DFT Foundations 2: Space-time coupling

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Central idea: DFT reaches higher cognition by combining

- 1 Space: coupling different fields over different low-dimensional spaces

- 2 Time (dynamics): inducing selective peaks through the instabilities …

- (3… which enable autonomous sequence generation)

Central idea: DFT reaches higher cognition by combining

- 1 Space: coupling different fields over different low-dimensional spaces

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This lecture addresses 1+2, 3 comes next

- Background: different notions of binding

- Joint representations and coupling patterns

- Binding through space/ordinal dimension

- Coordinate transforms

Intuition for "binding"

red cutter
horizontally
aligned

where is the red cutter?

where is the red cutter?

what was here?

the red cutter

Binding

- classical notion: features shape, color, orientation, and location are all "bound" together..

Binding

- notion that fea
  an object are bound…

the round object is blue

- (could be also simply
  due to the fact that
  objects are localized, so
  features are bound to a
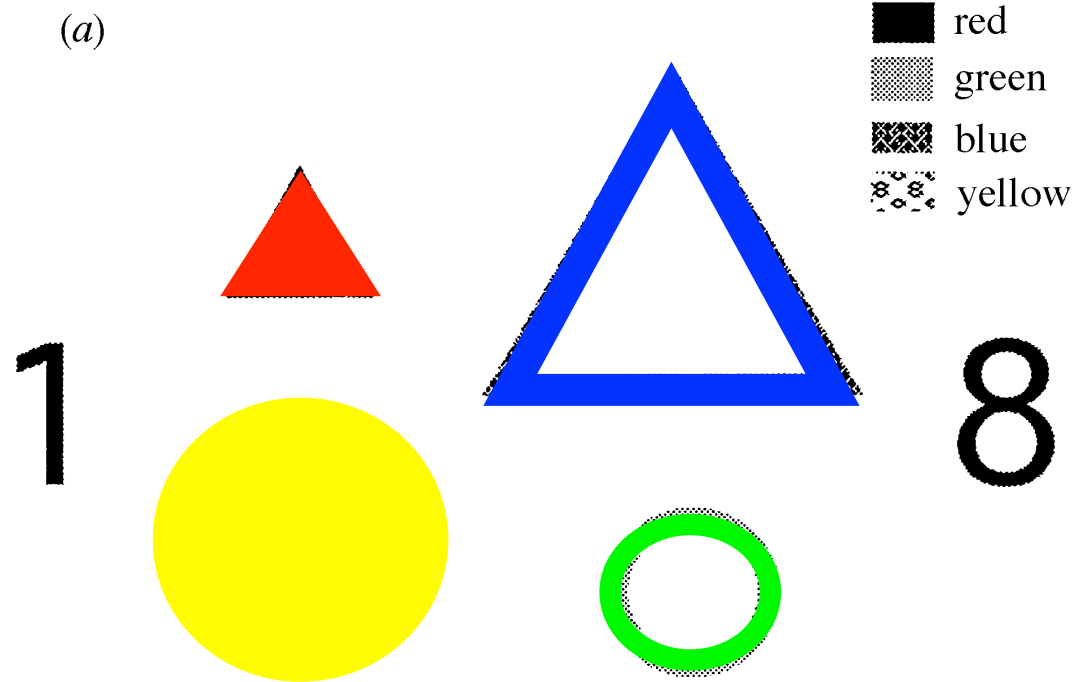 location)

[Faubel, 2008]

Binding to categories

the "S" is green

Such binding is flexible

- feature combinations never seen before may be bound
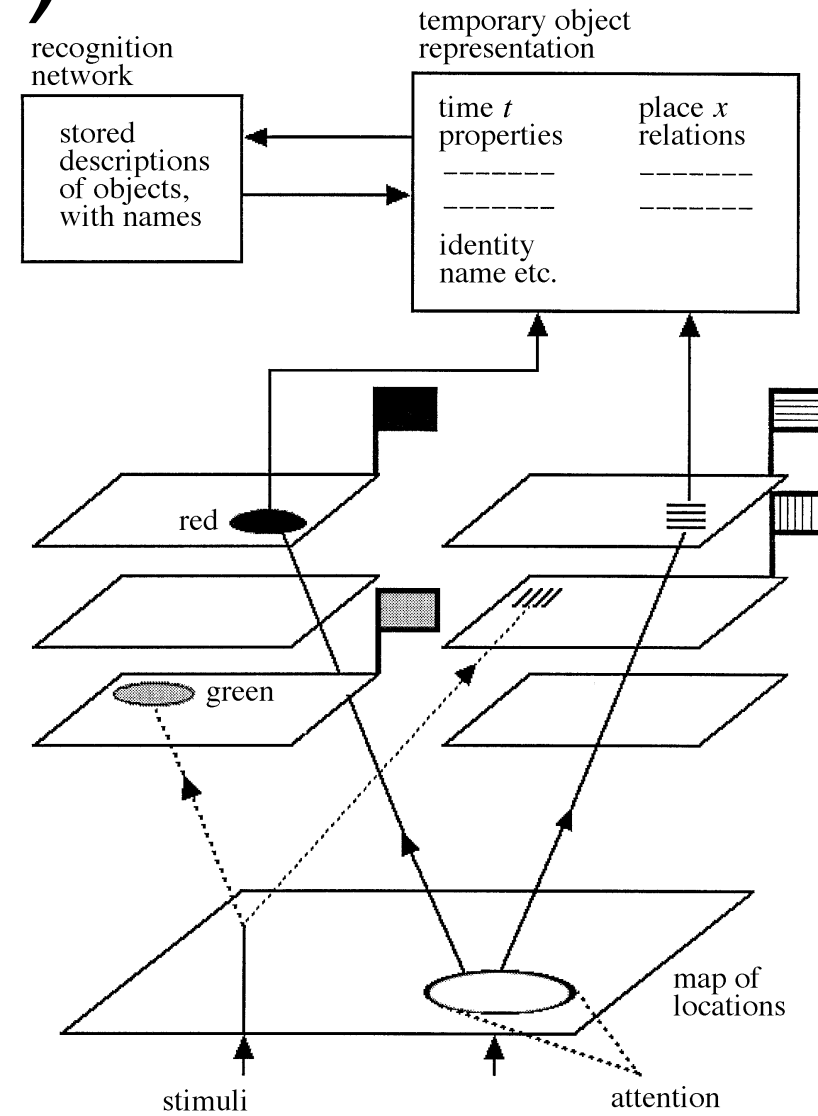
- mis-bindings may occur in "illusory conjunctions"

1) scene presented, then removed

2) report first the numbers (to generate a delay)

3) then report object features (shape, open/ closed, color)

(a)

red
yellow
blue

sample display

colour intrusion

letter intrusion

illusory conjunction

red
green
blue
yellow

[Treisman, 1998]

Treisman's Feature Integration Theory (FIT)

- "binding through space"

- combines neural notions (attention, feature maps)

- with information processing notions (files store feature combinations)

recognition network

temporary object representation

stored descriptions of objects, with names

time t properties

place x relations

identity name etc.

red

green

stimuli

map of locations

attention

[Treisman, 1998]

Binding in Vector Symbolic Architectures (VSA)

🟥 concepts represented by activation vectors:

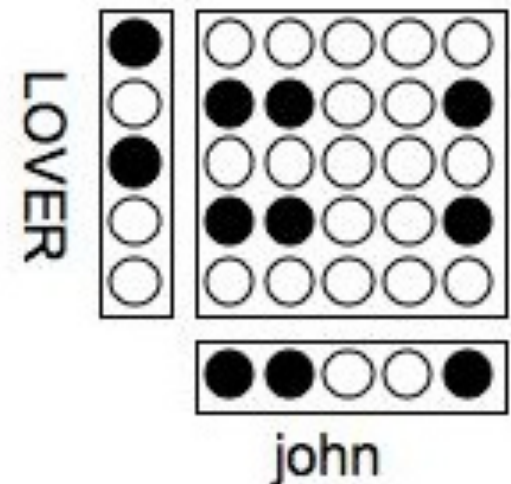🟪 $x_{\text{John}}, x_{\text{Mary}}, \ldots$

🟪 $y_{\text{LOVER}}, y_{\text{BELOVED}}$
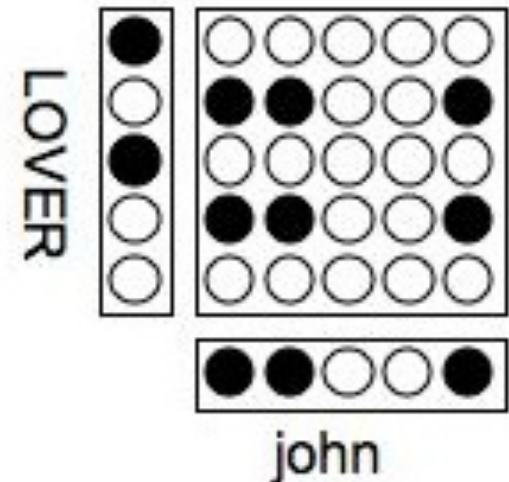
[Levy, Gayler, 2008]

Binding in VSA

■ represent "John loves" by binding x_{John} to y_{LOVER}

■ e.g. as a direct product


[Levy, Gayler, 2008]

Binding in DFT

- we will consider different forms of binding

- and the processes that bring these about, and make use of bindings

- these notions are not perfectly aligned with the classical notions

- but provide, in some cases, a neural process account of classical notions

- Background: different notions of binding

- Joint representations and coupling patterns

- Binding through space/ordinal dimension

- Coordinate transforms

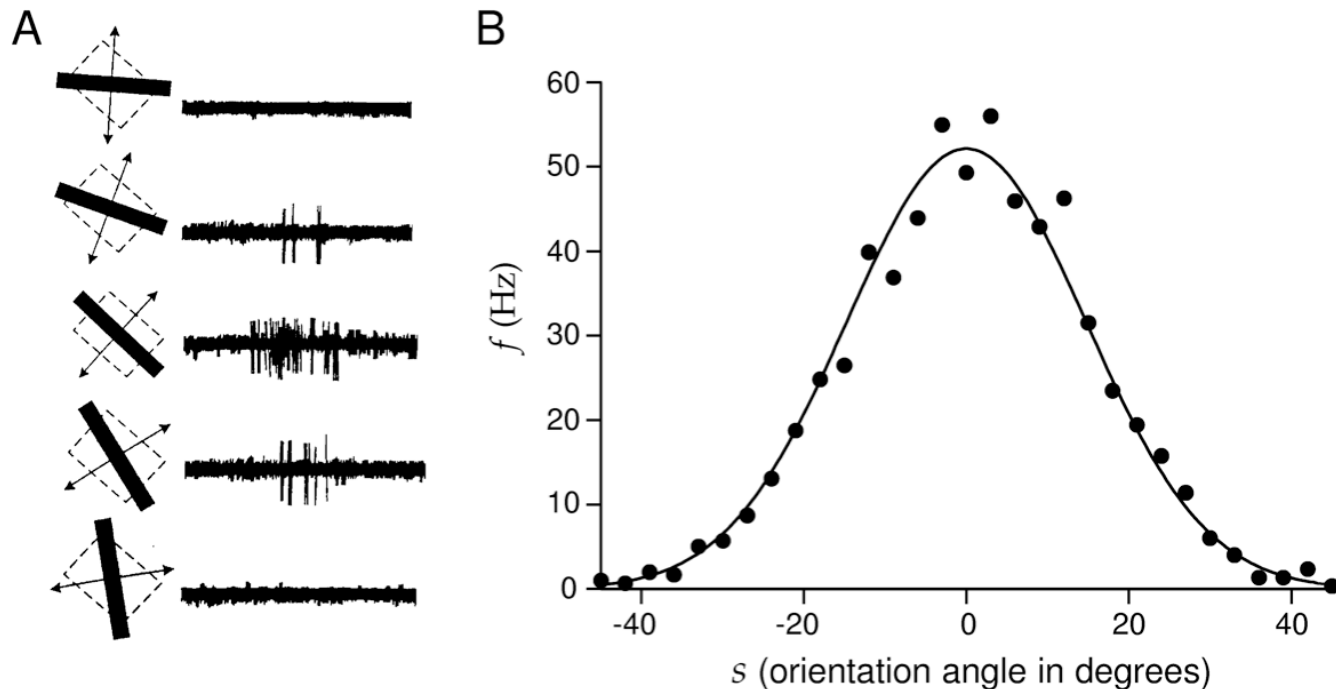# Joint representations: "anatomical" binding

- enables cognitive operations by

  - coupling different fields over different low-dimensional spaces

  - and using the dynamic instabilities to create peaks/operate on peaks

# Joint representations of different feature dimensions
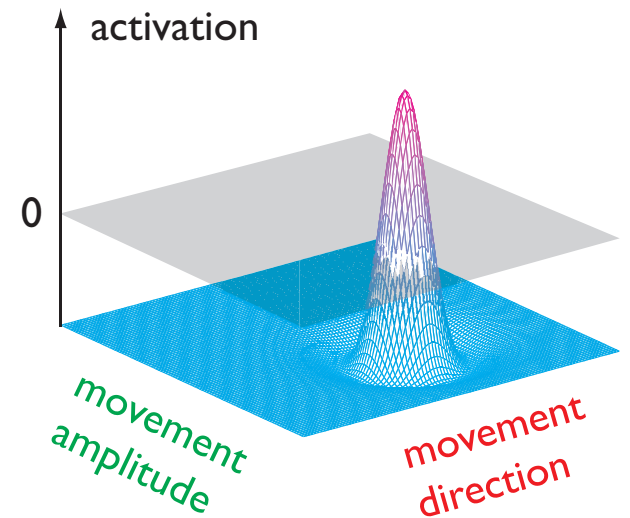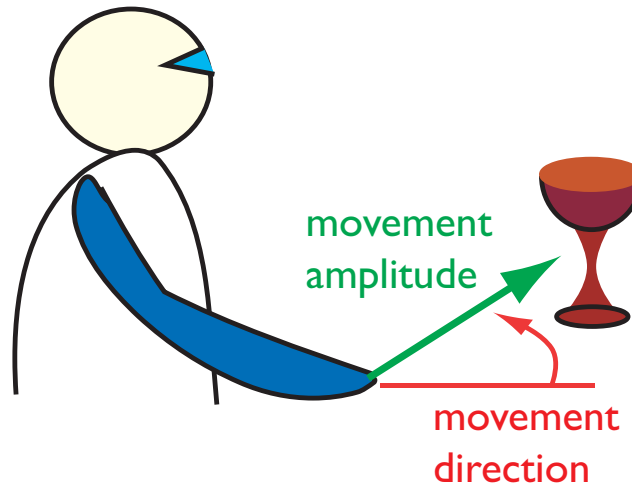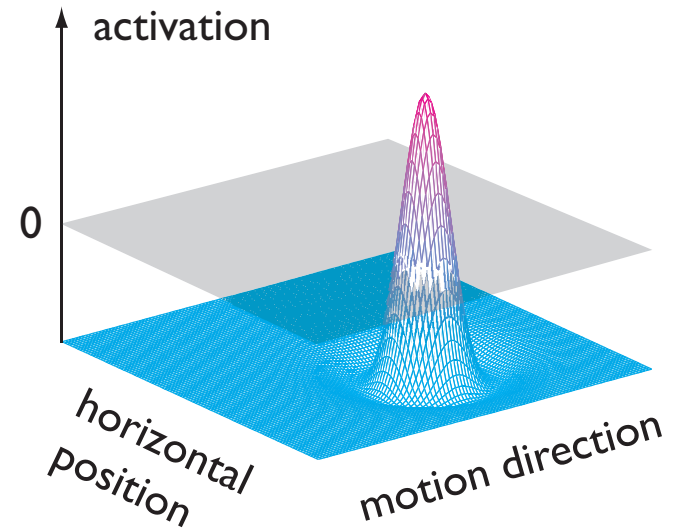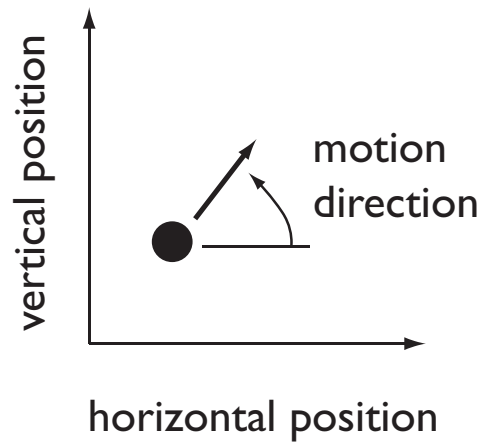
Based on neurons that are tuned to multiple different feature dimensions

- example: receptive field + direction tuning

- => combines visual space and orientation

[Hubel, Wiesel, 1962]

