DFT coupling among higher-dimensional fields

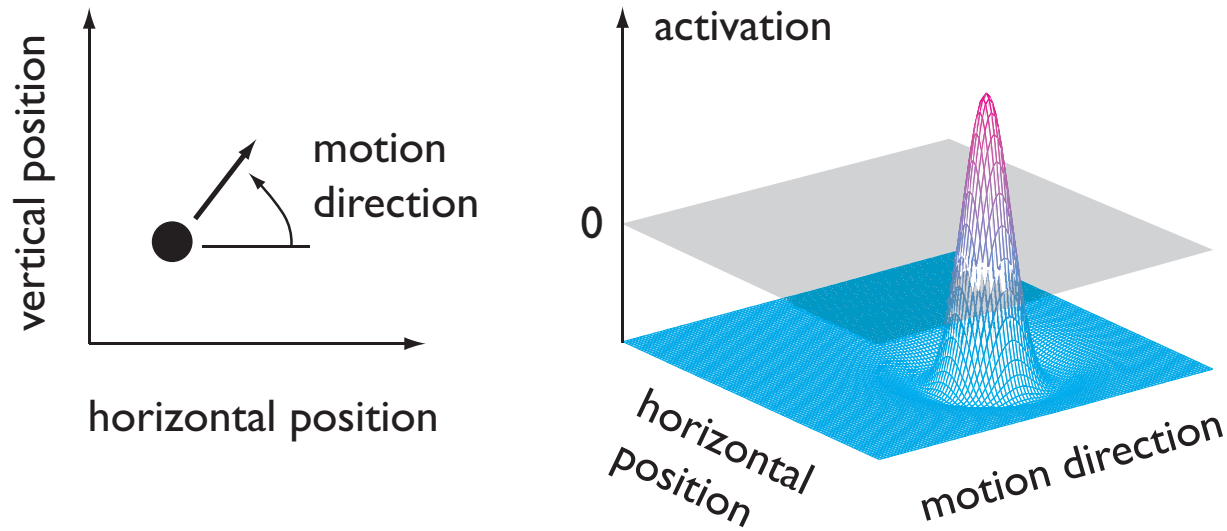
Gregor Schöner
Institute for Neural Computation (INI)
dynamicfieldtheory.org

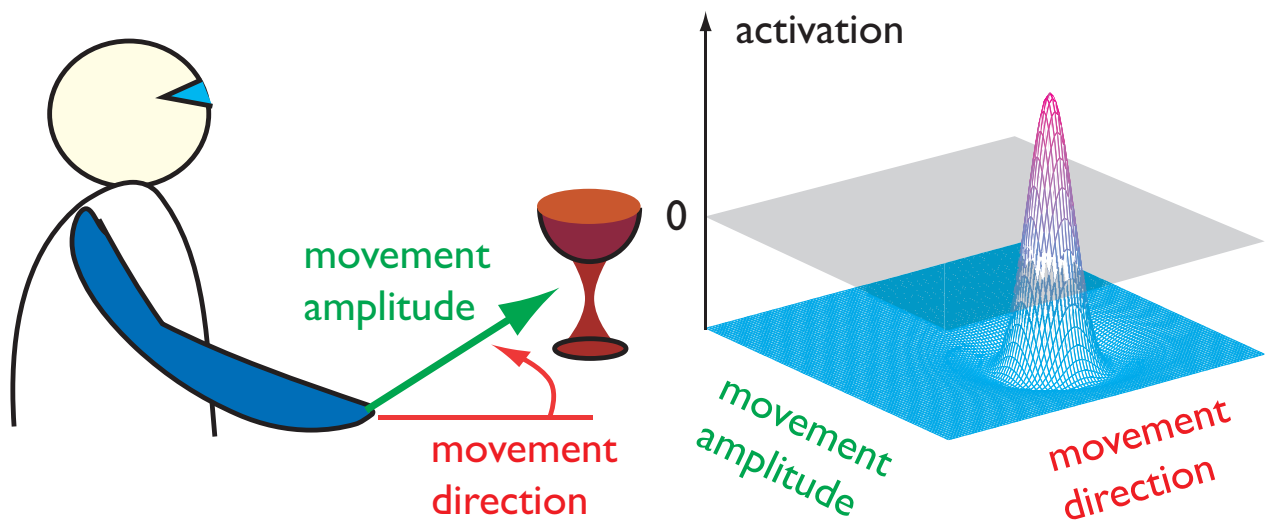
Roadmap

Foundations 2: Space-time coupling

- Background: different notions of binding
- Joint representations and coupling patterns
- Binding through space/ordinal dimension
- Coordinate transforms

Joint representations of different feature dimensions





Joint representations don't scale

- 2 spatial dimensions
- depth
- orientation
- color
- texture
- movement direction
- size
- etc…

=>

- e.g. 8 dimensions
- 100 neurons per dimension
- $10^{2*8} = 10^{16}$!
- more than there are in the entire brain!
- => only small sets of feature dimensions can be represented jointly

Joint representations are not flexible

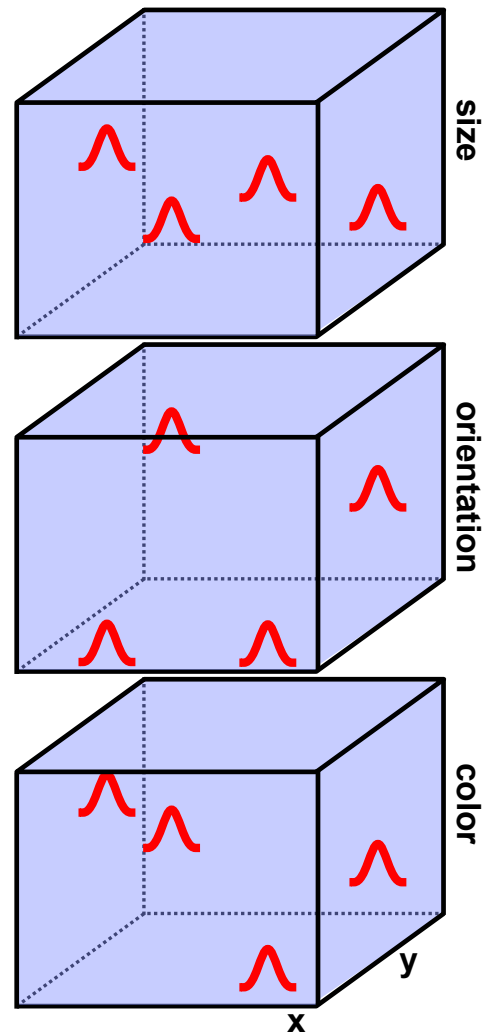
- needs dedicated substrate for every possible combination
- does not account for mis-bindings

Binding through shared dimensions

- separate fields for joint representations of limited number of dimensions (e.g. 3 to 4)
- all of which share a set of dimensions
  - visual space (~all neurons have receptive fields)
  - ordinal dimension

Binding through space

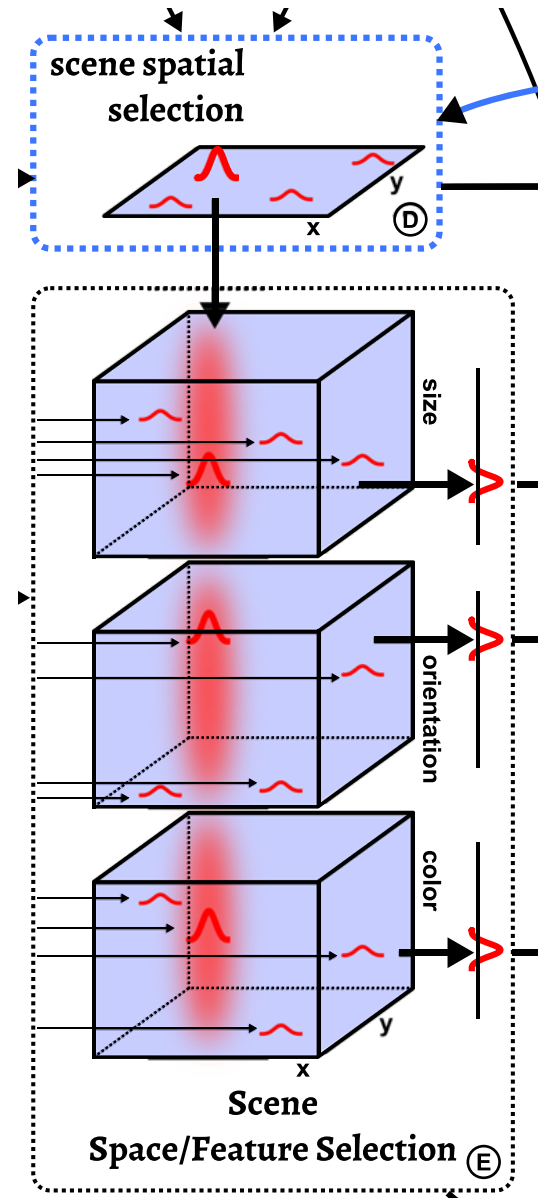
- space-feature fields
  - different features
  - all sharing visual space



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

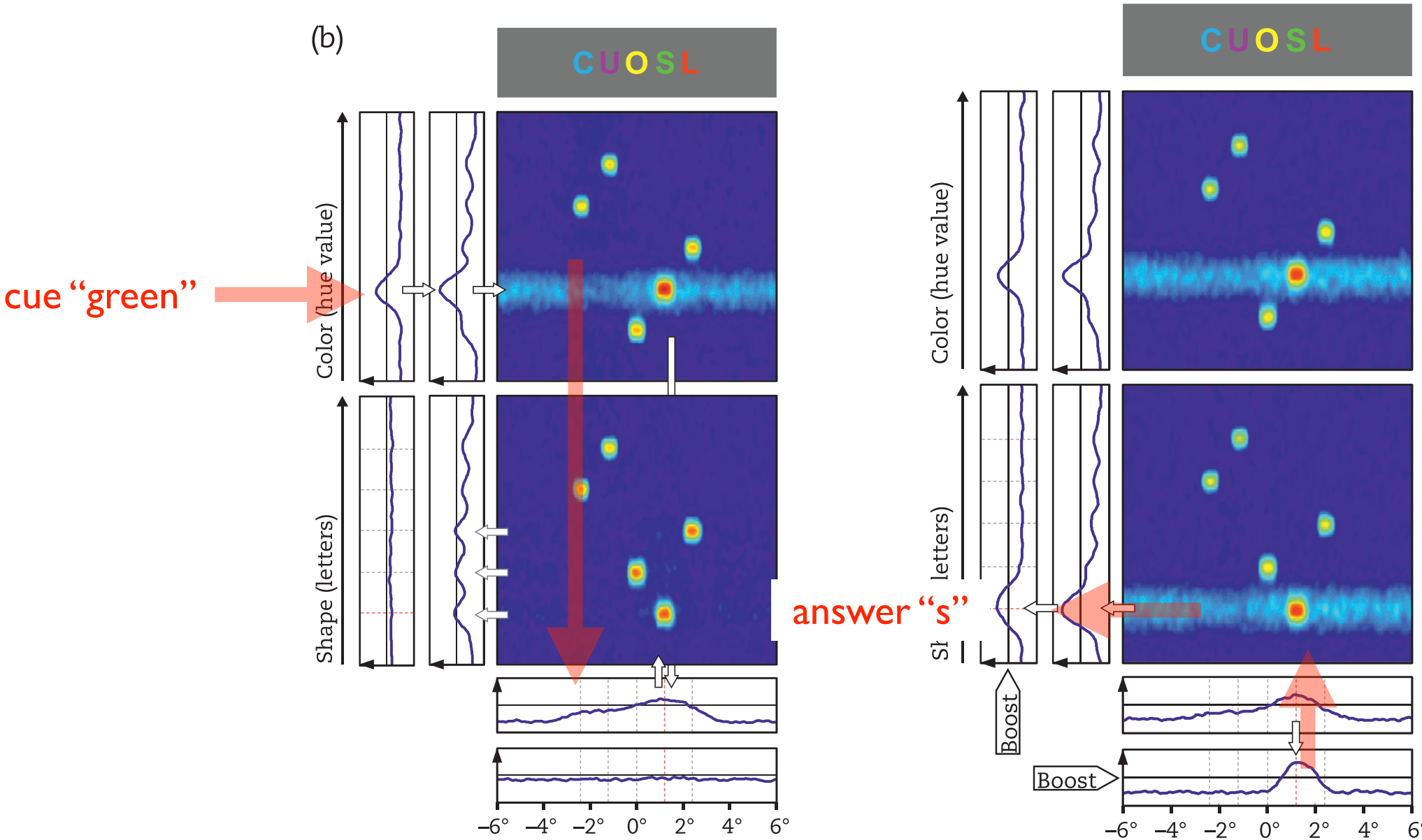
Binding through space

- bi-directional coupling along spatial dimensions

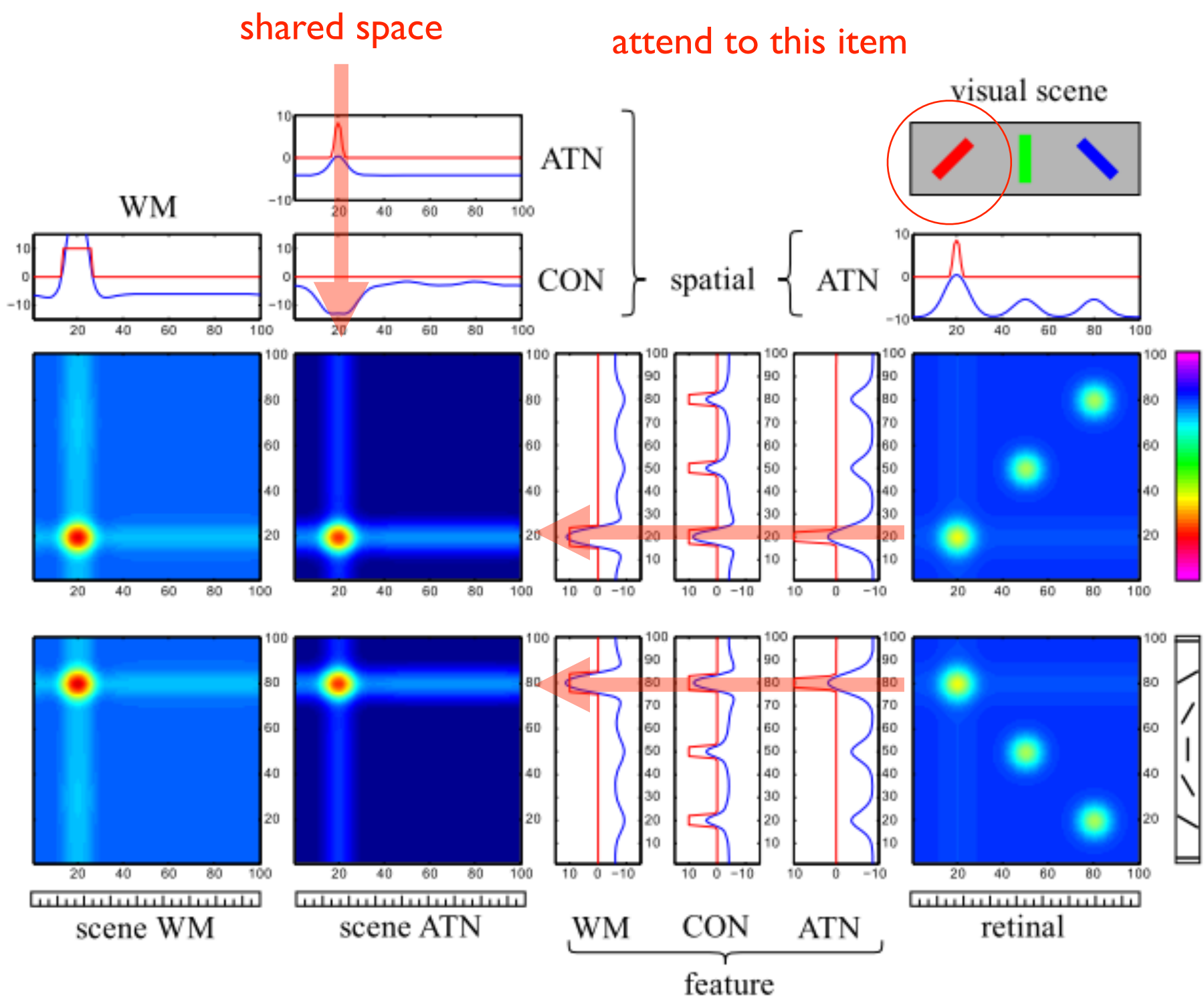


[Grieben et al. *Attention, Perception & Psychophysics* 2020]

