

Dynamic field theory

-- how stable behavior and embodied cognition emerge from continuous space-time neuronal dynamics

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continuous time

- although spikes are discrete events in time, these discreteness is unrelated to discrete behavioral events
- => cognitive processes are continuous in time and are continuously linked to sensory inputs. Scientific tasks are thus:
 - to understand how **discrete behavioral events may emerge** from continuous processes
 - how cognitive processes are **stabilized**
 - how **instabilities** release cognitive processes from domination by input, leading to the **emergence of cognitive function**

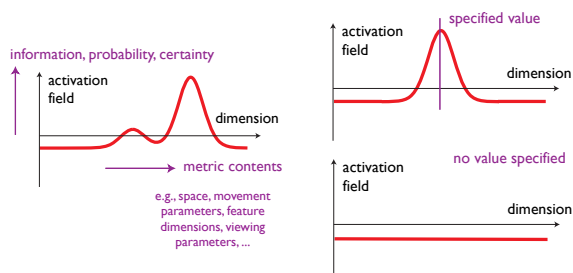
continuous space

- neurons are discrete units, but this discreteness is unrelated to discreteness in behavior
- => cognitive processes are based on continuous dimensions (space, feature spaces, parameter spaces). Scientific tasks are thus:
 - to understand how **categorical behaviors may emerge** from underlying continua
 - how **categories are formed**

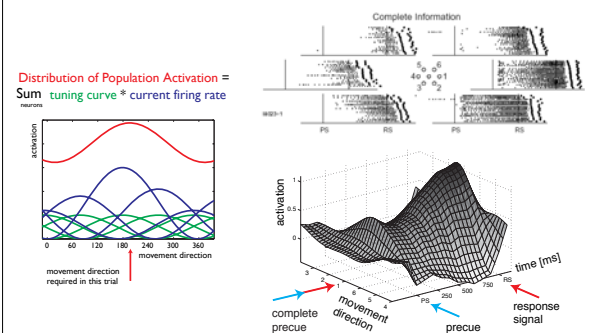
The Dynamic Field Theory program

- dynamical neural networks with strong interaction generating stable states
- linked to the sensory and motor surfaces, but not dominated by inputs
- sensitive to structured environments and behavioral history through simple learning mechanisms
- behavioral signatures provide evidence for such neuronal mechanisms

activation fields

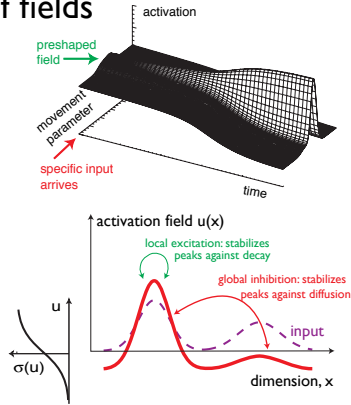


neural basis of activation field



the dynamics of fields

- field dynamics combines **input**
- with **strong interaction**:
 - local excitation
 - global inhibition
- => **generates stability**



Erlhagen, Schöner: Psychological Review 2002

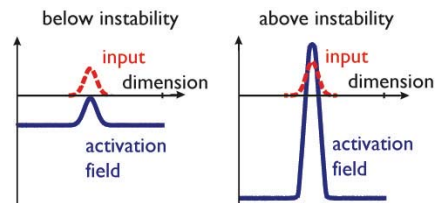
=> demonstration

instabilities

- detection from localized input
- selection-fusion
- detection from boost
- memory

detection instability

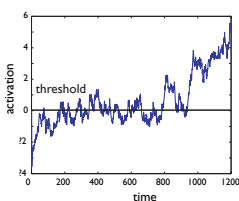
- even purely stimulus induced activation goes through an instability that marks the detection decision



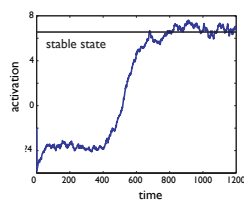
[from Bicho, Mallet, Schöner, Int J Rob Res 19:424(2000)]

the detection instability helps stabilize decisions

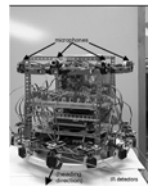
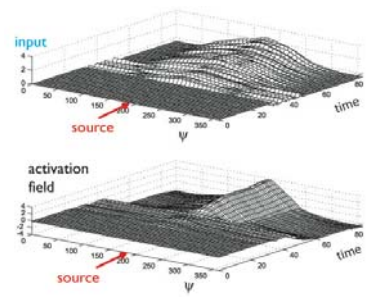
threshold piercing



detection instability



detection instability on a phonotaxis robot



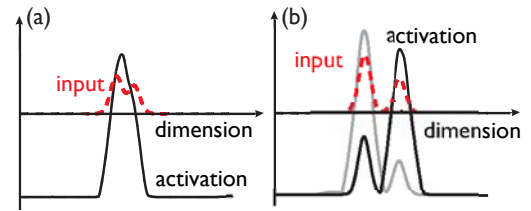
[from Bicho, Mallet, Schöner, Int. J. Rob. Res., 2000]

