Hands-on Neural Process Modeling through Dynamic Field Theory (DFT)

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What is DFT?

- =neural process account of thinking and acting…
  - that may actually bring about thoughts and action
  - that explains the laws of thinking and acting
  - while respecting neural principles

Central hypothesis of DFT: embodiment

- thinking and acting are brought about by the embodied and situated brain that is shaped by evolution and development

Central hypothesis of DFT: embodiment

- thinking and acting are brought about by the embodied and situated brain that is shaped by evolution and development
- => neural processes with continuous state, continuous time, potential coupling to the sensory and motor surfaces, and stability

Autonomy

- the neural principles of DFT ~ connectionism
- but: conceptually, most current neural network accounts are input driven
- while thought and action are driven by the inner state of the mind/brain = autonomous neural processing
- =>DFT must address how inner states arise, persist, and evolve in time

Integration

- (embodied) cognition entails many different processes probed in a large variety of paradigms
- DFT is aimed to provide a single theoretical language to understand all these processes and how they interrelate

Dynamic Field Theory (DFT)

- 1 Space: inner states are localized activation patterns in low-dimensional features spaces
- 2 Time: autonomy derives from neural dynamics, attractors and dynamic instabilities
- 3 Coupling: cognition emerges from dynamic coupling across low-dimensional features spaces
- 4 Integration: in DFT architectures

I Space

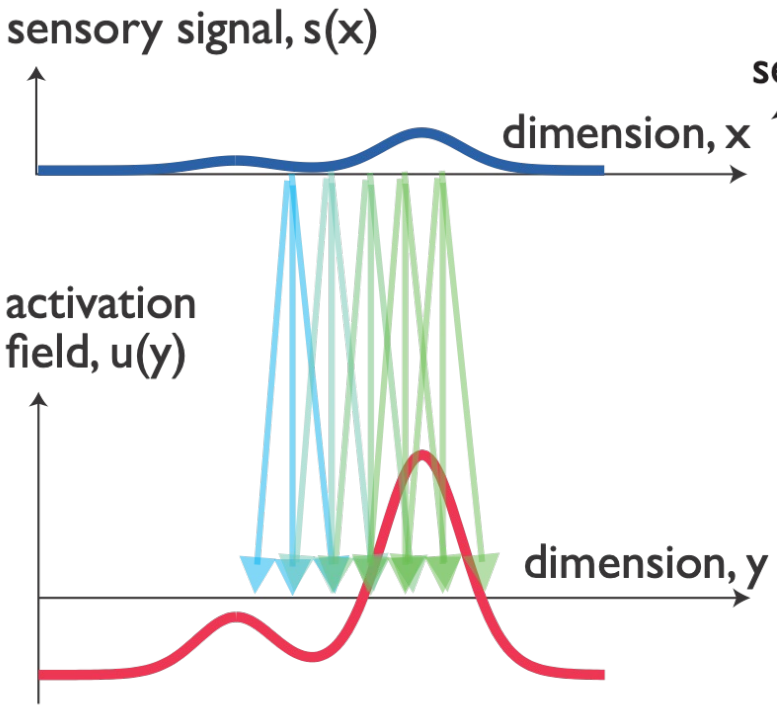
- activation in neural populations carries functional meaning
- activation: $u(x,t)$ where x spans low-dimensional spaces

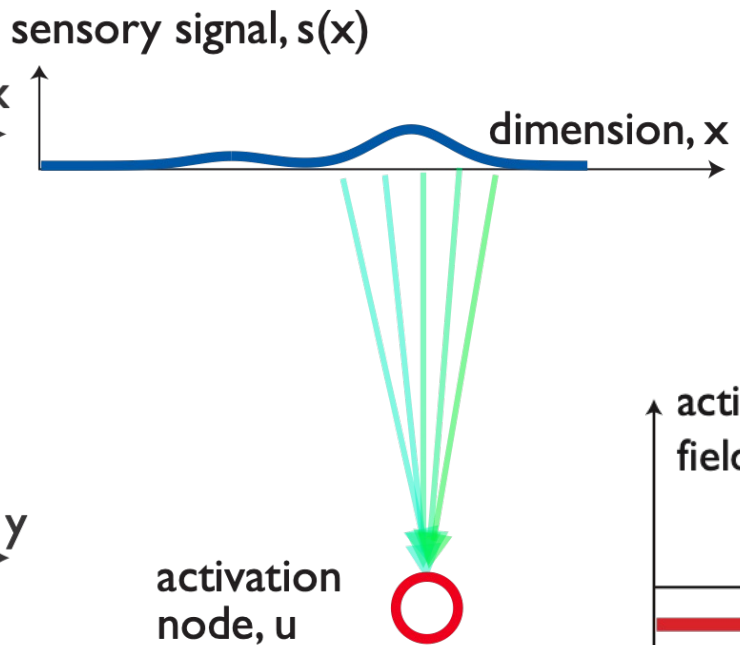
[Schöner TopiCS 2019]

Feature spaces from forward connectivity

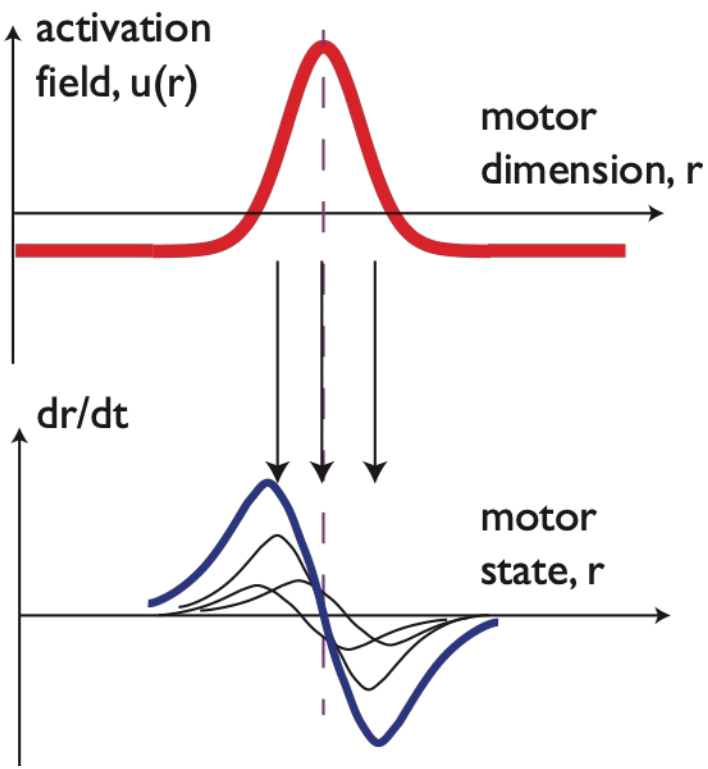
from sensory surfaces

to motor surfaces





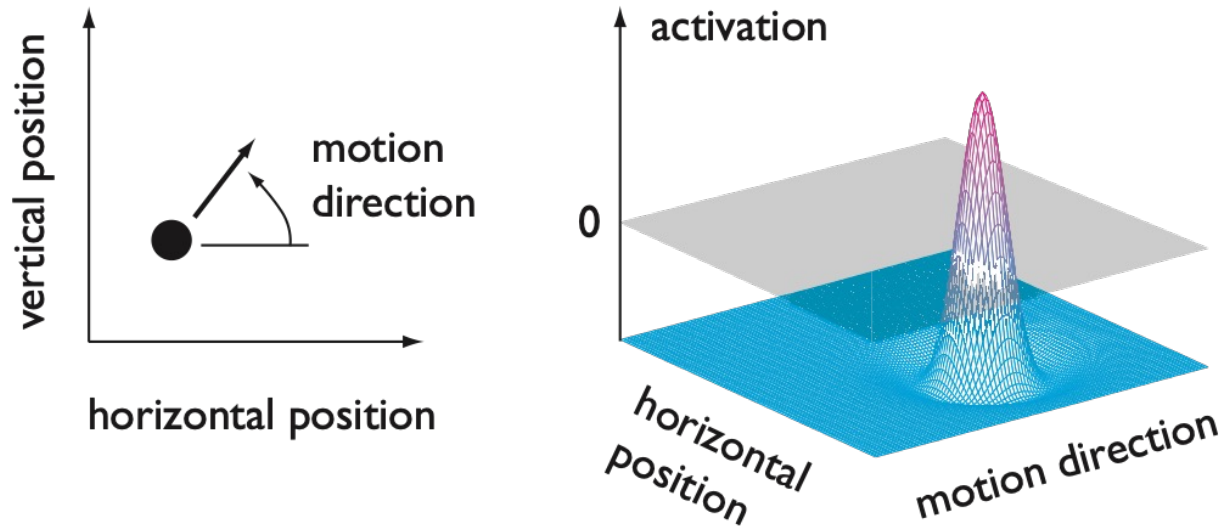
motor space

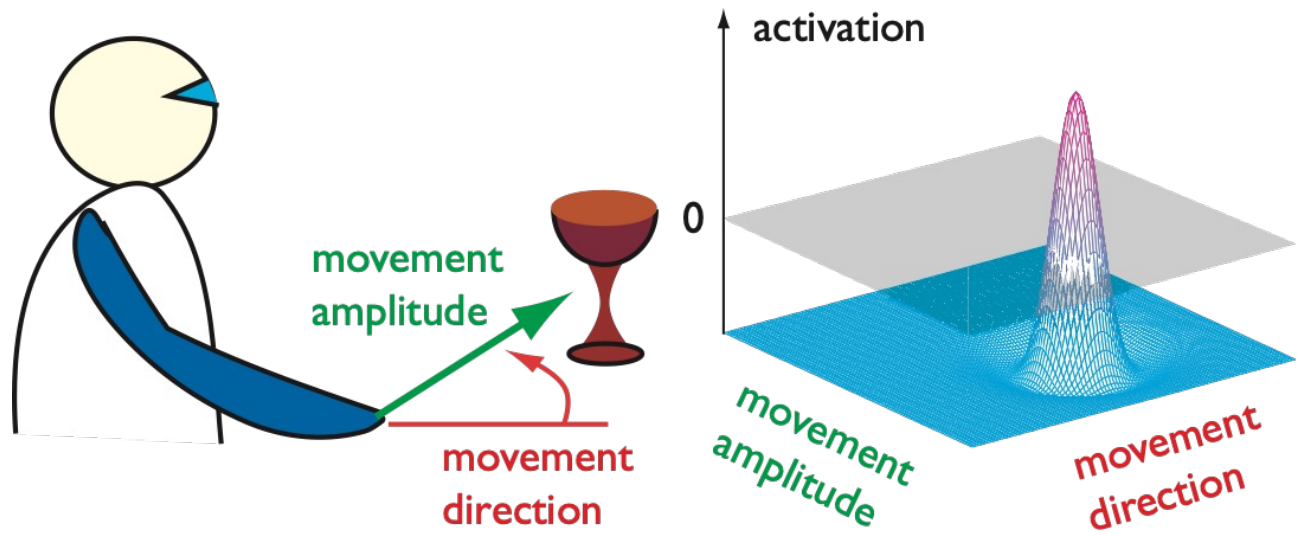


feature space

concepts

Hypothesis: mental states are activation patterns localized in low-dimensional feature spaces





- [~ *Gärdenfors*]

2 Time

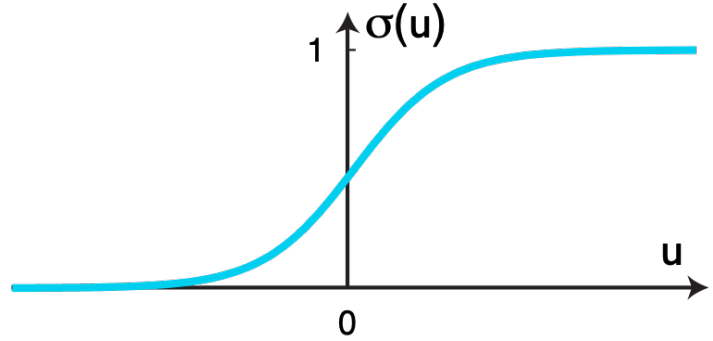
membrane dynamics

resting level

input

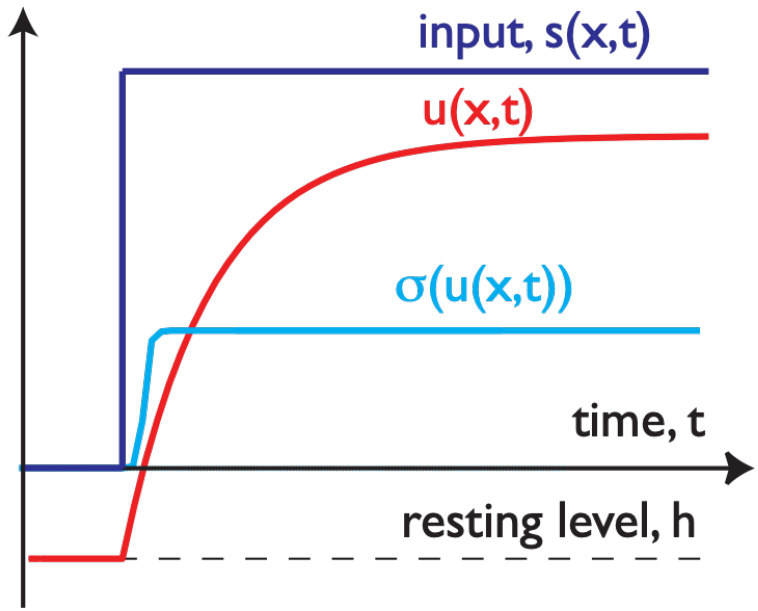
$$\tau \dot{u}(x,t) = -u(x,t) + h + s(x,t)$$

- Neural dynamics: continuous activation evolves in continuous time toward attractors



- [~ *Grossberg*]