Binding through space



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



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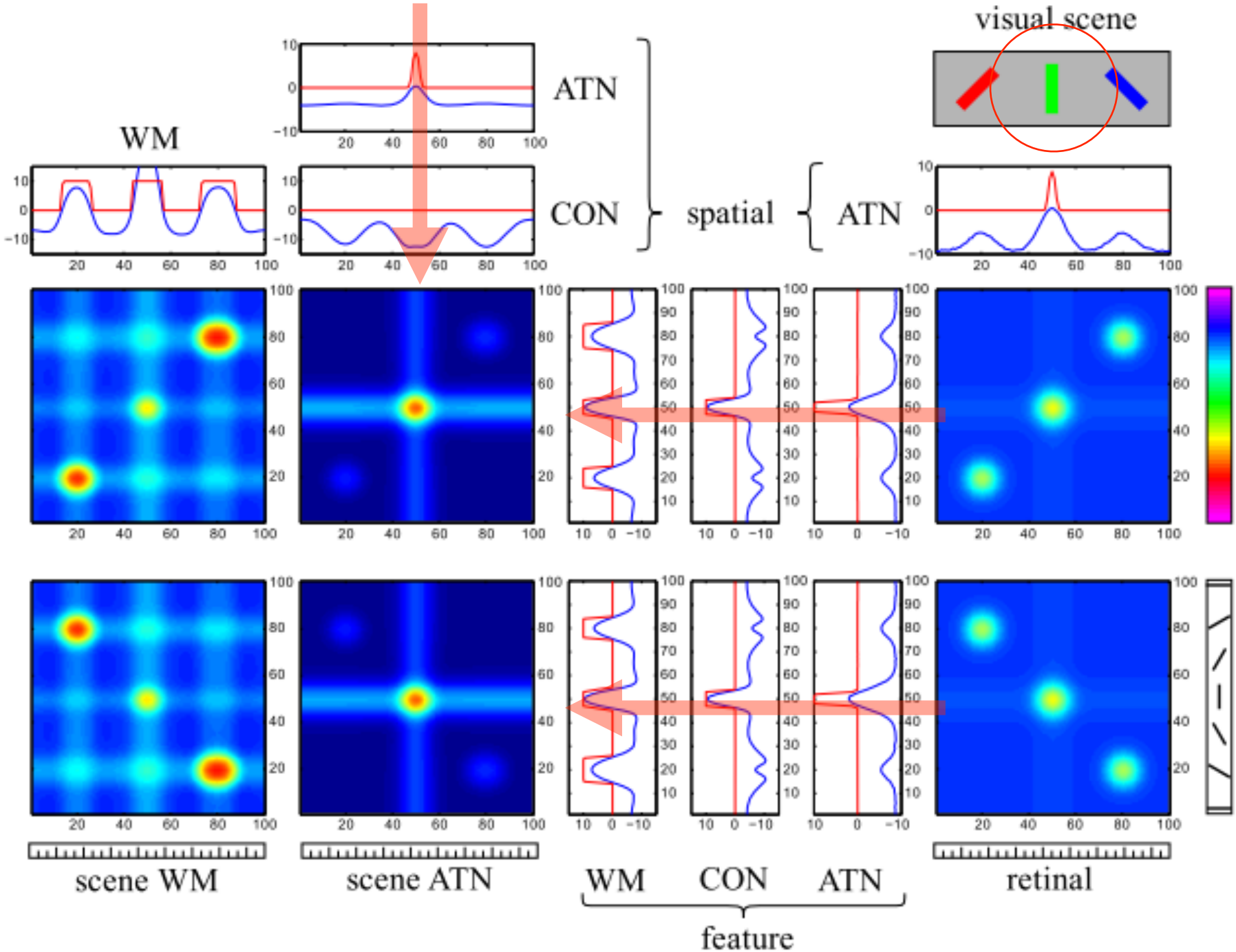
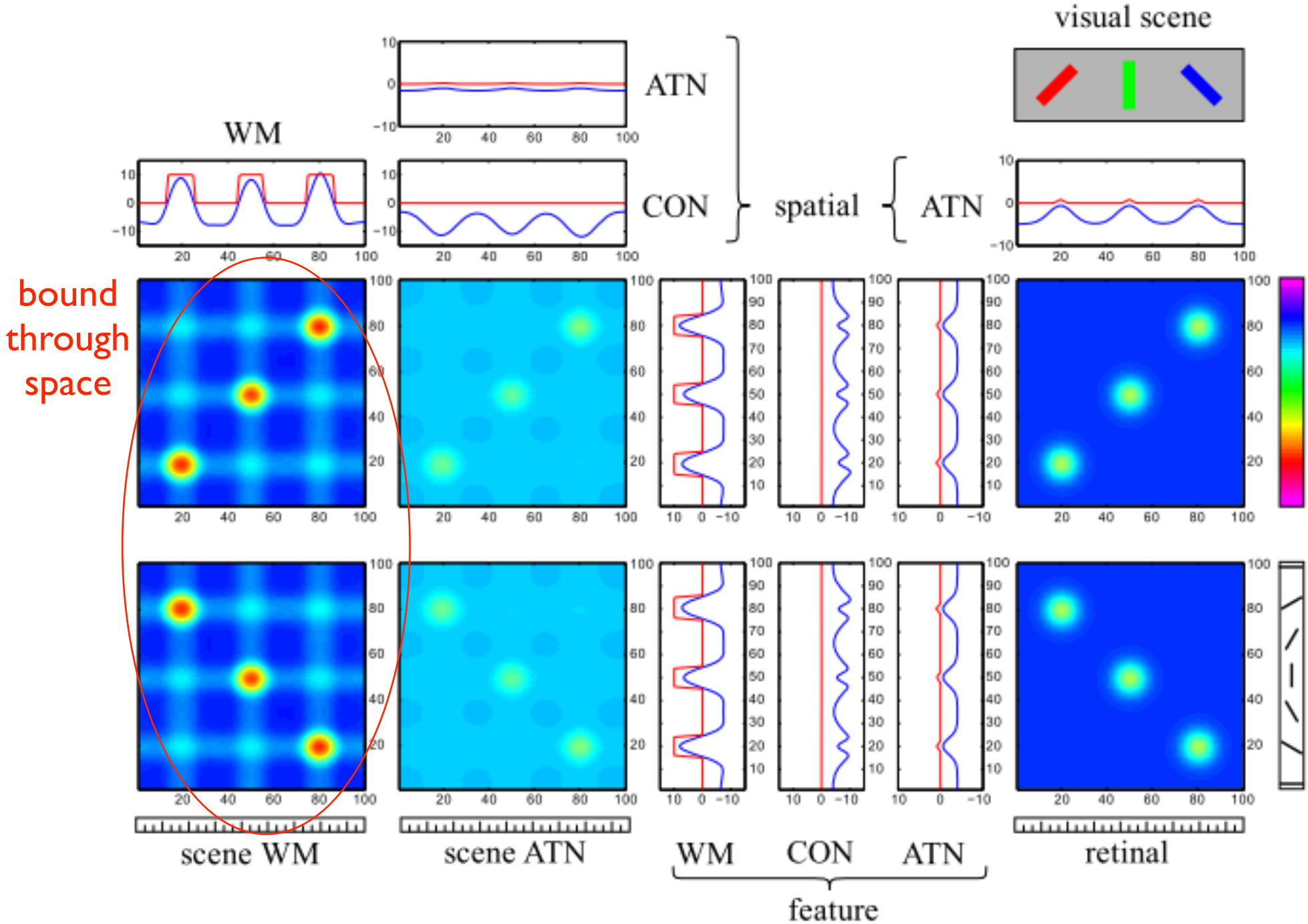


[Schneegans et al.,Ch 5 of *DFT Primer*, 2016]



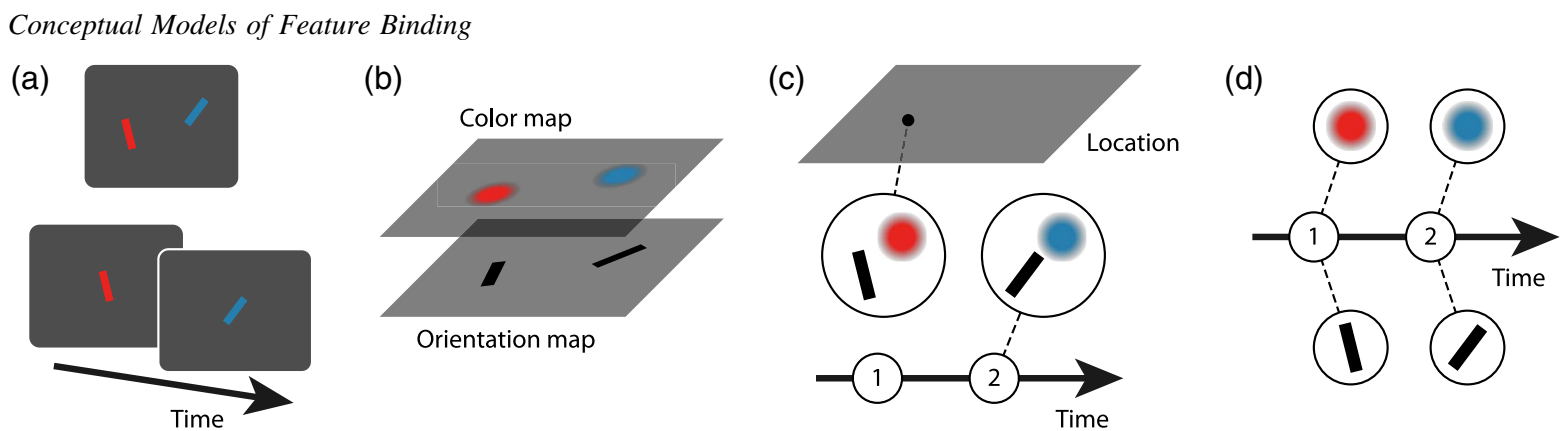
[Schneegans et al.,Ch 5 of *DFT Primer*, 2016]

Binding through space => sequential bottleneck

- binding through space must occur one time at a time..… to avoid binding problem
- => the sequential processing bottleneck may originate from this
- (more on this in a moment: coordinate transforms)

Binding through ordinal position

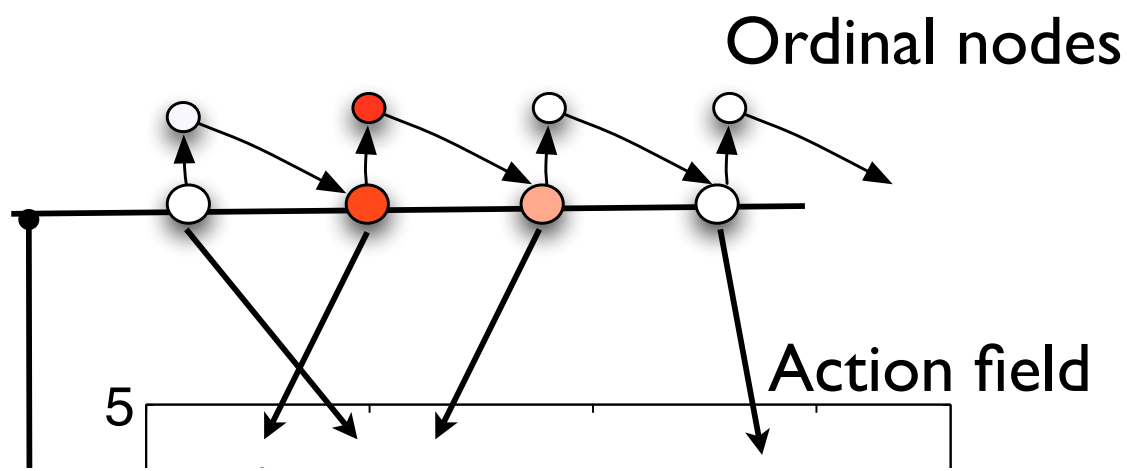
- feature dimensions presented at the same time (in a sequence) are bound in working memory



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

Binding through ordinal position

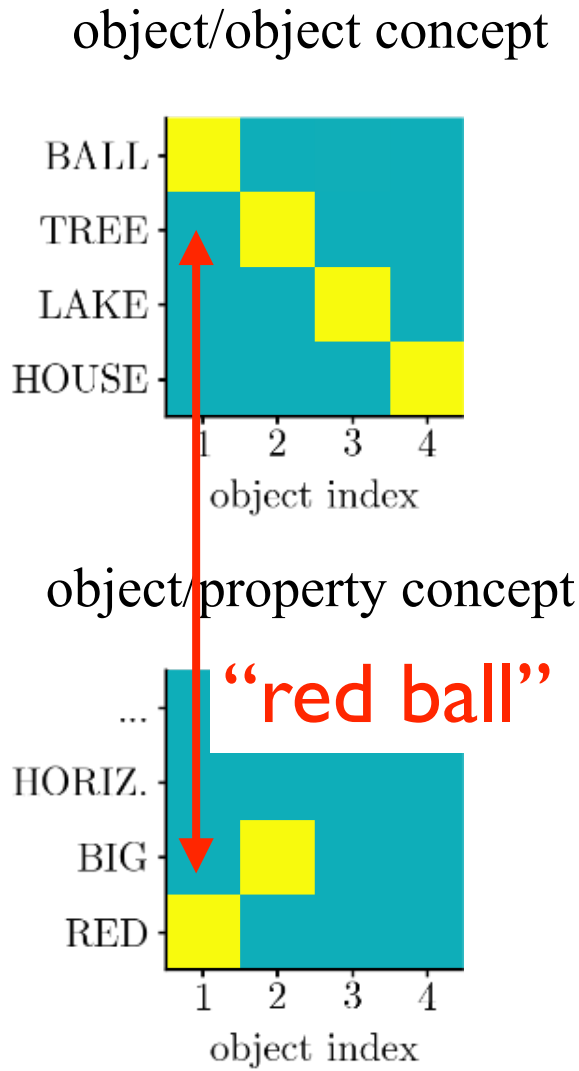
- ordinal position can be generated autonomously in DFT



