Higher-dimensional dynamics fields enable new cognitive function

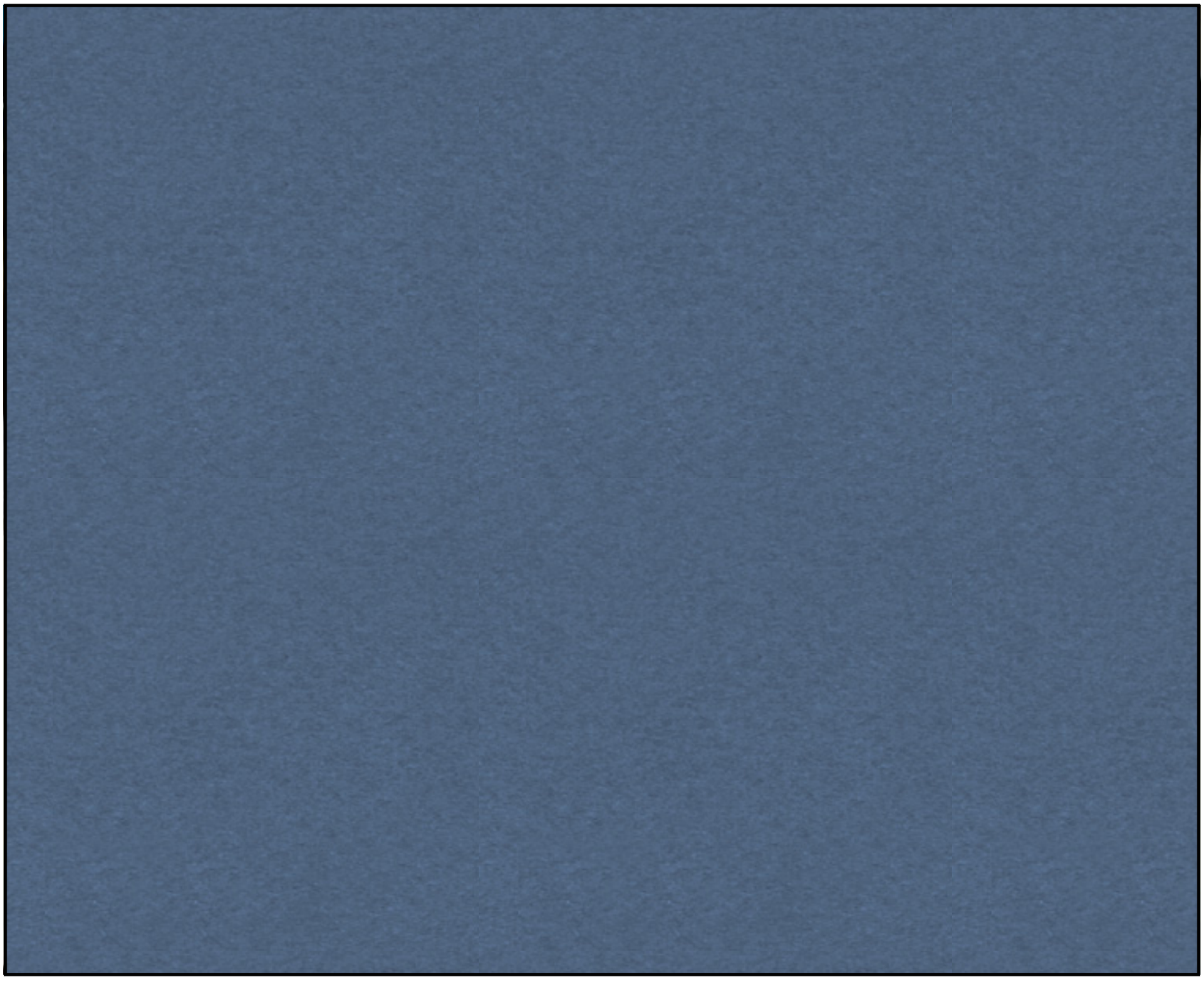
Gregor Schöner

The binding problem

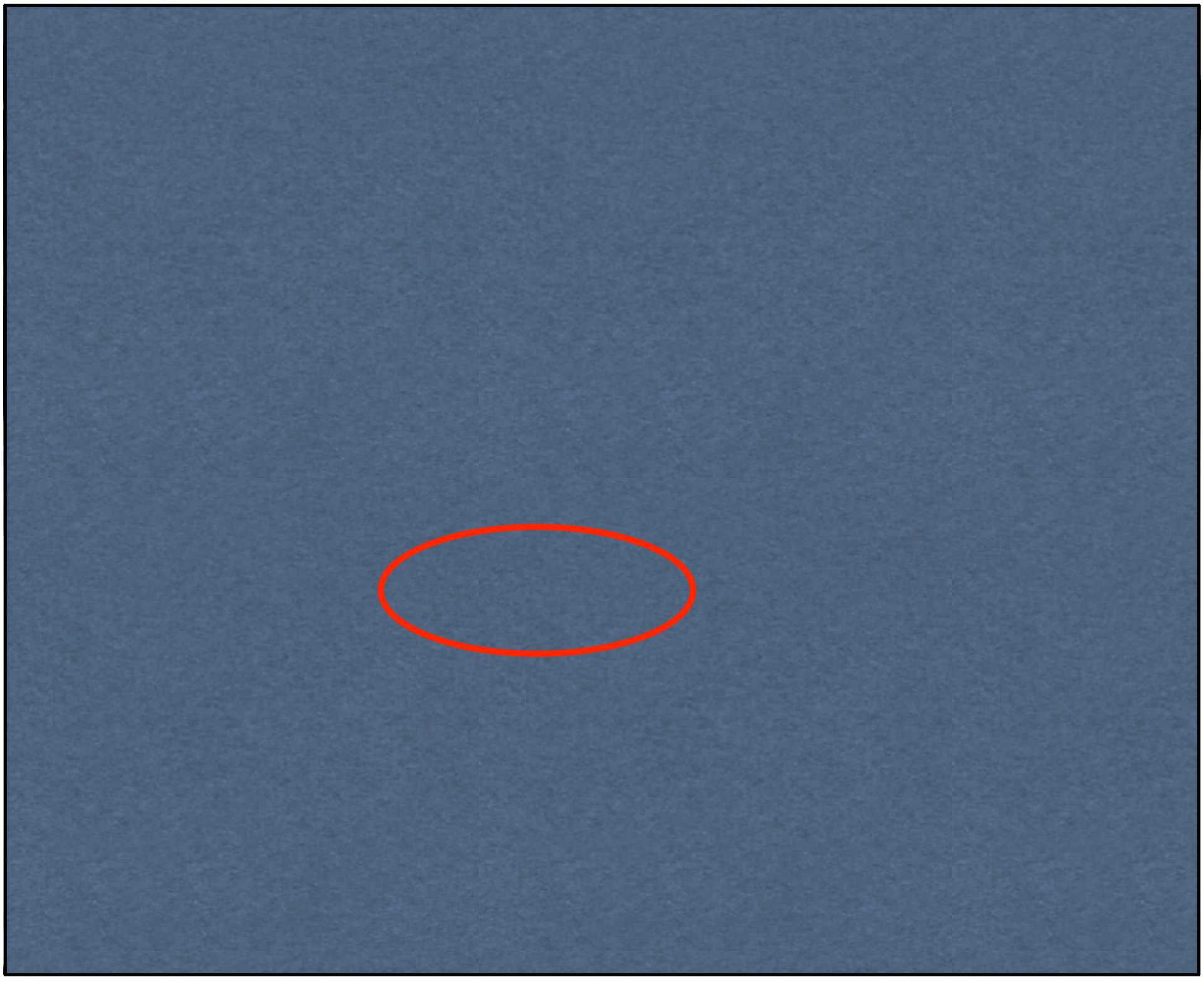
The binding problem

red cutter horizontally aligned

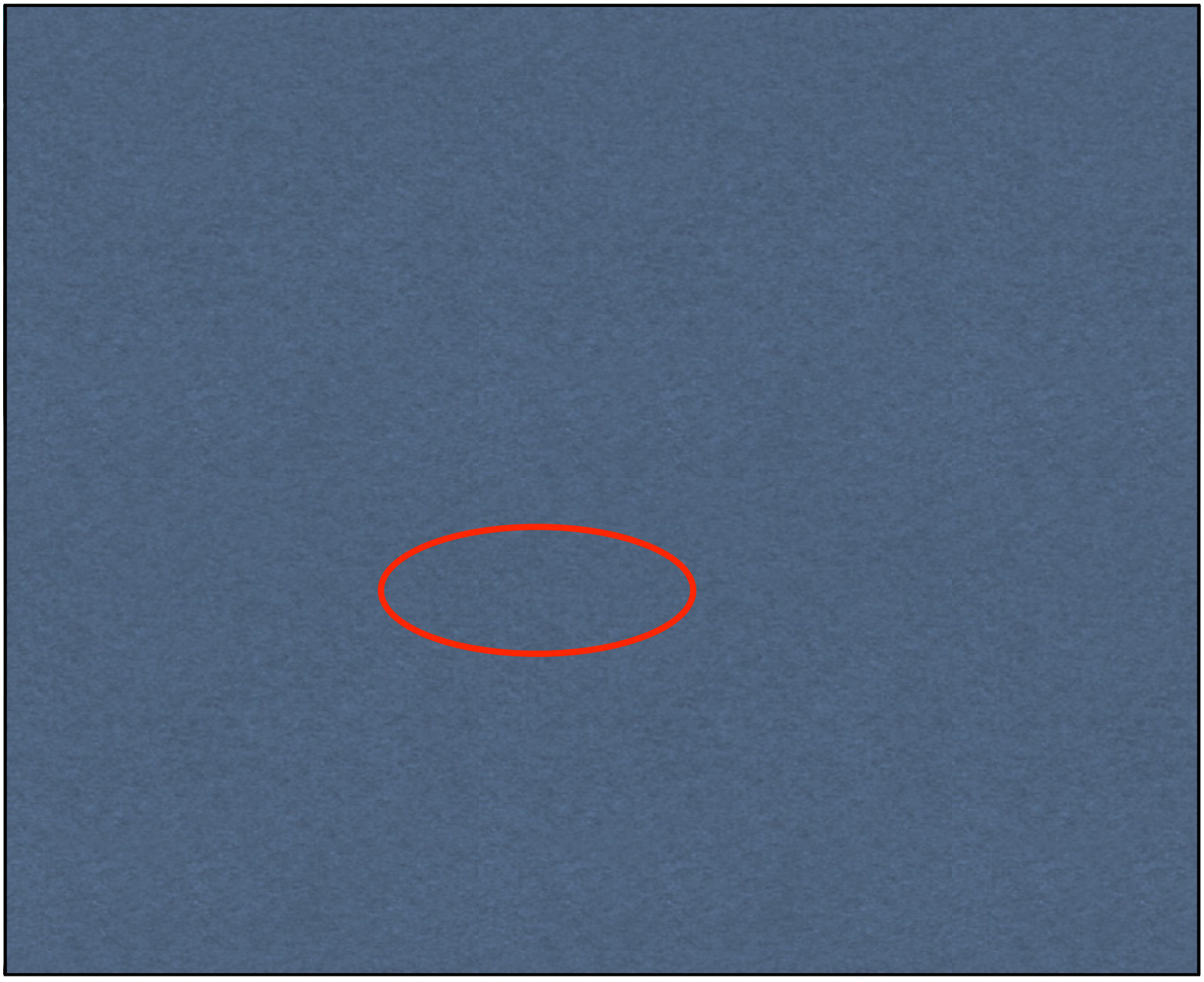
where is the red cutter?



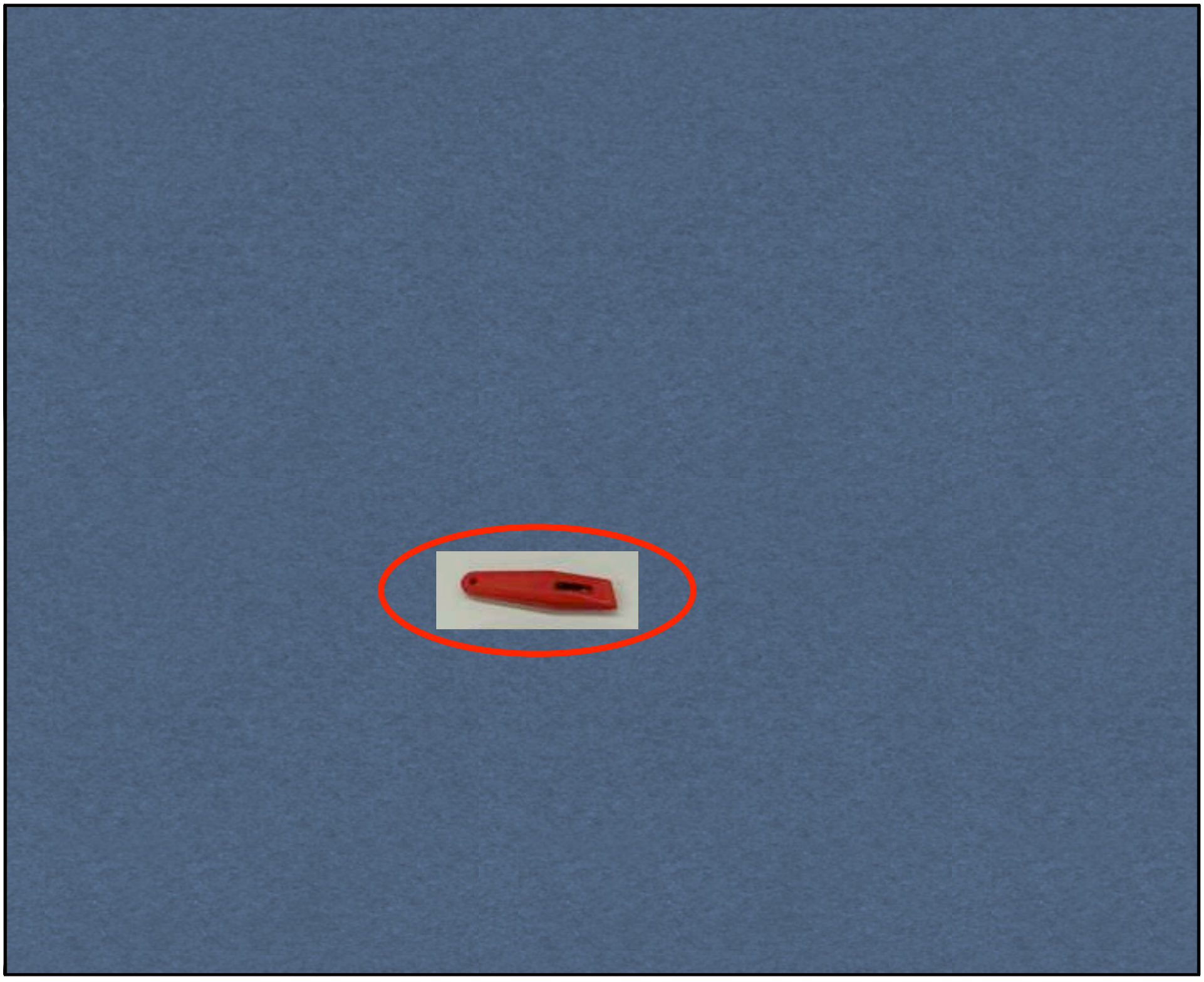
where is the red cutter?



what was here?



the red cutter



Binding to space

red cutter horizontally aligned

The binding problem

the round object is blue

- feature binding: shape-color

[Faubel, 2008]

The binding problem

the “S” is green

- feature binding: category-color

[Chapter 5, DFT book 2016]

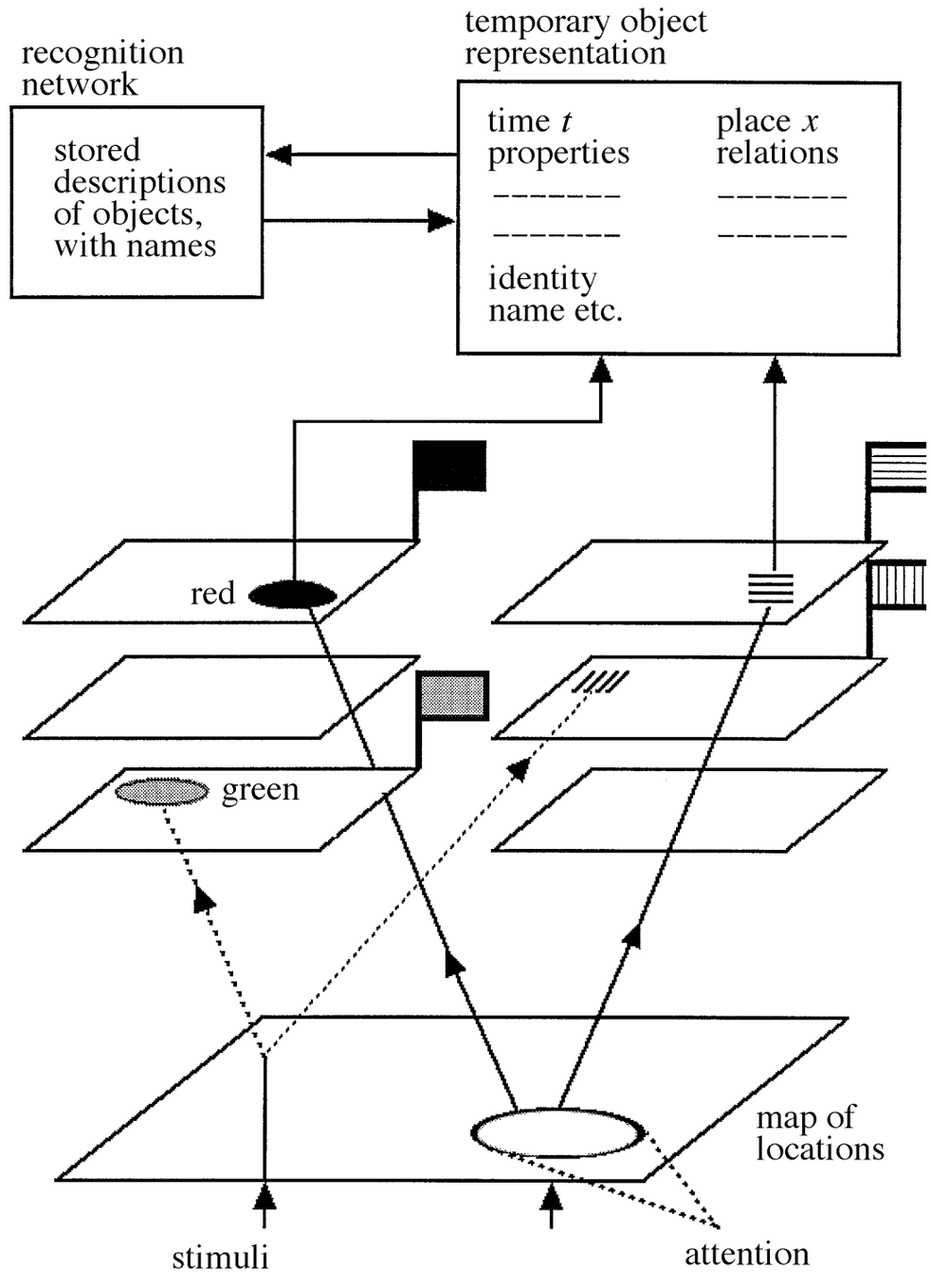
Feature binding is flexible

- able to bind ad hoc, combinations never seen before …
- mis-bindings occur in “illusory conjunctions”

1) scene presented, then removed
2) first report the numbers (to generate a delay)
3) then report objects (shape, open/closed, color)

[Treisman, 1998]