- but: so far only transmits and smooths input time courses



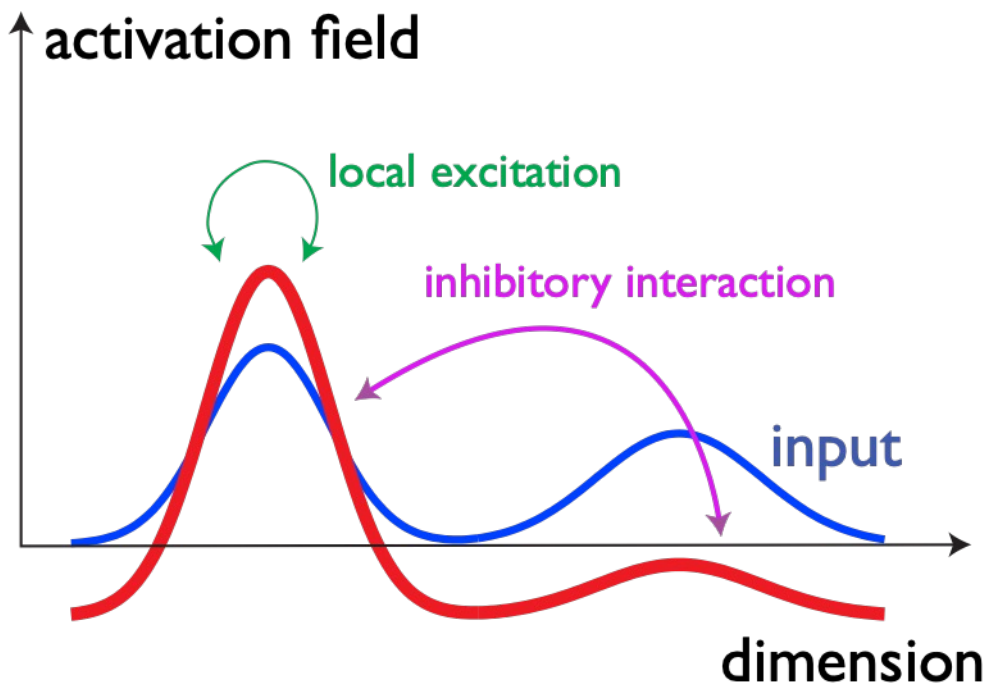
…beyond input driven activation

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

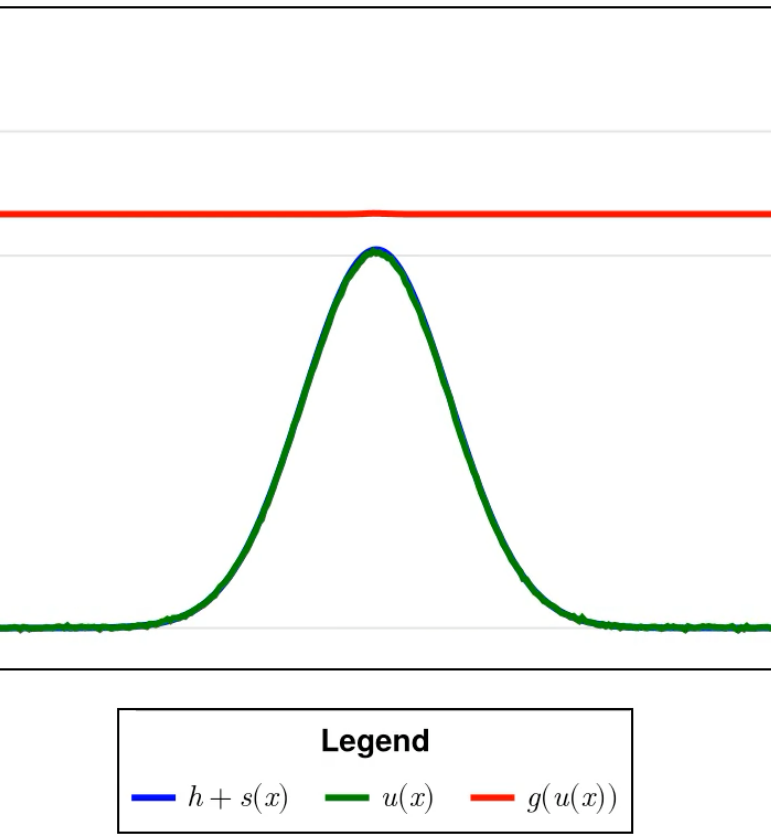
$$+\int w(x-x')\sigma(u(x',t))dx'$$

interaction

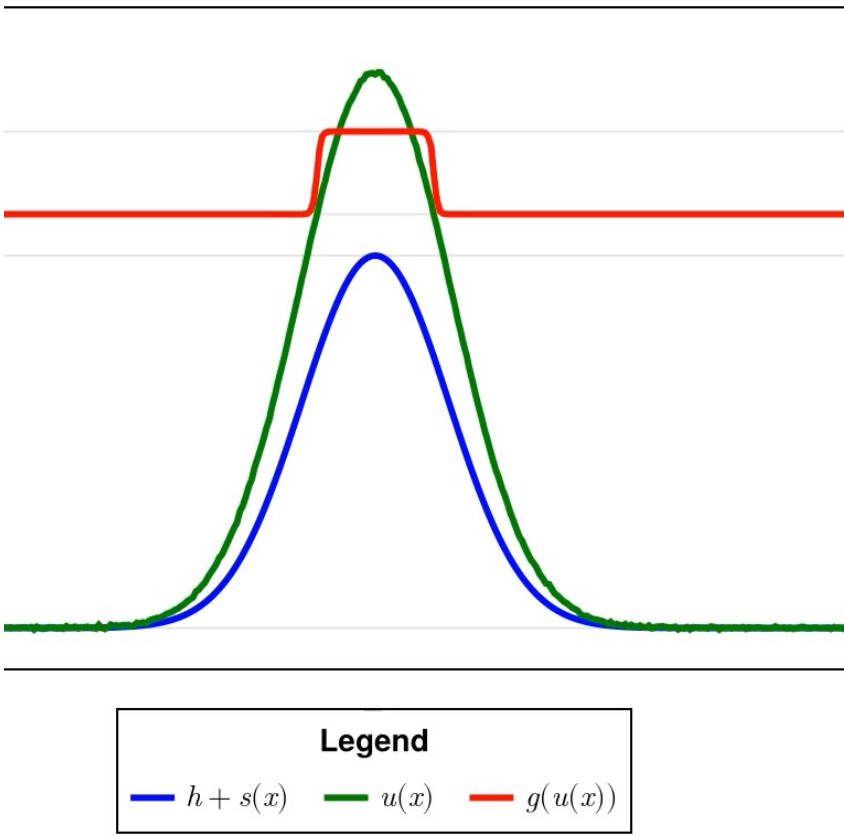
- strong recurrent connectivity within populations
- excitatory: *w>0* for neighbors in space
- inhibitory: *w<0* over larger spatial distance



- detection instability of sub-threshold state => peak
- peak persists below detection instability => bistable
- reverse detection instability of peak => sub-theshold



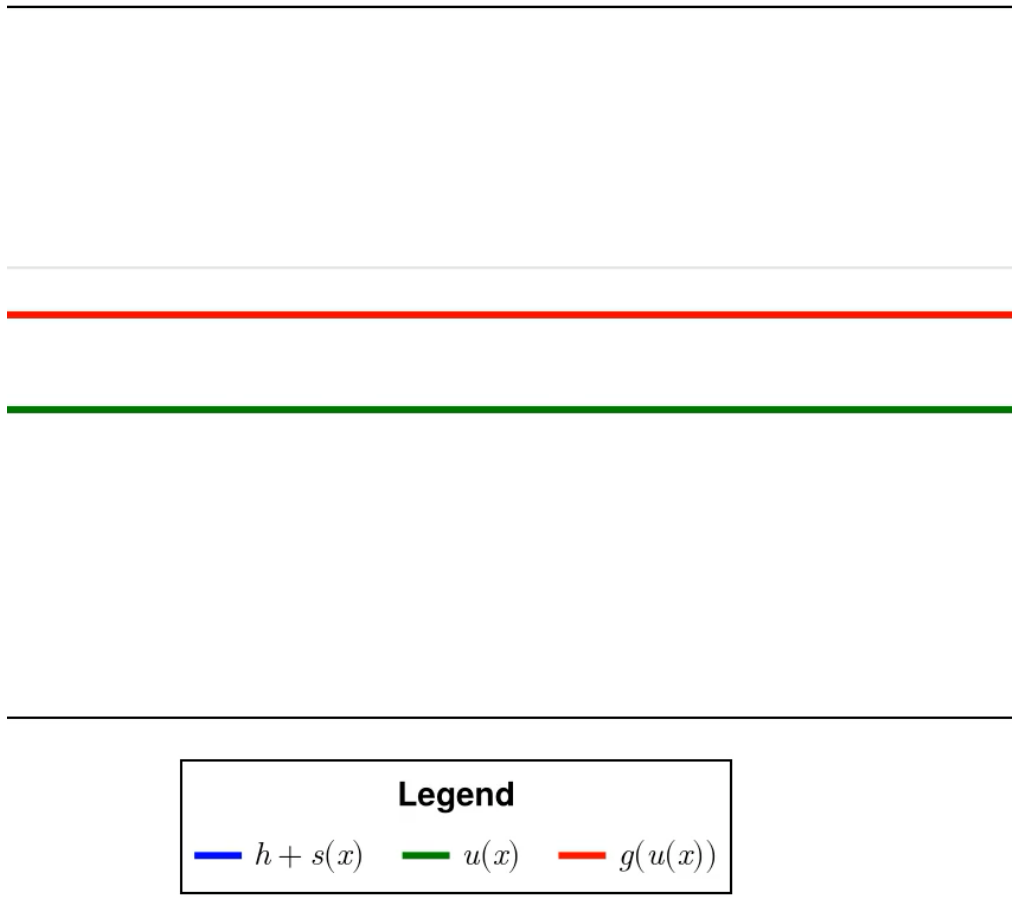
bistable:
same input
two stable
states



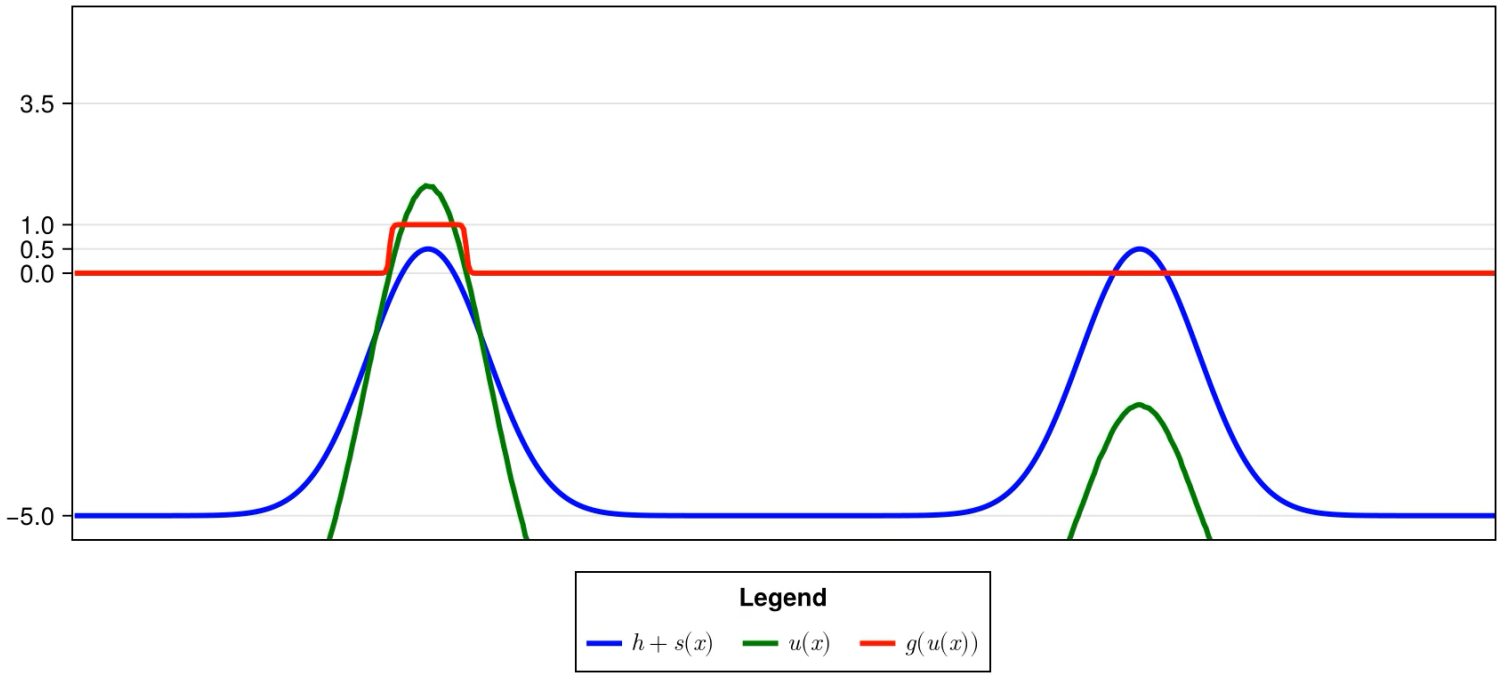
Autonomy from attractors and their instabilities

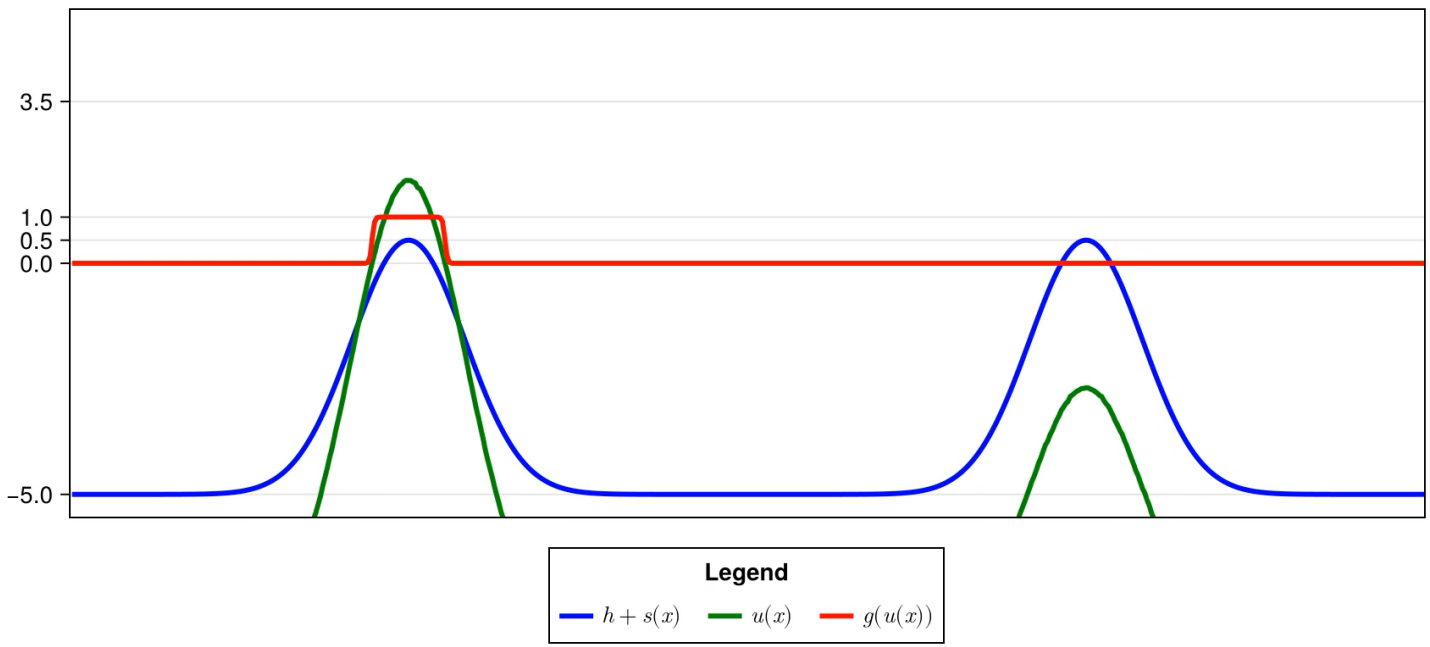
- detection instability
- reverse detection instability
- sustained activation
- selection
- selection instability
- boost driven detection/selection
- match events and sequences