empirical evidence for the stabilization of detection decisions

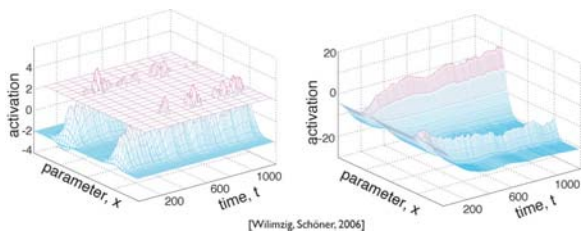
■ Hock...

fusion vs. selection instability

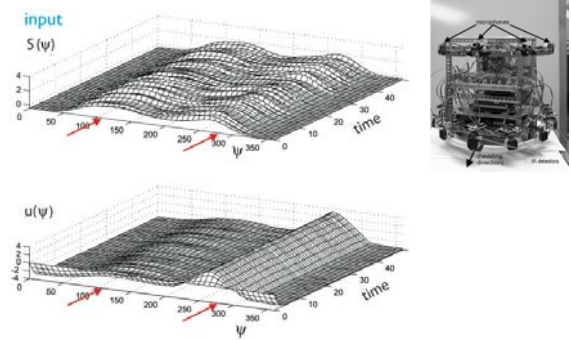
■ transition from monostable fusion to bistable selection regime as a function of metrics



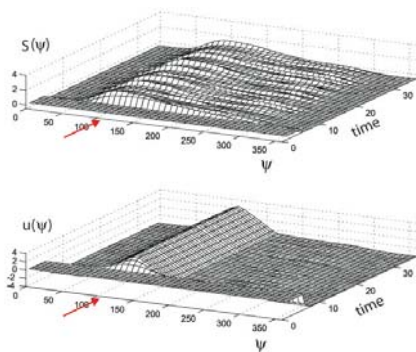
stabilizing selection decisions



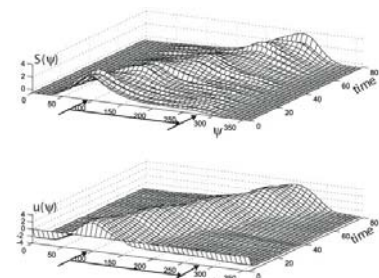
target selection on phonotaxis vehicle



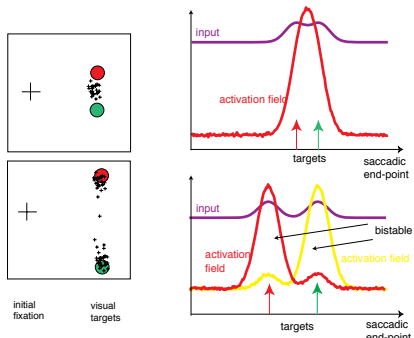
robust estimation



tracking



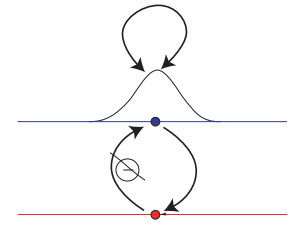
fusion/selection instability: saccades



[after: Ottes et al., Vis. Res. 25:825 (85)] [after Kopecz, Schöner: Biol Cybern 73:49 (95)]

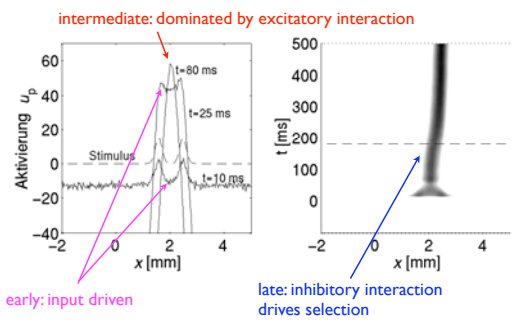
understanding the time course of selection

- based on Dale's law
- which requires a separate layer of inhibitory neurons



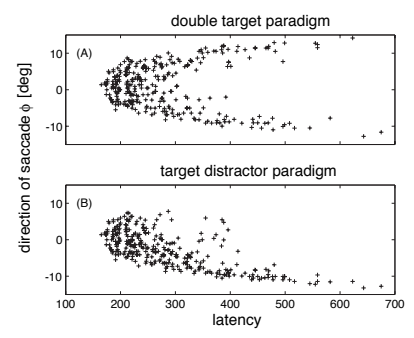
Wilmzig, Schneider, Schöner, Neural Networks, 2006

time course of selection



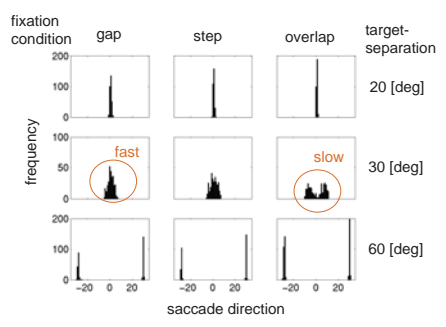
=>Wilmzig, Schneider, Schöner, Neural Networks, 2006