Joint space-feature representation

in a joint representation, localized peaks represent instances in which the different features dimensions are "anatomical bound"

fixed: need the neural substrate every possible bound state

[Schneegans et al., Ch 5 of *DFT Primer*, 2016]
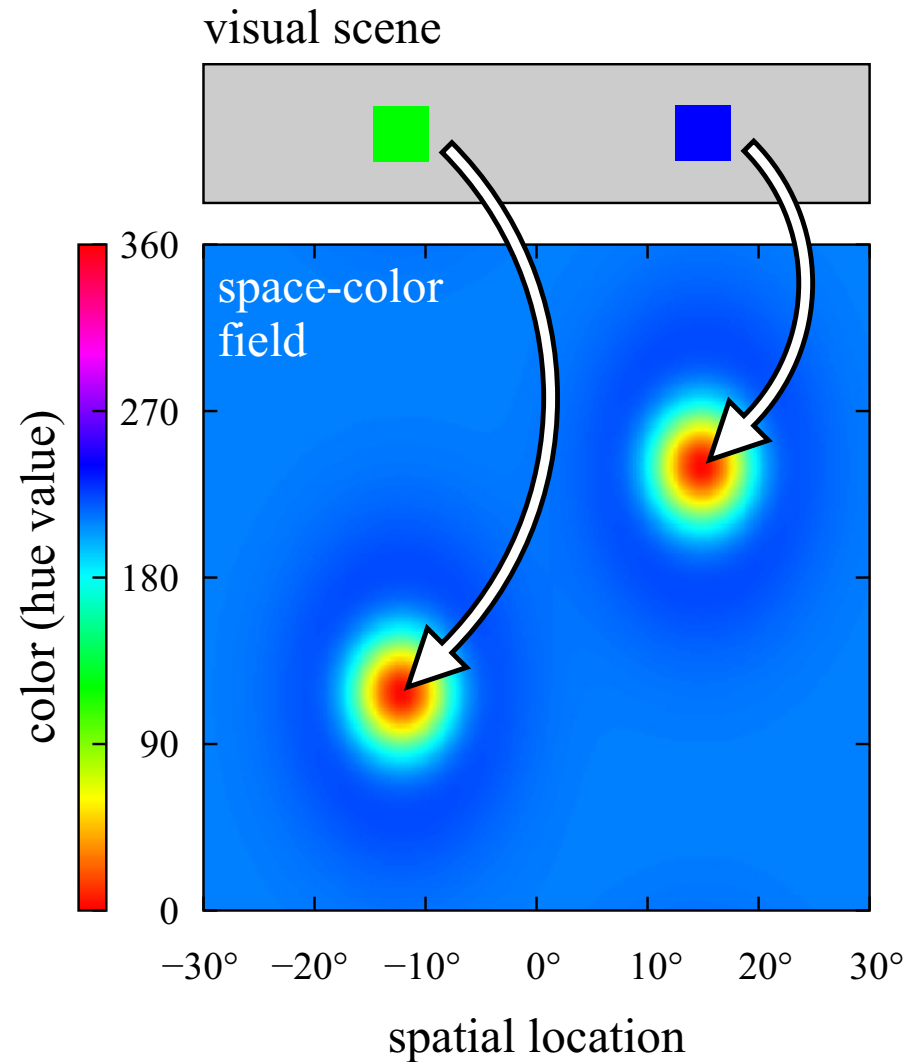
Extract features: unbinding

- projecting to lower-dimensional fields by summing along the marginalized dimensions

- contraction mapping

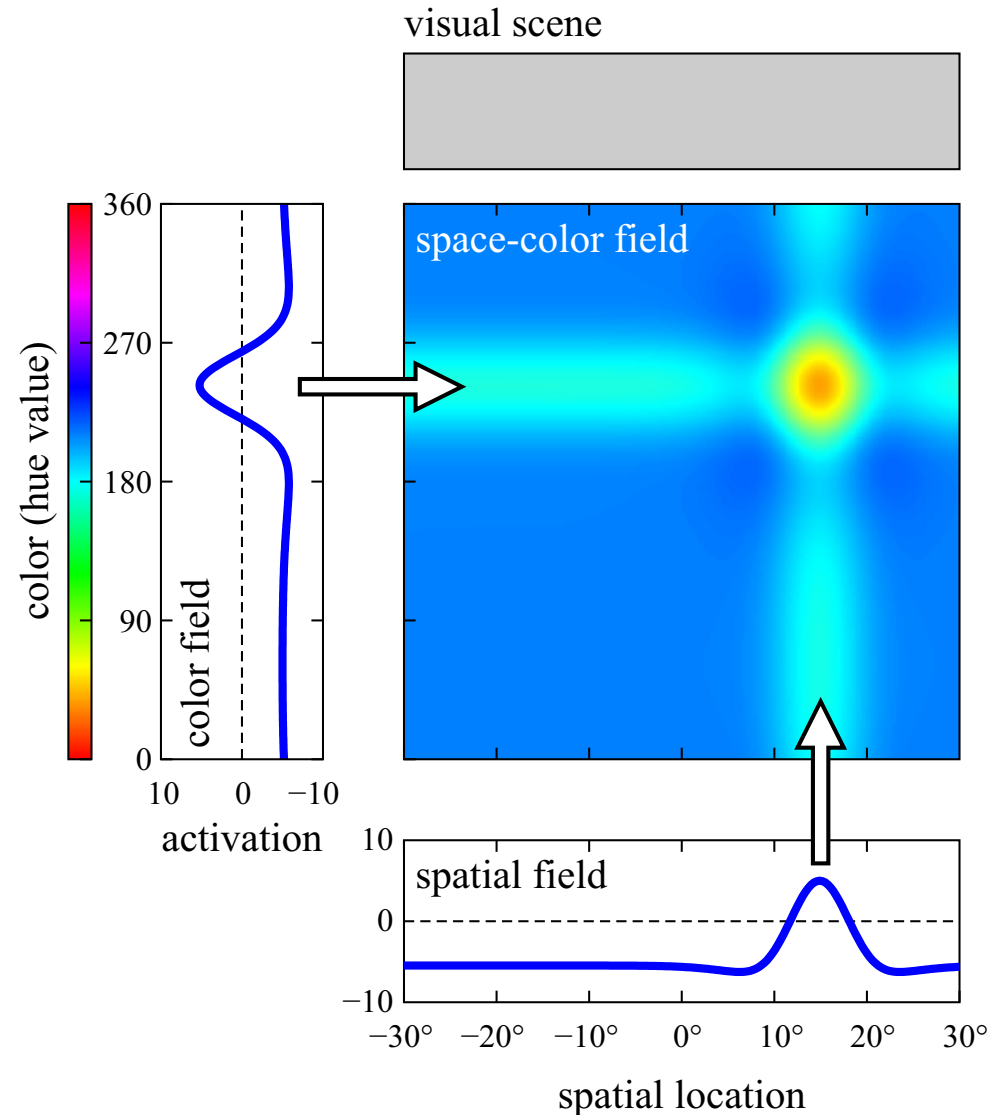[Schneegans et al., Ch 5 of *DFT Primer*, 2016]
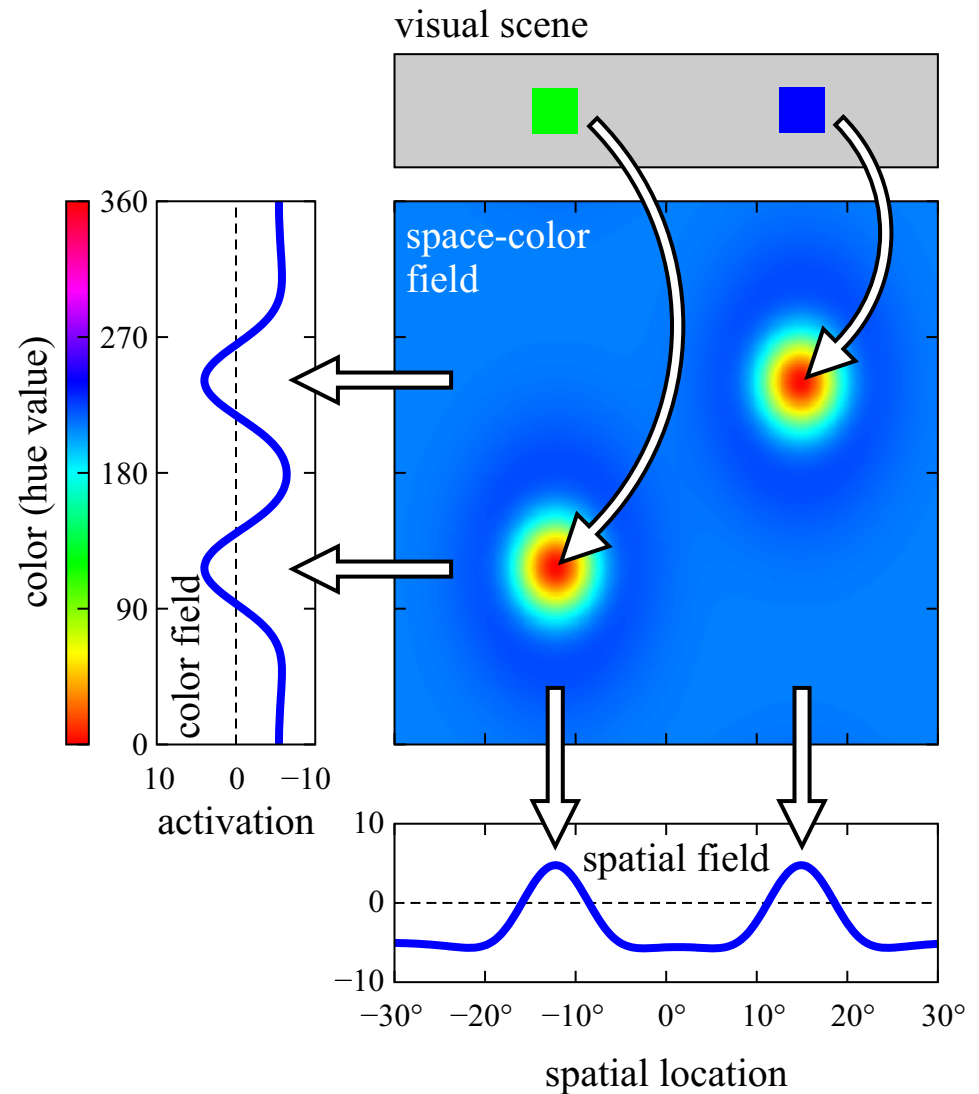
Bind features

- project lower-dimension field onto higher-dimensional field: expansion mapping
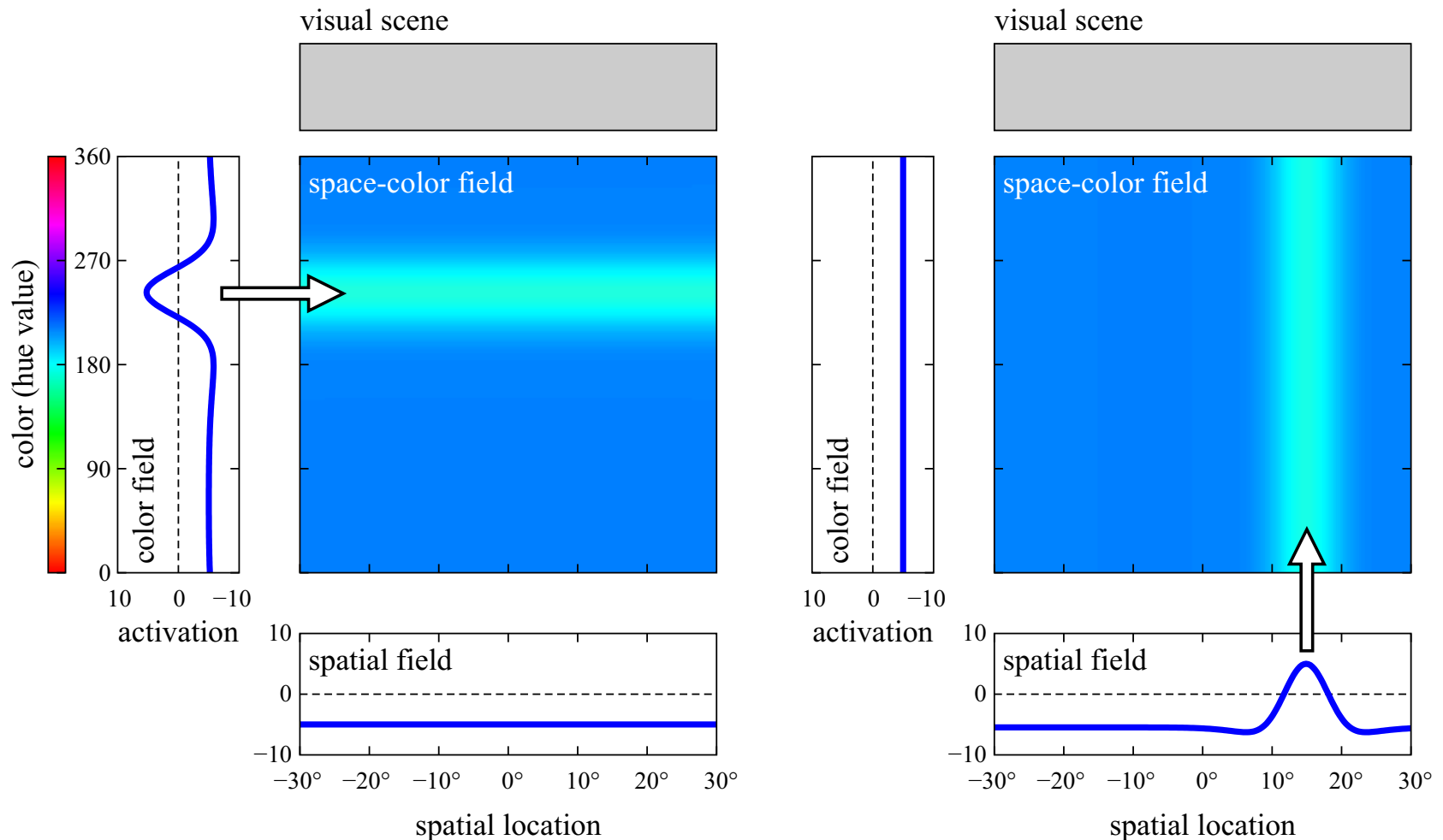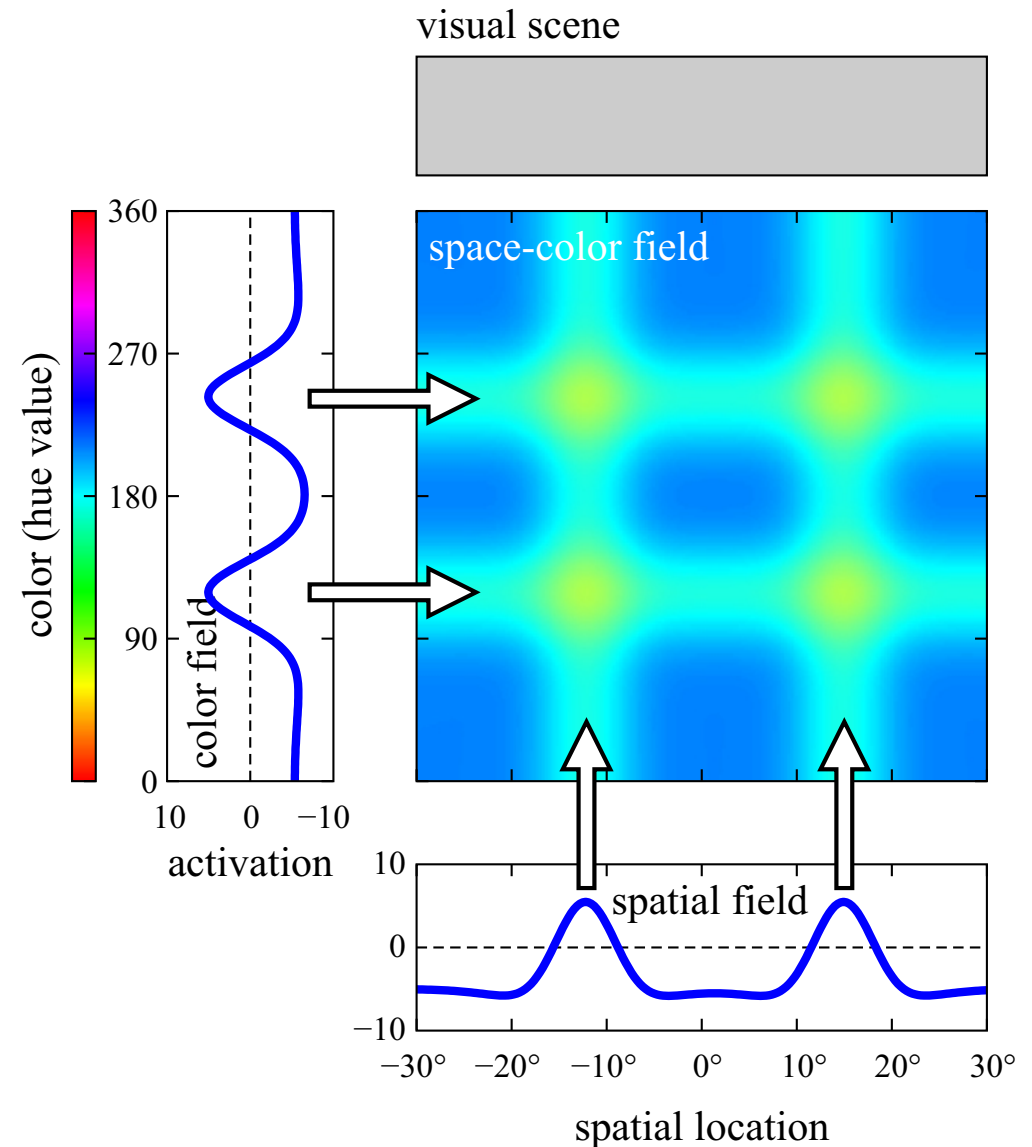

[Schneegans et al., Ch 5 of *DFT Primer*, 2016]