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

Binding through ordinal position

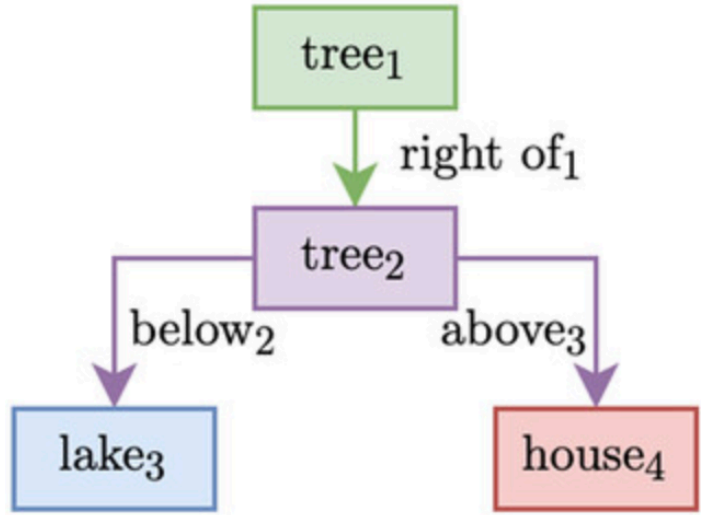
- using an ordinal position "index" to binds different concepts together

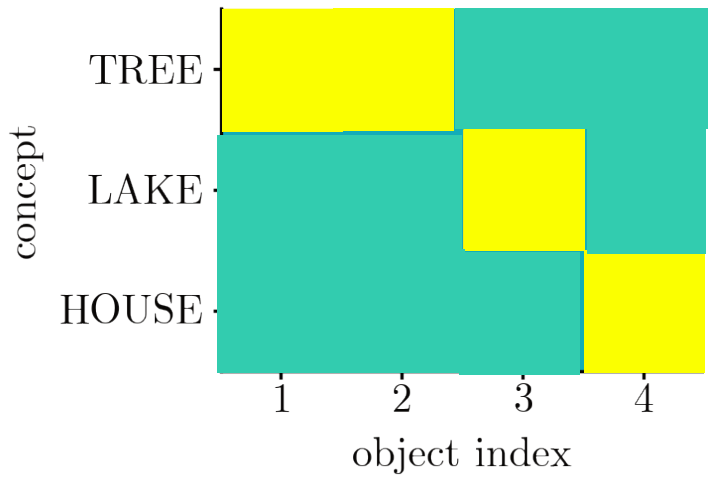


[Sabinasz, Richter, Schöner, *Cog. Neurodyn.* 2023]

Neural representation of conceptual structure

- (ordinal) object index
- separates two instantiations of "tree"
- solving the problem of two

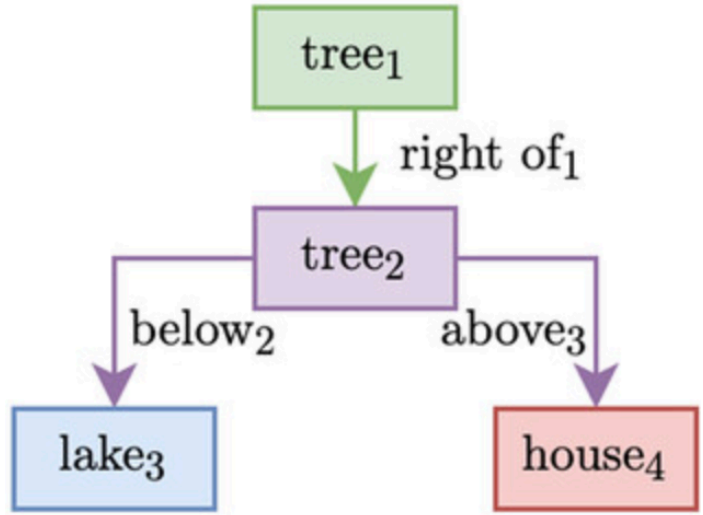


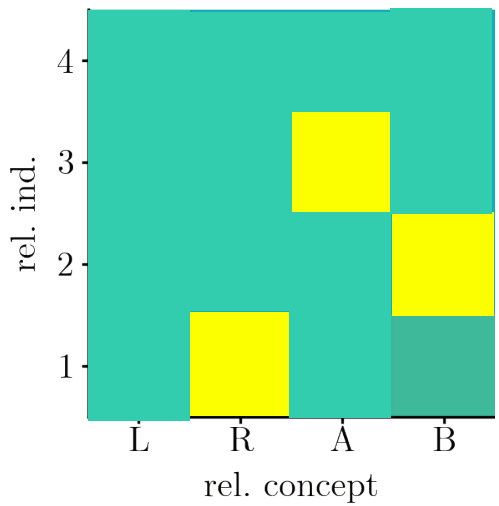


[Sabinasz, Richter, Schöner *Cog Neurodyn* 2023]

Neural representation of conceptual structure

- (ordinal) relation index
- enables multiple instances of same relation in a nested phrase

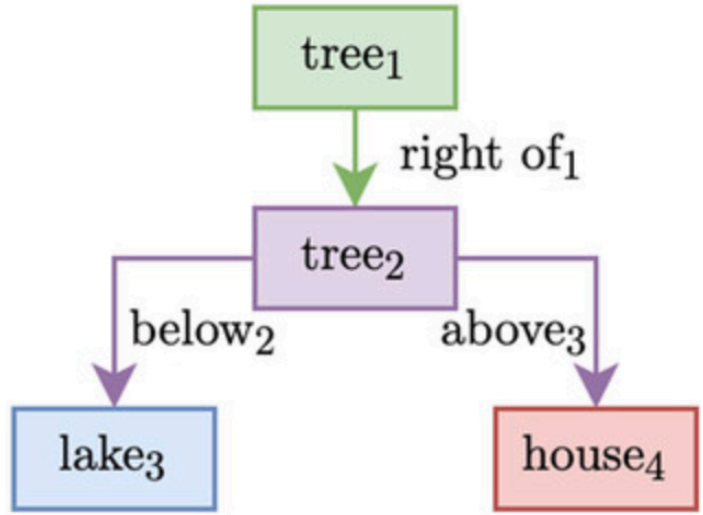


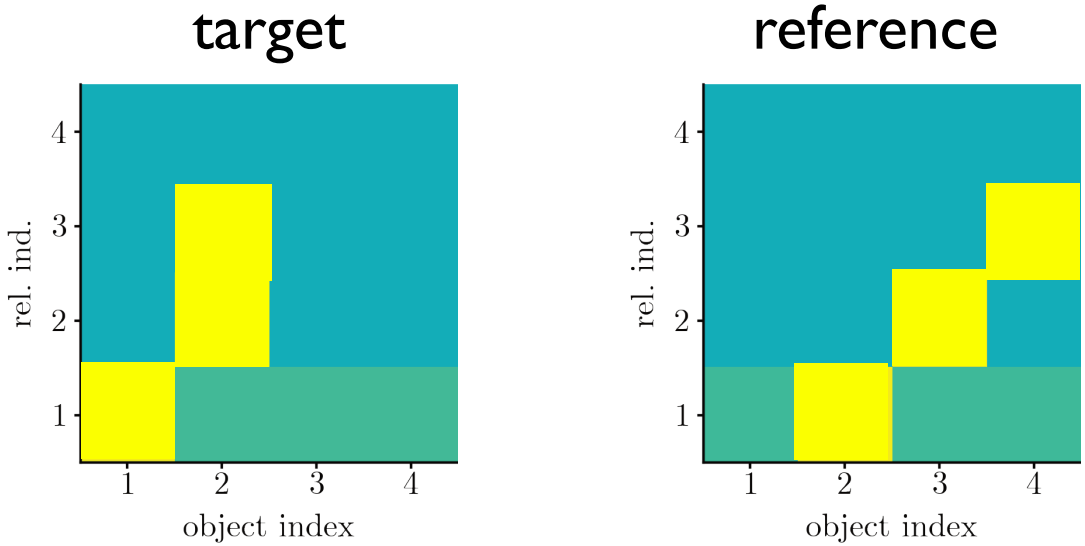


[Sabinasz, Richter, Schöner *Cog Neurodyn* 2023]

Neural representation of conceptual structure

- binding arguments in particular roles to relations
- through the index dimensions





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

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Foundations 2: Space-time coupling

- Background: different notions of binding
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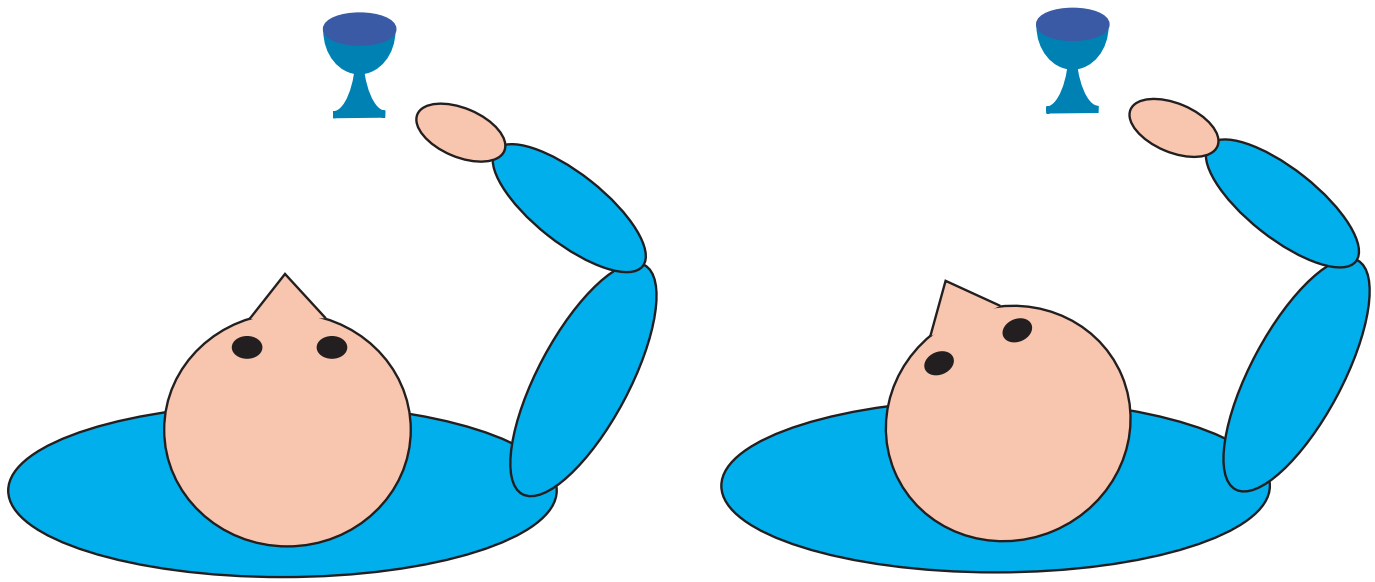
Coordinate transforms

- are fundamental element to sensory-motor cognition
- [but critical also to mental operations!]

- example: reaching is guided by body-centered, not by retinal visual representation



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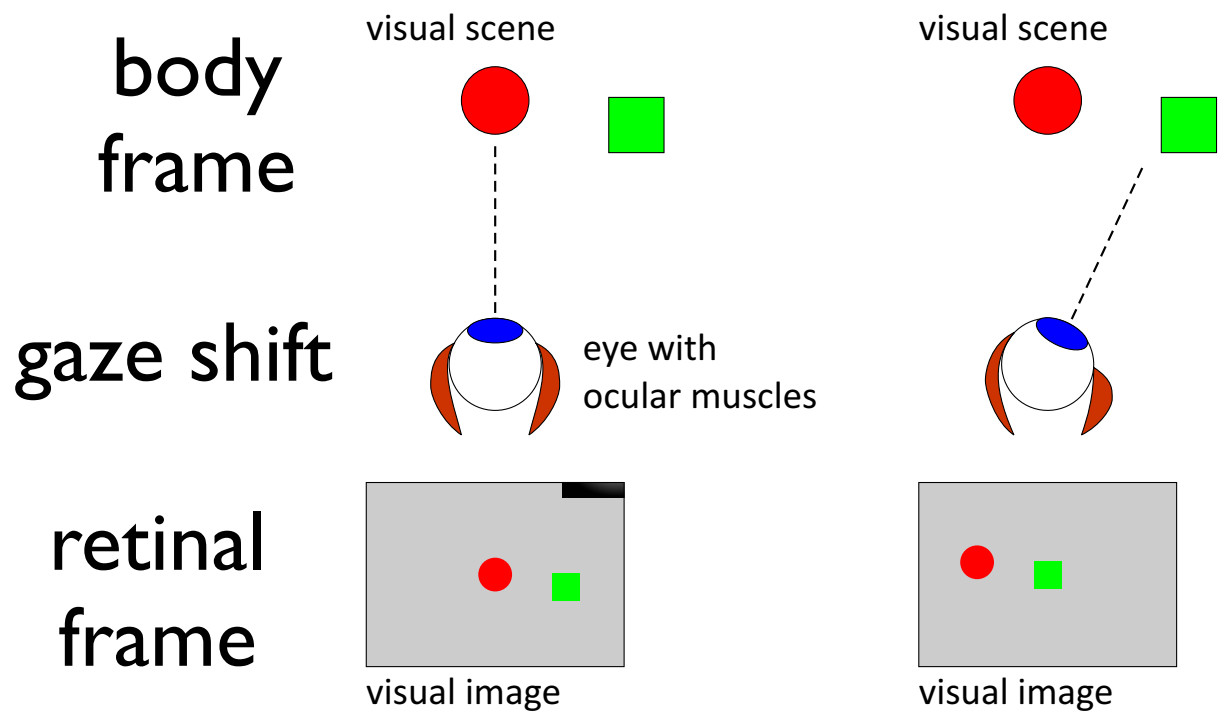


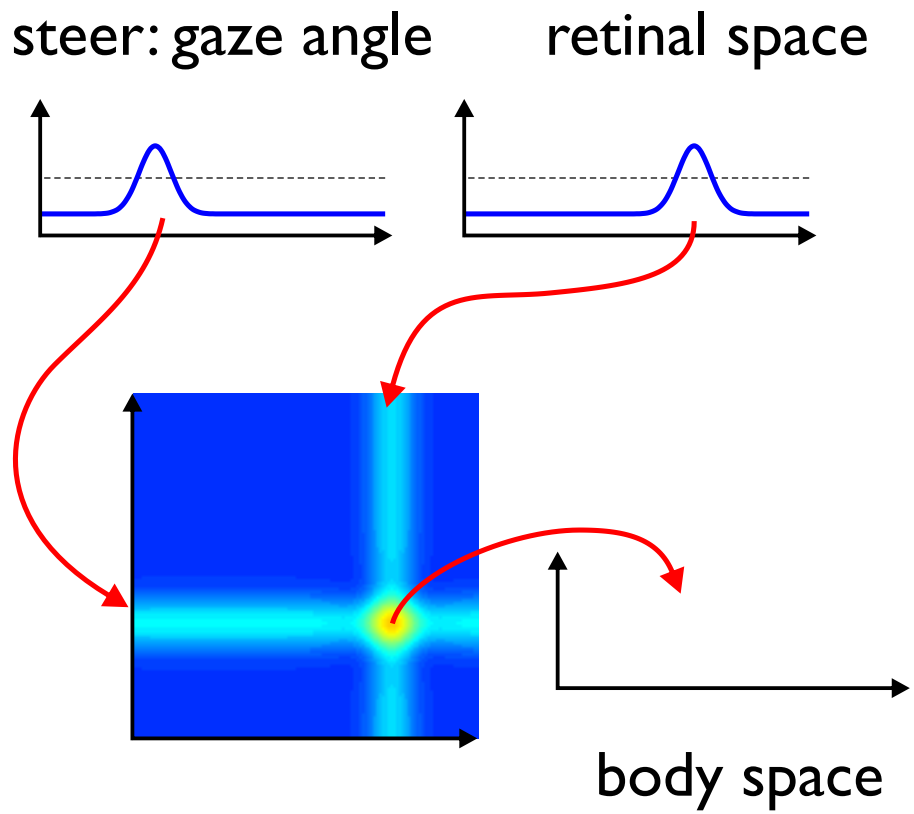
Coordinate transforms

- can be achieved in DFT by
  - binding the "to-be-transformed space" and the "transforming" dimension into a joint representation
  - and the unbinding into the "transformed space"