FIT: binding through space



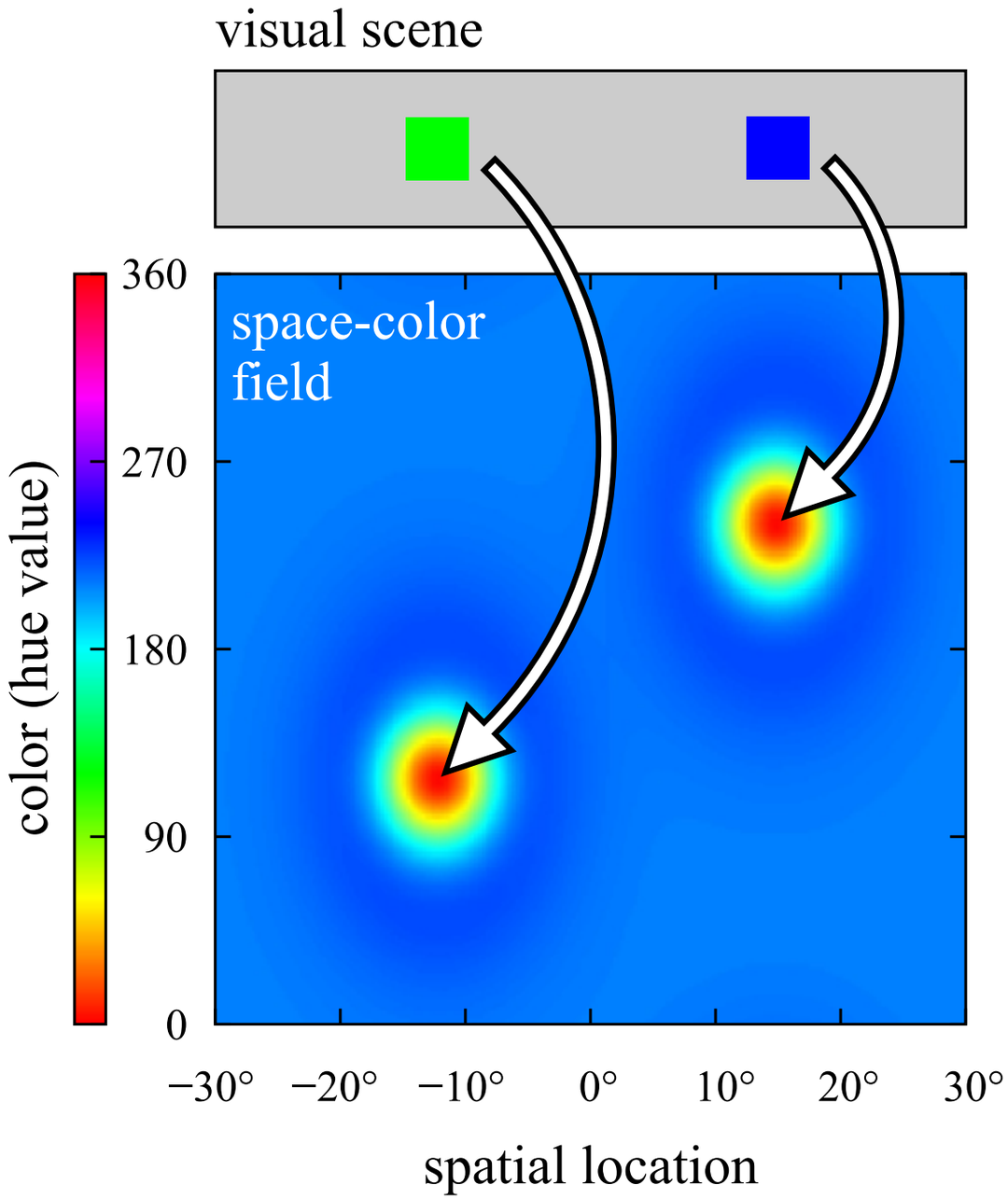
[Treisman, 1998]

Neural account for binding

- joint representation
- binding through space

Feature-space binding

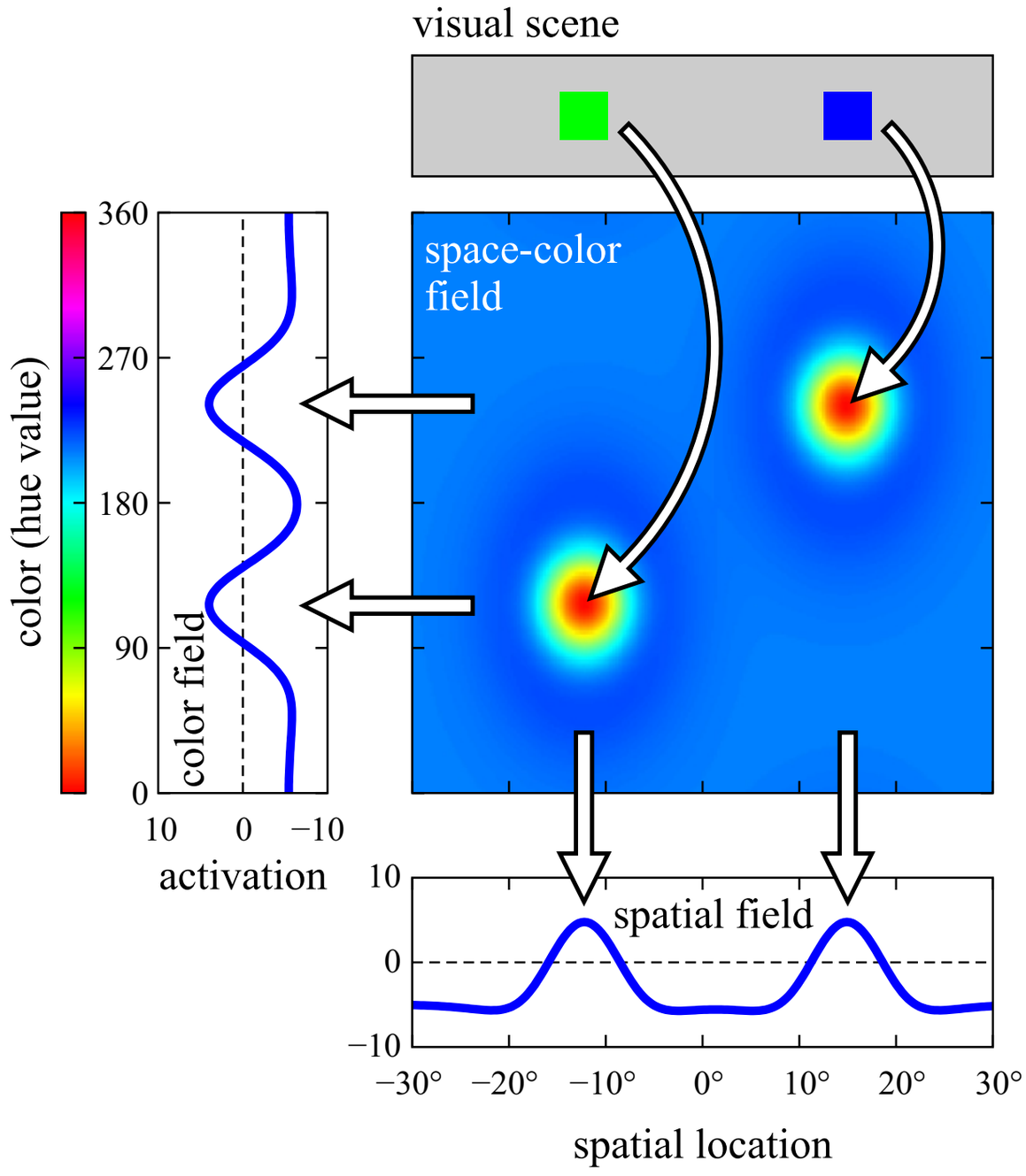
- through joint representations
- "anatomical binding"



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

Extract bound features

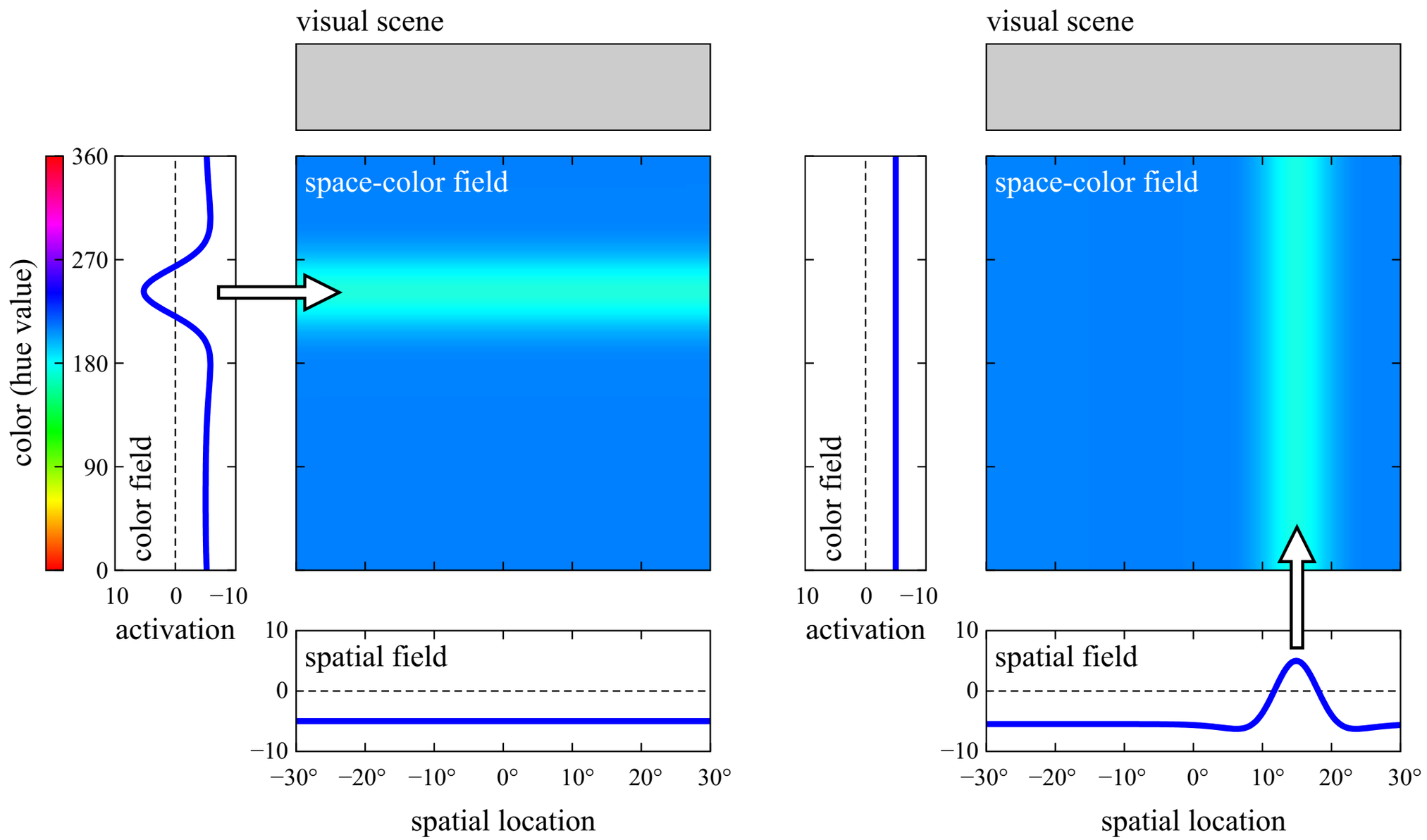
- project to lower-dimensional fields
- by summing along the marginalized dimensions
- (or by taking the soft-max)



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

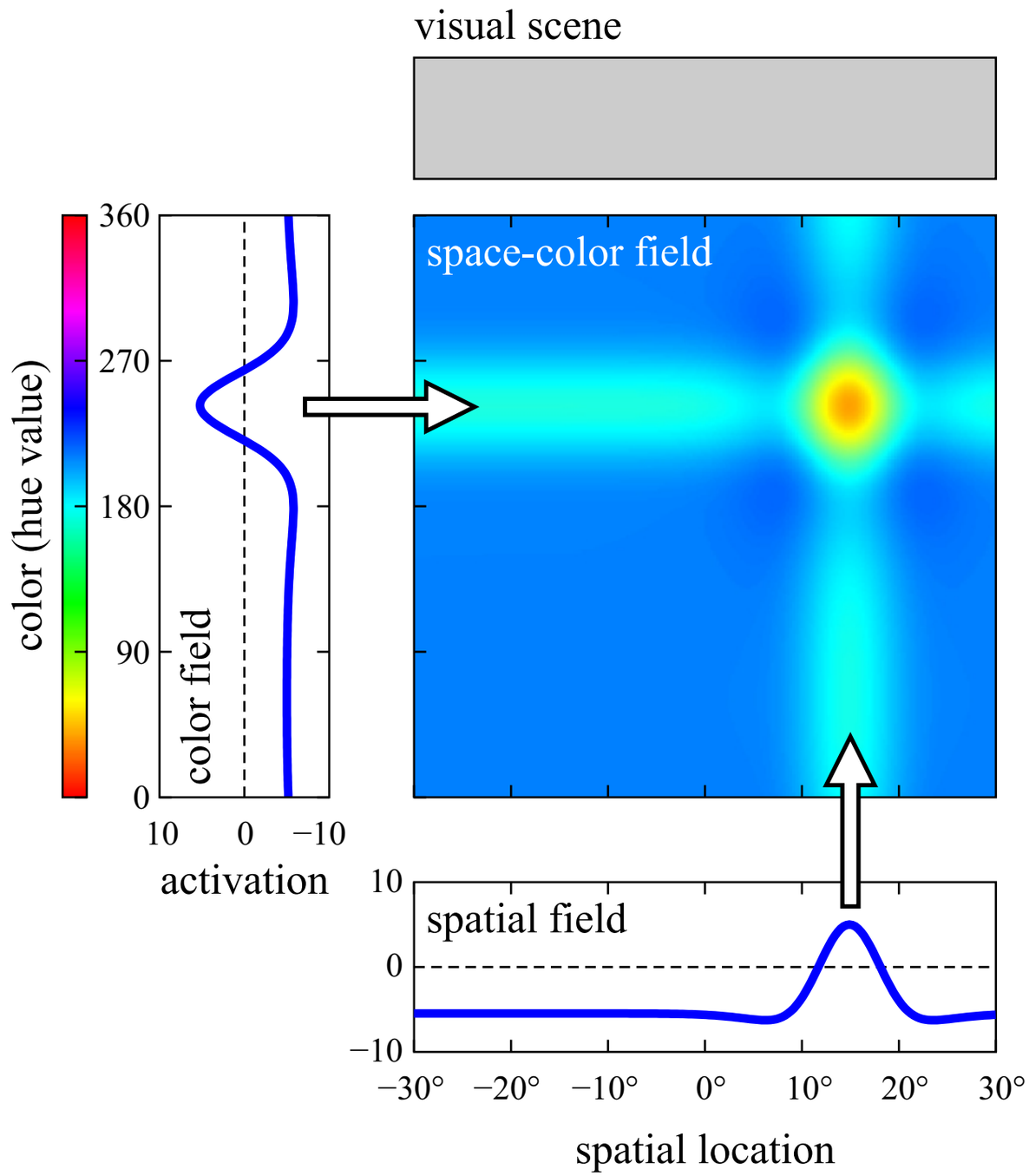
Assemble bound representations

- project lower-dimension field onto higher-dimensional field as "ridge input"



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

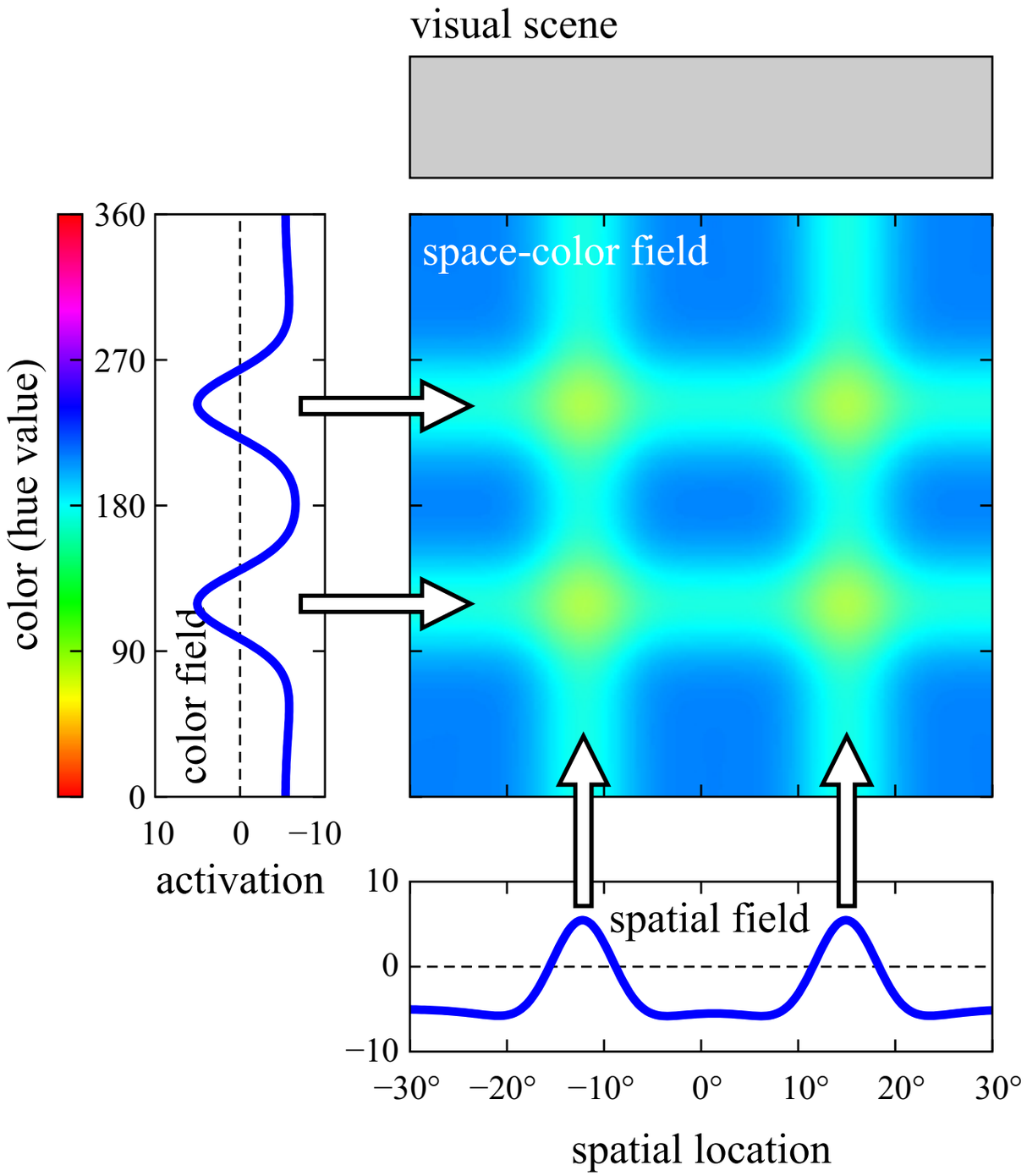
Assemble bound representations



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

Assemble bound representations

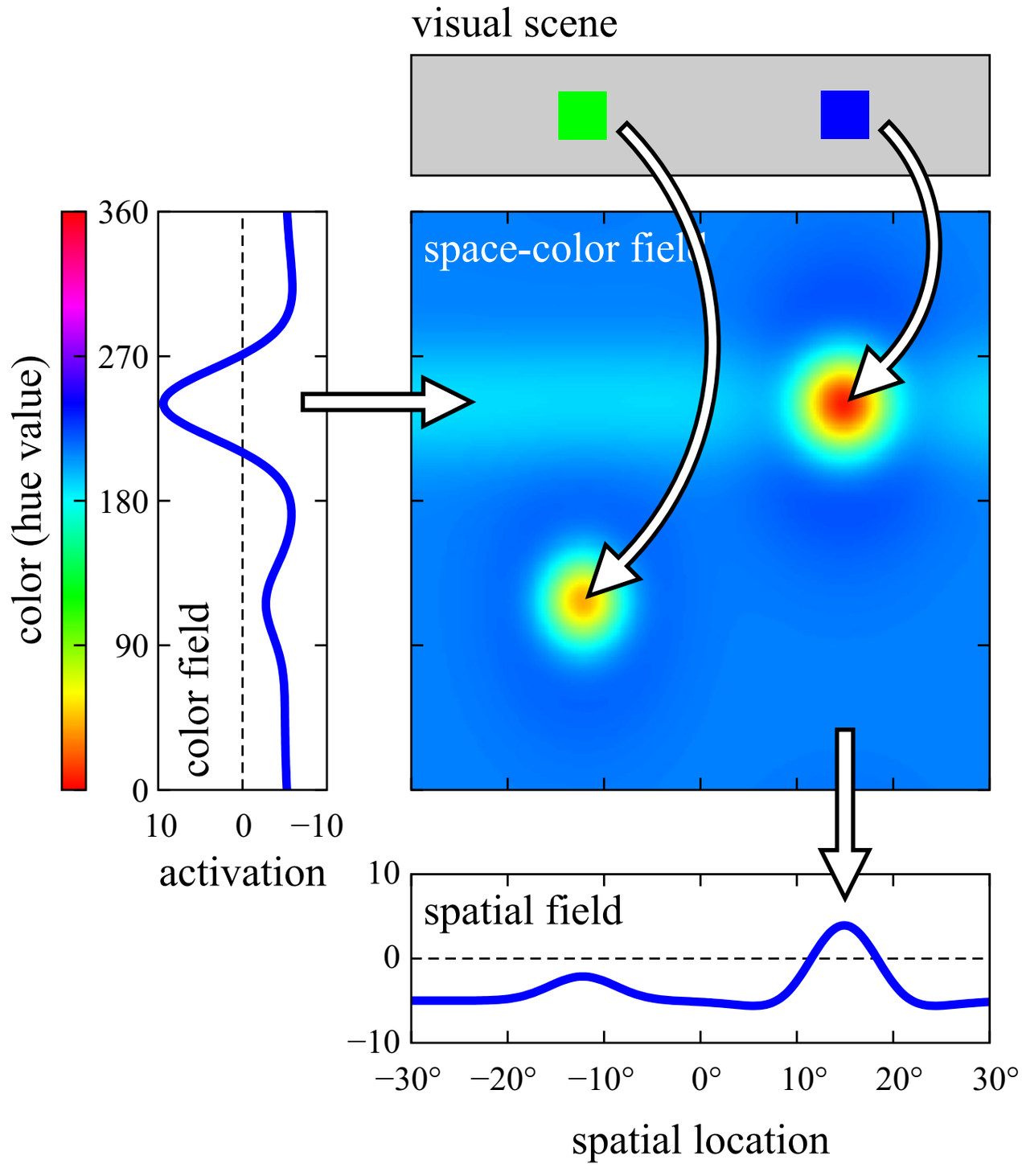
- binding problem: multiple ridges along lower-dimensional space lead to a correspondence problem
- => assemble one bound object at a time…
- => sequentiality bottle-neck!