- sustained activation
- ~working memory

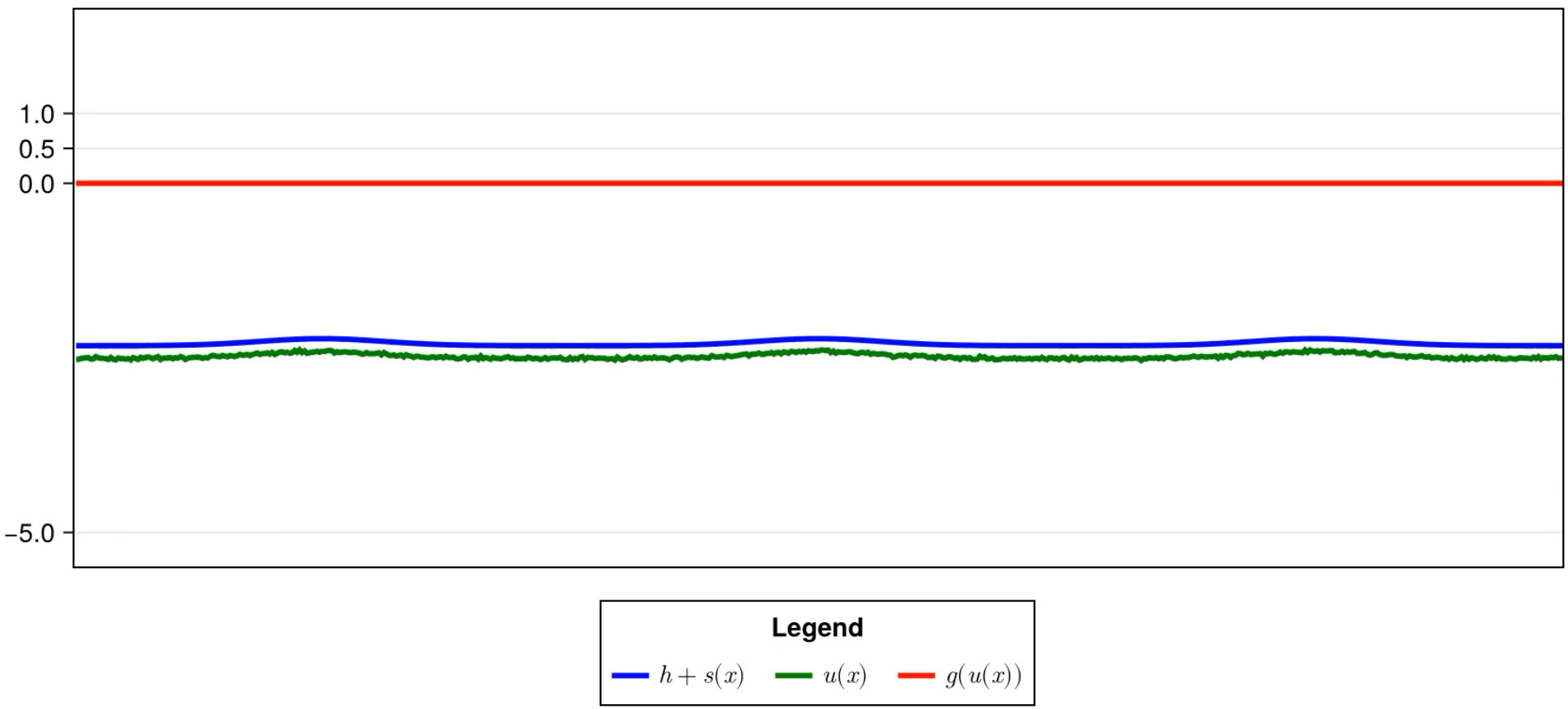


- selection
- selection instability

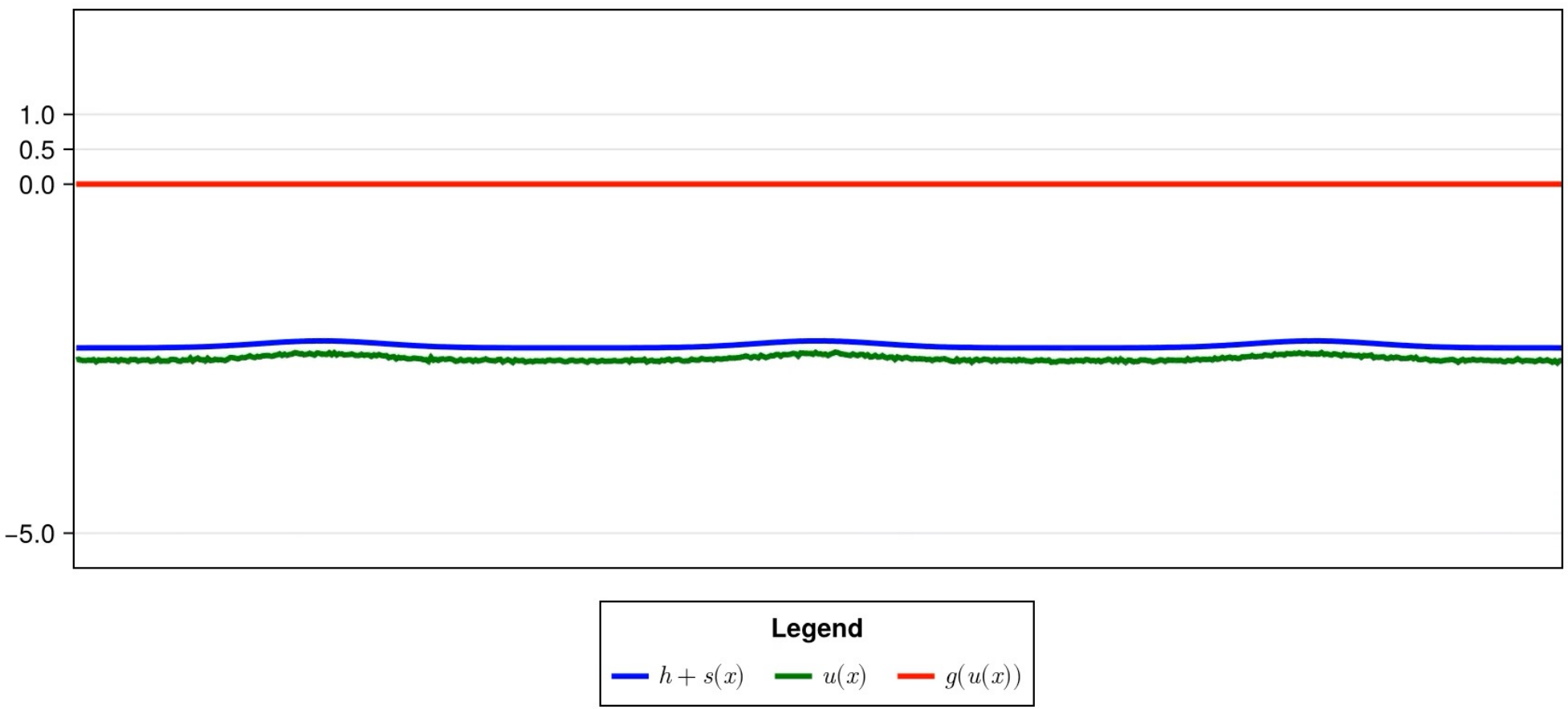




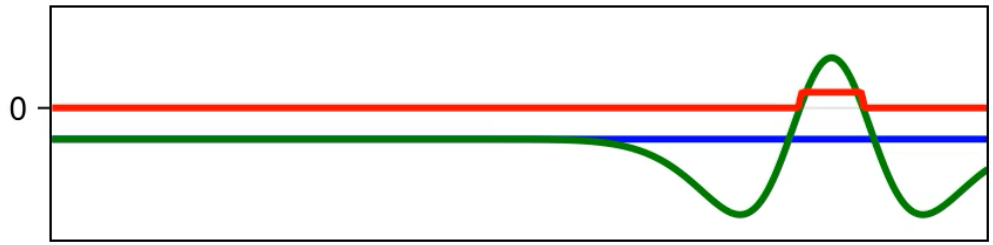
- detection and selection induced by homogeneous boost
- => peak forms that amplifies small inhomogeneities



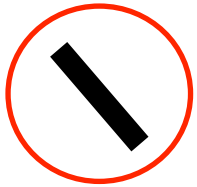
- detection and selection induced by homogeneous boost
- => categories emerge from continuous spaces



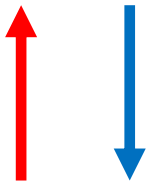
- match detection
- => event



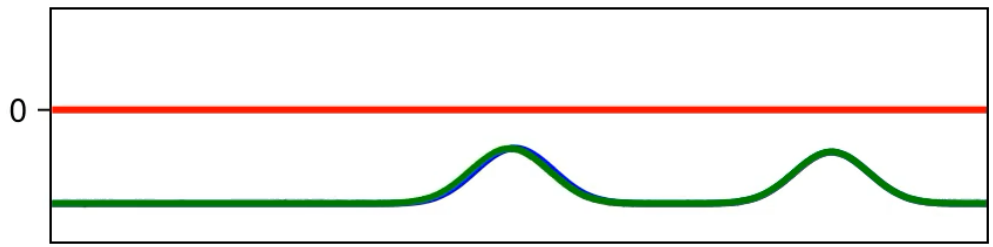
intention



inhibit



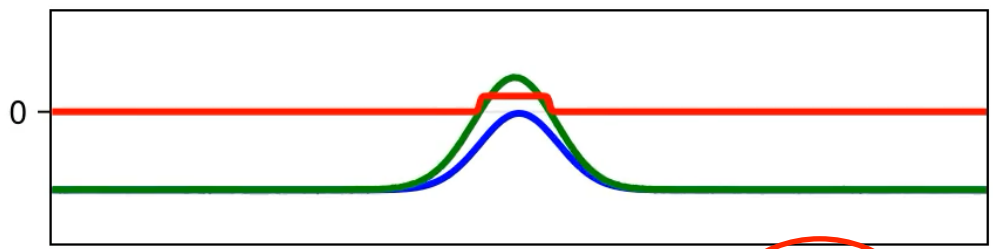
predict

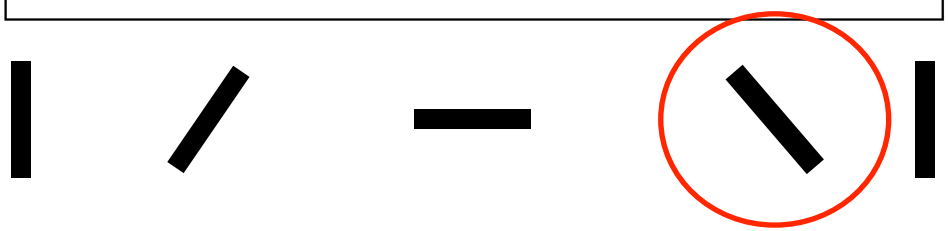


condition of satisfaction

stimulus

- => basis of autonomous sequence generation





percept

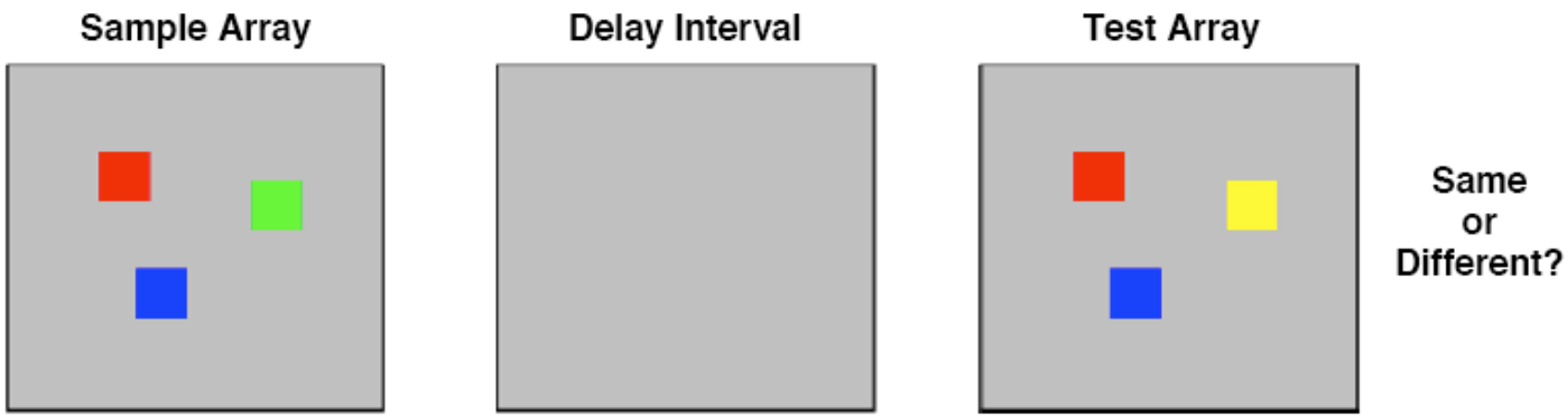
Autonomy from attractors and their instabilities

- detection instability
- reverse detection instability
- sustained activation
- selection
- selection instability
- boost driven detection/selection
- match events and sequences

Empirical evidence

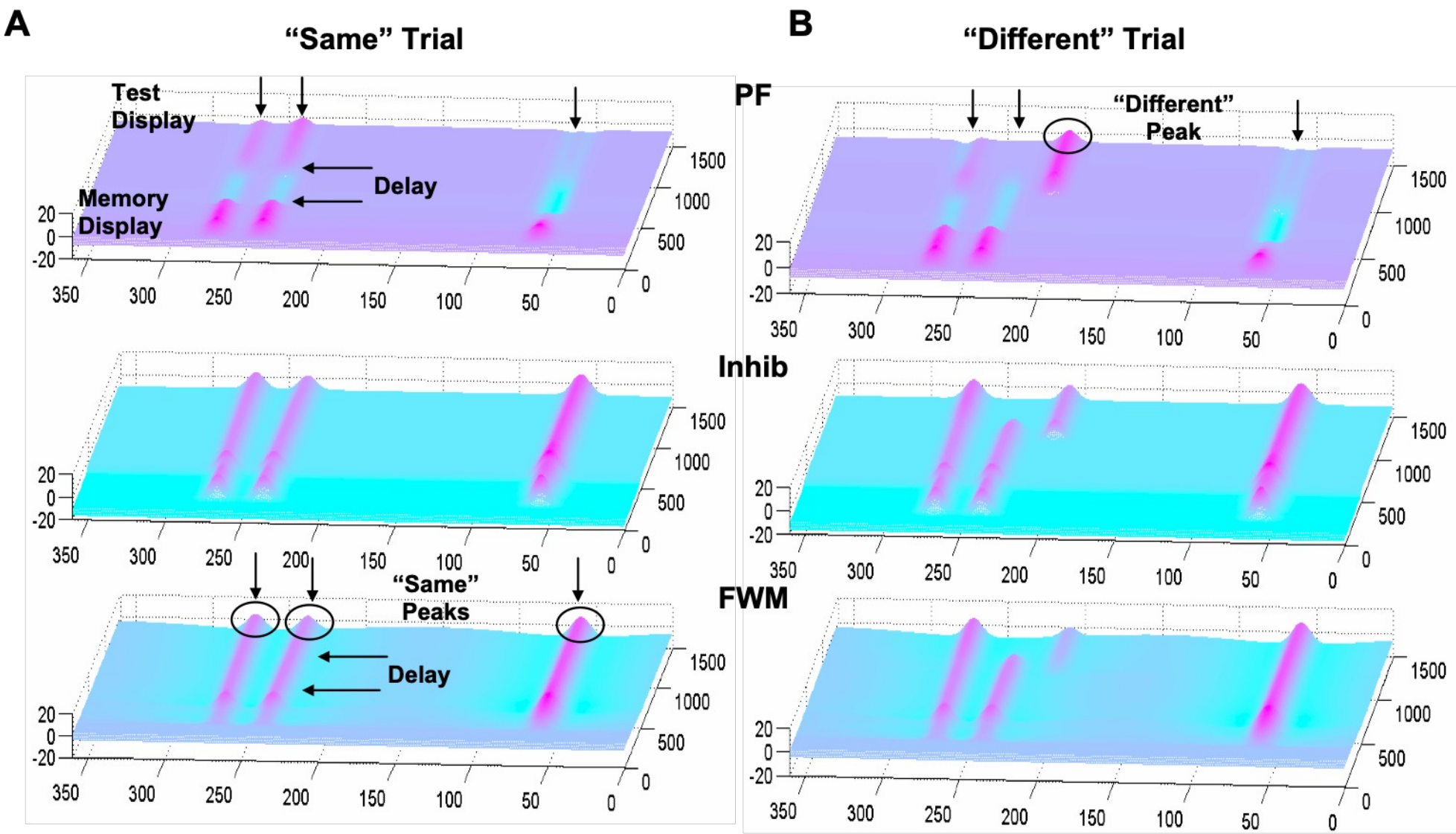
- DFT has been used in many different fields to account for experimental data
- Core: metric effects, space-time effects..

Example: visual working memory



[Johnson, Spencer, Luck, Schöner: *Psychological Science* 2008]

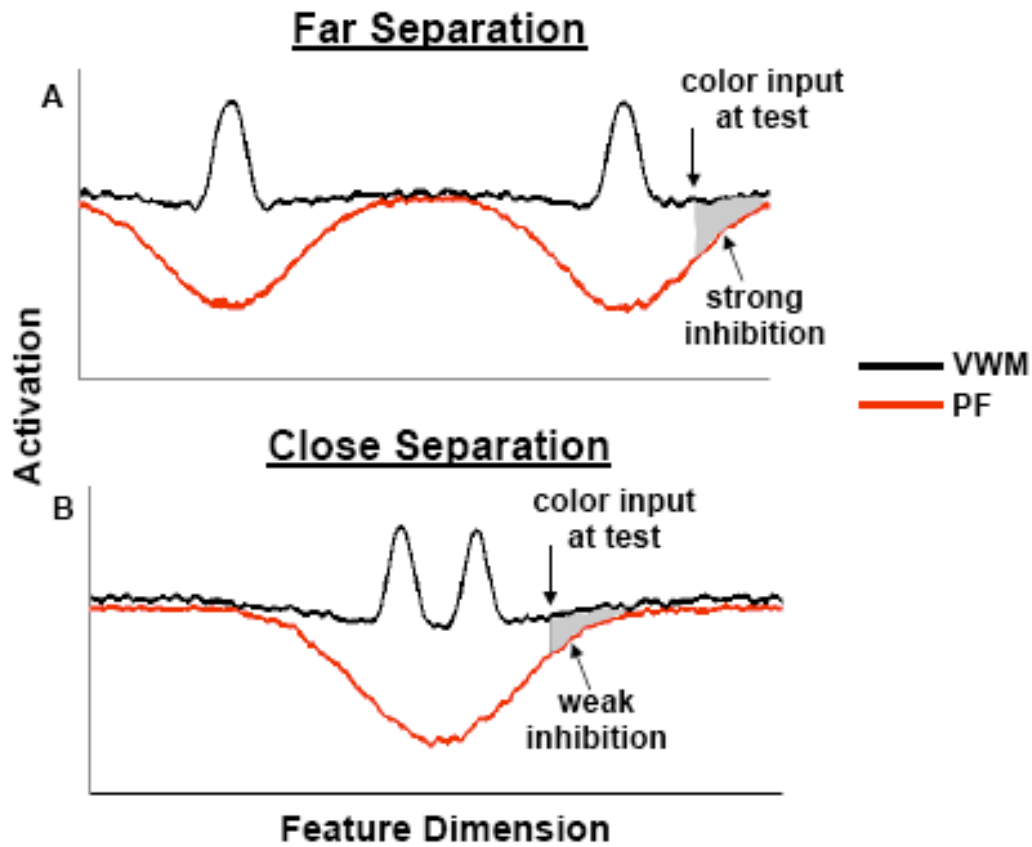
DFT model of change detection



[Johnson, Spencer, Schöner: *New Ideas in Psychology* 2008]

