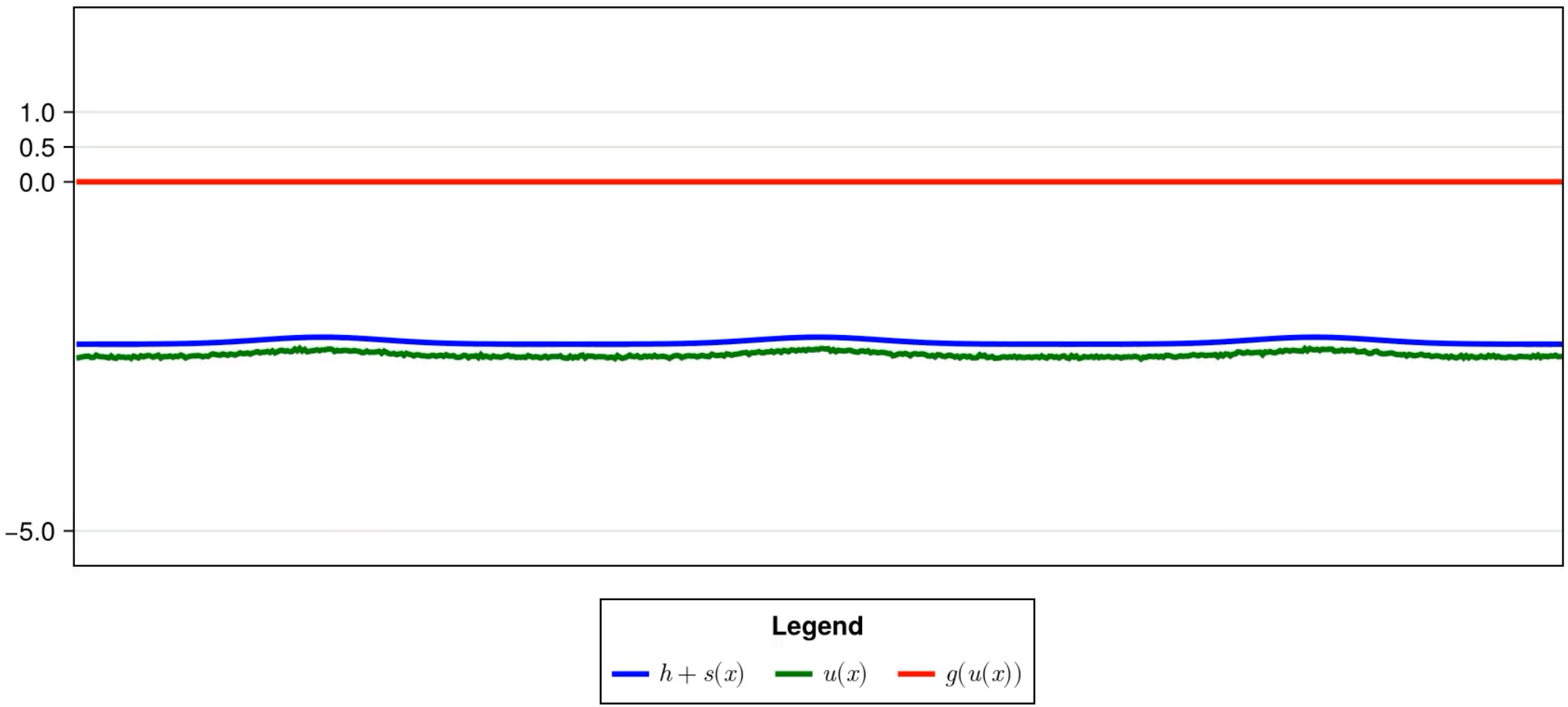




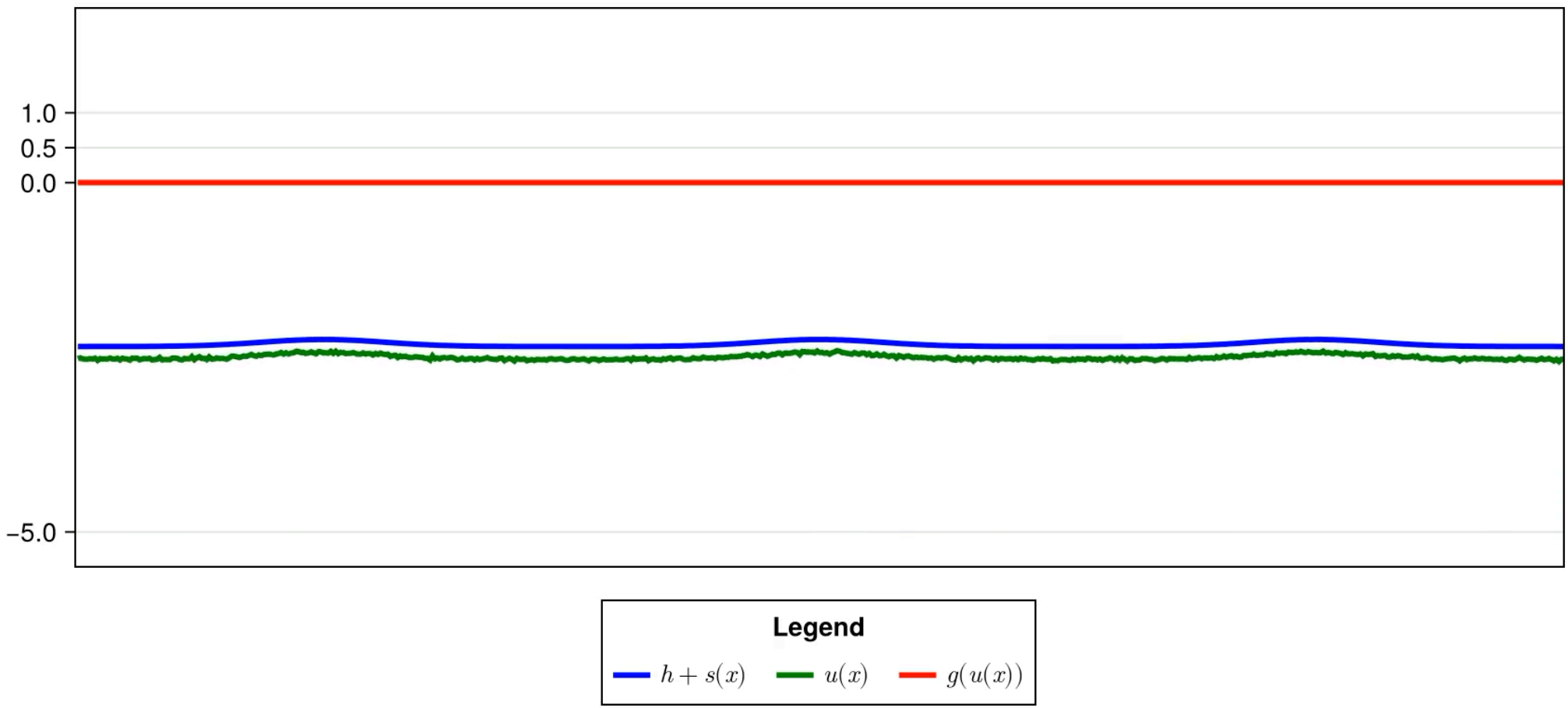
selection at detection



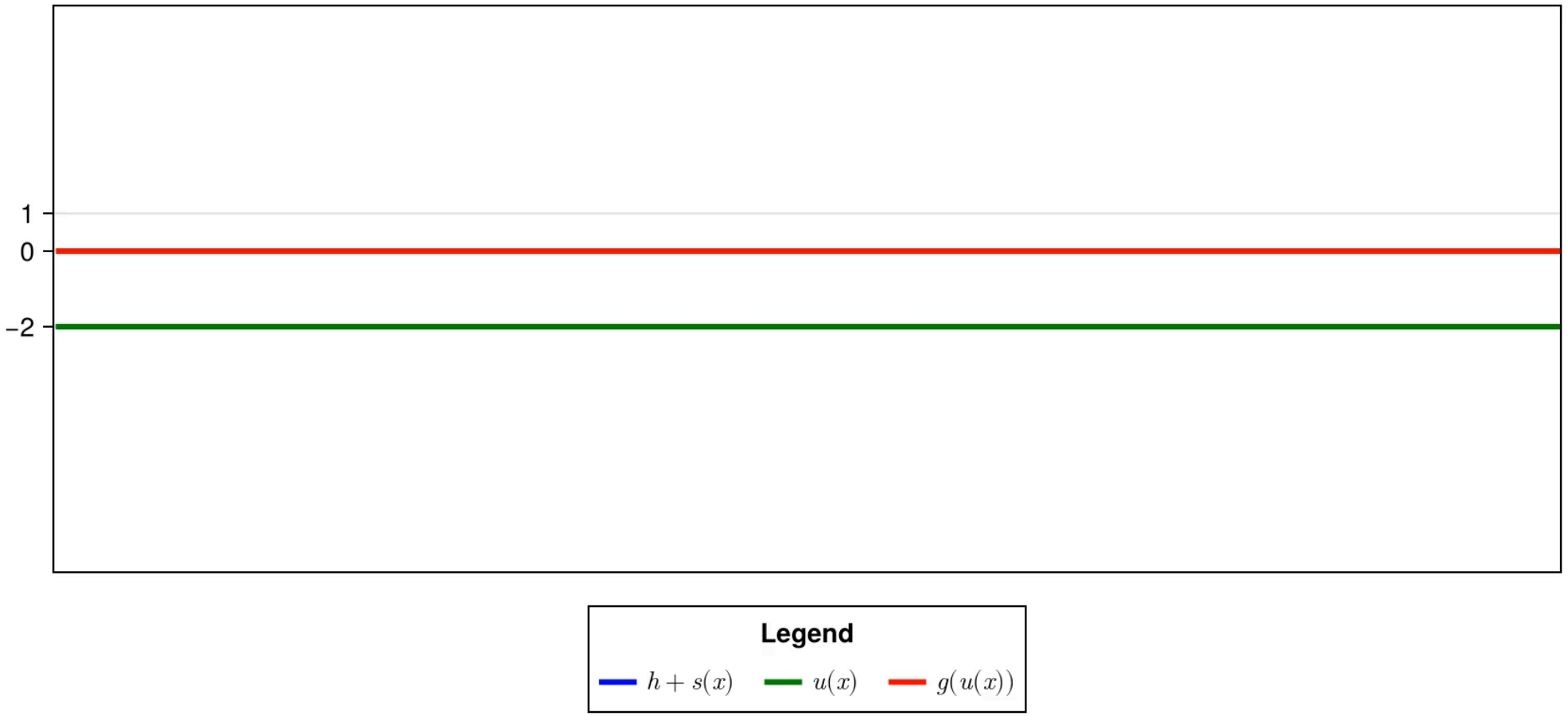
- selection at detection: induced by boost
- => amplifies small differences