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

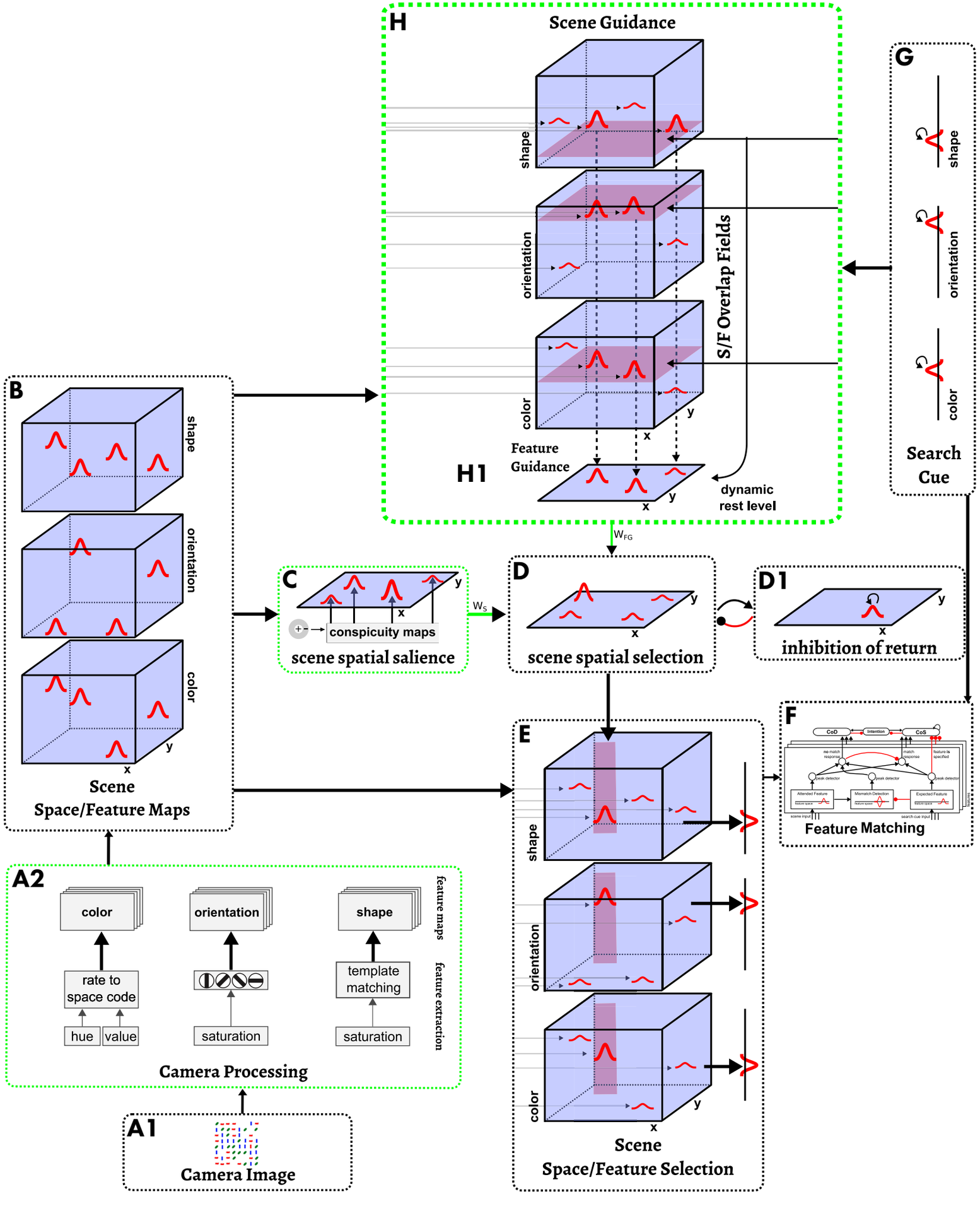
Search

- ridge input along one dimension extracts from bound representation matching objects
- other dimensions of those objects can then be extracted
- e.g. visual search



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

Visual search



[Grieben et al. *Attention, Perception & Psychophysics* 2020; *CogSci* 2021]

A2

color

orientation

shape

rate to space code

hue

value

saturation

template matching

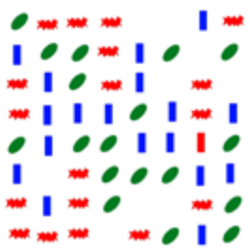
saturation

feature maps

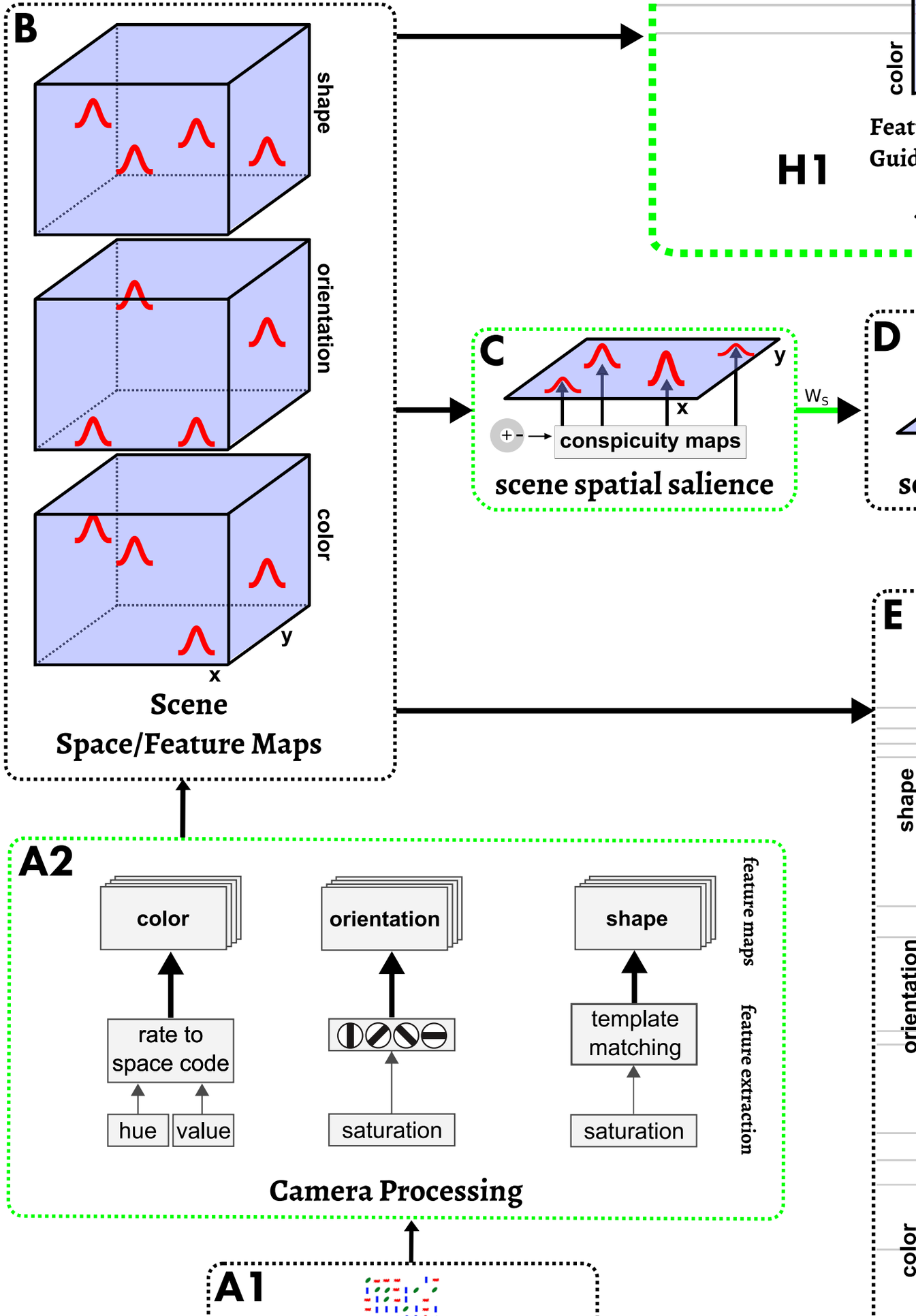
feature extraction

Camera Processing

A1



Camera Image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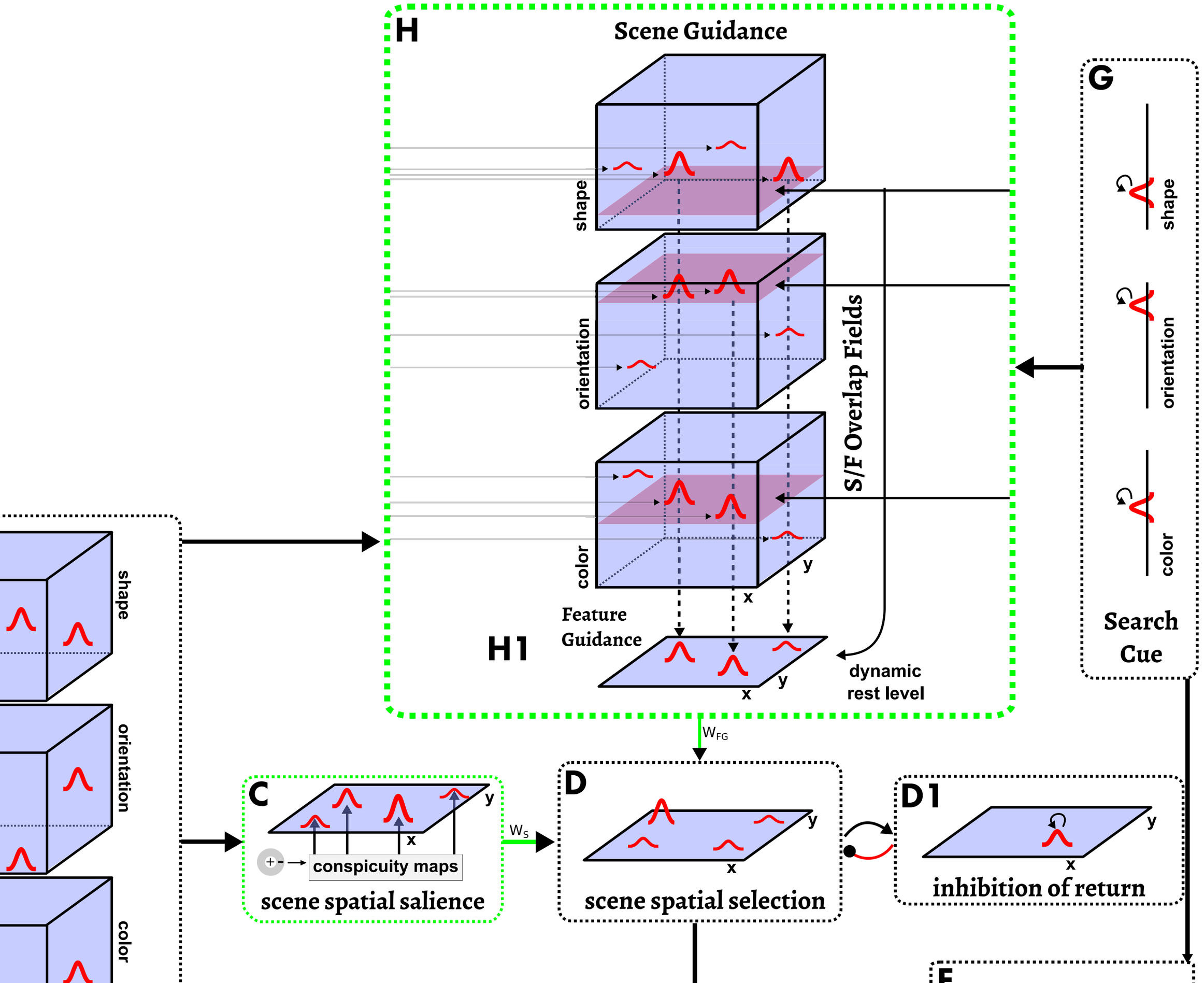
feature extraction
Camera Processing
A1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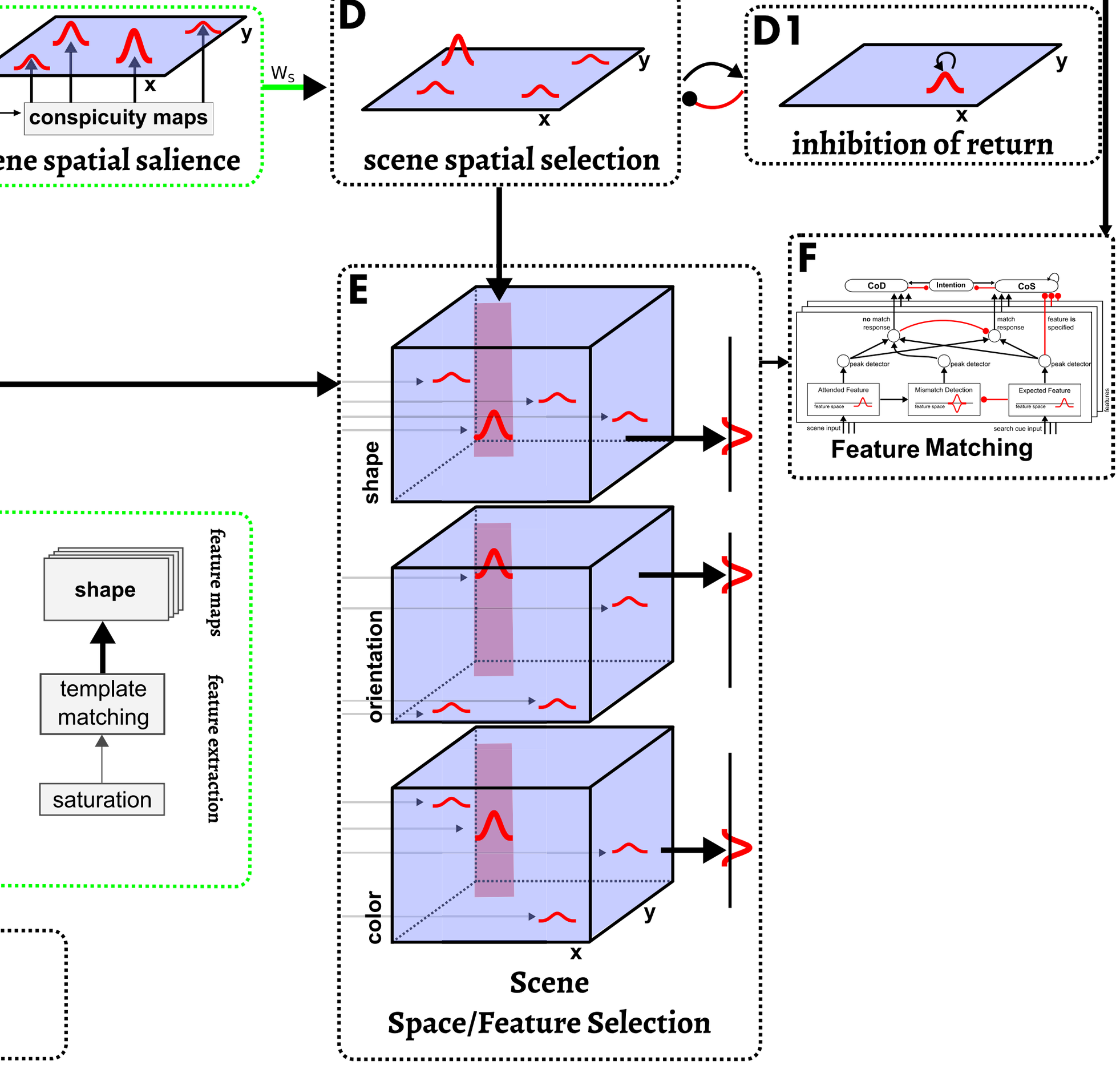
D1
inhibition of return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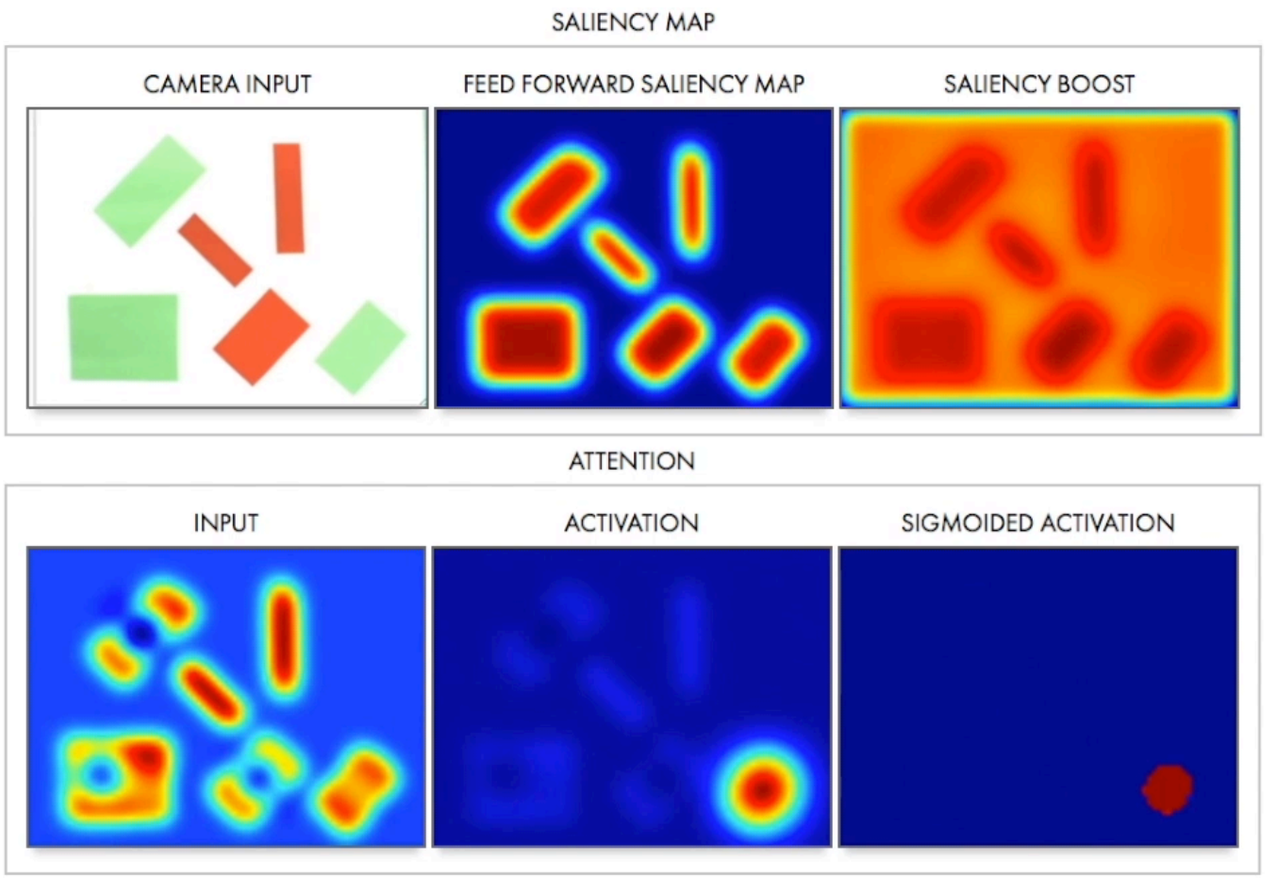
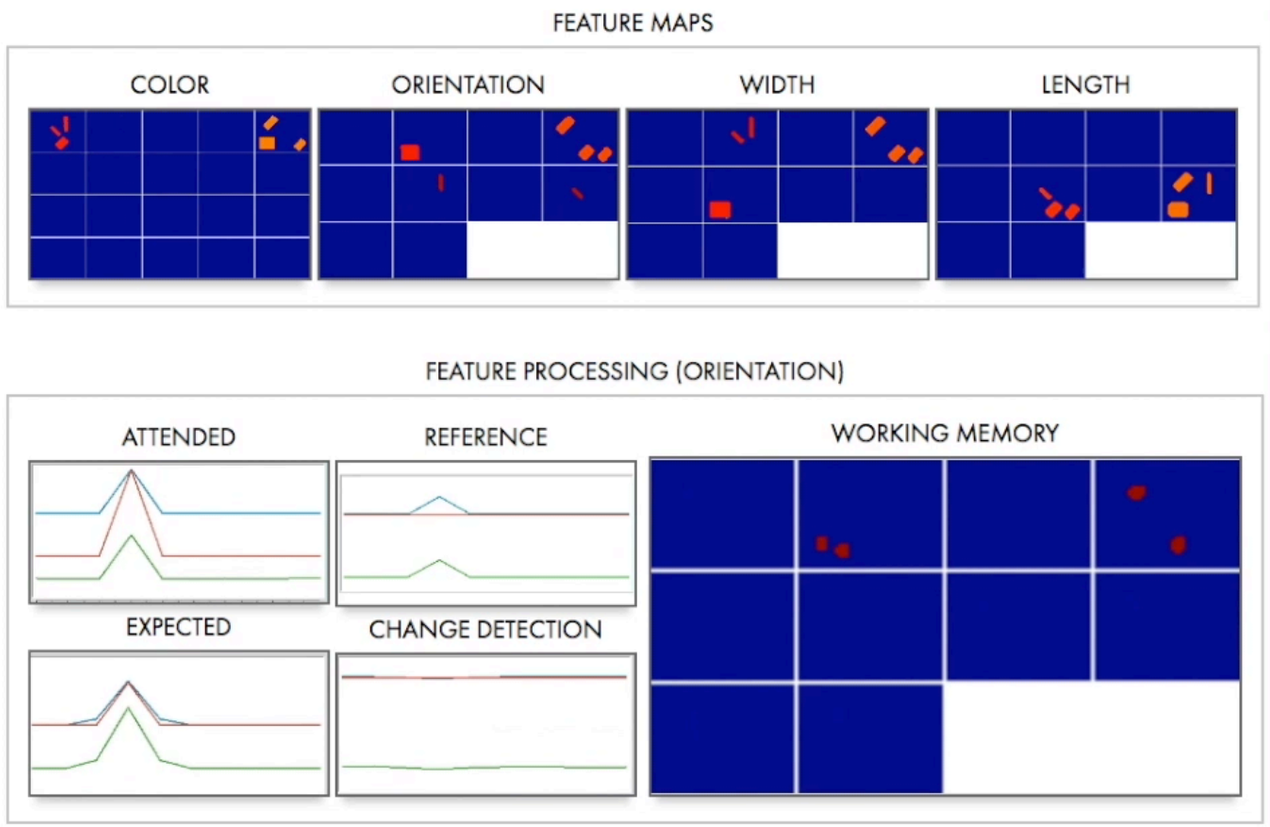
Feature Matching
feature maps
feature extraction
shape
template matching
saturation