Metric effect

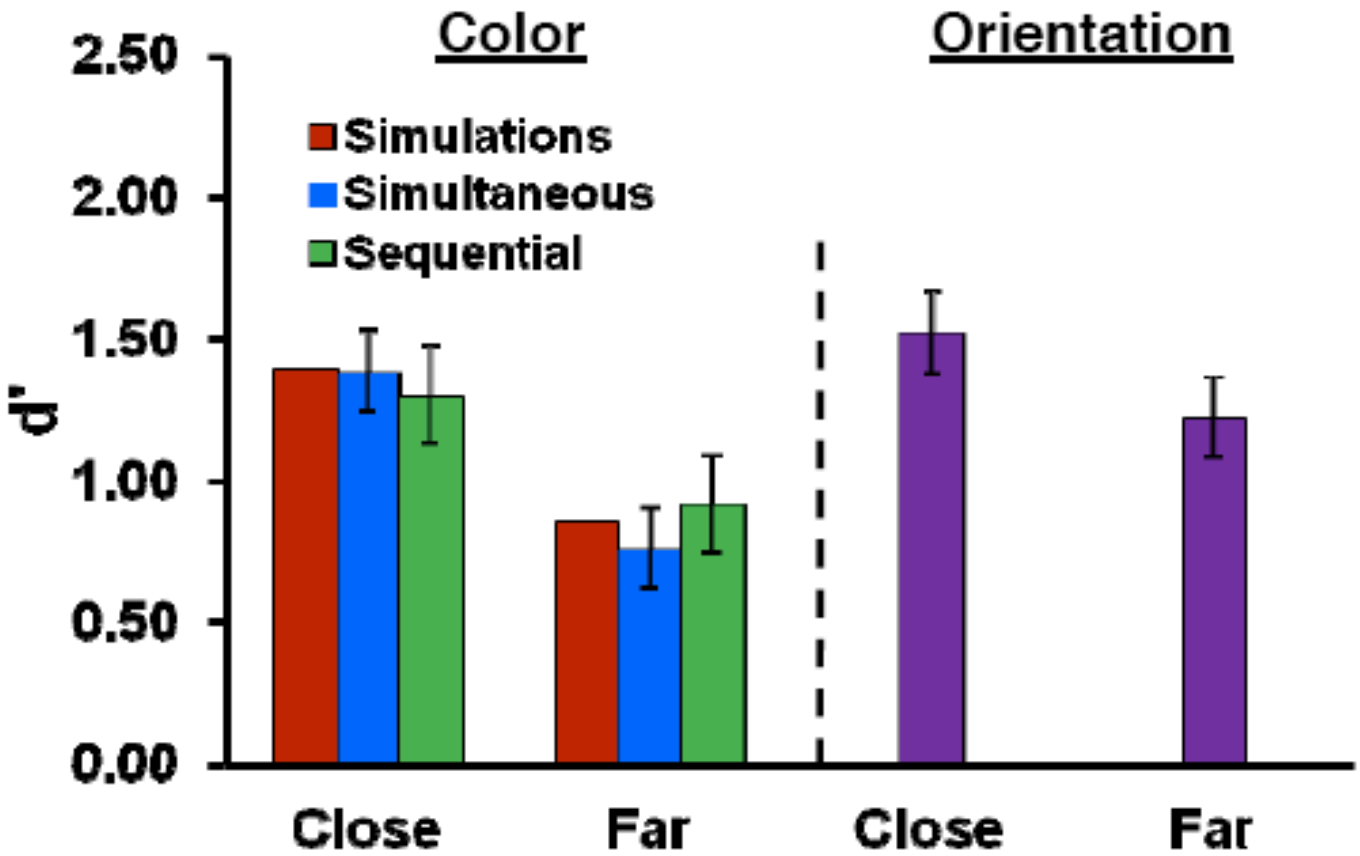
- close metric separation: peaks weakened by overlapping inhibition
- => less inhibition in perceptual layer
- => reduced threshold for change detection



[Johnson, Spencer, Luck, Schöner: *Psychological Science* 2008]

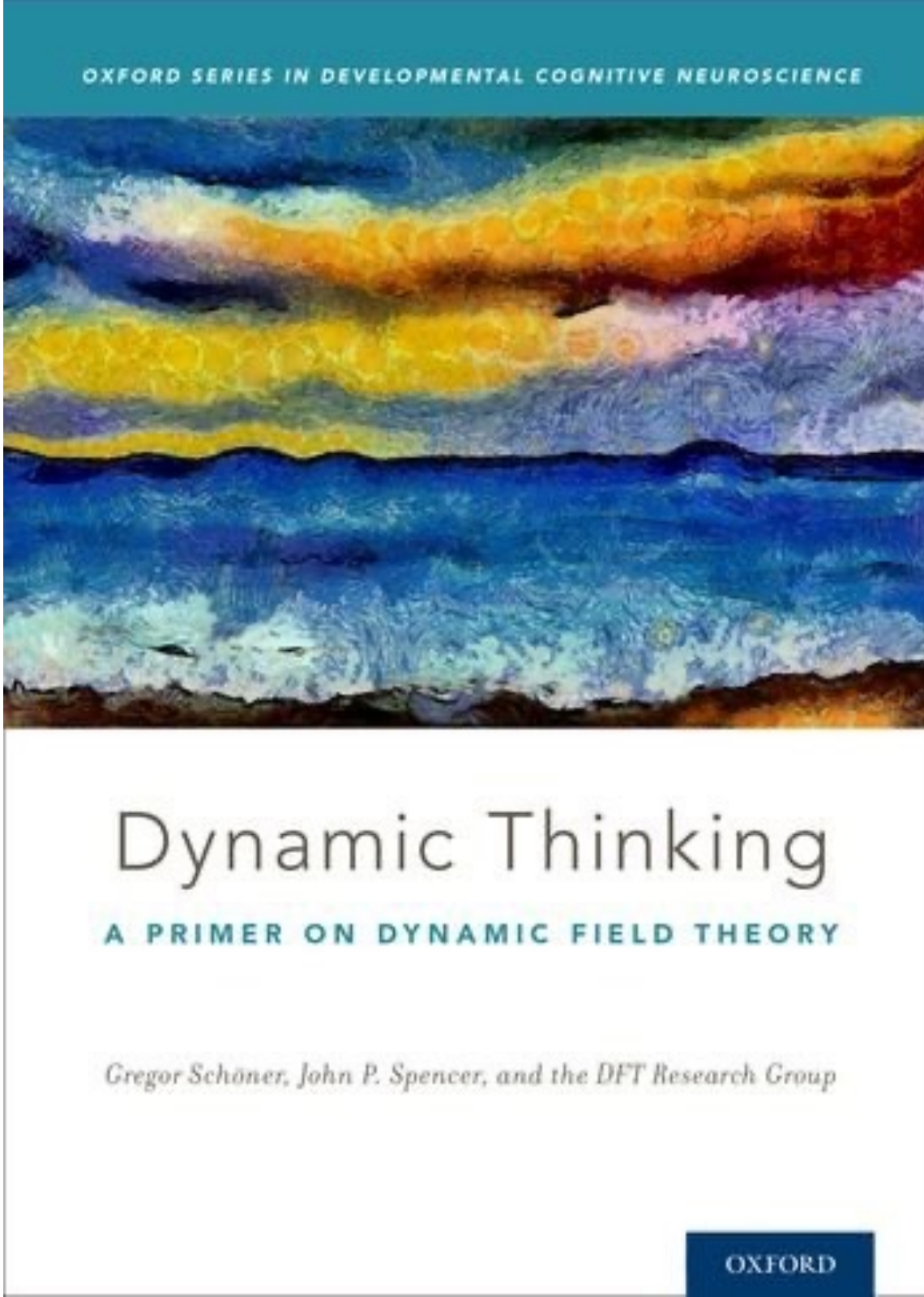
Experimental confirmation

- => predict more sensitive change detection for item that are metrically close!



[Johnson, Spencer, Luck, Schöner: *Psychological Science* 2008]

- the DFT primer
- dynamicfieldtheory.org



- reaction time classical selection decisions *[Erlhagen, Schöner Psych Rev 2002]*
- perseveration selection decisions (development) *[Thelen, Schöner, Scheier, Smith BBS 2001]*
- spatial and visual working memory (development) *[Spencer, Schutte, Simmering, Johnson JEP, Child development and others]*
- cognitive control (development) *[Buss, Spencer Monographs SRCD]*
- habituation and visual memory (development) *[Thelen, GS Psych Rev 2006; Perone, Spencer, Cog Sci 2013]*

- visual search [*Grieben et al. Att Perc & Psychophysics 2020, CogSci mult*]
- cognitive neuroscience of visual working [*Buss, et al., Psych Rev 2021*]
- situational word learning [*Bath, Spencer, Samuelson, Psych Rev 2021*]
- ideomotor theory [*Vogel-Blaschka, Kunde, Herbort, Scherbaum Psych Rev 2024*]

- perceptually grounding relations *[Richter, Lins, Schöner Cog Sci 2021]*
- perceptually grounding nested phrases [*Sabinasz, Schöner TopiCS 2023; Sabinasz, Richter, Schöner Cog Neurodyn 2023; Sehring et al. CogSci2024*]
- mental mapping *[Kounatidou, Richter, Schöner, CogSci2018]*
- truth value and polarity *[Kati, Sabinasz, Schöner, Gaup CogSci2024]*
- analogical mapping *[Hesse, Sabinasz, Schöner, CogSci 2022; Kang, Sabinasz, Schöner, CogSci 2024]*

Strength + challenge

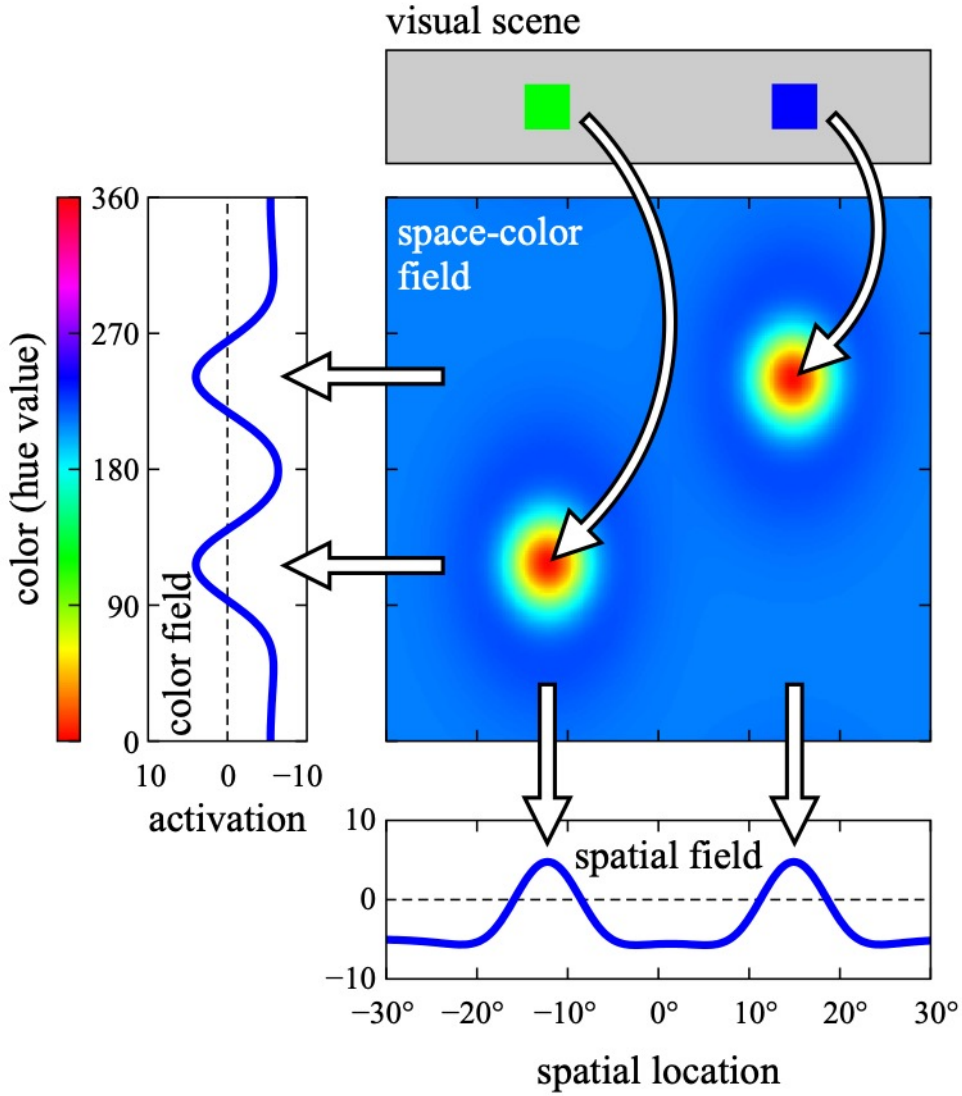
- DFT links to many different fields of research/sub-disciplines
- at different levels of description
  - behavioral: RT, errors, response metrics, movement
  - neural: population of single units
  - neural: cognitive neuroscience
- reaching into autonomous agents/AI

3 Coupling

- binding, unbinding
- mental maps
- cued selection
- binding through space
- coordinate transforms

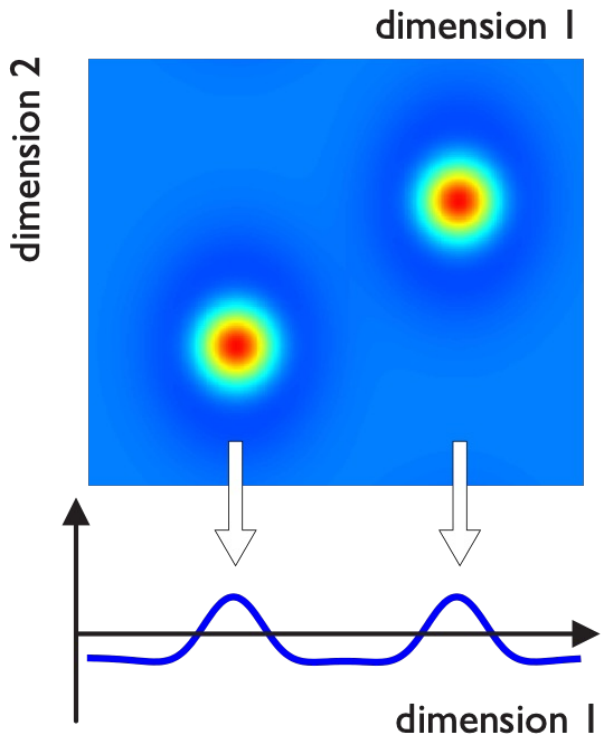
Joint representations

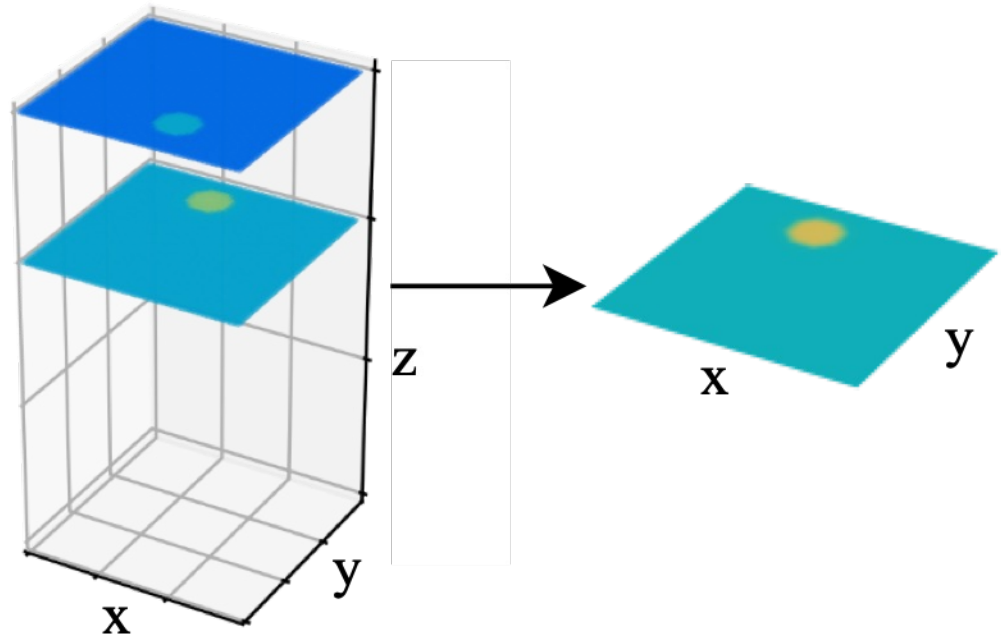
- unbinding = extracting features by contraction coupling



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

Contraction coupling

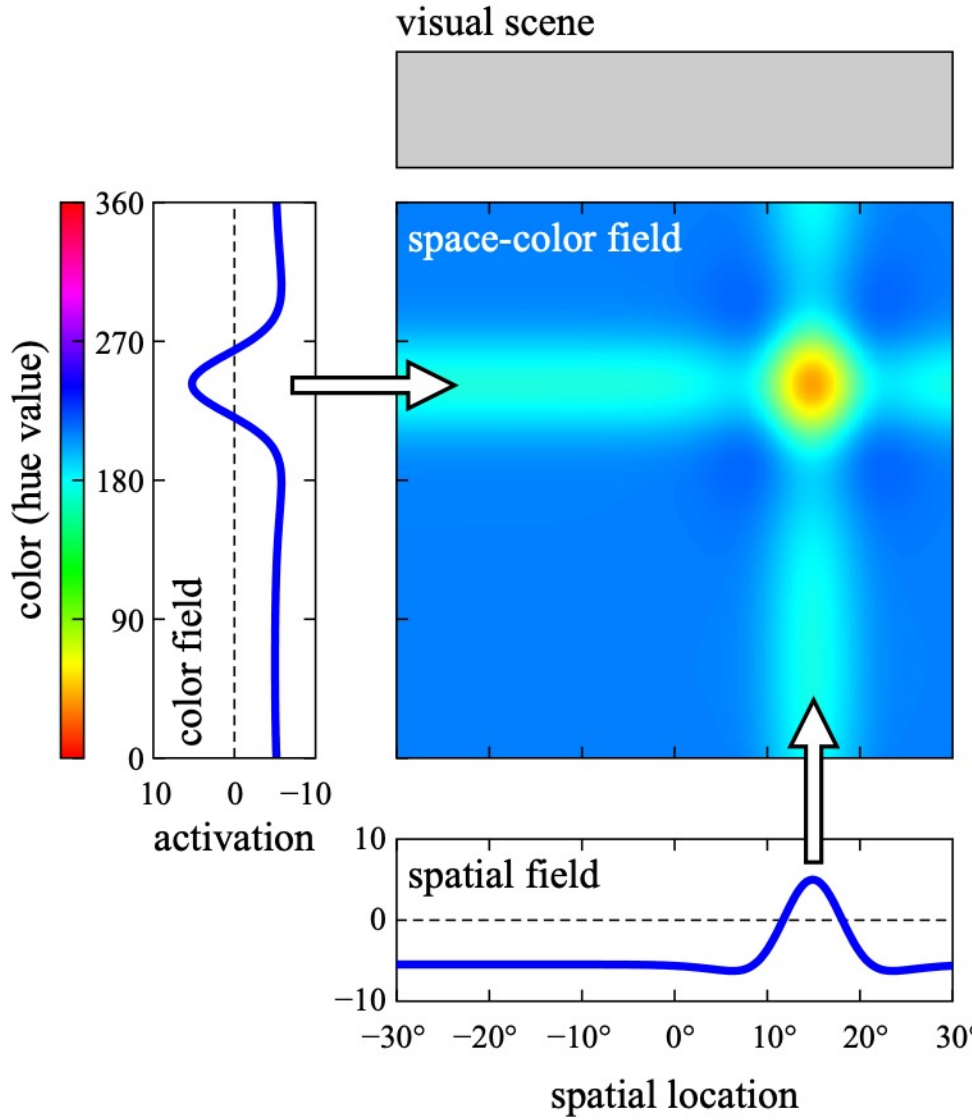




[Sabinasz, Richter, Schöner, *Cog. Neurodyn.* 2023]