=> categories emerge from continuous spaces

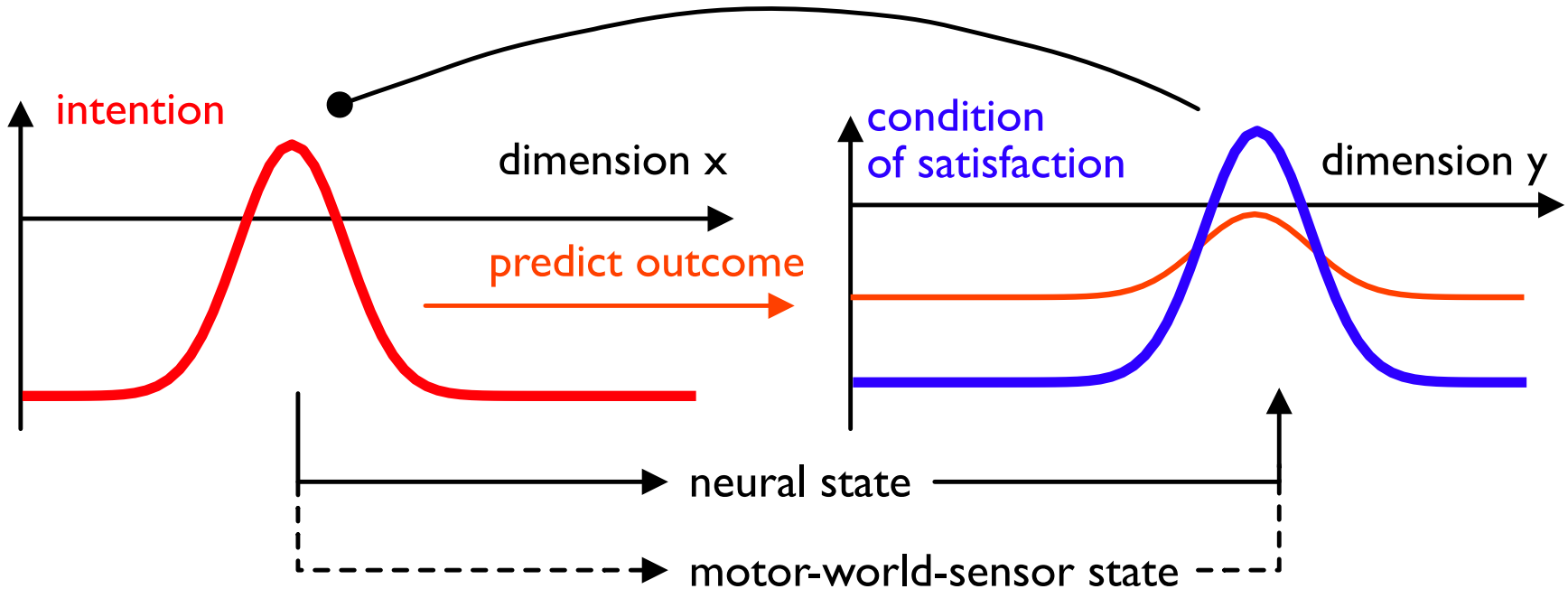


sustained activation ~ working memory



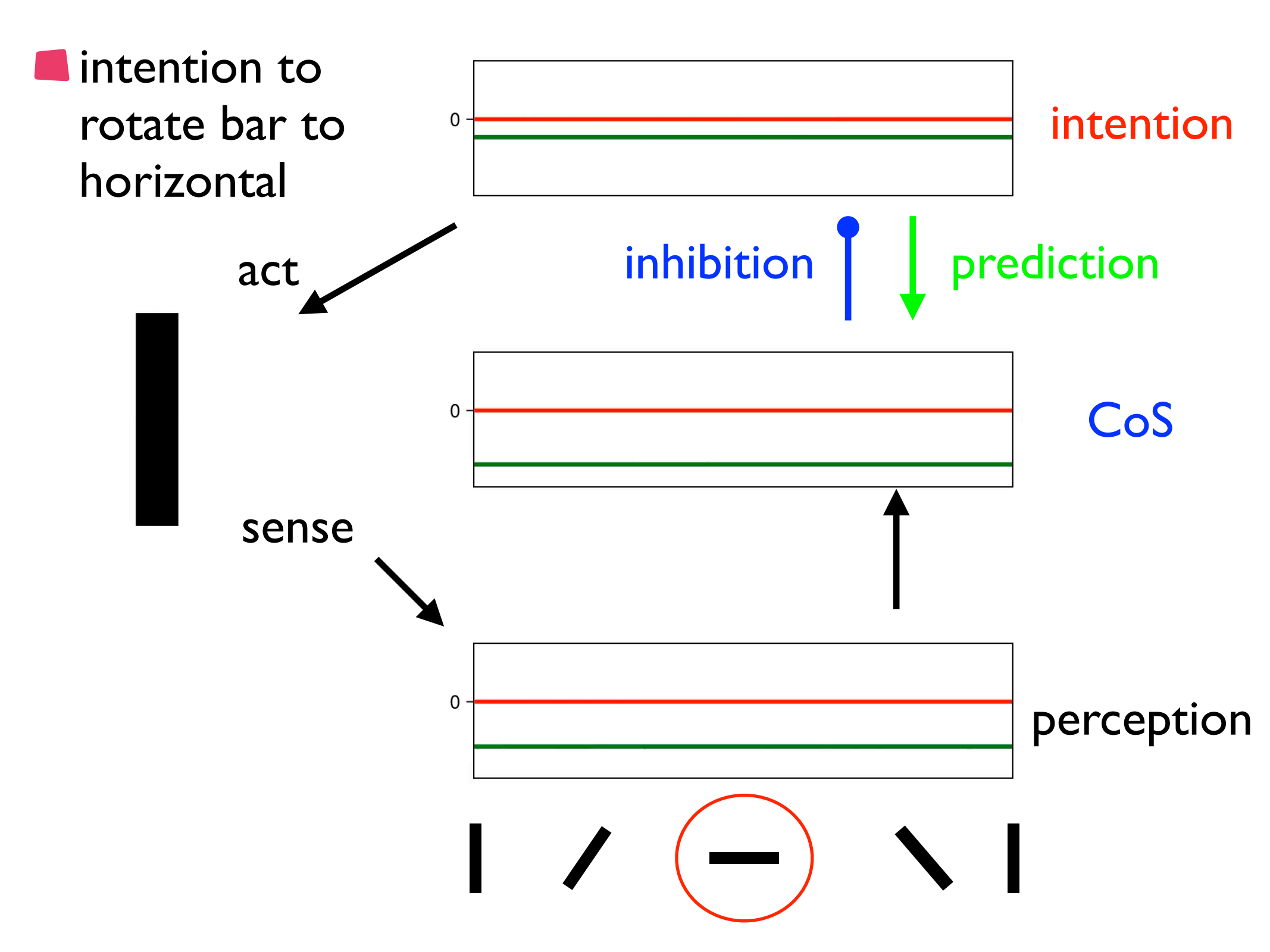
Autonomous acting/processing emerges from the instabilities

- a mini-architecture: intention and its Condition of Satisfaction (Cos)

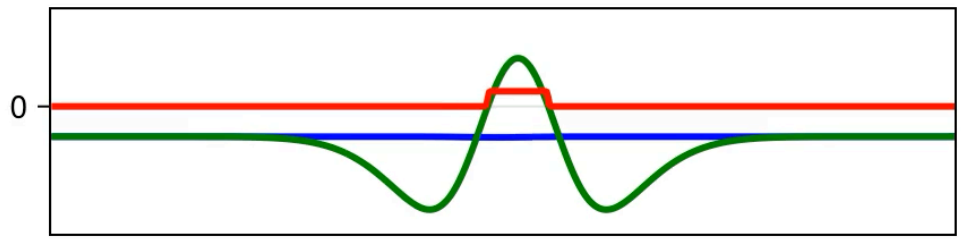


[Sandamirskaya, Schöner: *Neural Networks* 2010]

- intention to rotate bar to horizontal



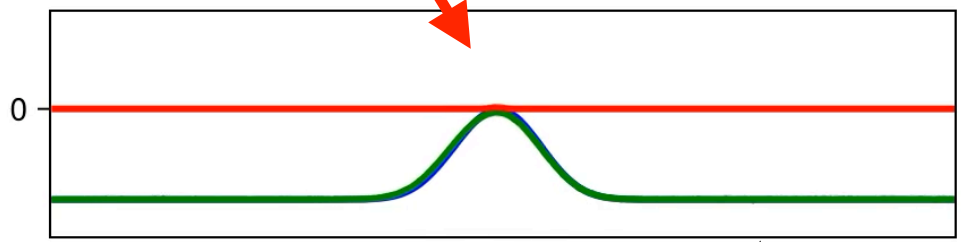
intention to rotate bar to horizontal



intention

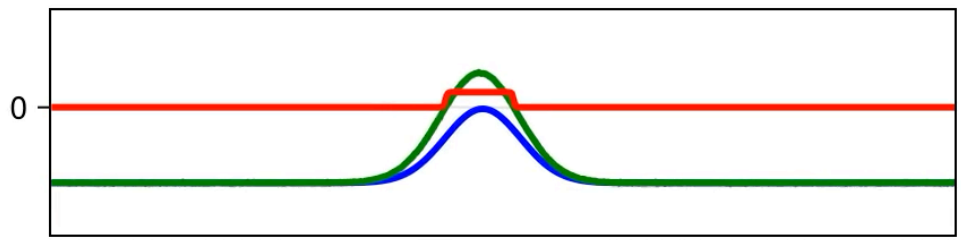
act

detection

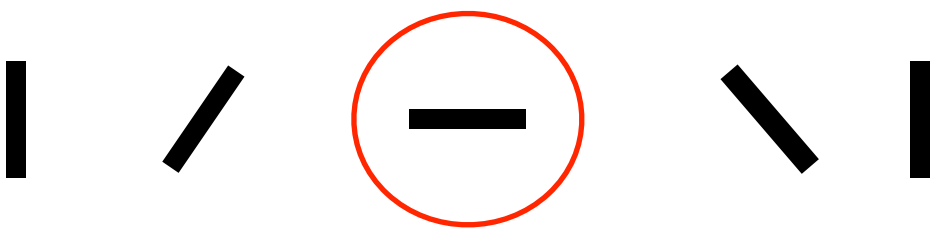


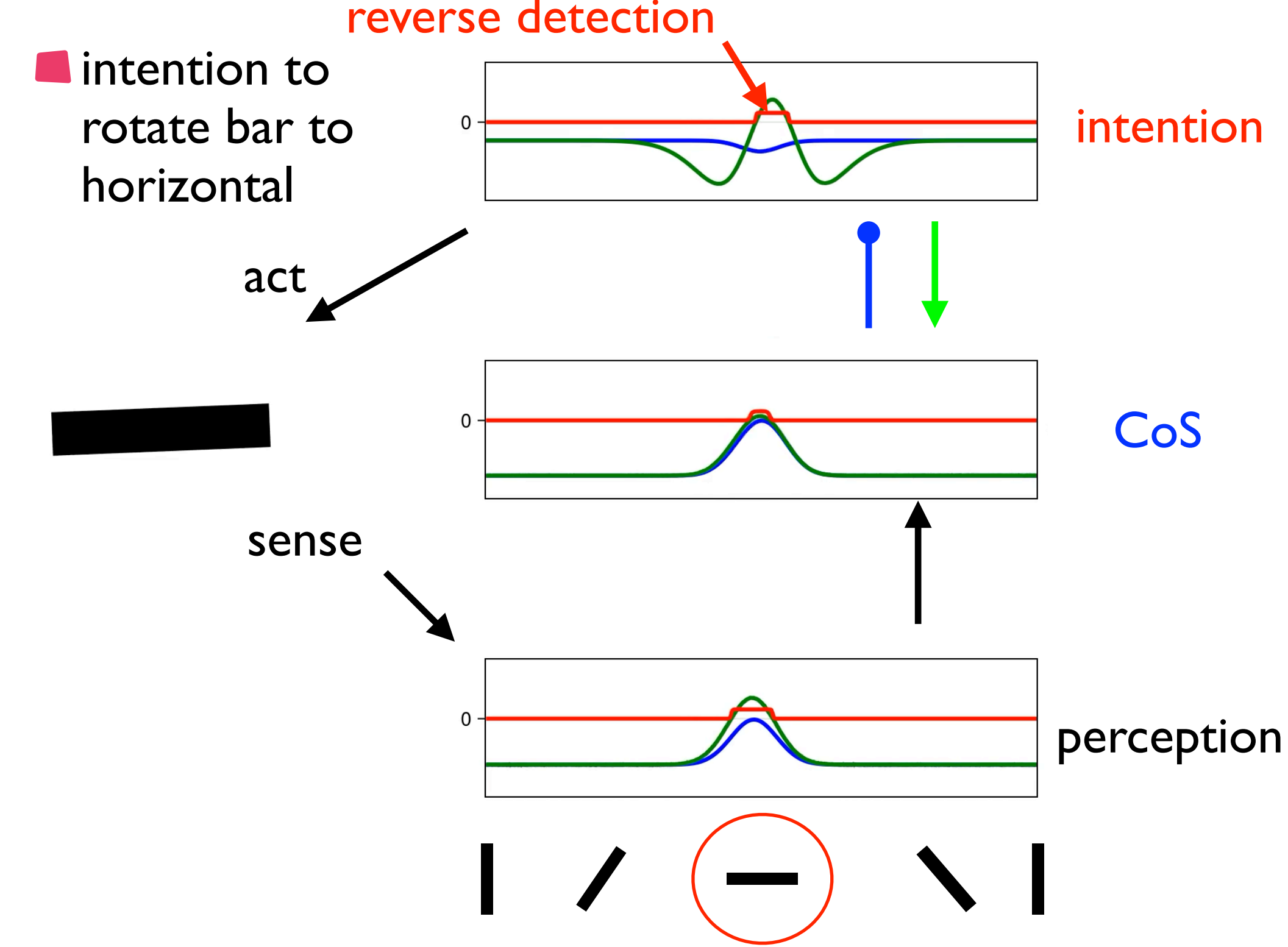
CoS

sense

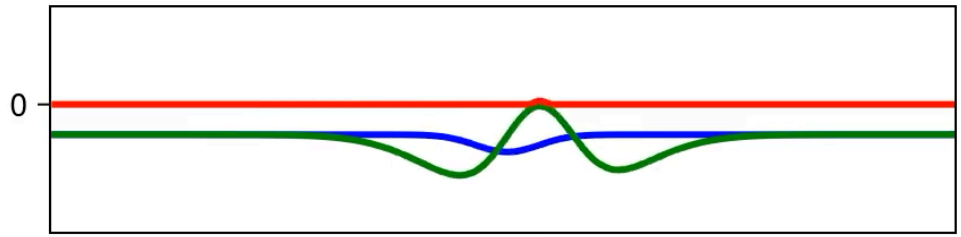


perception




reverse detection
intention to rotate bar to horizontal
0
intention
act
0
CoS
sense
0
perception

