Sequence generation in DFT

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Sequences

- all behavior and thinking consist of sequences of physical or mental acts
- sometimes in a fixed order as in action routines, or highly trained action patterns
- but potentially highly flexible … as in language, thinking, problem solving …

Probes of sequence generation

- serial order: separate from other aspects of memory (Lashley)
- implicit sequence learning
- sequential actions: timing

DFT challenge for sequences

- DFT postulates that all neural states underlying behavior/mental process are attractors that resist change…
- but generating sequences of such states require change of state! => conflicting constraints!
- answer: instabilities are induced systematically to enable switching to a next/new attractor

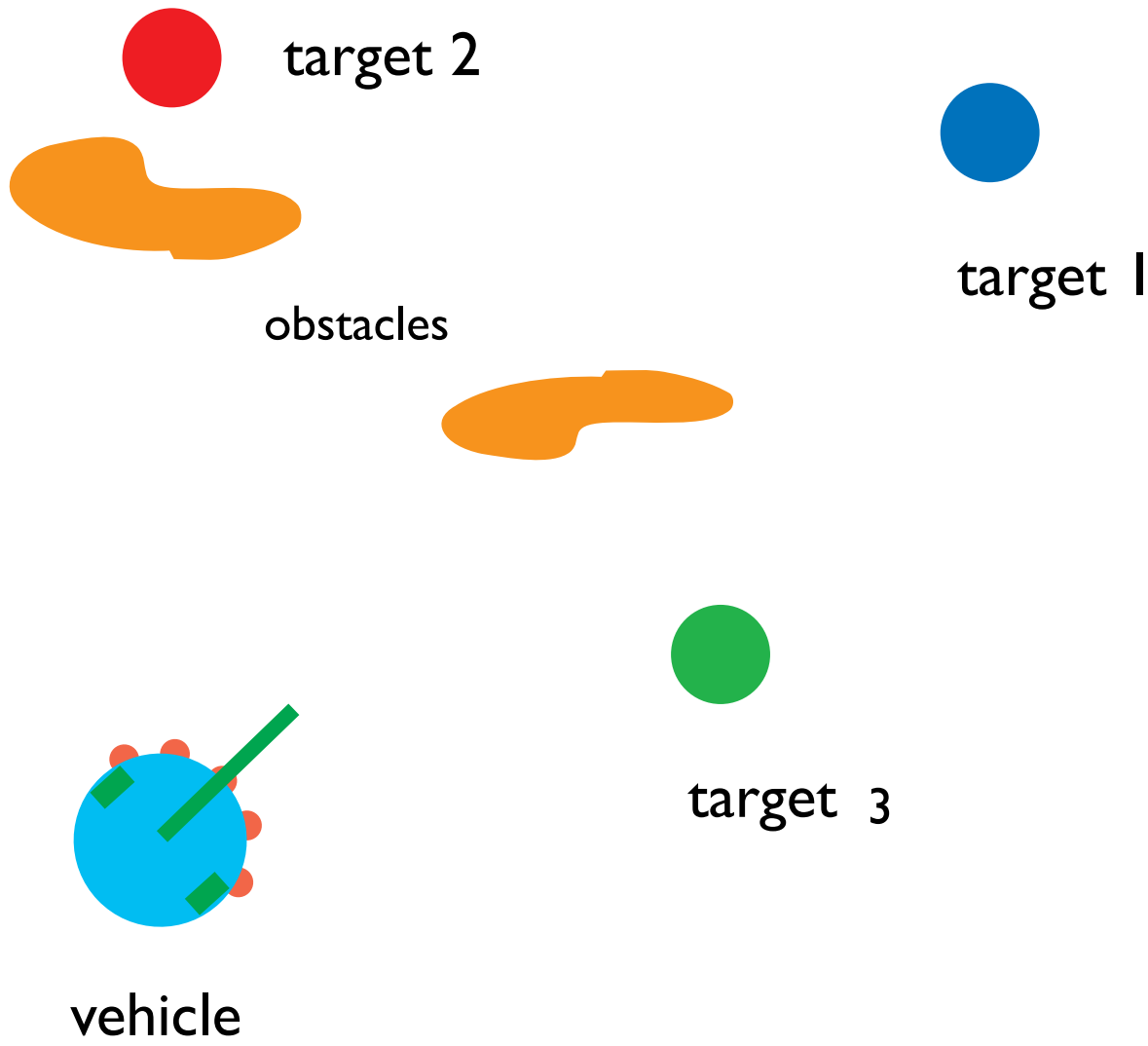
Roadmap

Sequence generation

- an illustrative example: the CoS
- the neural/mathematical mechanism of the CoS
- global view of sequence generation
- what state next?
- what if the CoS fails?
- a robotic demo

Illustration: sequence of actions

- task: search for objects of a given color in a given order
  - 1 blue
  - 2 red
  - 3 green

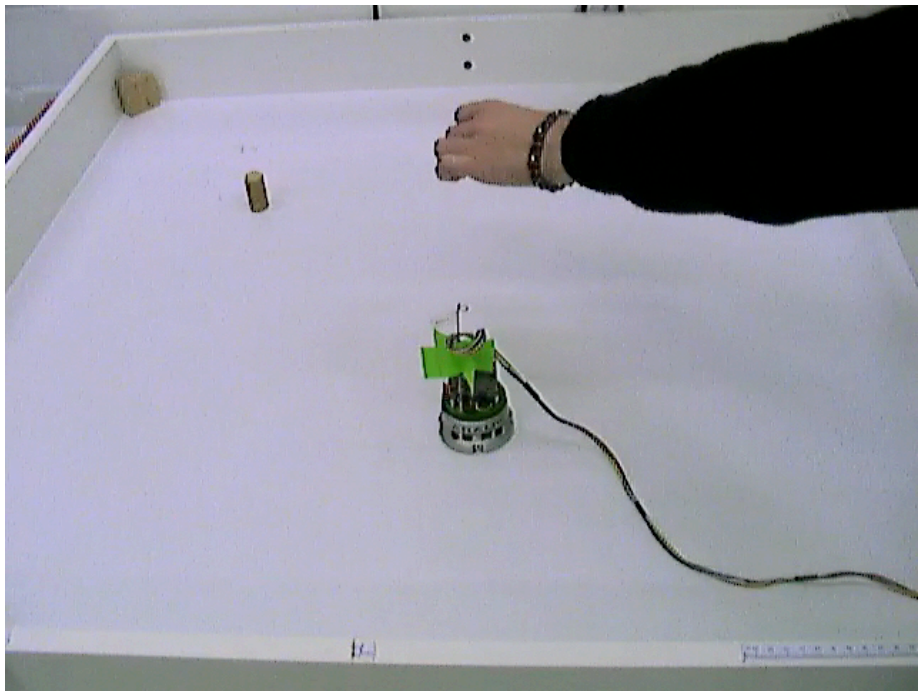


- stably couple to objects once they are detected
- ignore objects when their turn has not yet come (distractors)

Implementation as an imitation task

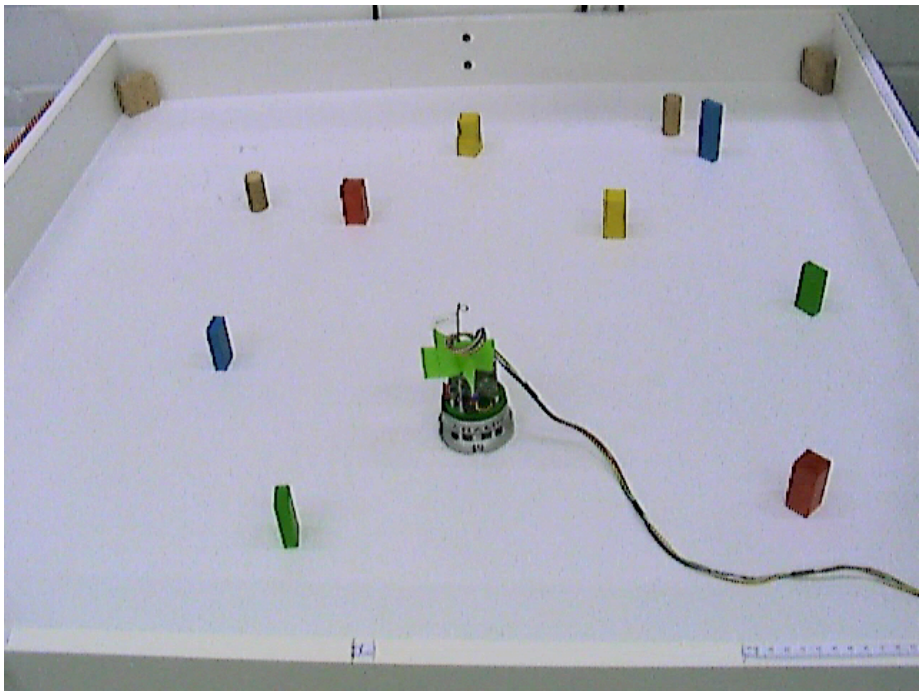
- learn a serially ordered sequence from a single demonstration

yellow-red-green-blue-red



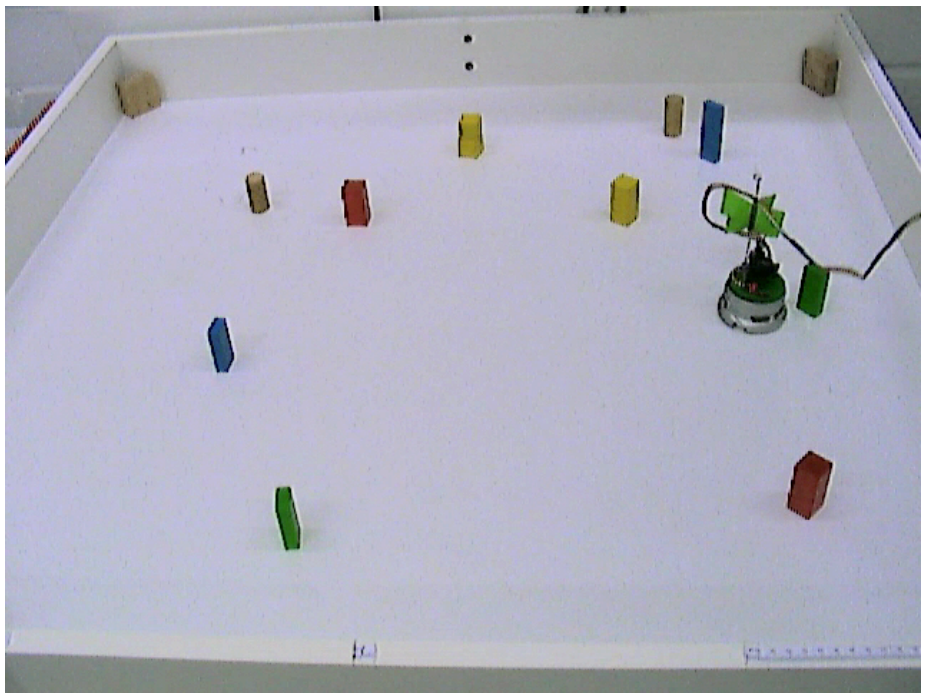
- perform the serially ordered sequence with new timing

yellow-red-green-blue-red

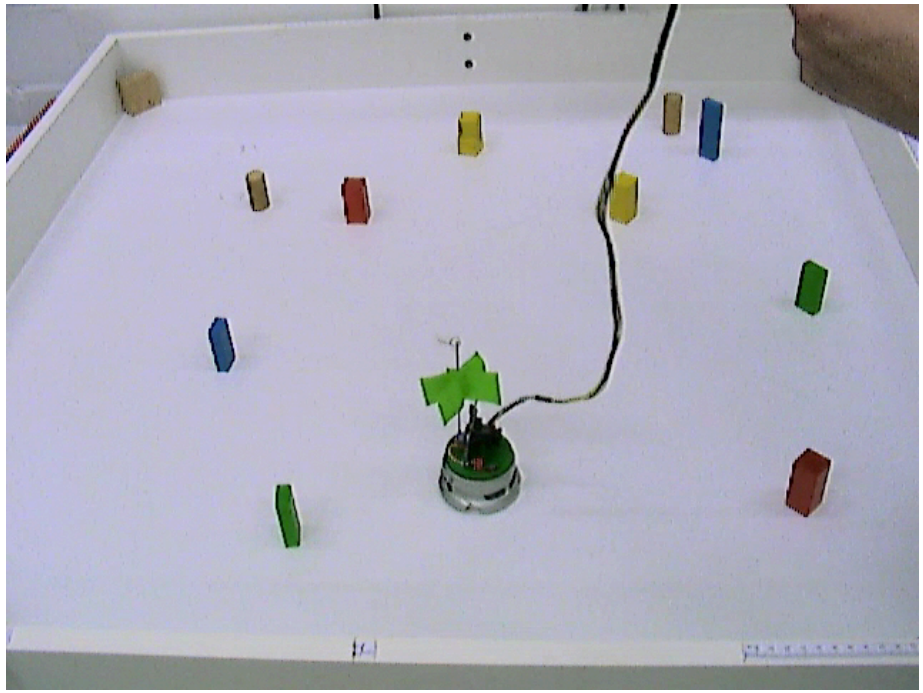


[Sandamirskaya, Schöner: *Neural Networks* 23:1163 (2010)]