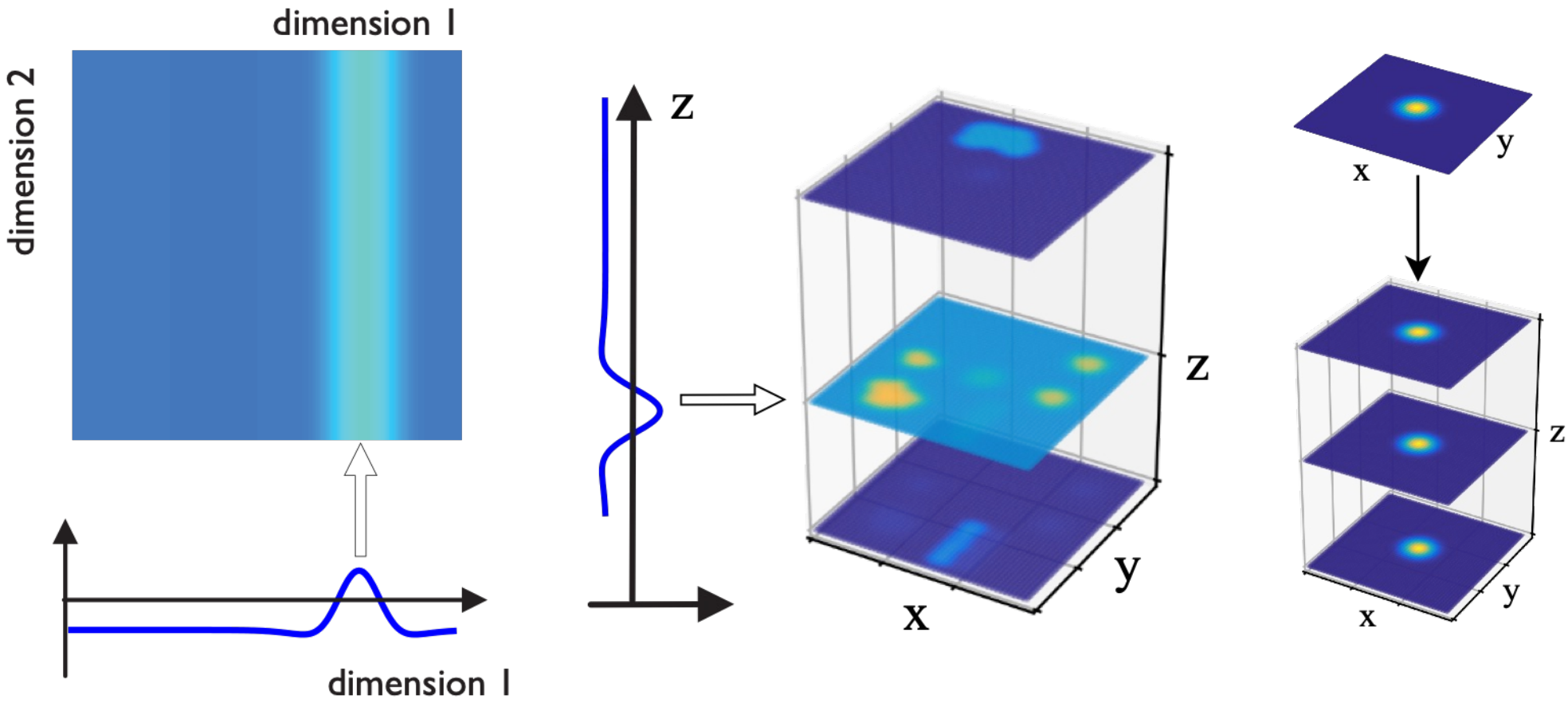
Binding in mental maps

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



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

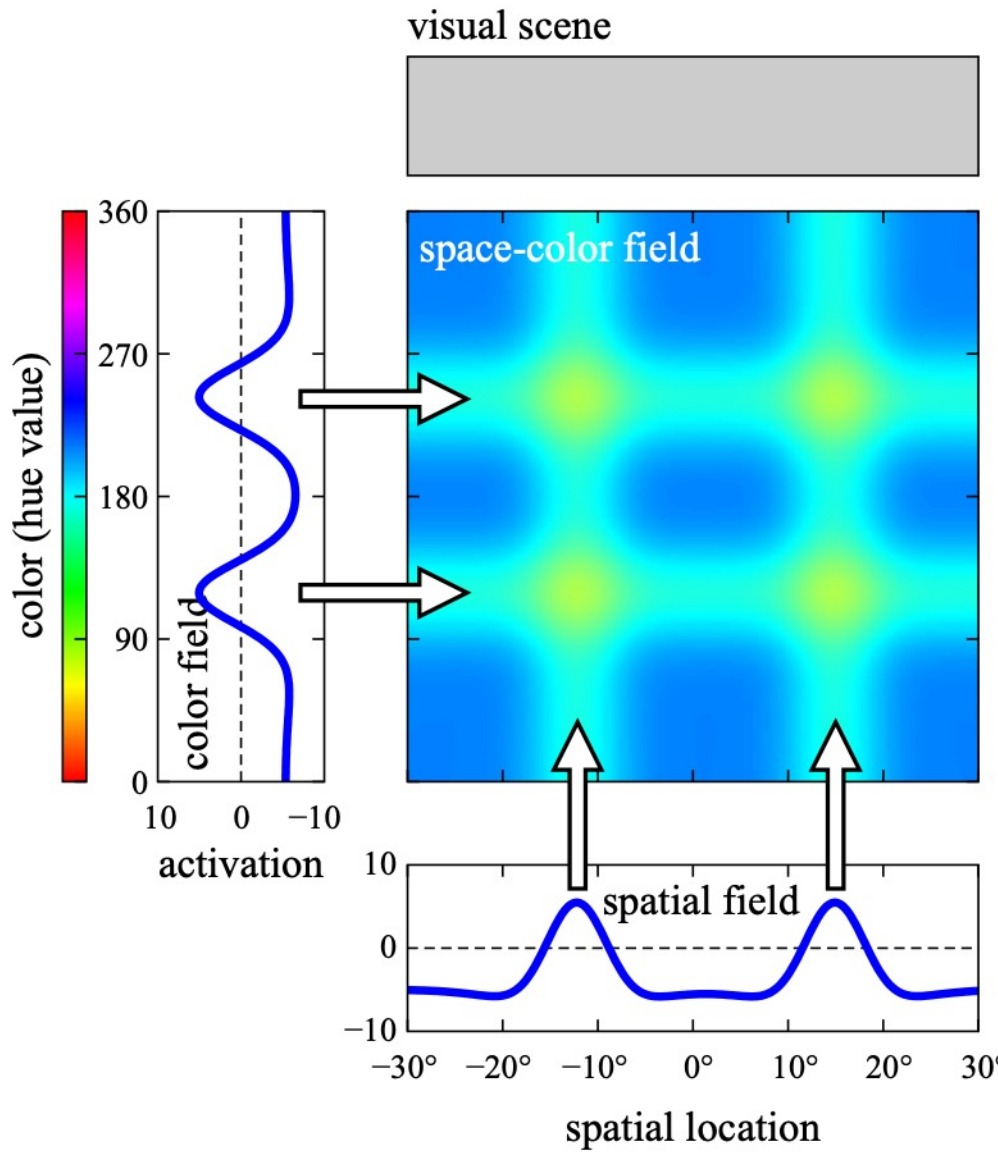
Expansion coupling



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

Binding problem

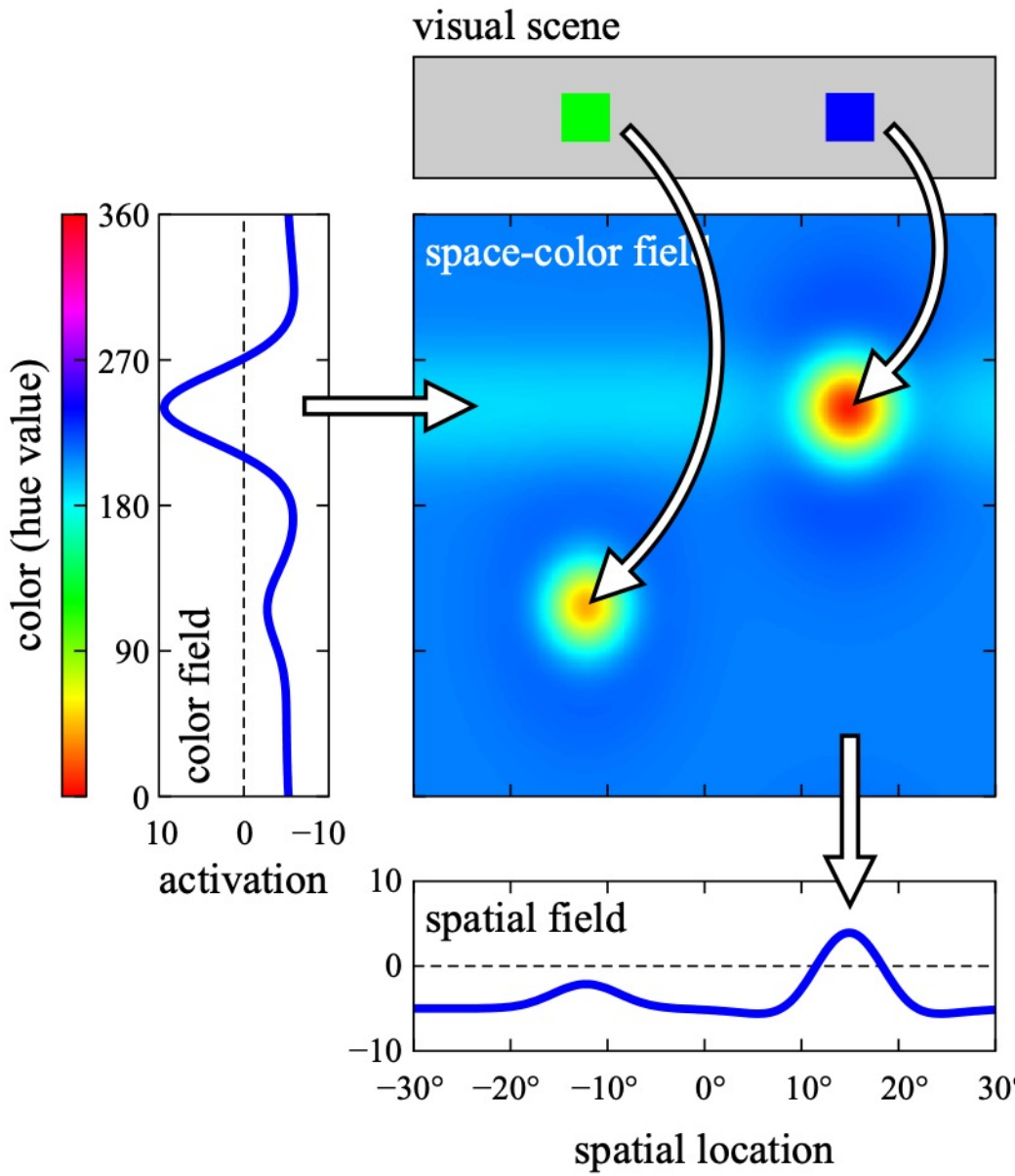
- => bind one object at a time
- => attentional bottleneck



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

Cued selection

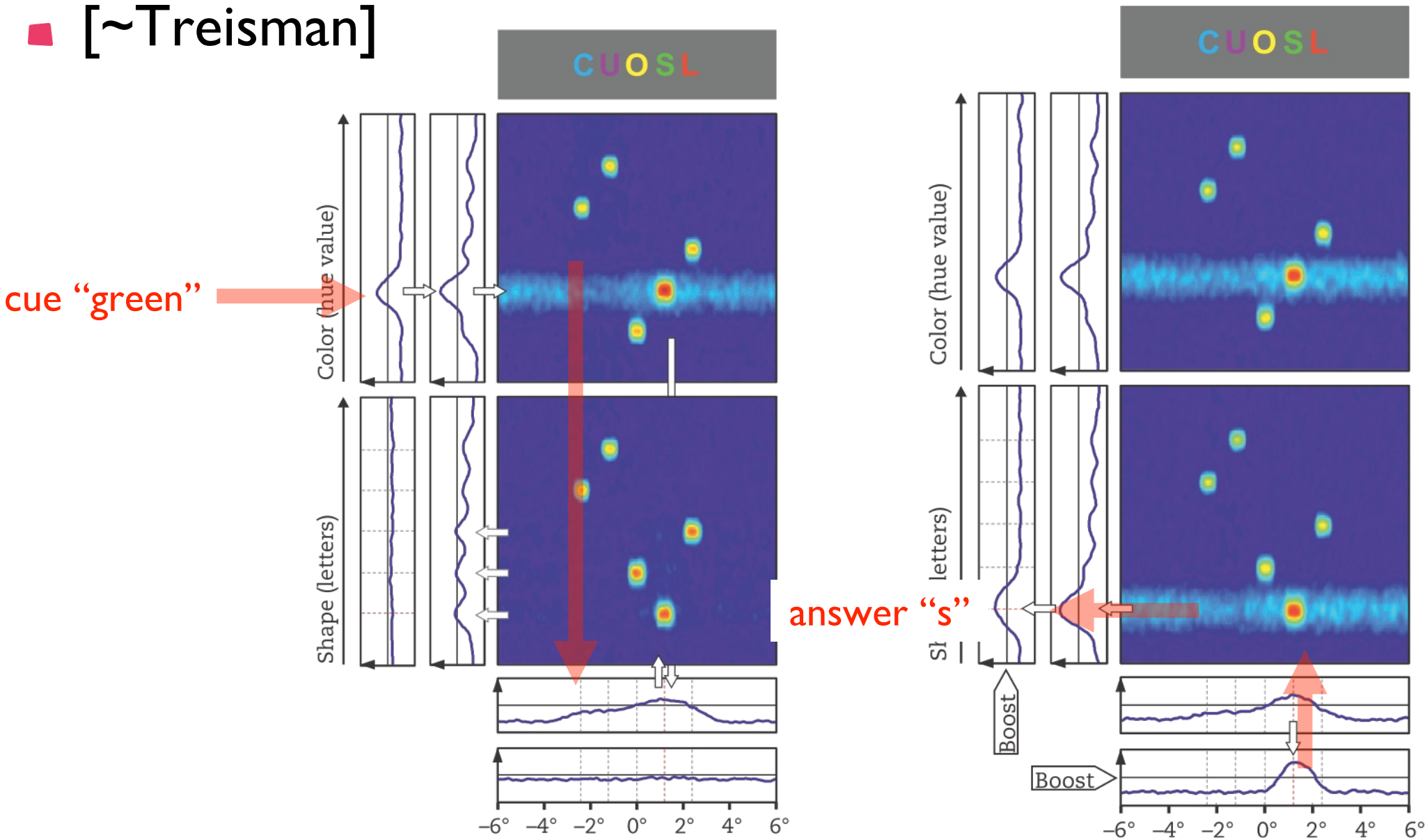
- combines expansion and contraction



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

Binding through space

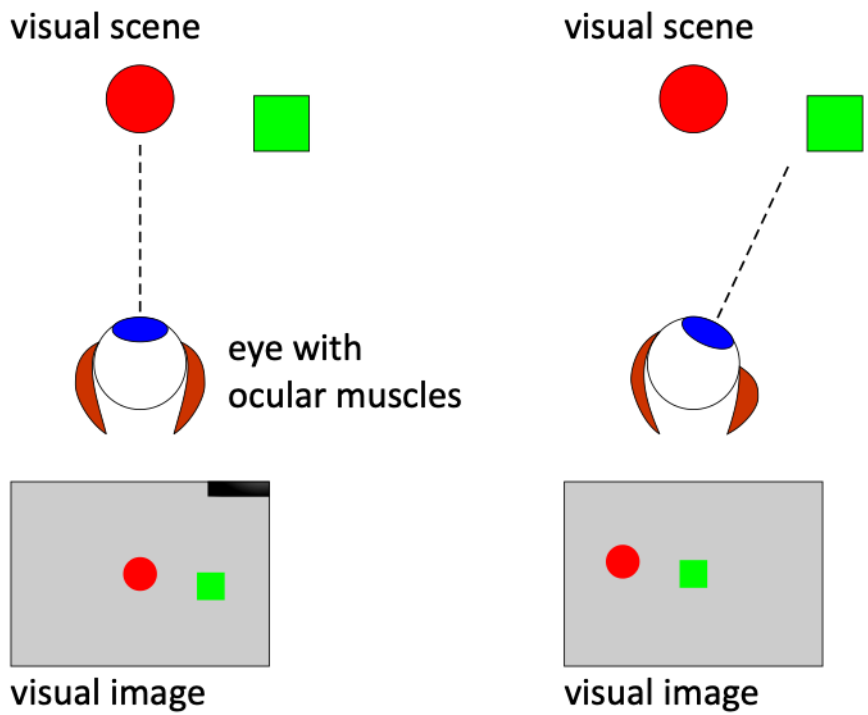
- [~Treisman]



