Higher-dimensional dynamics fields enable new cognitive function

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Core of DFT

- Field dynamics combines input
- With strong interaction:
  - Local excitation
  - Global inhibition
- Leading to stable peaks
- Instabilities:
  - Detection
  - Selection
  - Memory

Local excitation: stabilizes peaks against decay
Global inhibition: stabilizes peaks against diffusion
Dimensionality of fields

- all this was done primarily in fields defined over a single dimension…

- multi-dimensional fields are not per se fundamentally different….  

- in particular, they have the same kind of dynamics as one-dimensional fields
example: retinal space

- obviously two-dimensional

30 - 40 ms  40 - 50 ms  50 - 60 ms  60 - 70 ms  70 - 80 ms

[Jancke et al., 1999]
example: visual feature map

- orientation-retinal location

[Jancke, JNeursci (2000)]
example: visual feature maps

- the neural field representation a single feature (e.g. orientation) as well as retinal location is at least three-dimensional

- cannot be mapped onto cortical surfaces without cuts ...
Dynamic fields of varying dimensionality

- 0-dimensional: nodes, “on” vs “off” states
- 1, 2, 3, 4… dimensions: peak/blob states

![Graphs representing 0-dimensional, 1-dimensional, and 2-dimensional fields]

3-dimensional

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Visual cognition always entails attentional selection decisions. Figure 7 highlights the sub-system of the neural dynamic architecture that generates such selection decisions.

Central is the scene spatial selection field that represents the localization of spatial attention. It receives multi-peak input from the salience field and singles out the most salient location by being in the dynamic regime of selection, in which a single supra-threshold peak may be stable at any moment in time. The selection decision is biased toward previously unattended positions by additional input from the inhibition of return memory trace, which reflects the recent history of activation of the scene spatial selection field. The self-sustained spatial working memory field reinforces this effect, but its representation...
New cognitive functions emerge as dimensionality is varied
a joint representation of space and color

[Binding]

[Schneegans et al., Ch 5 of DFT Primer, 2016]
Extract bound features

- by projecting to lower-dimensional fields
- summing along the marginalized dimensions
- (or by taking the softmax)

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

- projecting into higher-dimensional field by "ridge input"

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

Ridge Intersections

−30° −20° −10° 0° 10° 20° 30°

0 10 0 −10

activation

360
270
180
90
0

color (hue value)

color field

visual scene

space-color field

spatial field

spatial location

[Schneegans et al., Ch 5 of DFT Primer, 2016]
Assembling bound representations

- binding problem: multiple ridges lead to a correspondence problem
- => assemble one object at a time... sequentiality bottle-neck!

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

- combine 1D (ridge) input with 2D input..
- so that only those 2D locations can form peaks that overlap with ridge (boost driven detection)
- activates objects consistent with 1D feature value

[Slides adapted from Sebastian Schneegans, see Schneegans, Lins, Spencer, Chapter 5 of Dynamic Field Theory-A Primer, OUP, 2015]
the selection from visual search can be propagated to the 1D feature representations…

[Slides adapted from Sebastian Schneegans, see Schneegans, Lins, Spencer, Chapter 5 of Dynamic Field Theory-A Primer, OUP, 2015]
in conventional connectionist networks associative relationships are learned by adjusting synapses between those color and space neurons that have been co-activated
connections must be learned, so does not account for how “where is the red square” works from current stimulation (seen for the first time ever)
learning multiple associations poses a binding problem:

connectionist associators learn one item at a time and need separate presentation of individual items!

the network may associate blue with left and red with right.
Binding by joint representations

- a “neuro-anatomical” form of binding
- => very costly

[Schneegans et al., Ch 5 of DFT Primer, 2016]
Binding by joint representations

- example: bind orientation, color, texture, scale, and 2D visual space => 6-dimensional field
- 100 neurons per dimension => $10^{12}$ neurons ~ the entire brain!
Binding through space

- separate 3 to 4 dimensional feature fields
- all of which share the dimension visual space (≈all neurons have receptive fields)
- bind through space à la Feature Integration Theory (Treisman)

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

bind through space à la Feature Integration Theory (Treisman) 

[Grieben et al. Attention, Perception & Psychophysics 2020]
At the start of each trial, a cue item is presented (not shown) and the color memory field is boosted concurrently. This causes a peak to build there, which is retained throughout the trial and reflects the target color. The projection to the color attention field activates the respective value there, which in turn biases activation in the space-color field.