=> early fusion, late selection



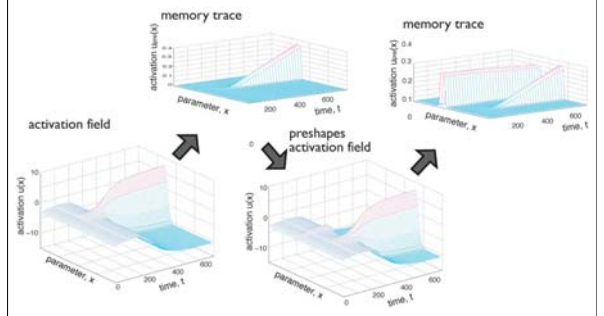
Wilmzig, Schneider, Schöner, Neural Networks, 2006

fixation and selection



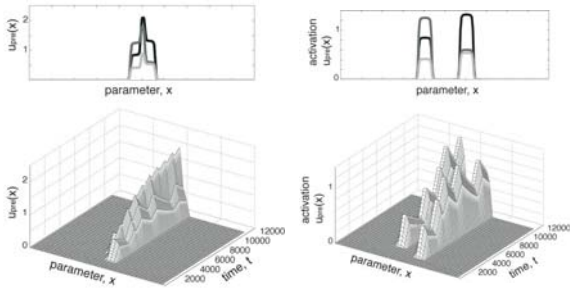
Wilmzig, Schneider, Schöner, Neural Networks, 2006

reshaping fields through a memory trace of prior activation



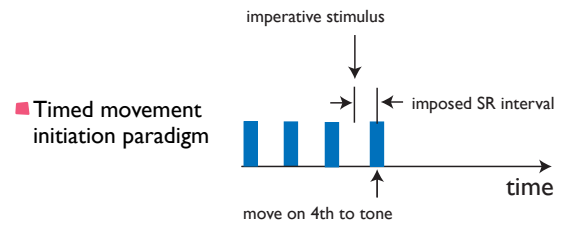
Wilmzig, Schöner 2006

leads to categories

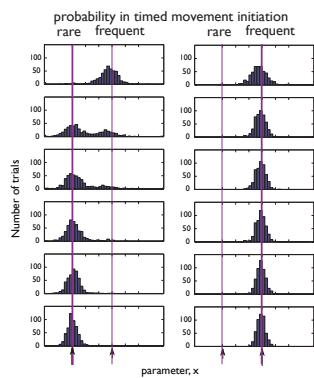


Wilmzig, Schöner 2006

direct behavioral observation of preshape

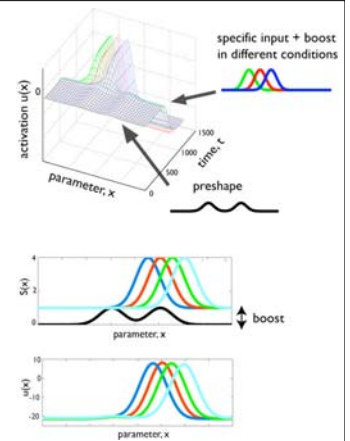


Direct behavioral observation of preshape: account for Ghez et al.



continuous response mode

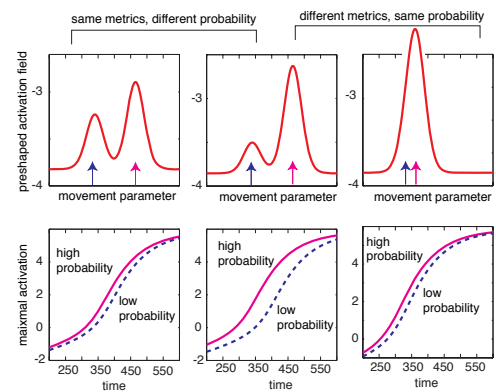
- specific (imperative) input dominates and drives detection instability