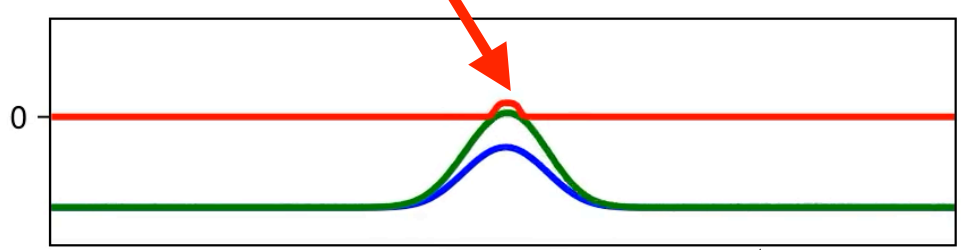
intention to rotate bar to horizontal



intention

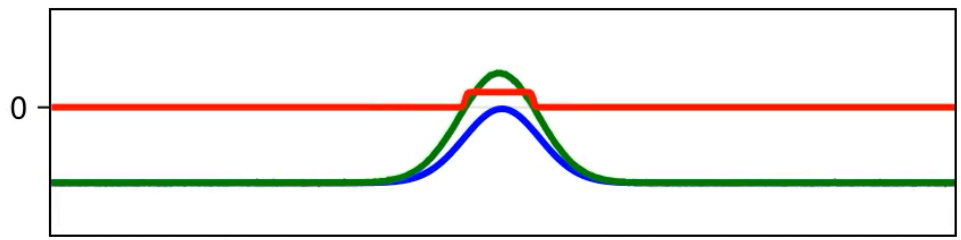
act

reverse detection

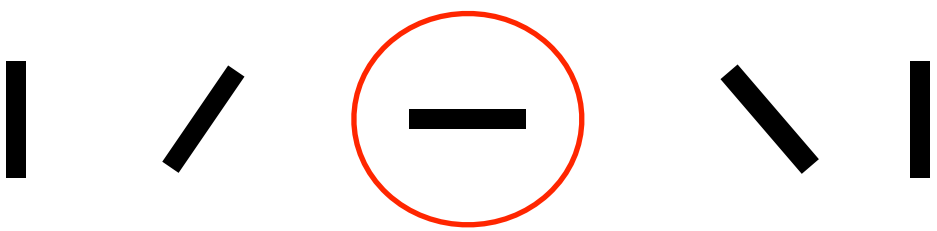


CoS

sense



perception

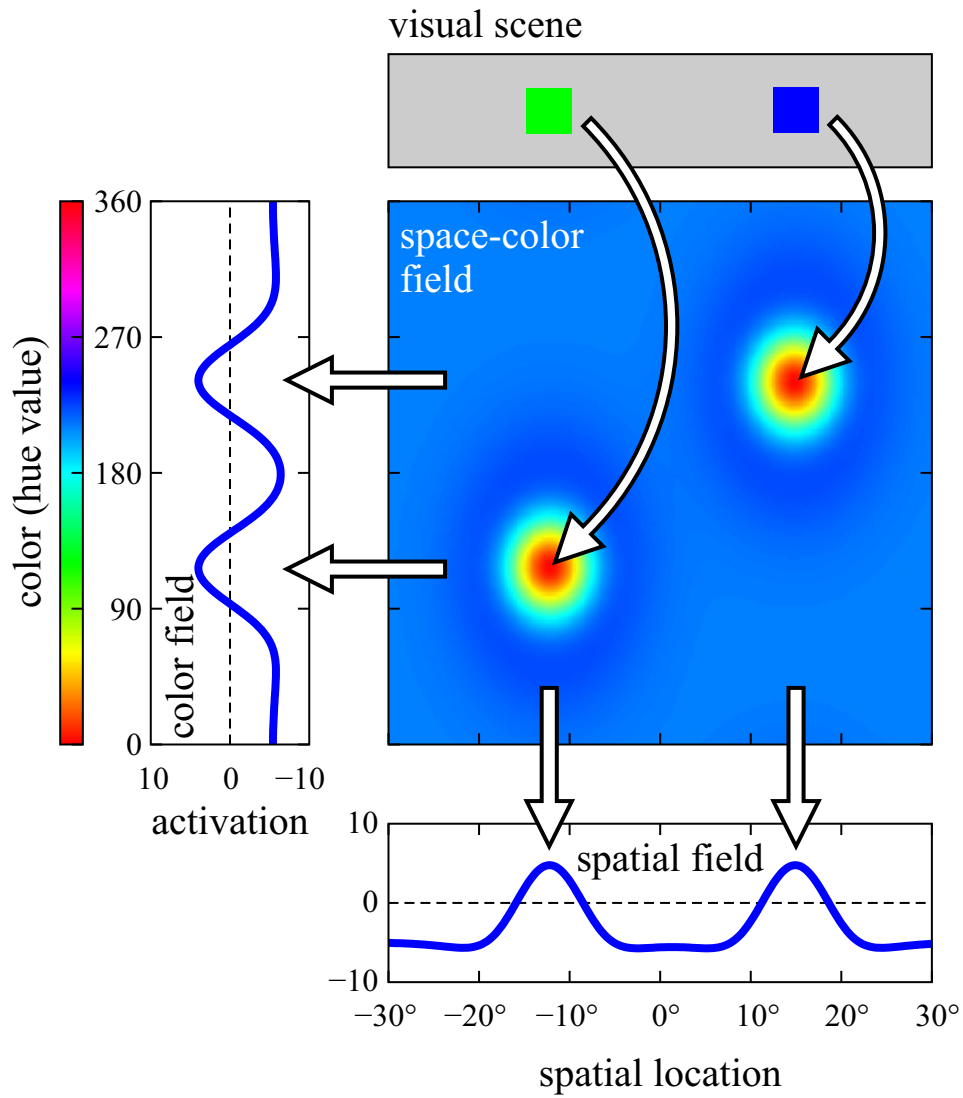


Coupling spaces + instabilities
=> higher cognition

- binding through shared dimensions

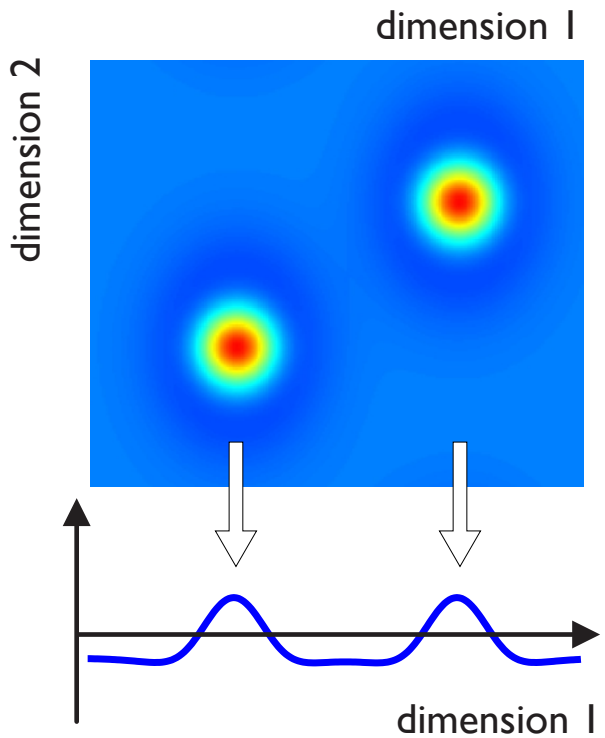
Joint representations

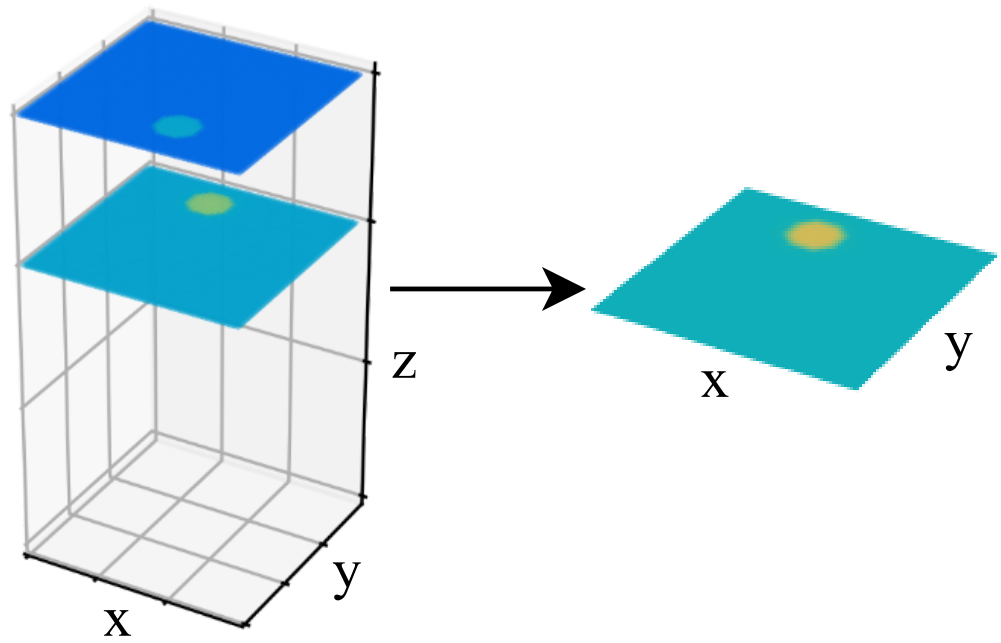
- unbind = extract features by contraction coupling



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

Contraction coupling

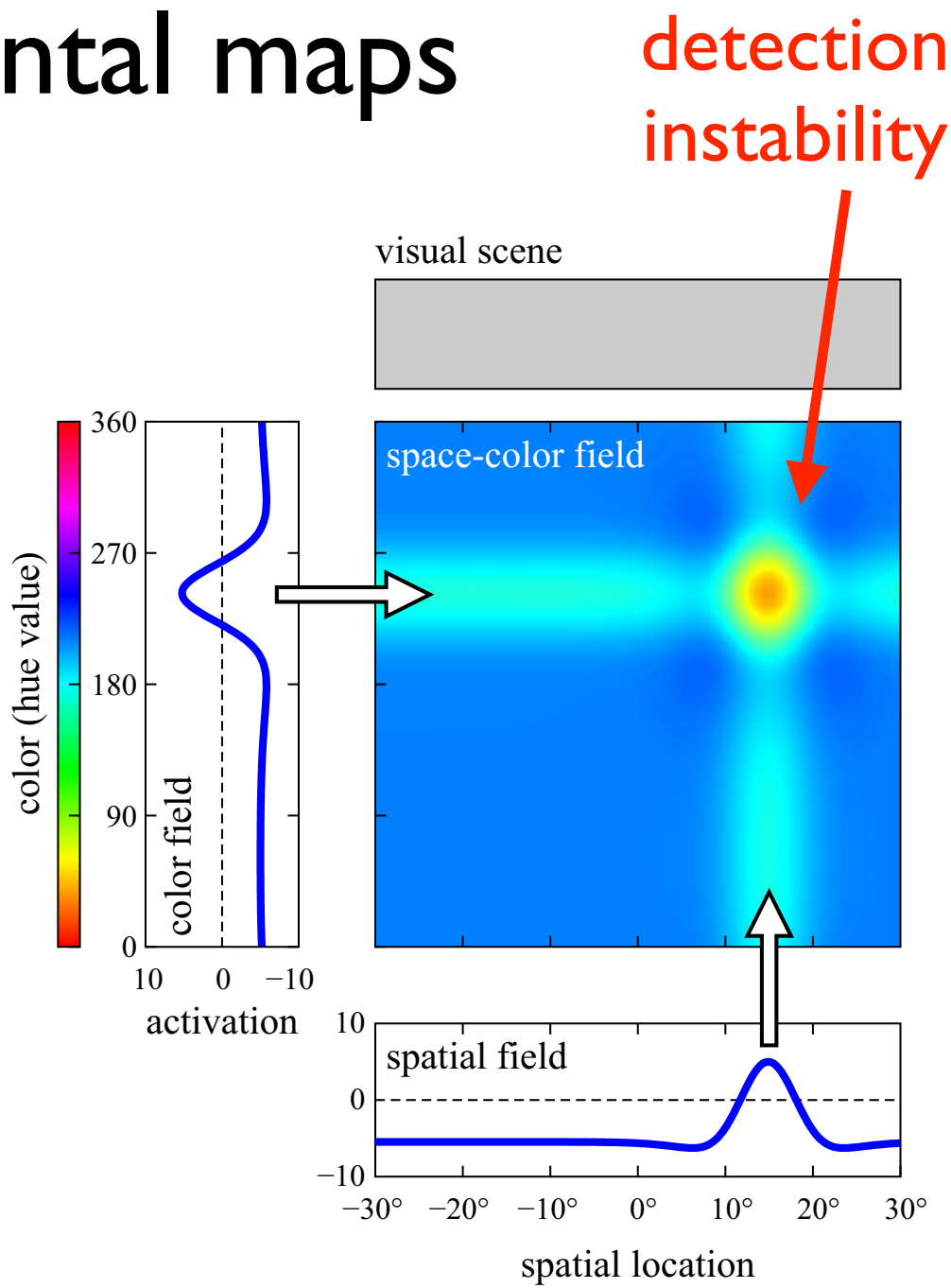




[Sabinasz, Richter, Schöner, *Cog. Neurodyn.* 2023]