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

Coordinate transforms

- enable representations that are more invariant than the sensory-motor surfaces



body/world frame

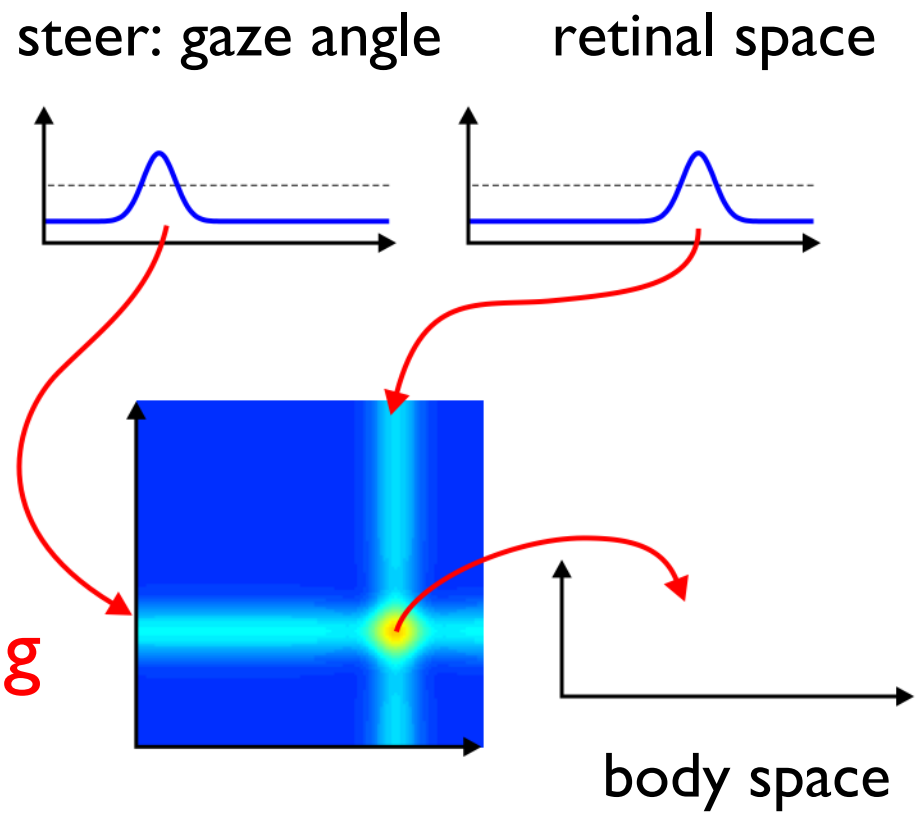
gaze shift

retinal frame

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

Example: retinal <=> body/world space

- joint representation of
  - retinal space
  - gaze angle
  - = gain fields [~*Andersen/Pouget]*



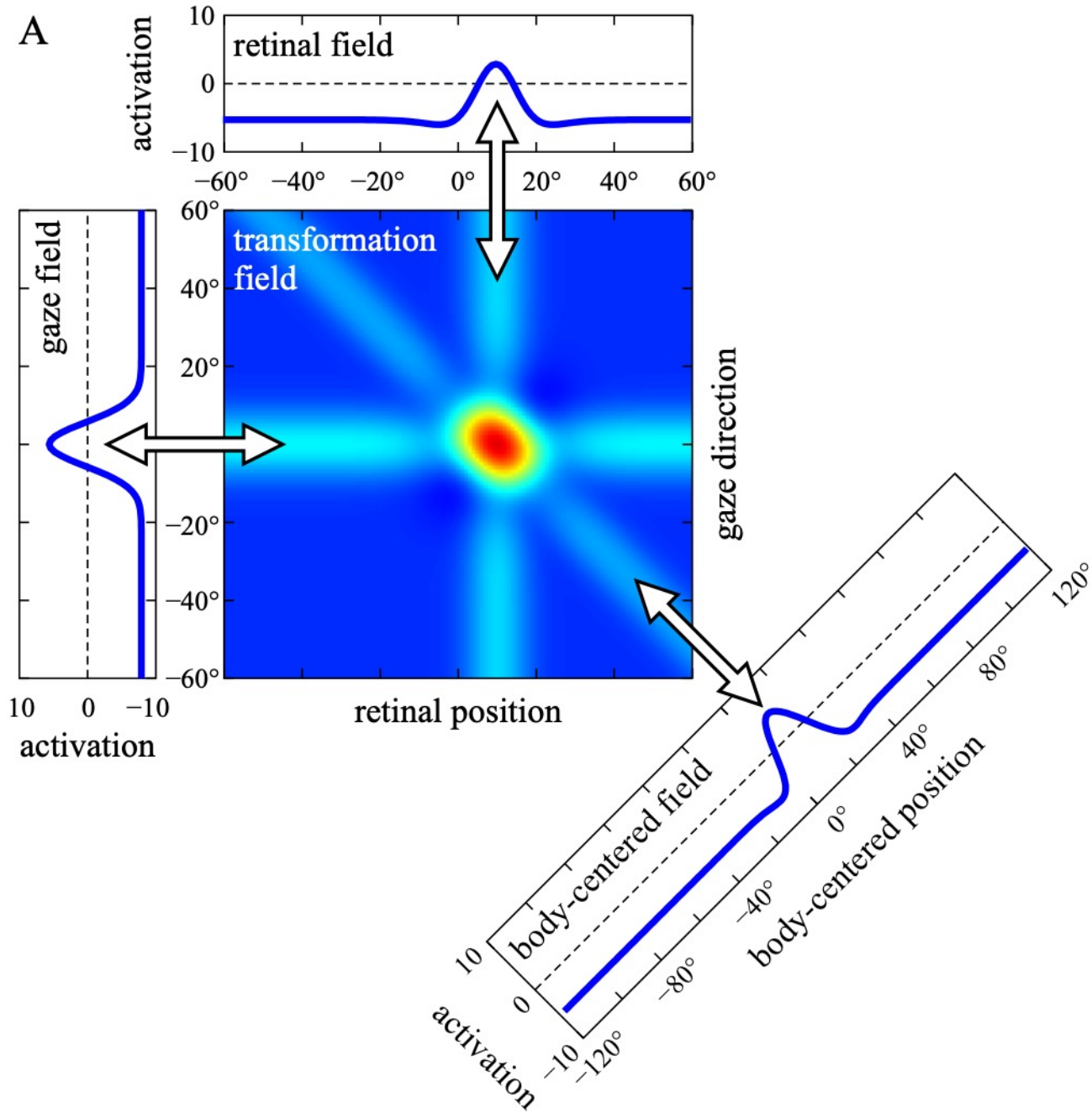
bind by
expansion coupling

contraction coupling

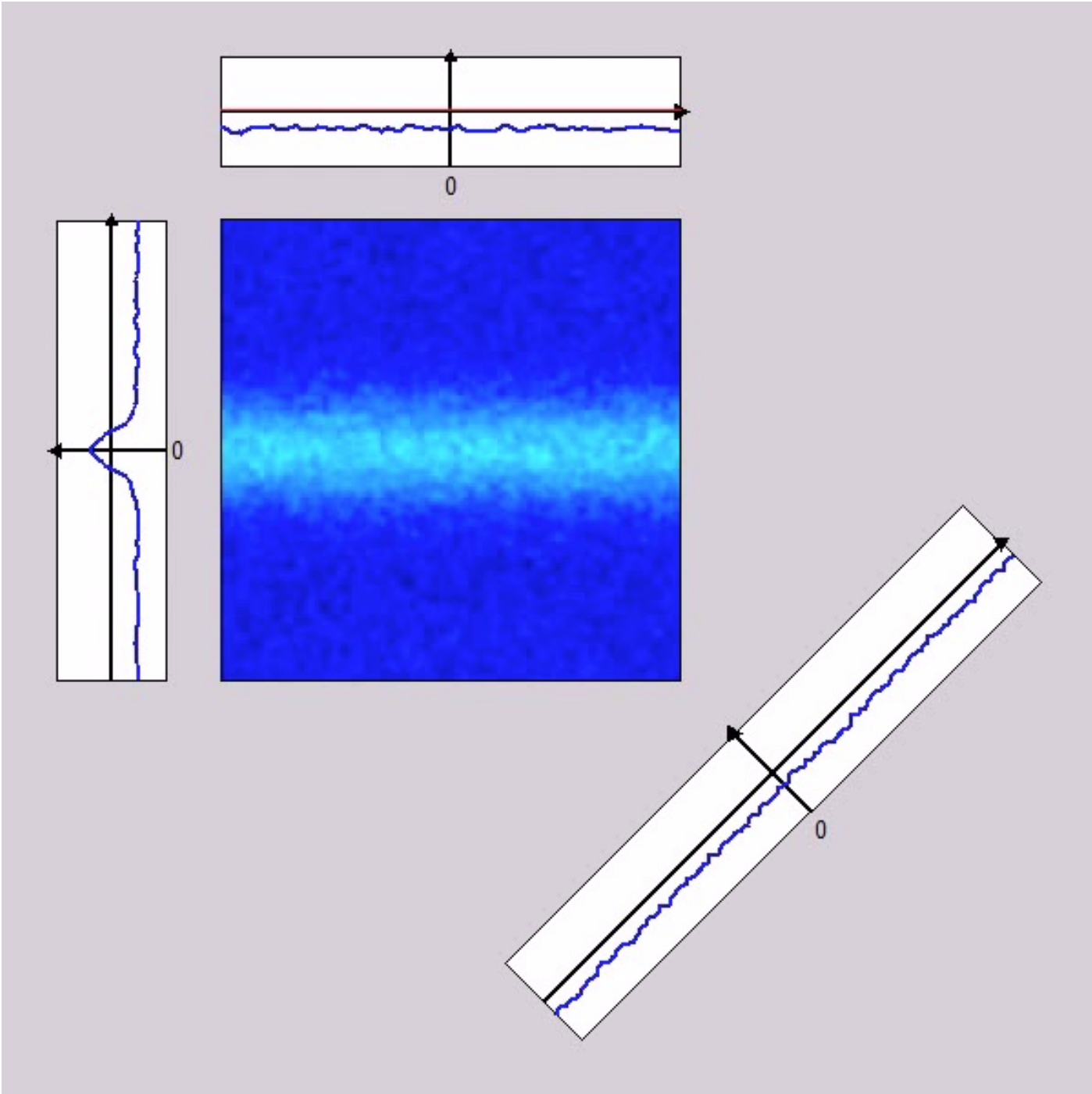
[Schneegans Ch 7, *DFT Primer*, 2016]

Retinal <=> body/world space

- bi-directional coupling



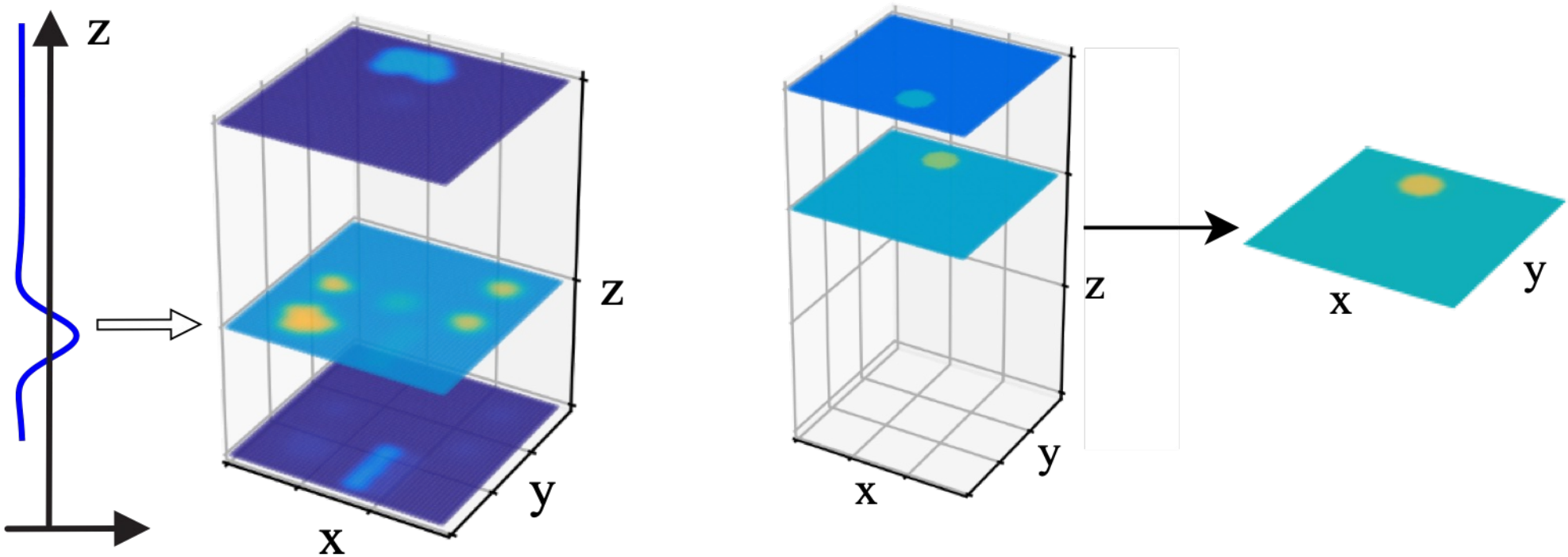
Spatial remapping during saccades



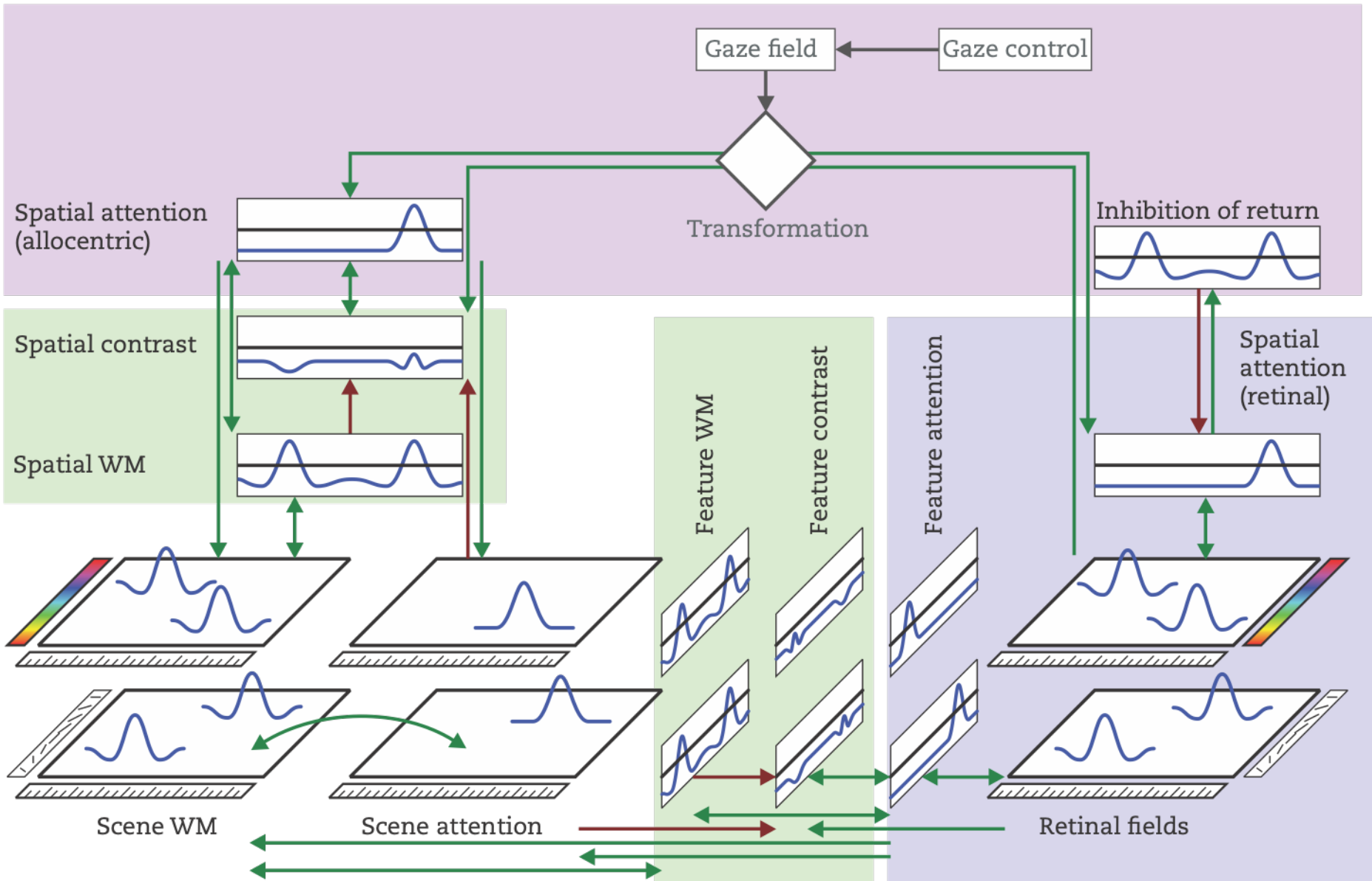
[Schneegans, Schöner *Biological Cybernetics* 2012]