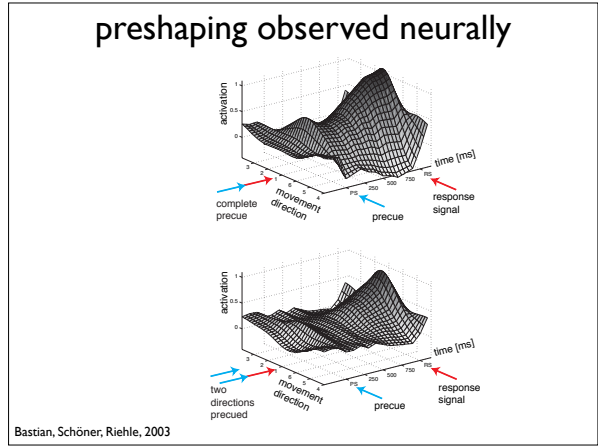
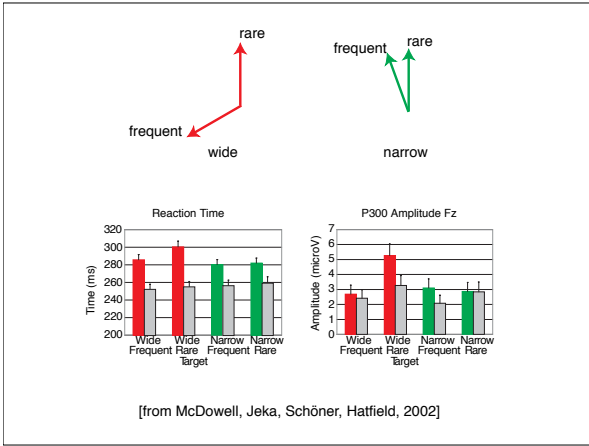
[Wilmzig, Schöner, 2006]

observation of preshape through reaction time

- time needed to go through the detection instability depends on
 - how much prior activation (e.g., probability)
 - metrics of prior information (e.g., metric effect)
 - relationship between prior information and current stimulus

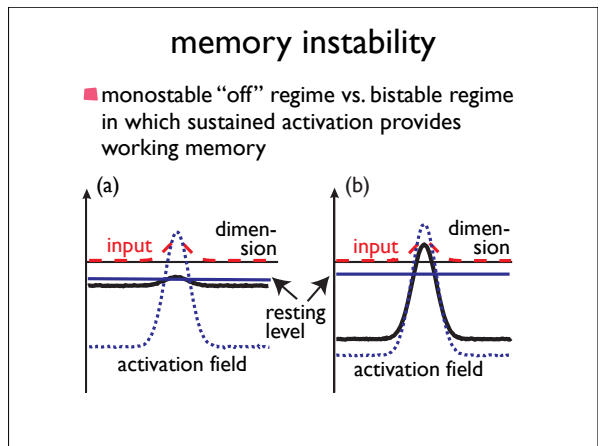
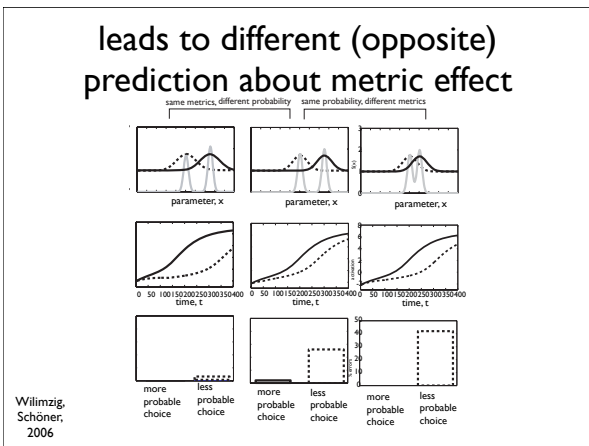
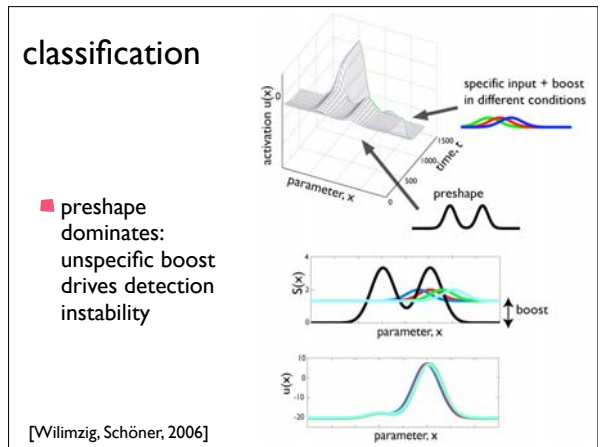


[from Erlhagen, Schöner: Psych. Rev. 2002]

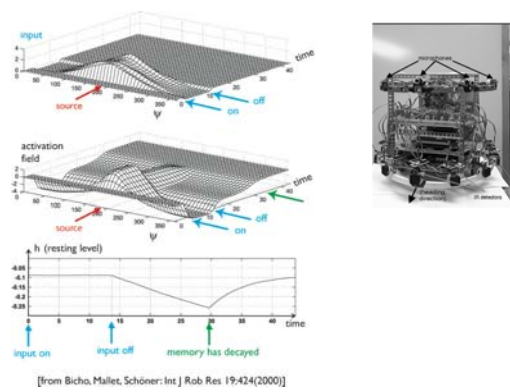


detection instability through boost

- leads to activation of categorical responses from preshaped field



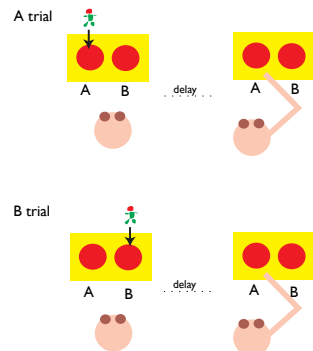
memory & forgetting on phonotaxis vehicle