red a distractor

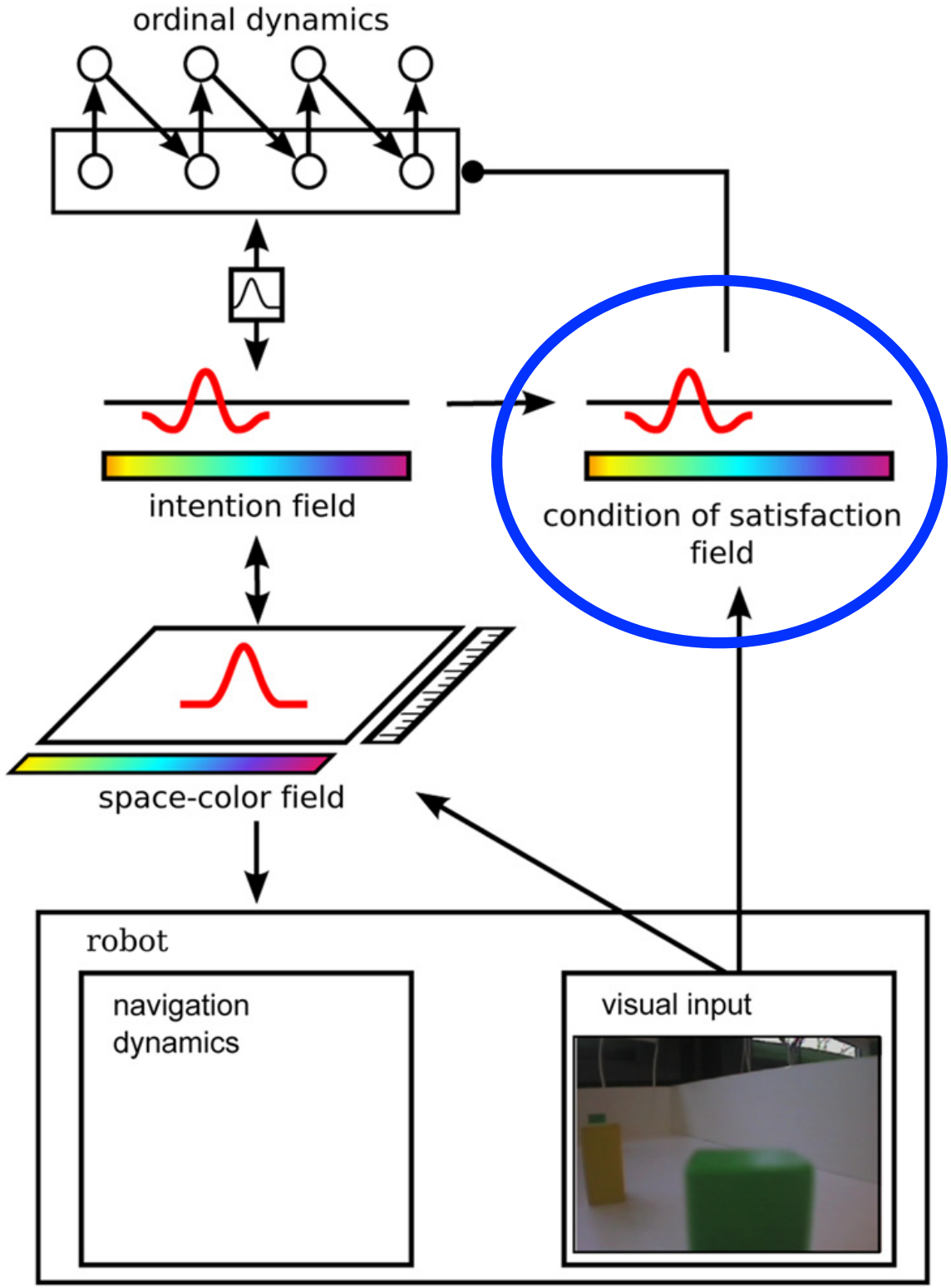


red a target



[Sandamirskaya, Schöner: *Neural Networks* 23:1163 (2010)]

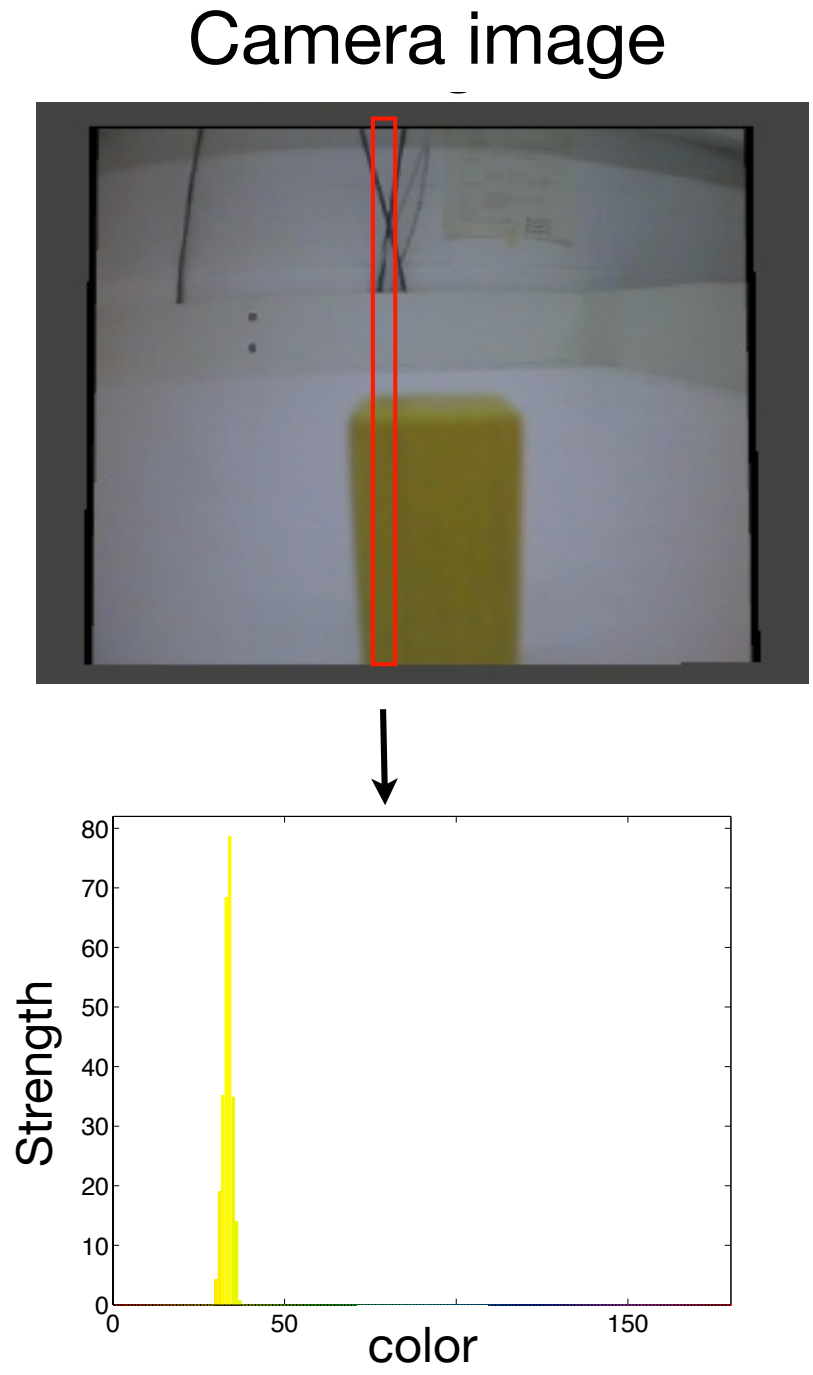
Condition of Satisfaction (CoS)



[Sandamirskaya, Schöner: *Neural Networks* 23:1163 (2010)]

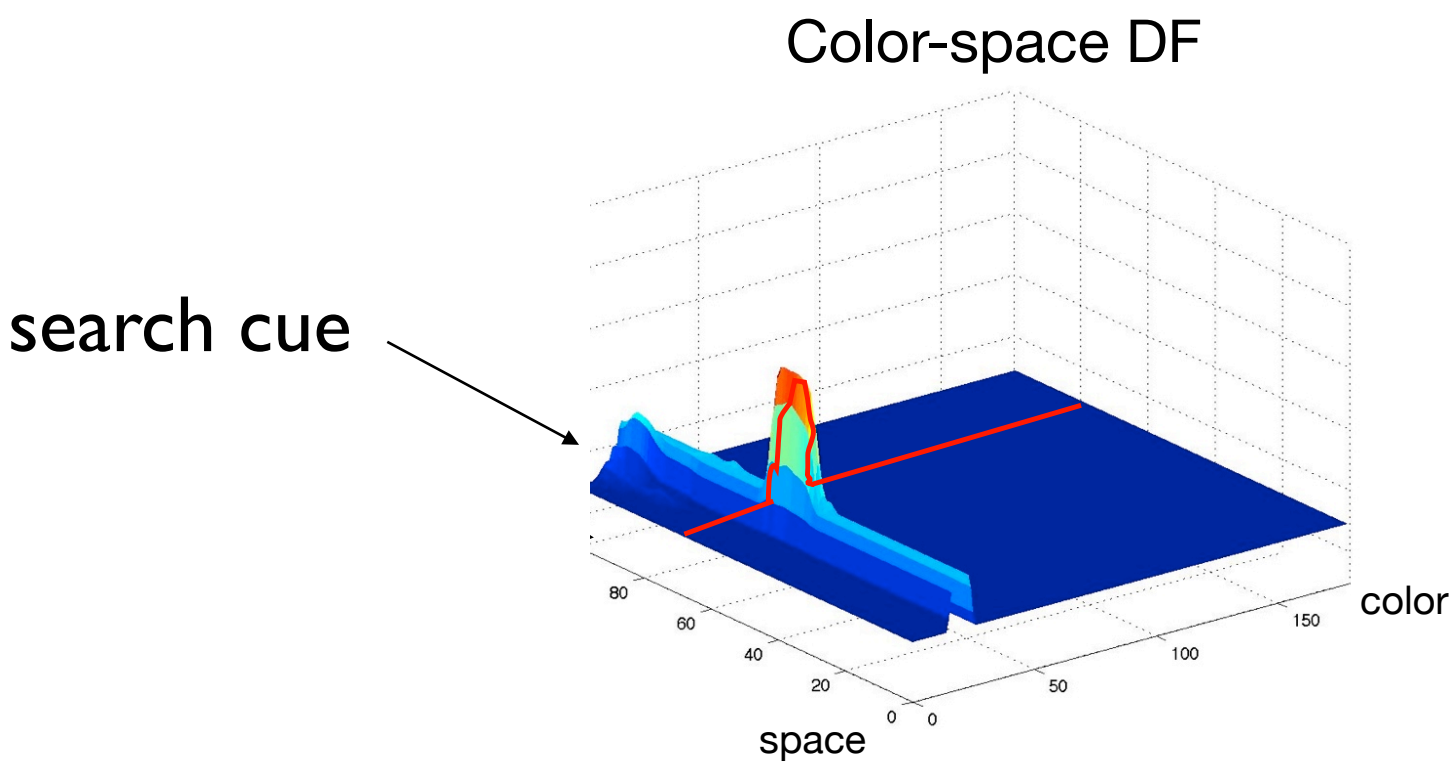
Visual input

- 2D visual input
  - horizontal space
  - color
- "intensity" of 2D input from color histogram at each horizontal location

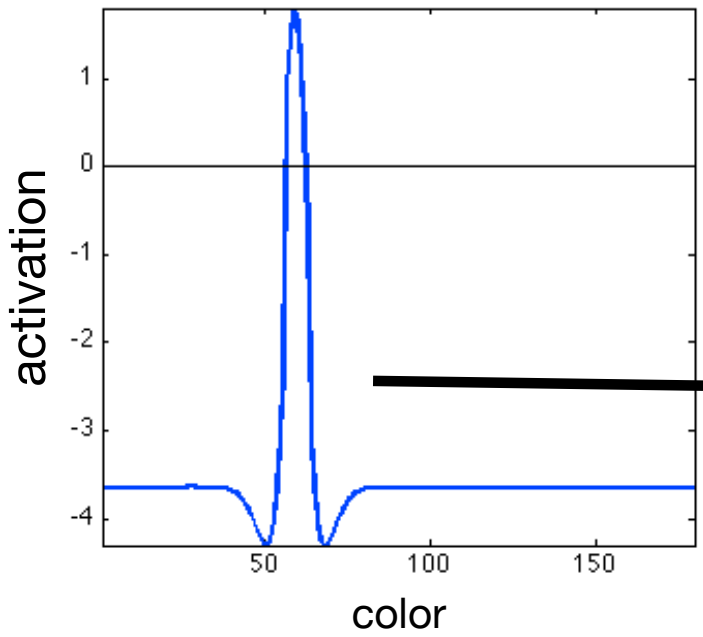


Visual search

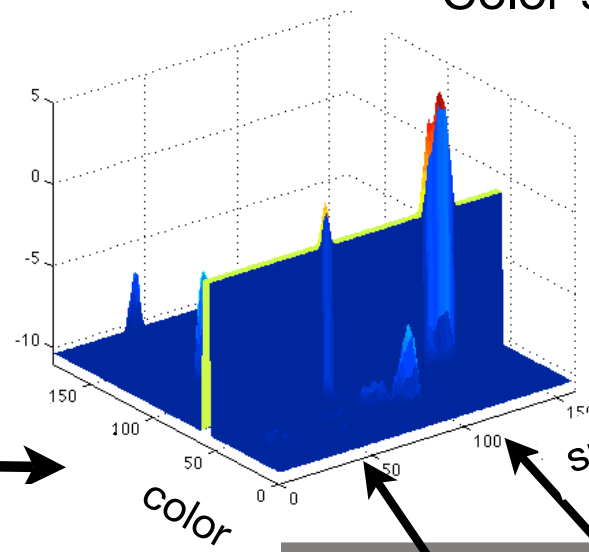
- intention=color cue provides ridge input into space-color field
- when that ridge overlaps with 2D space-color input => peak formed