4 Integration: DFT architectures

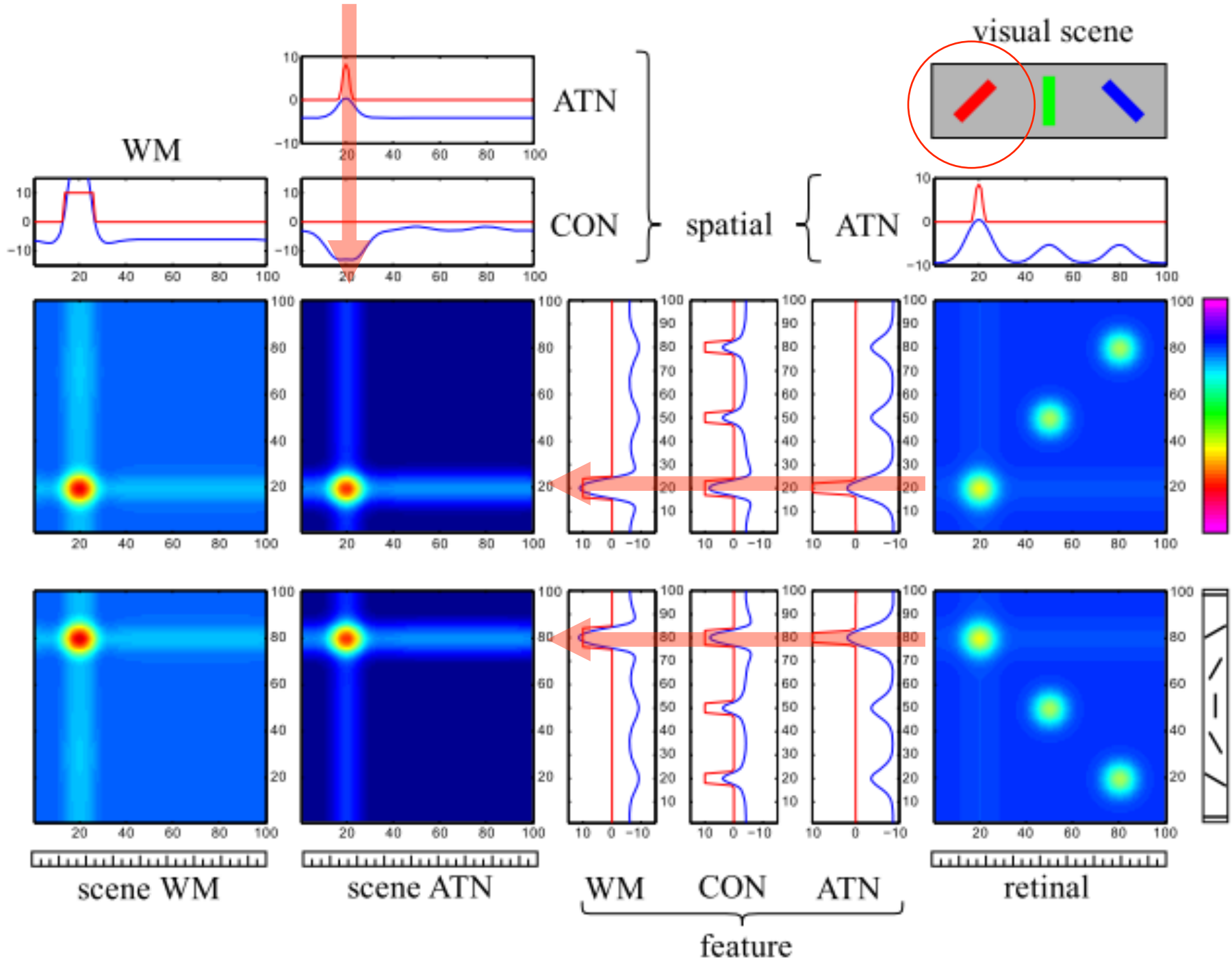
- dynamic modularity: fields retain their dynamic regime under coupling
- coupling must preserve feature dimensions: "non-synesthesia principle"



DFT architecture of scene memory



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



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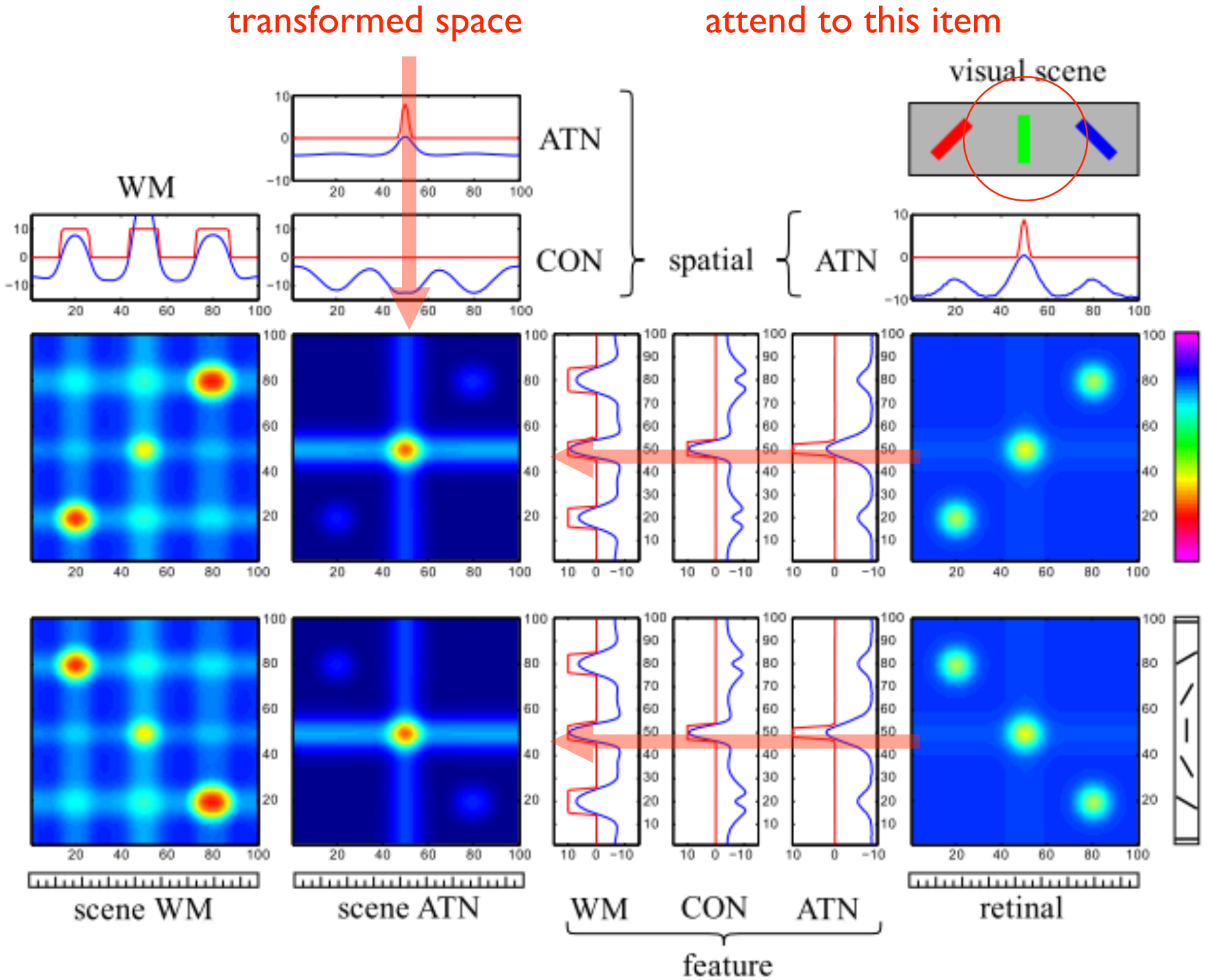

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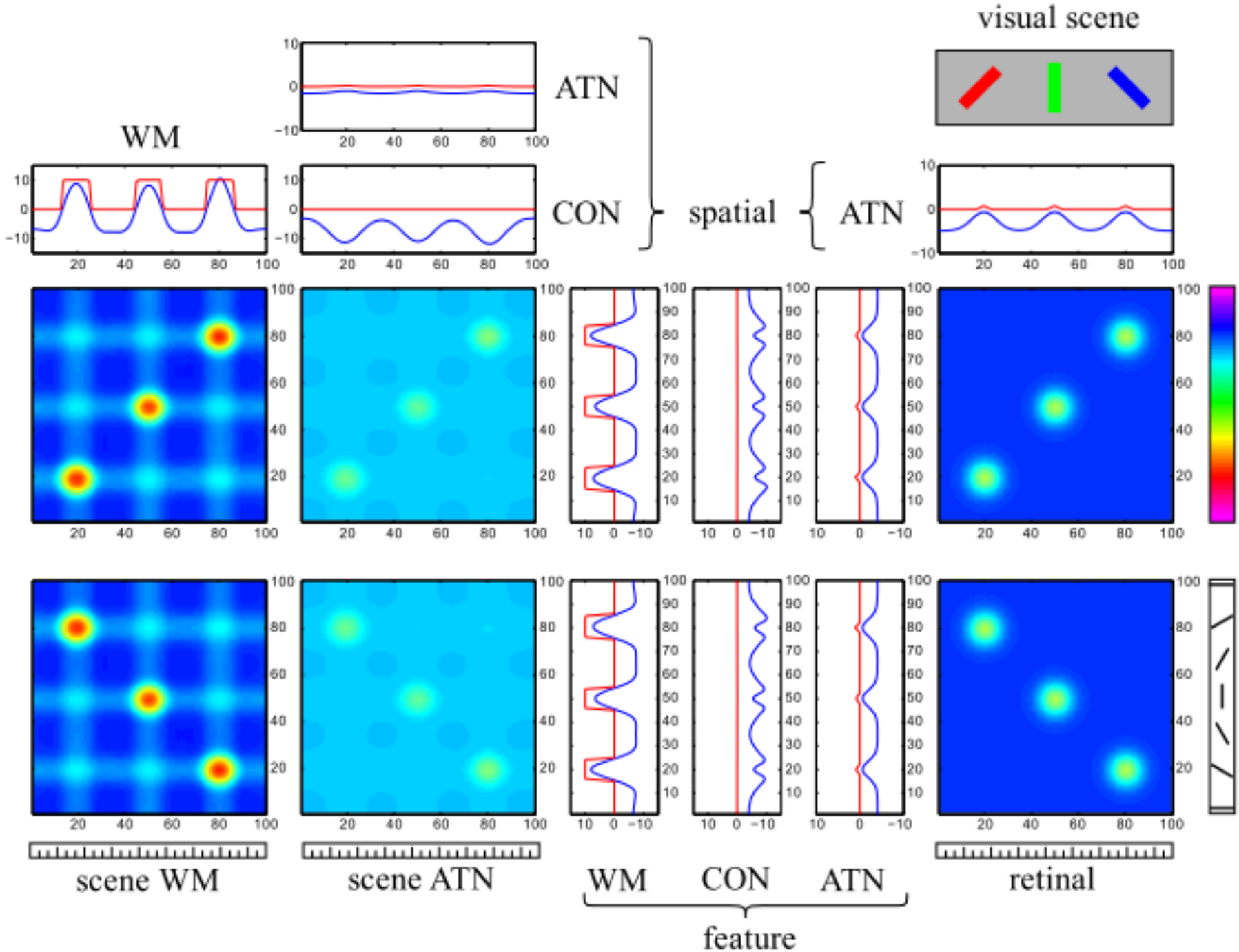

[Schneegans et al.,Ch 8 of *DFT Primer*, 2016]

Dynamic Field Theory (DFT)

- 1 Space: inner states are localized activation patterns in low-dimensional features spaces
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- 3 Coupling: cognition emerges from dynamic coupling across low-dimensional features spaces
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Dynamic Field Theory postulates

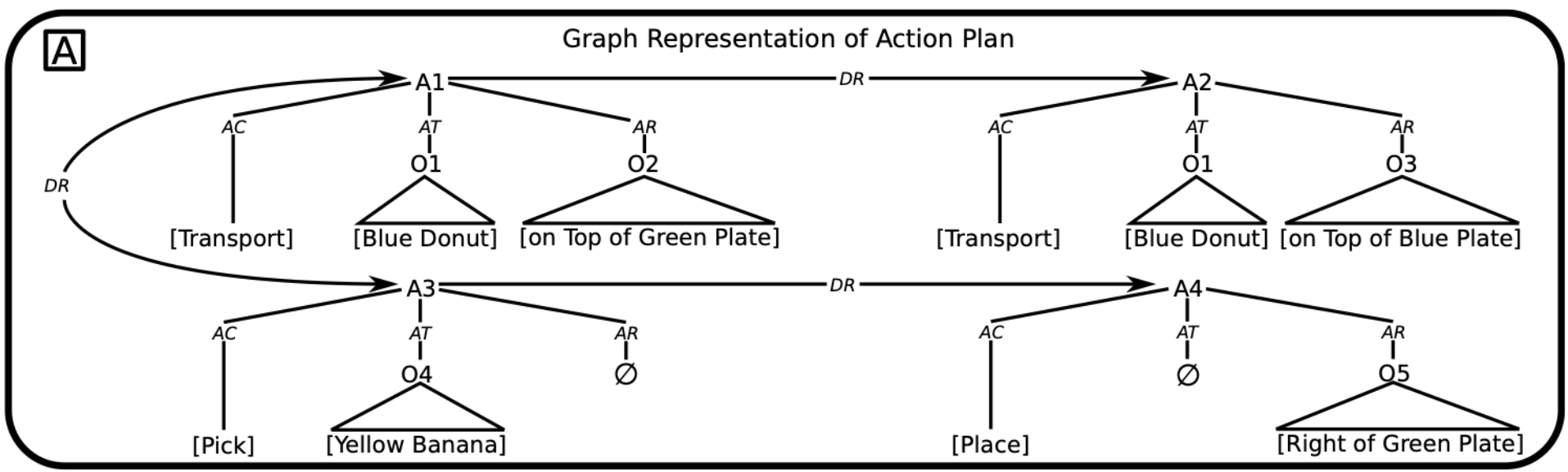
[differ from DNN/LLM]

- localist representations
- in low-dimensional spaces
- interaction dominated dynamics => attractor states
- instabilities generate sequences

… toward higher cognition

- Example: grounding nested imperative phrases
- conceptual structure

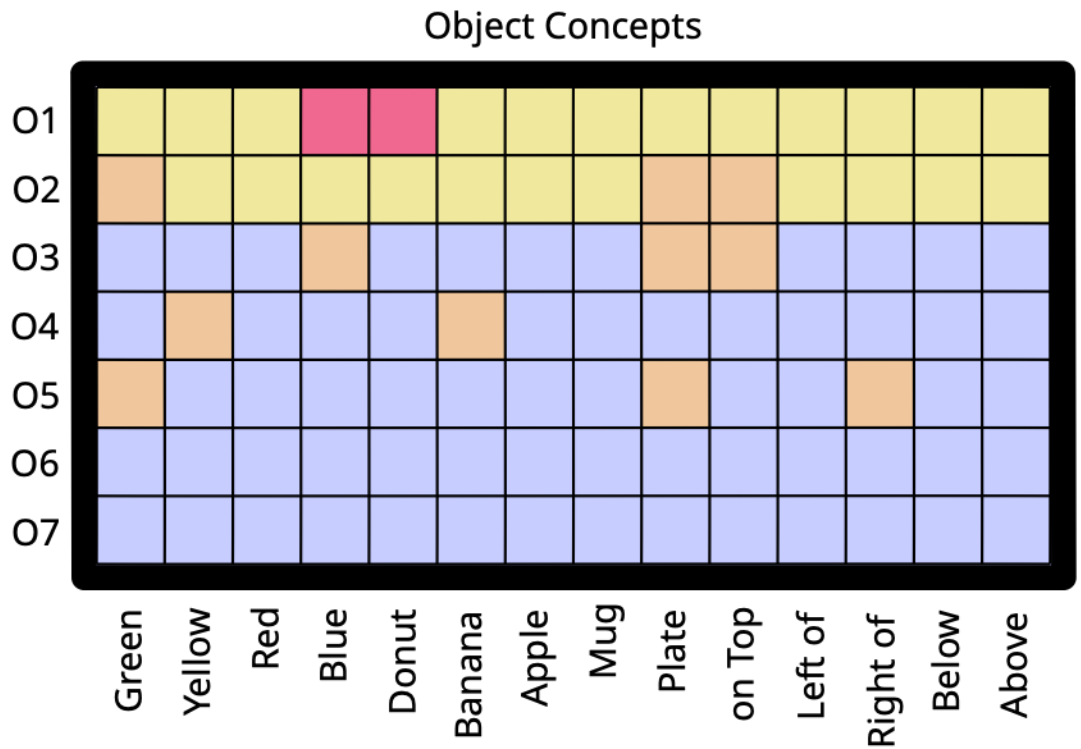
"transport blue donut onto green plate
then transport blue donut to blue plate
or pick yellow banana and place right of the green plate""



