The DFT and the Dynamics of Visuo-Spatial Cognition

Overview

Two central themes…

- Using DFT to integrate perception, action, and cognition (PAC)
- Using DFT to understand the integration of PAC over multiple time scales (real time, learning time, development)

Overview

Part 1

- Is DFT a good framework for thinking about embodied cognitive dynamics?
  - Within DFT, peaks are the unit of cognition
  - Self-sustaining peaks = working memory?
- Initial work on the integration of time scales
  - "preshape" as a form of long-term memory (Hebbian learning)
  - Development via the spatial precision hypothesis

Overview

Part 1

- These themes will all be demonstrated with a one-layer dynamic field (+preshape)
- And we'll provide empirical evidence of central concepts from our work on visuo-spatial cognition

Highlights the strong theory-experiment links that can be achieved with DFT

Overview

After showing that peaks provide an appropriate unit of cognition (WM, LTM), we'll move to Part 2…

- We'll achieve the real-time integration of PAC (focusing on the PC part) using a 3-layered dynamic field
- And we'll show how the integration of time scales can be achieved within this framework

Overview

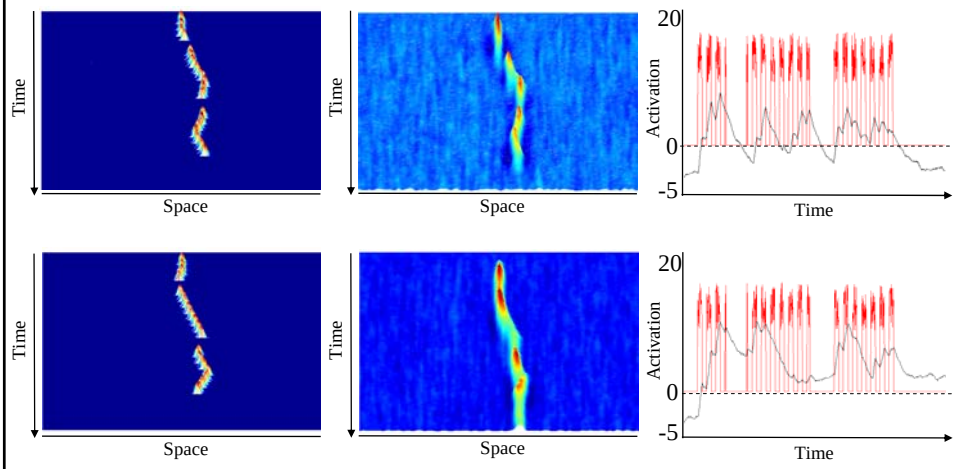
Part 2

- Once again, we'll provide empirical evidence of central concepts from our work on visuo-spatial cognition to highlight close theory-experiment links

[Later, Gregor will show evidence of embodiment with some robotics examples and move us toward "higher" ground, that is, higher-level cognition...]

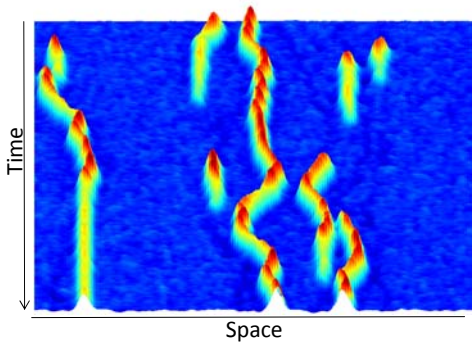
Peaks as the Unit of Cognition

What do peaks buy us?



This is pretty close to input--can we do something more cognitive

Multi-Item Working Memory?

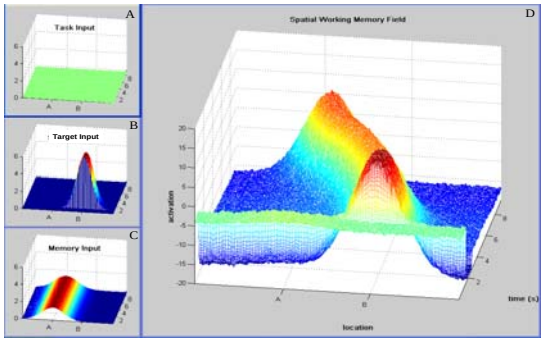


Stability (not-so-slight return)

- Work on A-not-B Robotics demo showed we need stability for cognitive systems to talk to motor systems
- Also need stability for cognitive systems to talk to other cognitive systems
- “Working” memory

Self-Sustaining Peaks = WM?

Prediction: Delay-dependent Spatial Drift

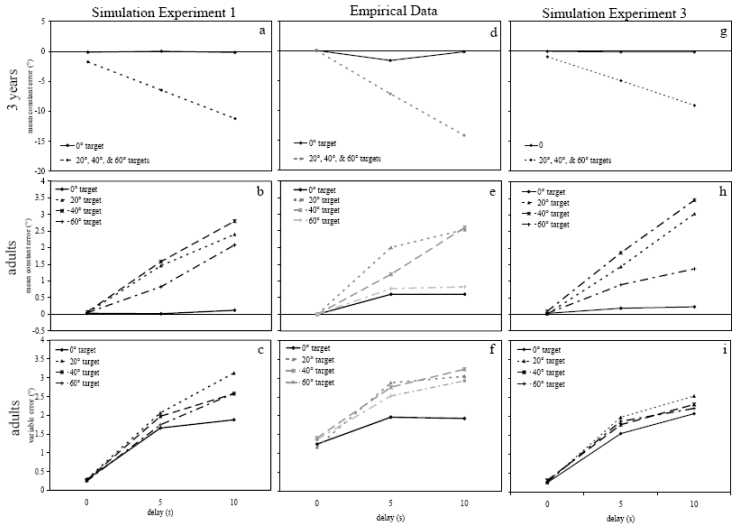


Interactive Simulator

Metric Working Memory Tasks

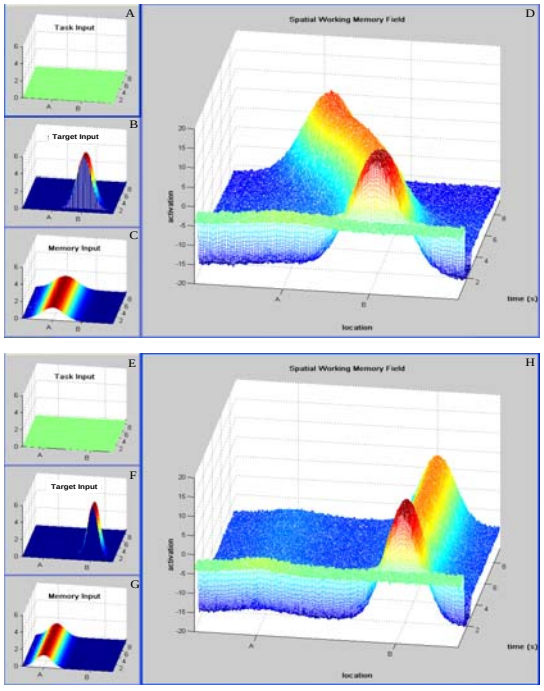
2000 ms | 10 sec delay | Ready, Set, Go!