Bind features

■ => bind individual features into bound (joint) representations

■ enables the generation of mental maps


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

Binding problem

- this binding operation runs into the binding problem

- solution: bind one object at a time

- => attentional bottleneck

visual scene

space-color field

color (hue value)

color field

activation

spatial field

spatial location

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

Cued selection

- an operation that uses joint and individual representations

- combining expansion and contraction
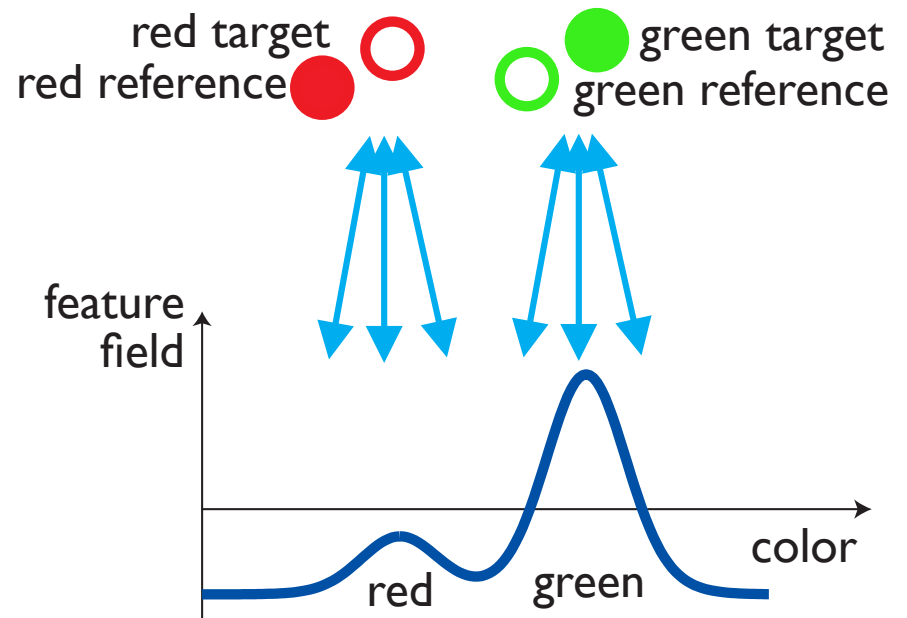
[Schneegans et al., Ch 5 of *DFT Primer*, 2016]
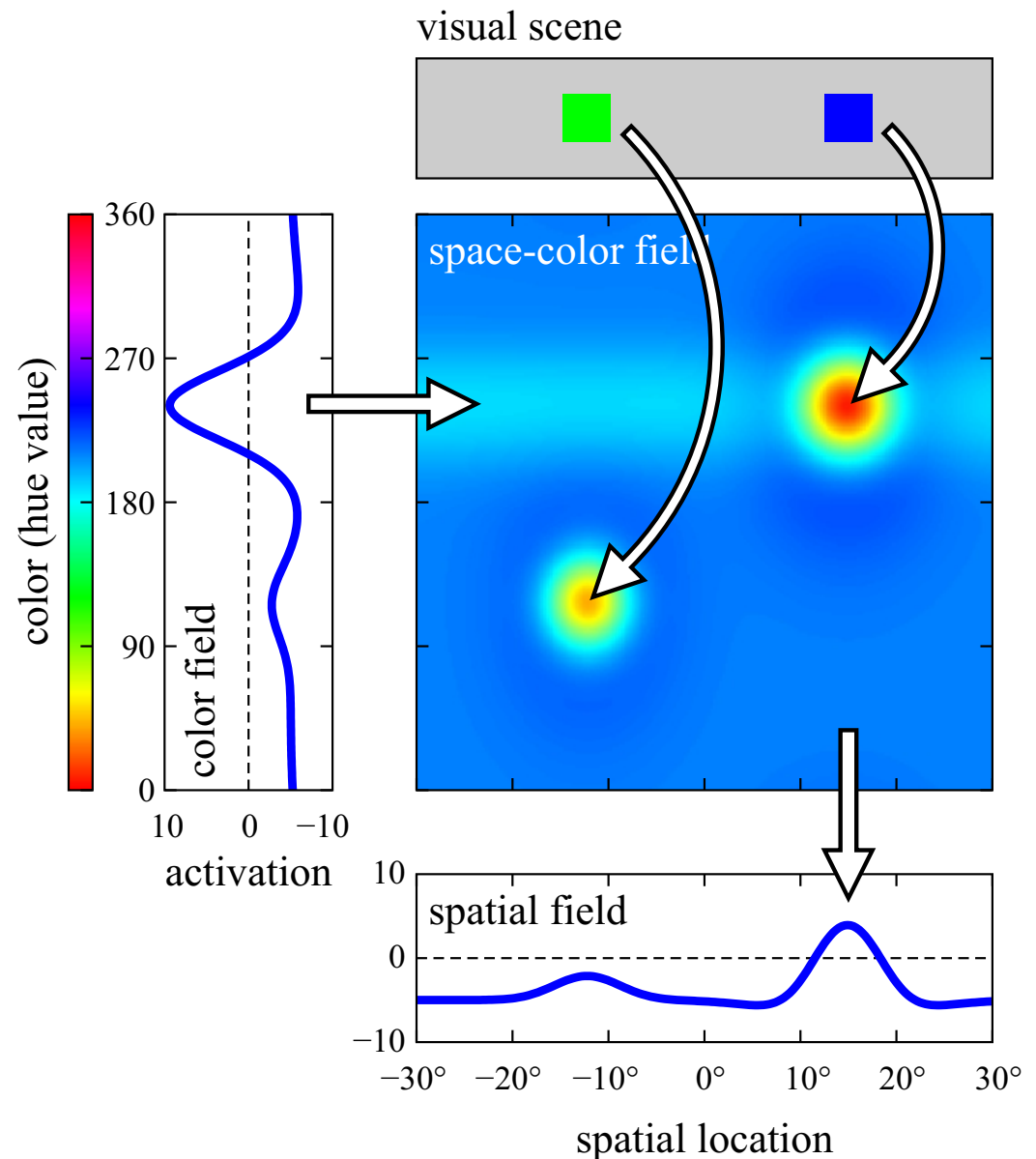
Role-filler binding

"green to the right of red"

- in conceptual structures concepts appear in roles:

- e.g. reference, target, agent, tool, …
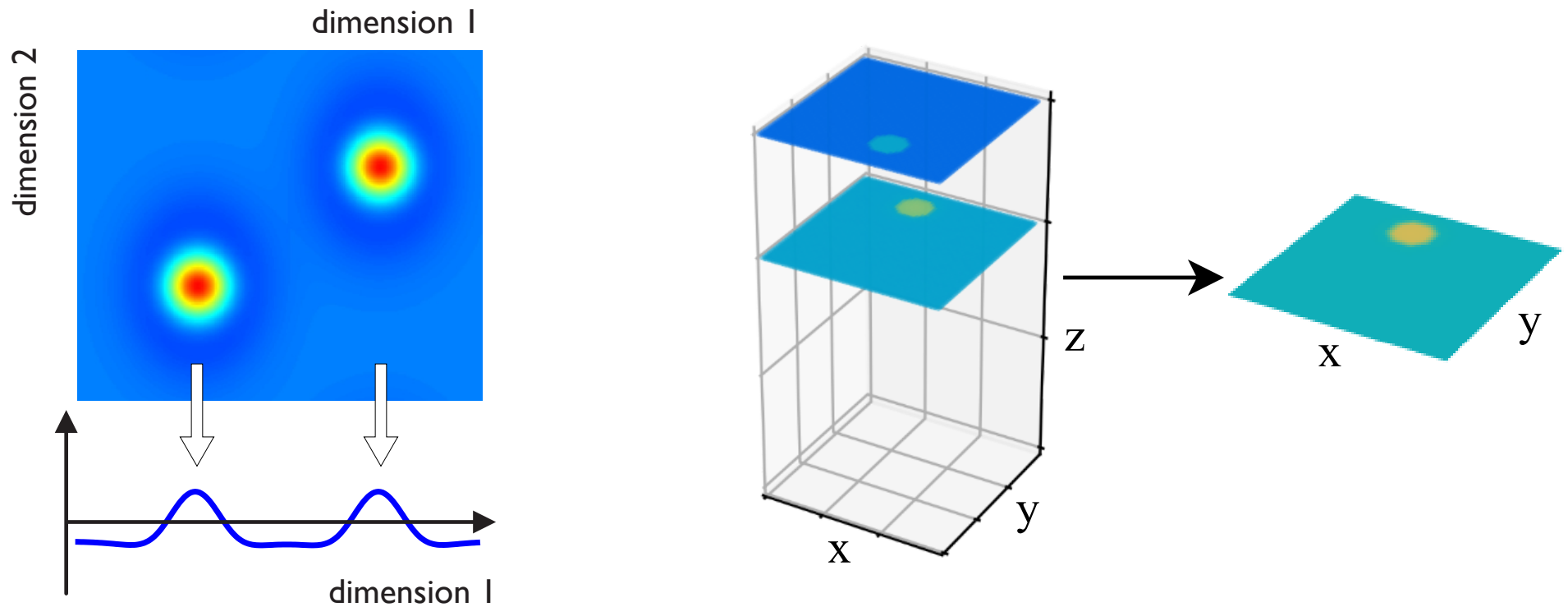
- these may be bound to concepts by joint representation

reference   target

red target
red reference

green target
green reference

feature
field

red   green   color

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

Coupling patterns

that are at play here…

Contraction coupling

dimension 1

dimension 2

dimension 1

z

y

x

y

x

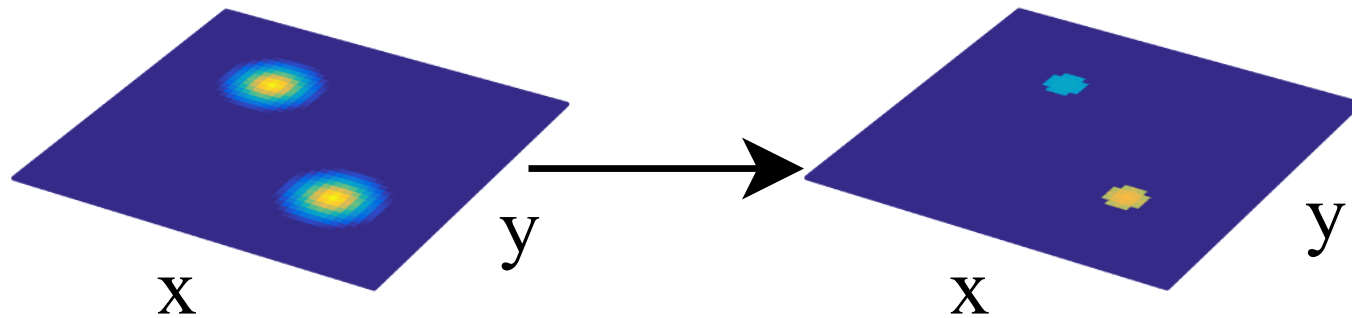[Sabinasz, Richter, Schöner, *Cog. Neurodyn.* 2023]

Expansion coupling
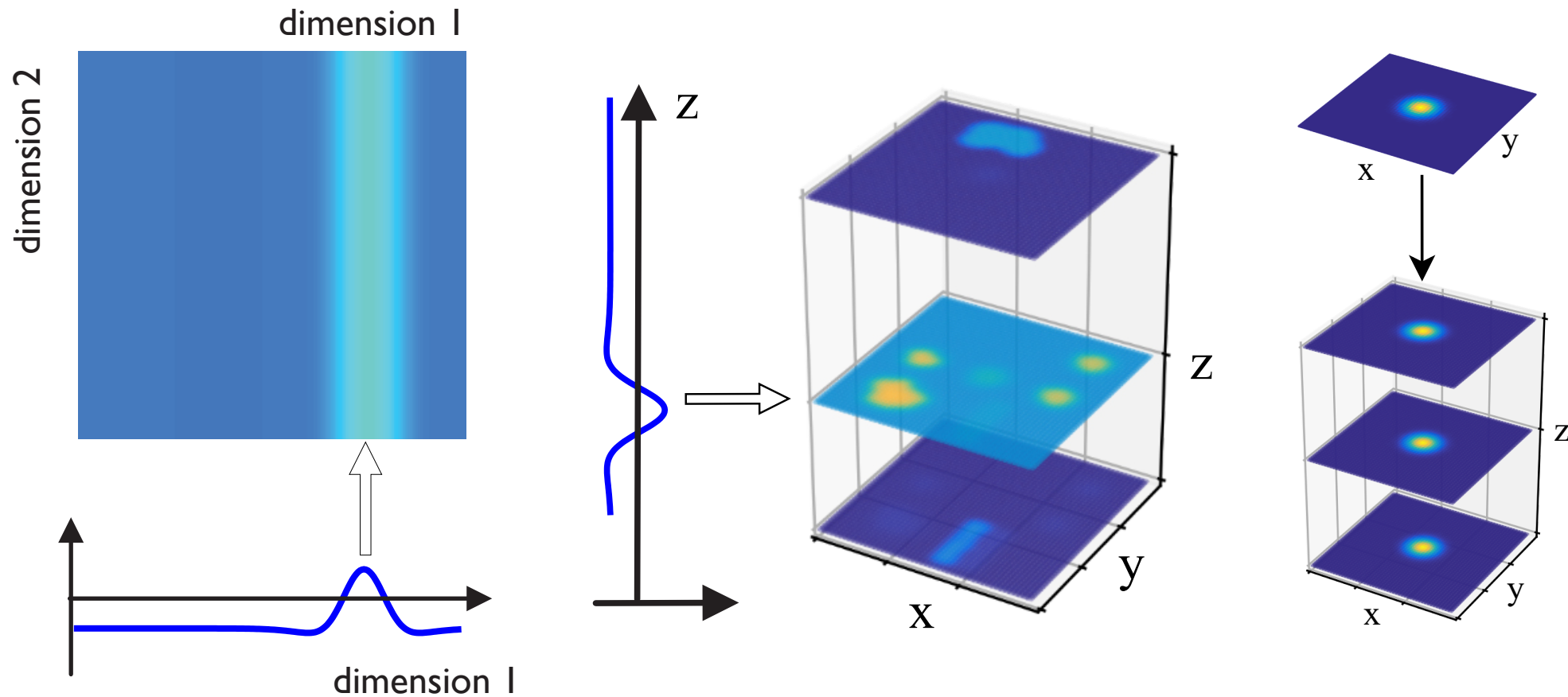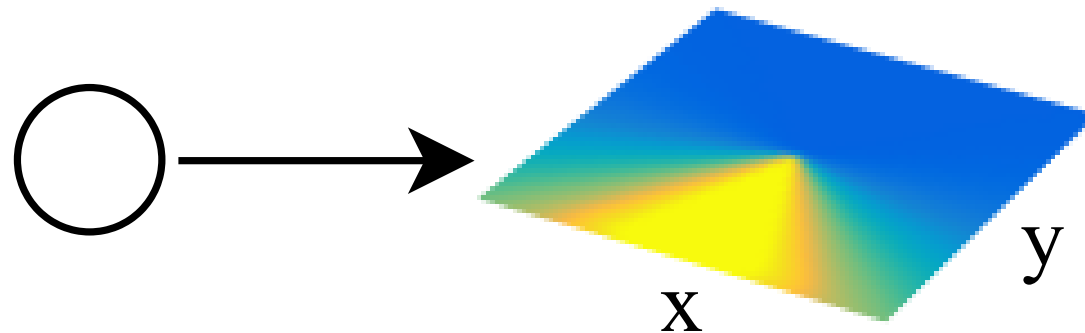

[Sabinasz, Richter, Schöner, *Cog. Neurodyn.* 2023]

Coupling patterns used later

■ one-to-one mapping

■ patterned coupling

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

- Background: different notions of binding

- Joint representations and coupling patterns

- Binding through space/ordinal dimension

- Coordinate transforms

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
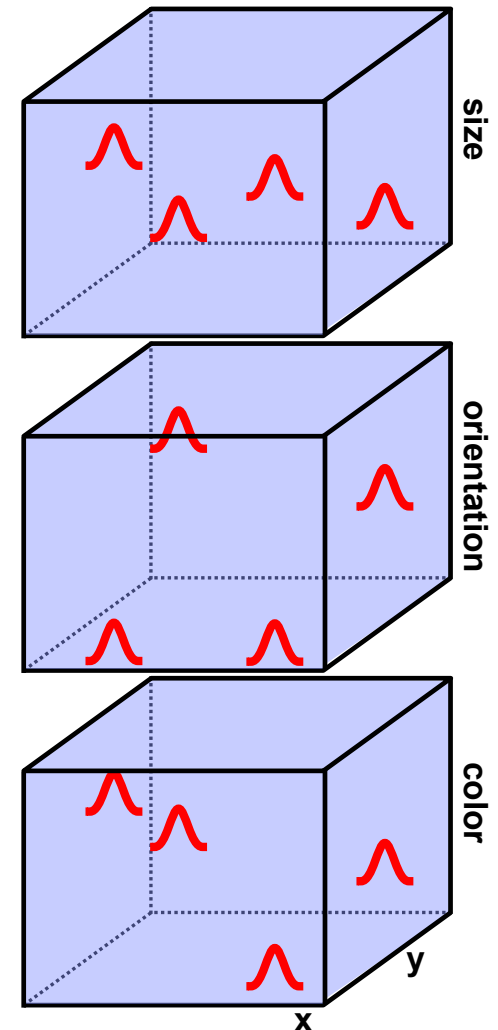
Binding through shared dimensions