Visual search





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

Binding

- “anatomical” binding does not scale with increasing number of dimensions

Scaling feature dimensions

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

=>

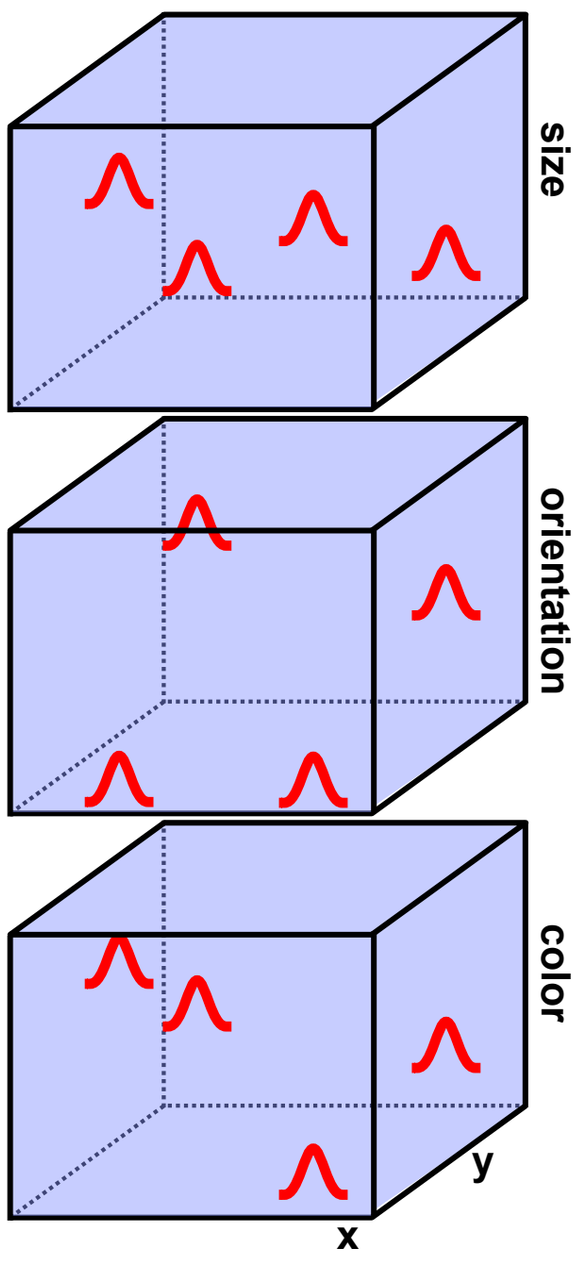
- e.g. 8 dimensions
- 100 neurons per dimension
- $10^{2*8} = 10^{16}$!
- more than there are in the entire brain!
- => only small sets of feature dimensions can be bound “anatomically”

Binding

- "anatomical" binding is not flexible…
- does not account for misbindings
- => look for neural implementation of FIT

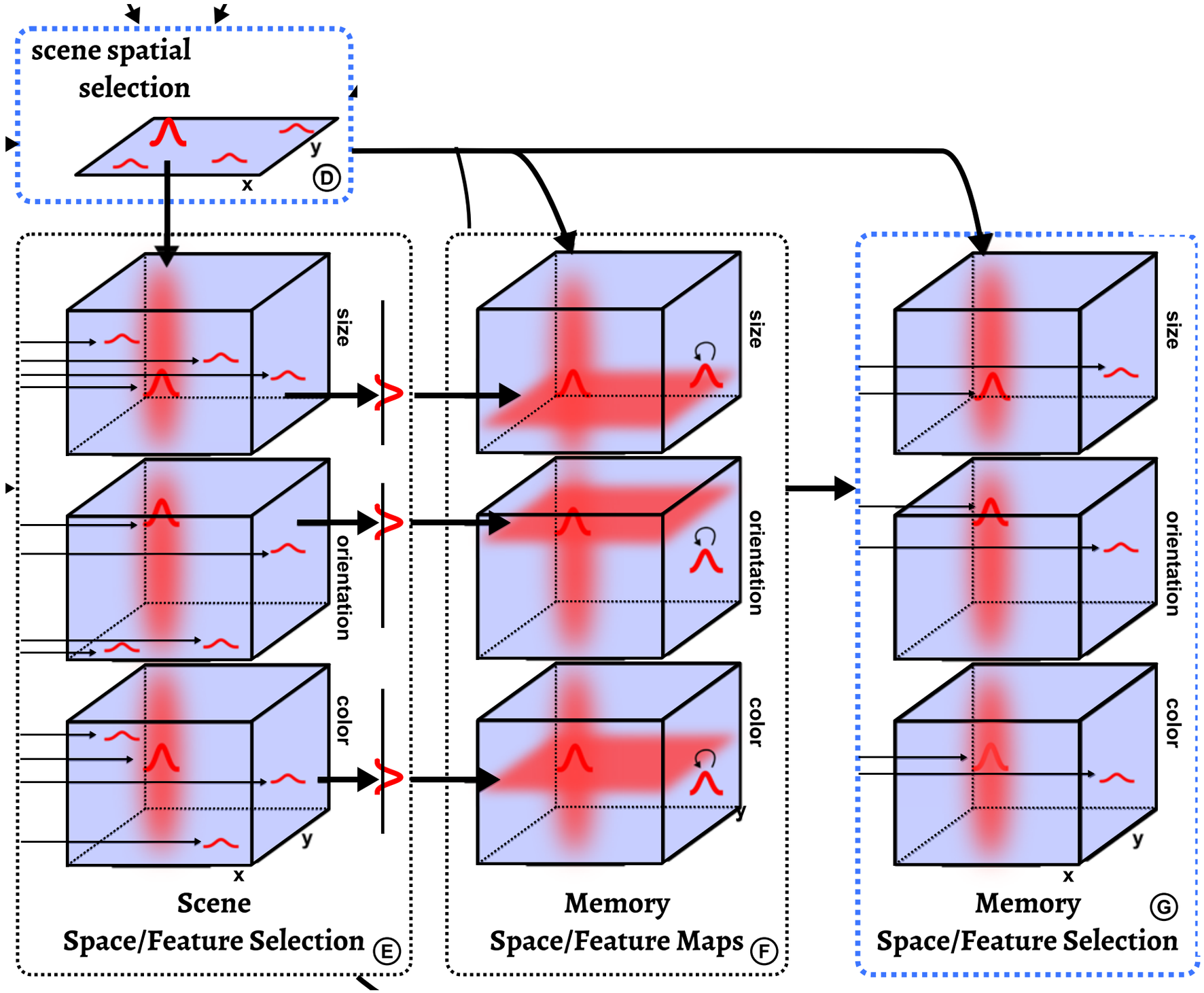
Binding through space

- many 3 to 4 dimensional feature fields
- all of which share the one dimension: visual space (~all neurons have receptive fields)

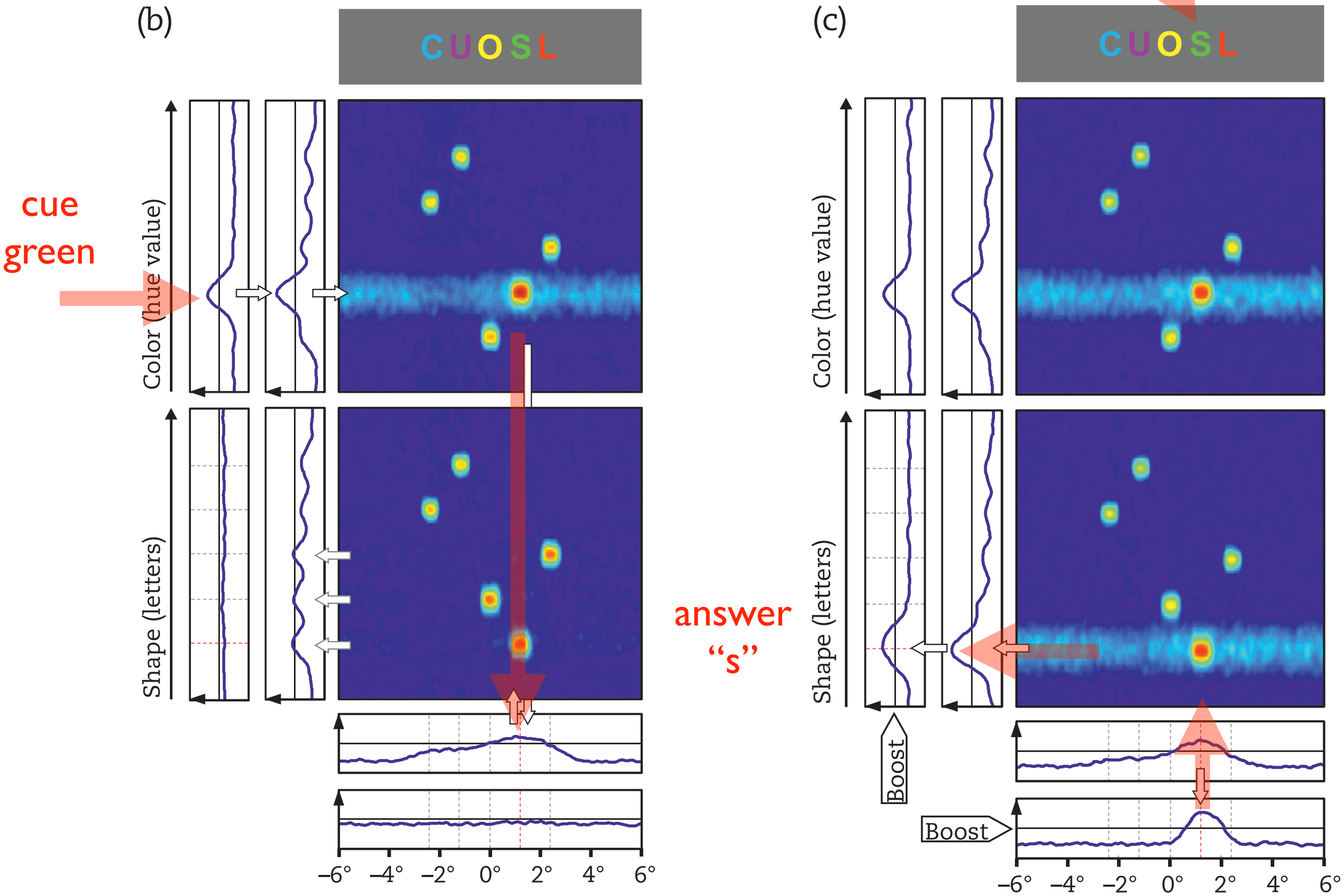


[Grieben et al. *Attention, Perception & Psychophysics* 2020]

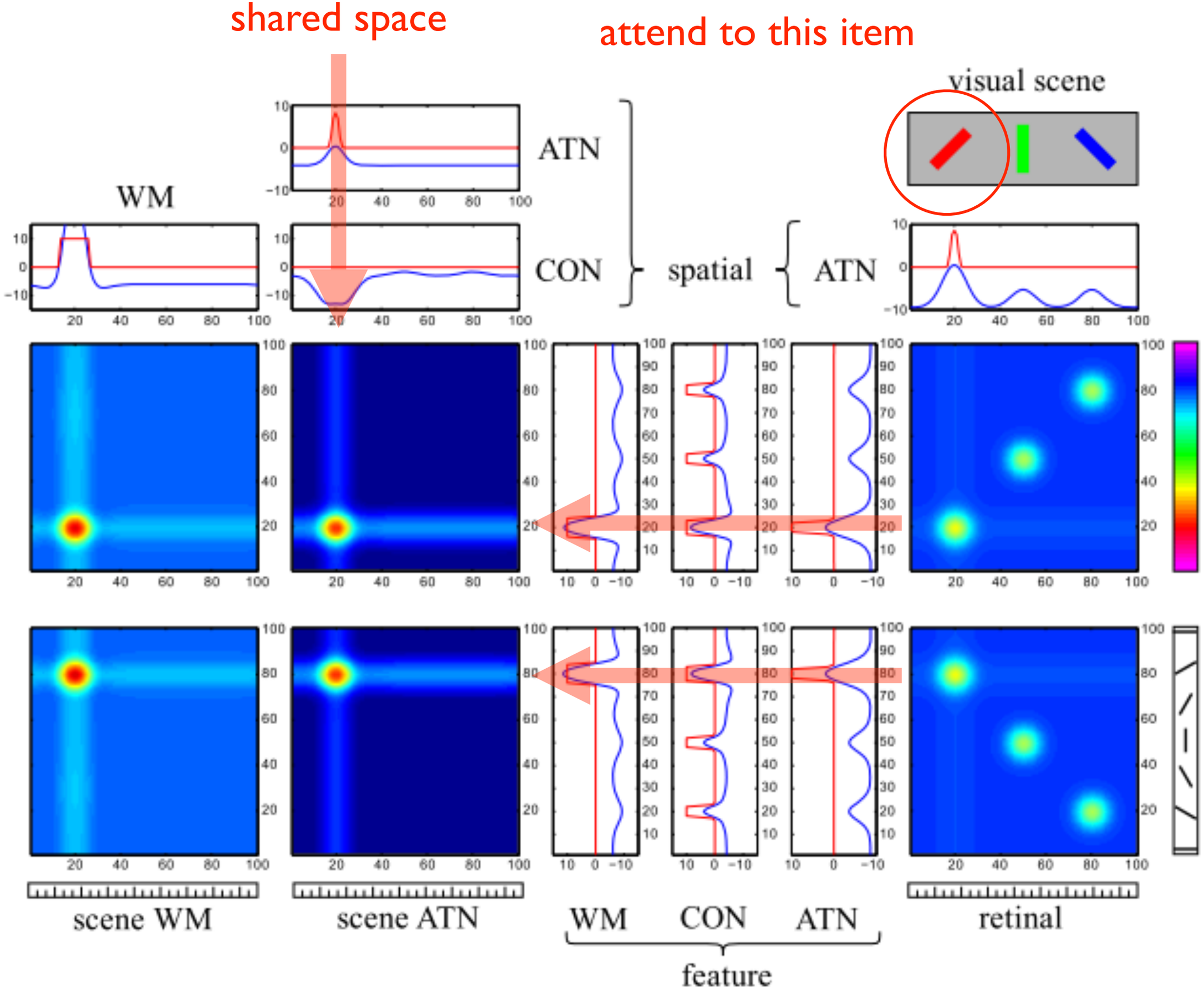
Binding through space



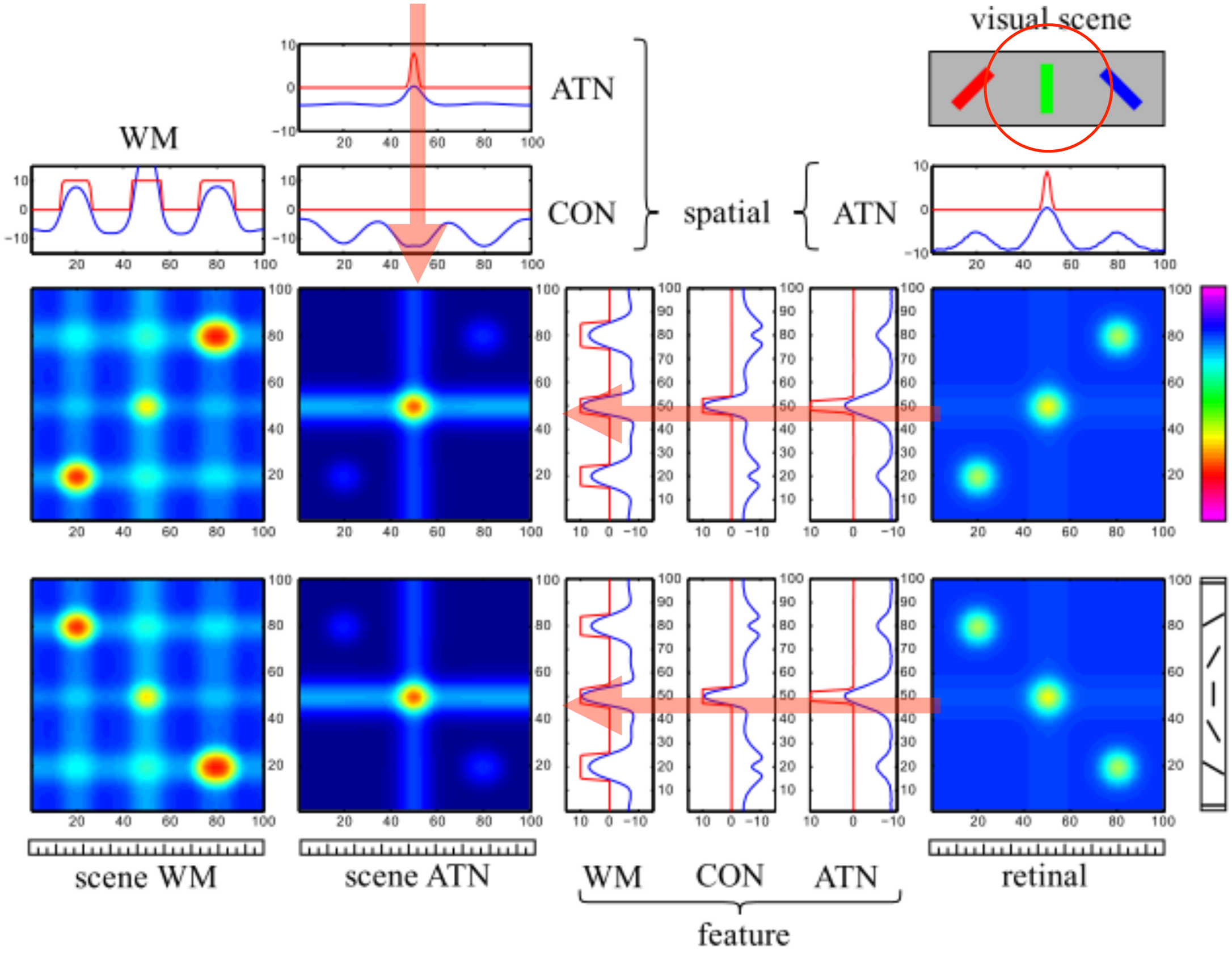
[Grieben et al. *Attention, Perception & Psychophysics* 2020]



