Higher-dimensional dynamics fields enable new cognitive function

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Multi-dimensional fields per se

are not fundamentally different....

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

- obviously two-dimensional

![Graphical representation of retinal space evolution over time]

[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 ...
mathematics of 2D fields

- => simulation
- no problem ... self-stabilized peaks work just fine...
But: higher-dimensional fields enable new cognitive functions
Example 1: Feature binding

- 1D spatial location (for illustration)
- 1D color dimension (hue)
- visual input: 2D
- => 2D peaks

[Slides adapted from Sebastian Schneegans, see Schneegans, Lins, Spencer, Chapter 5 of Dynamic Field Theory-A Primer, OUP, 2015]
2D input

- creates 2D peaks that form combined (bound) representations of objects

[Slides adapted from Sebastian Schneegans, see Schneegans, Lins, Spencer, Chapter 5 of Dynamic Field Theory-A Primer, OUP, 2015]
extracting features

- read-out from 2D to 1D by projection
- by summing along the other dimension (marginalization)
- or by taking the (soft)max

[Slides adapted from Sebastian Schneegans, see Schneegans, Lins, Spencer, Chapter 5 of Dynamic Field Theory-A Primer, OUP, 2015]
assembling bound representations

- from 1D to 2D: ridge input is constant along the other dimension

[Slides adapted from Sebastian Schneegans, see Schneegans, Lins, Spencer, Chapter 5 of Dynamic Field Theory-A Primer, OUP, 2015]
assembling bound representations

Peaks form at the intersections of ridges and form bound representations of the two dimensions.

[Slides adapted from Sebastian Schneegans, see Schneegans, Lins, Spencer, Chapter 5 of Dynamic Field Theory-A Primer, OUP, 2015]
assembling bound representations

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

[Slides adapted from Sebastian Schneegans, see Schneegans, Lins, Spencer, Chapter 5 of Dynamic Field Theory-A Primer, OUP, 2015]
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]
visual search

the selection from visual search can be propagated to the 1D feature representations...

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contrast: synaptic association

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.
Example 2: coordinate transformations which are analogous to the instantaneous associations between stimulus features demonstrated earlier.
coordinate transformations

- eye movement: visual target from retinal representation to head-centered representation for reaching

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

- every gaze shift changes the spatial reference frame of the visual perception
- how to memorize location when the reference frame keeps shifting?
- => transformation to gaze-invariant reference frame

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

- head movement: transform visual target from retinal representation to body-centered representation
coordinate transformations

- hand movement: transform movement target from body-centered representation to hand-centered representation for reaching

[Erlhagen, Schöner, Psych Rev 2002]
coordinate transformations

- need mapping between different reference frames: retinocentric (moving with the eye) to body-centered (gaze-invariant)

- mapping is a variable shift, depends on current gaze direction

- as a formula $x_{body} = x_{retinal} + x_{gaze}$

- but how to implement this in DNFs, using space code representations?

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

- fixed mapping: neural projection in a neural network
- flexible mapping that depends on gaze/eye position?

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

- expand into a 2D field
- free output connectivity to implement any mapping

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coordinate transformations

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coordinate transformations

- bi-directional coupling: reversing the transformations

[Slides adapted from Sebastian Schneegans, see Schneegans, Chapter 7 of Dynamic Field Theory-A Primer, OUP, 2015]
spatial remapping during saccades

[Slides adapted from Sebastian Schneegans, see Schneegans, Chapter 7 of Dynamic Field Theory-A Primer, OUP, 2015]
Case Study: Spatial Remapping during Saccades

A

B

C

D

E

transformation field

body-centered field

retinocentric field

gaze field

0° 30° -30°

0°

30°

-30°

0° 30° -30°

-60° 60°

-60°

0°

30°

-30°

60°

0° 30° -30°

0°

30°

-30°

B

C

D

E

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

- predict retinal location following gaze shift

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

[Schneegans, Schöner, BC 2012]
Combine feature binding and coordinate transforms
Scaling dimensionality
Scaling dimensionality

- example: a single 6-dimensional field is needed to transform the coordinates of a 3D field:
  - 1 feature dimension $\times$ 2 spatial dimensions on input side
  - 1 feature dimension $\times$ 2 spatial dimensions on output side
- sample each dimension with 100 neurons: $10^{12}$ neurons = entire brain!
Scaling dimensionality

- Example: a few features over space
  - color
  - orientation
  - disparity
  - line-length
  - 2D space

=> 6 dimensions \(\sim 10^{12}\) neurons!
solution

- break down the feature fields into many low dimensional fields… all 3 or maximally 4 dimensional
- coordinate transform only space…
- and bind the features to space by combining the ridge values: operating sequentially!
- => coordinate transforms are at the origin of the binding bottleneck
Memorization of left item

[Slides adapted from Sebastian Schneegans, see Schneegans, Spencer, Schöner, Chapter 9 of Dynamic Field Theory-A Primer, OUP, 2015]
Adding third item to scene

[Slides adapted from Sebastian Schneegans, see Schneegans, Spencer, Schöner, Chapter 9 of Dynamic Field Theory-A Primer, OUP, 2015]
Post sequential memorization of all three items

[Slides adapted from Sebastian Schneegans, see Schneegans, Spencer, Schöner, Chapter 9 of Dynamic Field Theory-A Primer, OUP, 2015]
Conclusion: multi-dimensional fields

- enable new cognitive functions that derive from association and cannot be realized by synaptic networks
- instantaneous association or linkage (referral) enabling dimensional cuing
- cued recall
- coordinate transforms instantaneous real-time
- representing associations, rules etc. in a manner that can be activated/deactivated
need to span only a limited number of dimensions (2 and 3), which are expanded by binding through space

span by small number of neurons
Outlook

- multi-dimensional fields help us move toward higher cognition