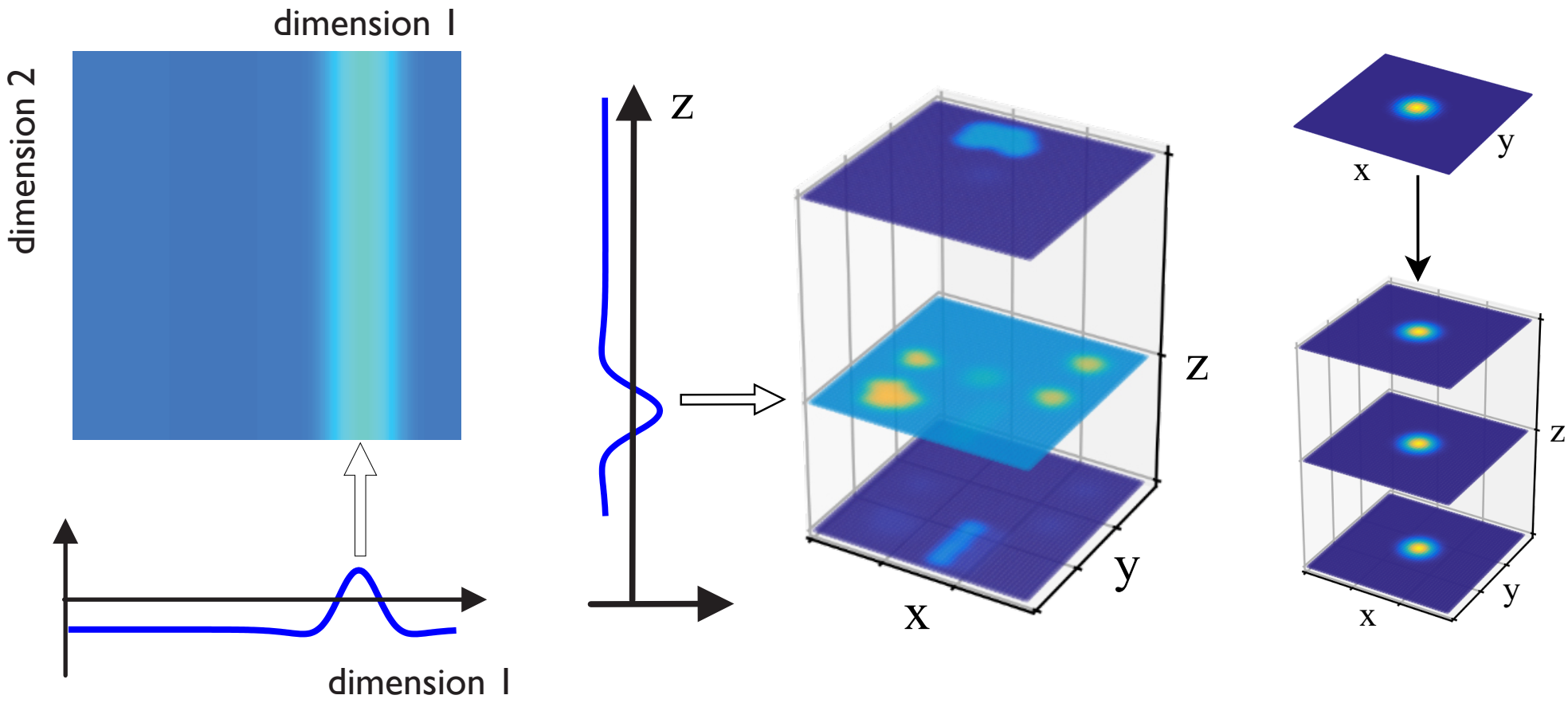
Bind in mental maps

- bind separate features into objects in mental maps
- by expansion mapping



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

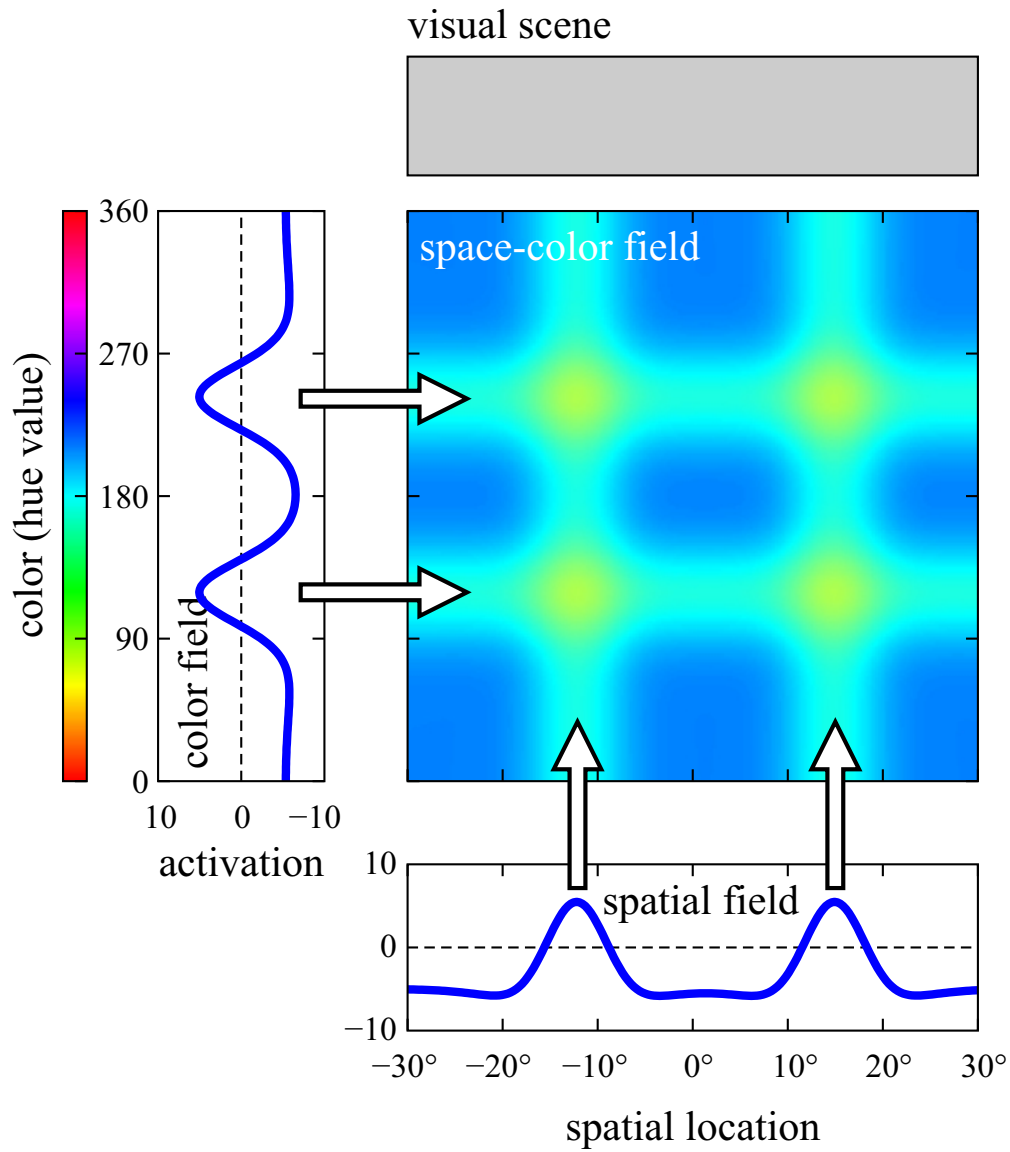
Expansion coupling



[Sabinasz, Richter, Schöner, *Cog. Neurodyn.* 2023]

Binding problem

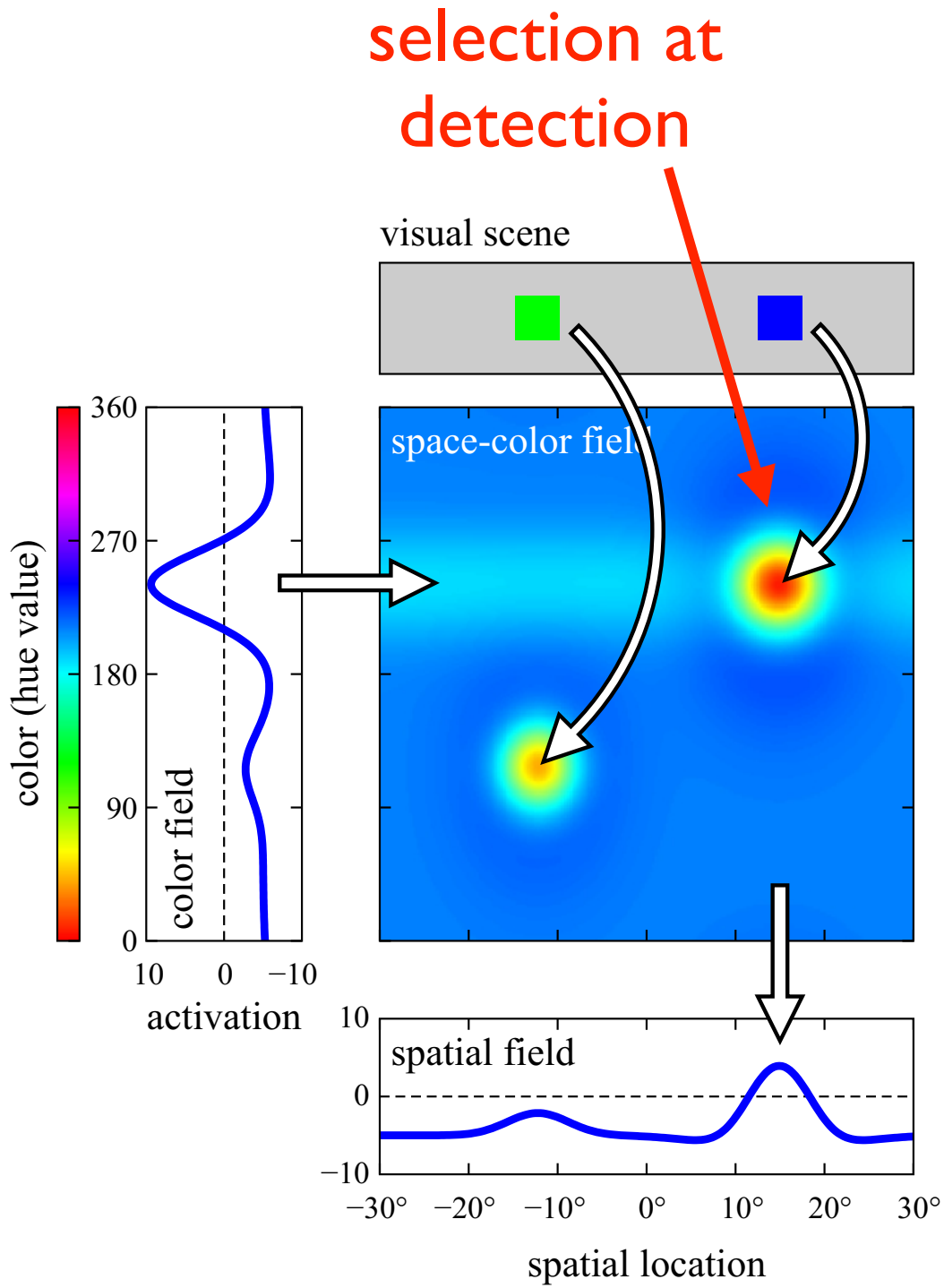
- => bind one object at a time
- (plus coordinate frame issue)
- => attentional bottleneck



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

Cued selection

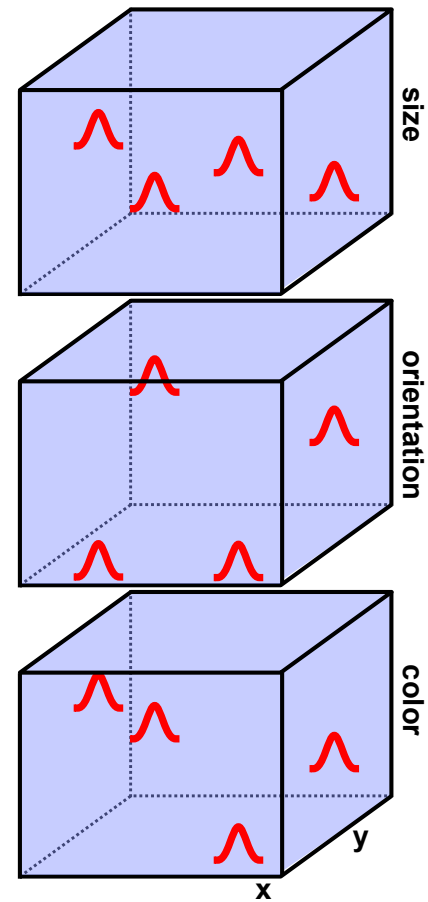
- combines expansion and contraction coupling



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

Binding through space

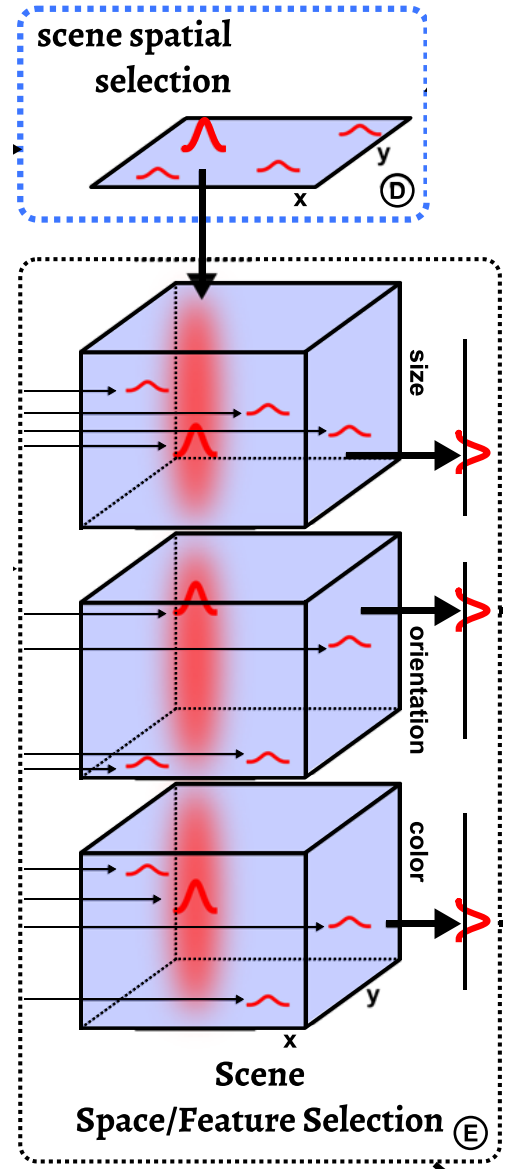
- multiple separate space-feature fields all share the spatial dimension