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

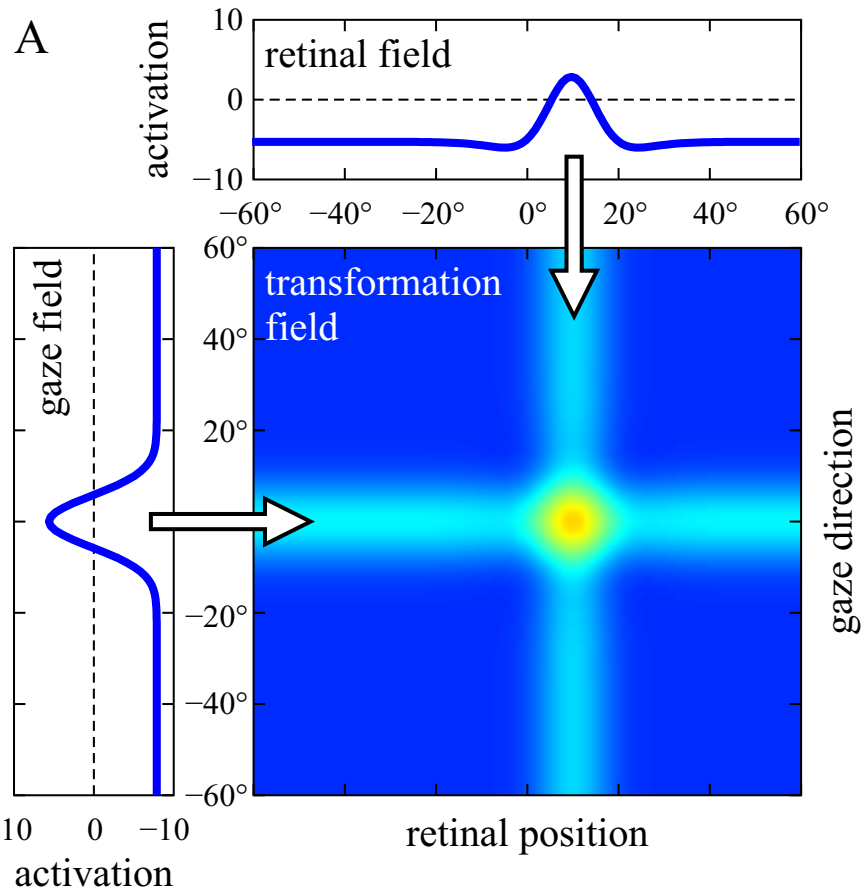
Coordinate transforms

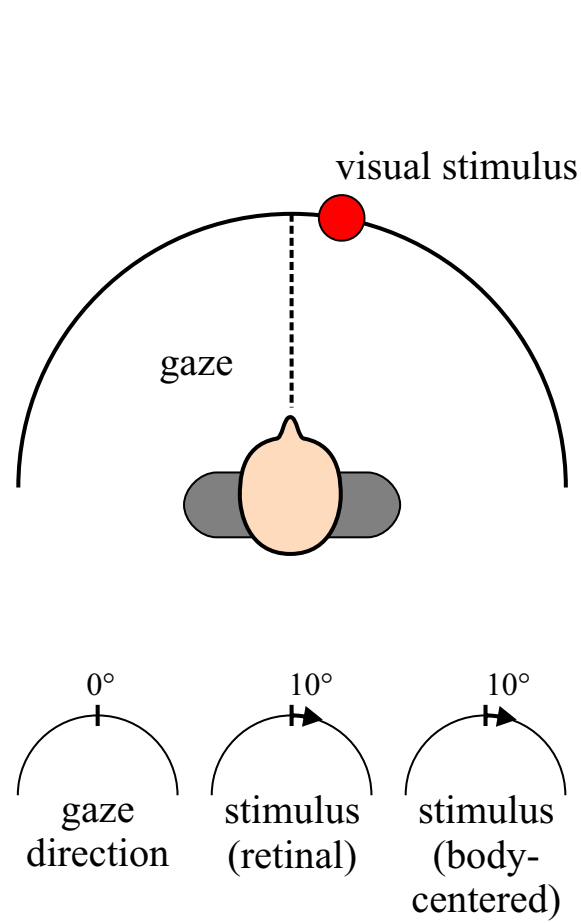
- bind neural representations of
  - retinal space
  - gaze angle
- into a joint representation
  - (gain field ~Andersen/Pouget
- then contract to body space



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

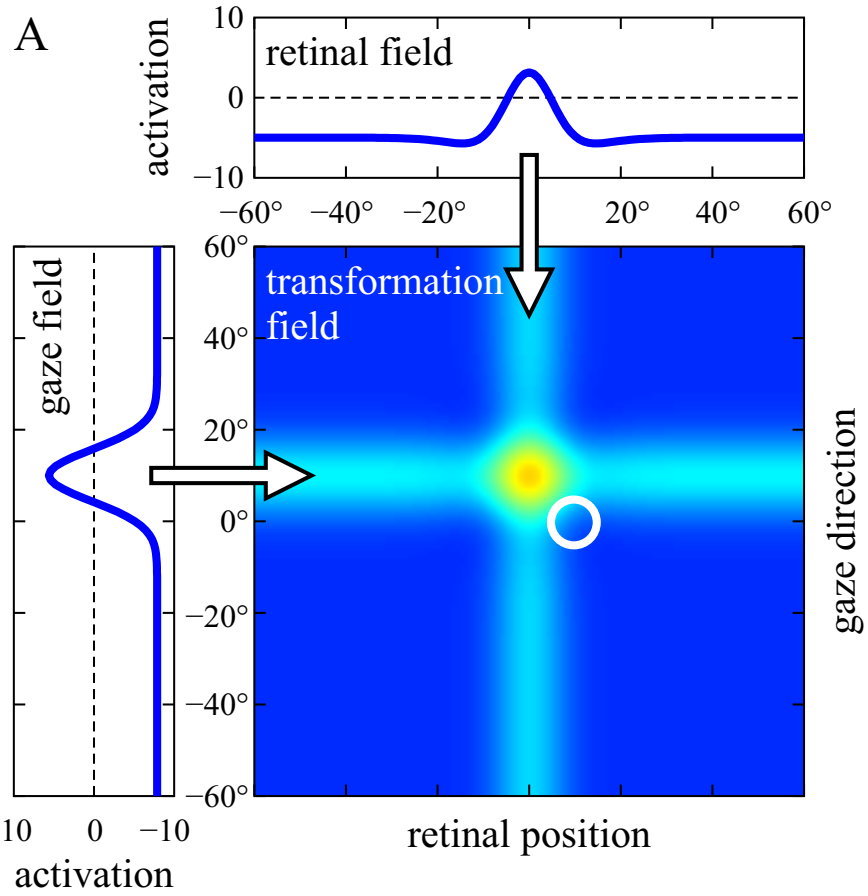
Coordinate transform

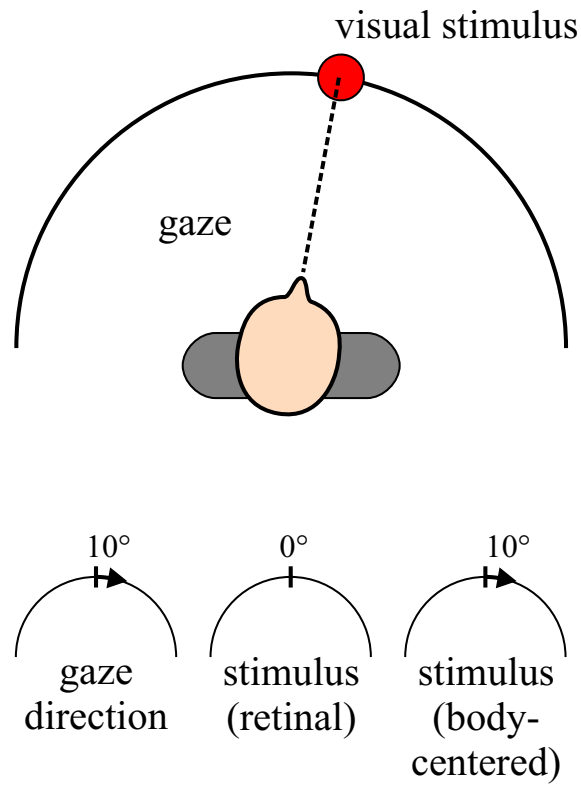




[Schneegans Ch 7 of *DFT Primer*, 2016]

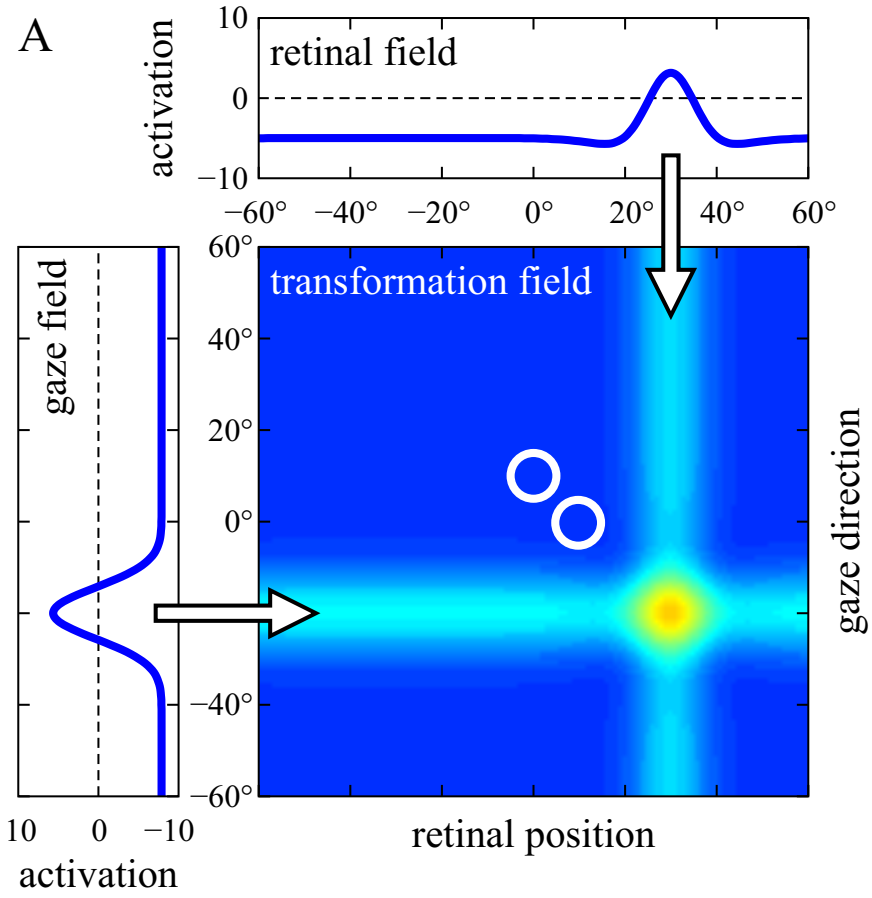
Coordinate transform

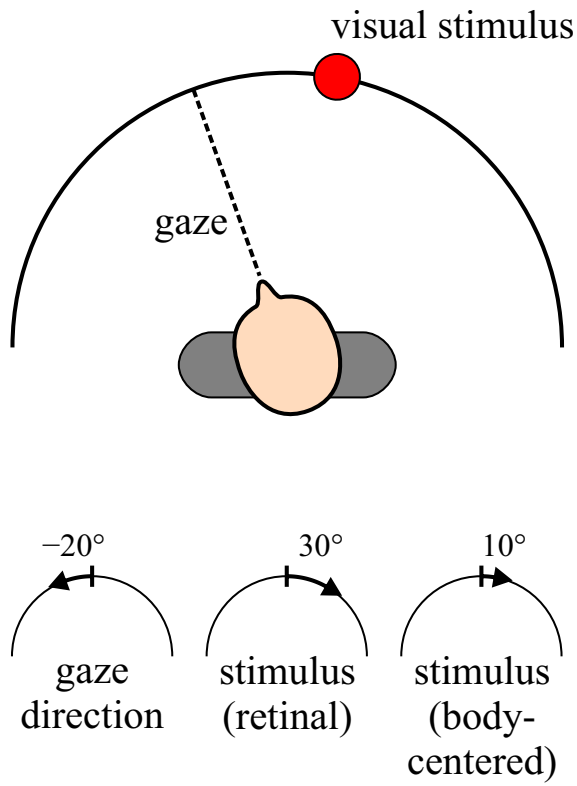




[Schneegans Ch 7 of *DFT Primer*, 2016]