■ 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

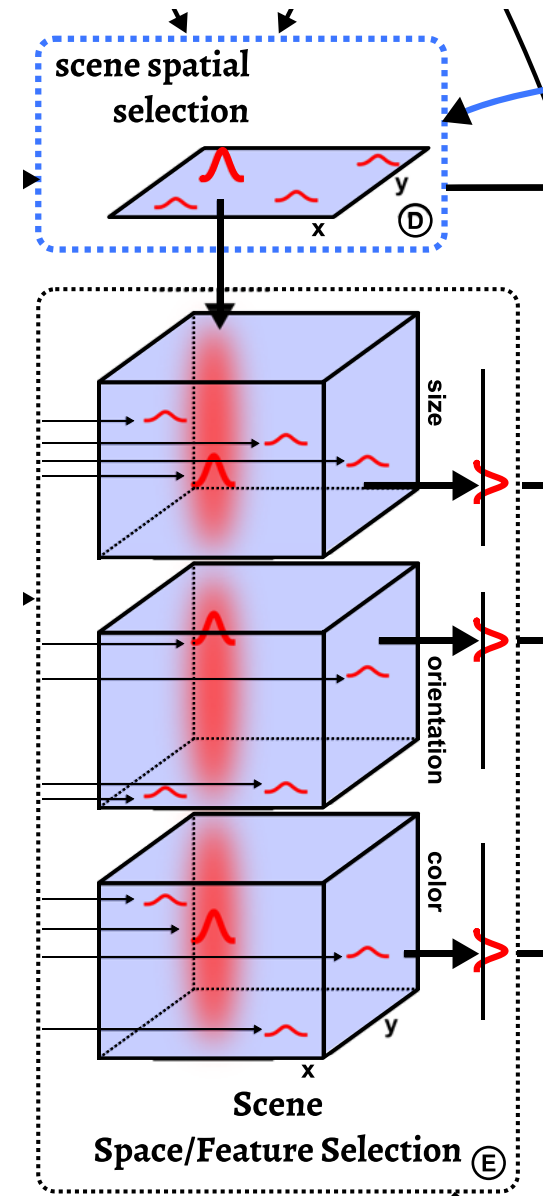# Binding through space

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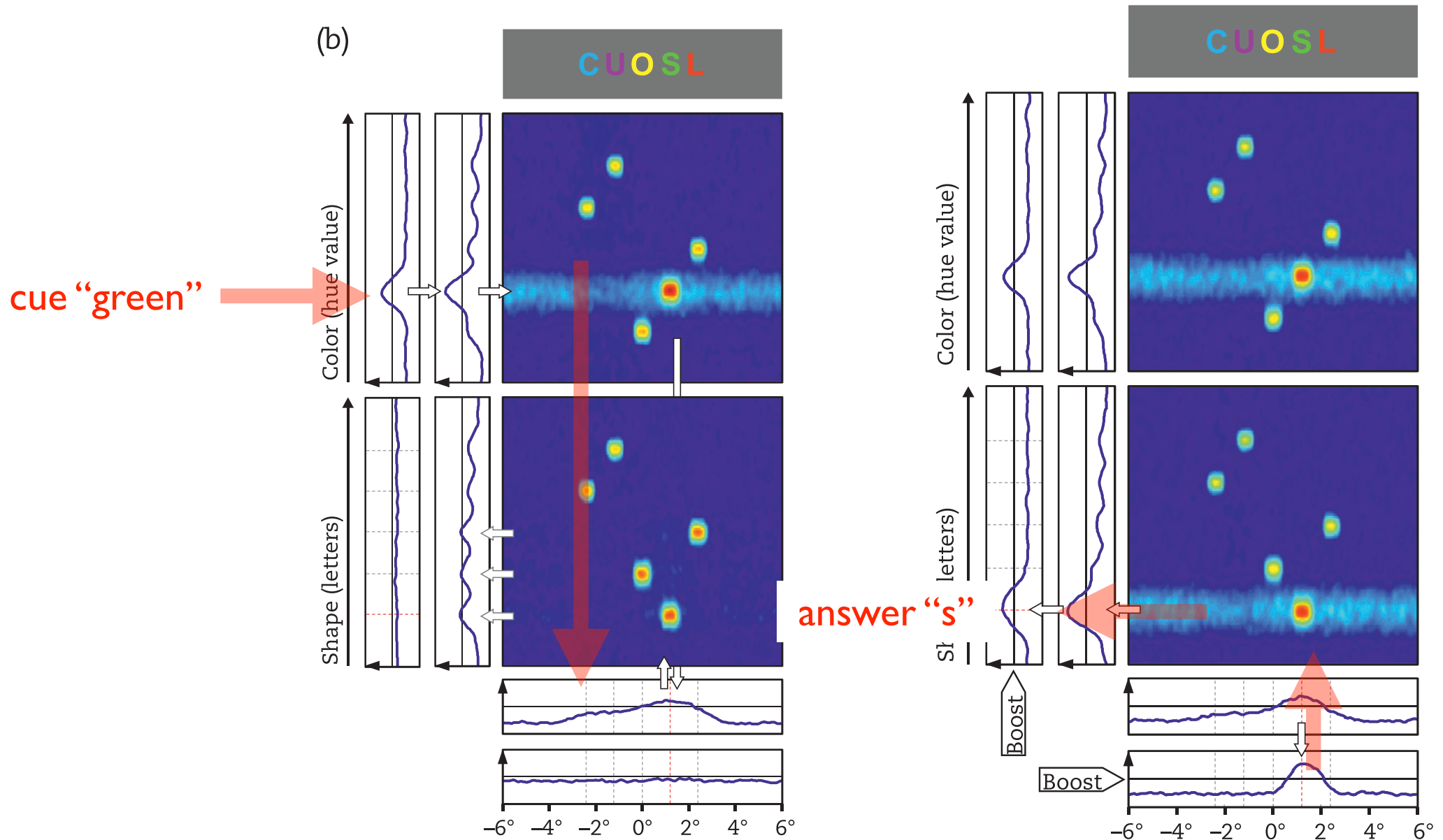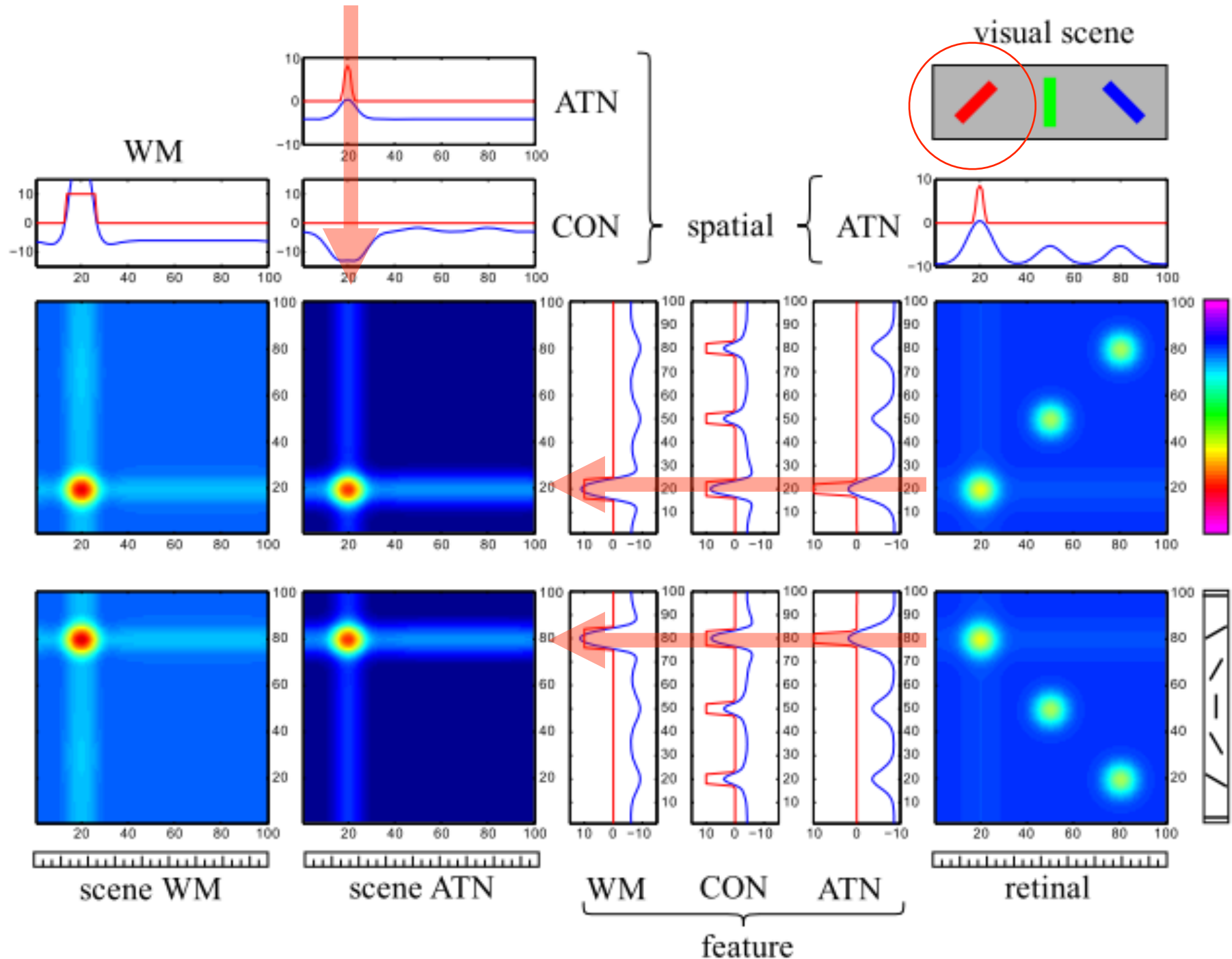
[Grieben et al. *Attention, Perception & Psychophysics* 2020]

Binding through space

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

shared space

attend to this item

visual scene

WM

ATN

CON · spatial · ATN

scene WM   scene ATN   WM   CON   ATN   retinal

feature

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

WM

ATN

CON

spatial

ATN

visual scene

scene WM

scene ATN

WM CON ATN

retinal

feature

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

bound through space

WM

ATN

CON

spatial

ATN

visual scene

scene WM

scene ATN

WM   CON   ATN

retinal

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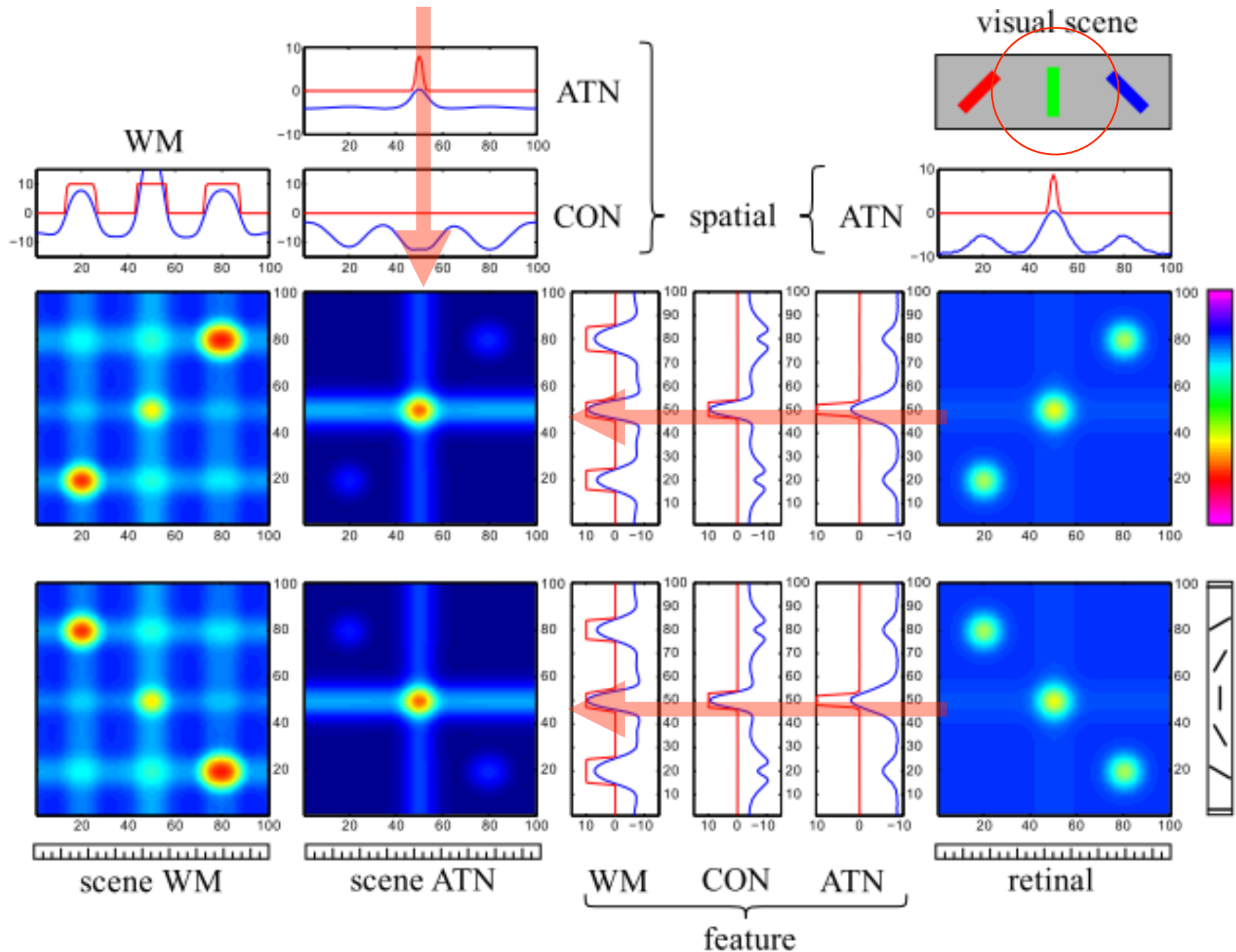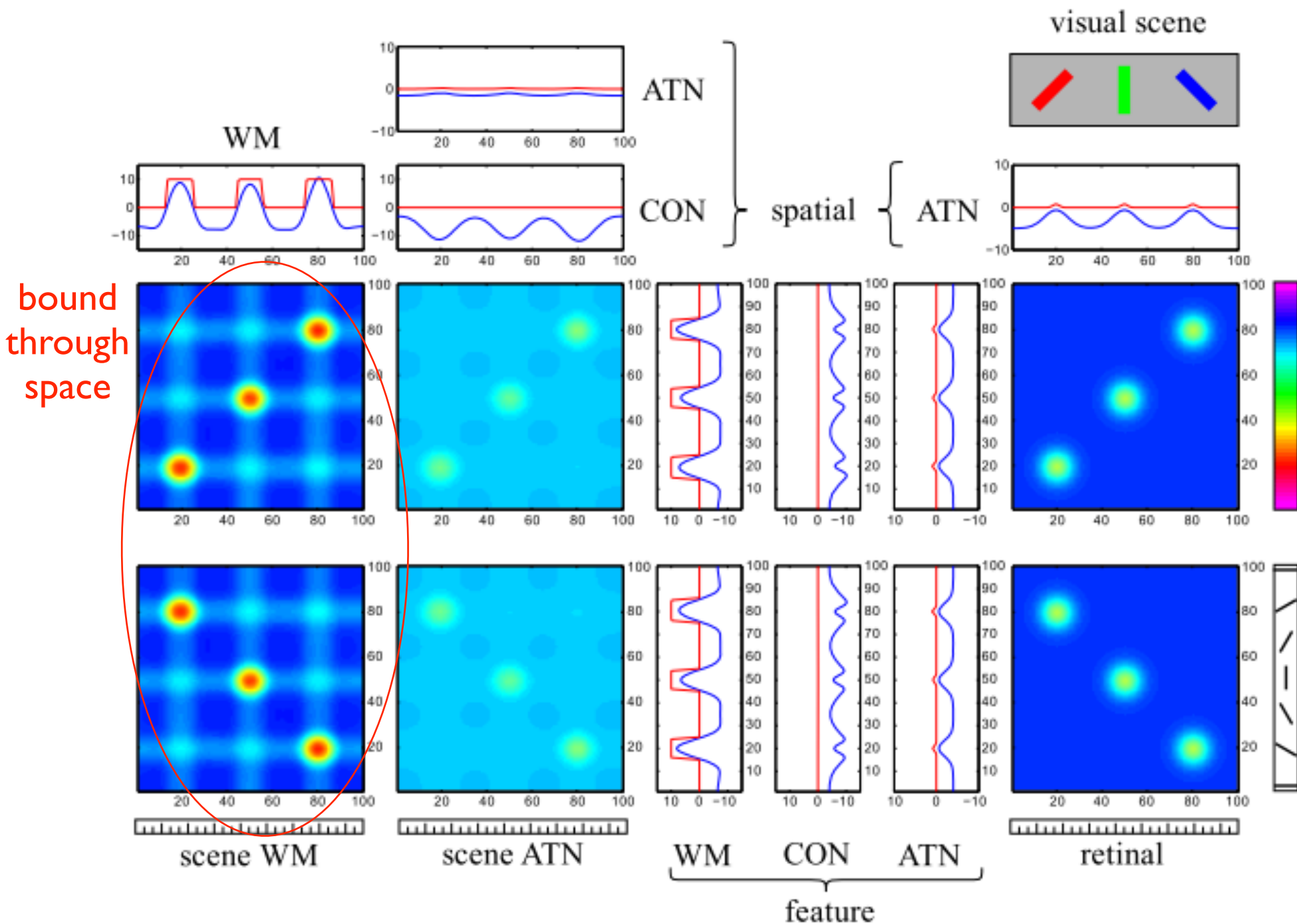
[Schneegans et al., Ch 5 of *DFT Primer*, 2016]

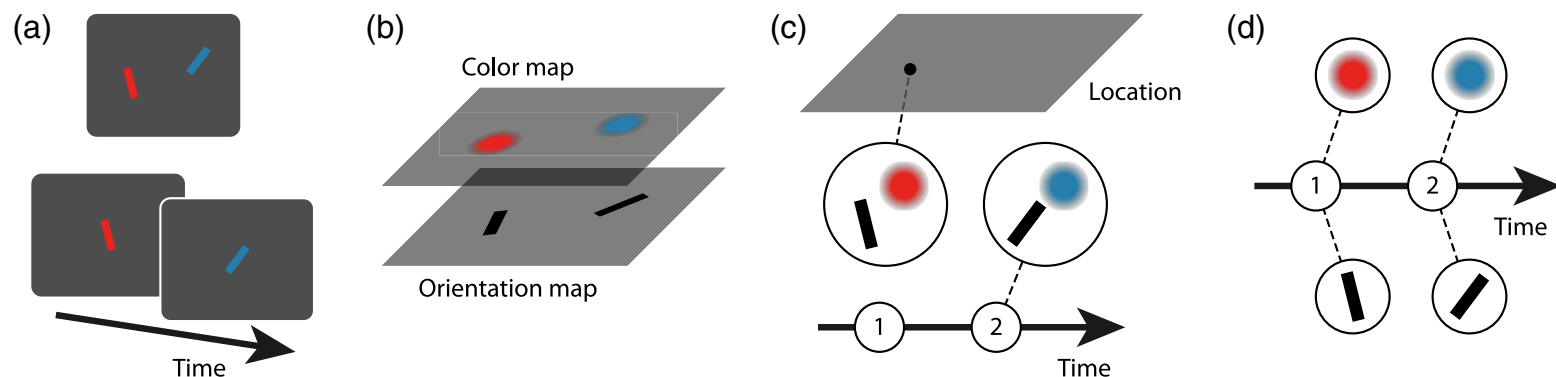# Binding through space => sequential bottleneck