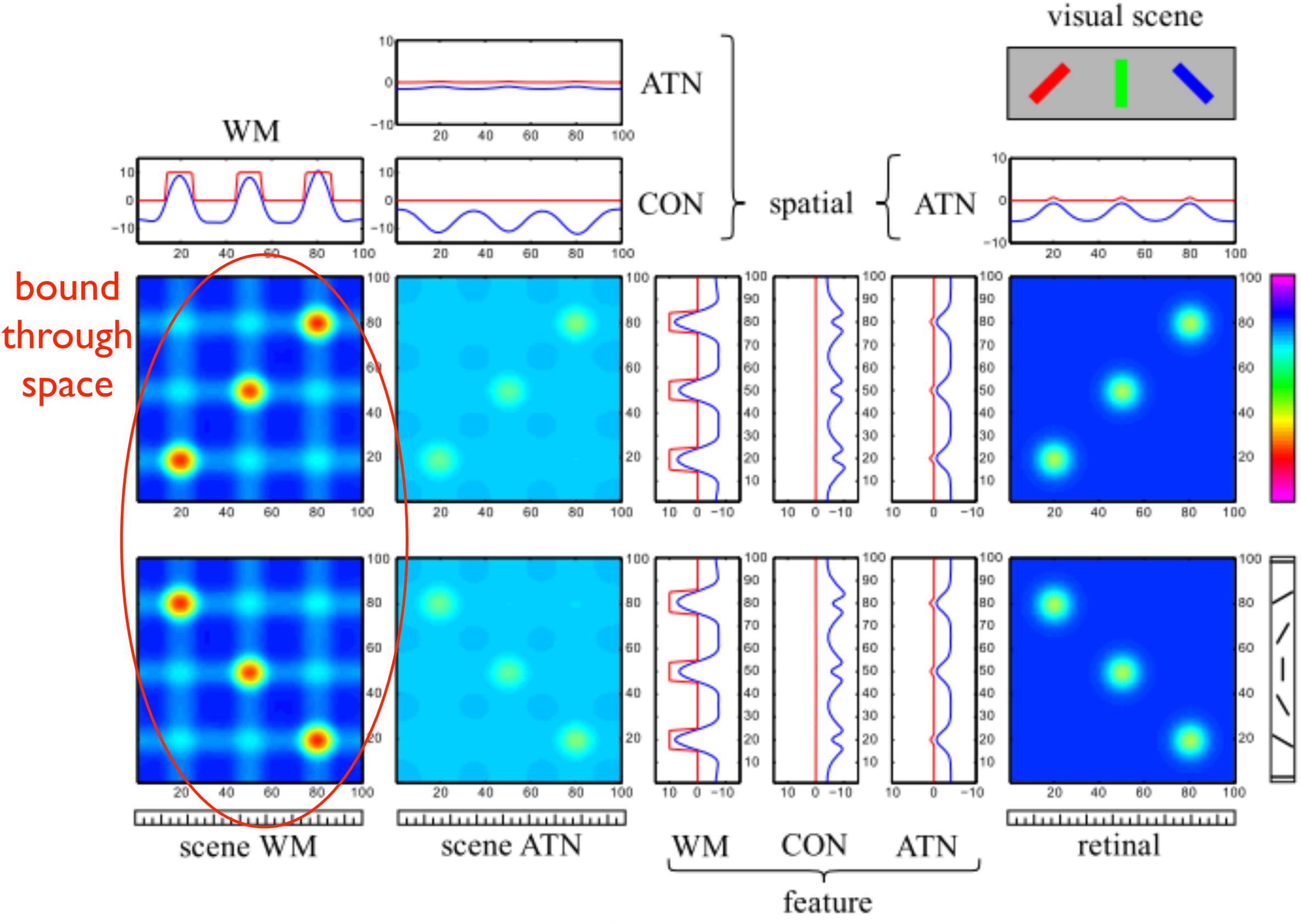
[Schneegans et al.,Ch 5 of *DFT Primer*, 2016]



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



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



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

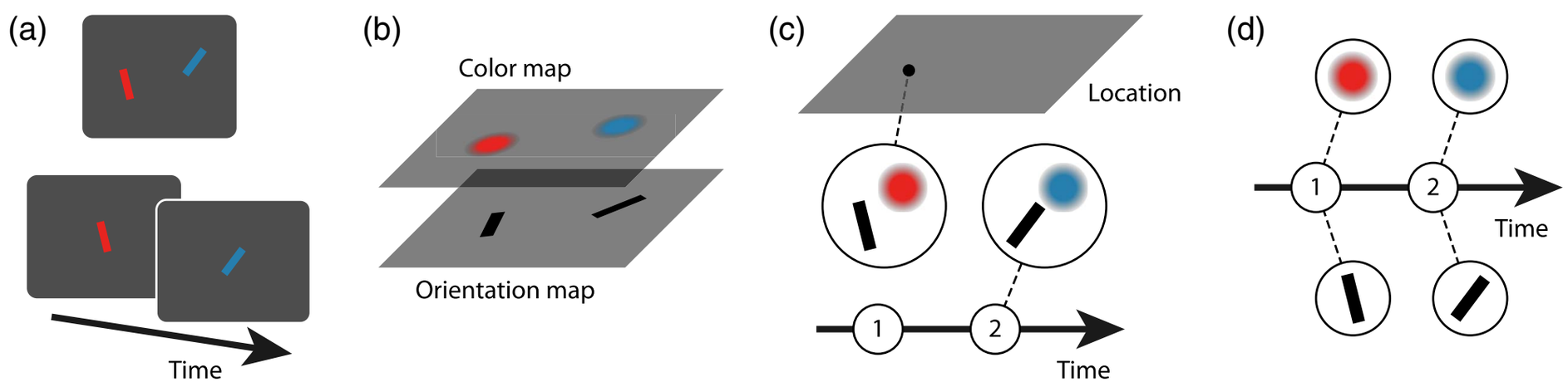
Binding through space => sequential bottleneck

- binding through space must occur one time at a time..... to avoid binding problem
- => the sequential processing bottleneck may originate from this

Binding through ordinal position

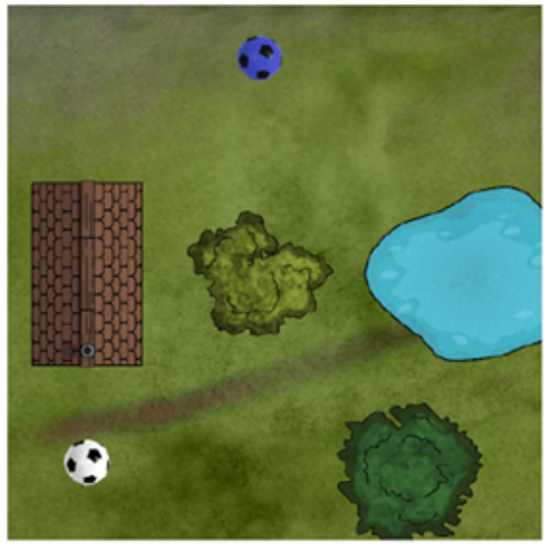
- empirical evidence: Schneegans, McMaster, Bays, 2022

Conceptual Models of Feature Binding

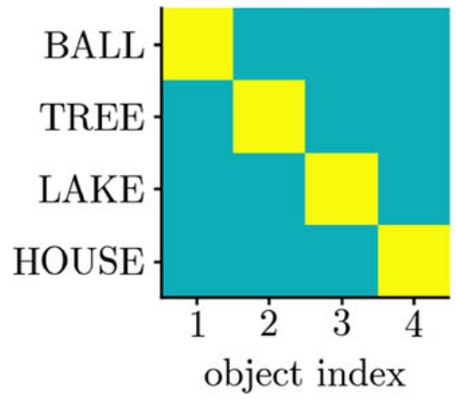


Binding through ordinal position

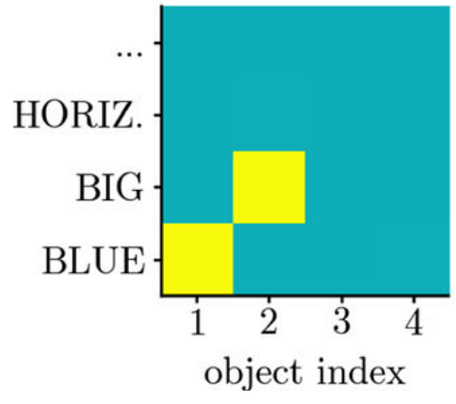
- which serves a shared dimension…
- “index”.. (Sabinasz, Schöner, 2023)



object / object concept



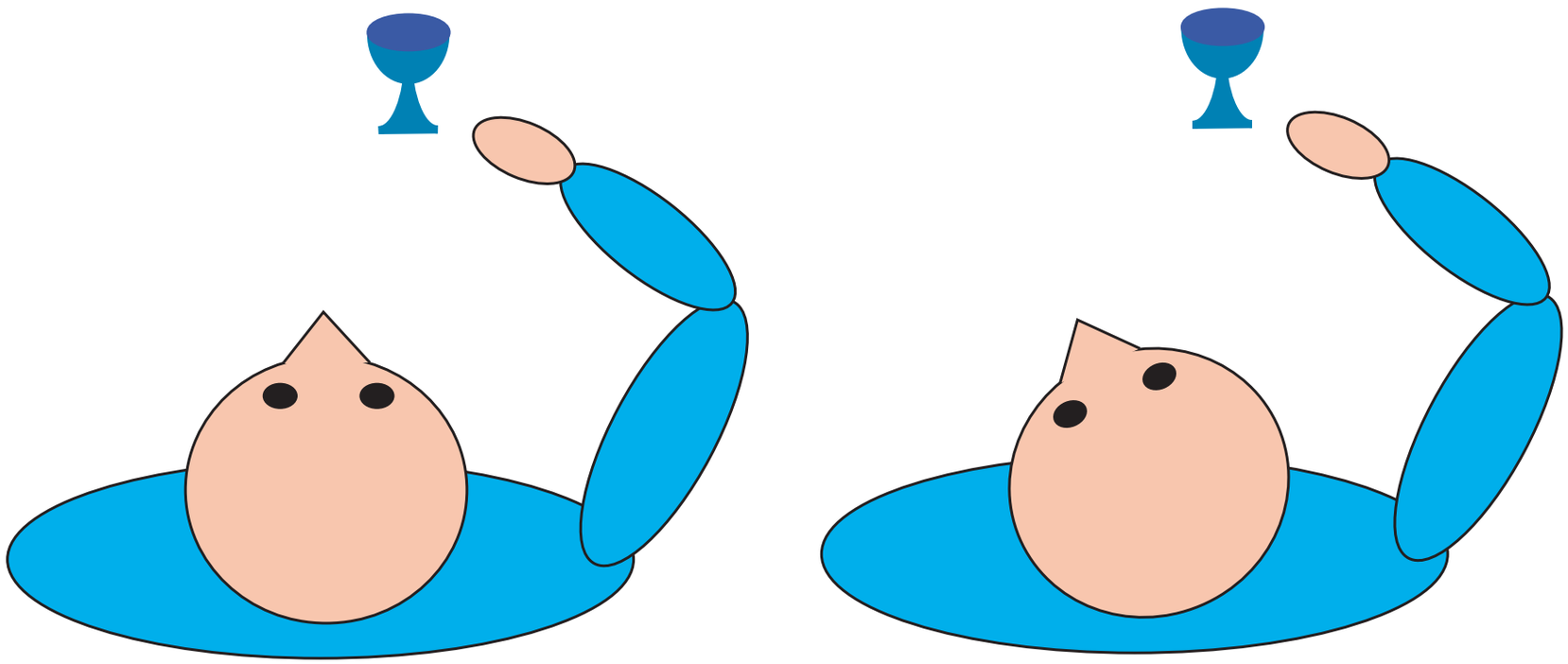
object / property concept



Coordinate transforms

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

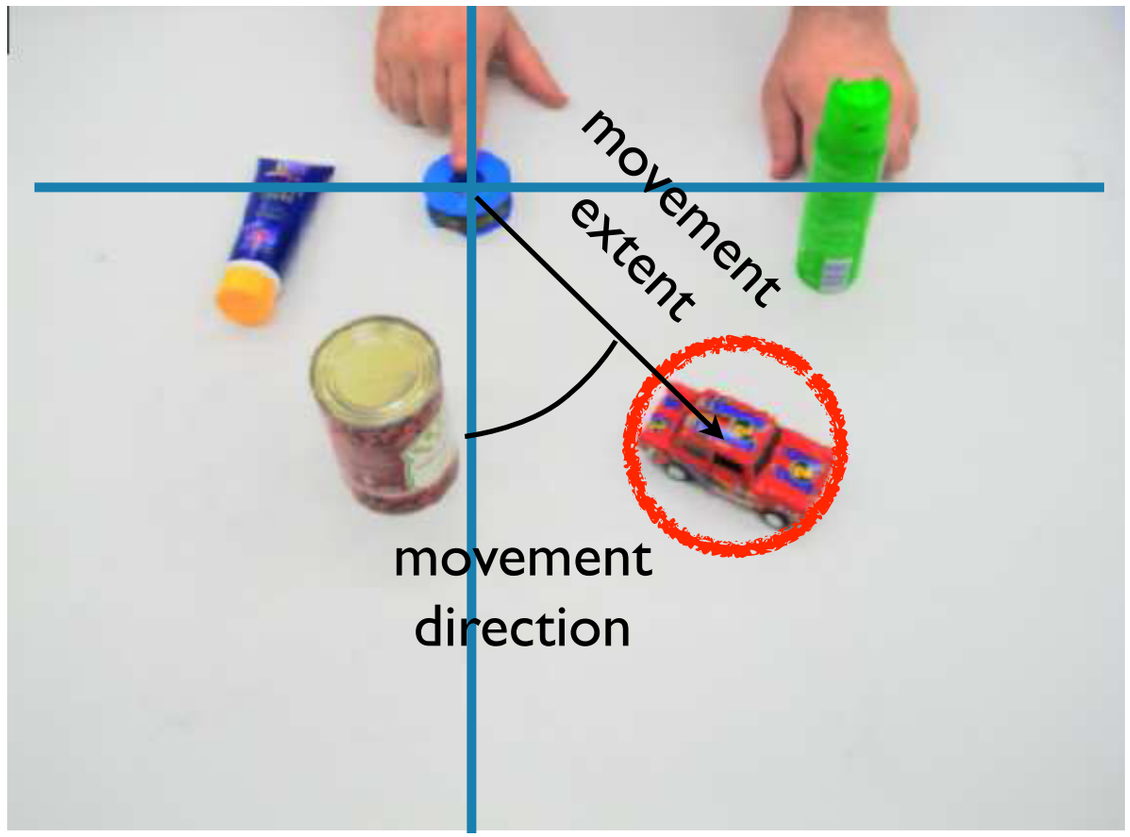
- example:
  reaching is
  guided by body-
  centered, not by
  retinal visual
  representation



Coordinate transforms

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

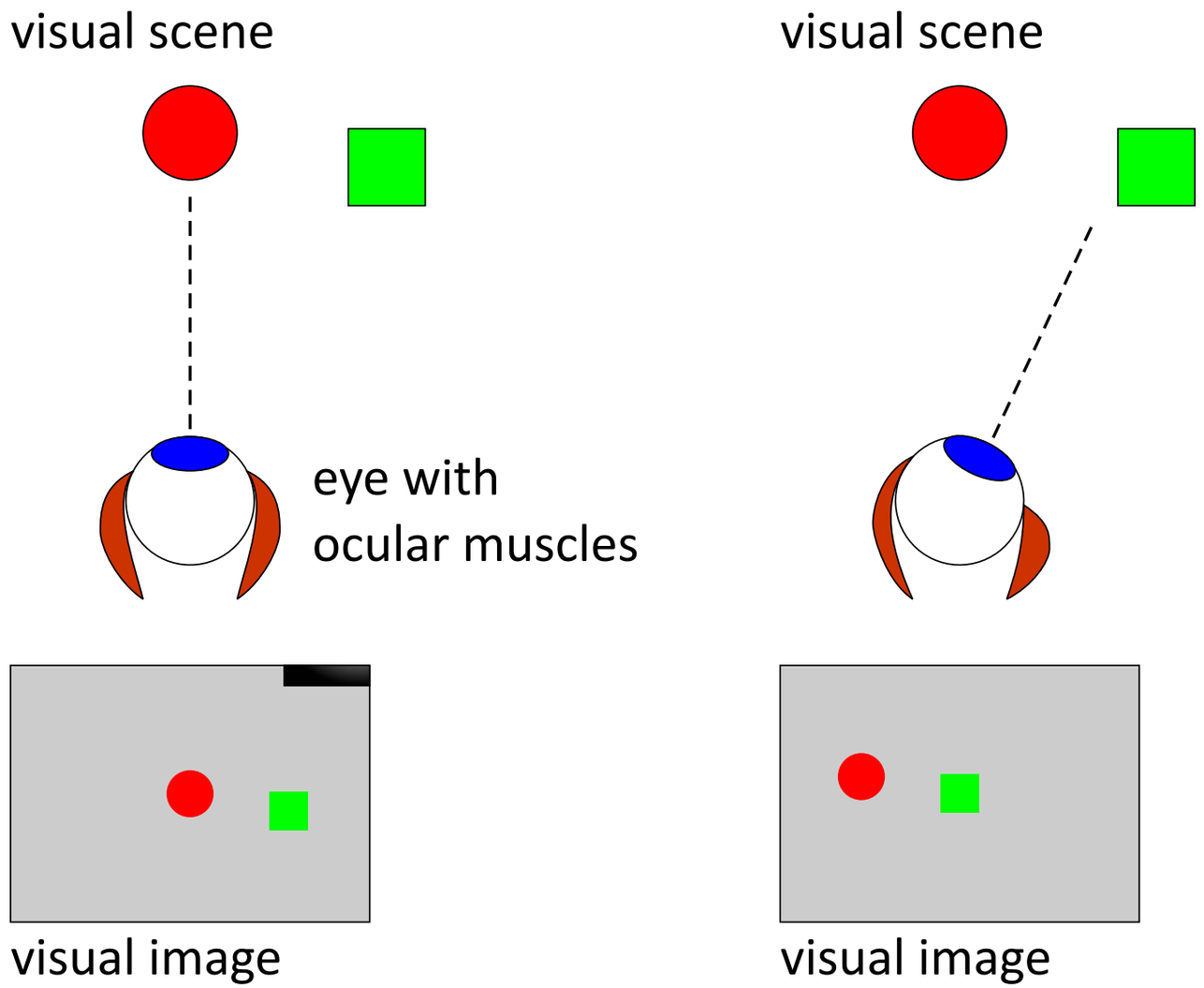
- example: movement parameters are extracted by representing movement target in coordinates centered in the initial position of the hand



Coordinate transforms

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

- worked example: from retinal to head-centered/ body-centered frame

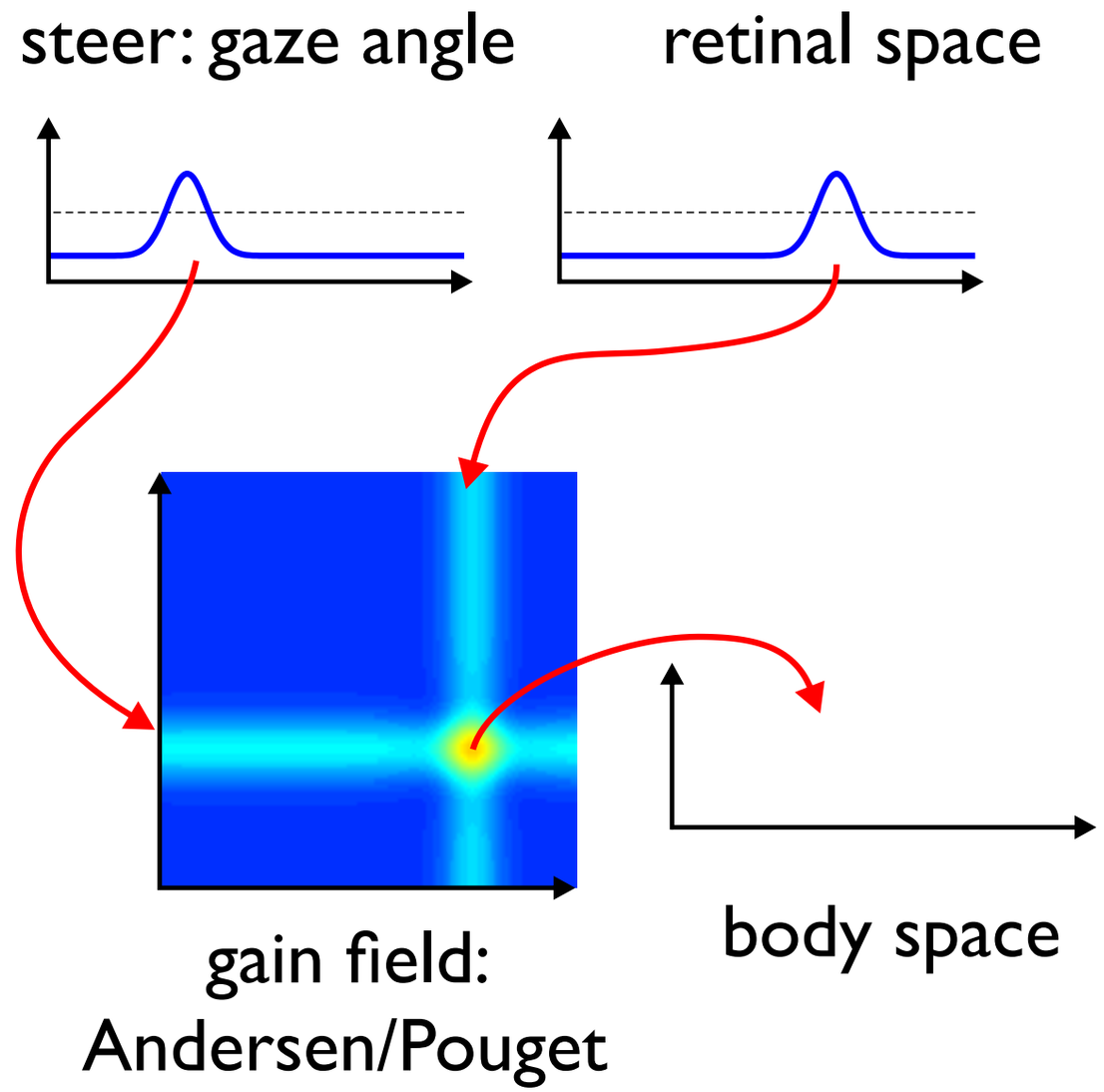


[Schneegans Ch 7 of *DFT Primer*, 2016]