Coordinate transform





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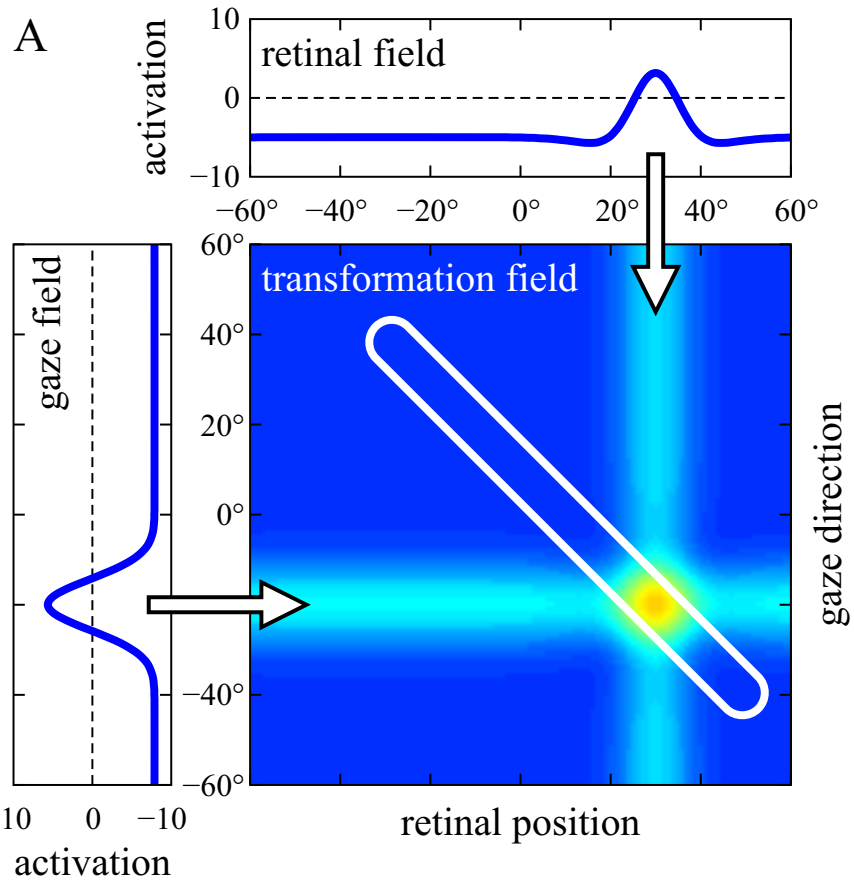
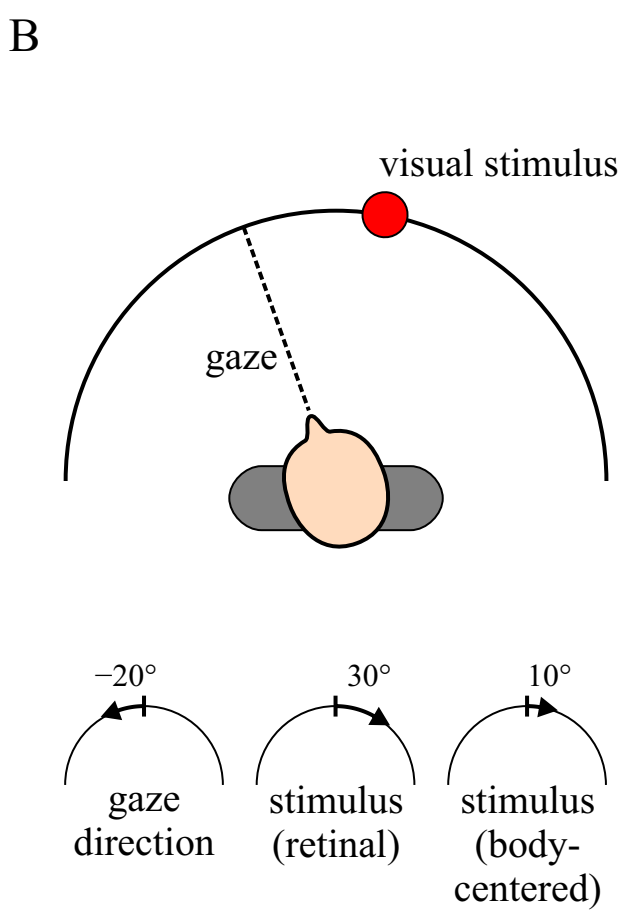
Coordinate transform





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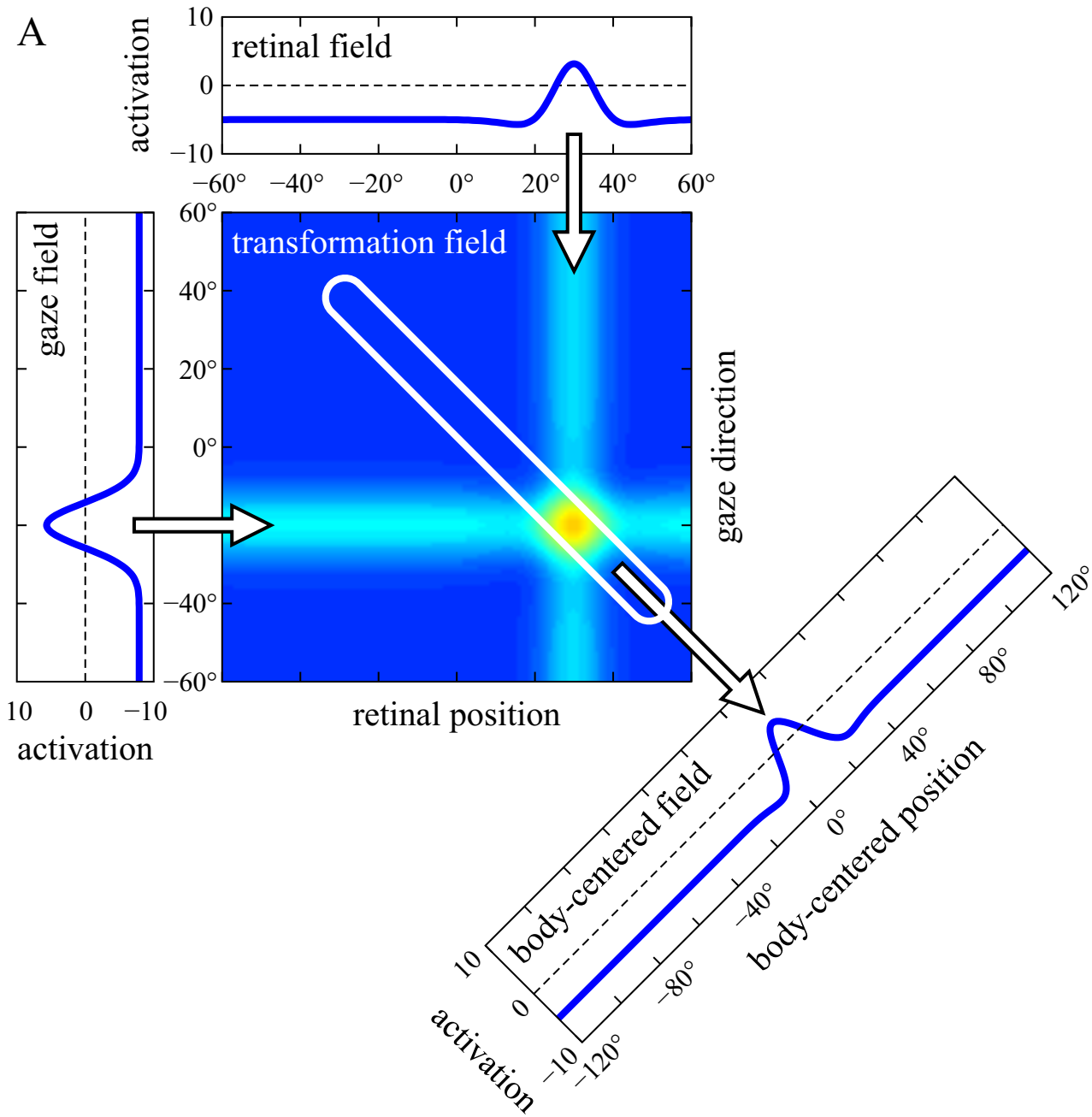
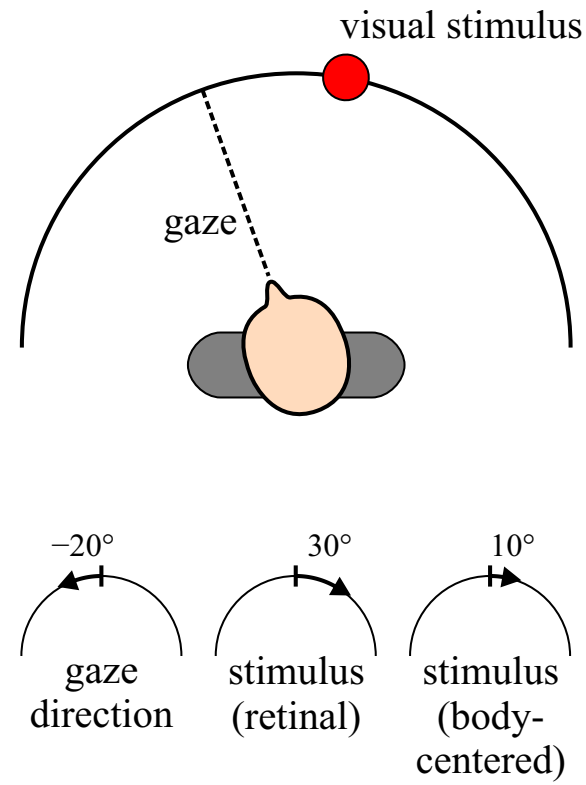
Coordinate transform

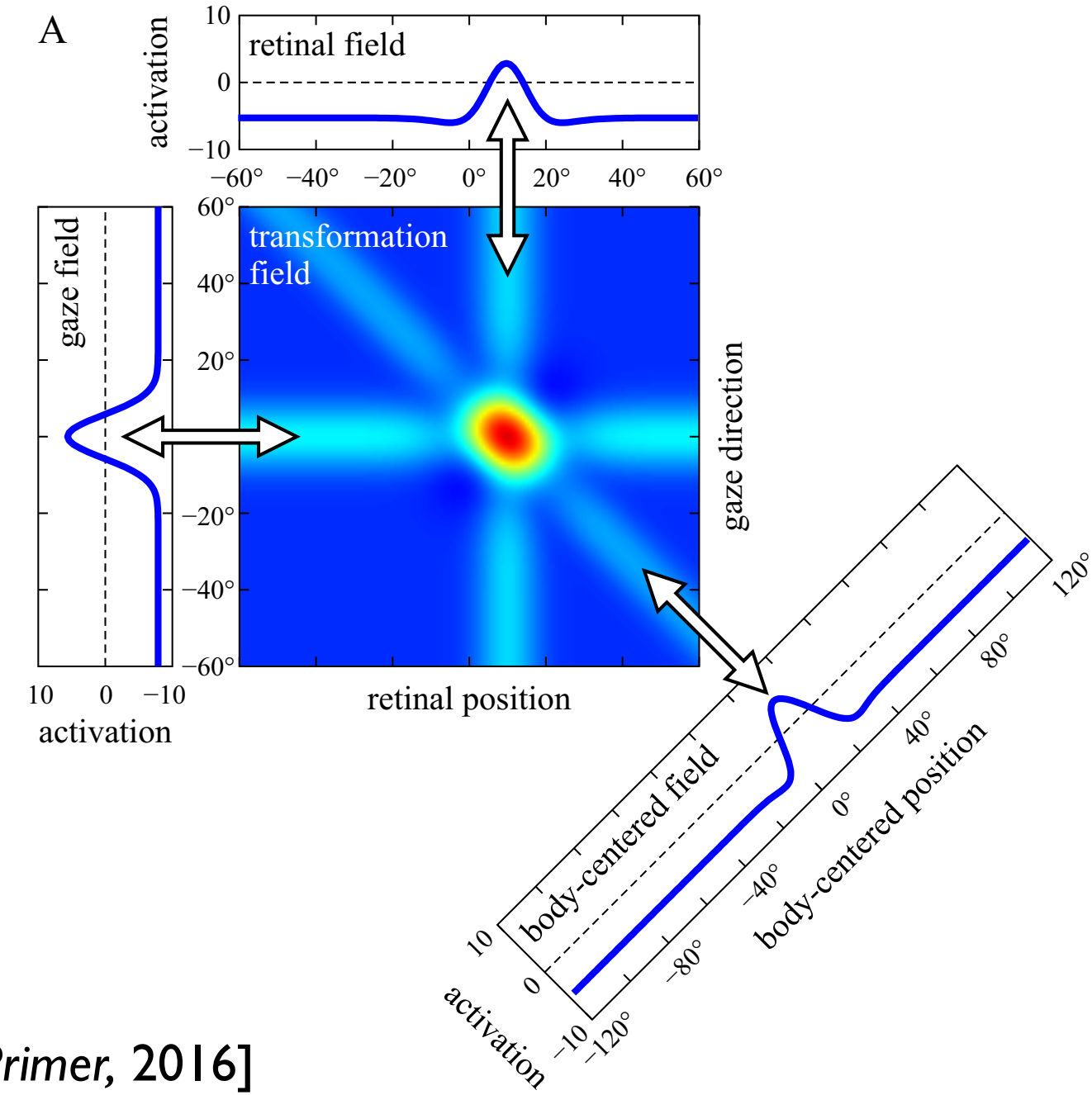




[Schneegans Ch 7 of *DFT Primer*, 2016]