Empirical Test



Direct Evidence for Metrics of DFT

- Delay-dependent spatial drift provides direct evidence for metric WM
- Need metrics and real-time dynamics to capture this effect (not all WM models have these features)



<u>Prediction #2:</u>

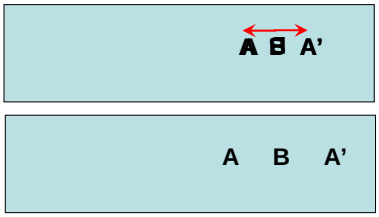
We can eliminate metric biases by moving source of bias farther away…

- Example: A-not-B biases result from overlap of a LTM input with a peak

Interactive Simulator

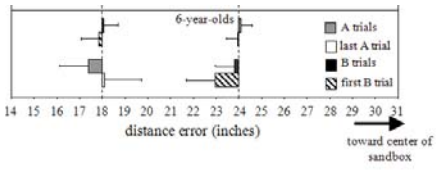
Schutte, Spencer, & Schöner (2003). *Child Development*.

- Experience-dependent biases in spatial memory

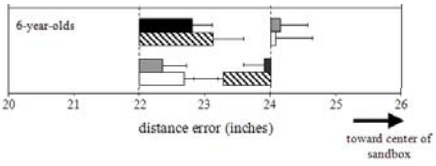


Empirical Tests of Prediction

No Bias



A-not-B-type Bias



Direct Evidence for Metrics of DFT

- Dependency of A-not-B-type biases on separation between A and B provides additional evidence for metrics of DFT

These examples start to build a case that peaks are a good unit of cognition

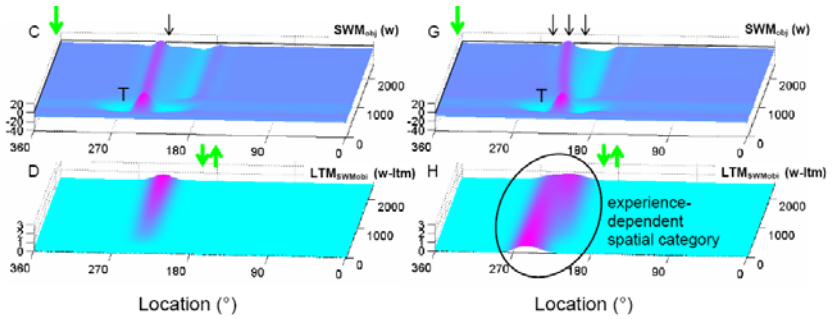
Integration of Time Scales

- Previous examples also show that the DFT can capture real-time processes

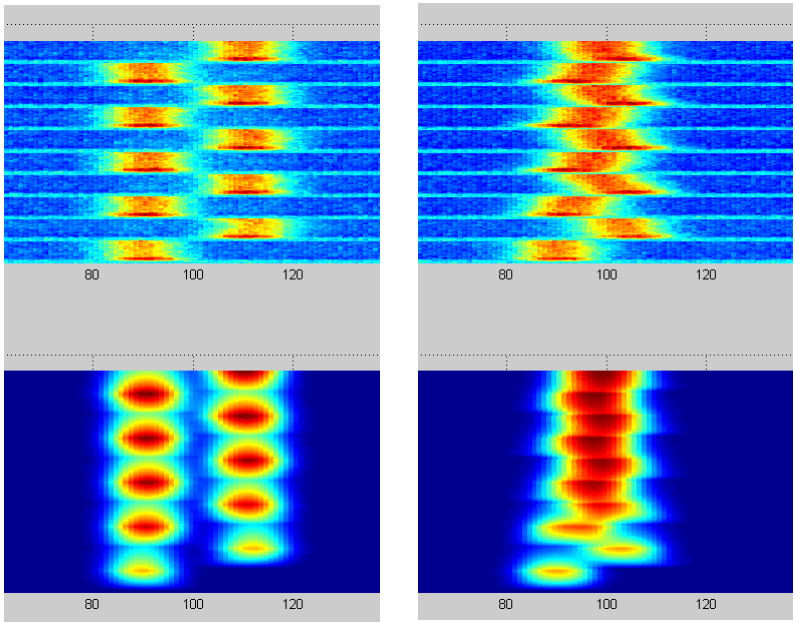
What about the longer time scales of learning and development?

What are Children Drifting Toward?

- Experience-dependent categories
- LTM fields = form of Hebbian learning



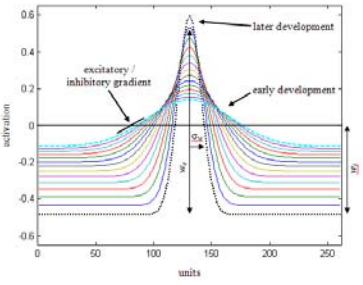
LTM Dynamics and Metrics



What about Development?

How does the DFT capture development?

- The spatial precision hypothesis
  - Early in development the local excitation/lateral inhibition profile is broad and weak
  - Later this profile becomes narrower and more precise
  - This developmental change happens gradually over time

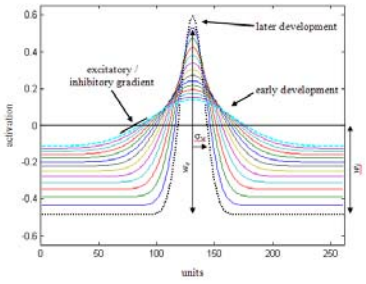


  - *Quantitative changes in precision can account for developmental changes in working memory biases…*

How does the DFT capture development?