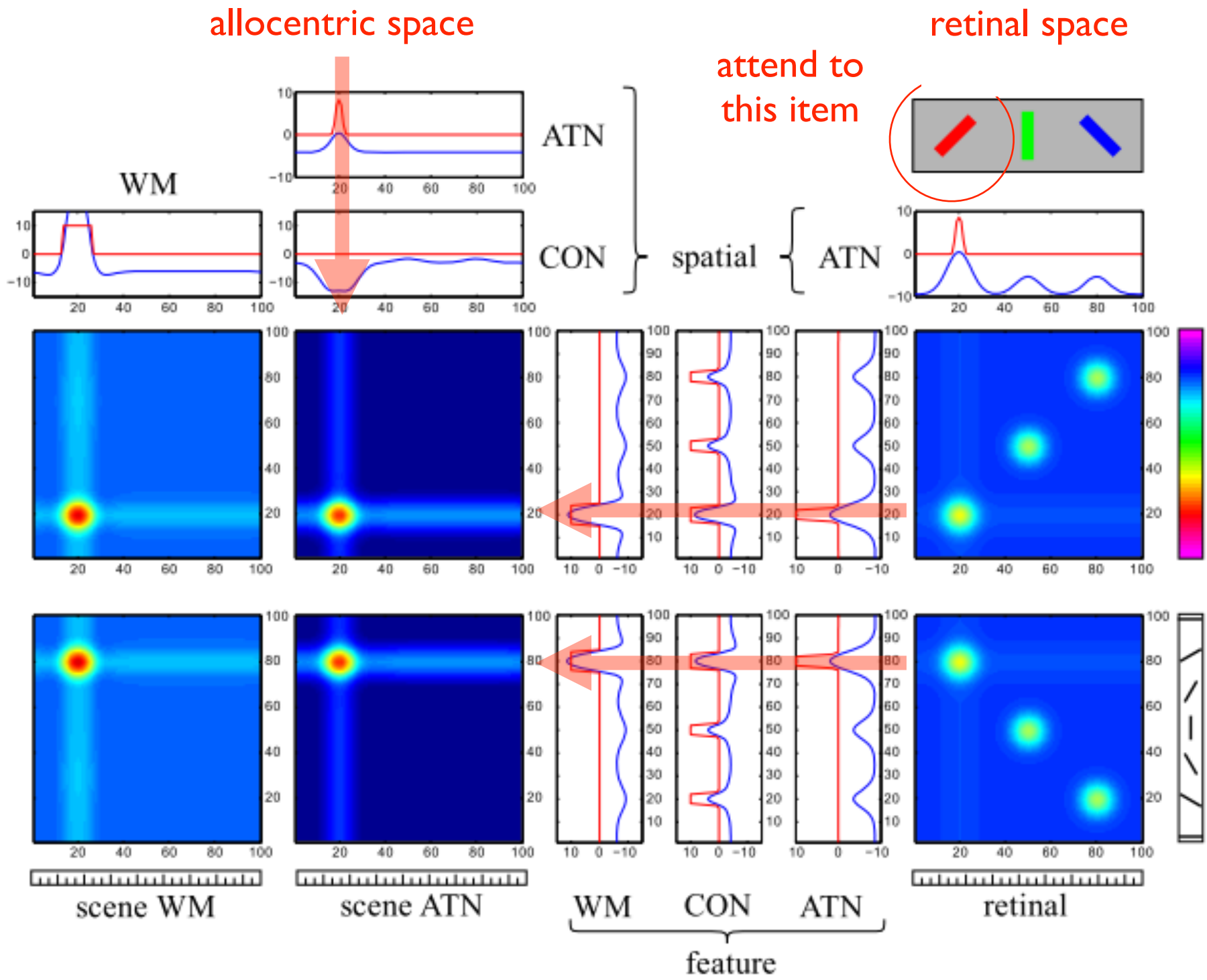
[Grieben et al. *Attention, Perception & Psychophysics* 2020]

Binding through space

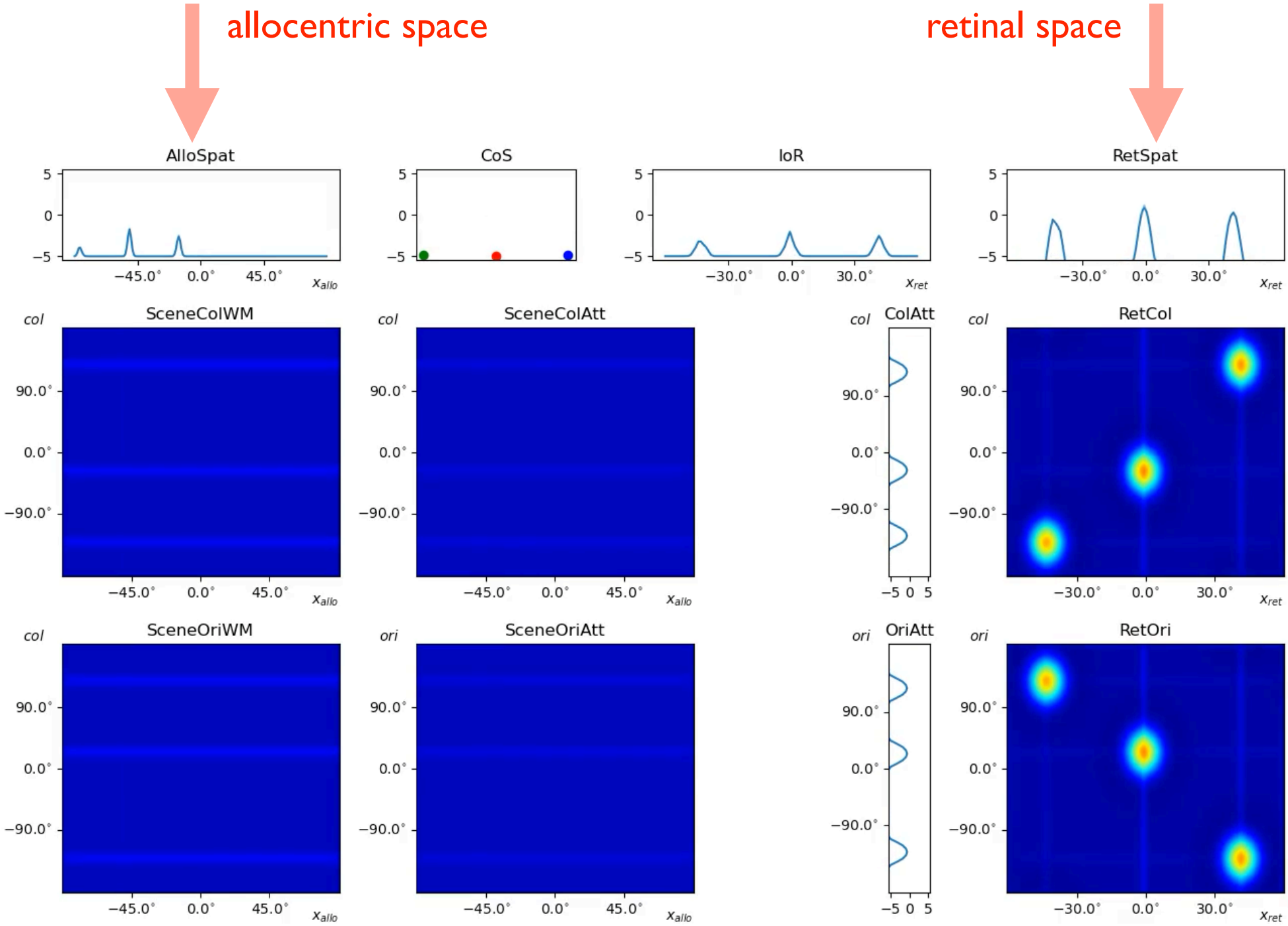
- expansion/contraction coupling along the spatial dimension enables binding/ unbind



[Grieben et al. *Attention, Perception & Psychophysics* 2020]

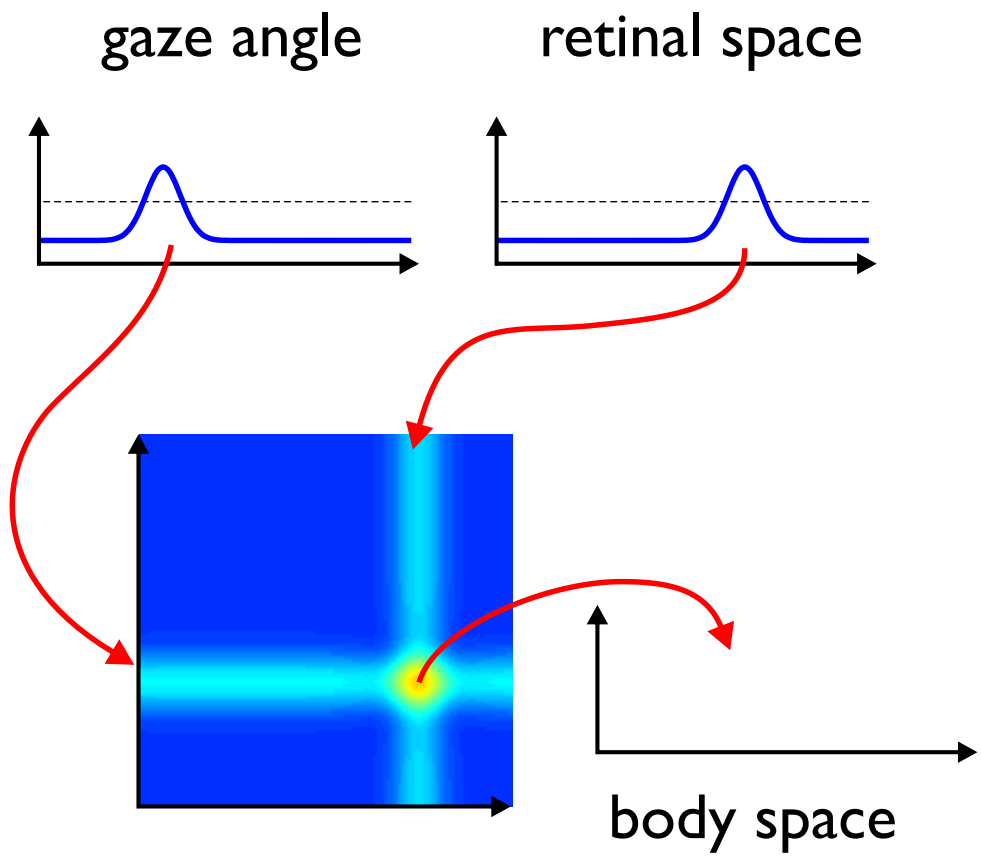


[Schneegans et al.,Ch 8 of *DFT Primer*, 2016]


allocentric space
retinal space
AlloSpat
CoS
IoR
RetSpat
SceneColWM
SceneColAtt
ColAtt
RetCol
SceneOriWM
SceneOriAtt
OriAtt
RetOri
col
ori
x_{allo}
x_{ret}

Coordinate transforms

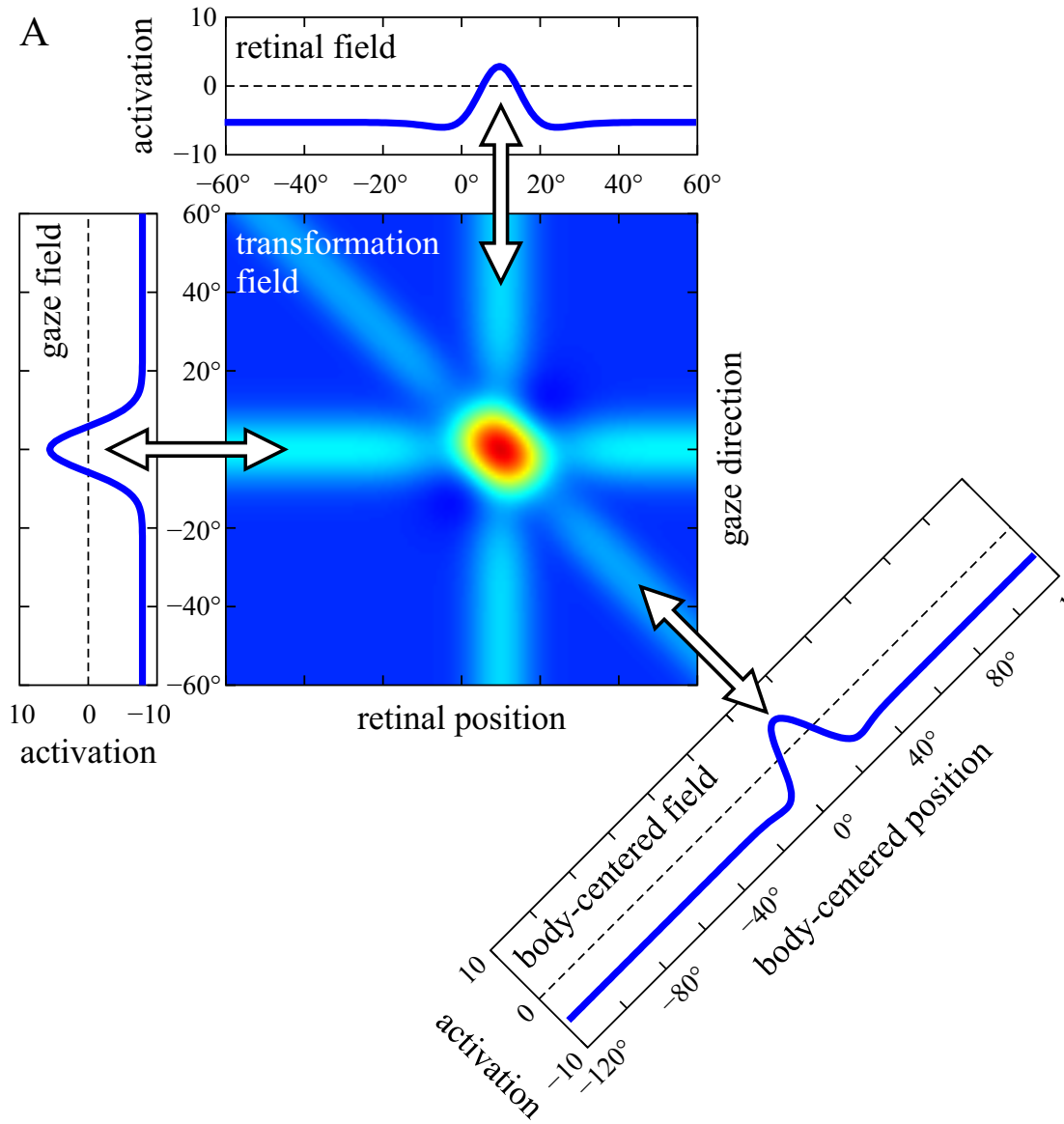
- binding retinal space to gaze angle
  - gain fields ~Andersen/Pouget
- unbinding: body space