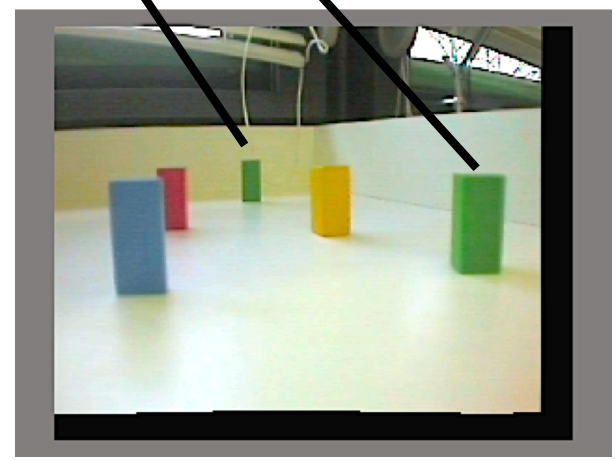
Intention DF



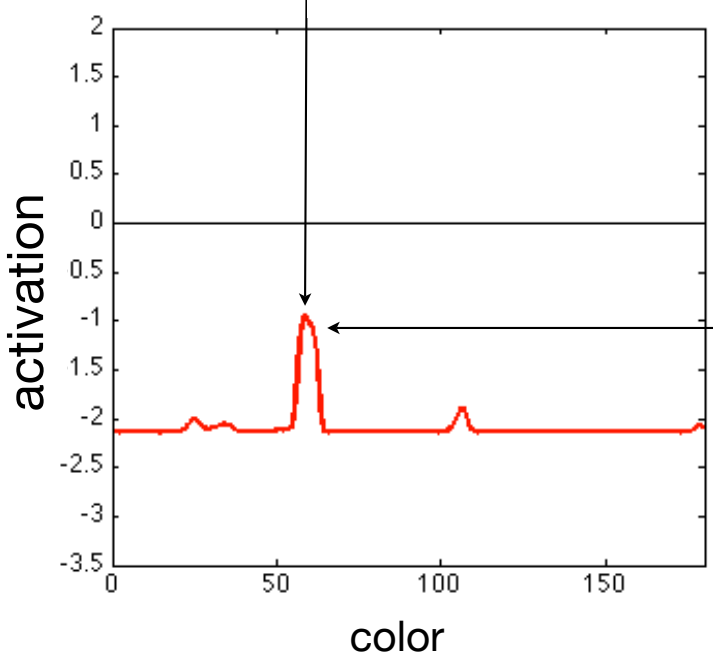
Color-space DF



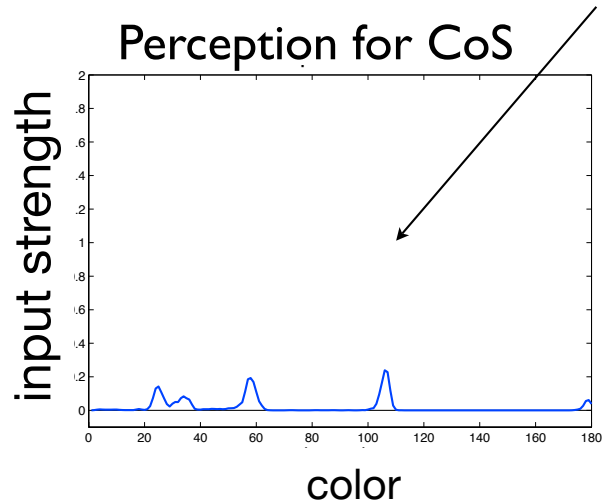
Camera image



CoS DF



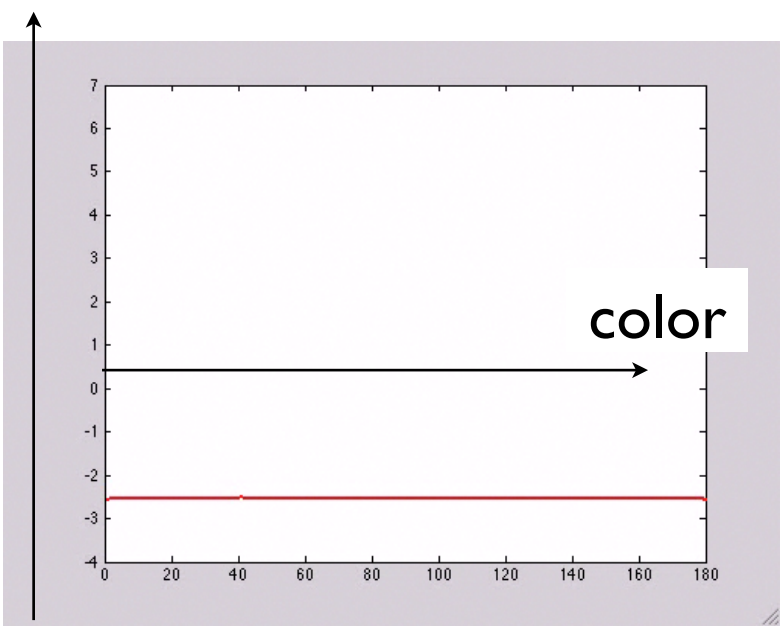
Perception for CoS



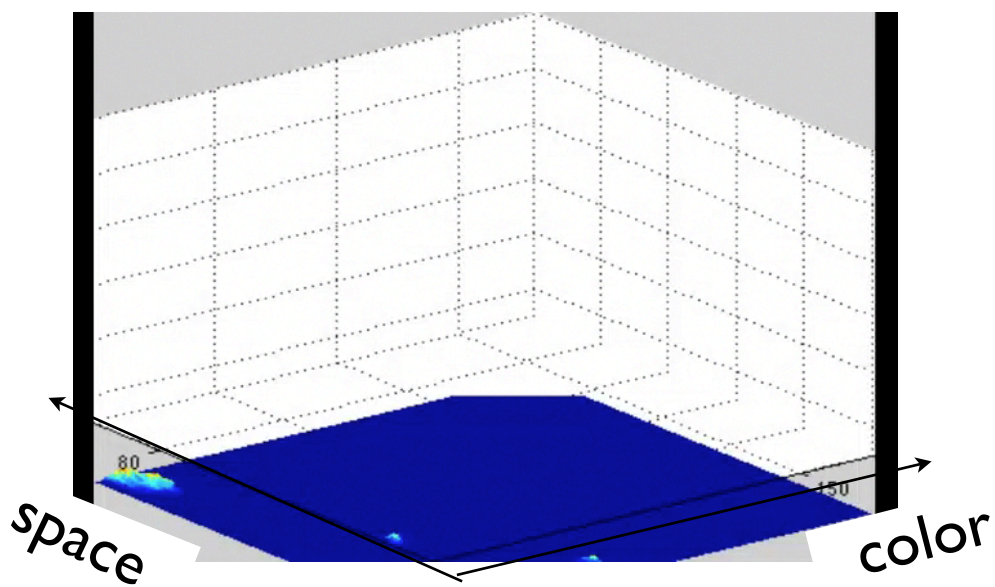
ordinal stack

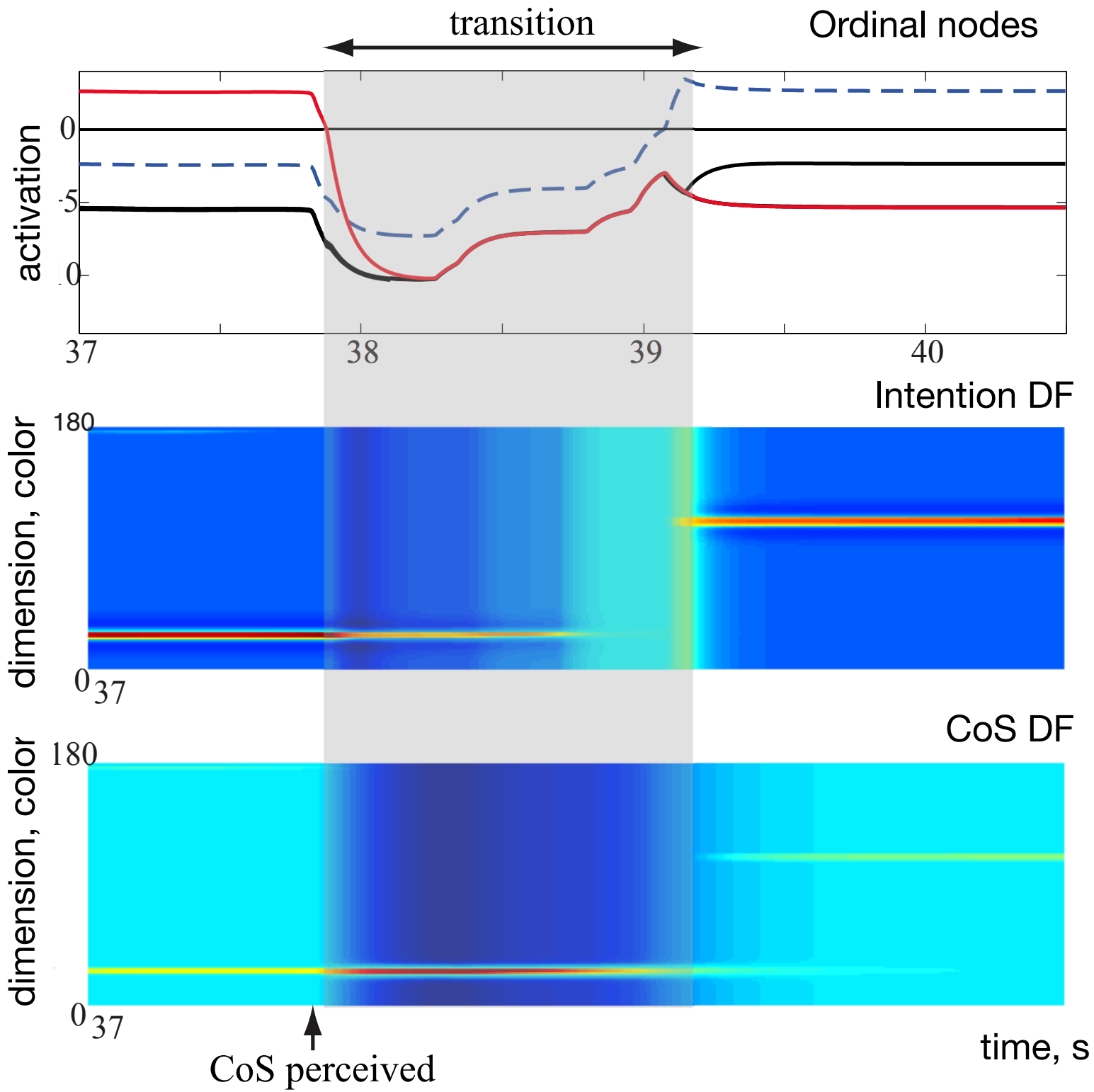
condition of satisfaction (CoS)

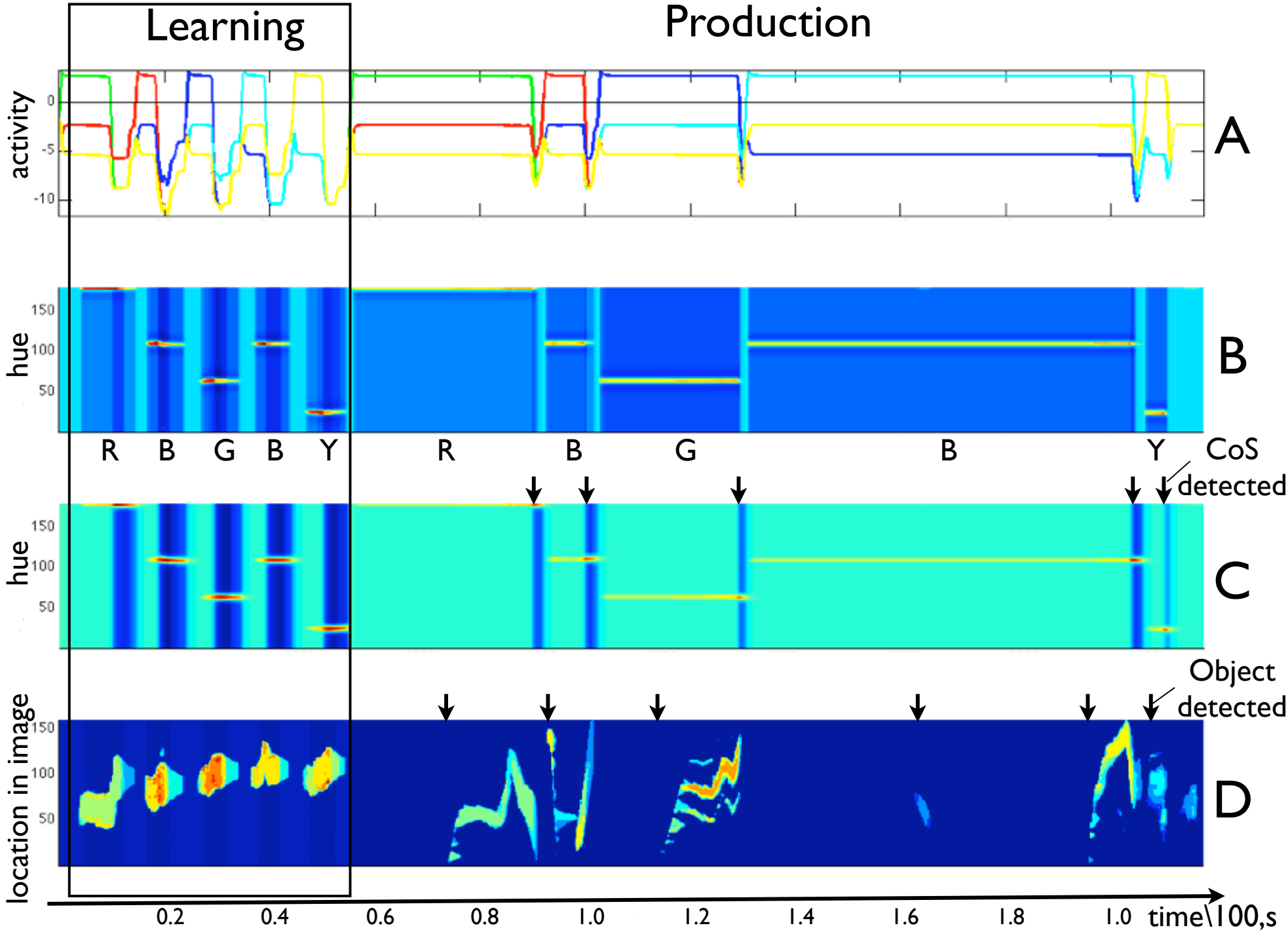
intentional state



2D color-space field




transition
Ordinal nodes
activation
0
-5
0
37
38
39
40
Intention DF
dimension, color
180
0
37
CoS DF
dimension, color
180
0
37
CoS perceived
time, s


Learning
Production
activity
0
-5
-10
A
hue
150
100
50
B
R B G B Y R B G B Y
CoS detected
hue
150
100
50
C
Object detected
location in image
150
100
50
D
0.2 0.4 0.6 0.8 1.0 1.2 1.4 1.6 1.8 1.0
time\100,s