[Sehring et al. *CogSci* 2024]

Neural representation of conceptual structure

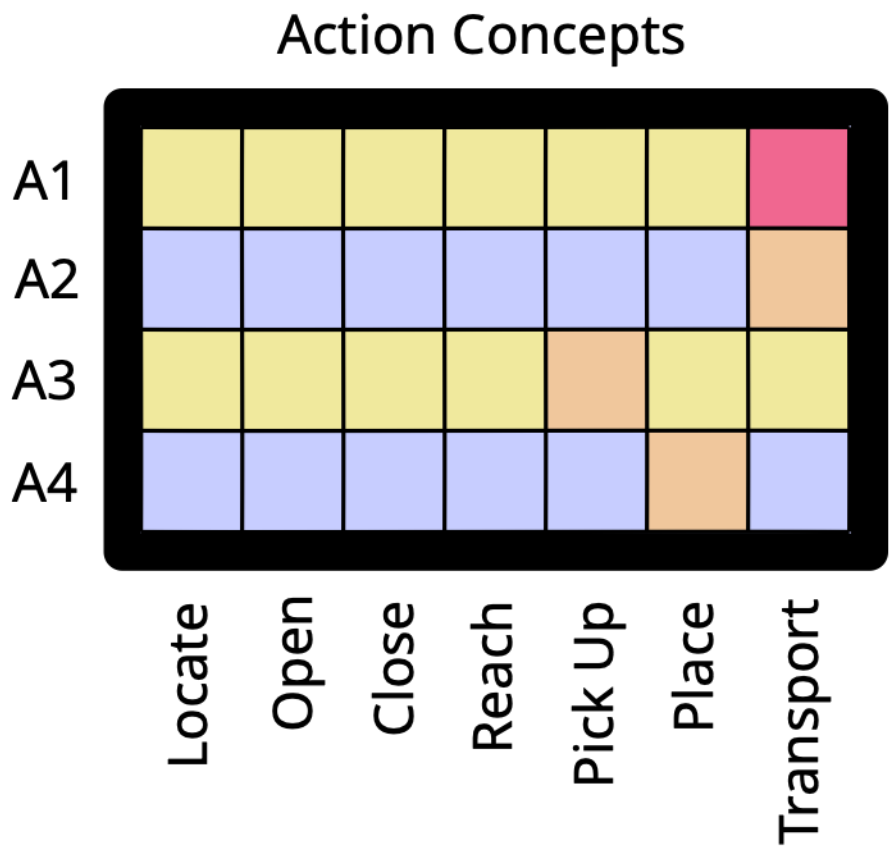
- ordinal index given to each instance (token) of an object concept
- enables representing multiple instances of an object concept
- serves as a binding dimension



[Sabinasz, Richter, Schöner *Cog Neurodyn* 2023; Sehring et al. *CogSci* 2024]

Neural representation of conceptual structure

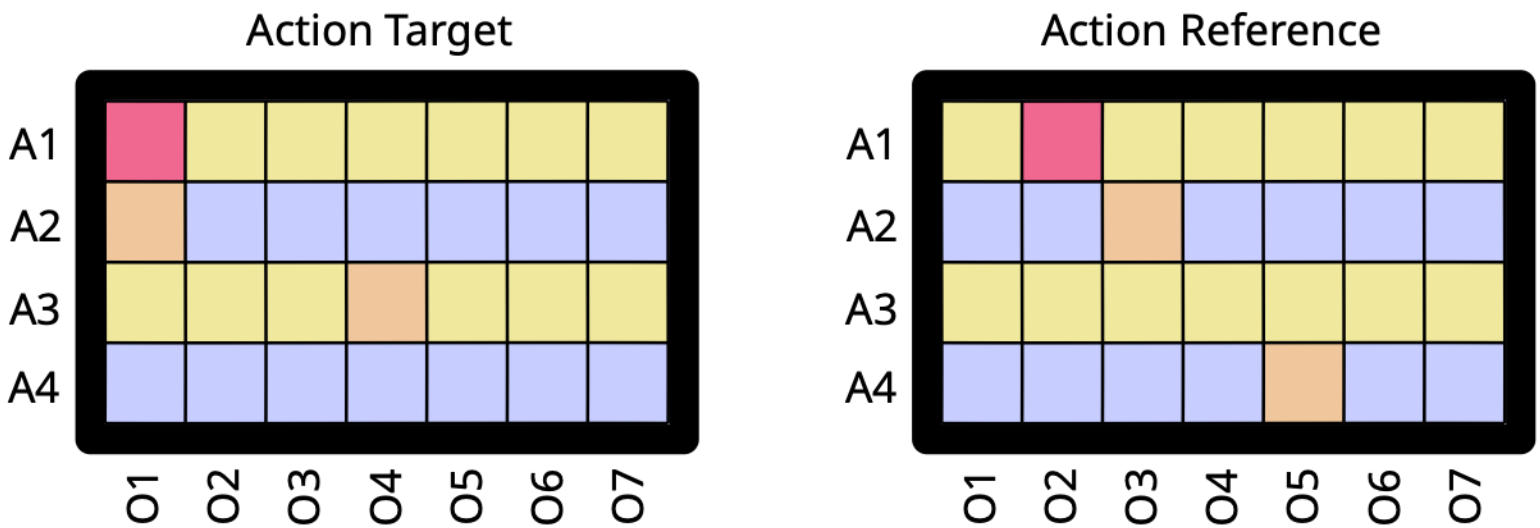
- ordinal index given to each instance of a relation/action concept
- enables representing multiple instances of same relation in a nested phrase

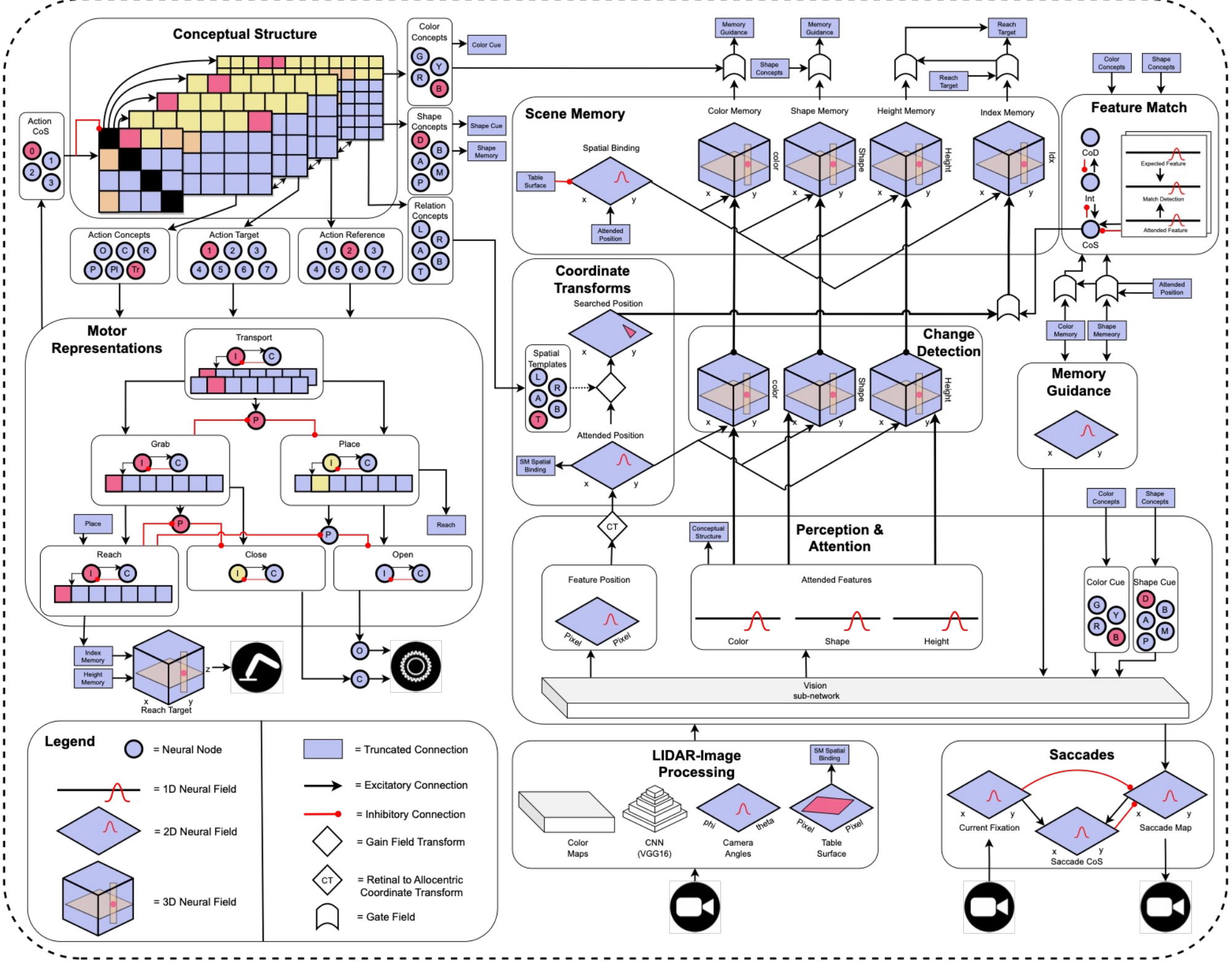


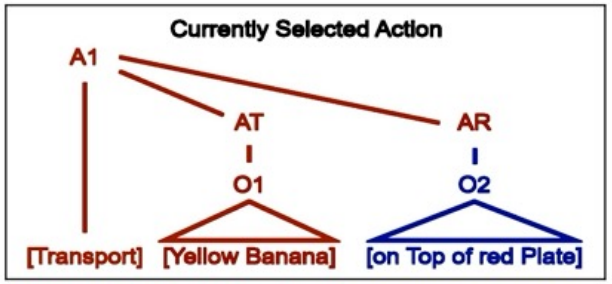
[Sabinasz, Richter, Schöner *Cog Neurodyn* 2023; Sehring et al. *CogSci* 2024]

Neural representation of conceptual structure

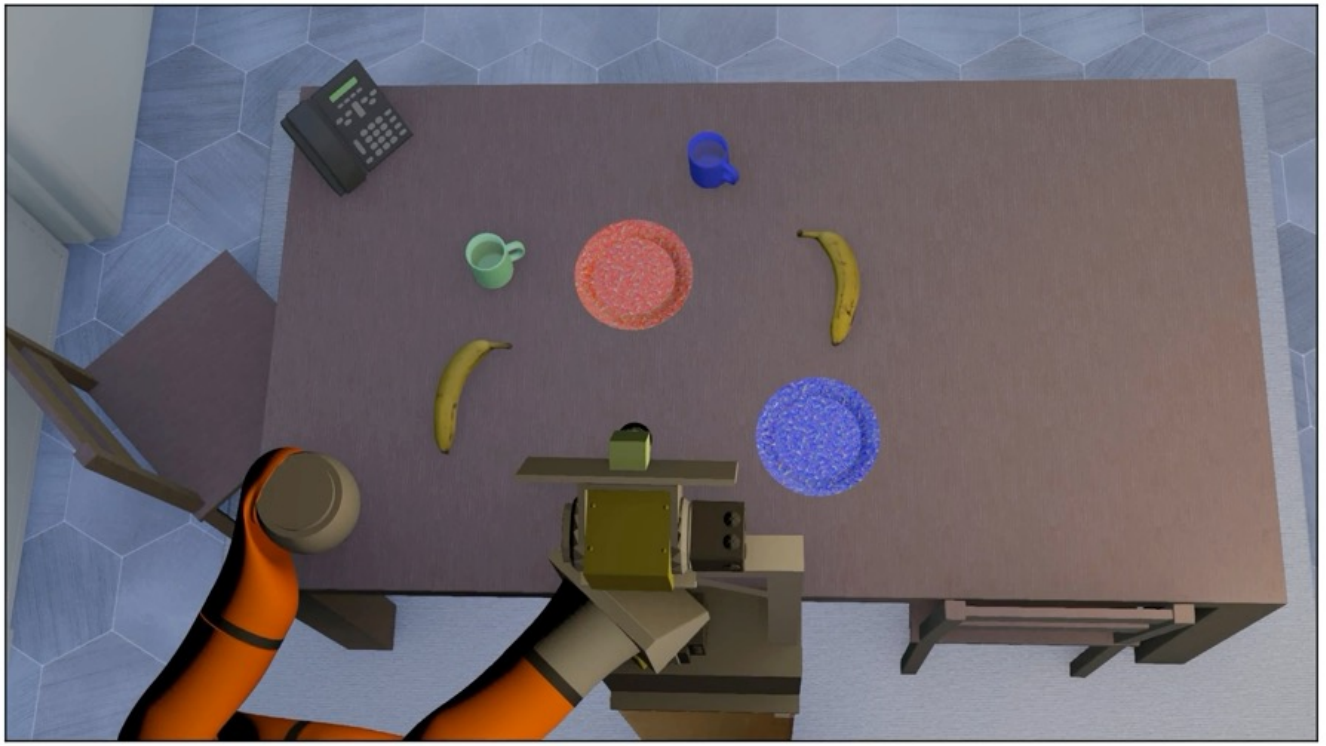
- bind action concepts to object concepts in given roles through in a joint representation of
  - ordinal object concept index
  - ordinal action concept index
  - roles



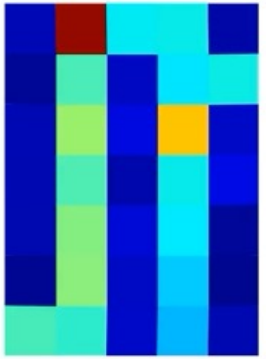

Conceptual Structure
Color Concepts
Color Cue
Shape Concepts
Shape Cue
Shape Memory
Relation Concepts
Action CoS
Action Concepts
Action Target
Action Reference
Memory Guidance
Shape Concepts
Reach Target
Scene Memory
Color Memory
Shape Memory
Height Memory
Index Memory
Spatial Binding
Table Surface
Attended Position
Feature Match
CoD
Int
CoS
Expected Feature
Match Detection
Attended Feature
Coordinate Transforms
Searched Position
Spatial Templates
Attended Position
SM Spatial Binding
Change Detection
Color Memory
Shape Memeory
Memory Guidance
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)
phi
theta
Camera Angles
Table Surface
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



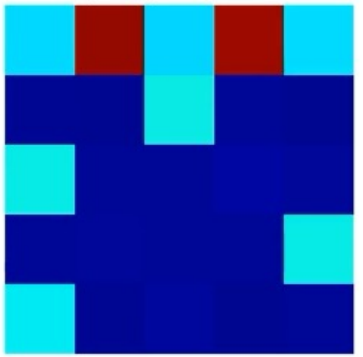
Scene



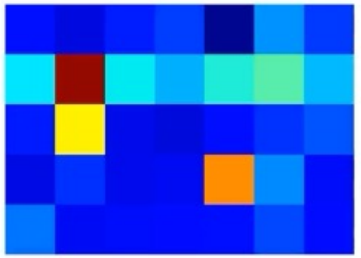
Act. Sel. - Activation



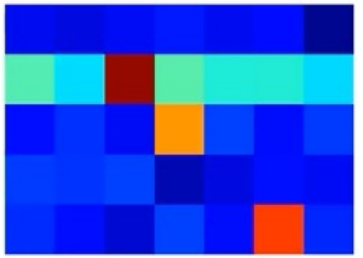
Seq. Dep. - Activation



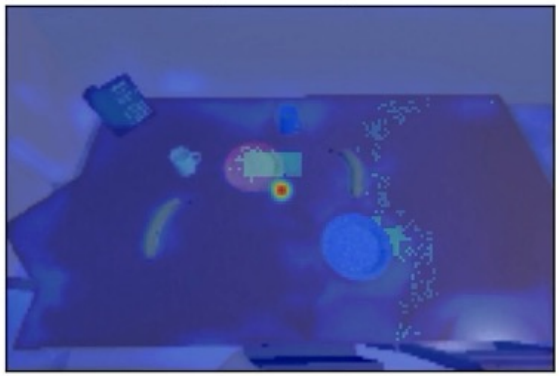
Target - Activation



Reference - Activation

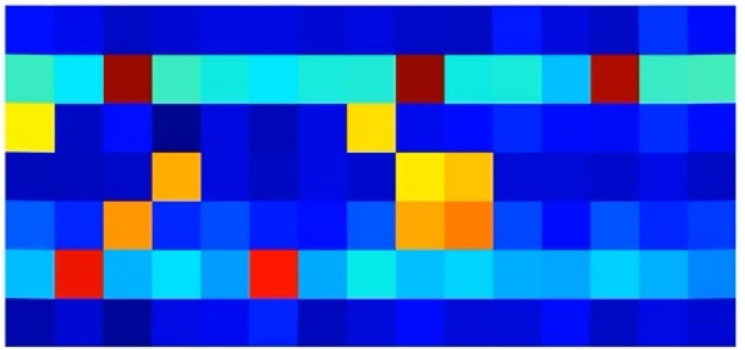


Expl. FVF - Input



Att. FVF - Activation

Obj. Sel. - Activation



Dynamic Field Theory postulates

[differ from DNN/LLM]

- localist representations
- in low-dimensional spaces
- interaction dominated dynamics => attractor states
- instabilities generate sequences
- binding through shared dimensions … toward higher cognition

- Summer school: August 25-30, 2025:
- dynamicfieldtheory.org