- 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

🟥 feature dimensions presented/operated on at the same time (in a sequence) are bound in working memory
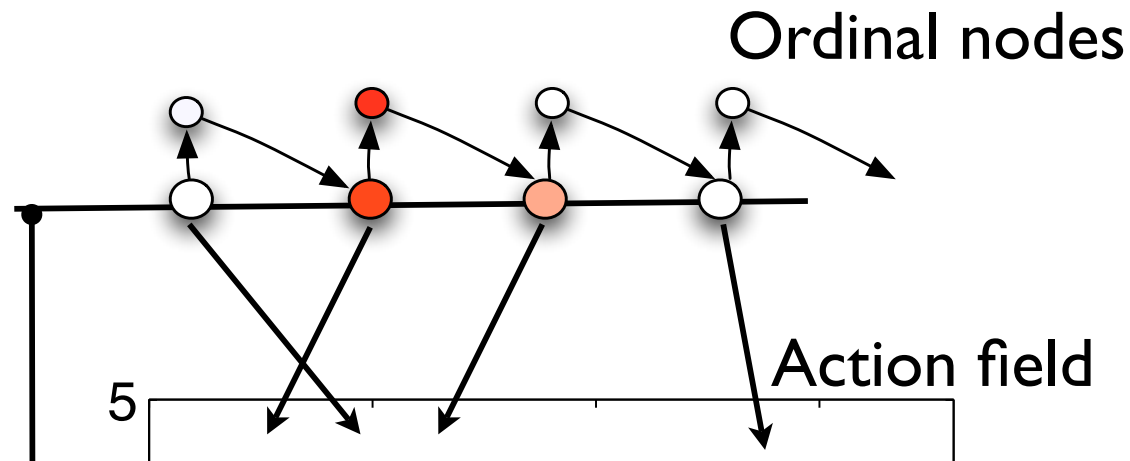

Conceptual Models of Feature Binding

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

Binding through ordinal position

🟥 ordinal position can be generated autonomously in DFT

Ordinal nodes

positi

Action field

5

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

Binding through ordinal position

object/object concept

using an ordinal position "index" to binds different concepts together
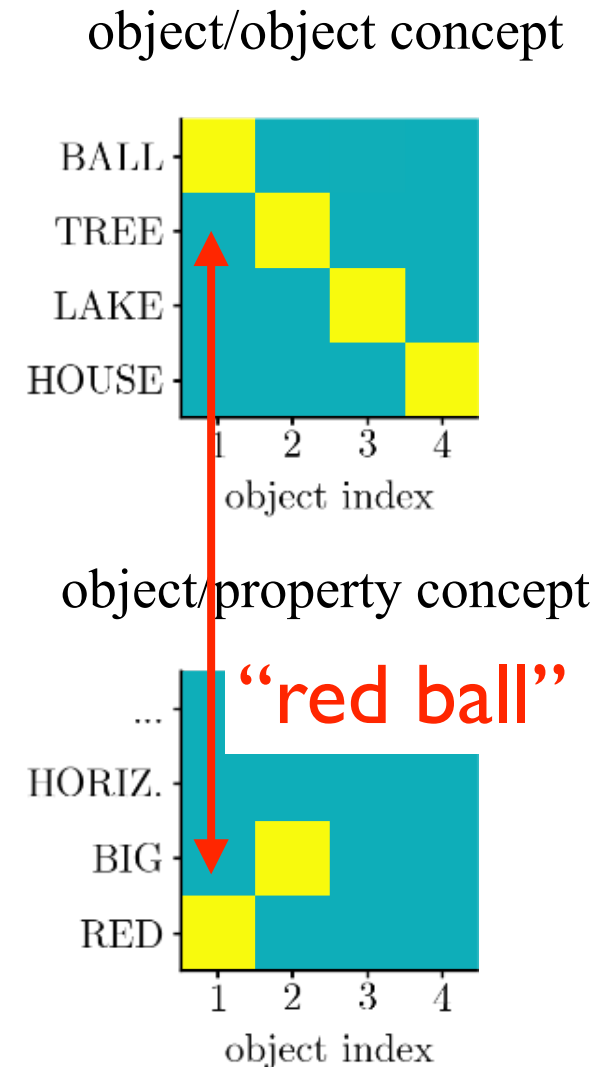
object/property concept

"red ball"

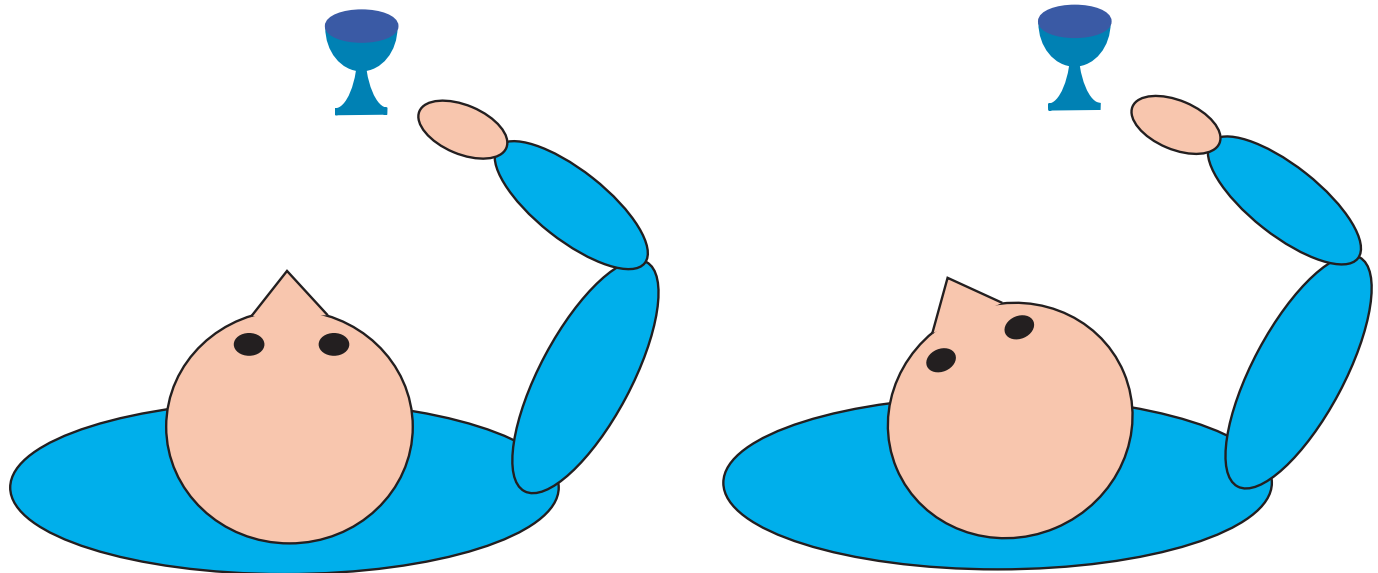[Sabinasz, Richter, Schöner, *Cog. Neurodyn.* 2023]

- Background: different notions of binding

- Joint representations and coupling patterns

- Binding through space/ordinal dimension

- Coordinate transforms

Coordinate transforms

- are fundamental element to sensory-motor cognition

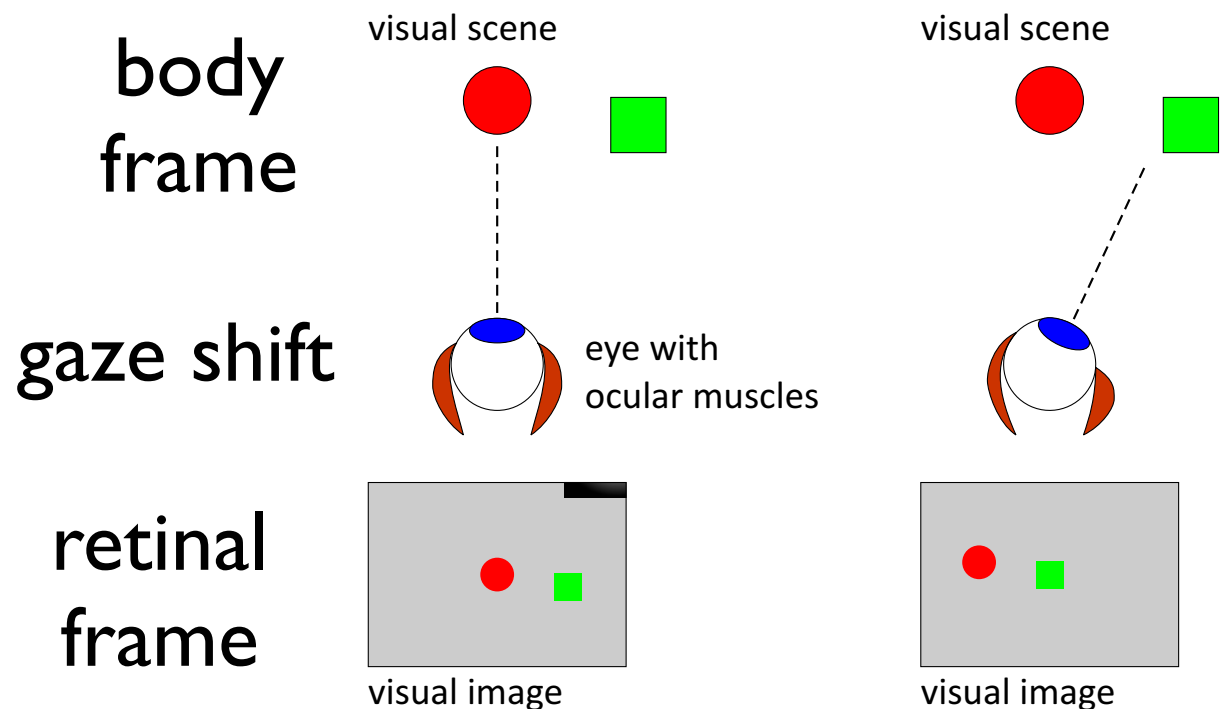- [but critical also to mental operations!]

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

body frame

gaze shift

retinal frame

visual scene

eye with ocular muscles

visual image

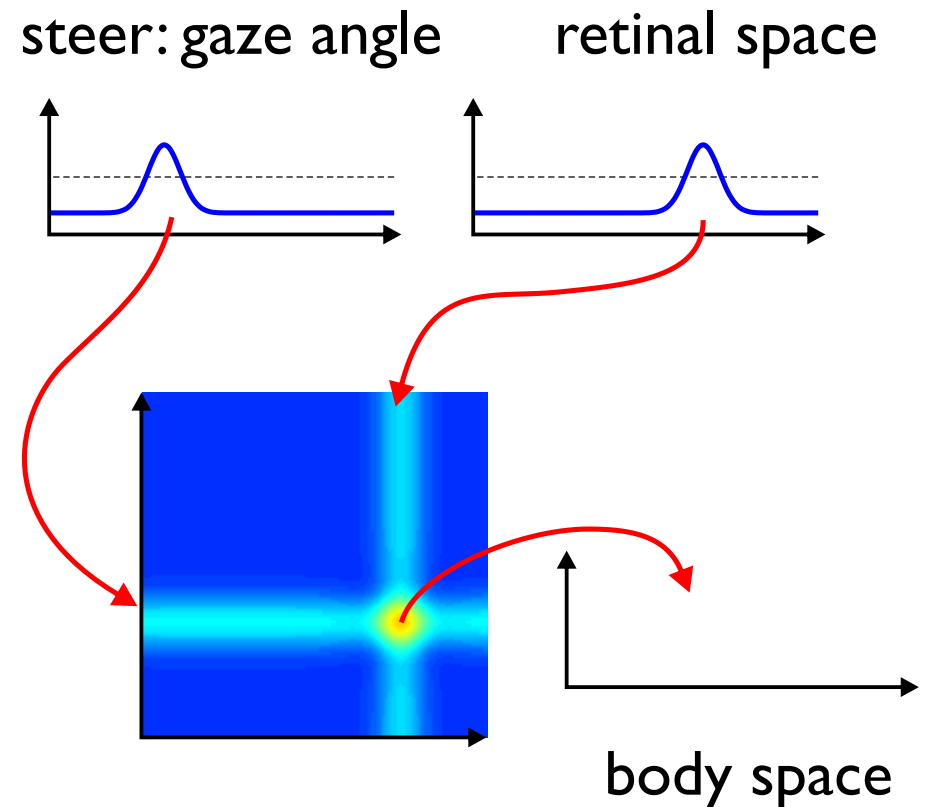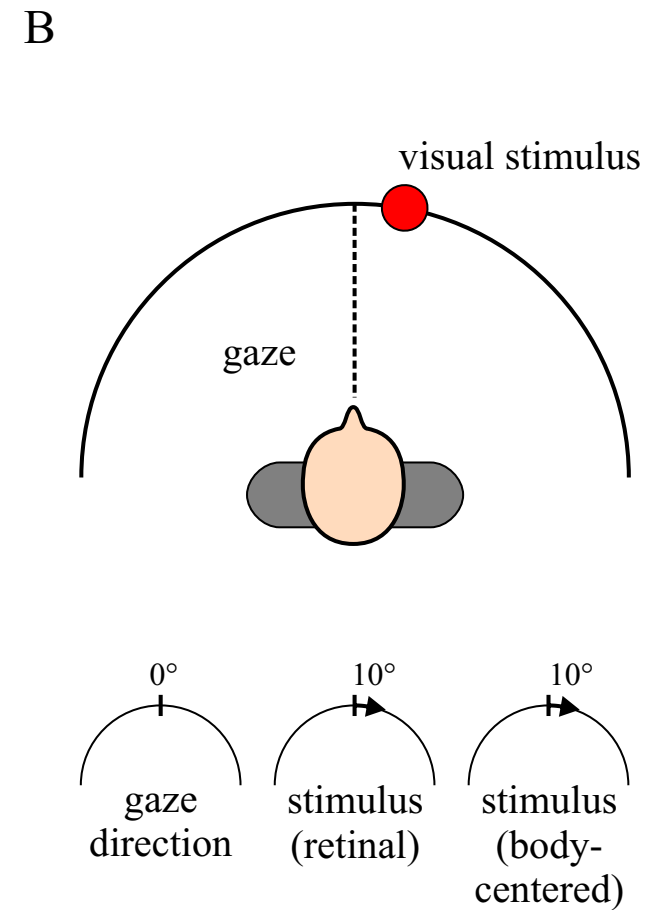visual scene

visual image

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
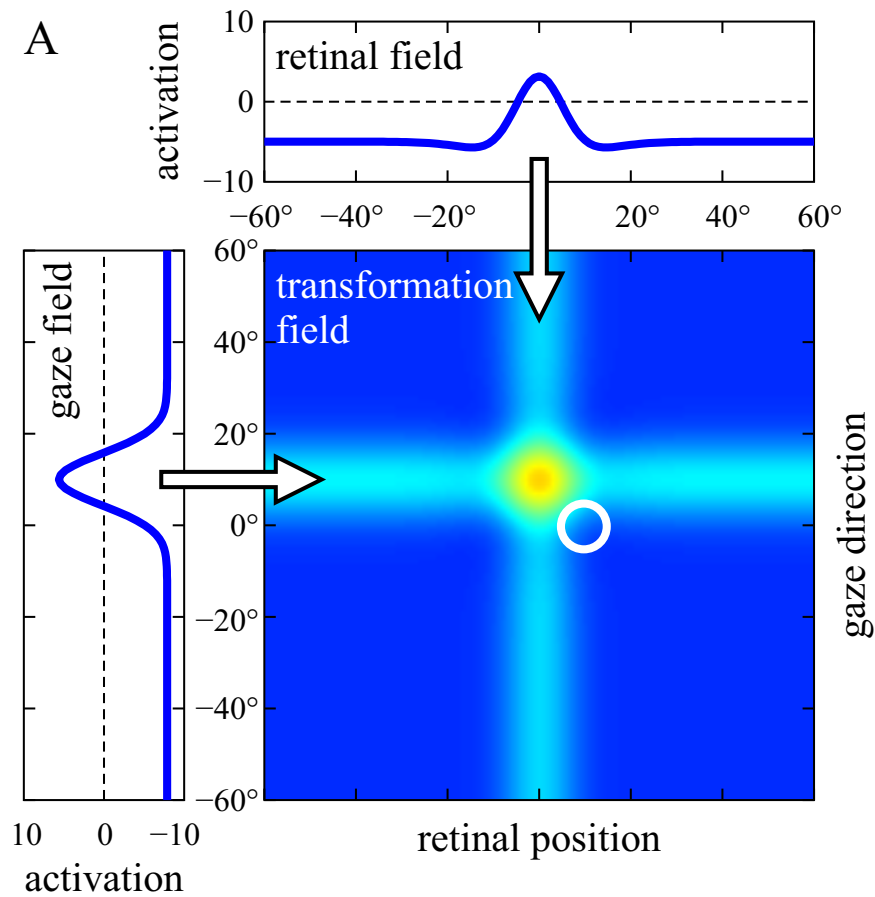
steer: gaze angle

retinal space

body space

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

Coordinate transform

A
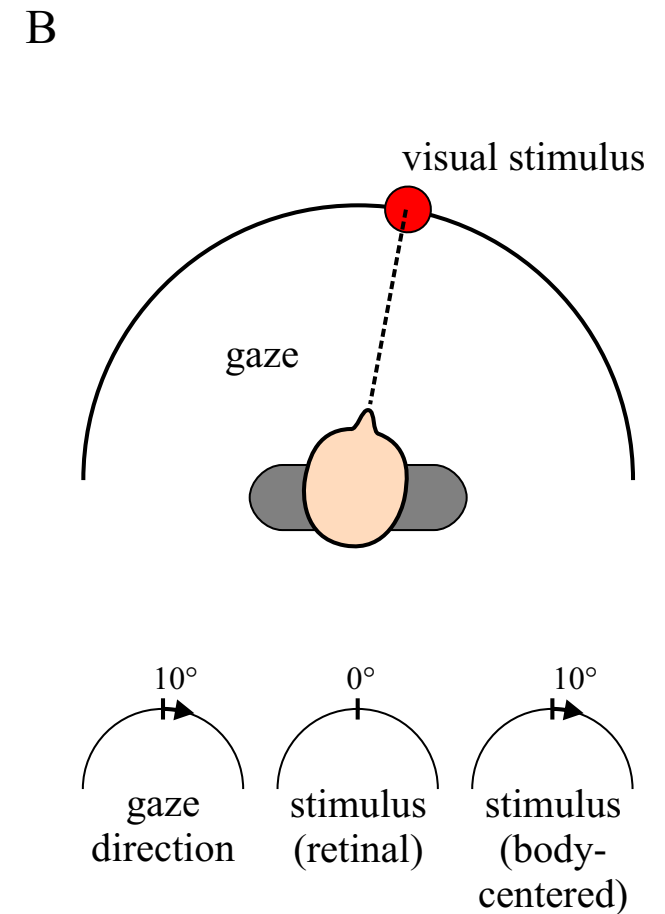
retinal field

activation

10
0
−10

−60° −40° −20° 0° 20° 40° 60°

gaze field

60°
40°
20°
−20°
−40°
−60°

transformation field

gaze direction

10   0   −10
activation

retinal position

B

visual stimulus

gaze

0°   10°   10°

gaze direction   stimulus (retinal)   stimulus (body-centered)