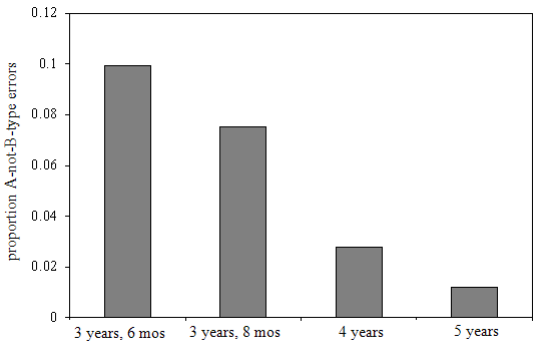
- SPH captures a suite of developmental changes…
  - Infant A-not-B: peaks die out
  - Toddler A-not-B: peak stick around if supported by input
  - Childhood: peaks more robust delays, but pushed around by inputs

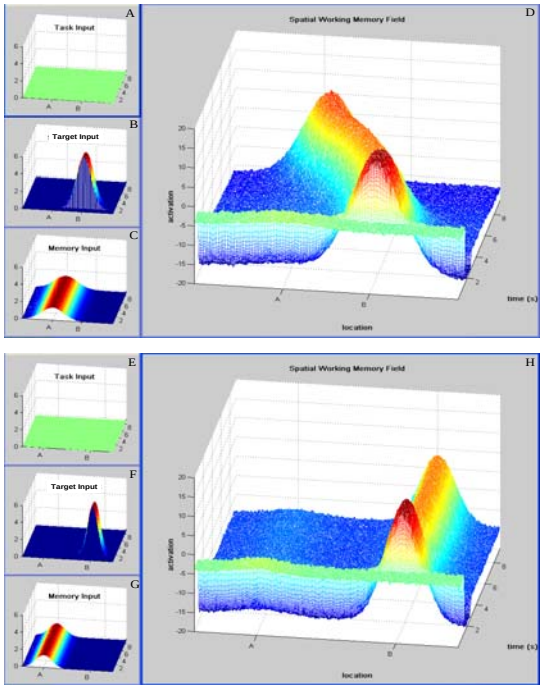
Interactive Simulator



Direct Evidence that Peak Stability Changes over Development

- Two locations far apart; opposite sides of midline
- A-not-B-type error = WM peak loses stability and new peak pops up at other site



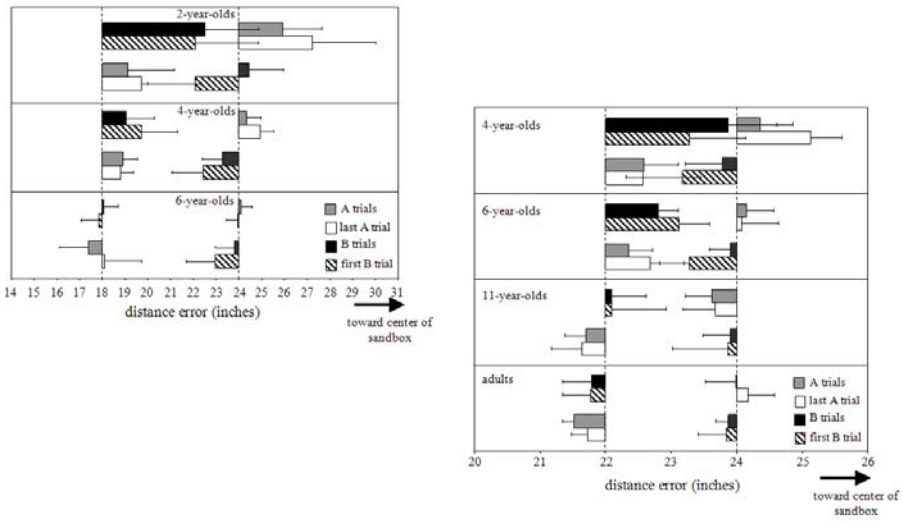


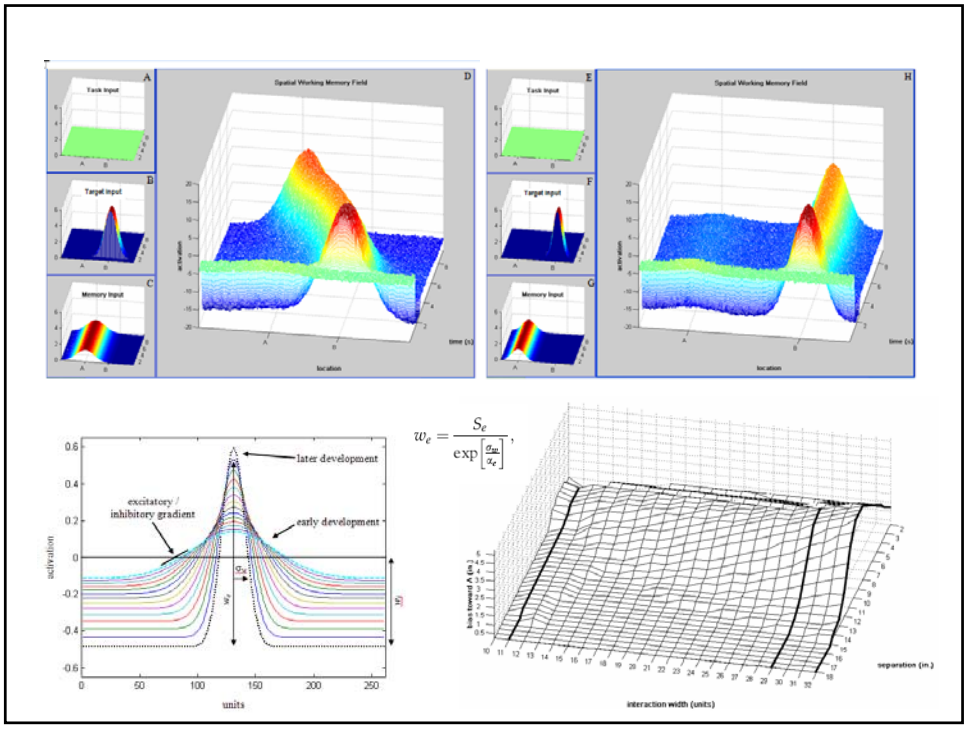
Prediction of spatial precision H:

Separation at which A-not-B-type effects occur should change over development

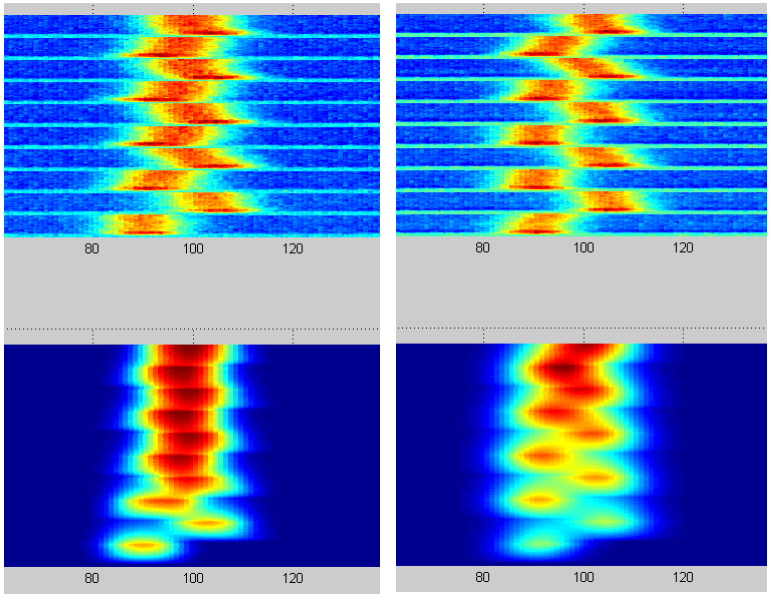
- See biases across a broad range early in development
- Only see biases at close separations later in development

Sandbox Data & Development





Learning and Development Interact!



Summary: Part 1

- Self-sustaining peaks = WM
  - Delay-dependent drift and metric effects as signature of field dynamics
- Memory traces of peaks = LTM
  - First step toward category formation
- Changes in neural precision do a lot of work when embedded within other time scales

Perception AND Working Memory

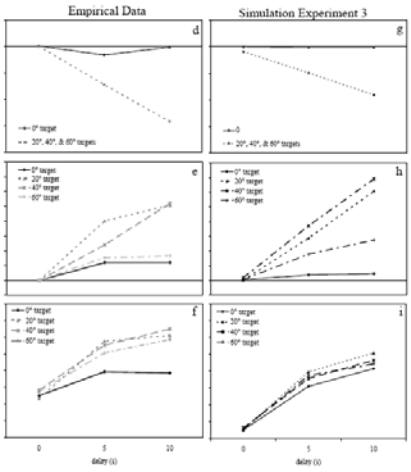
We have all the ingredients needed to do more…

- PAC not just about single peaks—multiple peaks are possible in a field
- PAC is not just about self-stabilized (perceptual state) VS. self-sustaining (WM state)…it can be about ***both simultaneously***

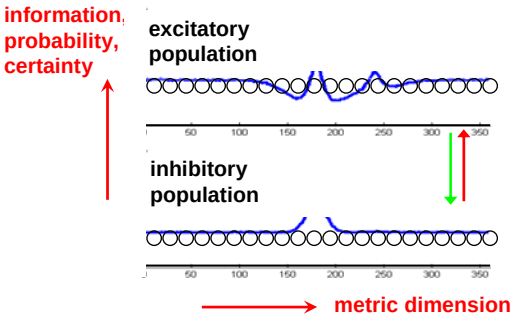
Perception AND Working Memory

- When remembering locations, people are continuously anchored to perceptual cues (e.g., landmarks)

How do we coordinate perception and WM in real time?



Multi-layer fields



– Input induces formation of localized peak of activation in field

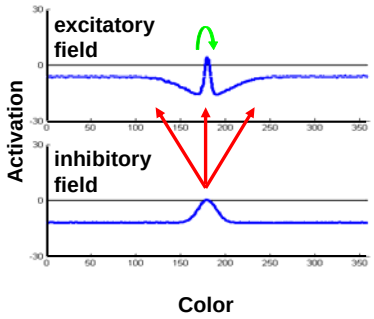
– Localized peaks are instances of the dimension (i.e. a particular color)

– Peaks of activation are basic units of representation at the neural population level

– Peak + Graded activation represents certainty or probability of a given estimate

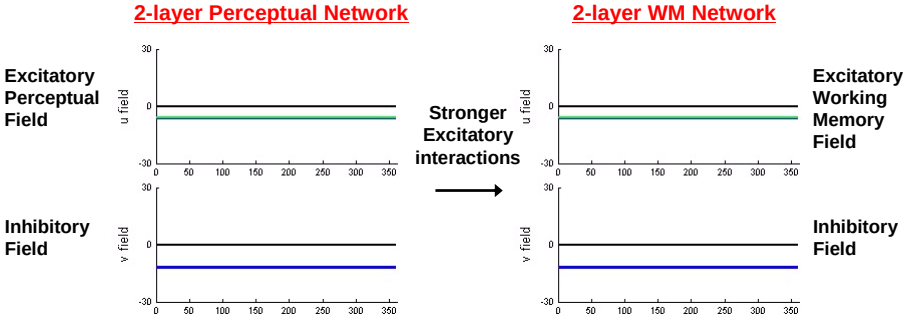
Dynamics of fields

- Field dynamics combines input with strong interaction:
  - local excitation
  - lateral inhibition



- Allows stable peaks of activation to be formed and maintained in the absence of input, a form of WM