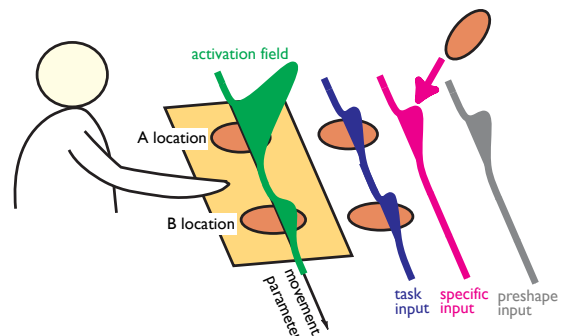
Cognitive function emerging from neural field dynamics

- perseverative reaching: all instabilities come into play
- input-driven detection
- selection
- memory
- boost-driven detection

Piaget's A not B paradigm

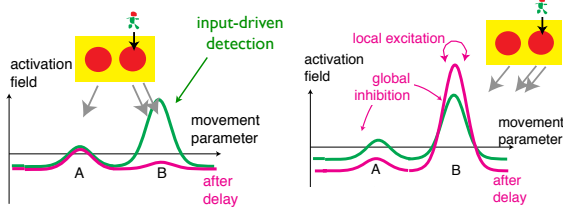


DFT of infant perseverative reaching



B trial, young infants

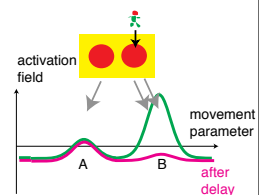
B trial, older infants



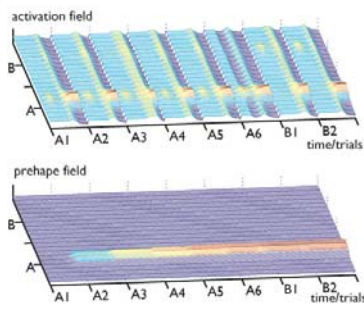
=> going through the **memory instability** during development

but: do young infants really reach based on low level activation?

- that would be a mechanism lacking stability! Does not work!
- => stabilization of the decision at reach initiation (when box enters reaching space) through **boost-driven detection instability**



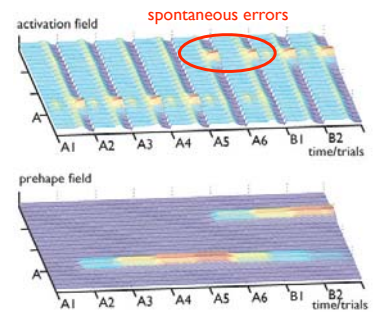
DFT of infant perseverative reaching



[Dinveva, Schöner, 2005]

accounts for spontaneous errors

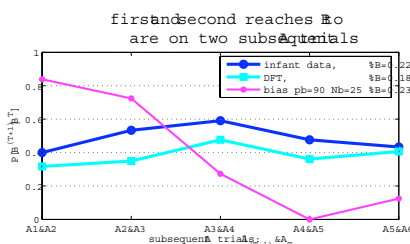
- reaches to B on A trials leave memory trace at B
- which reduces the A not B error: behavioral history matters!



[Dinveva, Schöner, 2005]

DFT of infant perseverative reaching

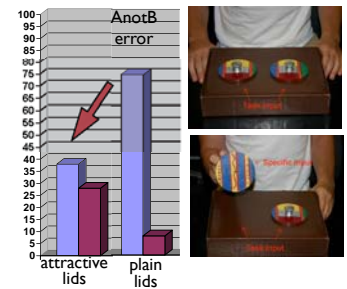
- spontaneous errors promote more spontaneous errors



[Evelina Dineva, Indiana Univ.]

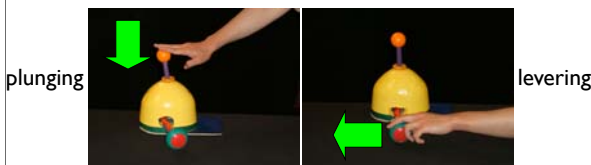
emergence: suppressing A not B error by pumping up energy

- making both locations more attractive: reduced A not B error



[Anderson, Schöner, Thelen (2006)]

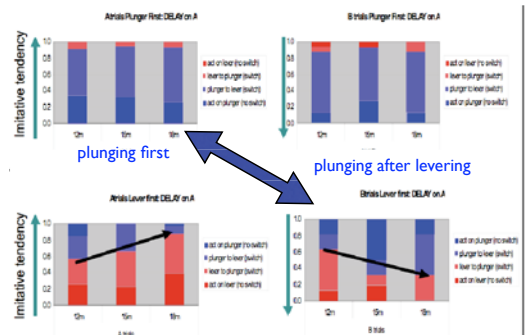
imitation (emulation): depends on behavioral history as well !