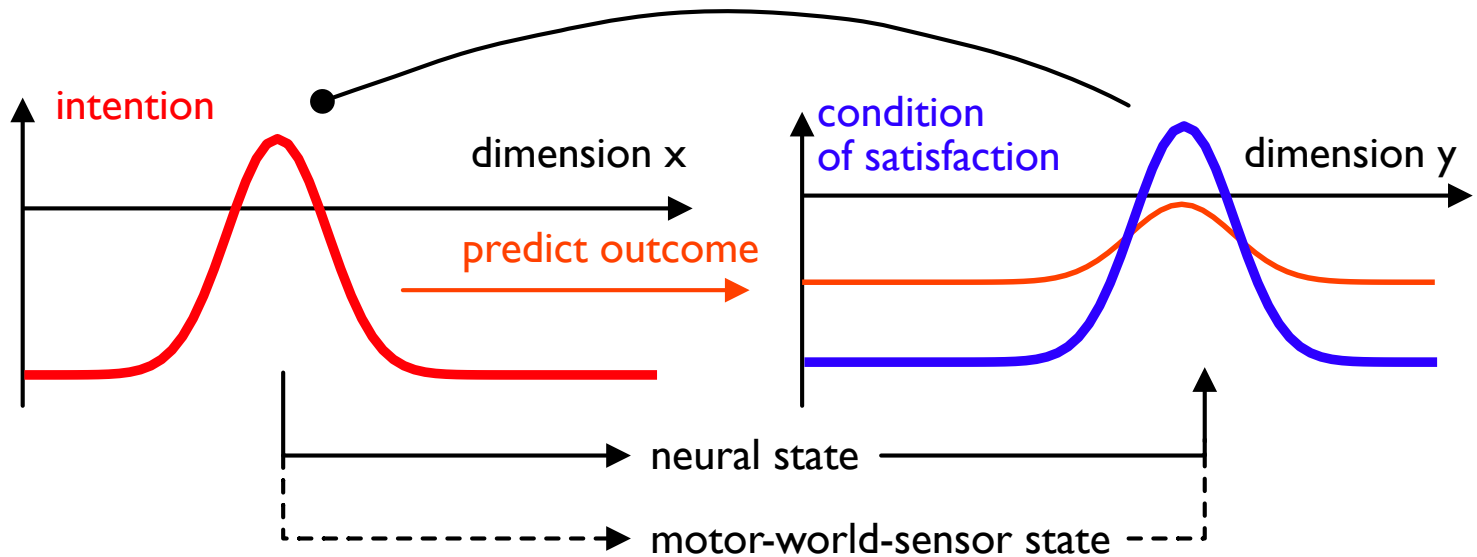
Roadmap

Sequence generation

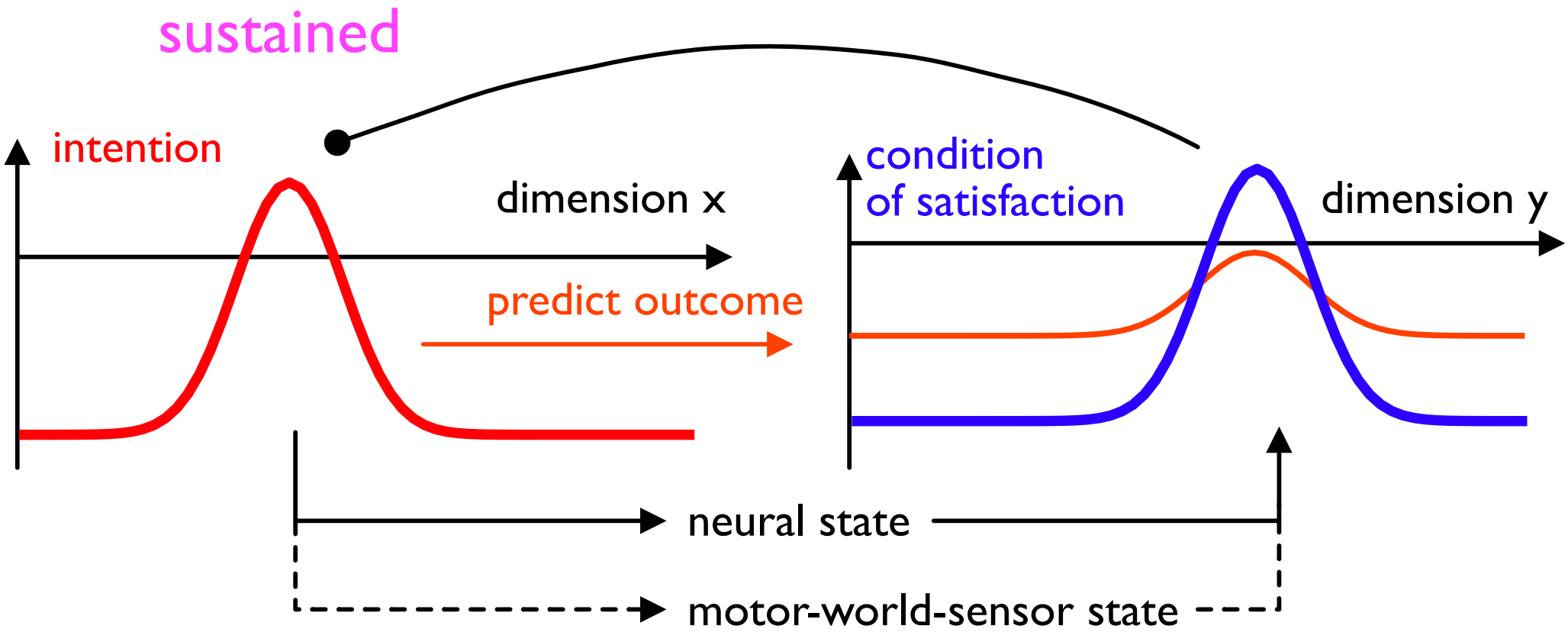
- an illustrative example: the CoS
- the neural/mathematical mechanism of the CoS
- global view of sequence generation
- what state next?
- what if the CoS fails?
- a robotic demo

Neural dynamic principle

- the current neural attractor state = intention
- predicts its condition of satisfaction (CoS)
- input matching prediction: CoS activated
- CoS inhibits intention…



[Sandamirskaya, Schöner: *Neural Networks* 2010;
Sandamirskaya *DFT primer* 2016]



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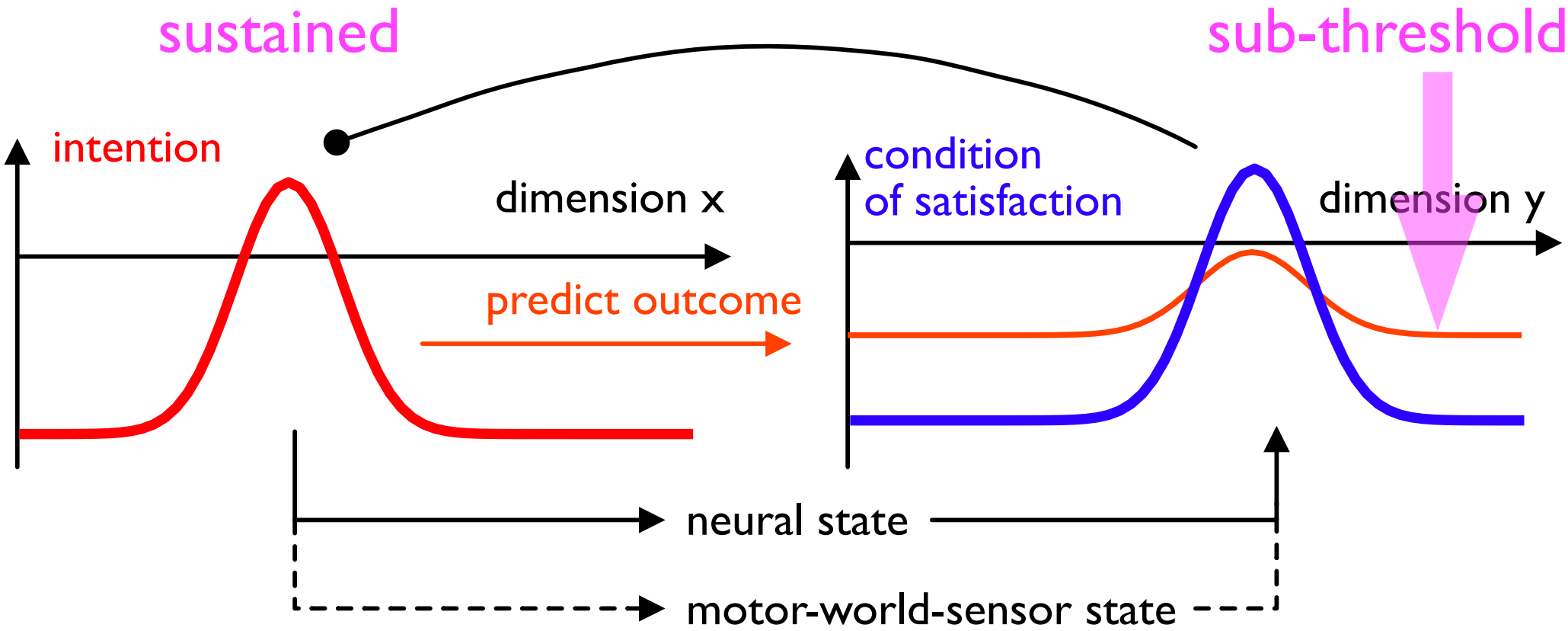
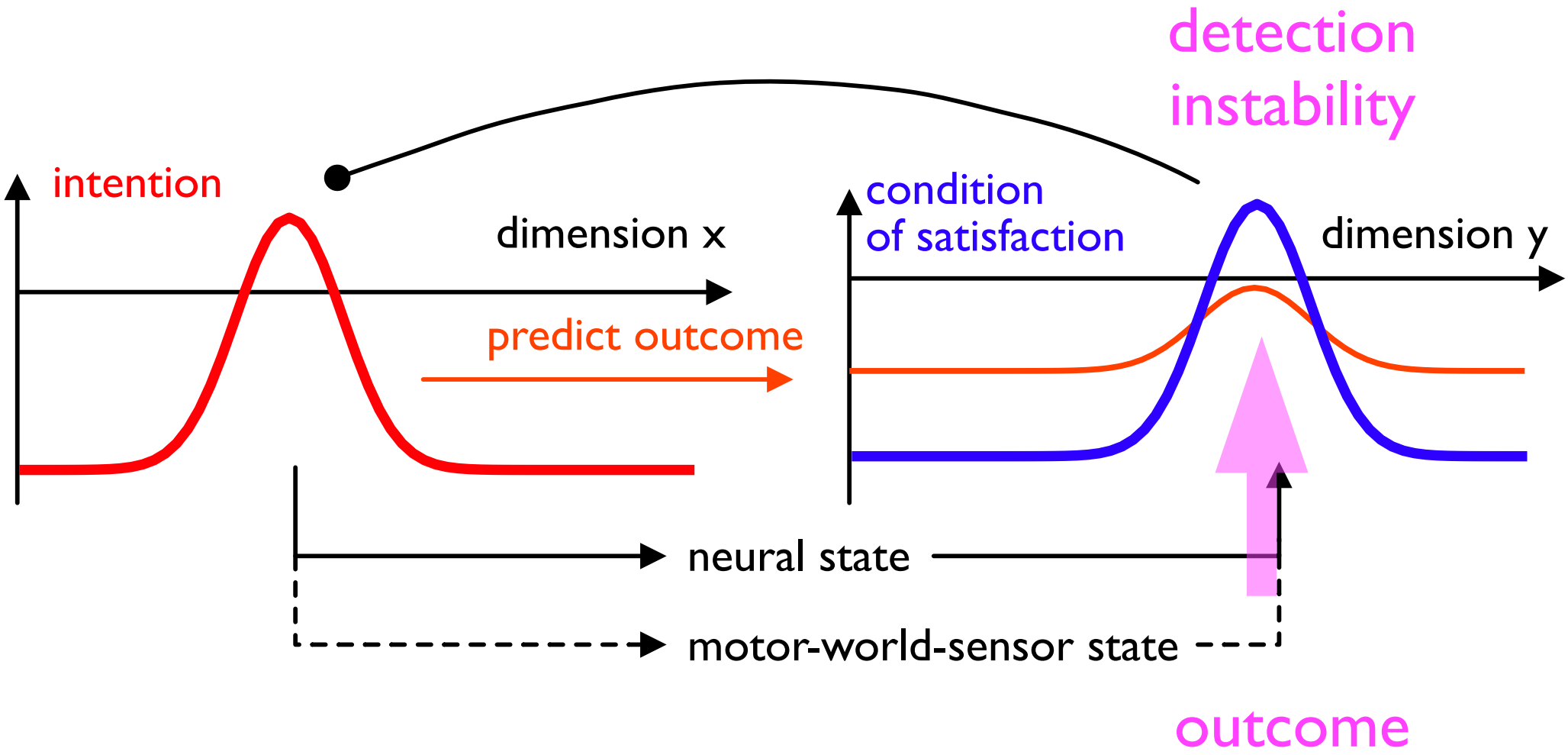


[Sandamirskaya, Schöner: Neural Networks 2010]

=> sequence generation



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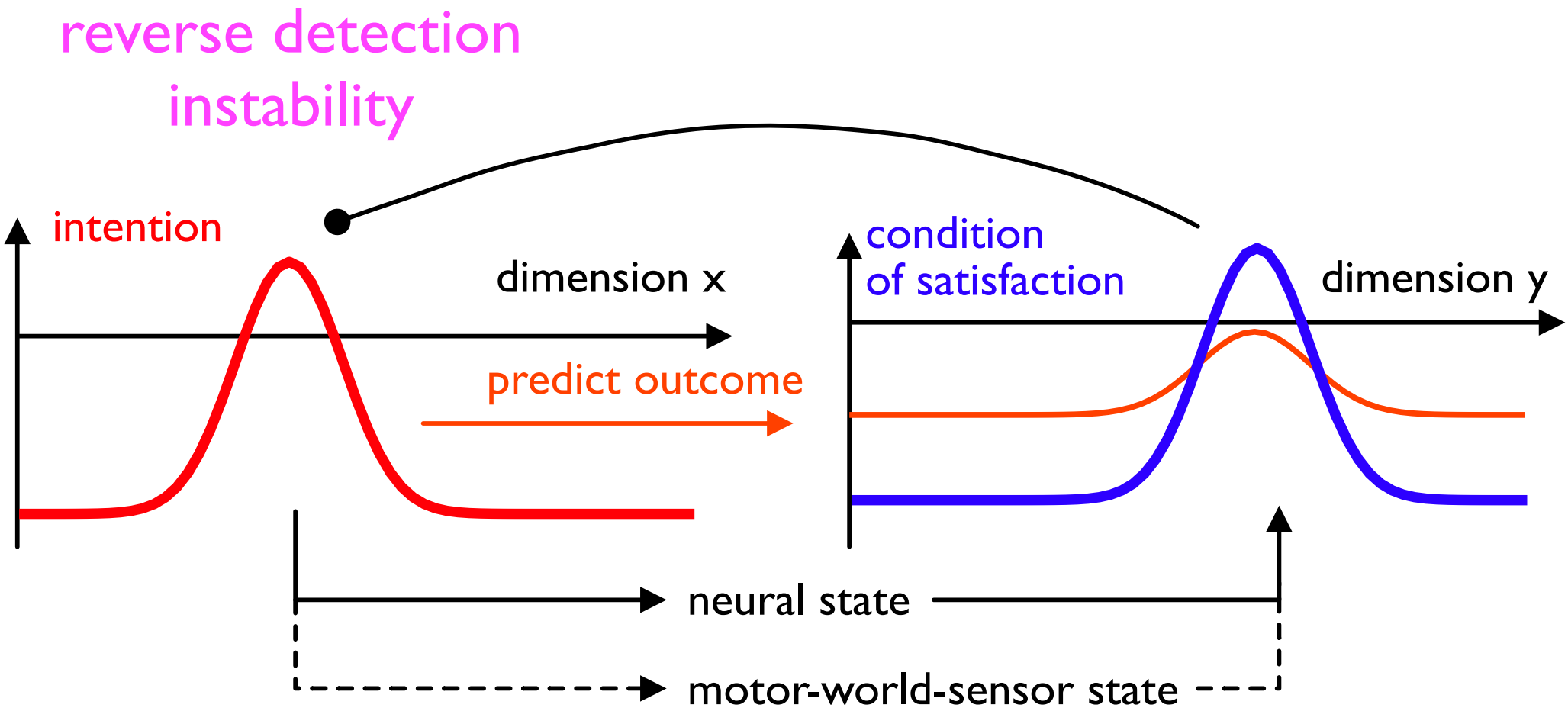