Dynamics of fields

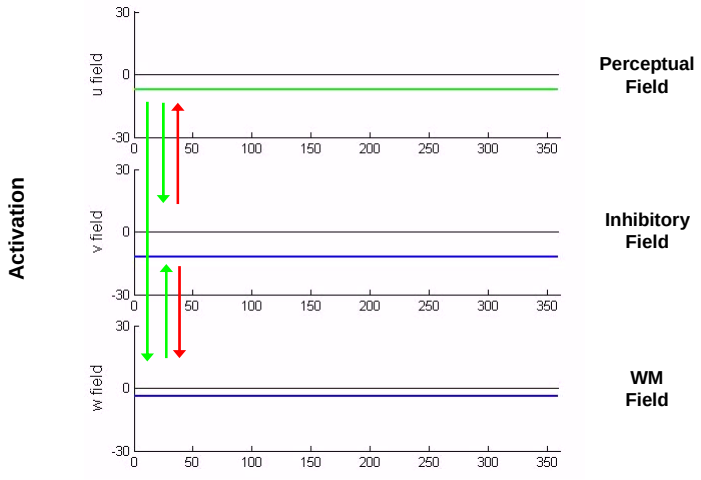


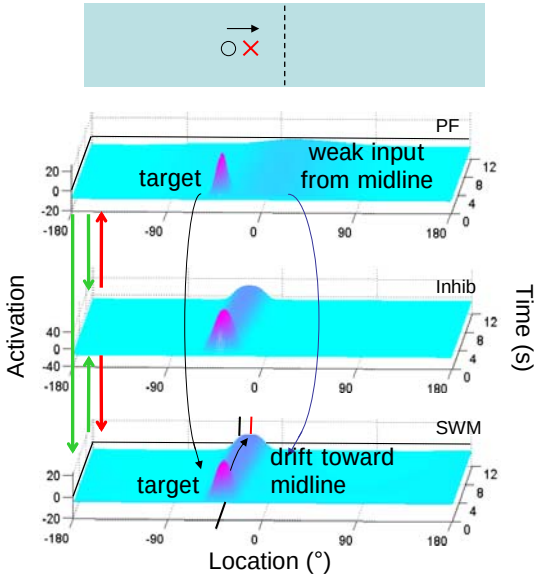
- **The dynamic properties of neural fields give us a way to think about the real-time dynamics of perceptual and memory processes**
- **Combined properties of 2-layer DNFs give us a way to do that**
  - **Simplest case is to combine networks in a 3-layer architecture with shared inhibitory layer**

A DNF Model of VWM

(Johnson, Spencer, & Schöner, in press; submitted)

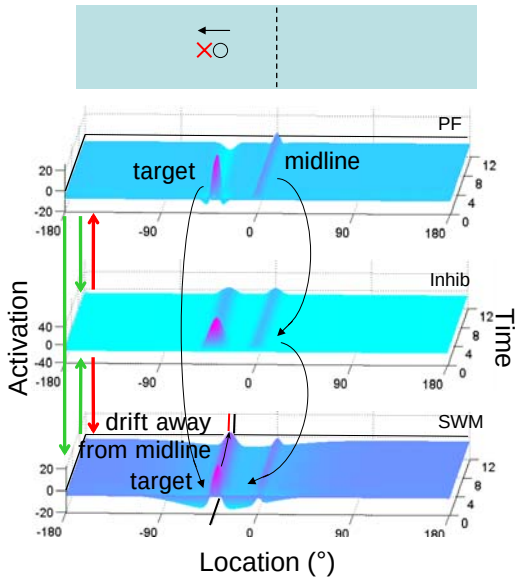
- **3-layer architecture: 2-layer perceptual network + 2-layer WM network**





Simmering, Schutte, & Spencer (2007) Brain Research

- Perceptual input from task space
- Self-sustained target peak
- Interaction of perception and memory



Simmering, Schutte, & Spencer (2007) Brain Research

- Perceptual input from task space: **midline peak**
- Shared inhibition
- Interaction of perception and memory

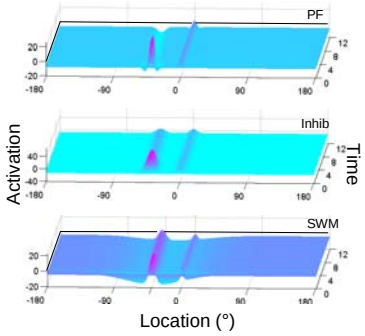
Interactive Simulator

Coordinating Perception and WM

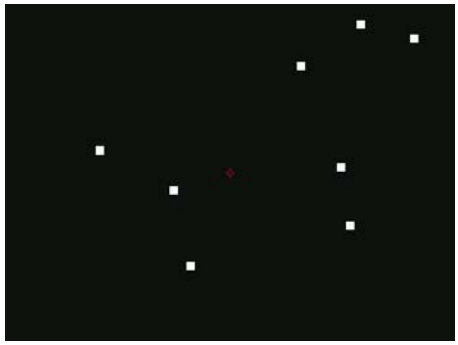
- Still living in IP-land…
- Can't we think of something more dynamic?!?
- *Multi-object tracking…*

DFT and the integration of perception, action, and cognition in real time

Spatial recall biases emerge from the interaction between perception and working memory

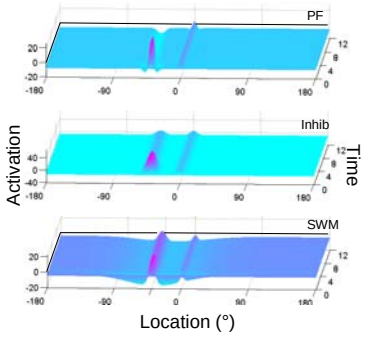


WANTED: a real-time spatial task

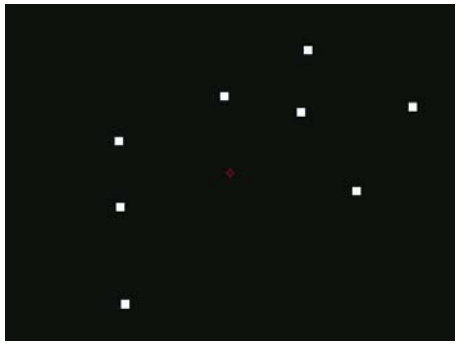


DFT and the integration of perception, action, and cognition in real time

Spatial recall biases emerge from the interaction between perception and working memory

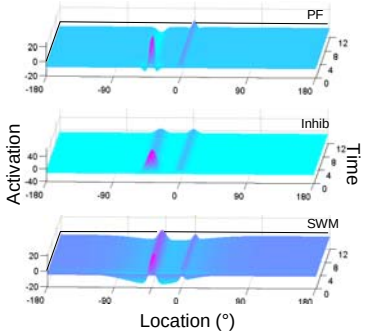


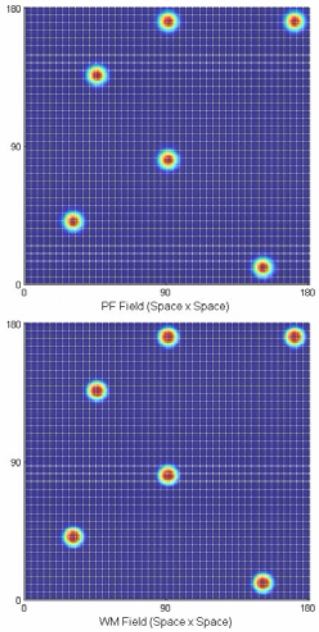
WANTED: a real-time spatial task



DFT and the integration of perception, action, and cognition in real time

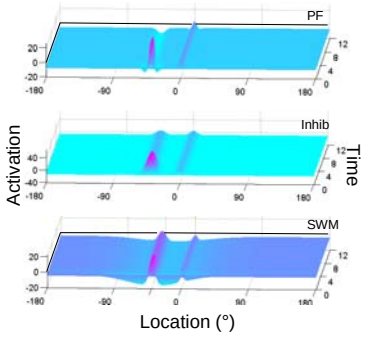
Spatial recall biases emerge from the interaction between perception and working memory