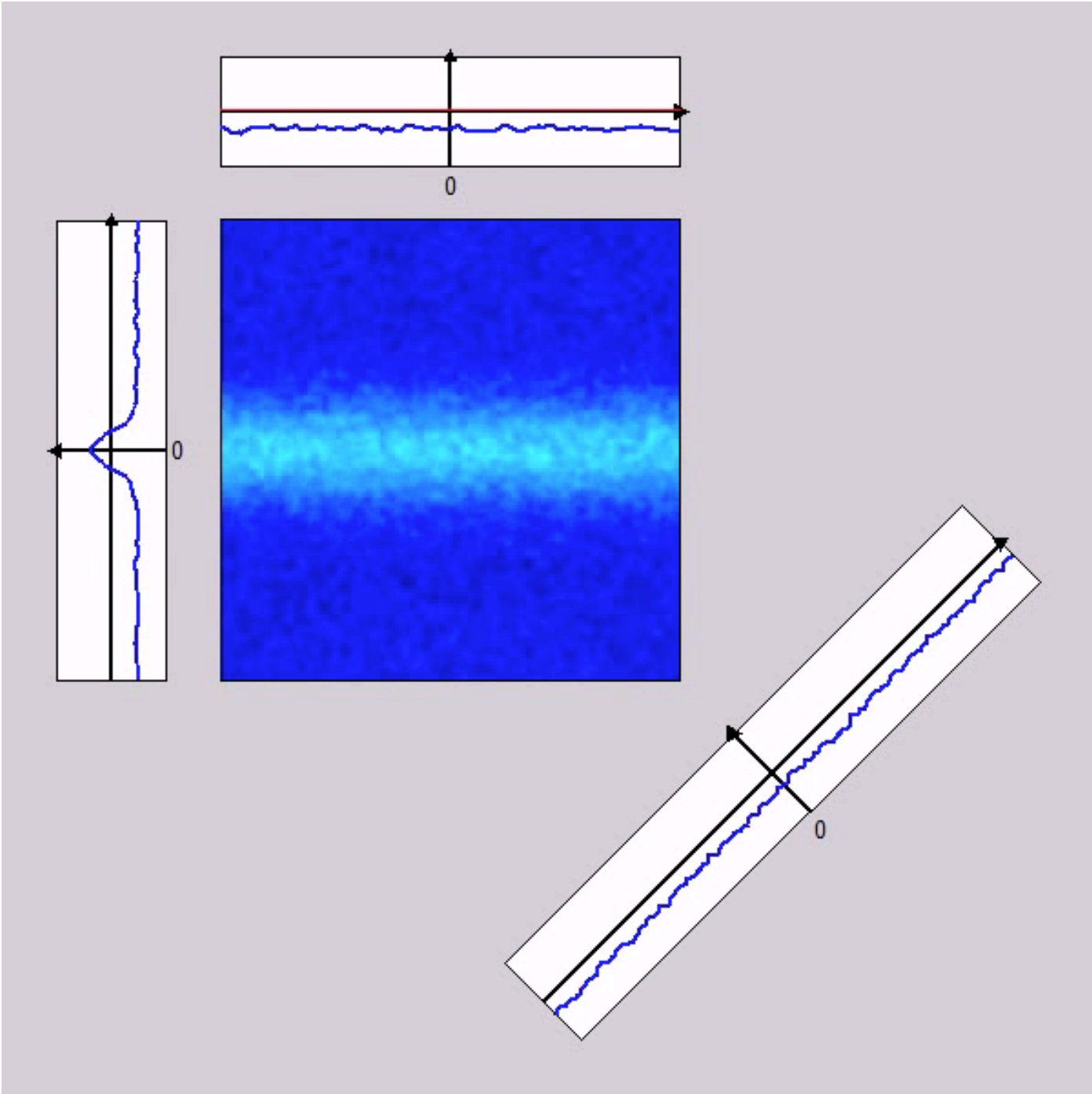
Retina => body space

- bi-directional coupling
- => predict retinal coordinates



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

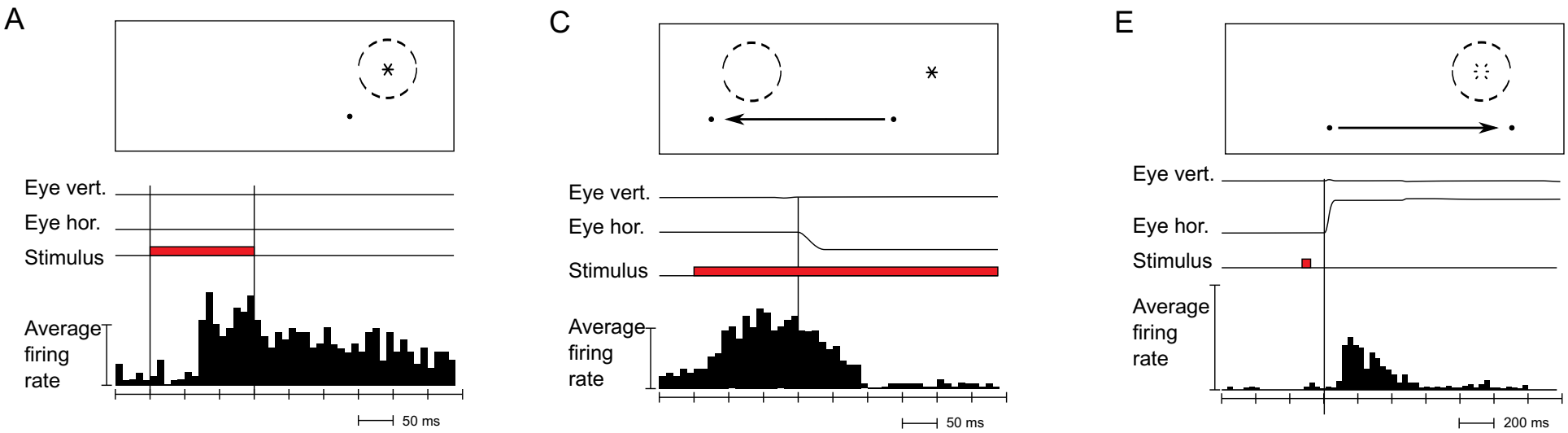
Spatial remapping during saccades



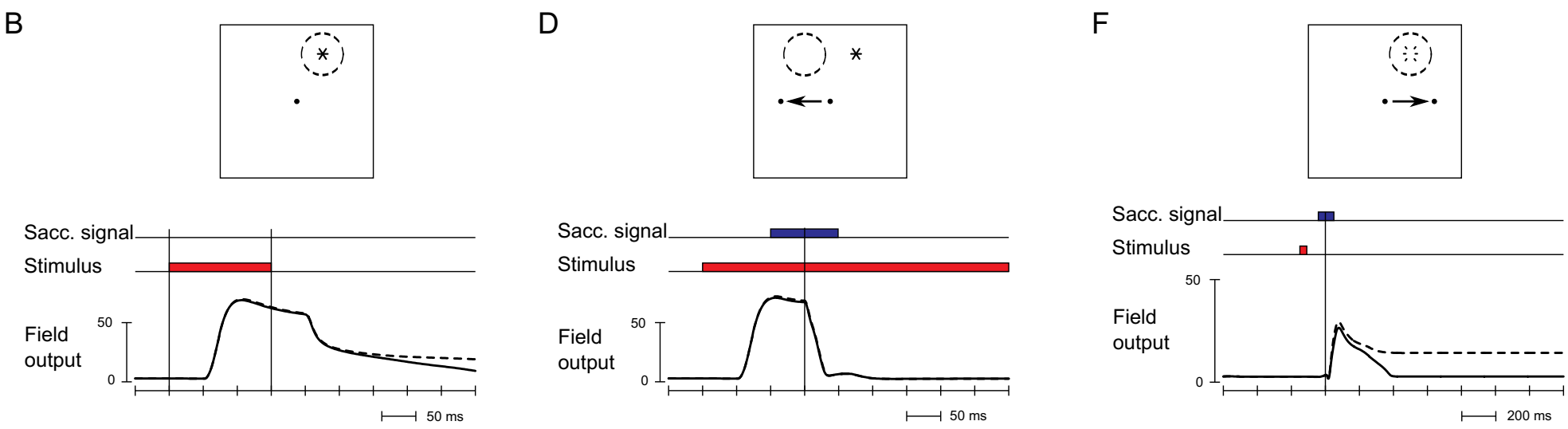
[Schneegans, Schöner *Biological Cybernetics* 2012]

Accounts for predictive updating

[neural data: Duhamel, Colby, Goldberg, 1992, LIP]



[model: Schneegans, Schöner *Biological Cybernetics* 2012]

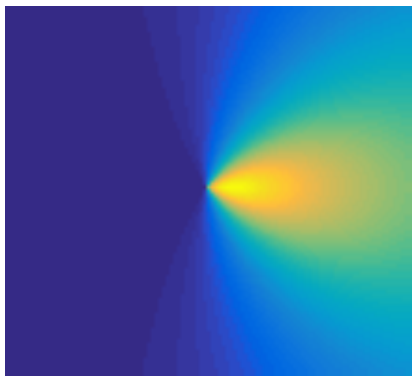


Coordinate transforms for cognition

"green to the right of red"

reference target

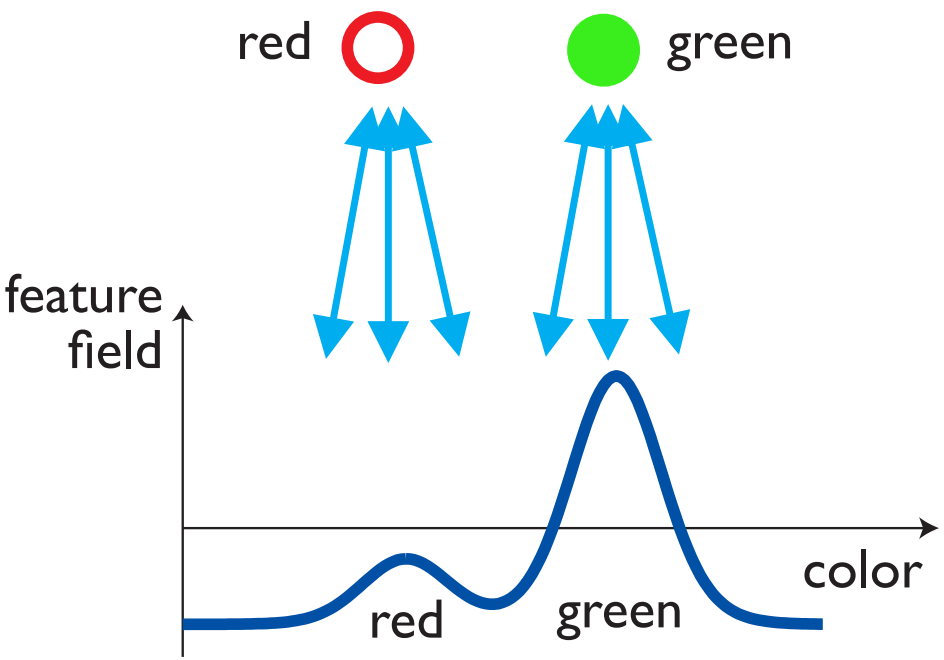
- to perceptually ground relations/actions etc
- use relational concepts that have patterned coupling



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

Role-filler binding

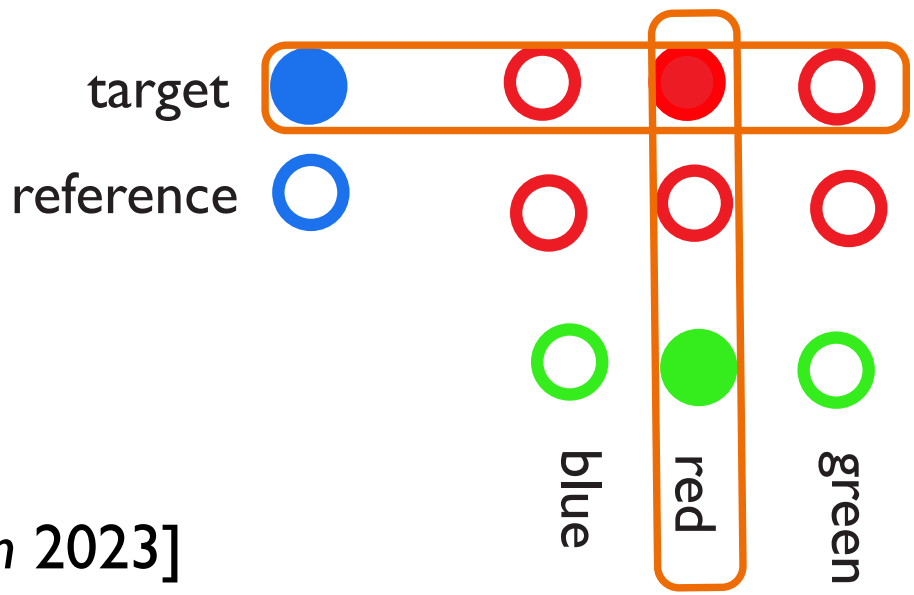
- color concepts… grounded in feature fields



- roles: reference, target, agent, tool, …

"green to the right of red"
target reference

- joint representation of roles and concepts

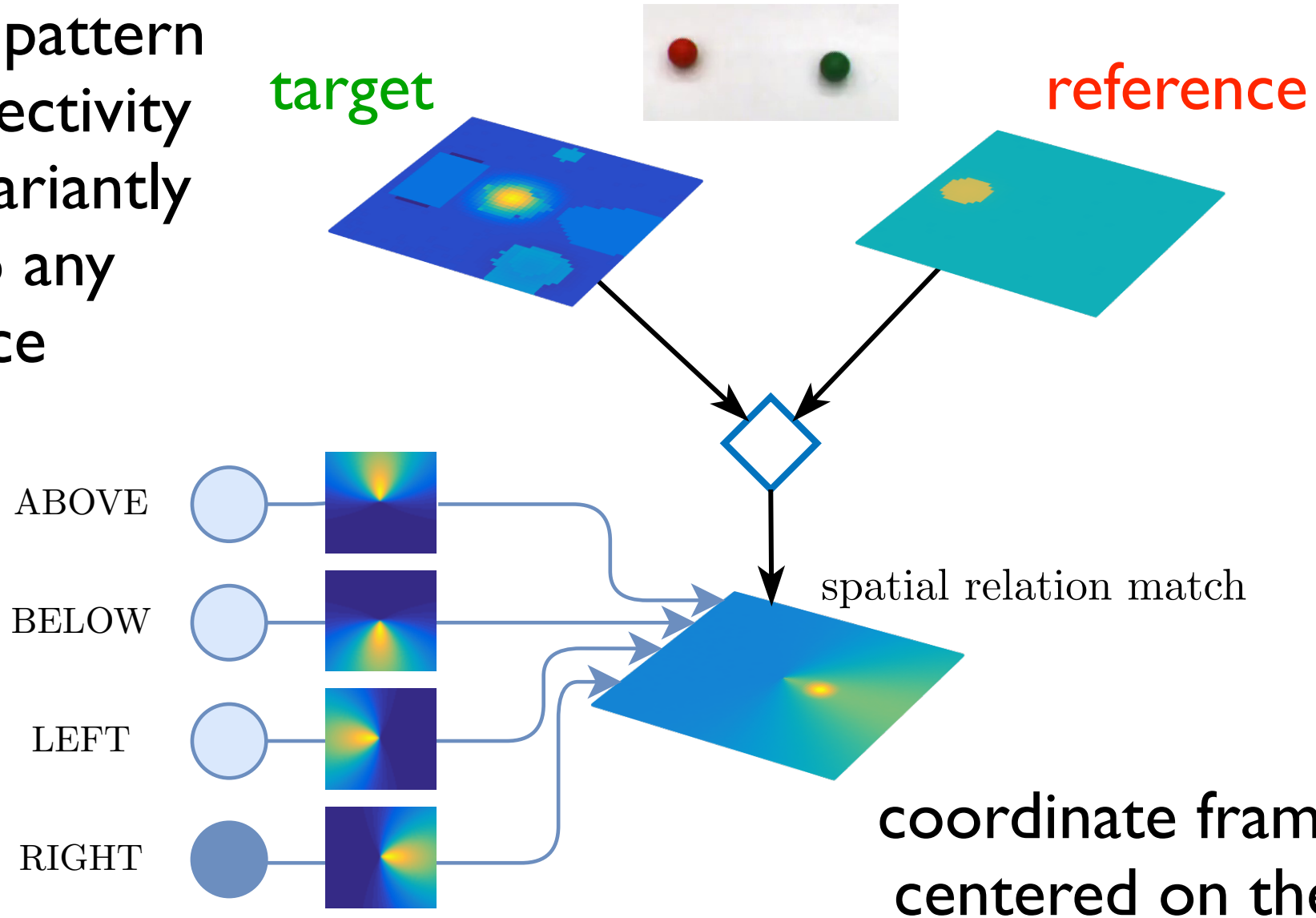


[Sabinasz, Richter, Schöner: *Cog Neurodyn* 2023]