[Schneegans Ch 7, *DFT Primer*, 2016]

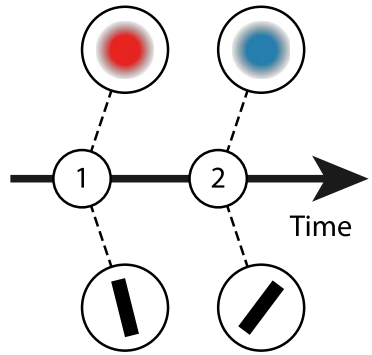
Coordinate transforms

- binding retinal space to gaze angle
  - gain fields ~Andersen/Pouget
- unbinding: body space



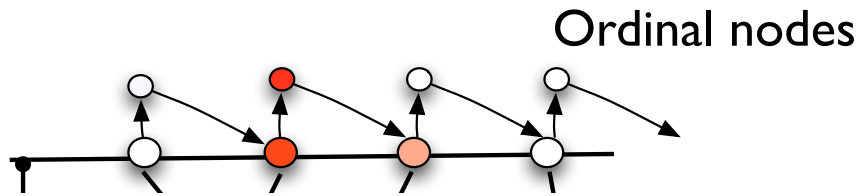
Binding through ordinal dimension

- experimental evidence from VWM: binding through time…



[Schneegans, McMaster, Bays: *Psych Rev* 2022]

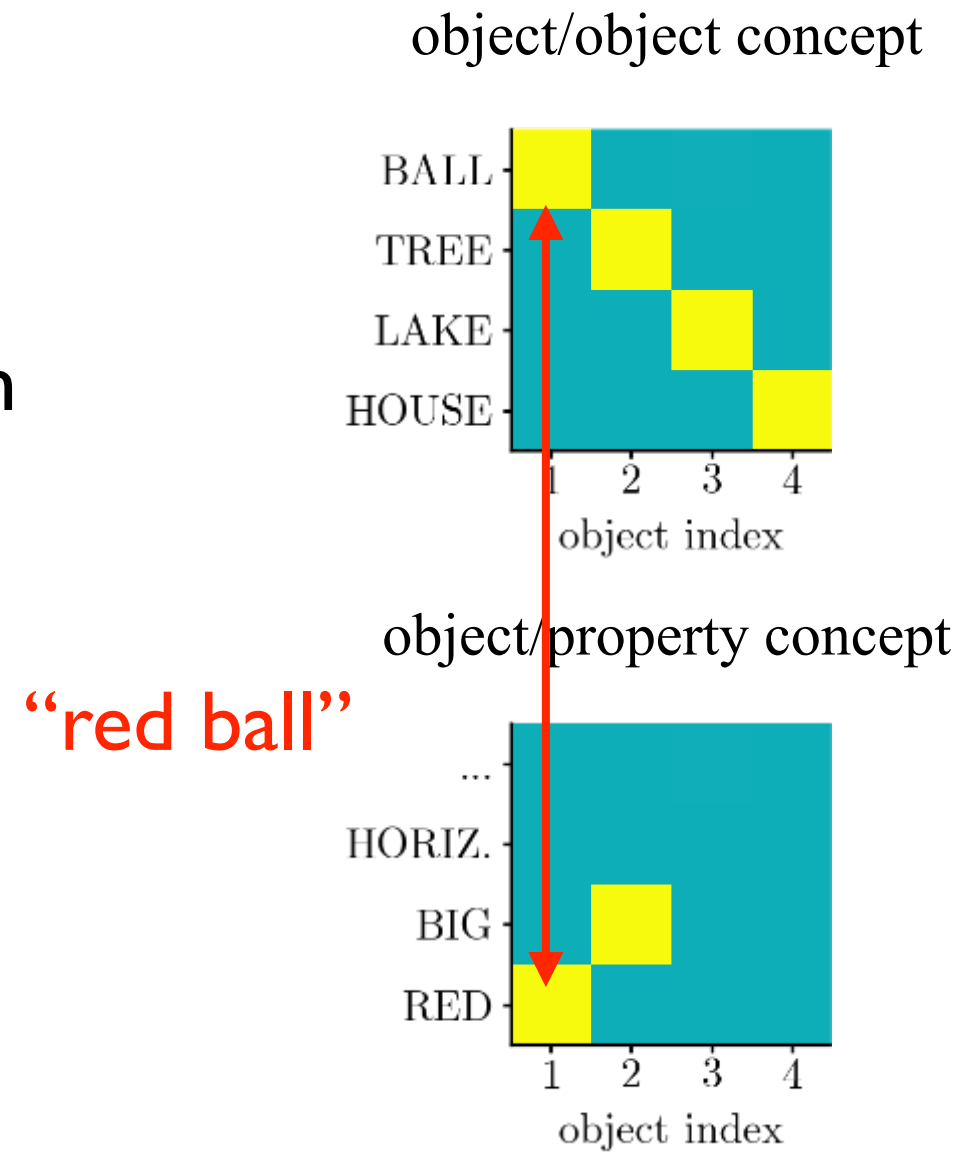
- process account in DFT: ordinal dimension from sequence generation



[Sandamirskaya, Schöner, *Neural Networks*, 2010]

Binding through ordinal dimension

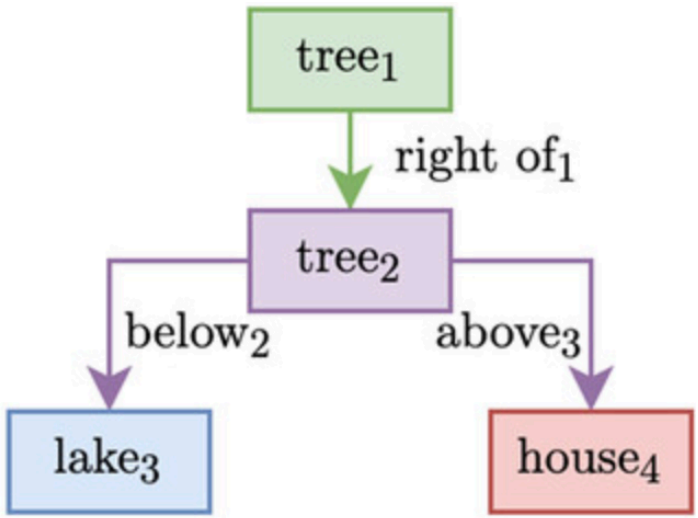
- concepts embedded in a shared ordinal dimension

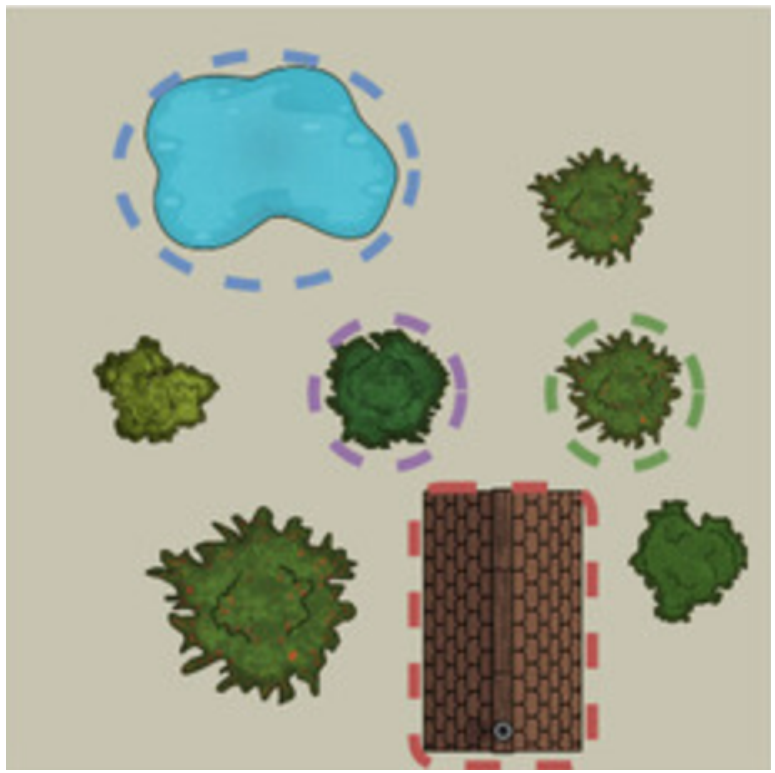


[Sabinasz, Schöner, TopiCS 2023;
Sabinasz, Richter, Schöner Cog Neurodyn 2023]

Binding through ordinal dimension => grounded higher cognition

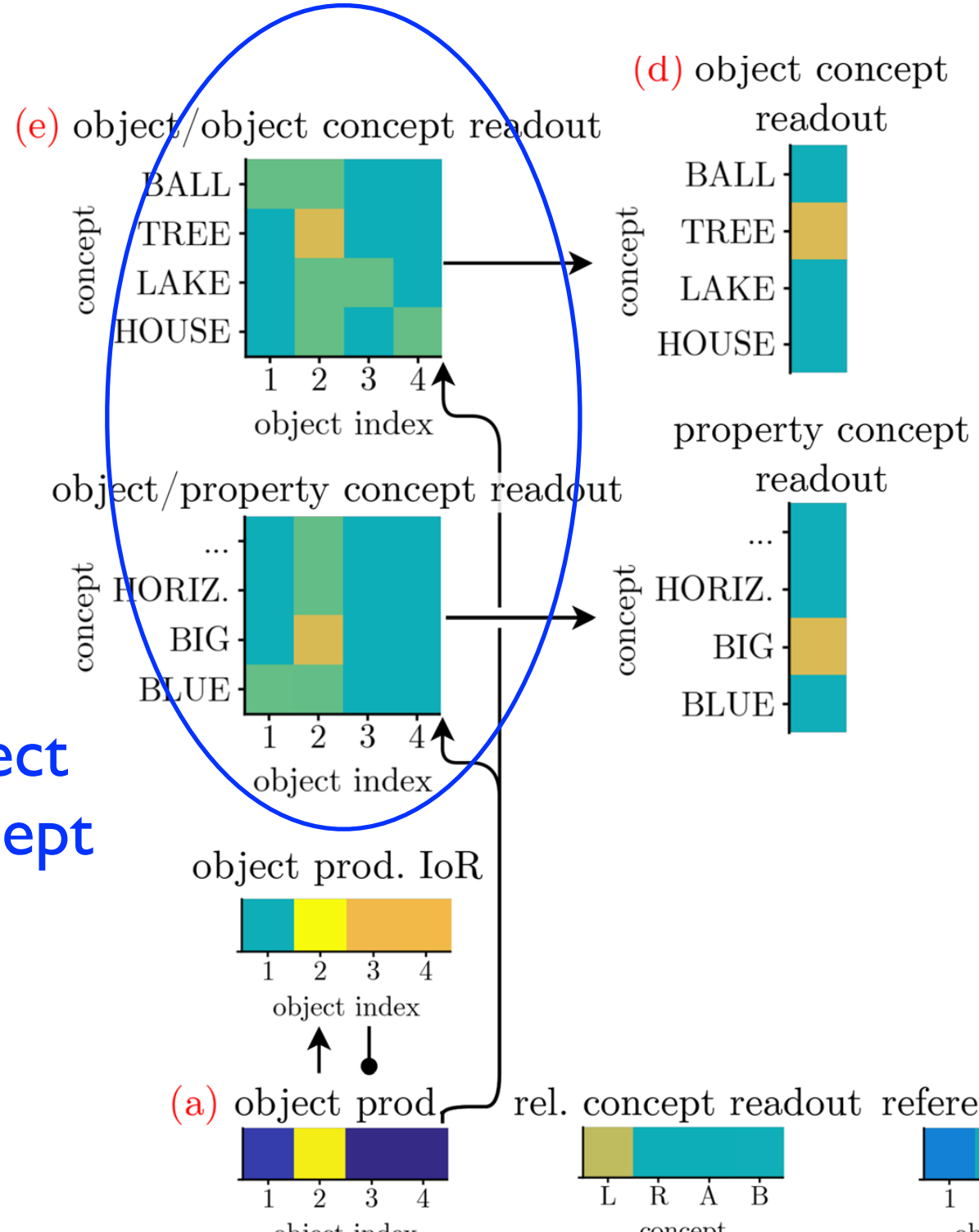
"the tree to the right of the tree that is below the lake and above the house"





[Sabinasz, Schöner, TopiCS 2023;
Sabinasz, Richter, Schöner Cog Neurodyn 2023]