Retina => body space

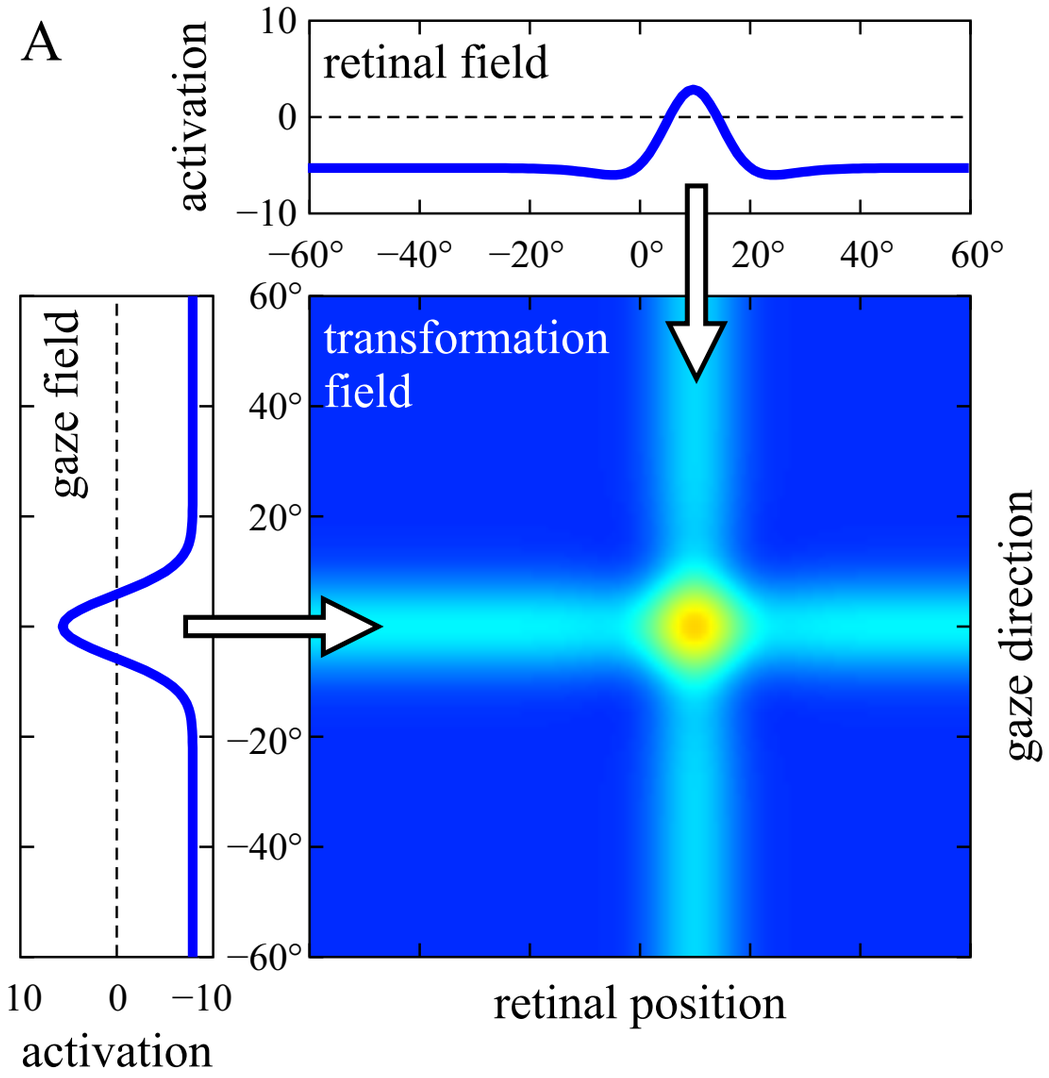
- transformation depends on the gaze angle = steering dimension

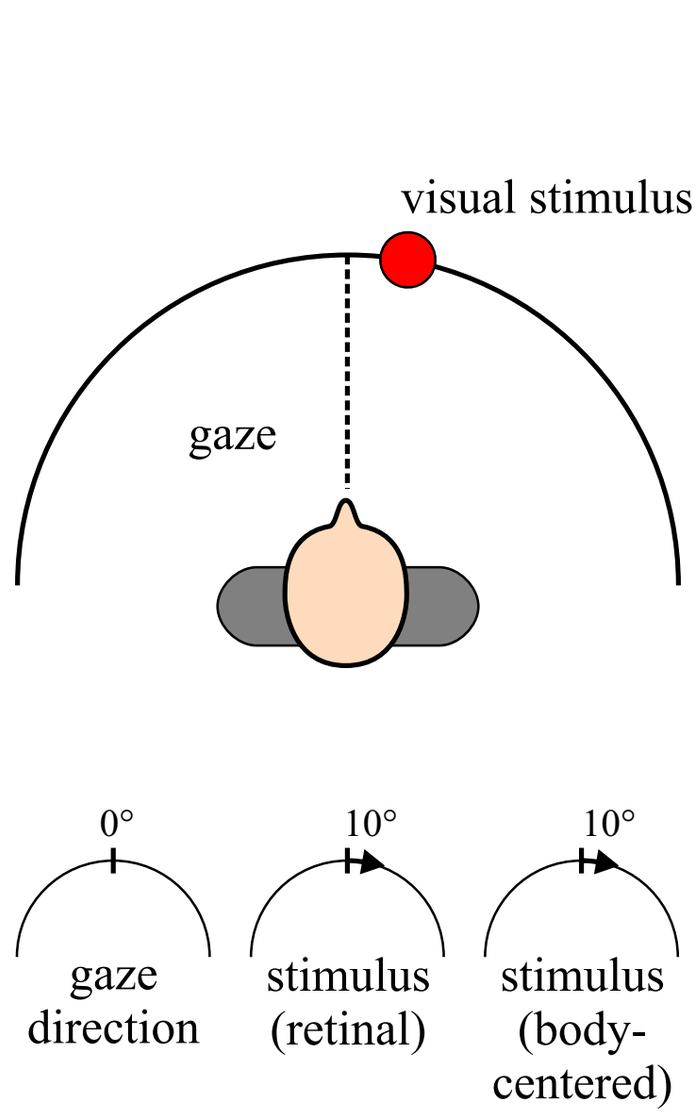
- need a (anatomically) bound neural representation of
  - retinal space
  - gaze angle
- obtained from ridge/slice input to bind these
- project to body space



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

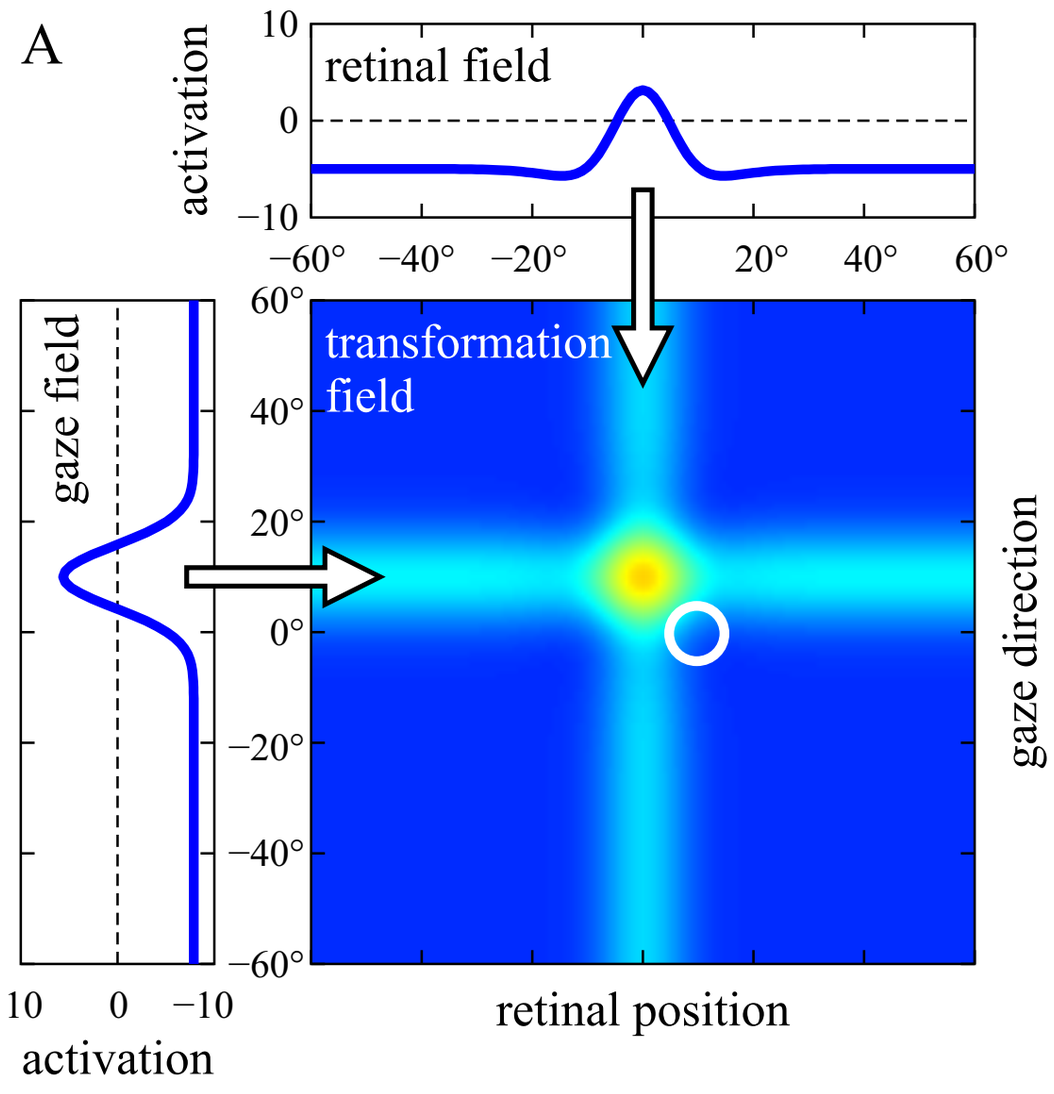
Retina => body space

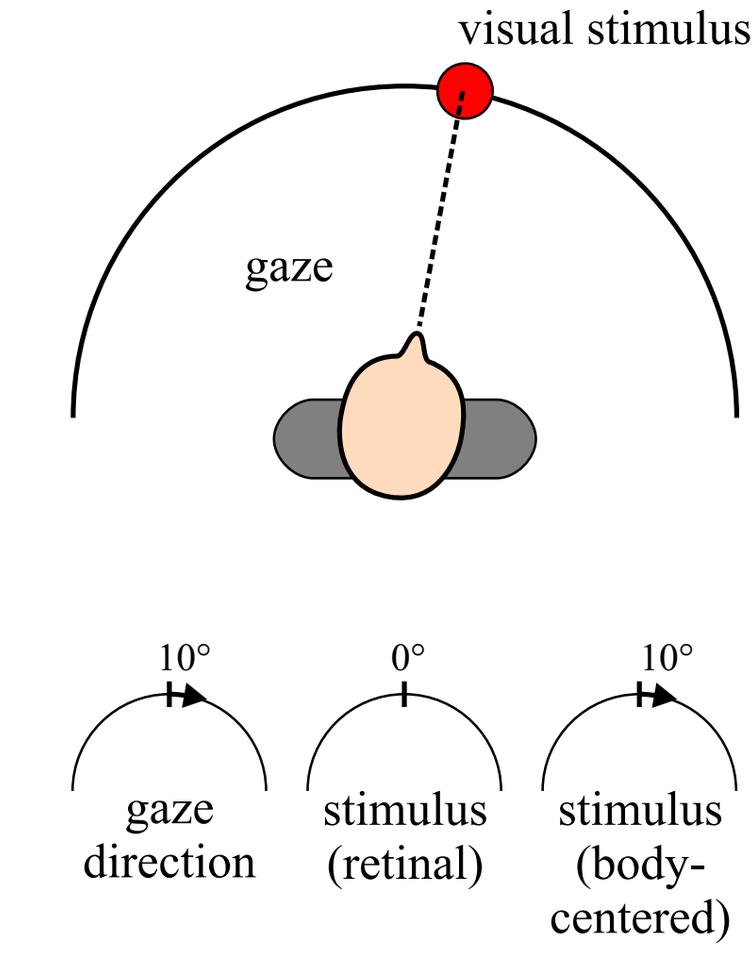




[Schneegans Ch 7 of *DFT Primer*, 2016]

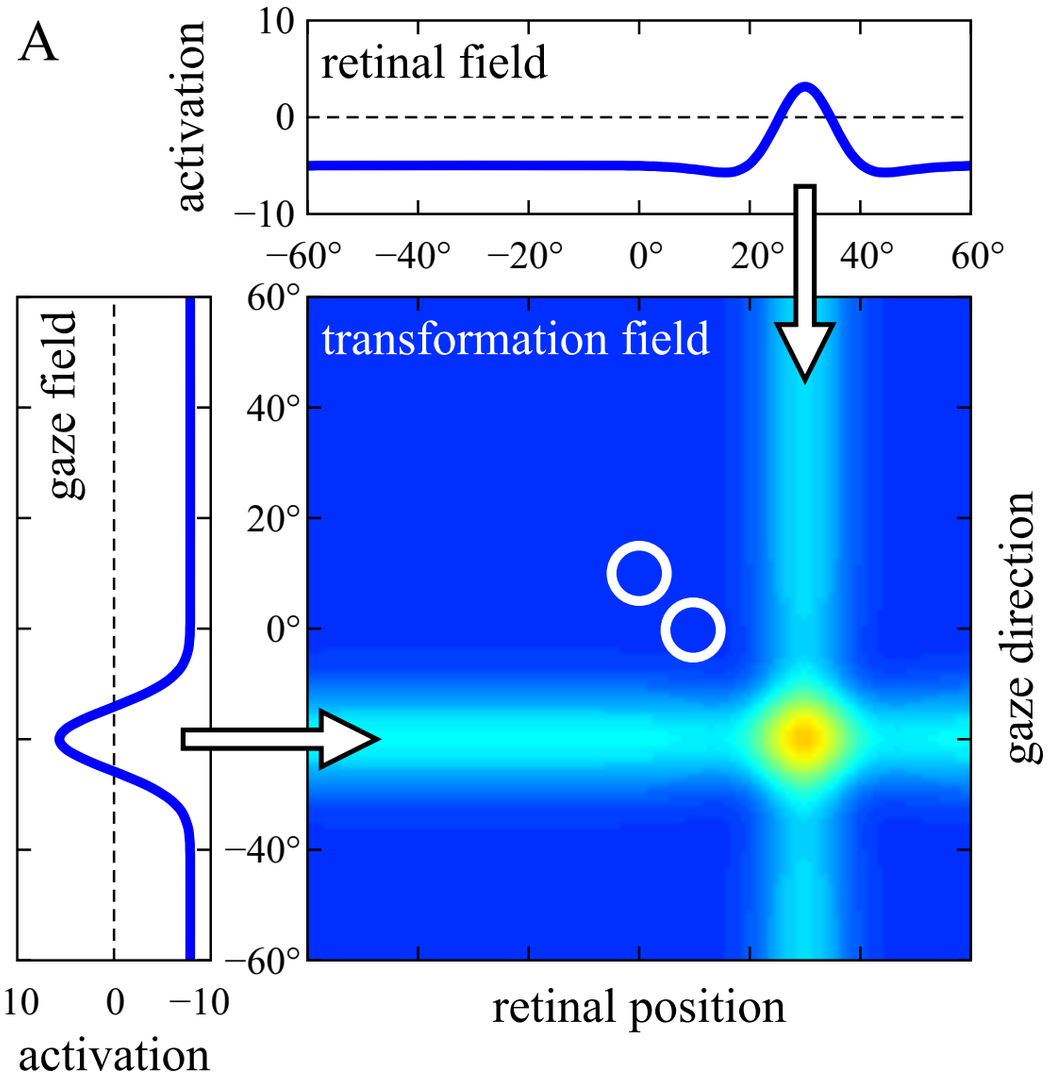
Retina => body space

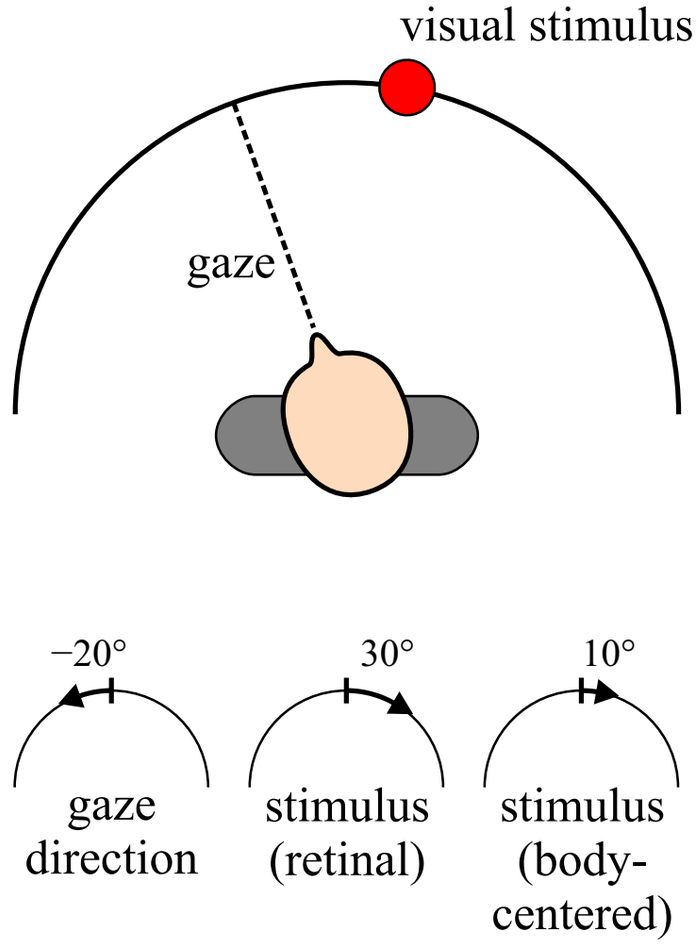




[Schneegans Ch 7 of *DFT Primer*, 2016]