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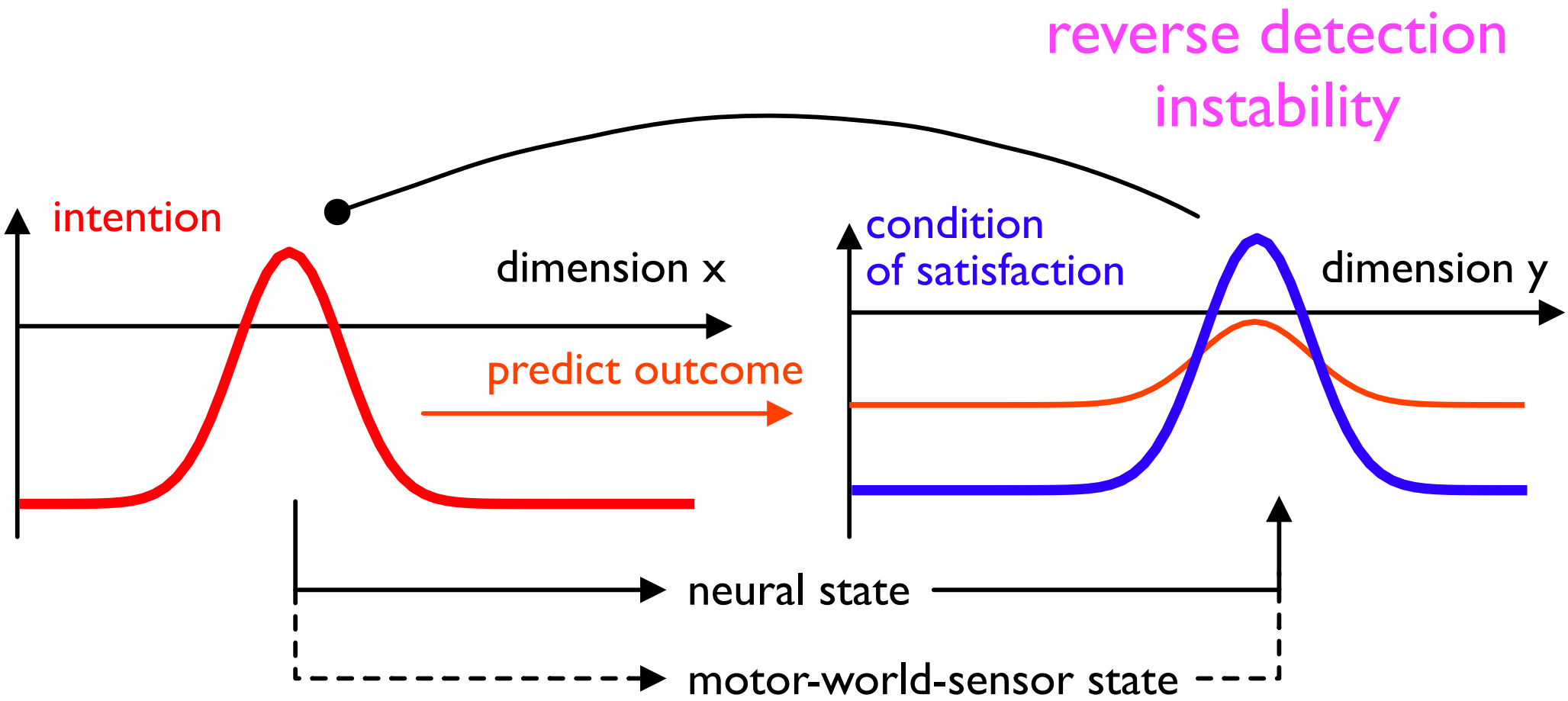
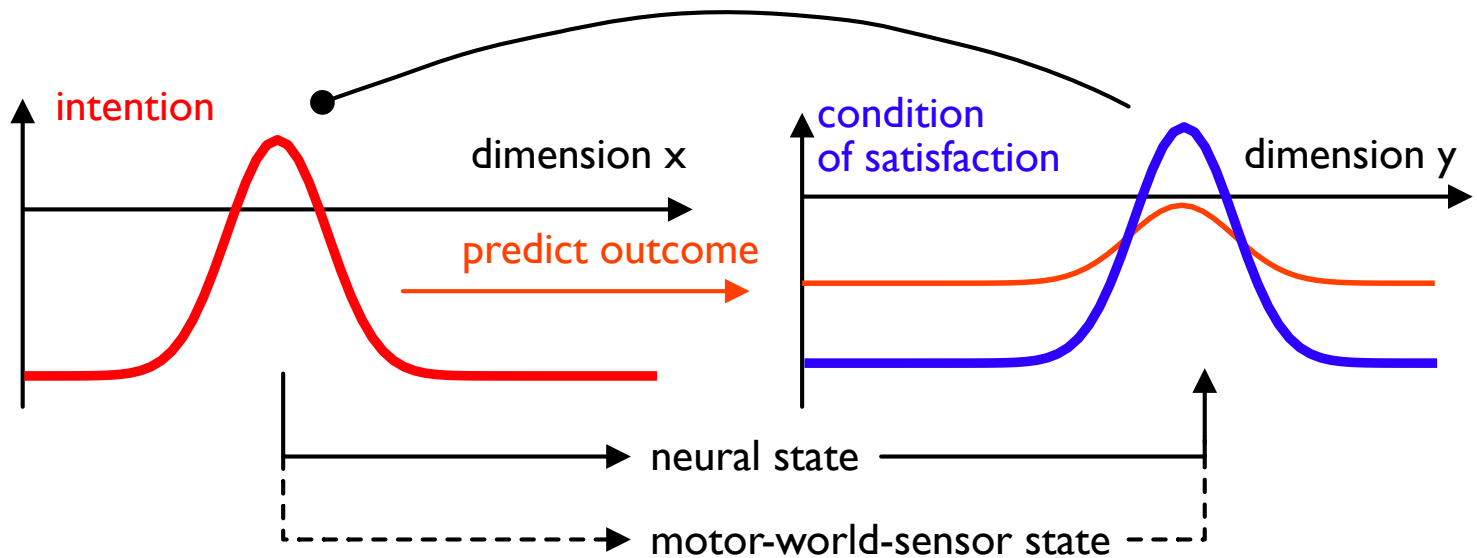


[Sandamirskaya, Schöner: Neural Networks 2010]

Neural dynamic principle

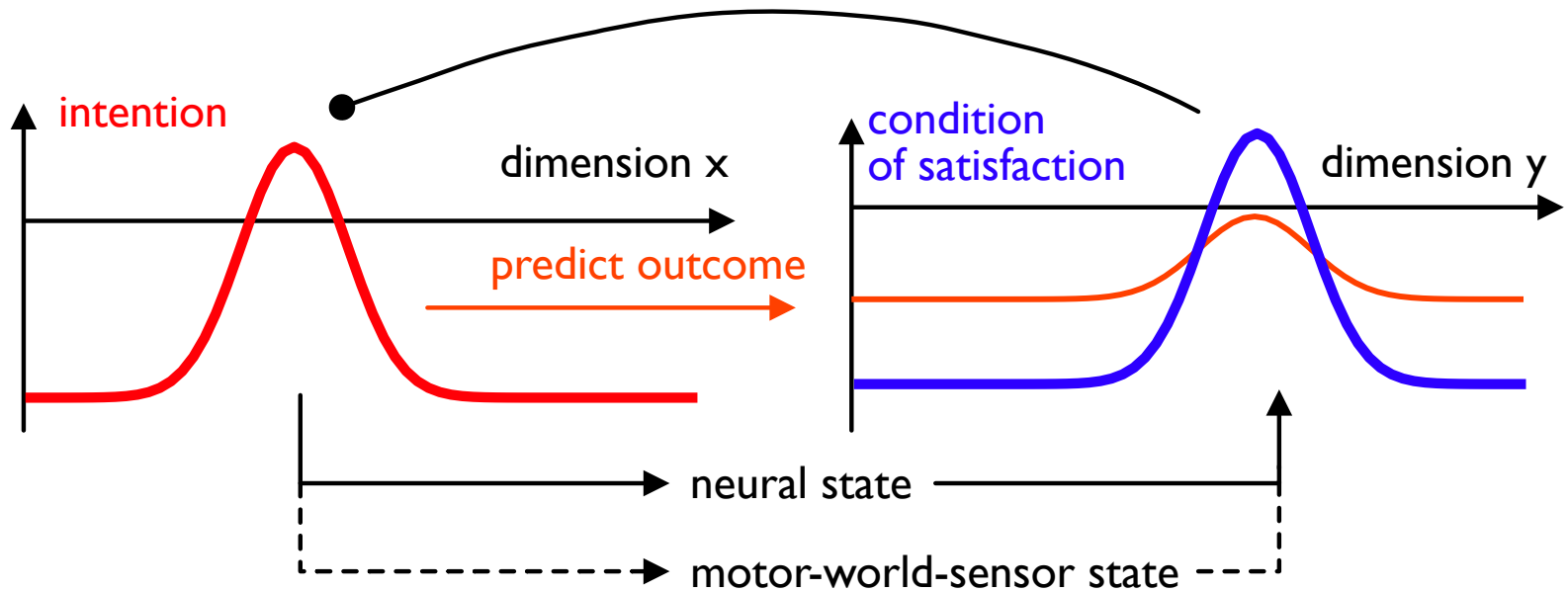
- this works also for purely "mental neural processes…
- in which the matching signal is internally generated



[Sandamirskaya, Schöner: *Neural Networks* 2010;
Sandamirskaya *DFT primer* 2016]

Theoretical question

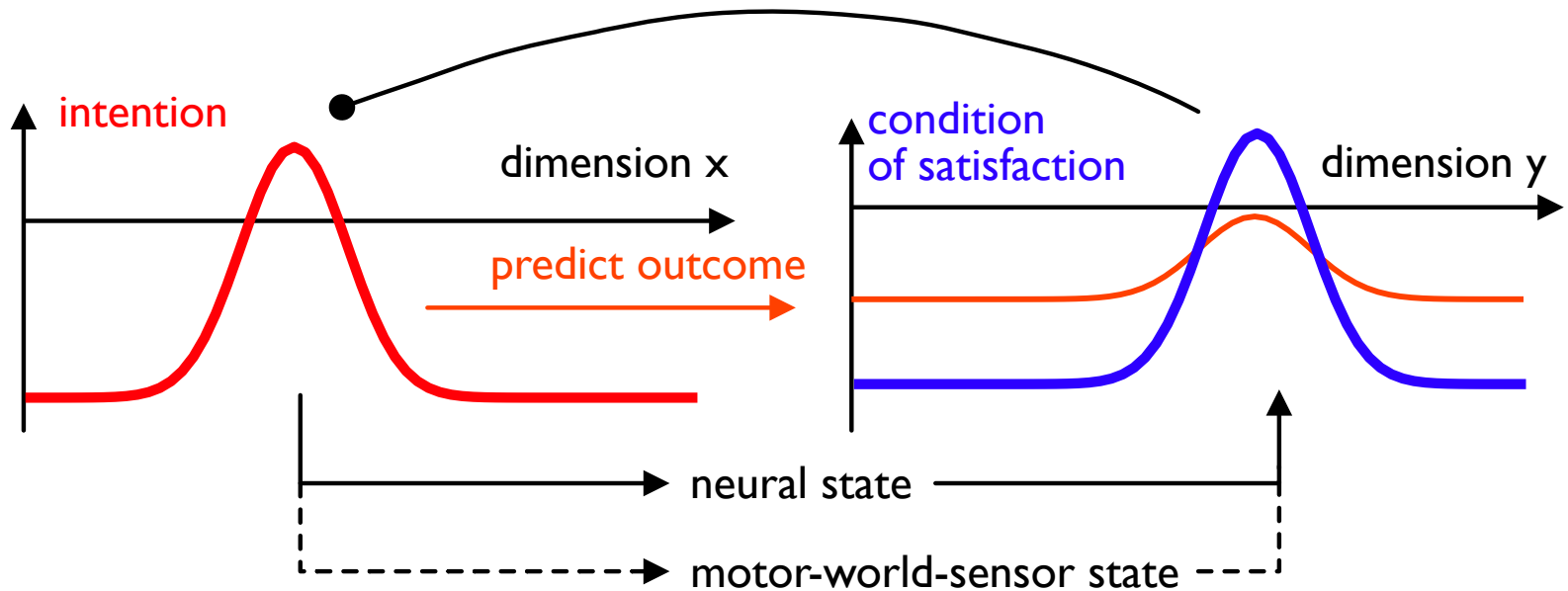
- CoS detection instability: requires an excitatory field with local excitatory interaction …
- inhibiting the intentional system: requires an inhibitory field…
- => violates Dale's law!



[Sandamirskaya, Schöner: Neural Networks 2010]

Solution: two layer field

- excitatory layer represents the "perceptual" state on which CoS builds
- inhibitory layer projects to intentional field
- the one field version: adiabatic elimination of inhibitory layer… is conservative



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Roadmap

Sequence generation

- an illustrative example: the CoS
- the neural/mathematical mechanism of the CoS
- global view of sequence generation
- what state next?
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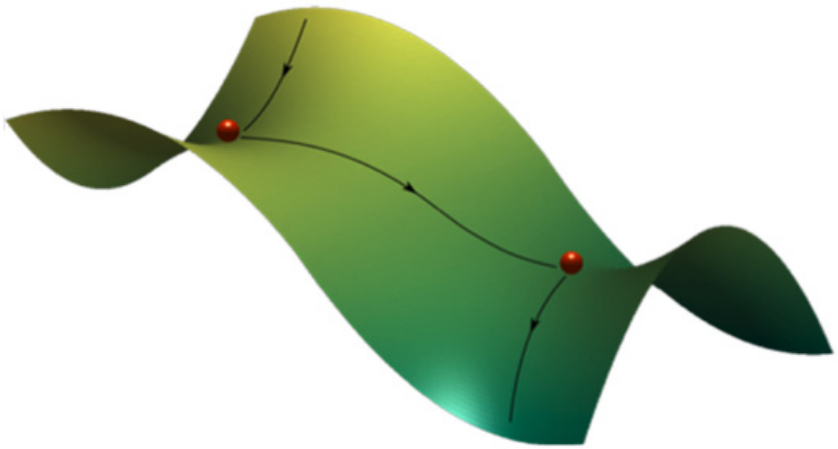
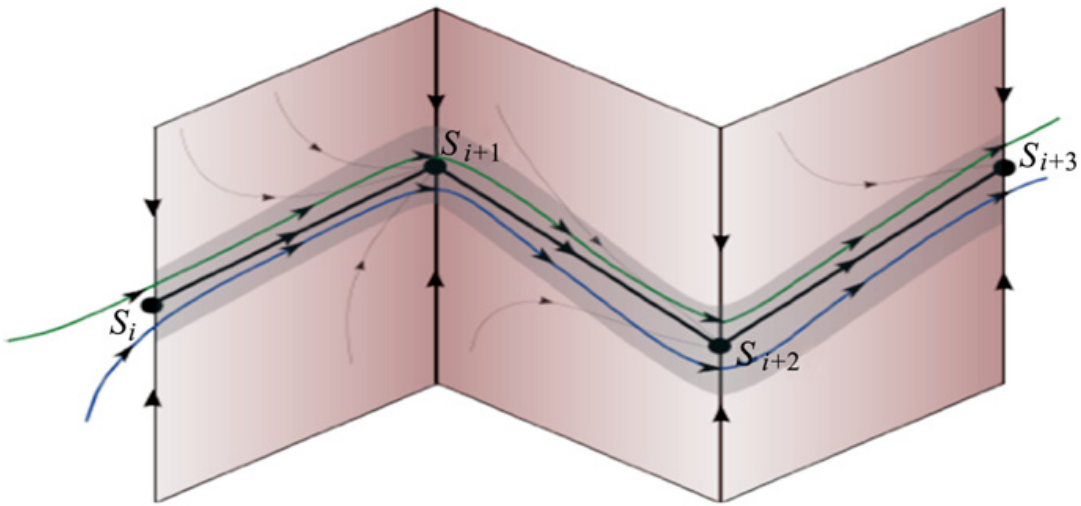
Global view of sequences