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

Coordinate transform

A

B

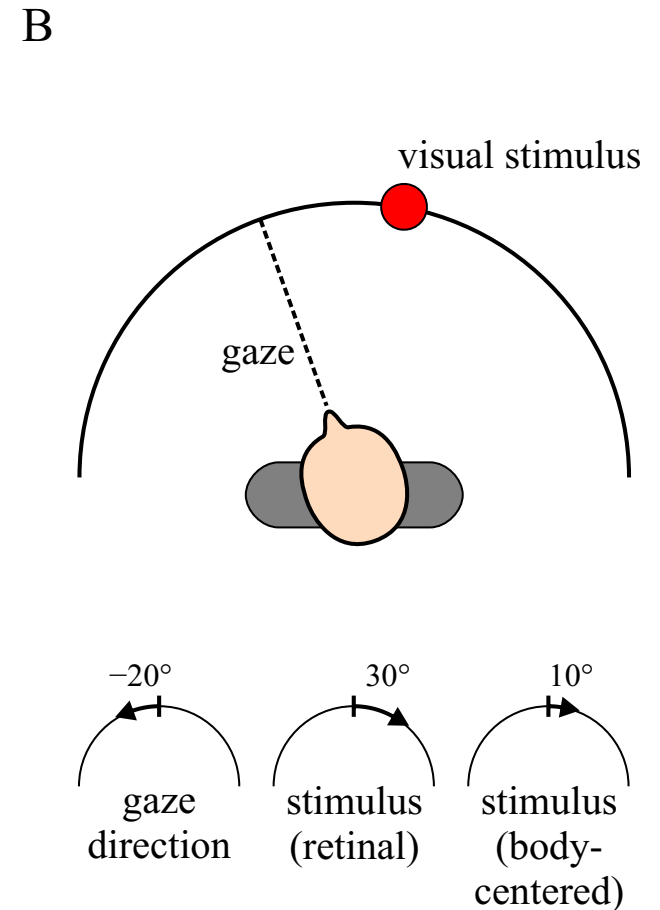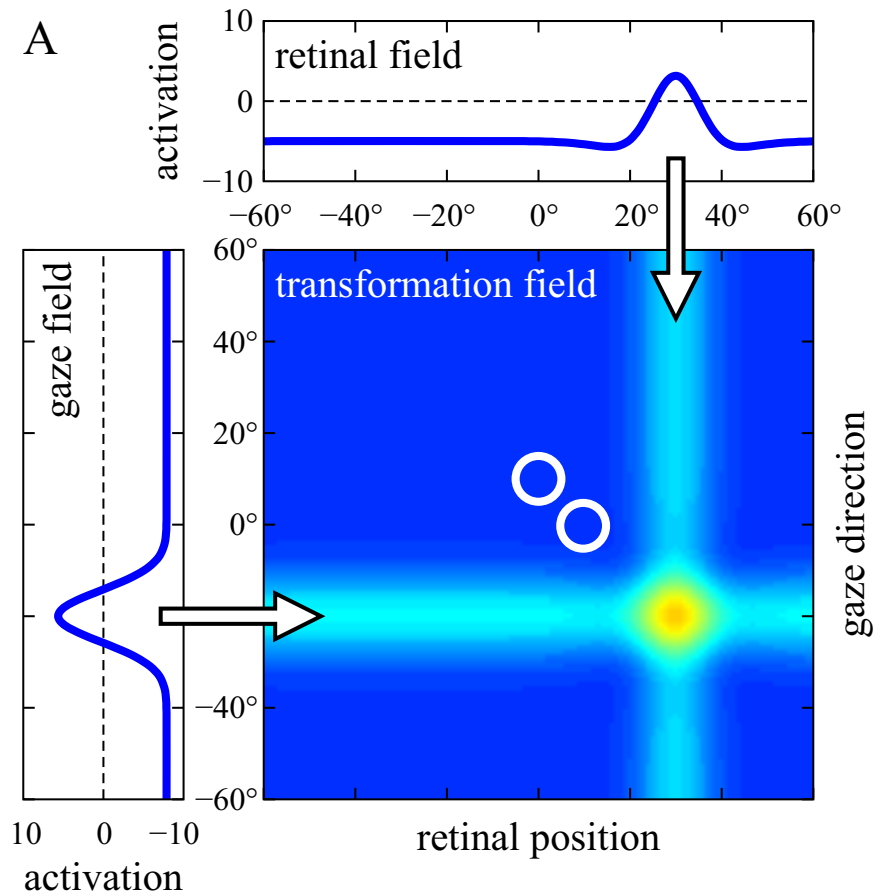[Schneegans Ch 7 of *DFT Primer*, 2016]

Coordinate transform

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

Coordinate transform

A

retinal field

activation

gaze field

transformation field

gaze direction

retinal position

activation

B

visual stimulus

gaze

−20°   gaze direction

30°   stimulus (retinal)

10°   stimulus (body-centered)
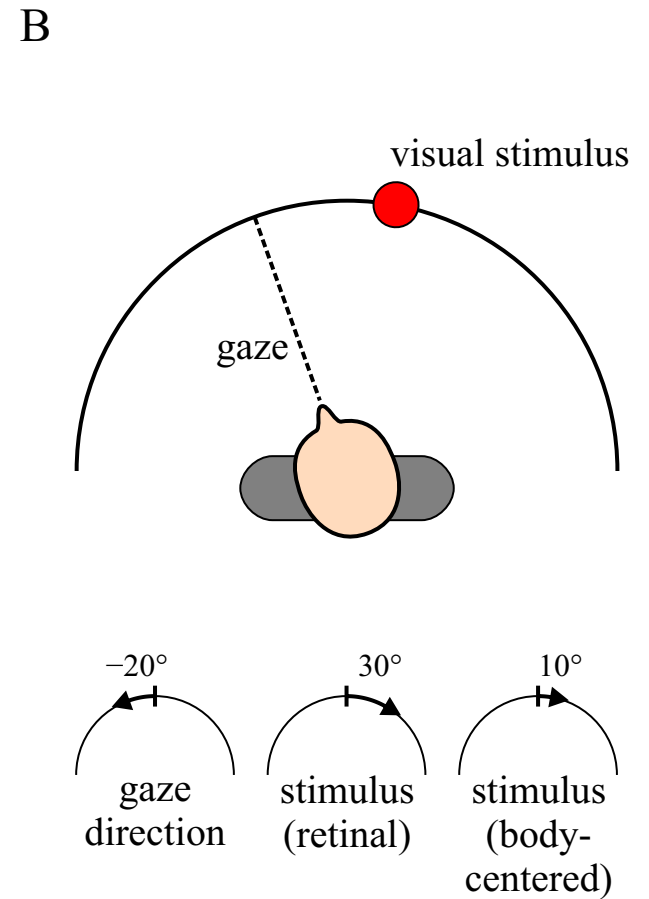
[Schneegans Ch 7 of *DFT Primer*, 2016]

Coordinate transform

A

retinal field

activation

−60° −40° −20° 0° 20° 40° 60°

gaze field

activation

10 0 −10

60°

40°

20°

0°

−40°

−60°

transformation field

retinal position

gaze direction

body-centered field

activation

10 0 −10

120°

80°

40°

0°

−40°

−80°

−120°

body-centered position

B

visual stimulus

gaze

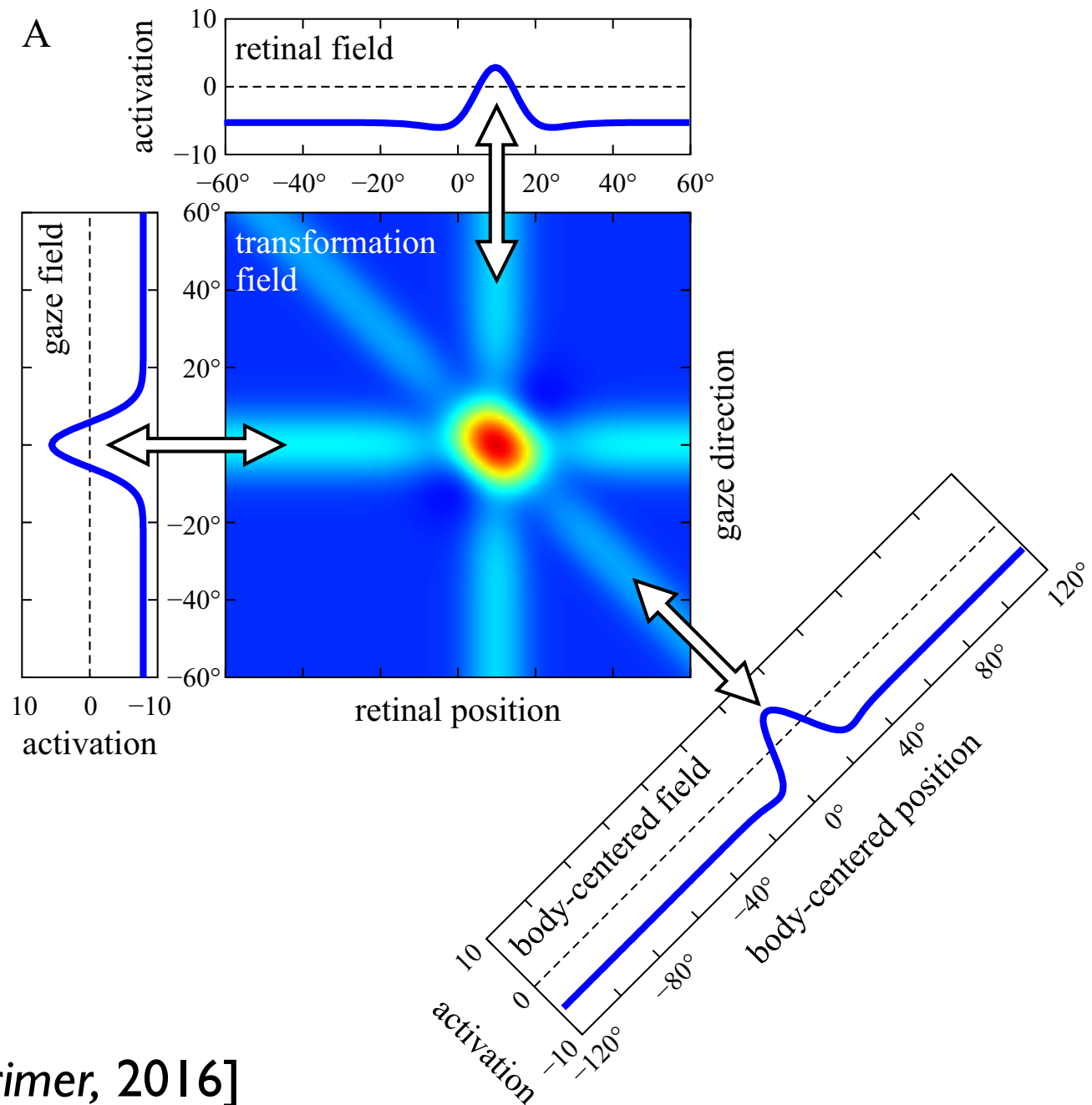−20°

gaze direction

30°

stimulus (retinal)

10°

stimulus (body-centered)
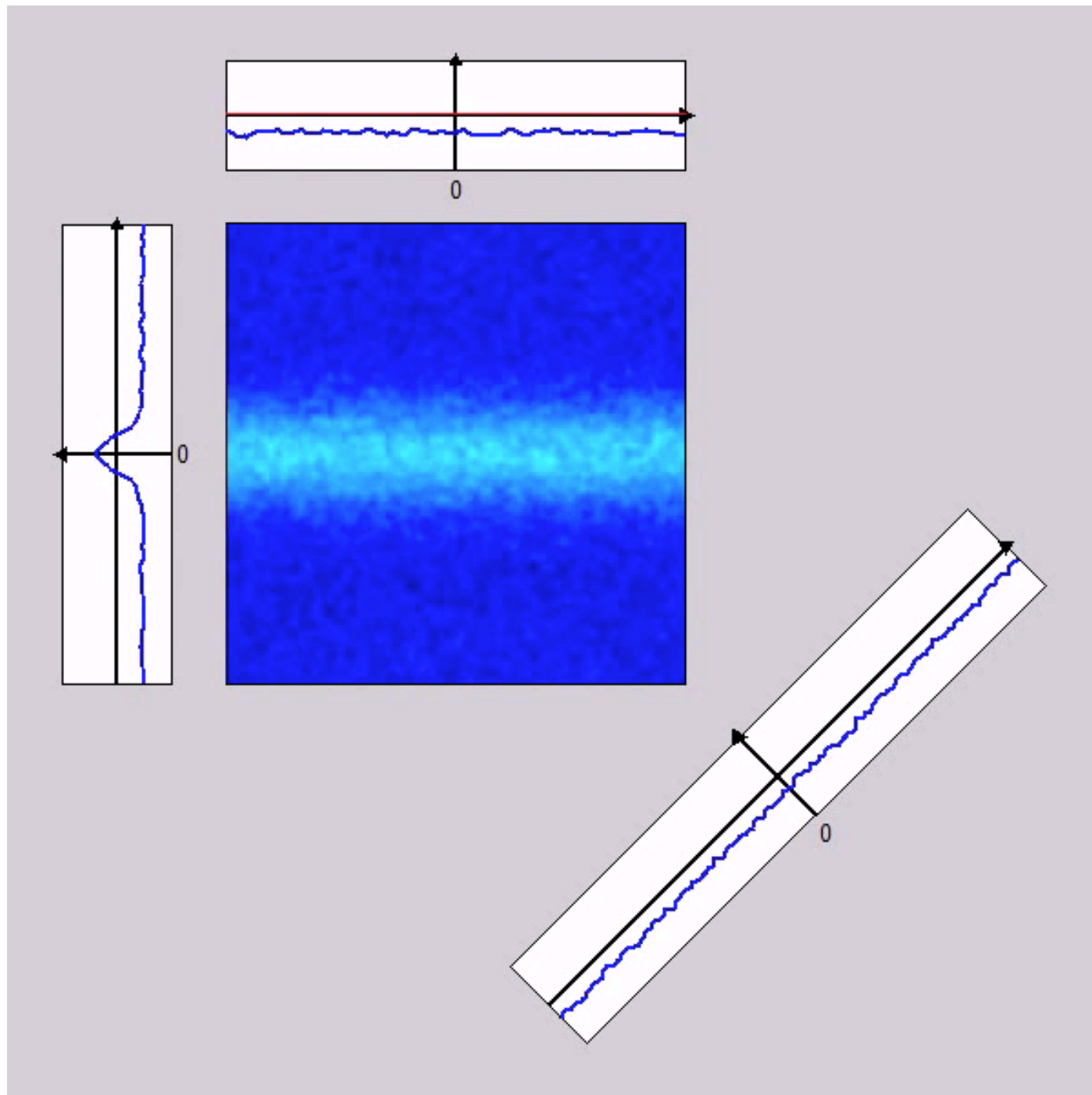
[Schneegans Ch 7 of *DFT Primer*, 2016]

Retina => body space

- bi-directional coupling

- => predict retinal coordinates

A

retinal field

activation

−60° −40° −20° 0° 20° 40° 60°

gaze field

transformation field

gaze direction

activation

retinal position

body-centered field

body-centered position

120° 80° 40° 0° −40° −80° −120°

activation

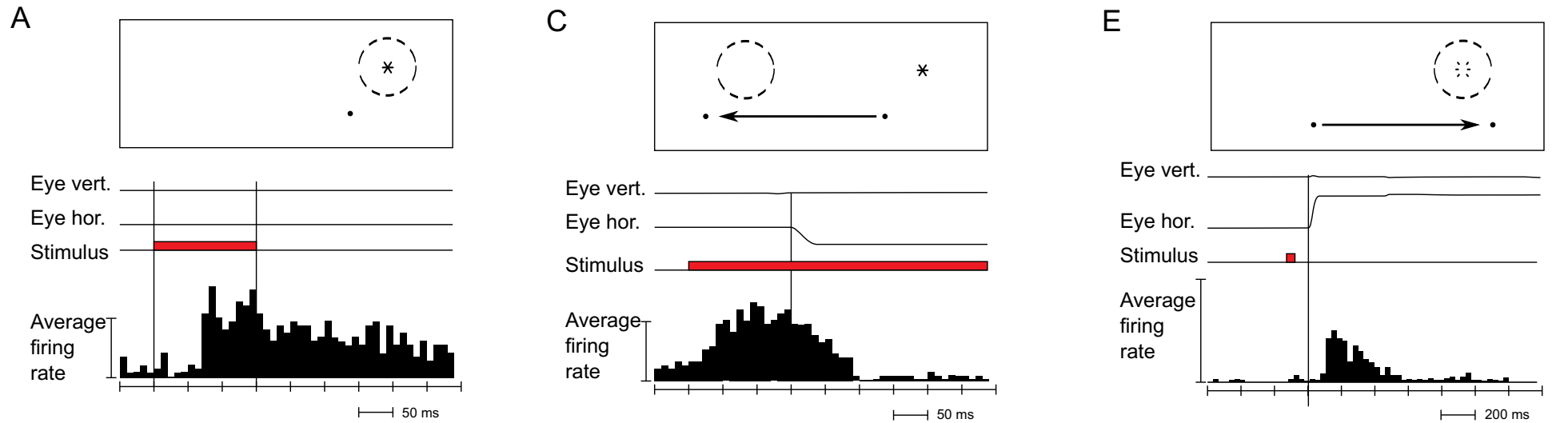[Schneegans Ch 7 of *DFT Primer*, 2016]
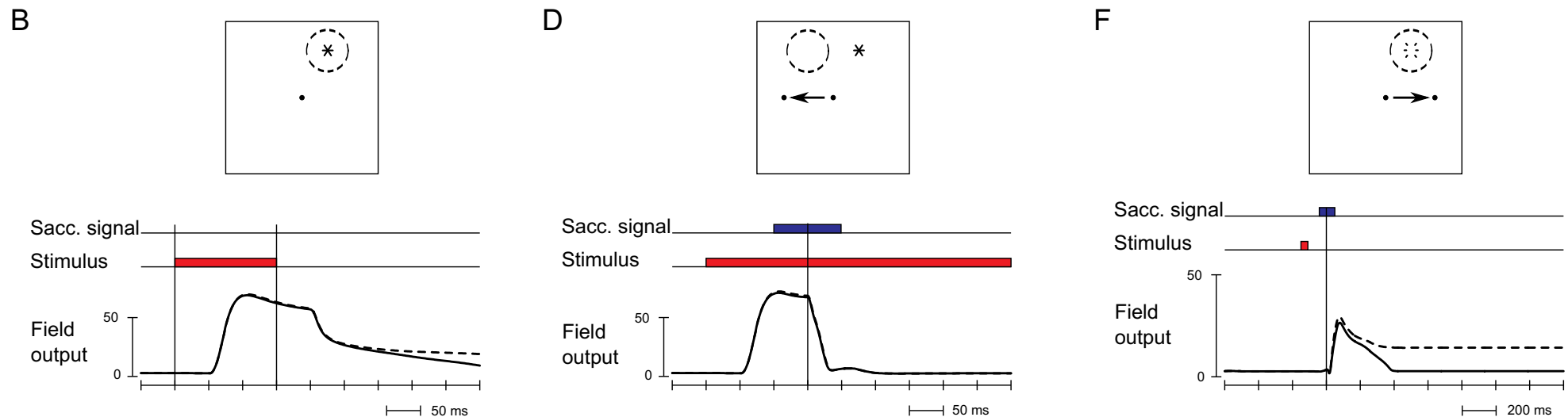
Spatial remapping during saccades