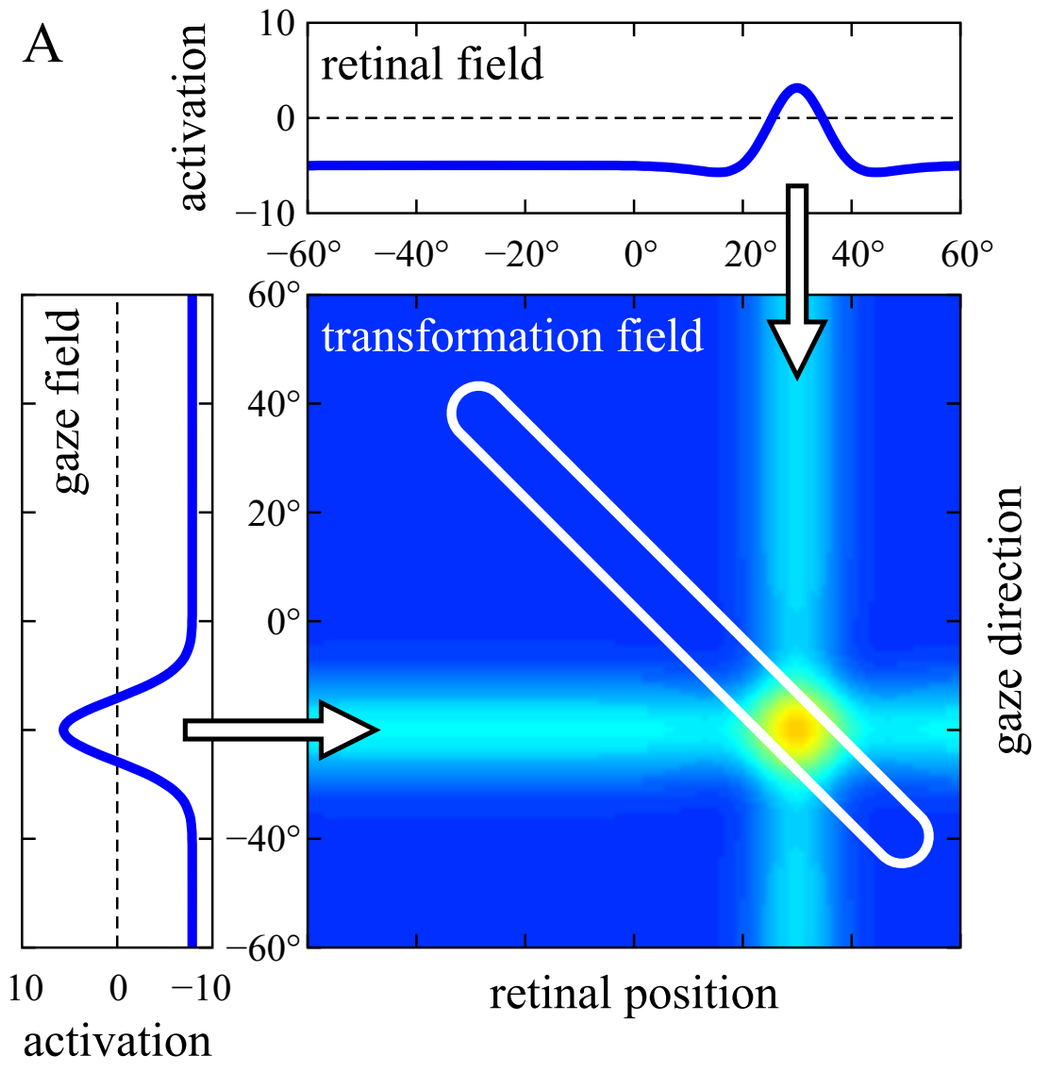
Retina => body space

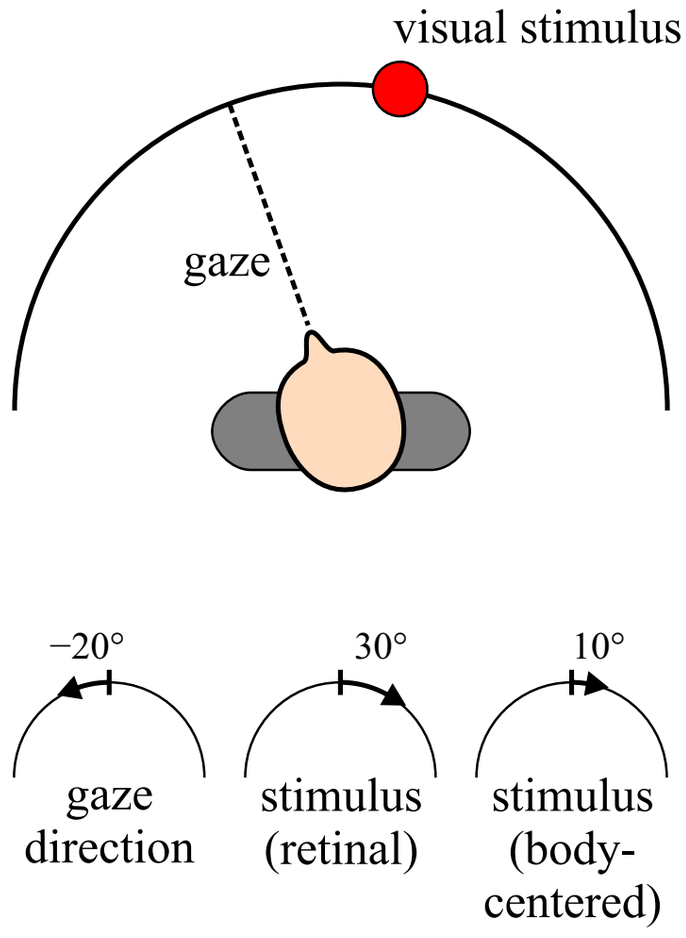




[Schneegans Ch 7 of *DFT Primer*, 2016]

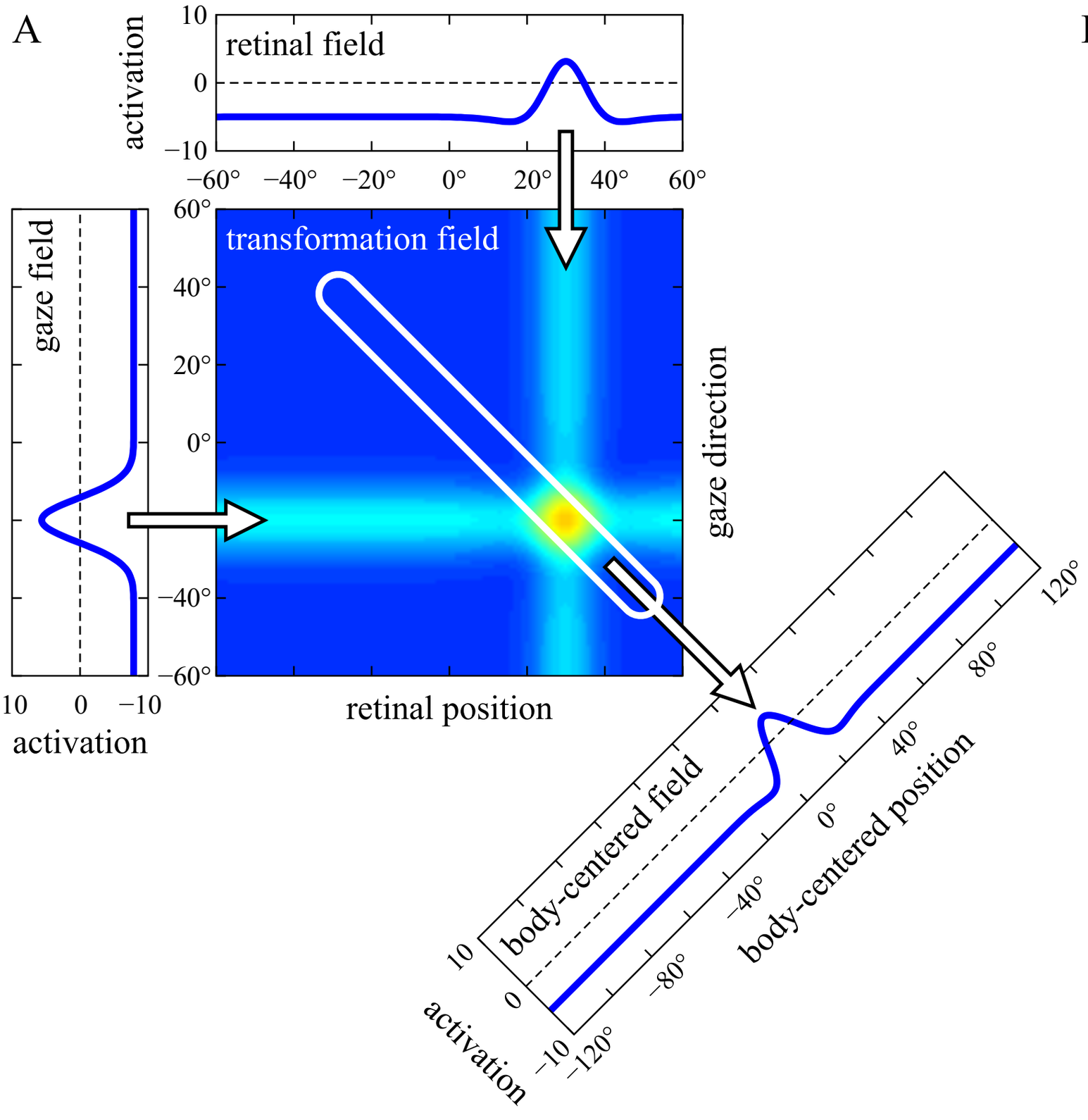
Retina => body space

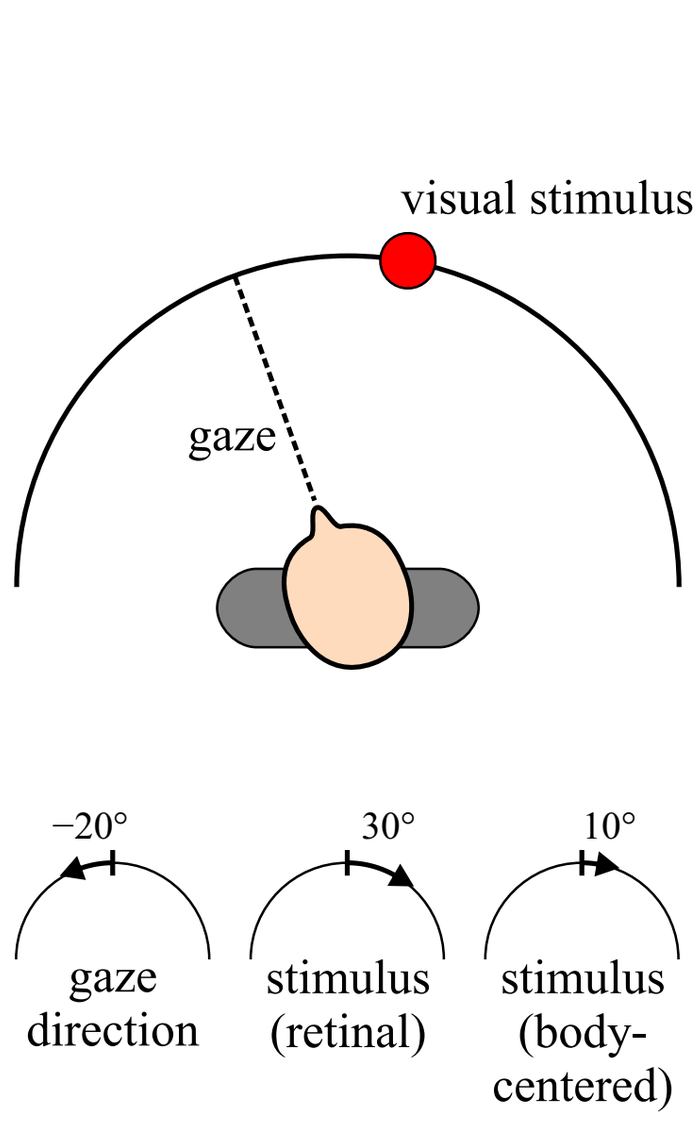




[Schneegans Ch 7 of *DFT Primer*, 2016]

Retina => body space

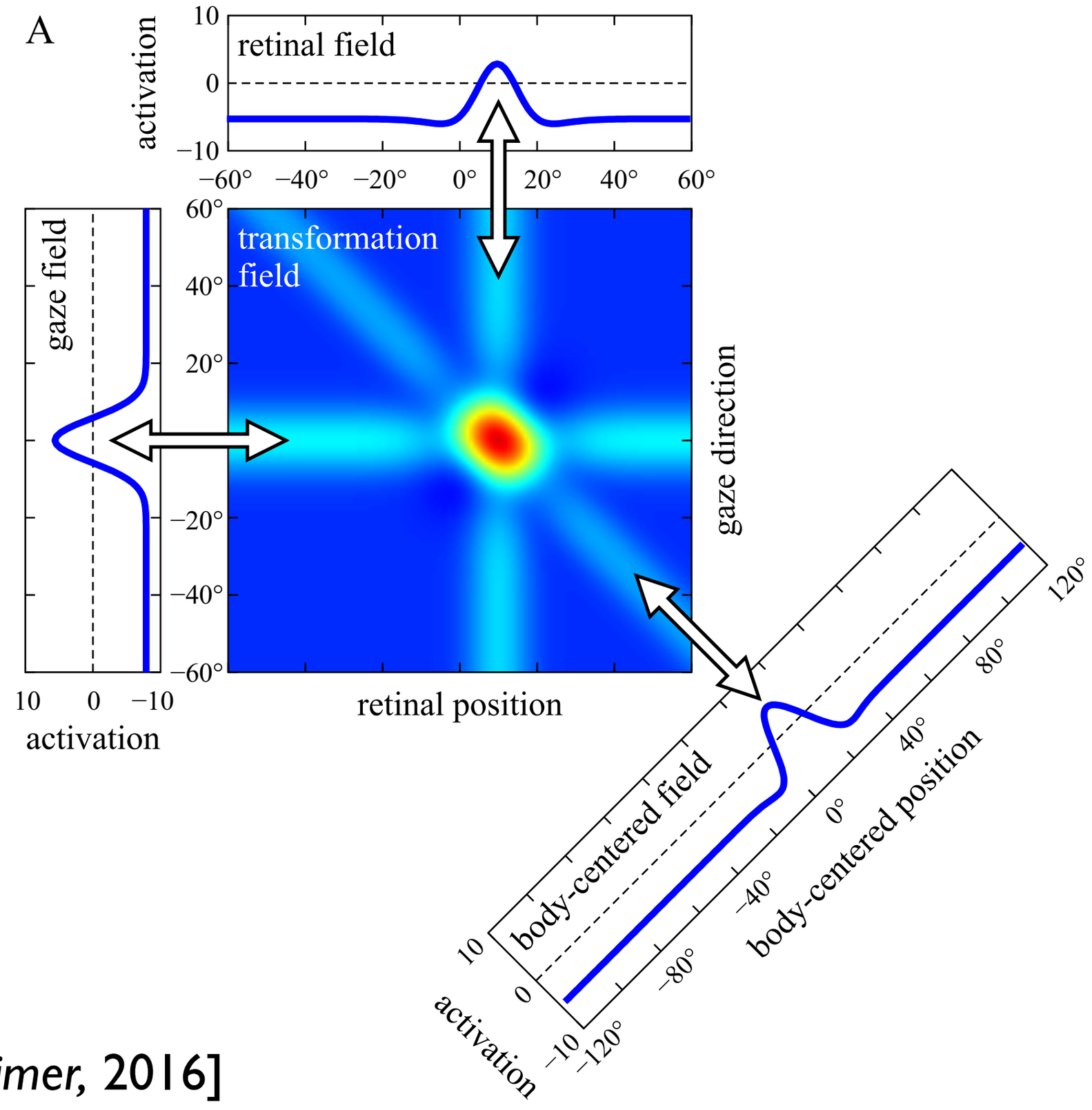




[Schneegans Ch 7 of *DFT Primer*, 2016]

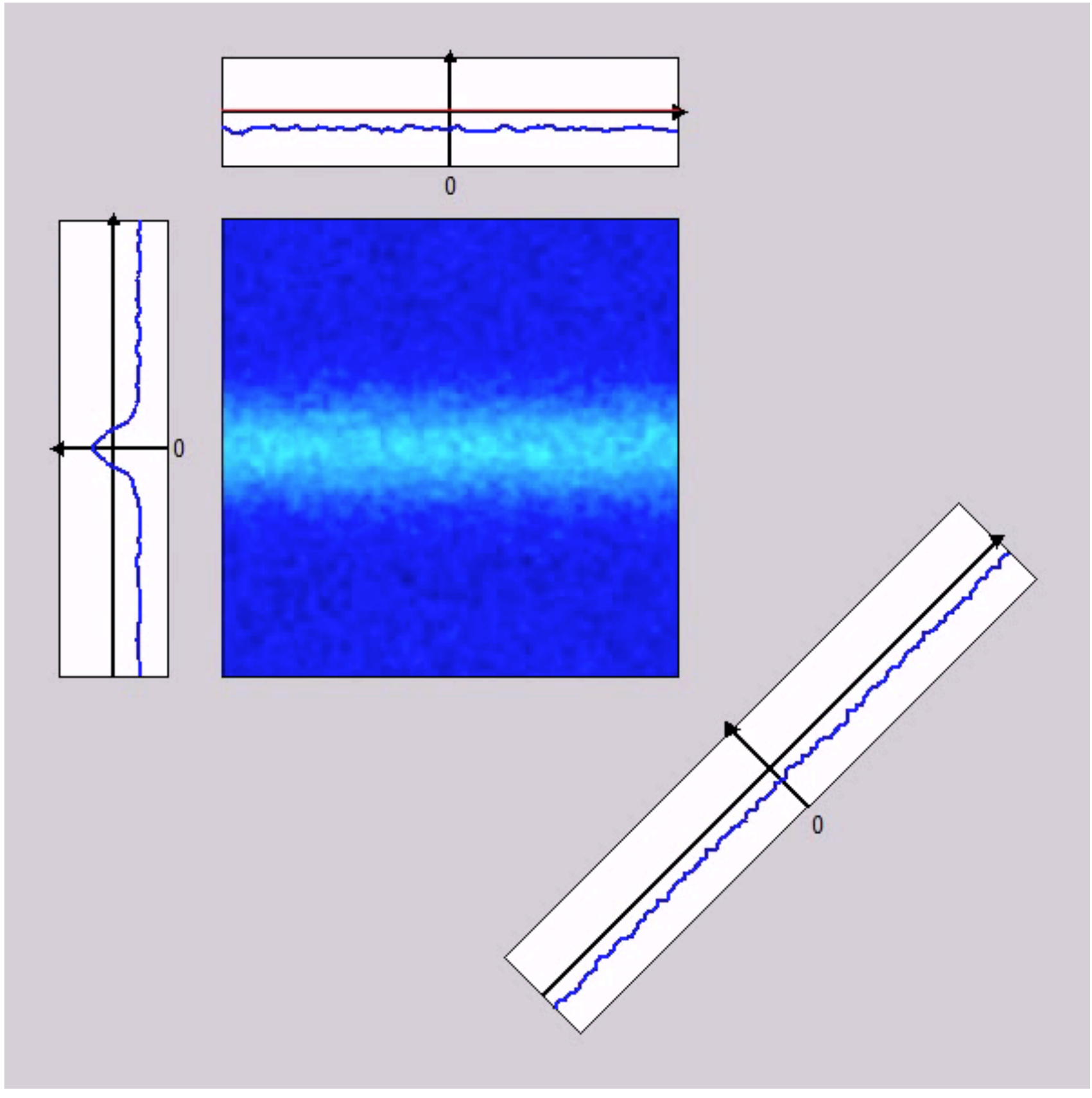
Retina => body space

- bi-directional coupling
- => predict retina coordinates



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

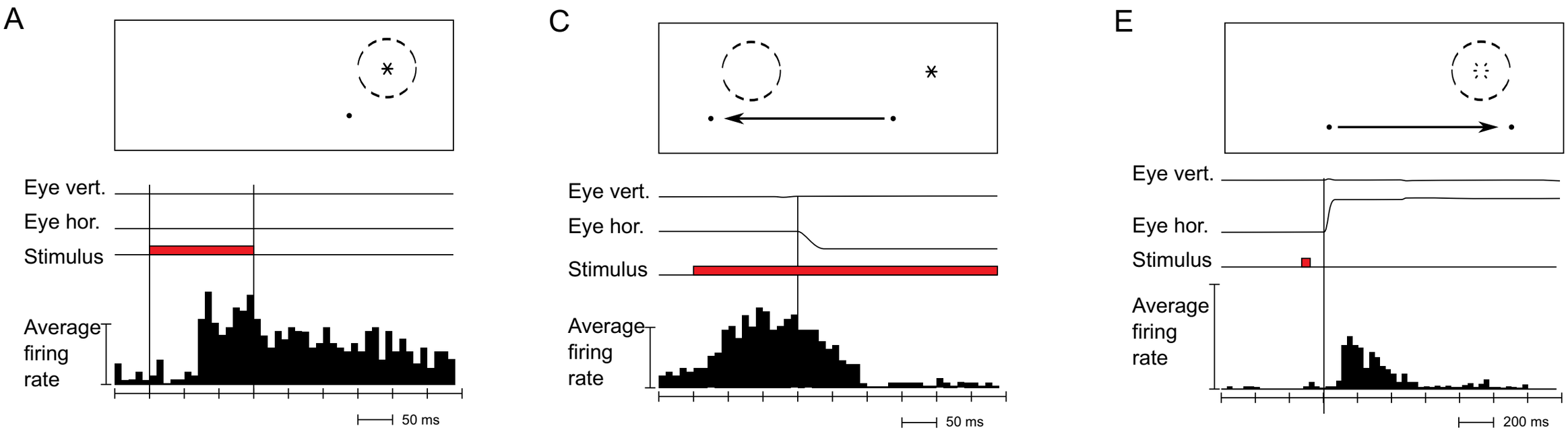
Spatial remapping during saccades



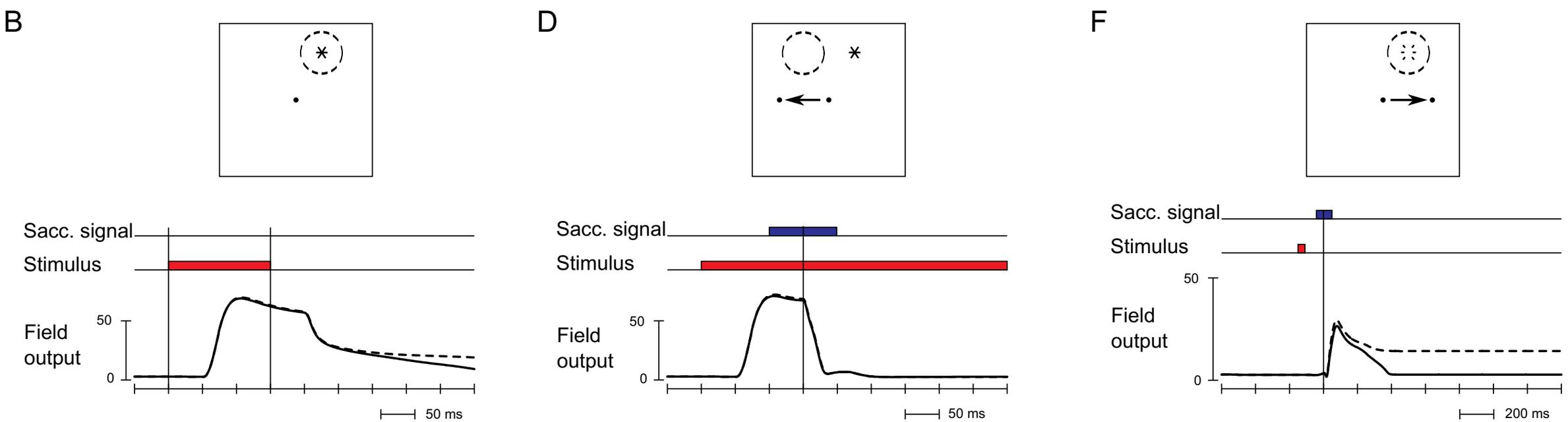
[Schneegans, Schöner *Biological Cybernetics* 2012]