- globally, the neural dynamics system is NOT in an attractor… there is a transient in some dimensions along which the CoS arises
- that is typically a small subspace
- => Rabinovich's heteroclinic chain

Rabinovich's heteroclinic chain

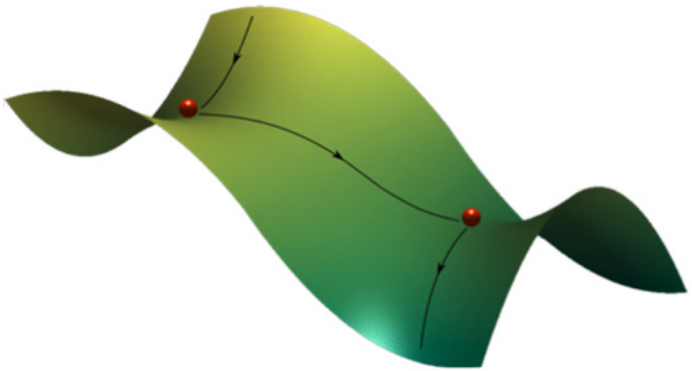


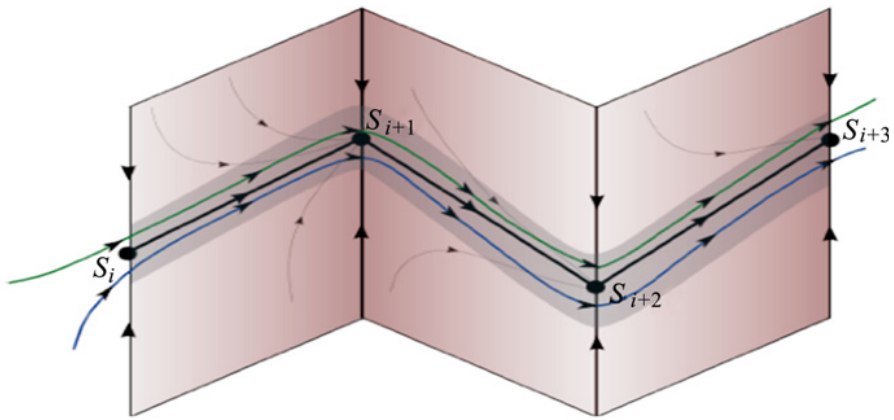


[Rabinovich et al., *Physics of Life Reviews* 2011]

Rabinovich's heteroclinic chain

- many more dimensions are stable then unstable…
- the stability of neural attractors is the organizing principle!





[Rabinovich et al., *Physics of Life Reviews* 2011]

What happens after a current intention state becomes unstable?

- Rabinovich: "winnerless competition"
- DFT: activation of another intentional state by the detection instability with selection

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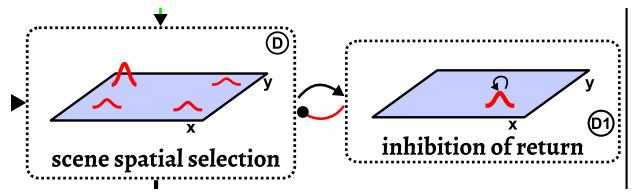
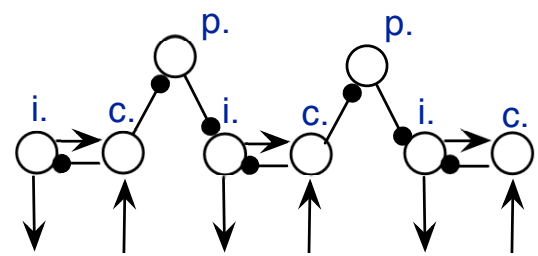
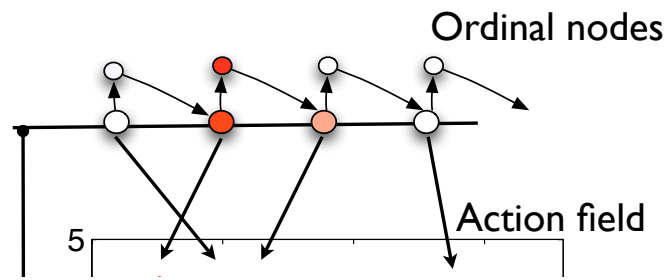
Selection of next state: three notions in cognitive psychology

- [Henson Burgess 1997]



- 1 gradient-based selection
- 2 chaining
- 3 positional representation





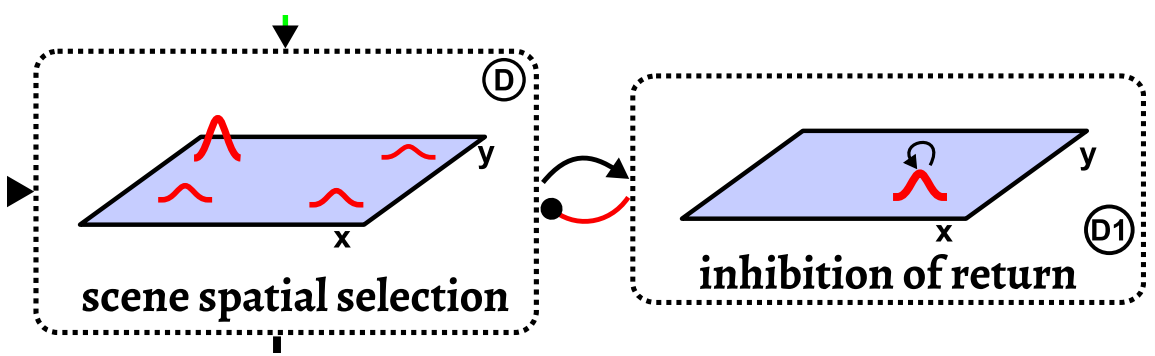
Gradient-based + DFT

- other possible states may have been in competition with the previous intentional state
- once that previous state is deactivated, these other states are released from inhibition
- => a new peak/node wins the selective competition based on inputs…
  - could be the previous inputs.. e.g. salience map for visual search
  - could be new inputs that are a consequence of the previous intentional stated

Gradient-based

- e.g. salience map
- e.g. input from guidance fields..
- re-activation of the previous intentional state may be prevented by inhibition of return

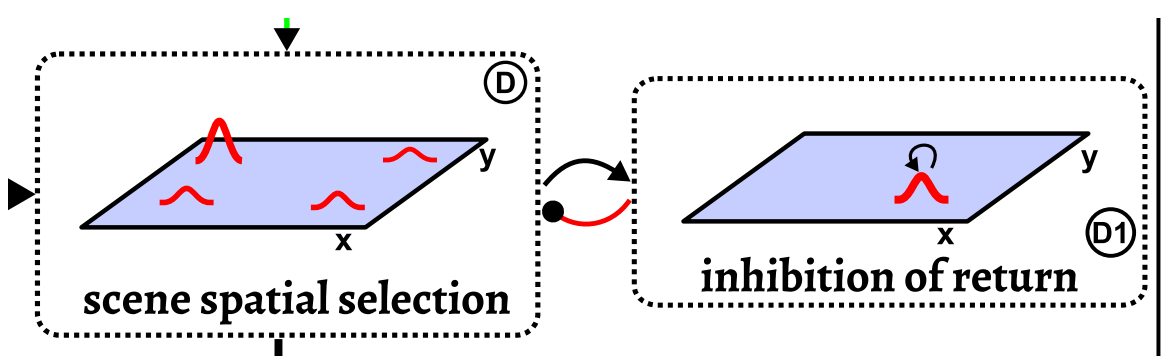
[Grieben, Schöner, CogSci 2021]



Gradient-based

- this is used in many DFT architectures
  - visual search
  - relational grounding
  - mental mapping

[Grieben, Schöner, CogSci 2021]



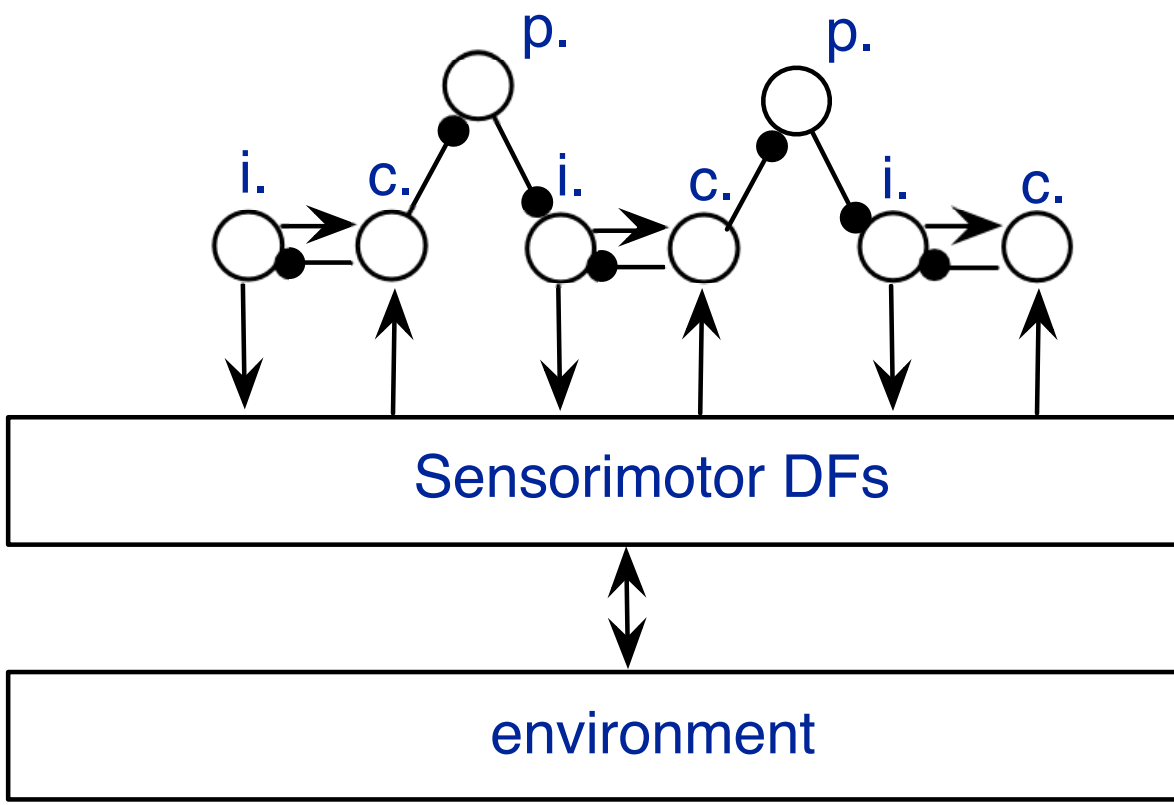
Chaining

- for fixed sequences…
  - e.g. reach-grasp
  - fixed order of mental operations… e.g. ground reference object first, then target object
- less flexible (e.g.. when going through the same state with different futures)
- could be thought to emerge with practice/habit from the positional system

Chaining + DFT

- "intention-CoS" pairs for different actions…
- chained by double inhibition

- the CoS of an earlier intention inhibits a pre-condition node that inhibits a later intention



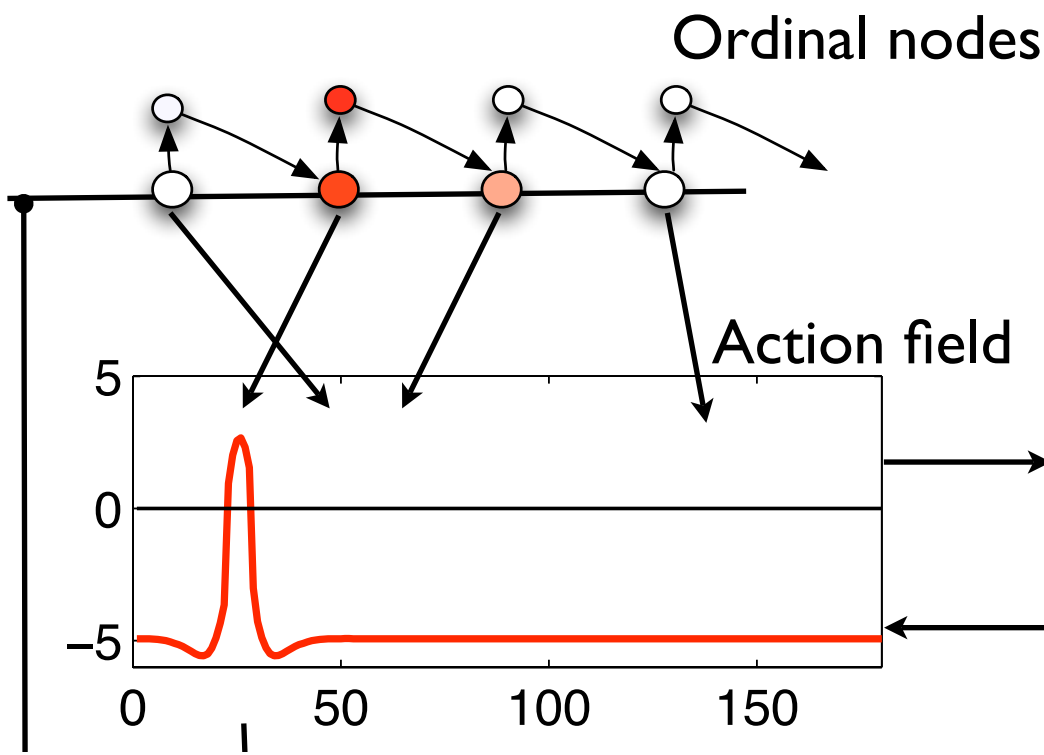
[Richter, Sandamirskaya, Schöner, *IROS* 2012]