Coordinate transforms for cognition

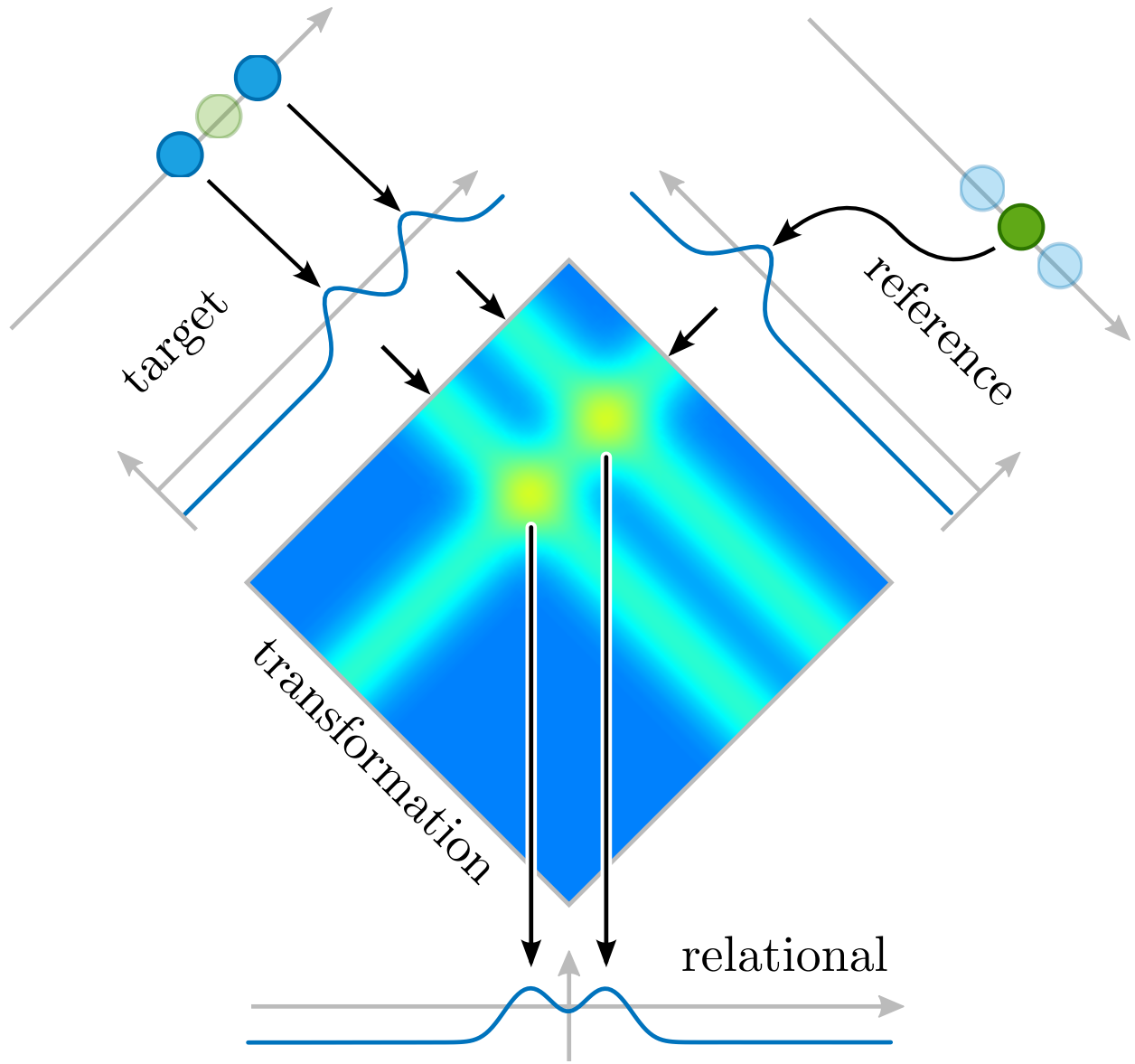
"green to the right of red"

- a single pattern of connectivity may invariantly apply to any reference objects



coordinate frame centered on the reference object

=>critical role of coordinate transforms for higher cognition



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

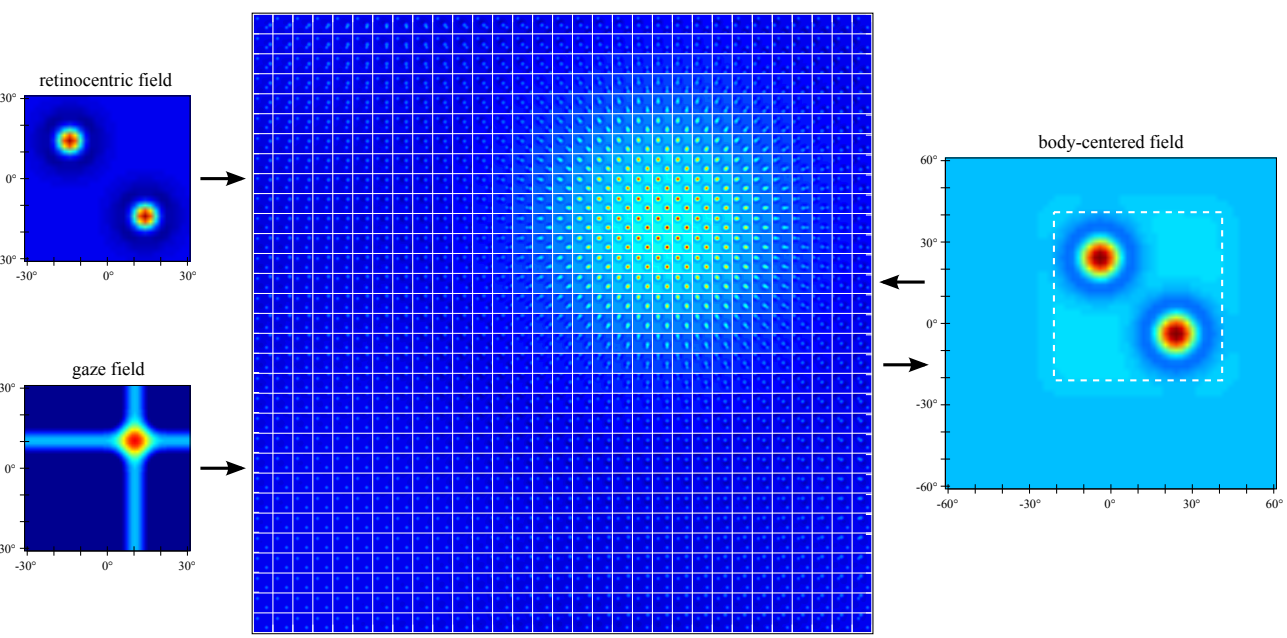
Coordinate transforms and binding through space

- to coordinate transform feature fields…
- do we need a joint representation of each space-feature field with the transforming dimension?

- No!
- coordinate transform space only!
- transport the feature values by binding through space!

[Schneegans, Schöner, 2012]

Coordinate transforms and binding through space



- coordinate transform space only!
- transport the feature values by binding through space!

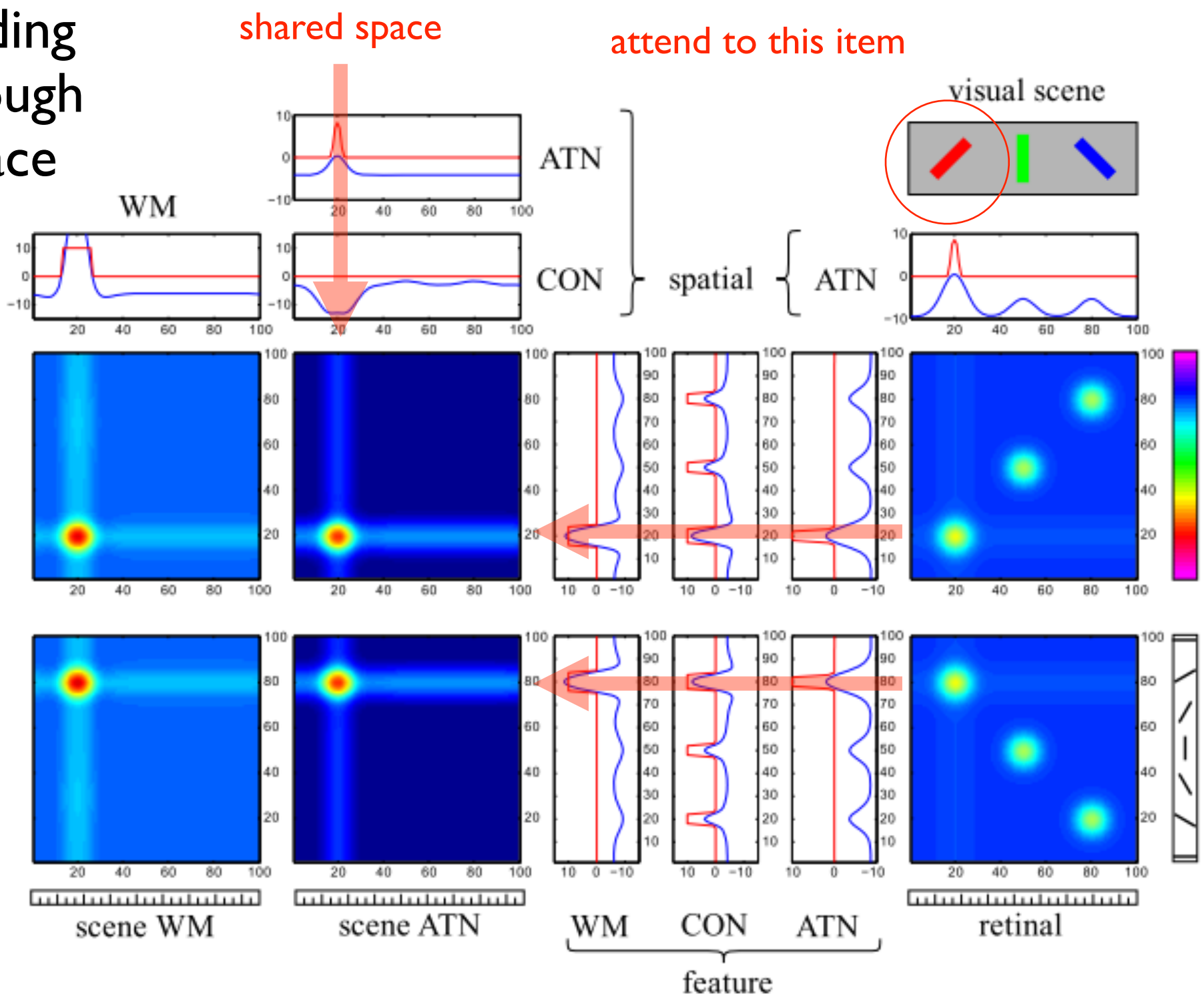
[Schneegans, Schöner, 2012]

Coordinate transforms and binding through space

- => binding through space (and the attentional bottleneck this implies) radically simplifies coordinate transforms
- parietal cortex (where gain fields are) may do coordinate transforms for every feature/category representation!

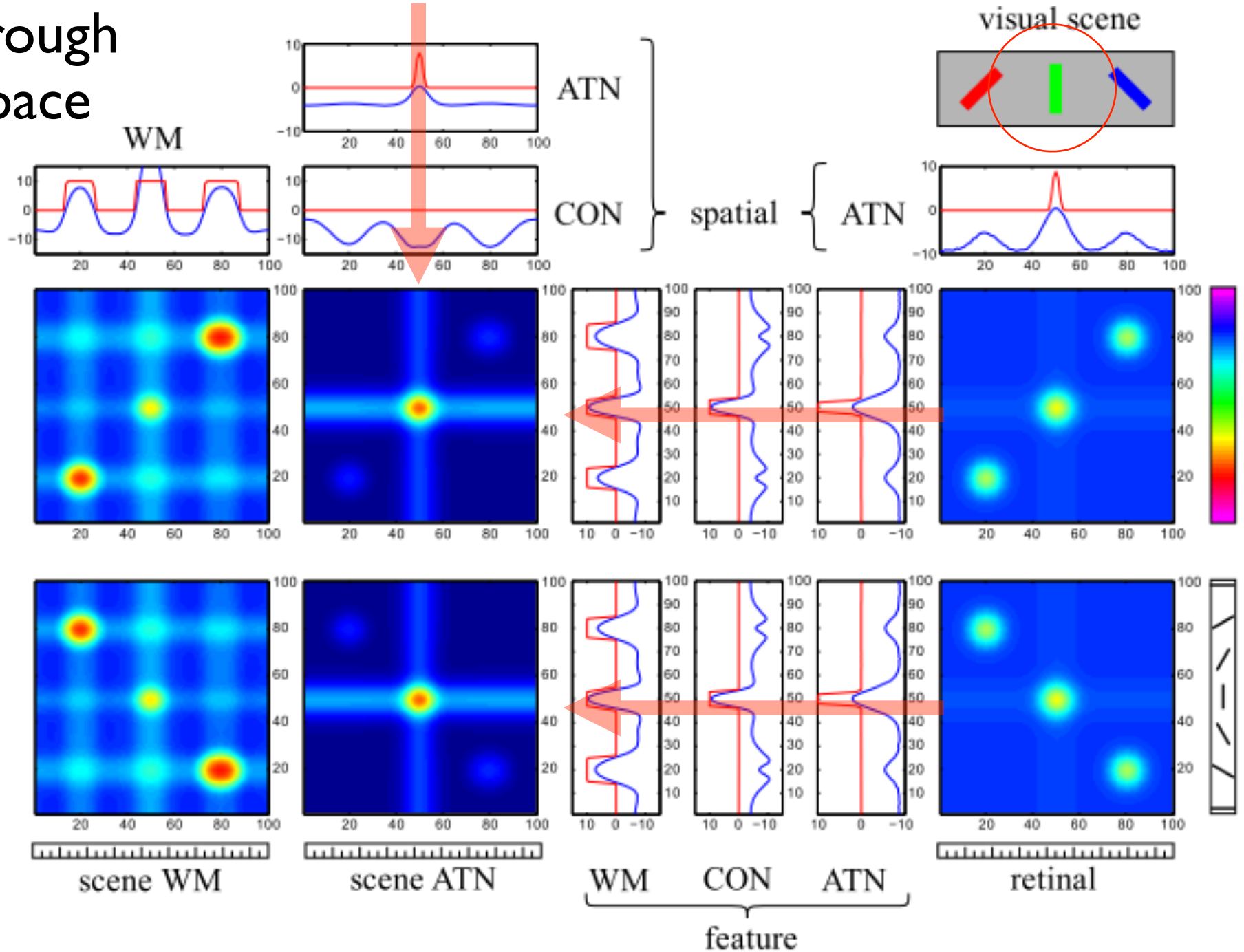
[Schneegans, Schöner, 2012]

binding through space



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

binding through space



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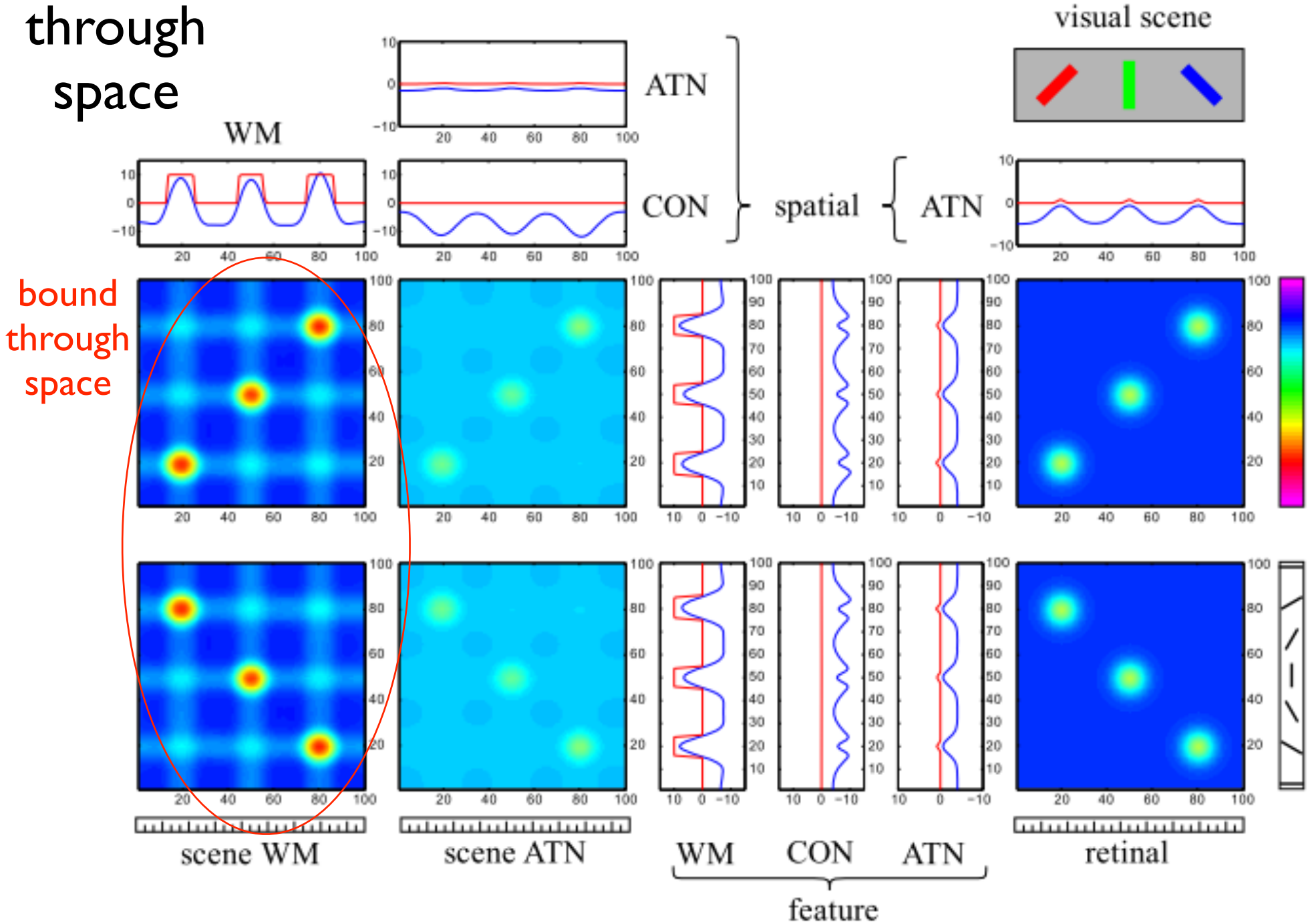
binding through space