[Schneegans, Schöner *Biological Cybernetics* 2012]

Accounts for predictive updating

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

[model: Schneegans, Schöner *Biological Cybernetics* 2012]
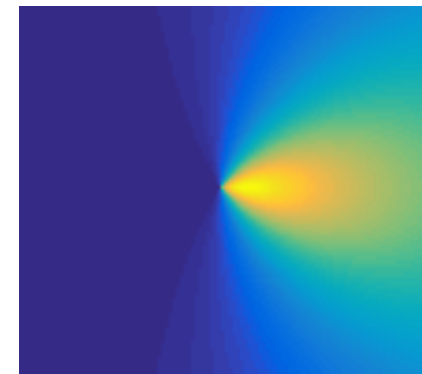
Coordinate transforms for cognition

"green to the right of red"

reference   target

- to perceptually ground relations/actions etc

- use relational concepts that have patterned coupling

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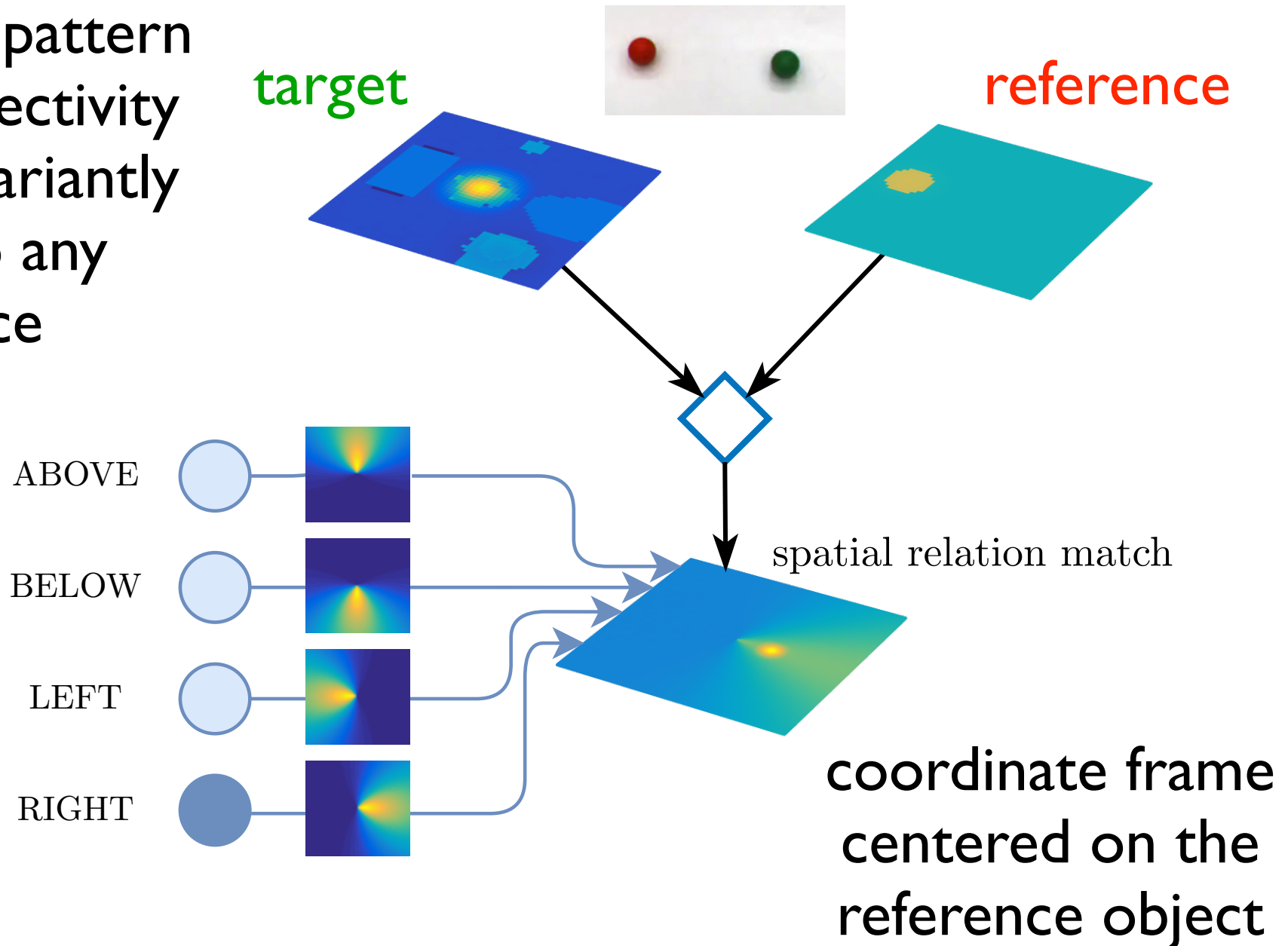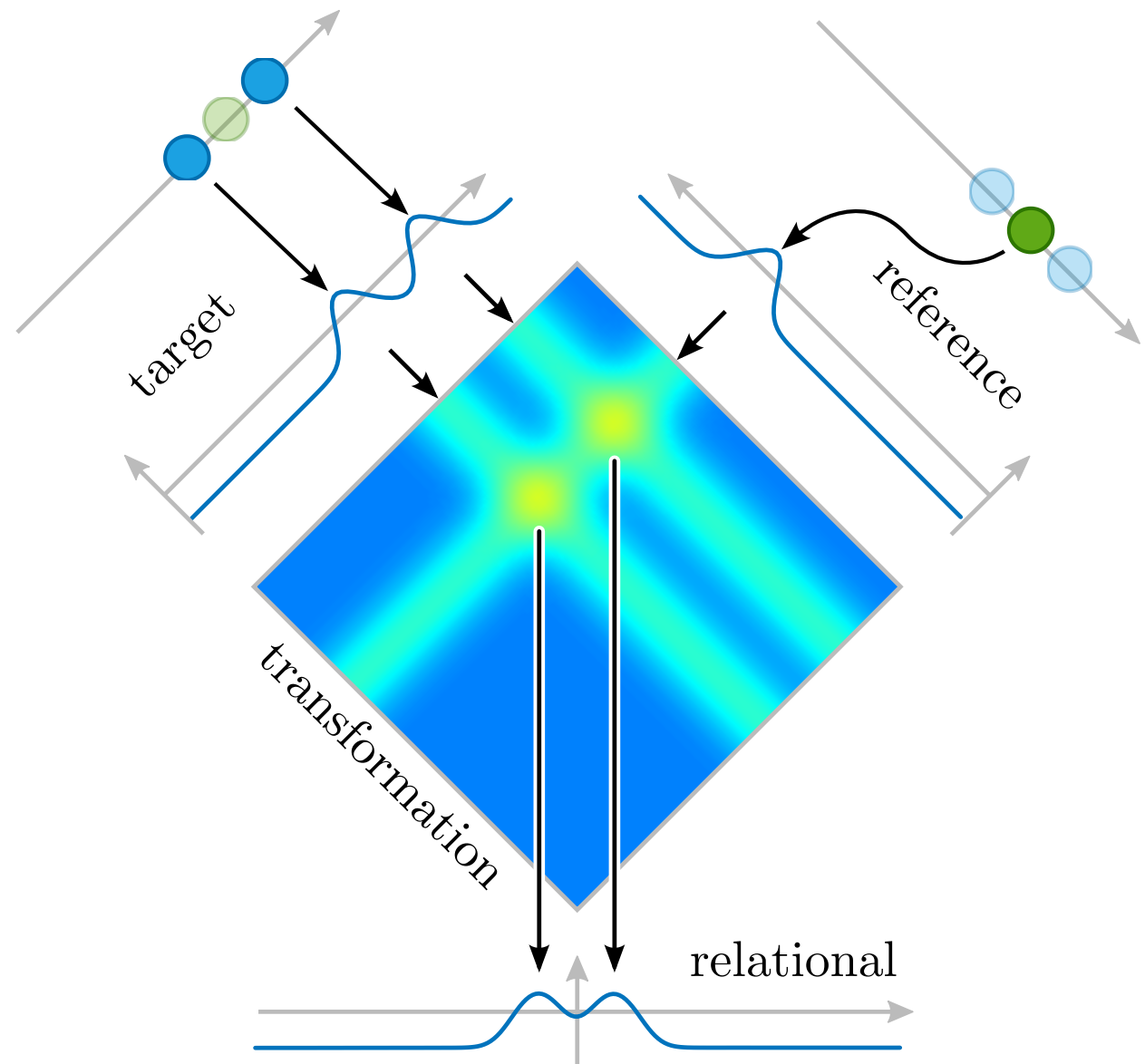*Cog Neurodyn* 2023]

Coordinate transforms for cognition

"green to the right of red"

target

reference

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

ABOVE

BELOW

LEFT

RIGHT

relation match

coordinate frame centered on the reference object

=>critical role of coordinate transforms for higher cognition
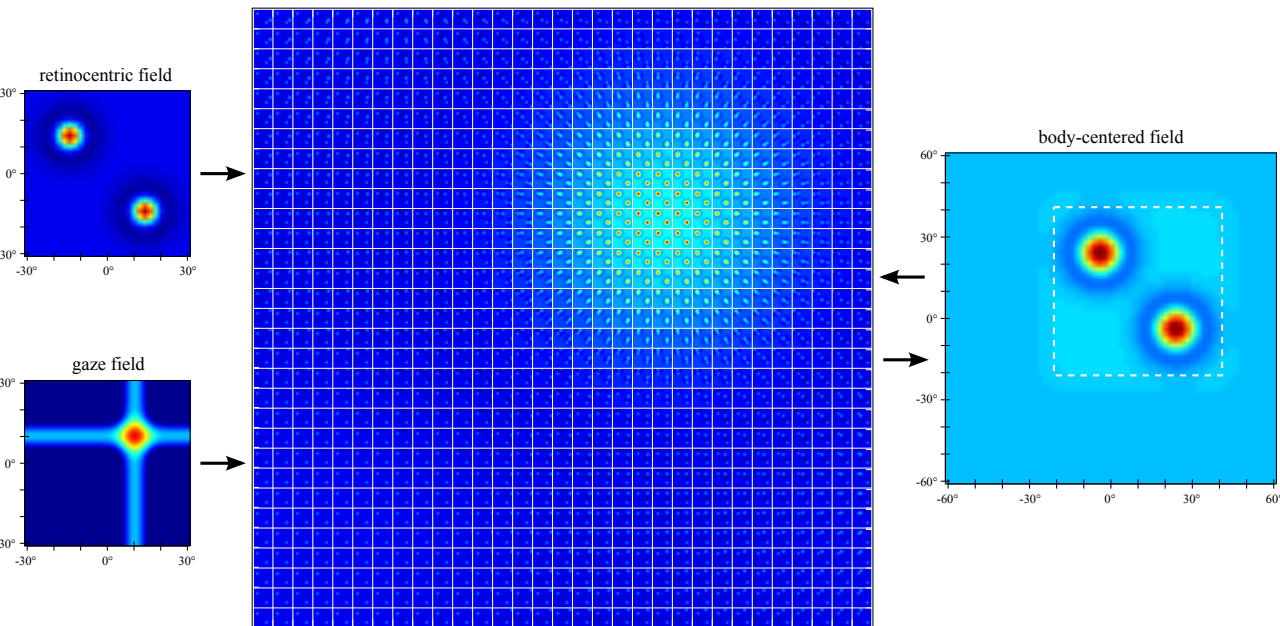

[Sabinasz, Richter, Schöner: *Cog Neurodyn* 2023]

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!

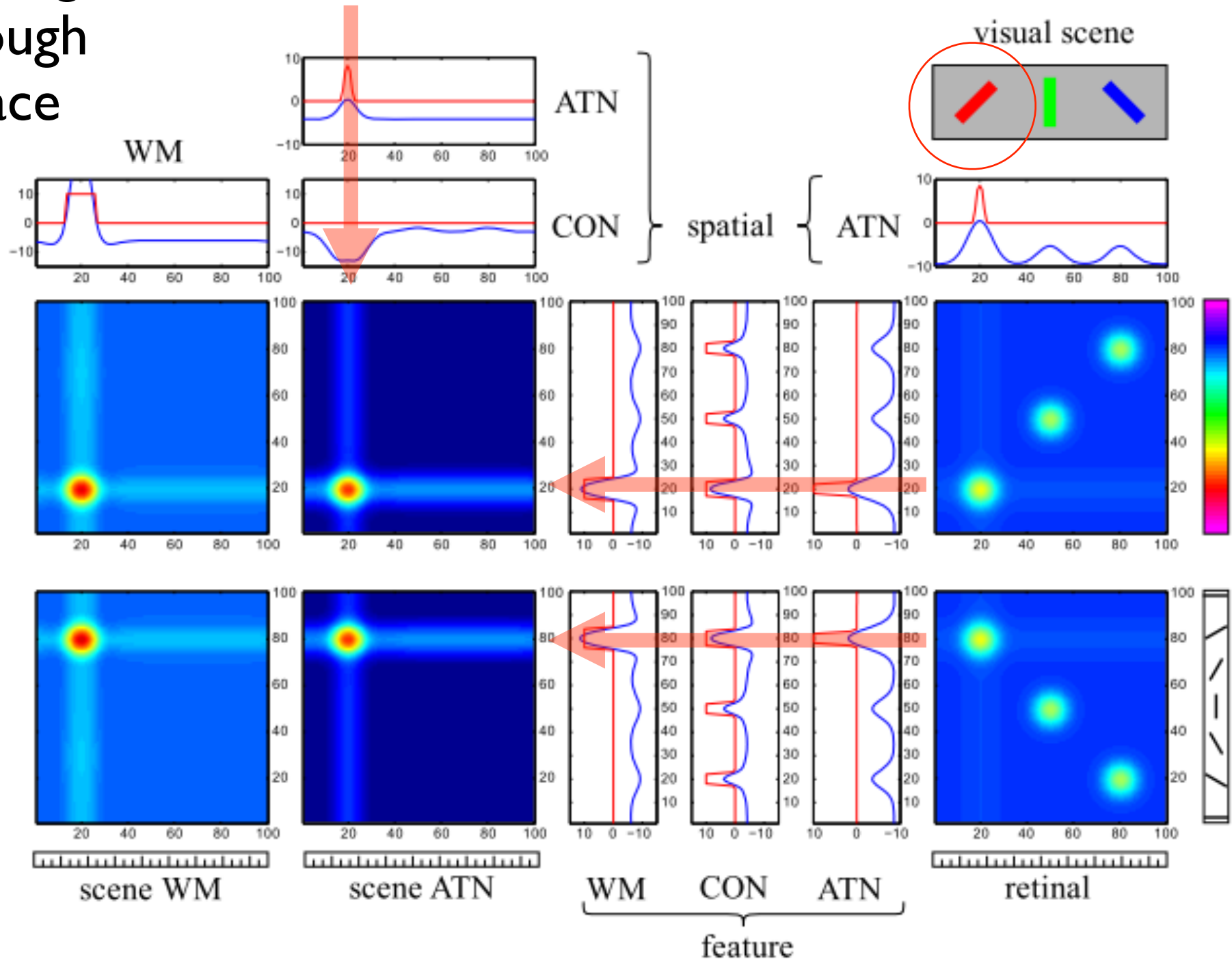[Schneegans, Schöner, 2012]