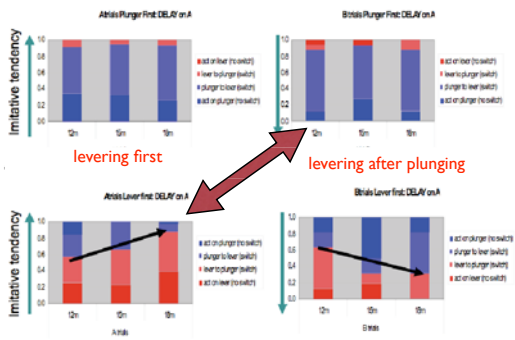
- use A not B task structure
- two conditions: plunging = A, levering = B and vice versa

[Murayama, Schöner, Spencer, Whitmyer, Thelen, 2006]

imitation: perseveration

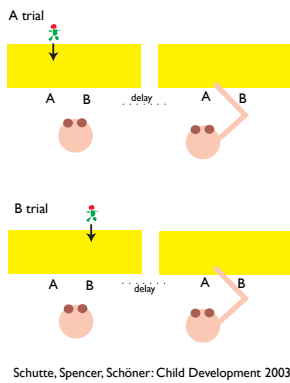


imitation: perseveration



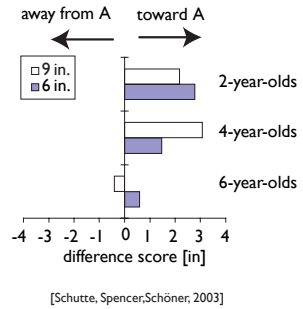
role of structured environment:
removing perceptual structure
leads to metric drift and
perseverative error in older
children

Sandbox version of A not B



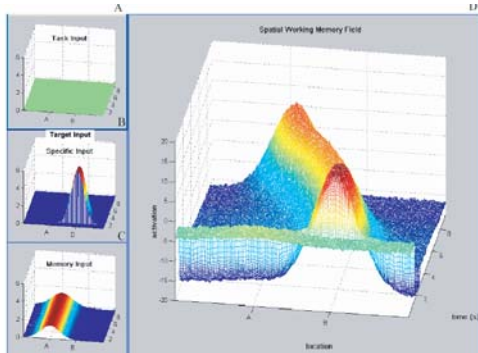
Schutte, Spencer, Schöner: Child Development 2003

Sandbox experiment



[Schutte, Spencer, Schöner, 2003]

DFT of sandbox A not B



Schutte, Spencer, Schöner: Child Development 2003

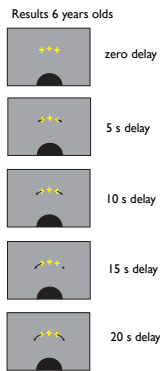
DFT of spatial memory

space ship task of John Spencer lab



spatial memory

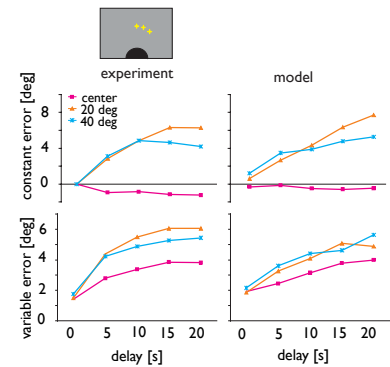
- repulsion from perceptual boundaries, e.g., midline



Spencer, Hund, JEP:G (2002)

spatial memory

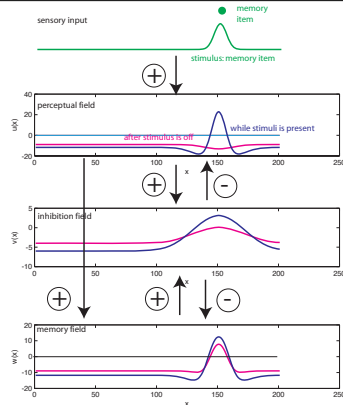
- attraction to other locations occurring in the task
- account for both biases through DFT