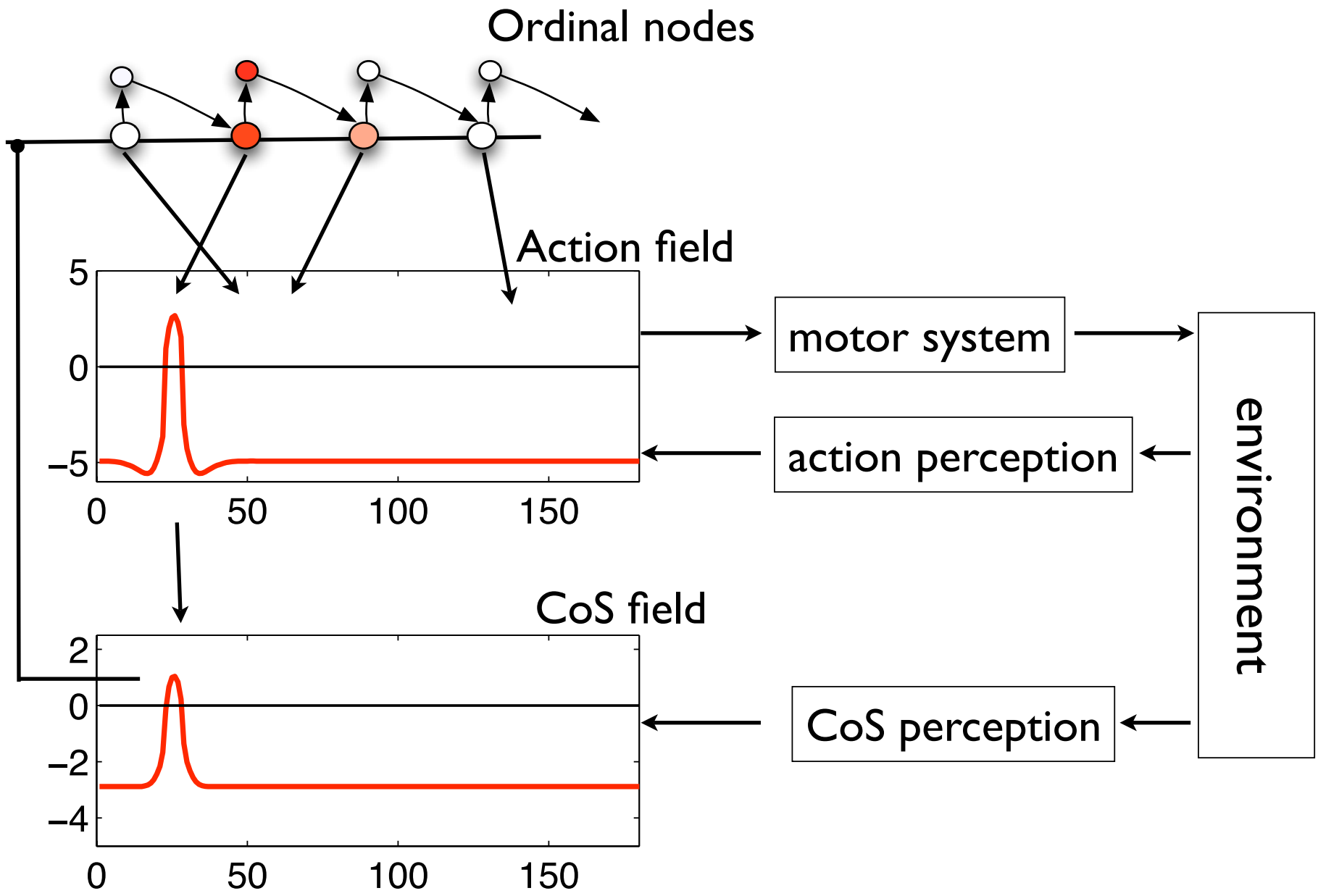
Positional representation

- a neural representation of ordinal position is organized by chaining
- the contents at each ordinal position is determined by neural projections from each ordinal node…

Positional representation + DFT

- in DFT, the ordinal dimension is spanned by ordinal nodes, coupled to enable chaining
- the transition along the ordinal dimension is organized by CoS!

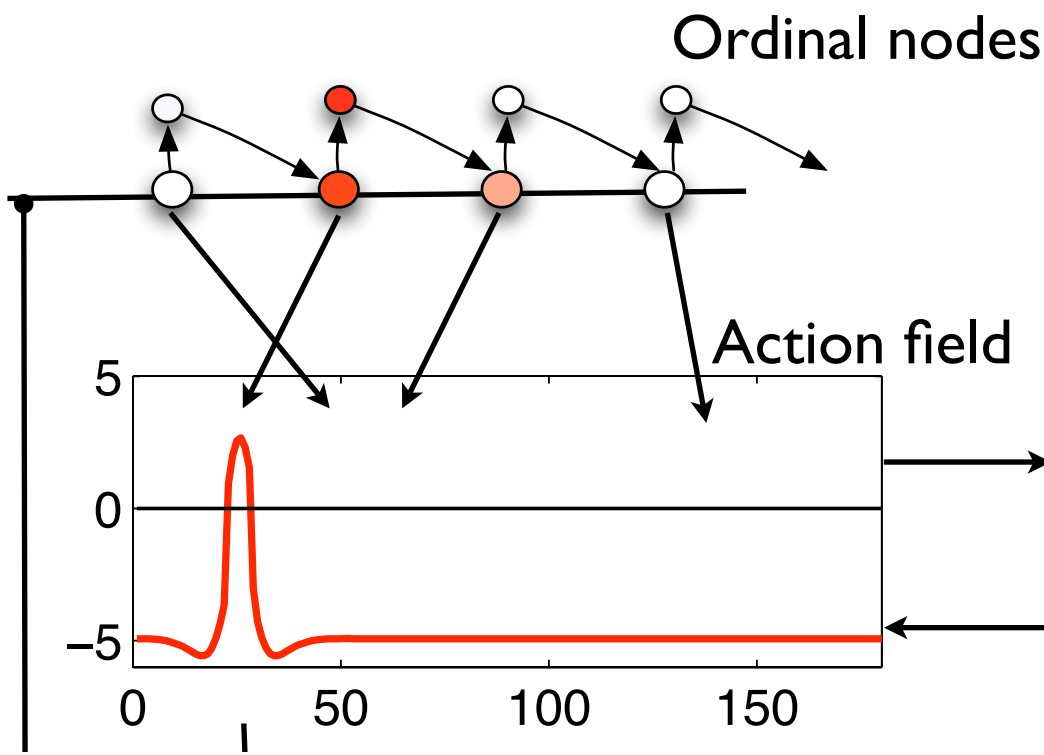




[Sandamirskaya, Schöner: Neural Networks 23:1163 (2010)]

Positional representation + DFT

- such ordinal dynamics can be used as "counters"
- generating indices for binding…



Frontier

- learning and activating multiple difference sequences…

Roadmap

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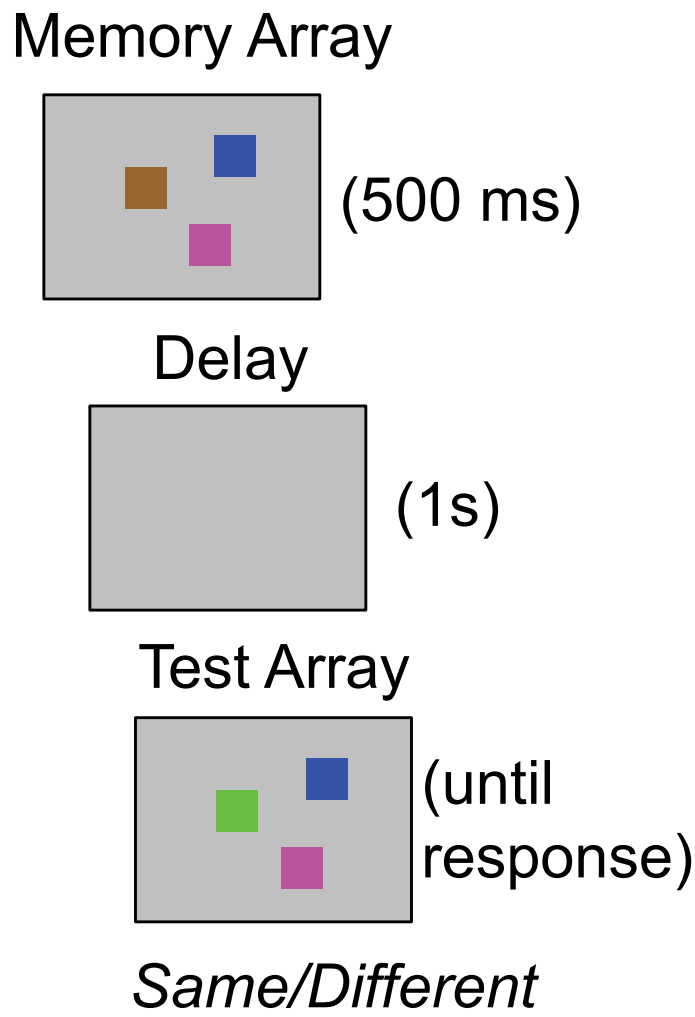
What if the CoS does NOT happen?

- two cases…
- a) nothing happens in the CoS field/subspace
- b) something happens in the CoS field/ subspace that differs from the prediction

a) nothing happens in the COS field

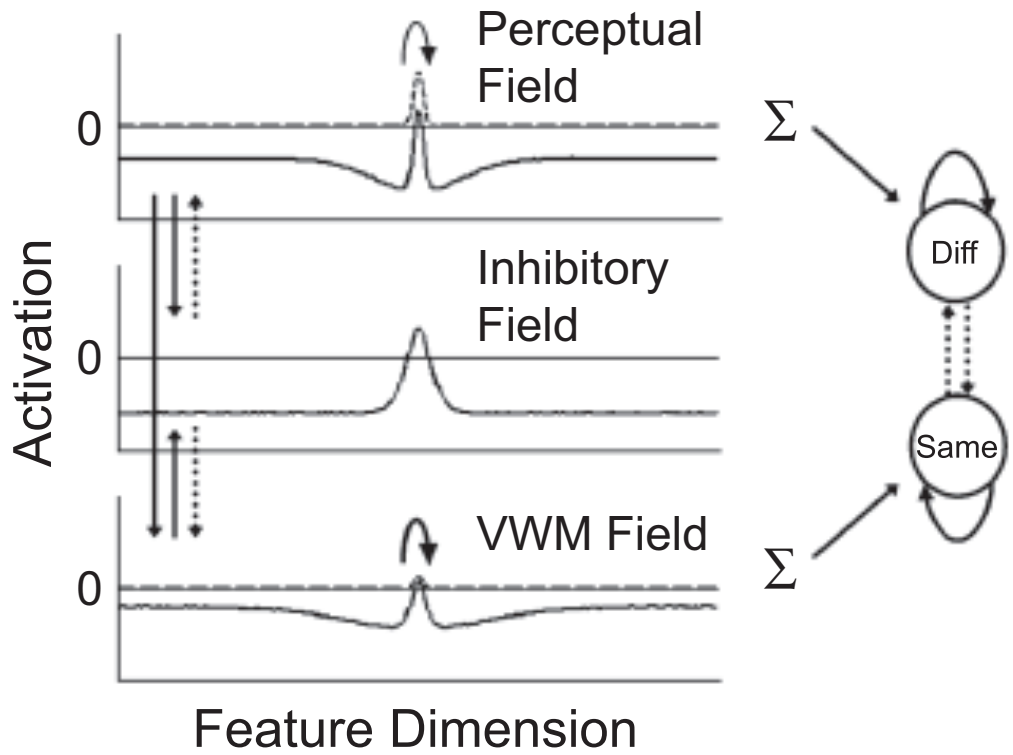
- example: change detection
- the "same" response



[Johnson, et al. 2009]

a) nothing happens in the COS field

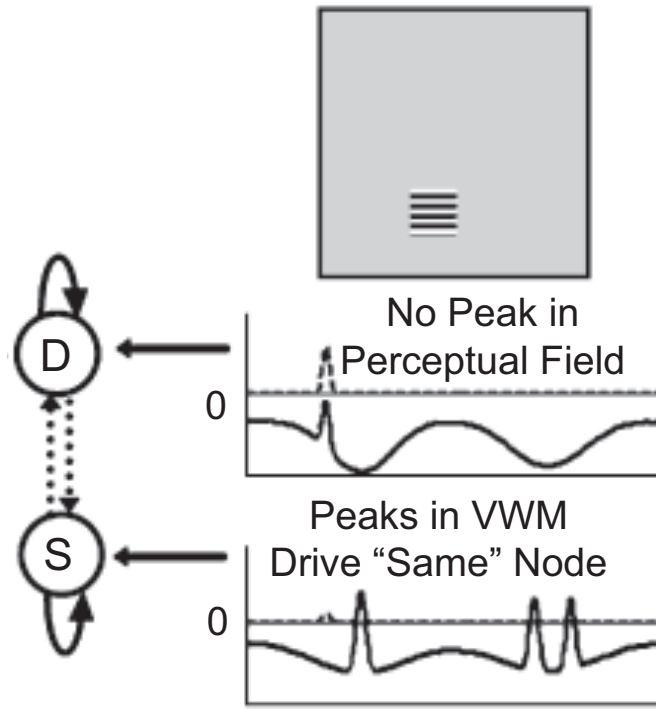
- "same" response as the default state
- that arises if there is no "different" response from change detection



[Johnson, et al. 2009]

a) nothing happens in the COS field

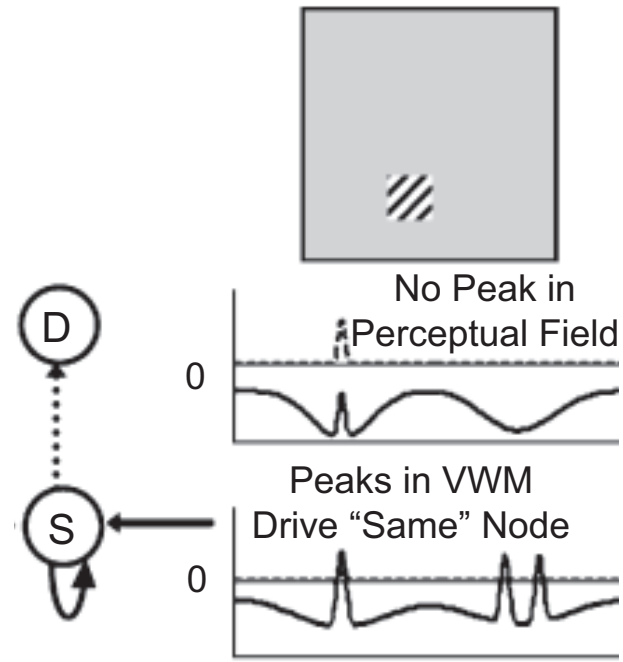
- "different" response from change detection
- stops "same" response