Next, the test display with multiple items is presented. Each of the items is represented by one peak in each visual sensory field. The activation ridge from the color attention field enhances the space-color peak of the target item (the green S), causing this peak to determine peak position in the spatial attention field. The spatial attention peak projects back into both visual sensory fields, enhancing the space-shape peak at that location (and less so the peaks of close-by items).

Brief boosts to the shape memory field and the spatial read-out field force these fields to form peaks, which correspond to the shape and spatial response of the model, respectively. In most cases, the correct shape and location are chosen, as shown here. In some cases, the feature-space peak of a distractor item spatially close to the target item (here, the space-shape peak of the yellow O) is overly enhanced by the ridge from the spatial attention field. In this case, the erroneously enhanced peak may prevail in determining peak position in the shape attention field and, thus, the shape response, resulting in an illusory conjunction. Illusory conjunctions are also associated with a shift of peak position in the spatial attention field, which is why the location response is as well displaced toward the spatial midpoint between the involved items.
shared space

attend to this item

visual scene

WM

CON

ATN

spatial

[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*]
Coordinate transforms

fundamental element of sensori-motor, but also of mental operations!
eye movement: from retinal to body-centered representation (e.g. for reaching)

Coordinate transforms

visual scene

visual scene

eye with ocular muscles

visual image

visual image

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

- eye movement: from retinal to body-centered representation (e.g. for reaching)
Coordinate transforms

- Hand movement: from body-centered to hand-centered representation

Movement preparation: movement is prepared before it is initiated; movement parameters like movement direction, amplitude, time, or force level can be predicted from the first 10 to 20 ms of movement.

Movement parameters are about the hand's movement in space.

[Erlhagen, Schöner, Psych Rev 2002]
Coordinate transforms

- relational concepts: from visual space to frame centered in reference object

- e.g. “vertical object to the left of horizontal object”
Coordinate transforms

- a mapping between two reference frame: e.g. retinocentric (moving with the eye) to body-centered (gaze-invariant)
- mapping = shift operation with amount of shift depending on current gaze direction
- \( x_{\text{body}} = f(x_{\text{retinal}}, x_{\text{gaze}}) \approx x_{\text{retinal}} + x_{\text{gaze}} \)
- but how to implement such functions neurally?

[Slides adapted from Sebastian Schneegans, see Schneegans, Chapter 7 of Dynamic Field Theory-A Primer, OUP, 2015]
Coordinate transforms

- **fixed mapping**: neural projection in a neural network
- **flexible mapping** steered by $x$
  - $x =$ gaze direction
  - $x =$ hand position
  - $x =$ position of reference object

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

- a joint representation of
  - the space to be mapped
  - the steering space
- bind the two spaces
- ridge/slice input
- peak
- project out to transformed space

[Schneegans Ch 7 of DFT Primer, 2016]
Coordinate transforms

A

B

[Schneegans Ch 7 of DFT Primer, 2016]
Coordinate transforms

A

B

[Schneegans Ch 7 of DFT Primer, 2016]
Coordinate transforms

A

retinal field

transformation field

B

visual stimulus

gaze

stimulus (retinal)

stimulus (body-centered)
Coordinate transforms

[Schneegans Ch 7 of DFT Primer, 2016]
Coordinate transforms

[Schneegans Ch 7 of DFT Primer, 2016]
Coordinate transforms

- bi-directional coupling
- enables new functions

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

predict retinal image from memorized scene

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

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

[Schneegans, Schöner Biological Cybernetics 2012]
accounts for predictive updating of retinal representation

[Schneegans, Schöner Biological Cybernetics 2012]
Coordinate transforms

estimate gaze by matching scene to memorizes scene

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

- joint representation of steering and transformed space ~ 4 dimensions
- binding through space… enables transforming only space!
- => coordinate transforms are linked to the sequentiality bottleneck!
higher-dimensional dynamic fields enable new cognitive functions: binding, attentional selection, matching, visual search, coordinate transforms