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

shared space

attend to this item

visual scene

WM

ATN

CON spatial ATN

scene WM scene ATN WM CON ATN retinal

feature

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

binding through space

WM

ATN

CON — spatial — ATN

visual scene

scene WM   scene ATN   WM   CON   ATN   retinal

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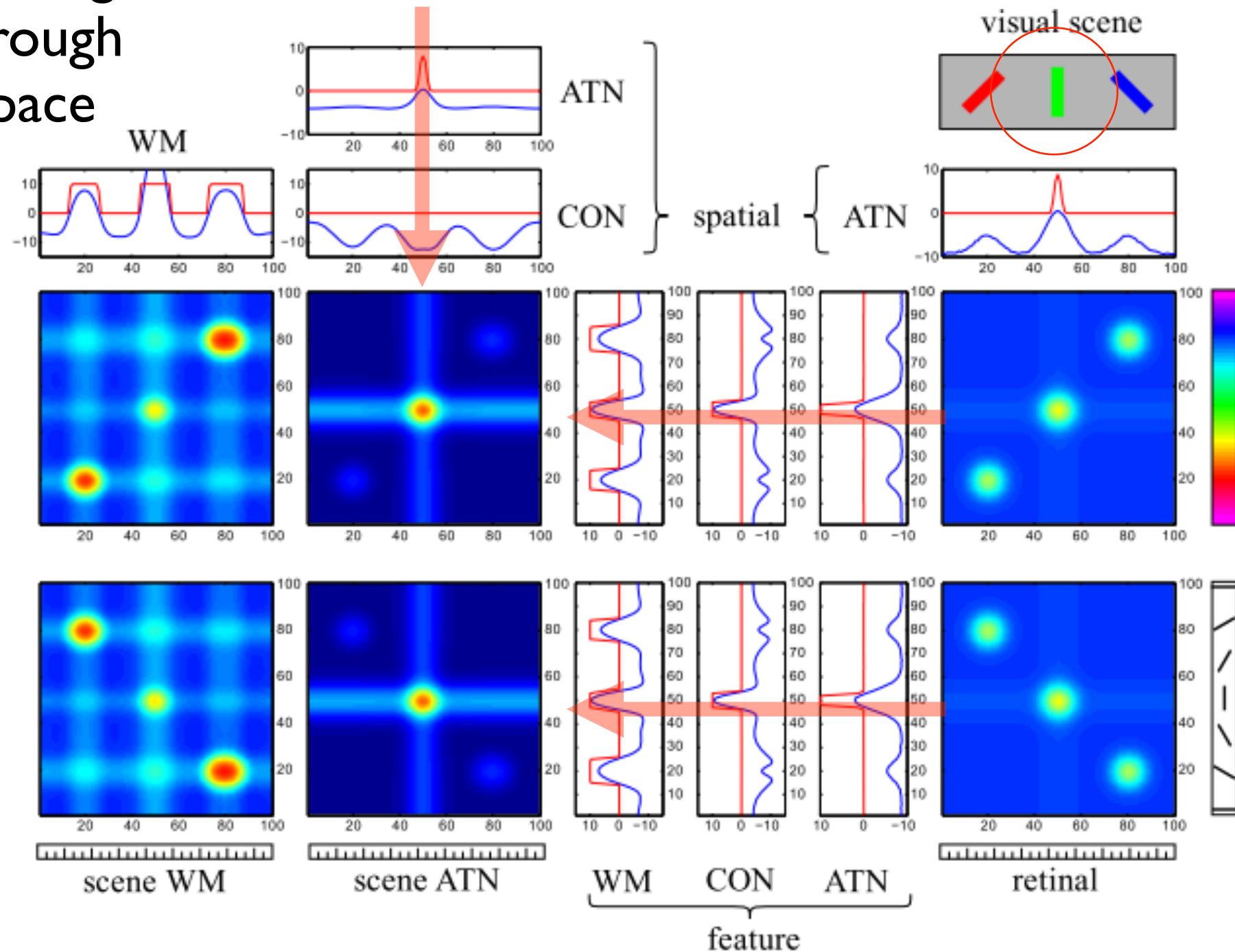
[Schneegans et al., Ch 5 of *DFT Primer*, 2016]

binding through space

bound through space

WM

visual scene

ATN

CON — spatial — ATN

scene WM

scene ATN

WM   CON   ATN

retinal

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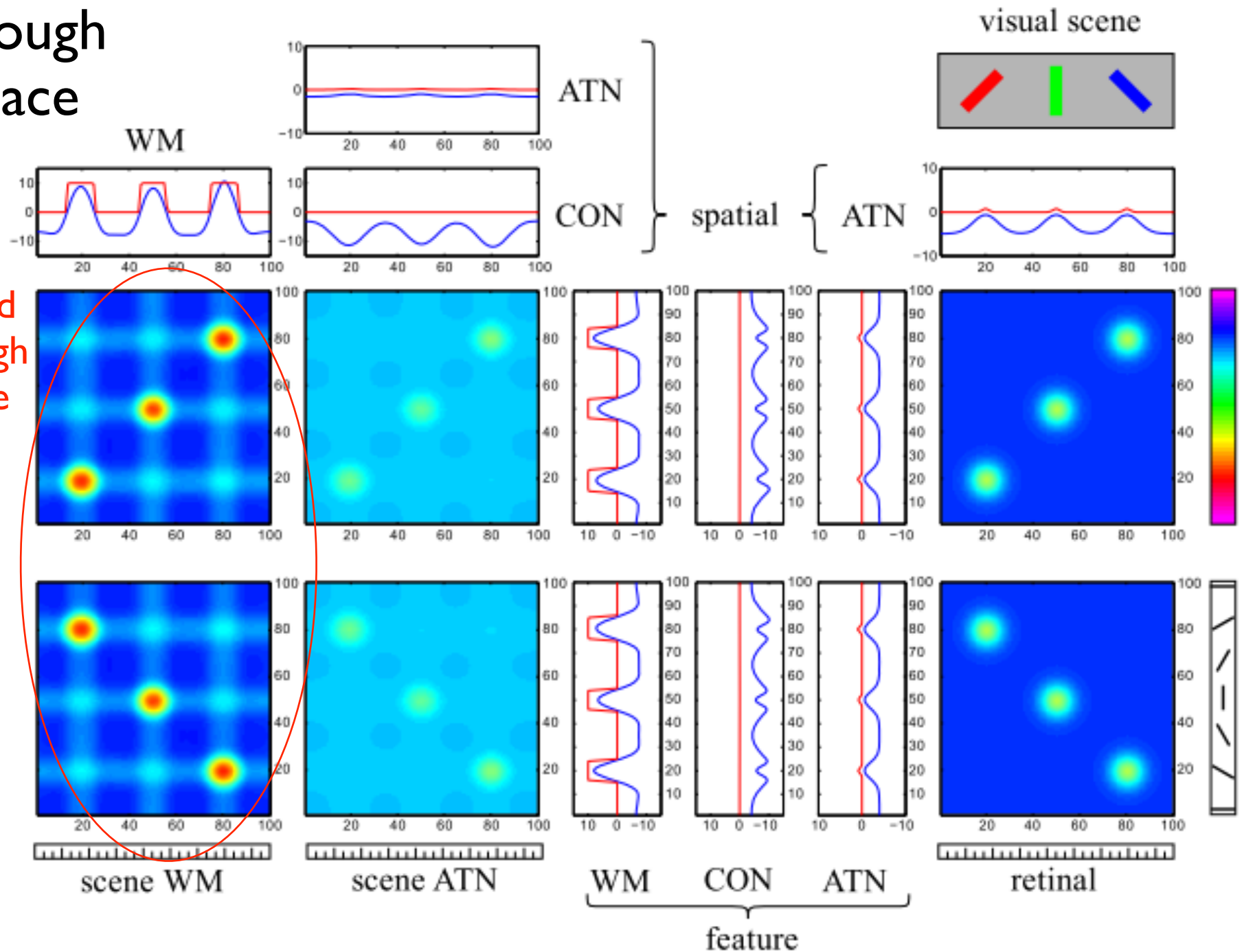
[Schneegans et al., Ch 5 of *DFT Primer*, 2016]

that space contains the coordinate transform!

allocentric space
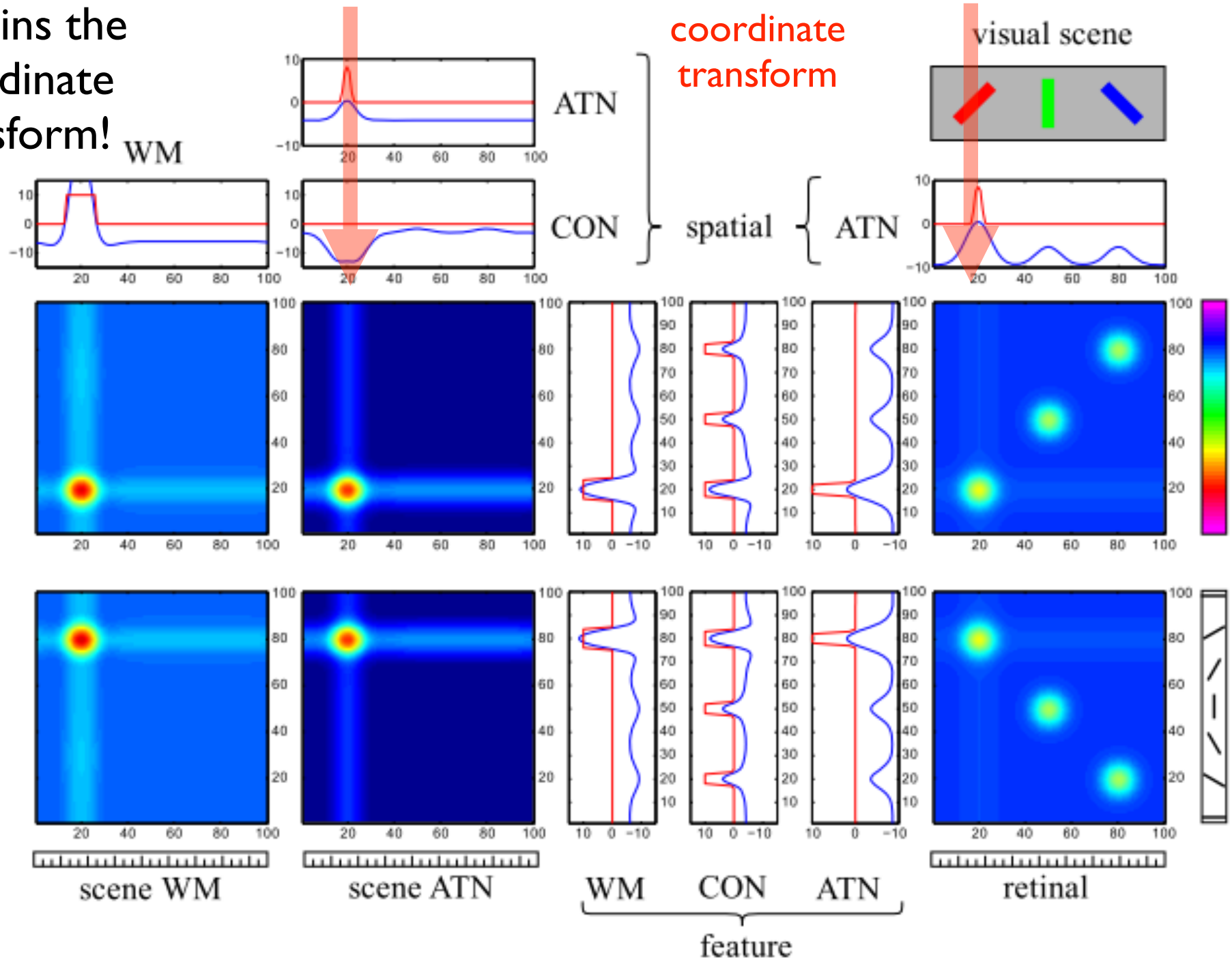
coordinate transform

retinal space

visual scene

WM

ATN

CON

spatial

ATN

scene WM

scene ATN

WM   CON   ATN

retinal

feature

[Schneegans et al., Ch 8 of *DFT Primer*, 2016]
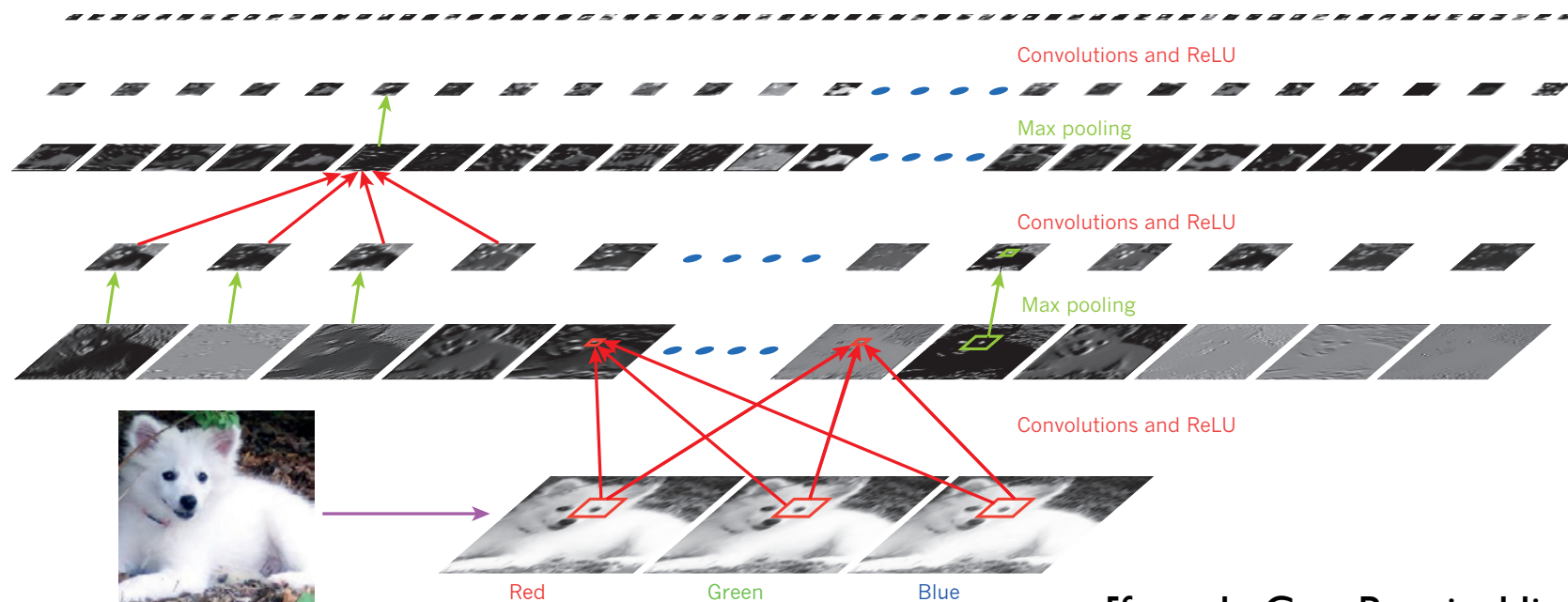
- Background: different notions of binding

- Joint representations and coupling patterns

- Binding through space/ordinal dimension

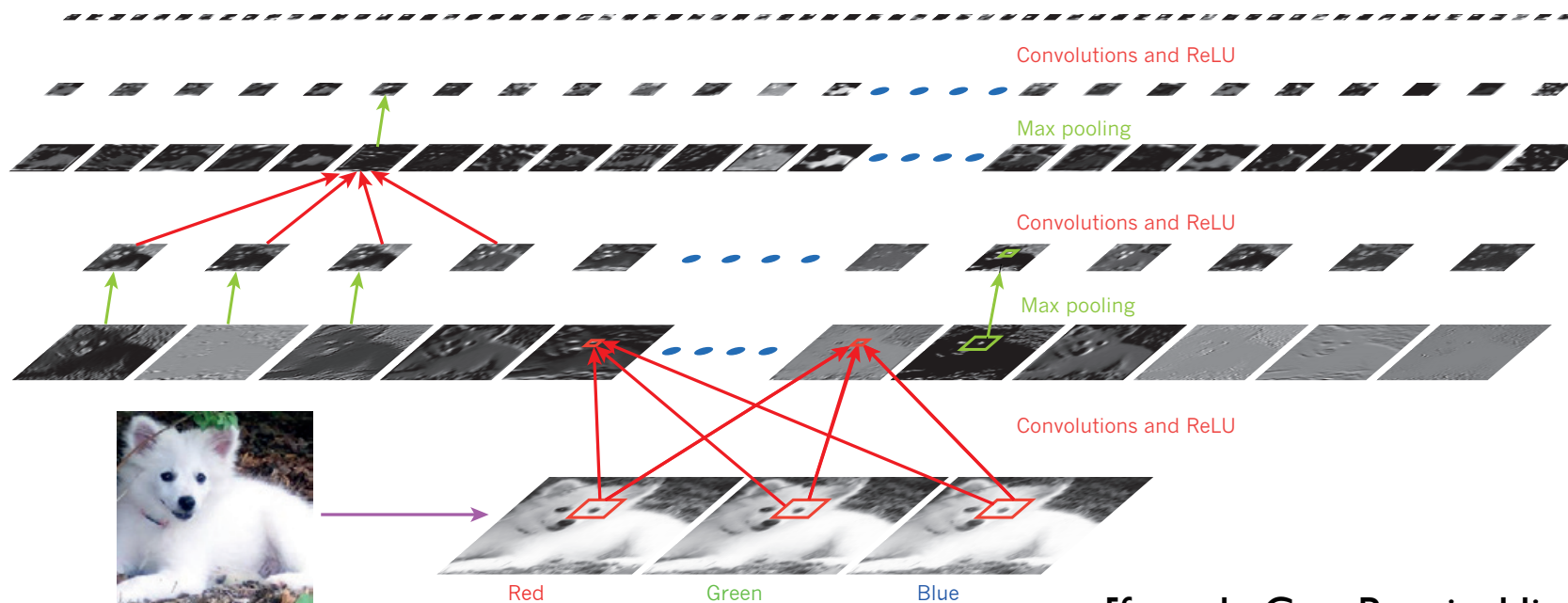- Coordinate transforms

Is there a binding problem for DNN?

🟥 complex learned features are represented jointly distributed across a DNN…. hidden layers

🟥 … old debate Poggio.von der Malsburg.. [*Neuron* 99]

Convolutions and ReLU

Max pooling

Convolutions and ReLU

Max pooling

Convolutions and ReLU

Red   Green   Blue

[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…

Convolutions and ReLU

Max pooling

Convolutions and ReLU

Max pooling

Convolutions and ReLU

Red   Green   Blue

[from LeCun, Bengio, Hinton, Nature 2015]

Is there a binding problem for DNN?

🟥 binding by joint representation is not flexible!

view-tuned cells

"complex composite" cells (C2)

"composite feature" cells (S2)

complex cells (C1)

simple cells (S1)

— weighted sum
— MAX

[Poggio, 1999]