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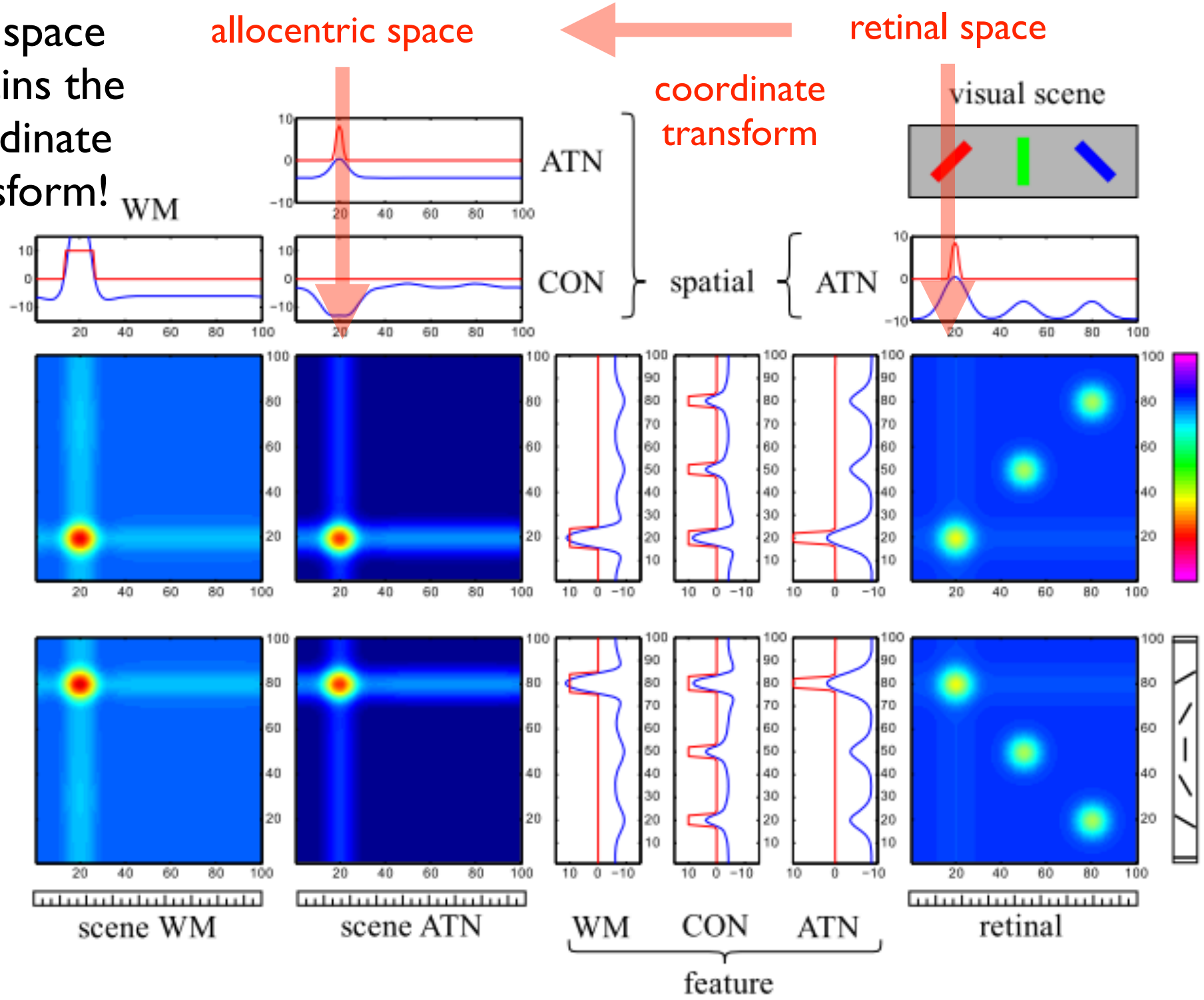
that space contains the coordinate transform!



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Foundations 2: Space-time coupling

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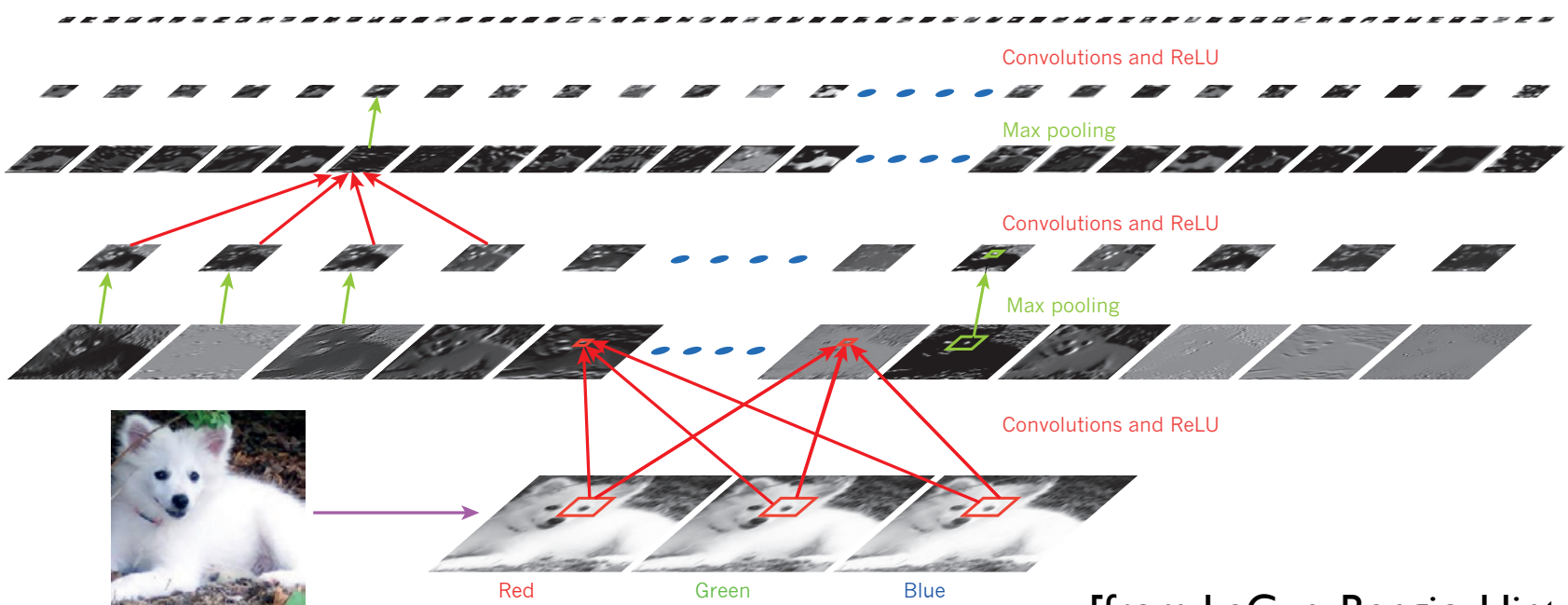
Is there a binding problem for DNN?

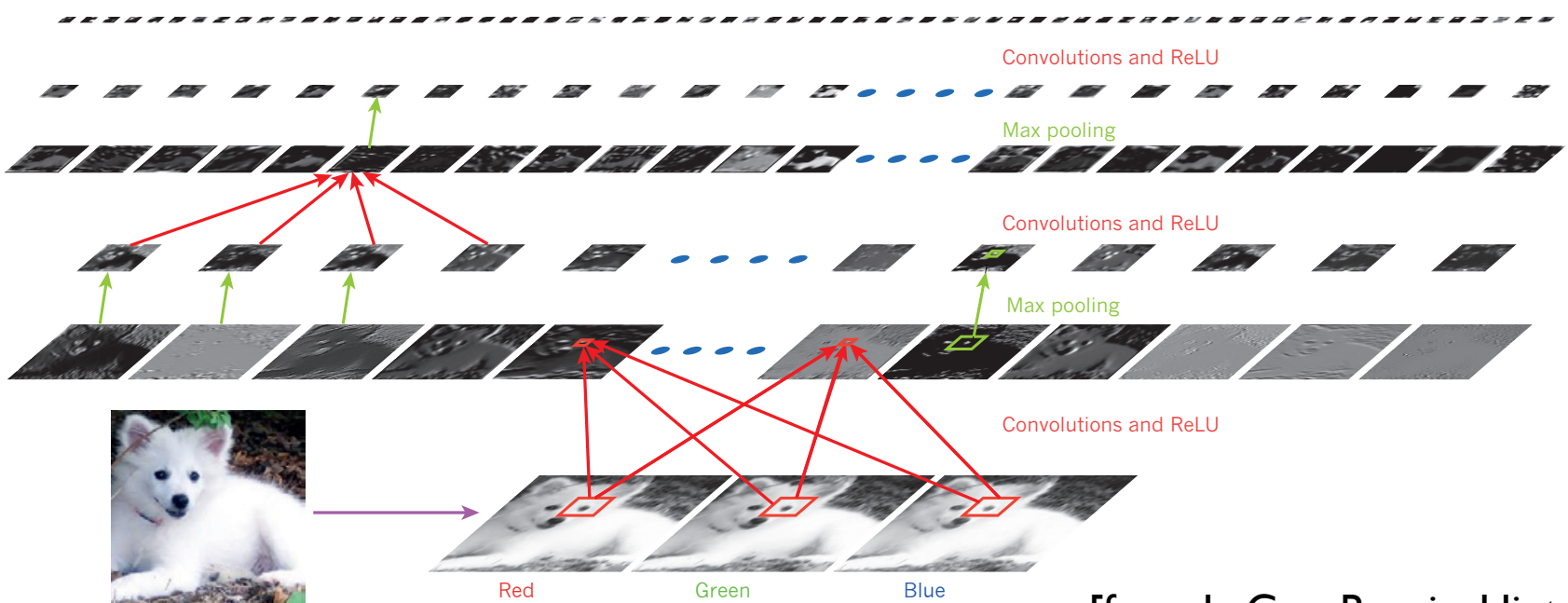
- … old debate Poggio.von der Malsburg.. [*Neuron* 99]
- complex learned features are represented jointly distributed across a DNN…. hidden layers



[from LeCun, Bengio, Hinton, Nature 2015]

Is there a binding problem for DNN?

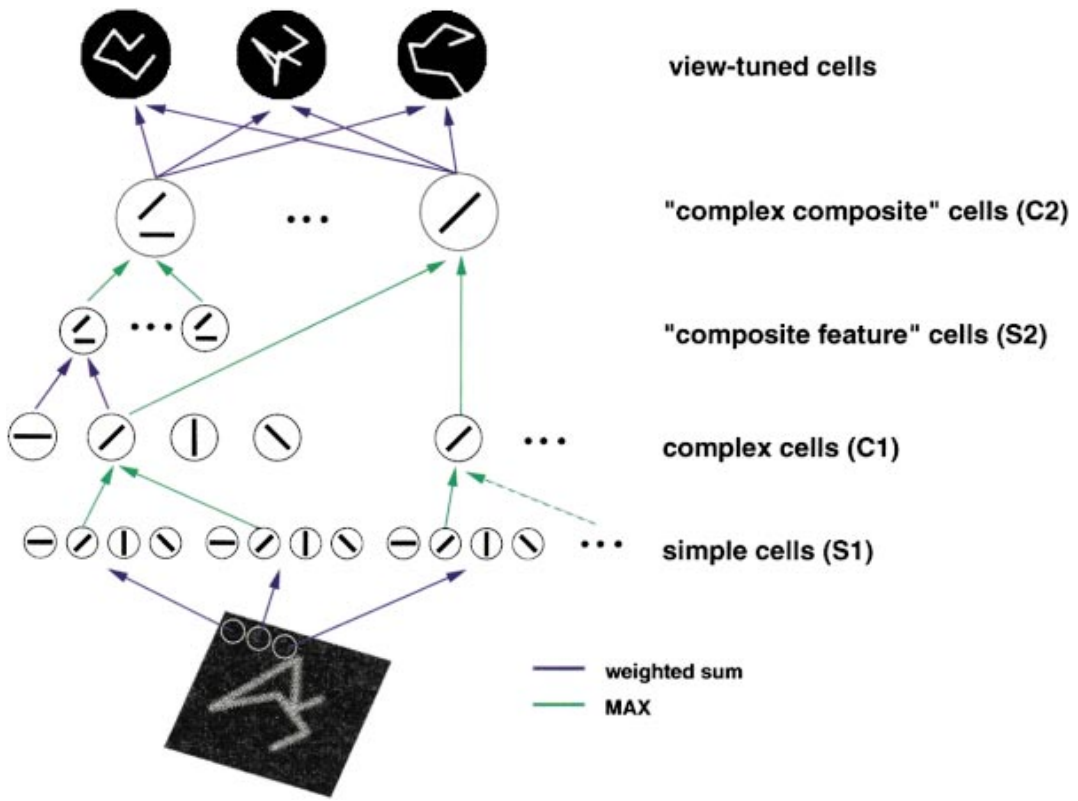
- => need the relevant patterns of connectivity across the visual array (done by weight sharing)
- e.g. Fei-Fei Li et al for relations…



[from LeCun, Bengio, Hinton, Nature 2015]

Is there a binding problem for DNN?

- binding by joint representation is not flexible!



[Poggio, 1999]

Roadmap

- next lectures:
  - sequence generation
  - grounding conceptual structure
  - analogy
  - itentionality