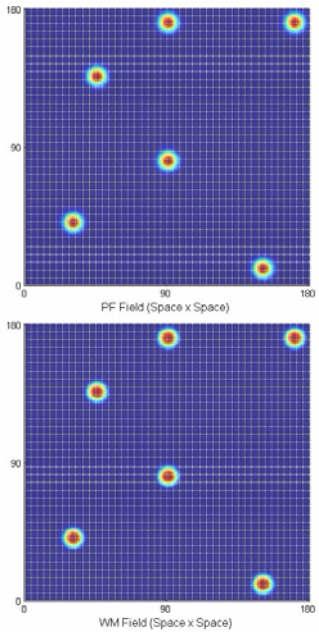




DFT and the integration of perception, action, and cognition in real time

Spatial recall biases emerge from the interaction between perception and working memory





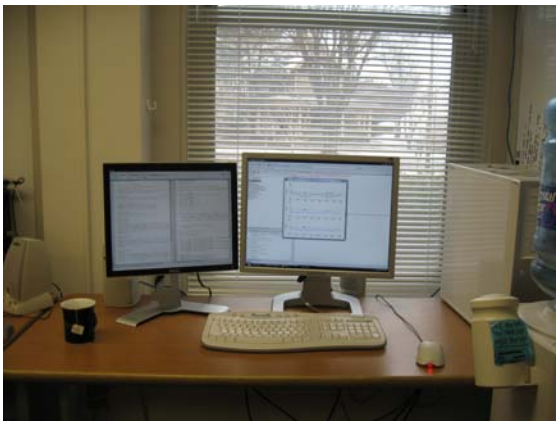
Space…yawn…

- Can't you talk about some "real" cognition already…

Perception and WM must be coordinated all the time!!

- Visual cognition is more about visual memory than visual search…
- Example:
  - Comparison of percepts that can not be simultaneously foveated
  - Identifying changes in the world when they occur

Comparison & Change Detection



Case 1: Large feature difference makes it easy

Case 2: Need to remember subtle featural details – can have real-world consequences!

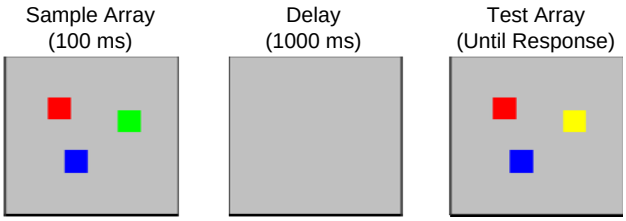
VWM in Early Development

- Take a more complex scene…

  And add in some kids!
- And chaos ensues!

The real-world is dynamic…

The Change-Detection task



Same or Different?

* Adapted from Luck & Vogel (1997)

Historically, this task has been broken down into a progression of stages that are studied in isolation:

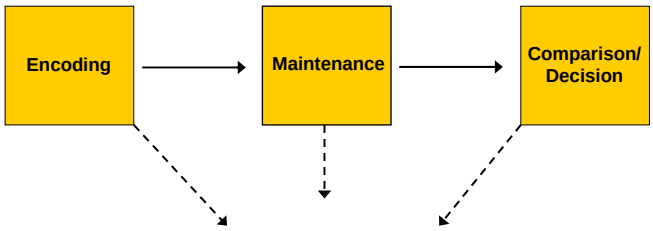
Change detection: Behavioral insights

- **Independent from maintenance**
  Woodman & Vogel, 2005
- **Very fast (~50 ms/item)**
  Vogel, Woodman, & Luck, 2006
  Sperling, 1967
- **An "all-or-none" process**
  Zhang, 2007

- **Capacity limited (3-4 items)**
  Luck & Vogel, 1997
  Phillips, 1974
  Woodman, et al., 2001
- **Stores integrated objects**
  Irwin & Zelinsky, 2002
  Luck & Vogel, 1997
  Johnson, et al, in press

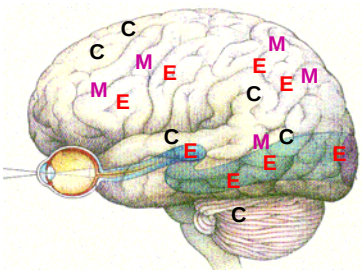
- **Elicits rapid shifts of eyes to changed location**
  Hyun, 2007

Change detection: Neural insights



fMRI/ERP

- Hyun et al, in press
- Pessoa, et al. 2002
- Todd & Marois, 2004
- Vogel & Machizawa, 2004
- Xu & Chun, 2005



Theories of Visual Working Memory

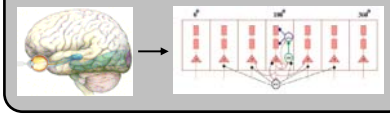
Verbal/Conceptual

- Emphasis on information processing concepts
- Slow to incorporate complex dynamics of brain

Need theories that embrace complex real-time dynamics of neural systems while maintaining tight interface with behavioral research looking at VWM

?

Neurodynamical/biophysical



- Amit & Brunel, 1997
- Constantinidis, et al., 2000
- Trappenberg, 2003

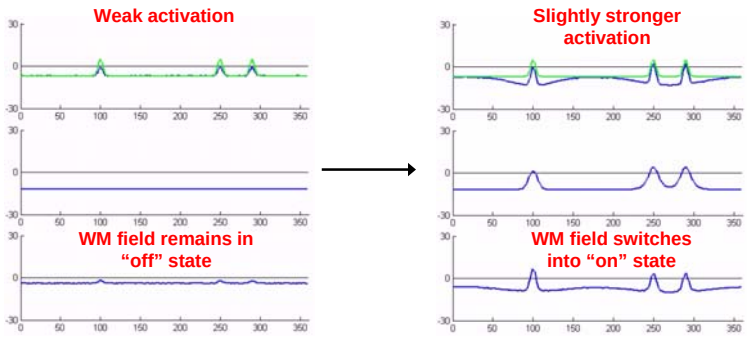
- Emphasis on biophysics and complex dynamics of neural systems
- Focus on SWM for single items
- Little contact with human behavioral literature on VWM