Accounts for predictive updating

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

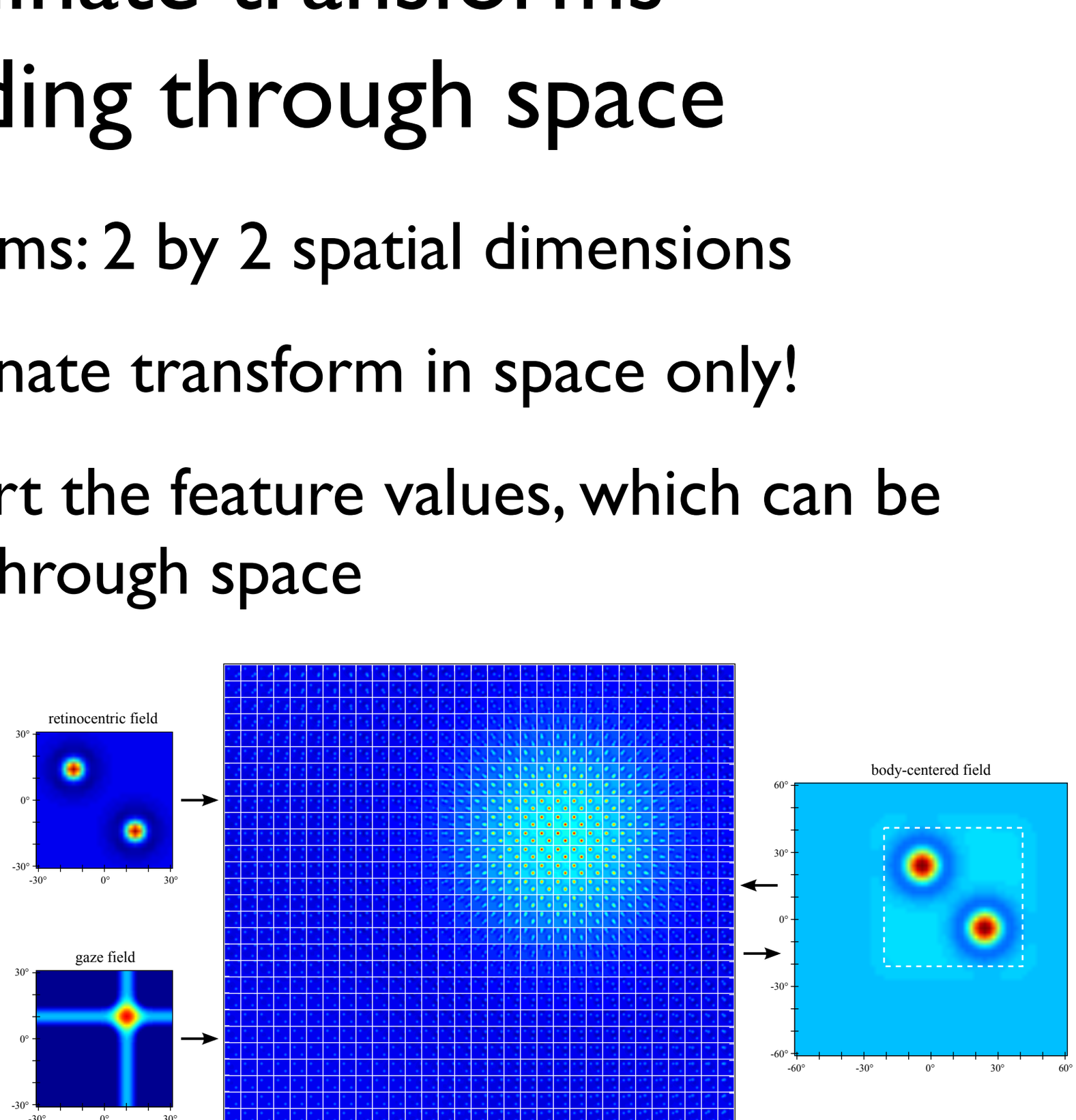


[model: Schneegans, Schöner *Biological Cybernetics* 2012]



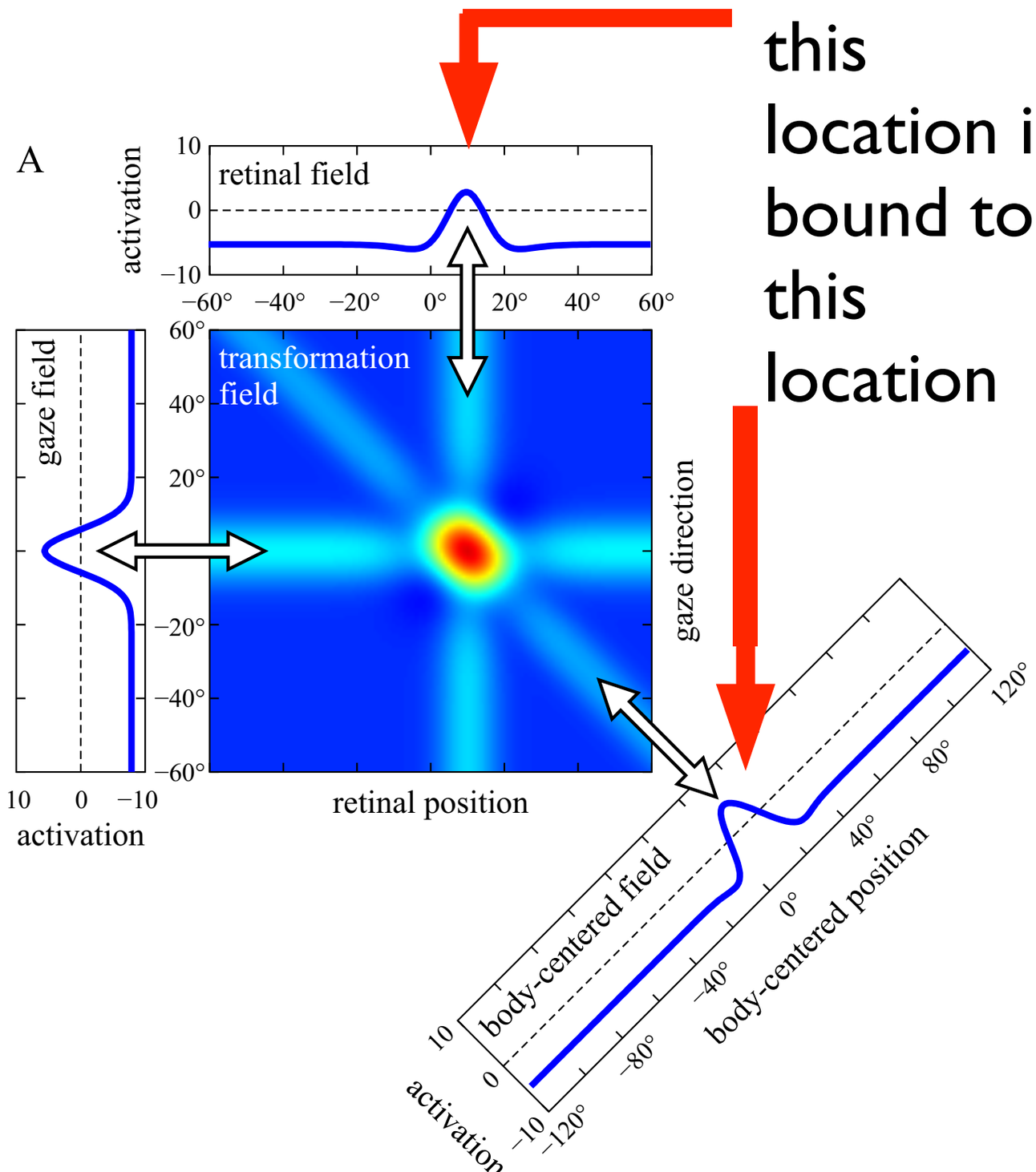
Coordinate transforms and binding through space

- coordinate transforms: 2 by 2 spatial dimensions
- perform the coordinate transform in space only!
- no need to transport the feature values, which can be filled in by binding through space

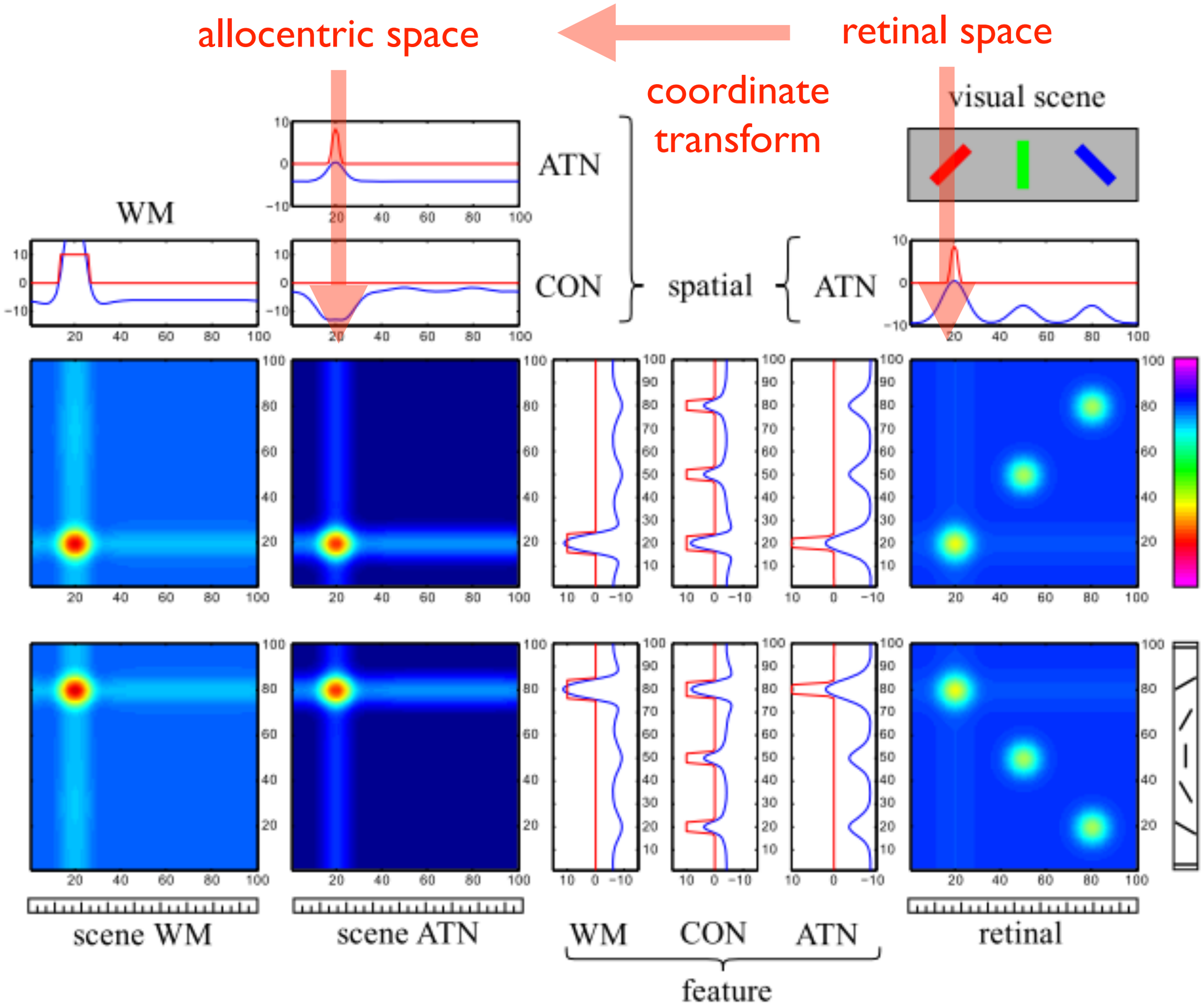


[Schneegans, Schöner, 2012]

Coordinate transforms are a from of binding through a shared representation



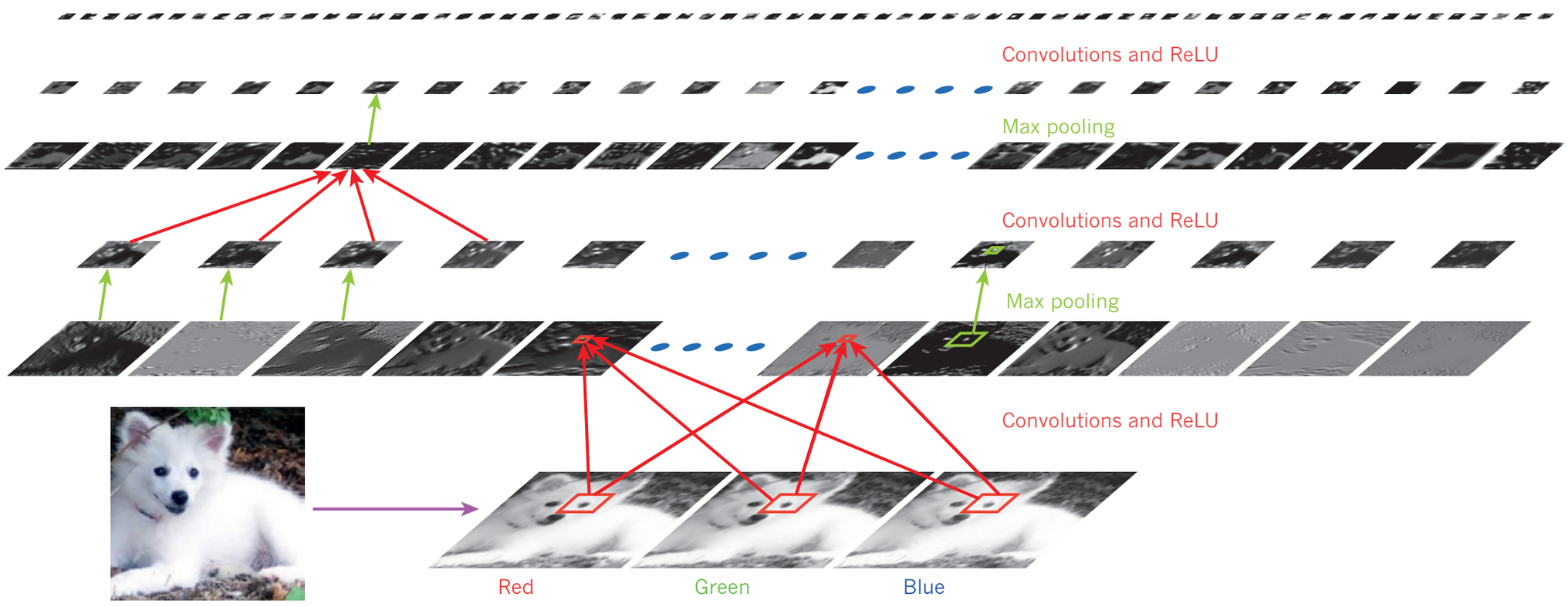
this location is bound to this location



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

Is there a binding problem for object recognition

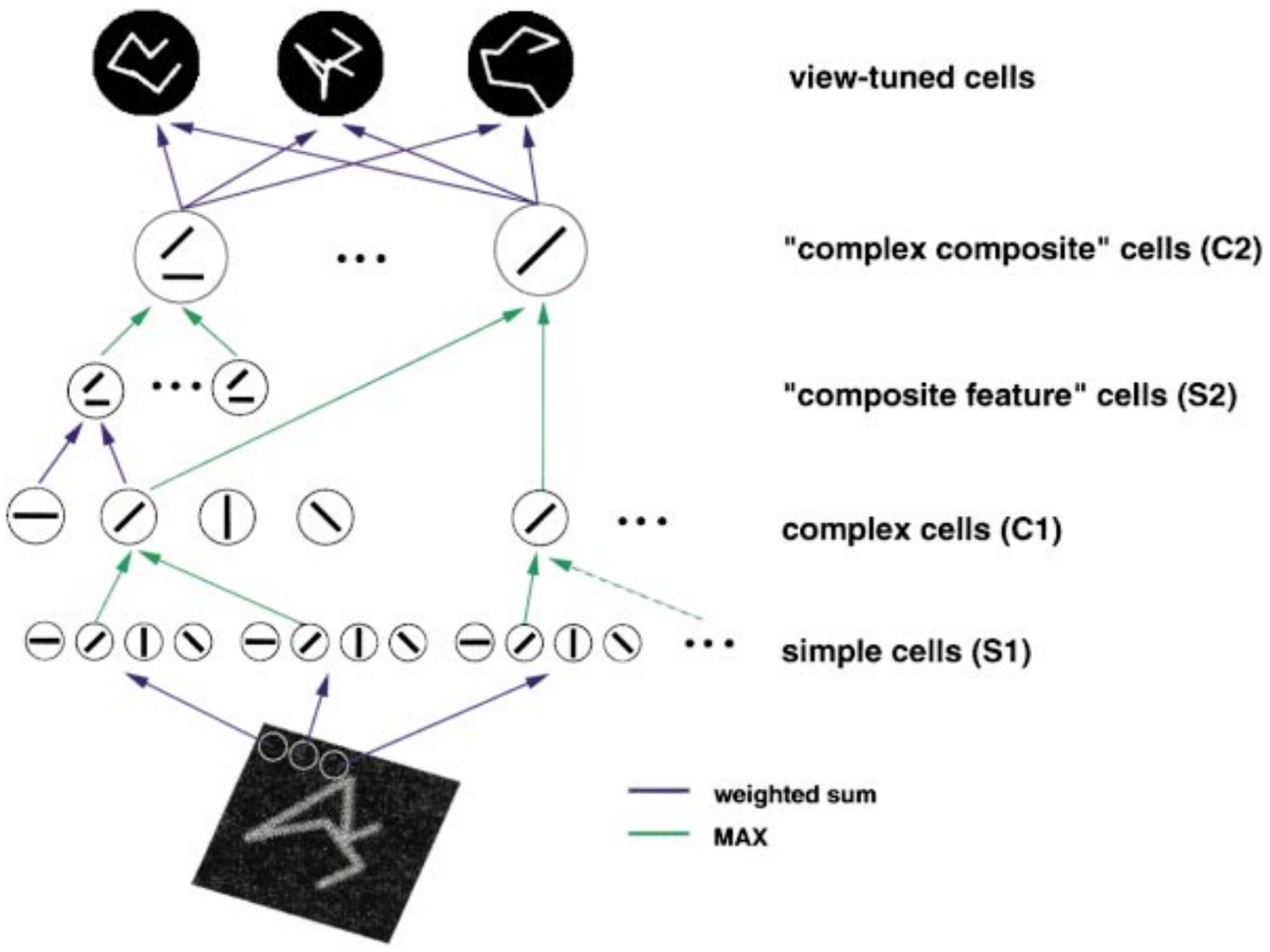
- complex learned object categories are represented by "anatomical" binding distributed across a DNN….



[from LeCun, Bengio, Hinton, Nature 2015]

Is binding a problem in general?

- not a flexible form of binding…



[Poggio, 1999]

Summary: binding

- (anatomical) binding: joint representations
- (flexible) binding: across different joint representations through a shared dimension
- neural coordinate emerge from such flexible binding
- binding and coordinate transforms => reduced dimensionality of flexible representation