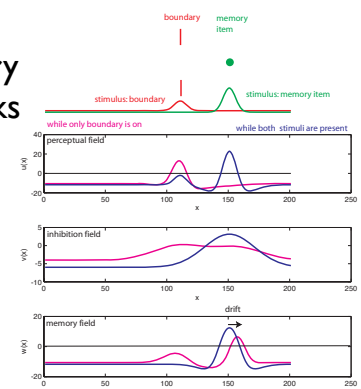
Spencer, et al. 2003

processing unit

- emergent working memory

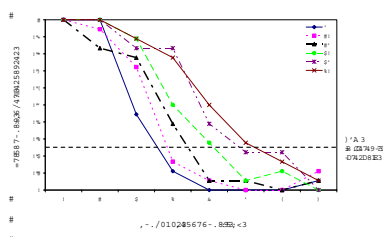


repulsion of spatial memory from landmarks



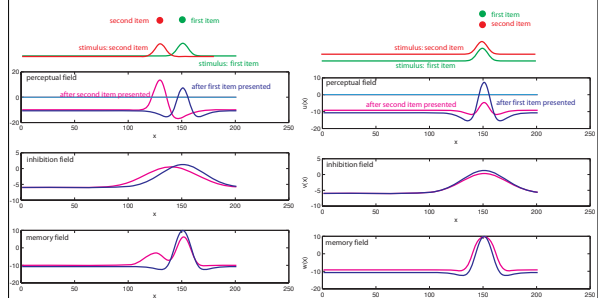
discrimination

- is improved near perceptual boundaries

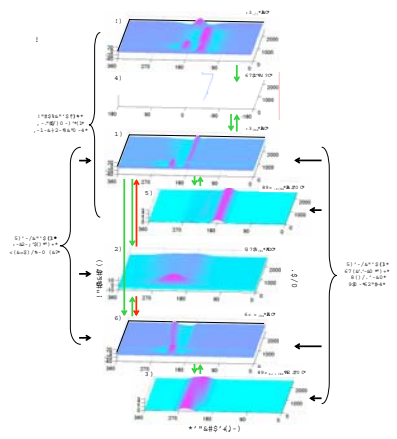


Simmering, Spencer, Schöner: Perc & Psychophysics (2006)

change detection



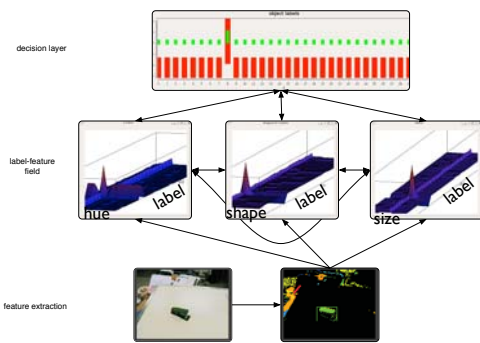
integrating it all...



robotic application: fast learning of visual objects

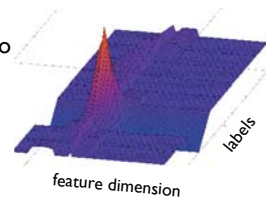
- robot learns to recognize objects interacting with a human user
- very few views of the object (1 to 9)
- => Christian Faubel

architecture



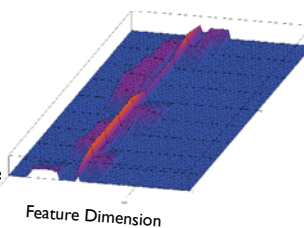
label-feature fields

- composed by one dynamic field for each object label to be represented
- competition along the feature dimension
 - but multiplex solutions possible
- competition along the labels
 - tuneable: multi-peak vs. single-peak regimes



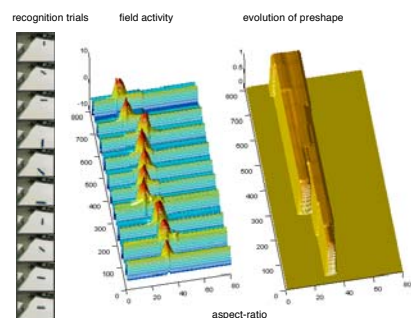
preshape

- laid down when activation peaks arise in the feature label fields
- facilitates activation if the input matches the preshape
- represents the variance of an object along the feature-dimension



preshape dynamics

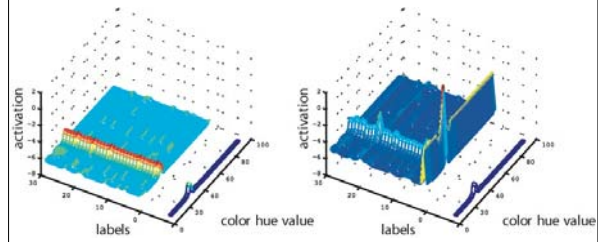
- learns updated feature values as object is viewed in different poses



peaks from broad vs. narrow preshape



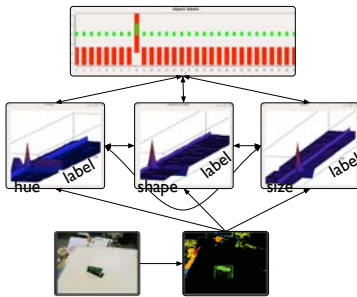
■ recognition in a feature-label field



recognition

■ competing label neurons

- receive activation from the feature-label fields
- forces a selection decision by simple majority voting
- once a label is selected, inhibition is sent to all non-matching labels