Encoding/Consolidation

- Consolidation = the process of transforming a fleeting perceptual representation into a stable WM representation
- Consolidation in the DFT = the formation of a self-sustained peak in the WM layer

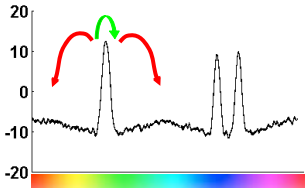
Encoding/Consolidation

- Consolidation an all-or-none phenomenon (Zhang, 2007)



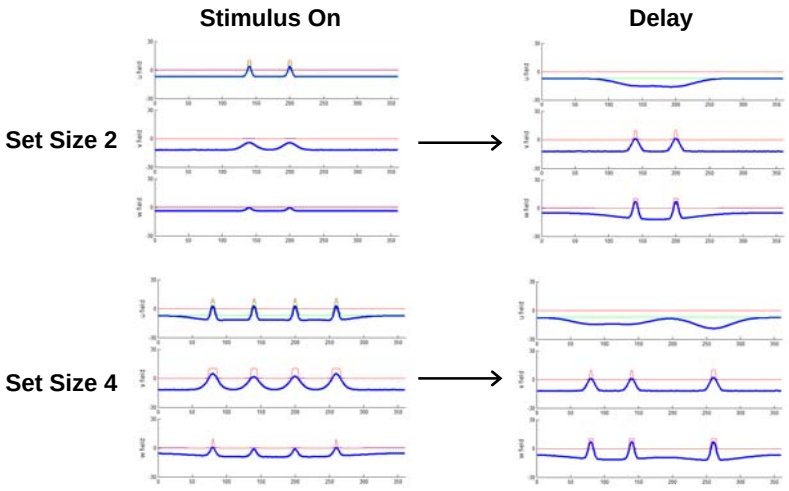
Multi-item WM & Capacity limits

- Capacity of WM limited to ~3-4 objects worth of information (Luck & Vogel, 1997)
  - Mexican-hat interaction function underlying maintenance allows multiple items to be maintained as long as inhibition is not too strong



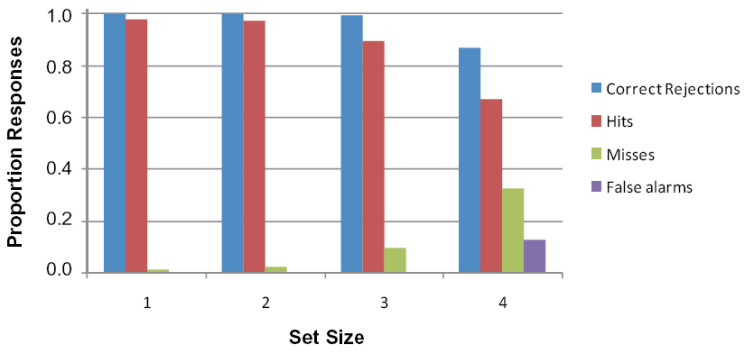
  - But, capacity is limited as a result of similarity (i.e., how close peaks are in field) and increased inhibition with more items

Multi-item WM & Capacity limits

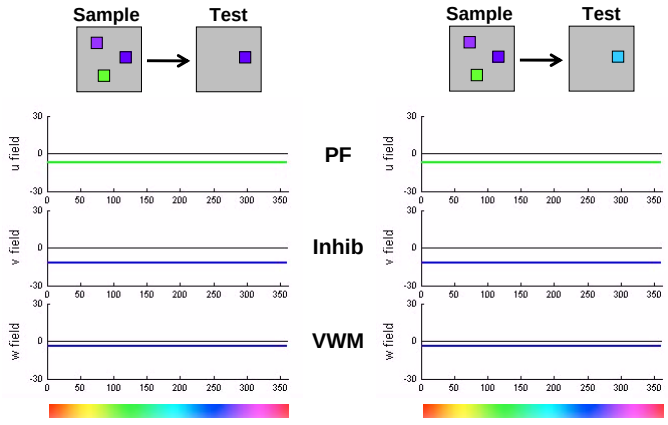


Multi-item WM & Capacity limits

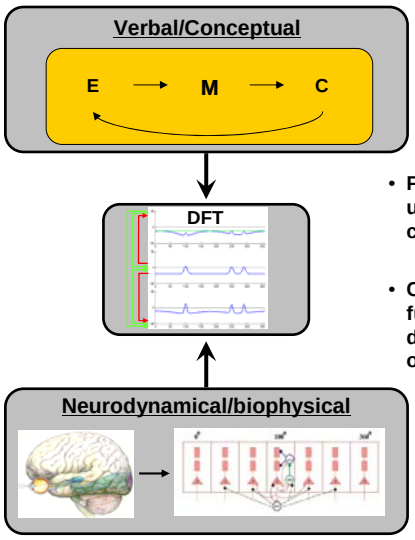
Figure 8. Simulation results for change detection set sizes one through four from Simmering et al. (2008). Note that proportions are shown relative to *change* and *no change* trials; therefore correct rejections and false alarms, as well as hits and misses, sum to 1.0.



Comparison/Change Detection



DFT Summary



- **Formalizes mechanisms underlying WM and change detection**
- **Components realized in fully integrated continuous dynamic neural system operating in real time**

Perception AND Working Memory

3-layer DNF architecture captures the real-time integration of PC…

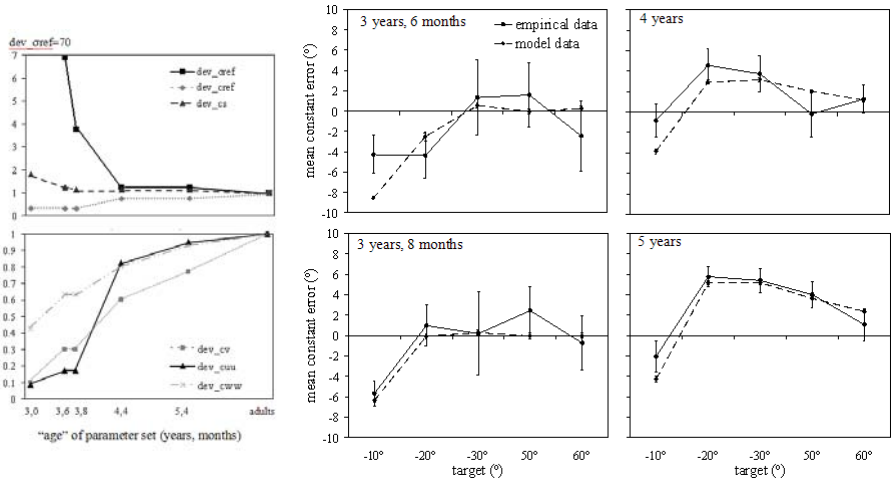
- Biases away from perceived reference frames in spatial recall
- Multi-object tracking
- Visual working memory and change detection