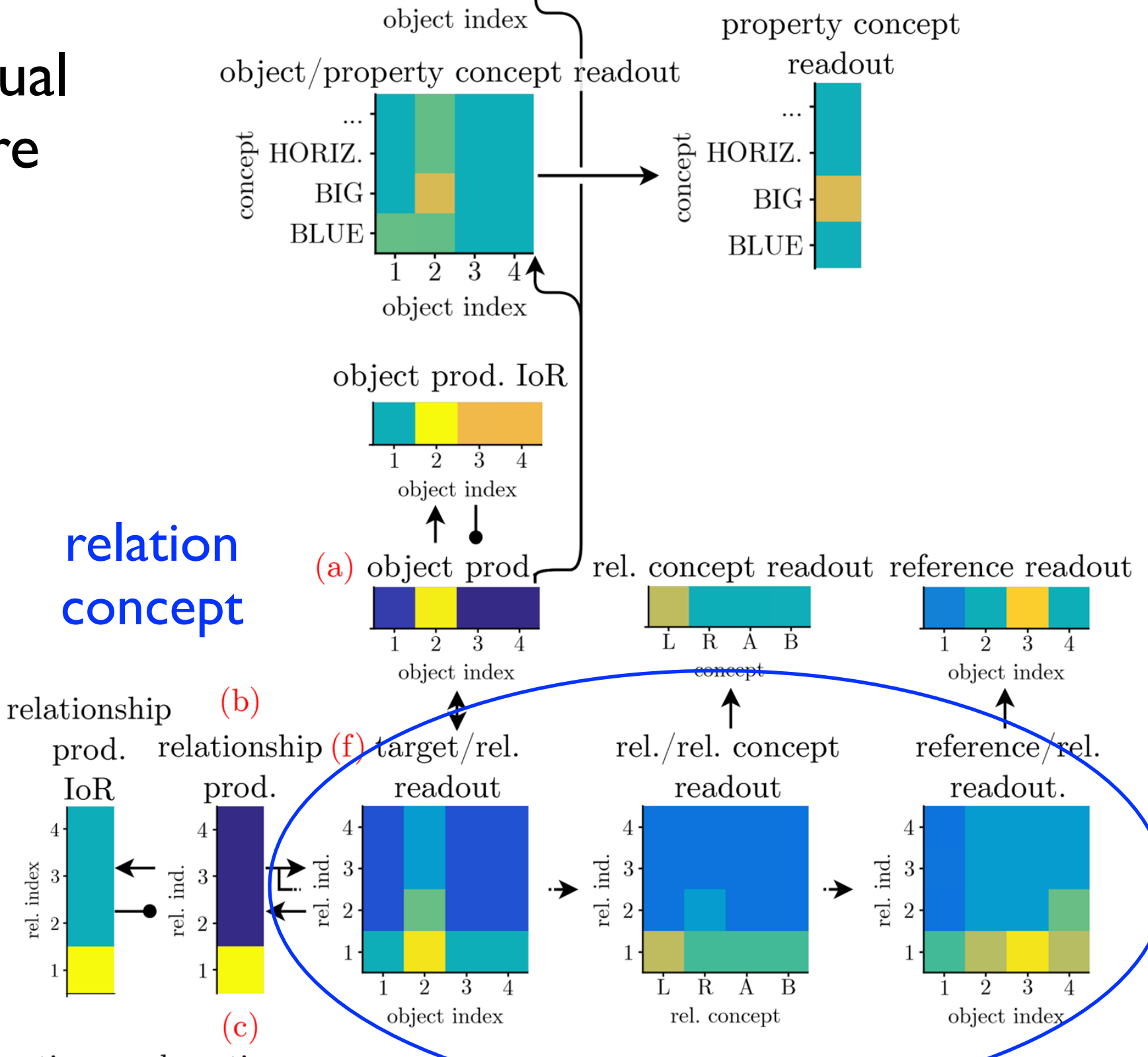
Conceptual structure



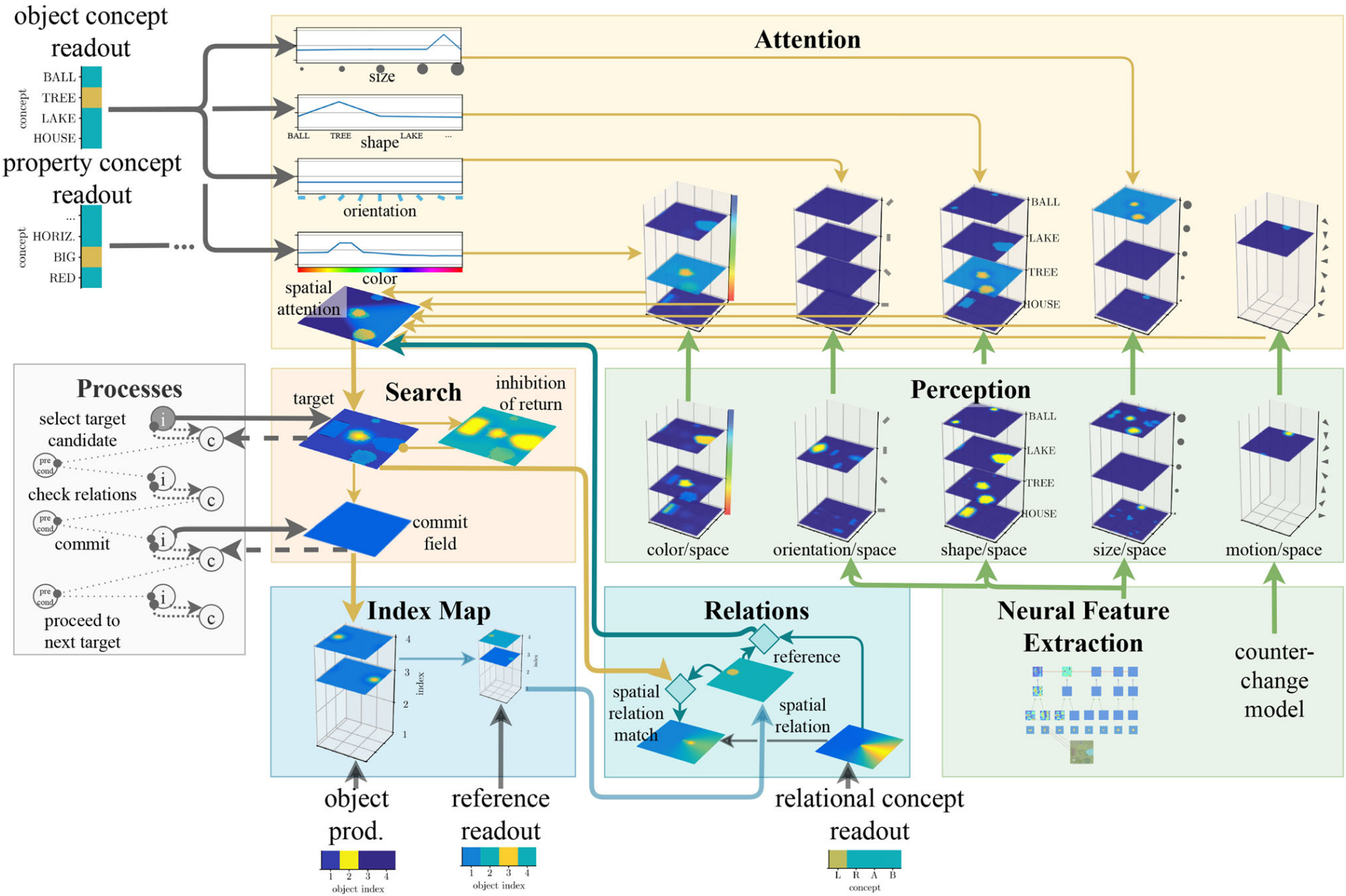
object concept

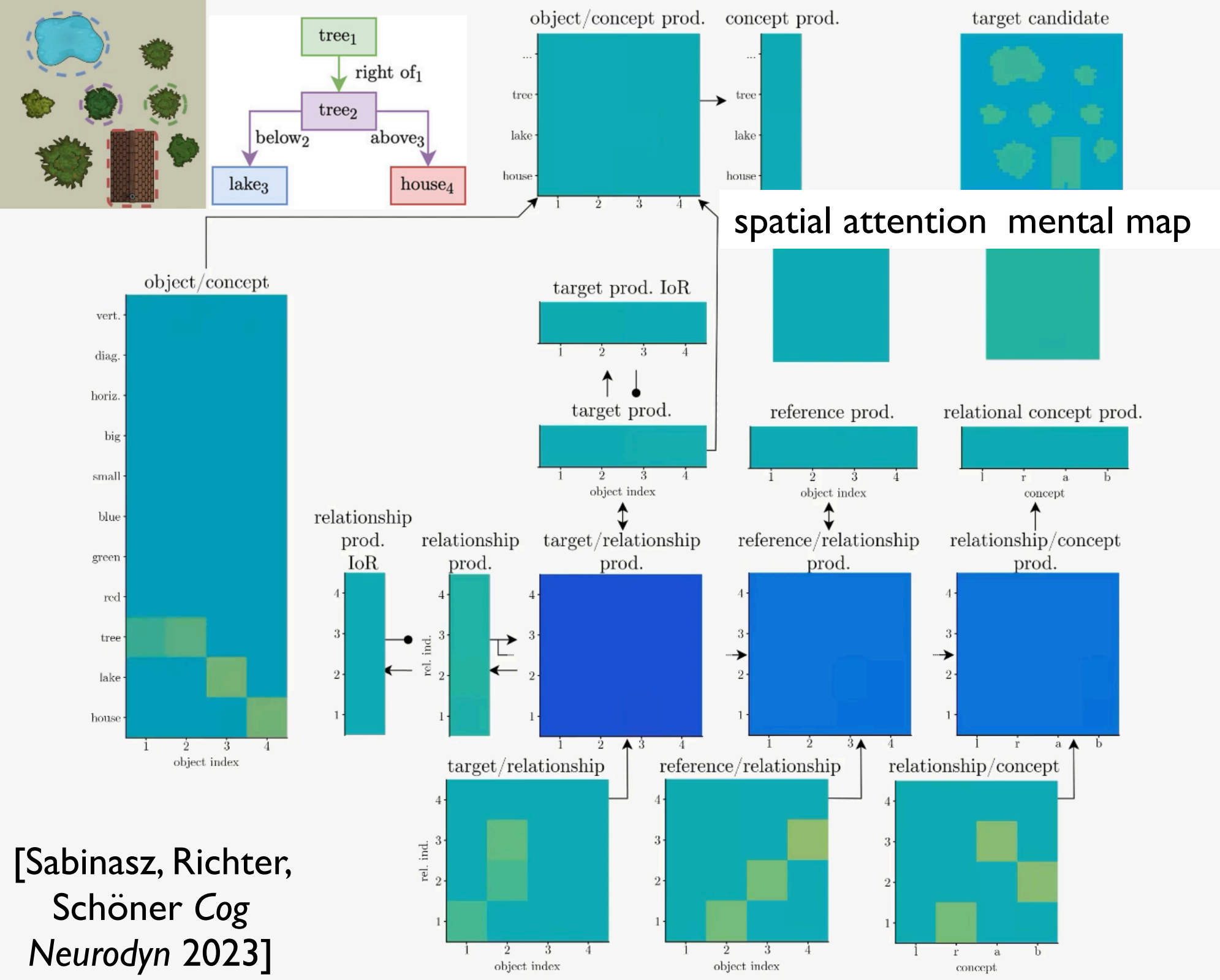
[Sabinasz, Richter, Schöner *Cog Neurodyn* 2023]