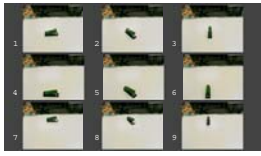


performance

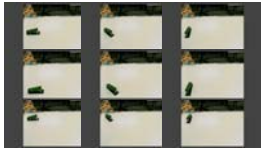
■ learning 30 objects



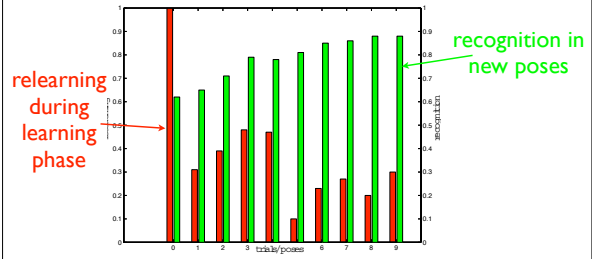
- each object presented in 3 location, and 3 rotations (0, 45, 90)



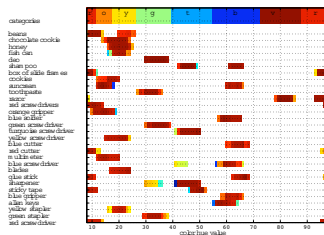
- test in new locations and rotations



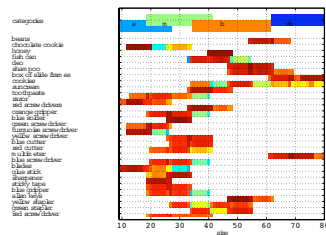
- recognition rates in new locations stabilize by about the 5th view, at levels of around 80 %
- terminal recognition rate after 9 views/object 83%



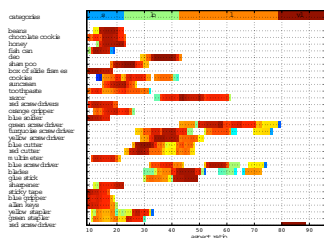
emergent categories



emergent categories



emergent categories



recognition is not based on categorical information only

- e.g., red beans and the box of slide frames are both categorically red, big and square, but can be readily discriminated...
- recognition picks up subtle metric properties within feature representations

what role for the interaction between feature dimensions?

- feature “binding”: are the values along the different feature dimensions pertaining to an object “bound” in some way?
- not explicitly once recognition has happened
- but in the process, different feature dimensions mutually support selection

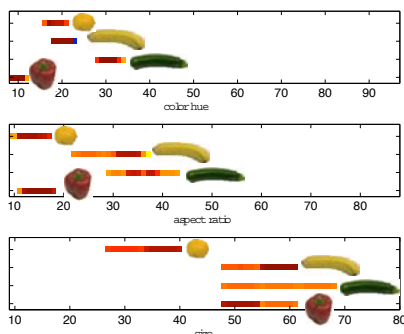
to study this, need simplified setting

- 4 objects whose similarities are overlapping differently along different feature dimensions

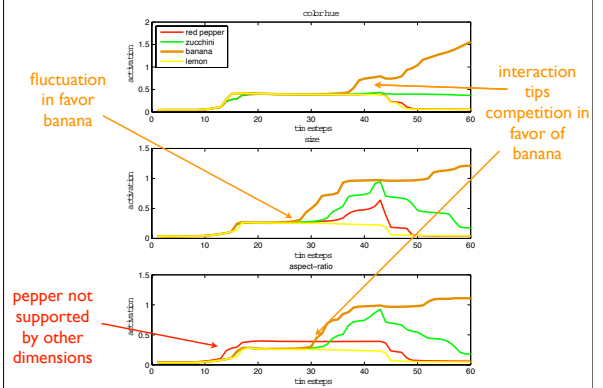


banana red pepper zucchini lemon

similarity reflected in memory traces



dynamics of recognition:



conclusion: binding

- interaction acts as a form of “binding” during the recognition process when different objects compete along different dimensions
- but as number of objects and of feature dimensions scales, these special situations become rare

Conclusions

- DFT as a framework for understanding how stable behavior and elementary forms of cognition emerge from spatio-temporally continuous neuronal dynamics
- supported by neuronal and behavioral signatures!
- provides a process account for emergence, multi-causality, and the dependence on individual behavioral history

thanks to students, postdocs, mentors, and colleagues

- Bochum: Claudia Wilimzig, Stefan Schneider, Valère Martin, Christian Faubel, Yulia Sandamirskaya, Claudia Grote, Ioannis Iossifidis
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- Iowa: John Spencer, Anne Schutte (now: Nebraska), Vanessa Simmering, Jeff Johnson, John Lipinski, Sammy Perone
- former: Klaus Kopecz, Wolfram Erlhagen (now: Minho), Martin Giese, Axel Steinhage (Bochum) Estela Bicho (now: Minho), Pierre Mallet (Marseille); Virgil Whitmyer (Iowa)