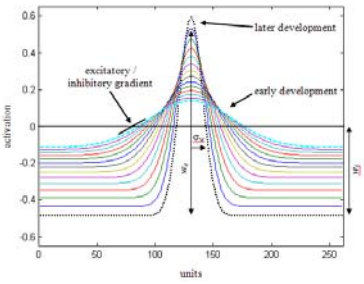
Can we capture changes in the coupling of PAC over learning and development?

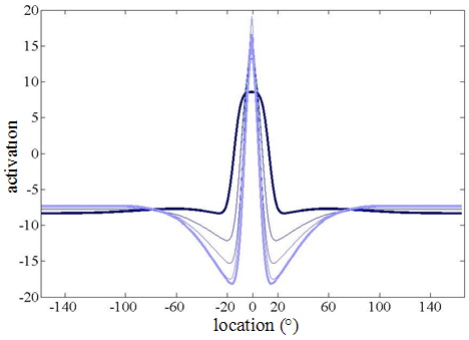
Learning Time Scale…

see Spencer Talk
Thursday 1:45pm

Development: Schutte & Spencer (2008)

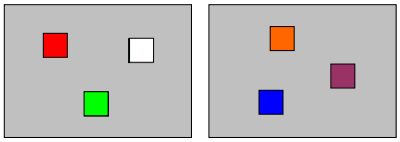






The Development of VWM

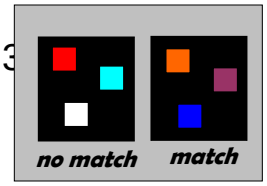
- Change Detection task
  - Adults: 3-4 items (e.g., Luck & Vogel, 1997)
  - Children: 1.5 items at 5 years (Riggs, et al., 2006)
- Preferential Looking
  - Infants: "capacity" of 1 item at 6 months, 3 items by 10-12 months (Ross-Sheehy, Oakes, & Luck, 2003)

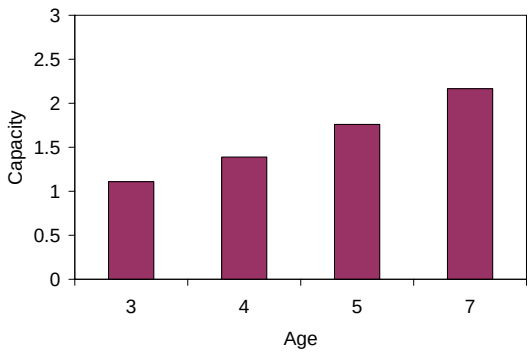


- What's happening over development?
  - Need to bridge the gap between 12 months and 5 years

The Development of VWM

- Updated change detection task: "card game"
  - Use space to our advantage
- Linear increase in capacity from 3

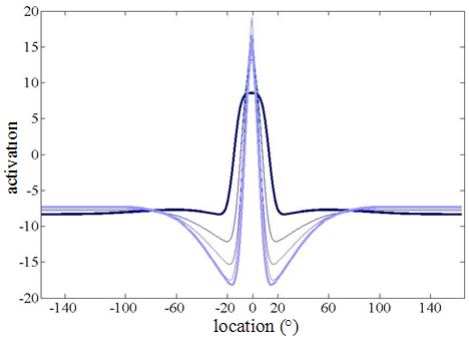




The Origin of Capacity Limits?

Spatial Precision Hypothesis

- Neural interactions in DFT based on a space code principle (specifies how neighboring neurons interact)
- Interactions become stronger over development (e.g., Kohonen, 1982)

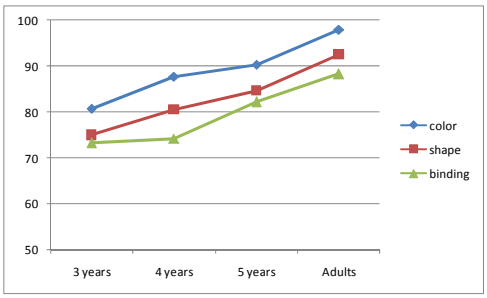


•…they also become emergently more precise!

• Simmering: SPH can quantitatively capture changes in capacity over development

Less-Is-More in VWM?

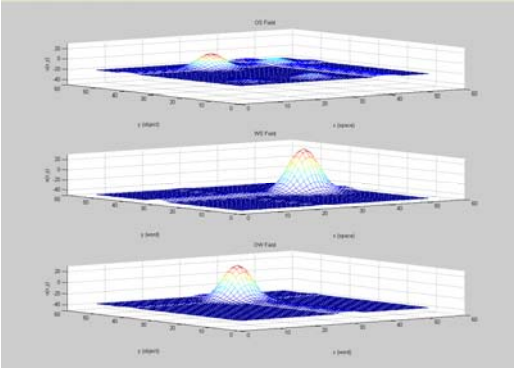
- Visual features may not be robustly bound together in early development (Spencer, Patterson & Simmering, 2008)
- Limited capacity may reduce spurious correlations of features when multiple items are present.



Less-Is-More in VWM?

- Another key achievement: language and word learning!
- Limited capacity may help children "bind" labels to objects

(Smith, Perry, Samuelson & Spencer, 2008)



Conclusions

Two central themes…

- Using DFT to integrate perception, action, and cognition (PAC)
  - 3-layer provides a robust example of this
  - Generalizes to spatial and non-spatial features and across a host of tasks
  - Has led to novel predictions tested in experiment…*tight theory-experiment link*
  - Next up: a full demo of embodiment using autonomous robotics

Conclusions

Two central themes…

- Using DFT to understand the integration of PAC over multiple time scales (real time, learning time, development)
  - Coupling between WM and LTM gives rise to changes over learning and emergence of categories (Dineva & Spencer poster)
  - Enhanced neural precision gives rise to a host of quantitative and qualitative behavioral changes by modifying the dynamics within neural fields (e.g., enhancing the stability of perceptual and WM processes)