Conceptual structure



Perceptual grounding a conceptual structure

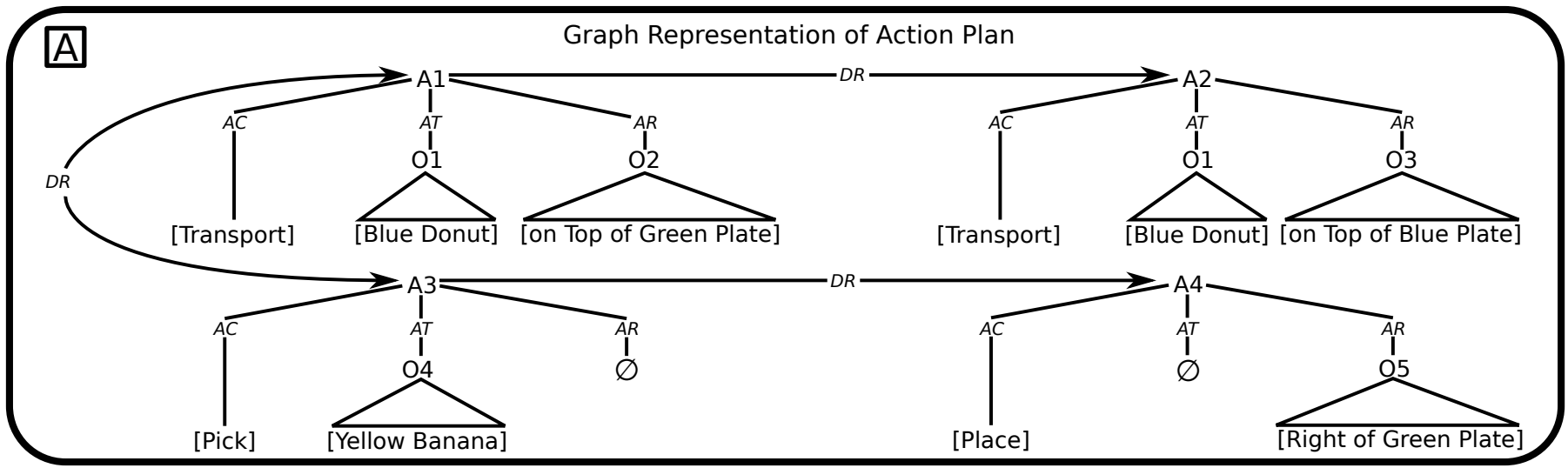




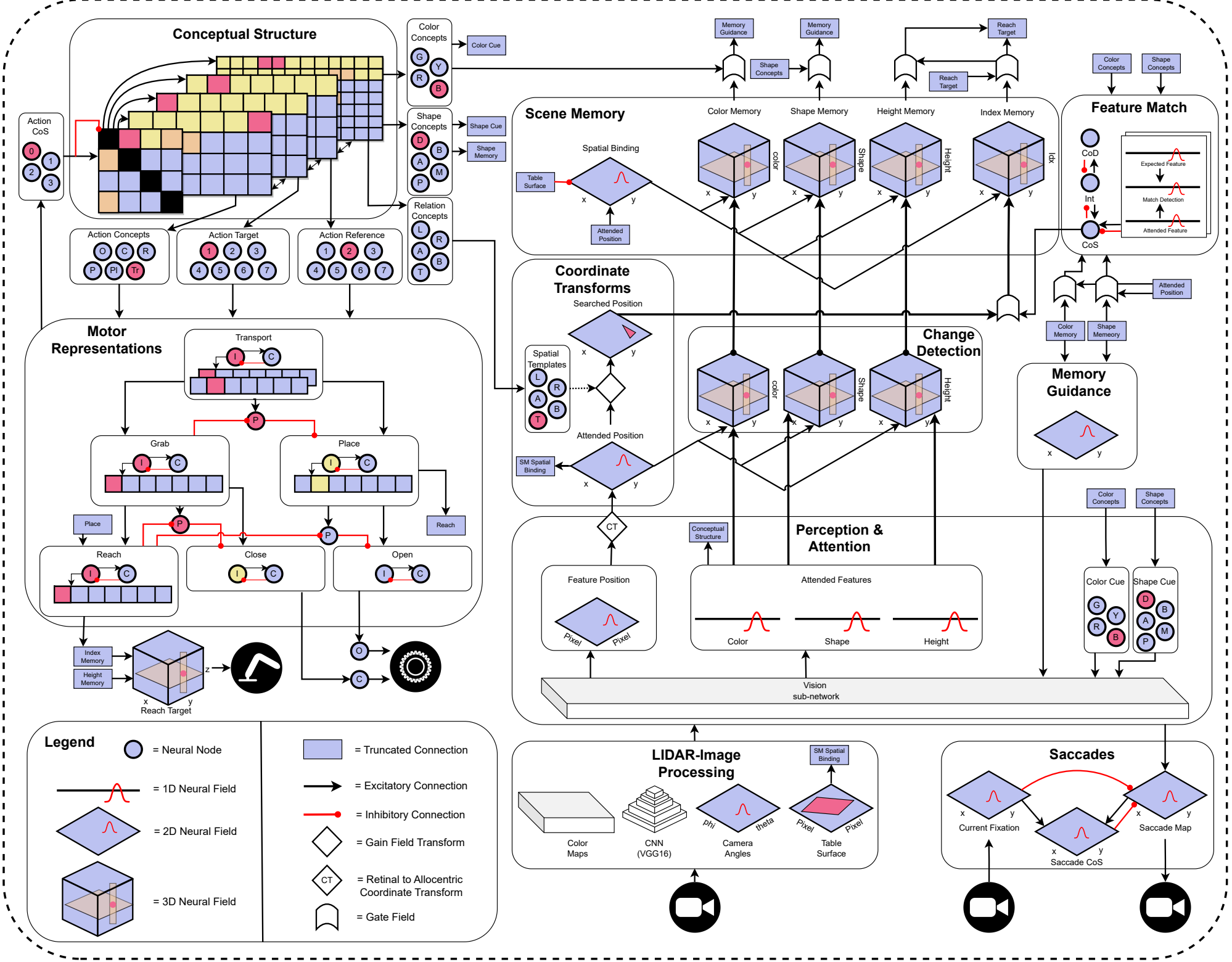
[Sabinasz, Richter, Schöner *Cog Neurodyn* 2023]

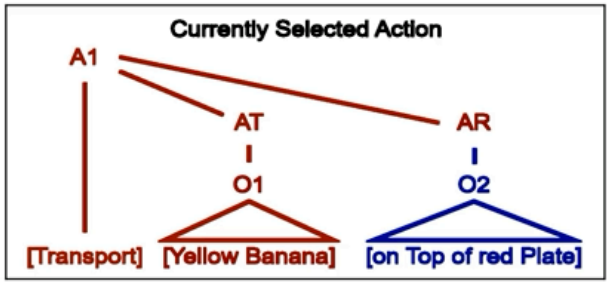
Binding through ordinal dimension => embodied higher cognition

"transport blue donut onto green plate
then transport blue donut to blue plate
or pick yellow banana
and place to the right of the green plate"

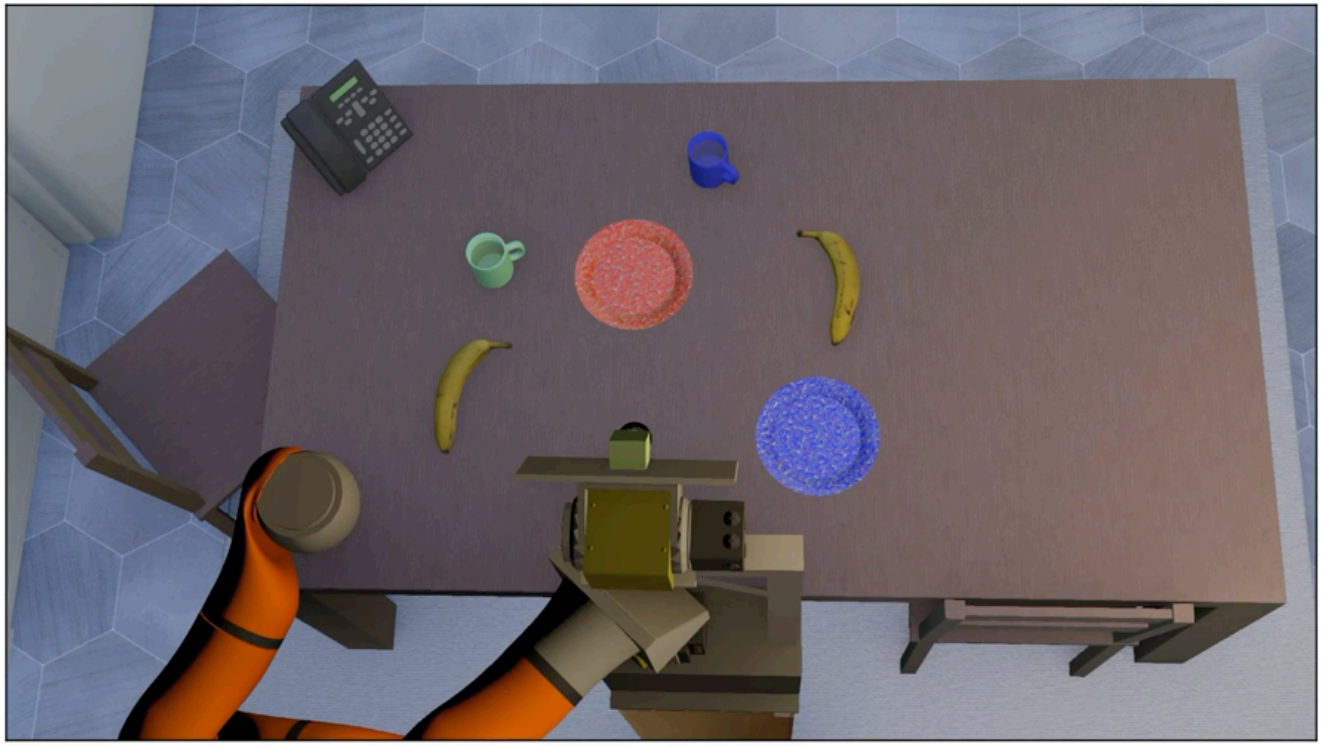


[Sehring et al. *CogSci* 2024]

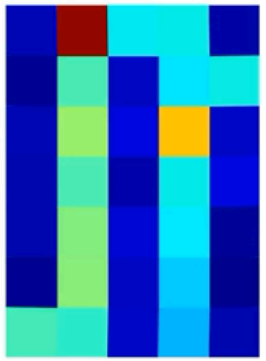

Conceptual Structure
Action CoS
Color Concepts
Color Cue
Shape Concepts
Shape Cue
Shape Memory
Relation Concepts
Action Concepts
Action Target
Action Reference
Memory Guidance
Reach Target
Scene Memory
Color Memory
Shape Memory
Height Memory
Index Memory
Spatial Binding
Table Surface
Attended Position
Feature Match
CoD
Int
CoS
Expected Feature
Match Detection
Attended Feature
Coordinate Transforms
Searched Position
Spatial Templates
SM Spatial Binding
Change Detection
Memory Guidance
Color Memory
Shape Memeory
Motor Representations
Transport
Grab
Place
Reach
Close
Open
Index Memory
Height Memory
Reach Target
CT
Conceptual Structure
Perception & Attention
Feature Position
Pixel
Attended Features
Color
Shape
Height
Color Cue
Shape Cue
Vision sub-network
LIDAR-Image Processing
Color Maps
CNN (VGG16)
Camera Angles
Table Surface
phi
theta
Saccades
Current Fixation
Saccade Map
Saccade CoS
Legend
= Neural Node
= 1D Neural Field
= 2D Neural Field
= 3D Neural Field
= Truncated Connection
= Excitatory Connection
= Inhibitory Connection
= Gain Field Transform
= Retinal to Allocentric Coordinate Transform
= Gate Field



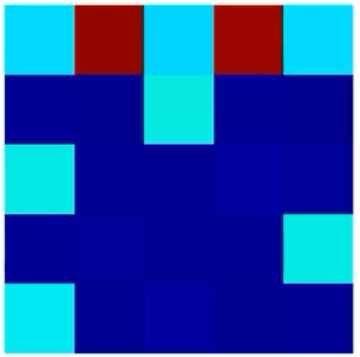
Scene



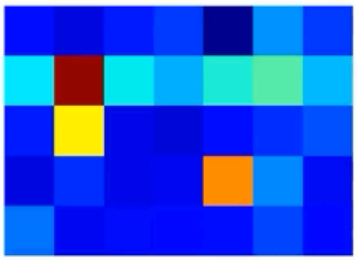
Act. Sel. - Activation



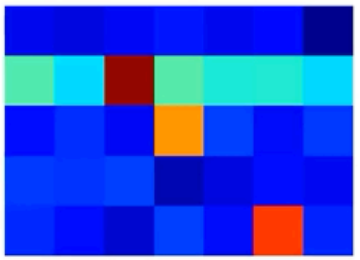
Seq. Dep. - Activation



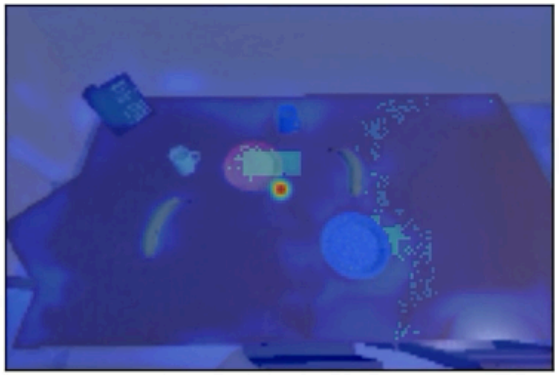
Target - Activation



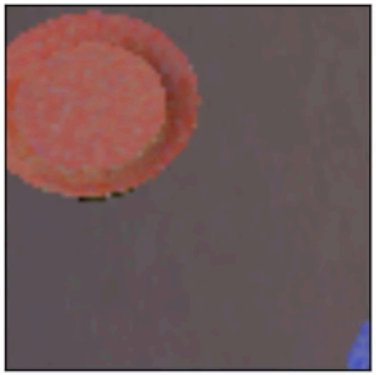
Reference - Activation



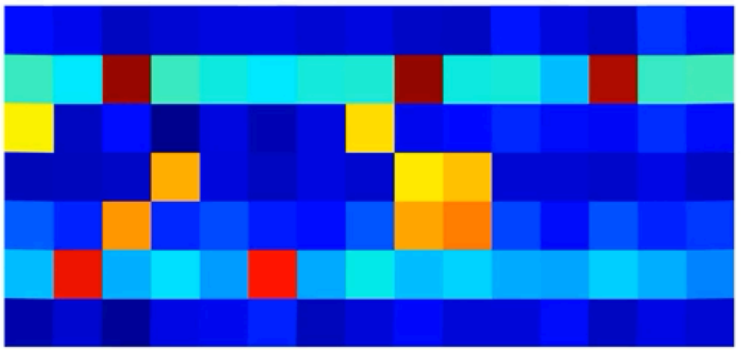
Expl. FVF - Input



Att. FVF - Activation



Obj. Sel. - Activation



DFT

- connectionism
- + space
- + attractors/ instabilities
- => autonomy
- => binding

- neural processes account of
  - grounded
  - embodied
  - higher
- cognition

Questions

- Why dynamics? Why attractors?
- Are not all neural processing transient?
- Why neural populations?
- Why continuous spaces?
- In which sense are neural fields low-dimensional?
- Why are neural representations in DFT localist?

Questions

- Is DFT part of computational neuroscience?
- Why is DFT not a computational theory?
- Are DFT architectures = cognitive architectures?
- Is DFT in conflict with VSA?
- Is DFT in conflict with NEF?