[Johnson, et al. 2009]

a) nothing happens in the COS field

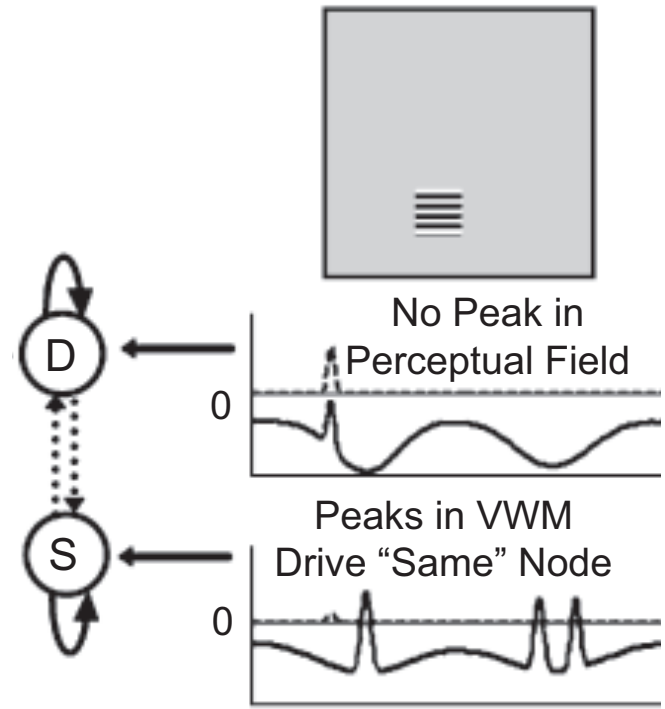
- "different" response from change detection timed out..
- "same response"



[Johnson, et al. 2009]

a) nothing happens in the COS field

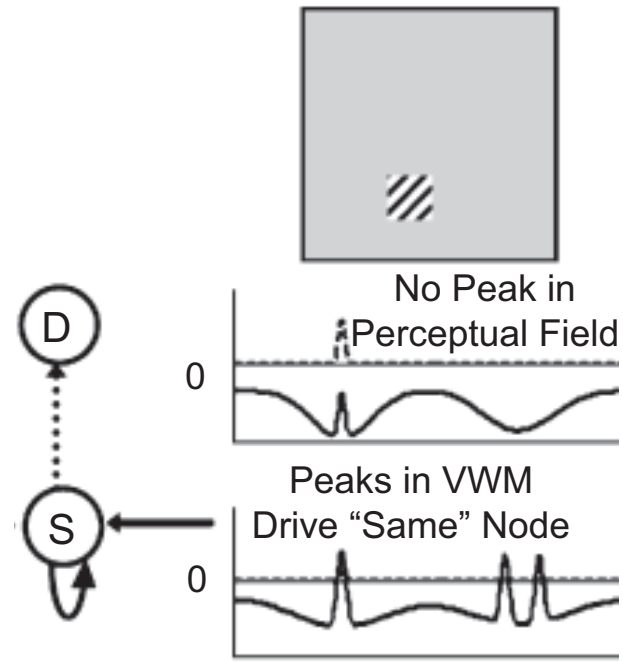
- "different" is the CoS of the change detection task



[Johnson, et al. 2009]

a) nothing happens in the COS field

- "same" is the Condition of Dissatisfaction (CoD) of the change detection task



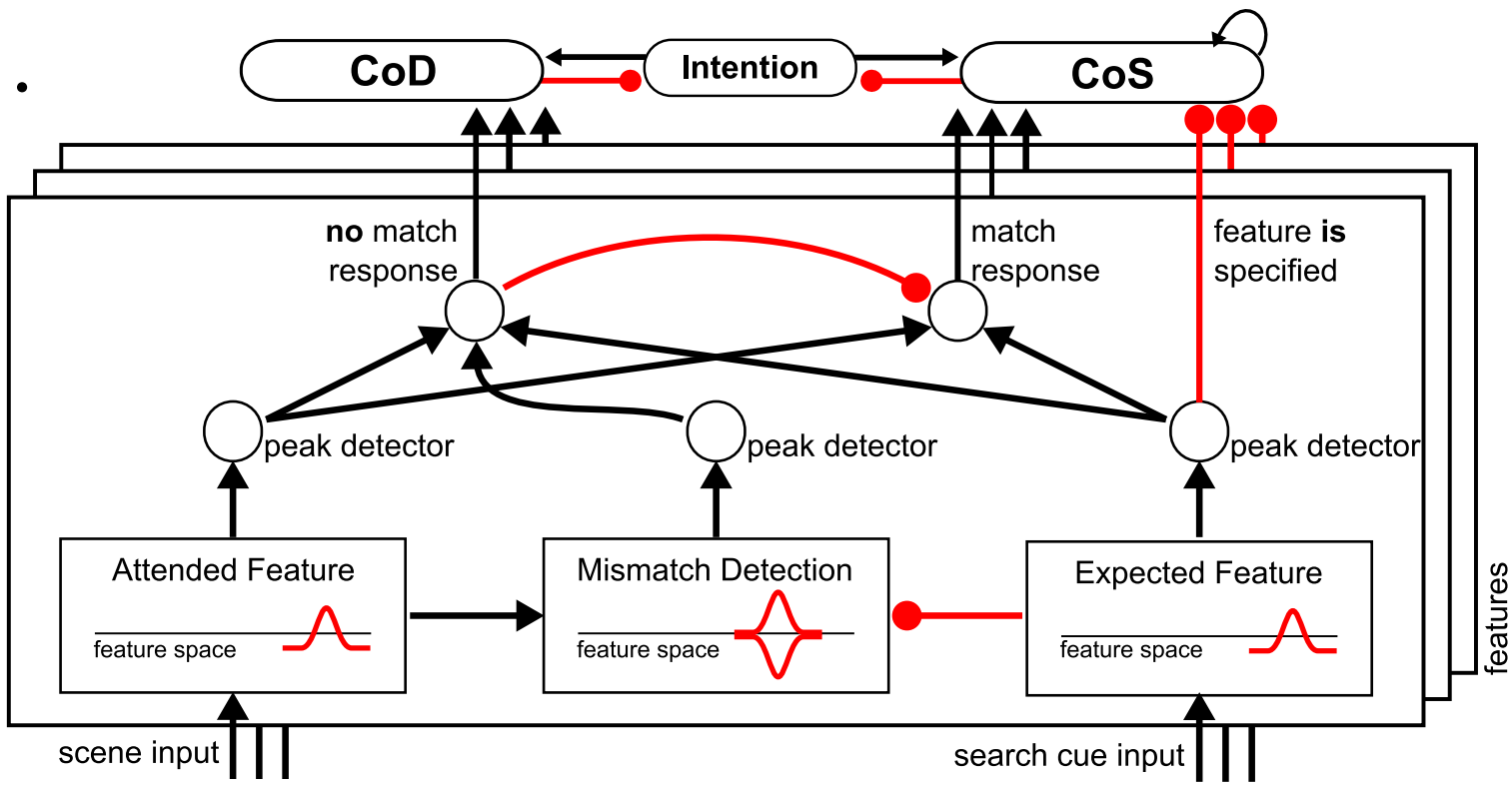
[Johnson, et al. 2009]

a) nothing happens in the COS field

- generally: CoD as a time out…
- the "clock" is started by the onset of the intention..
- frontier: how to bridge large temporal gaps …

b) something happens in the CoS field that differs from the prediction

- => mis-match detection…



[Grieben, Schöner, CogSci 2021]

b) something happens in the CoS field that differs from the prediction

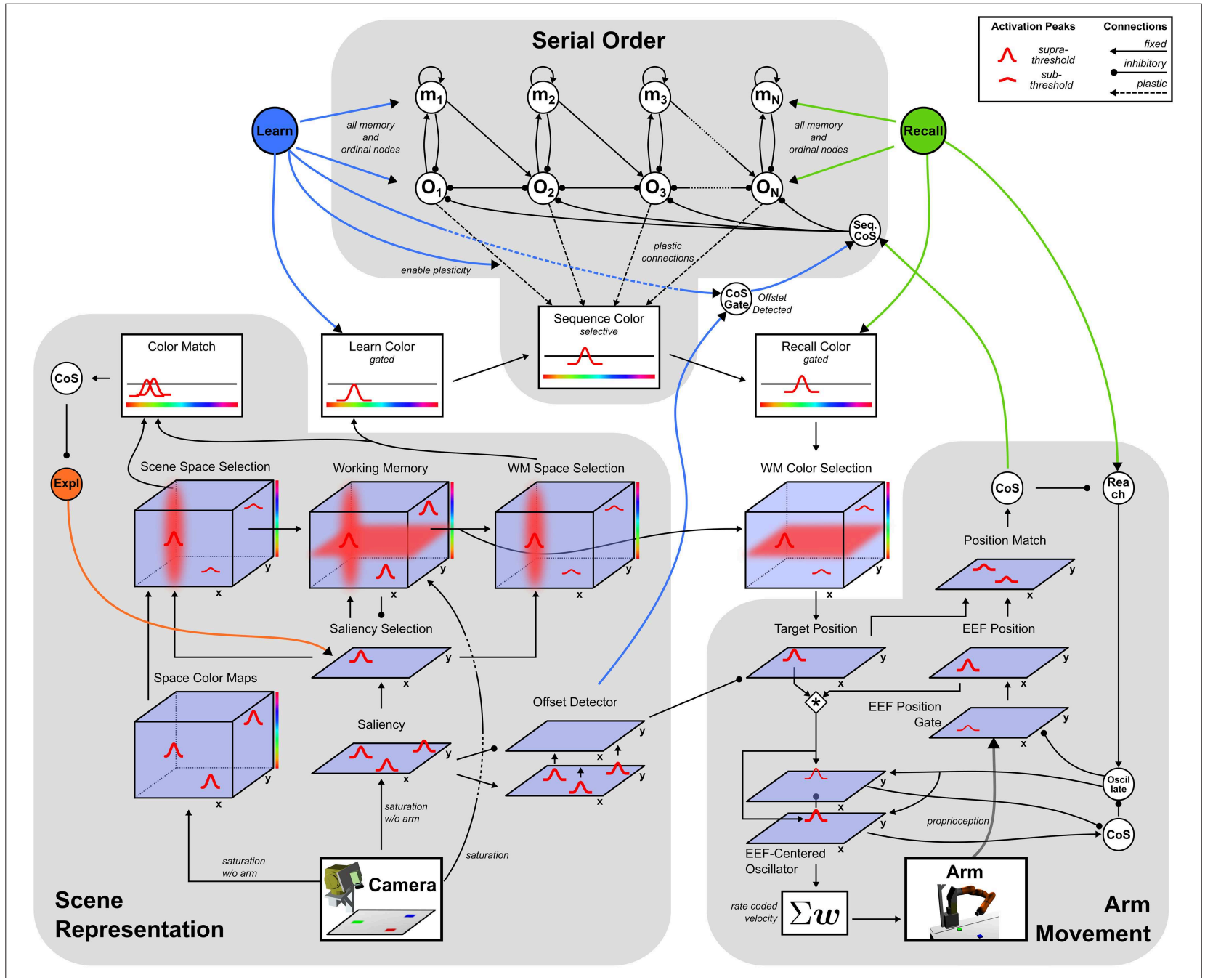
- [we have discarded the earlier CoD notion in which we postulated an explicit neural network for the "non" condition (e.g. Richter, Lins, Schöner 2021)]

Roadmap

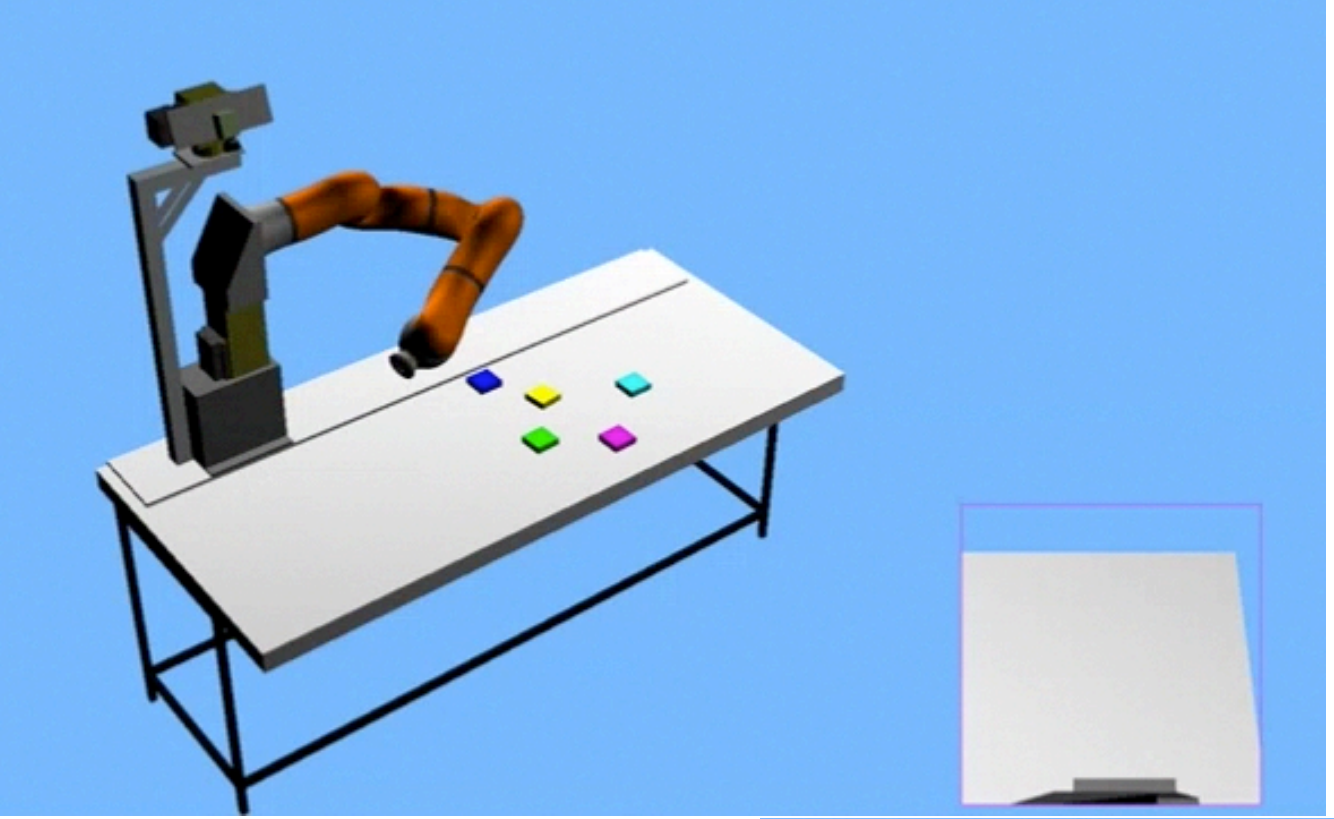
Sequence generation

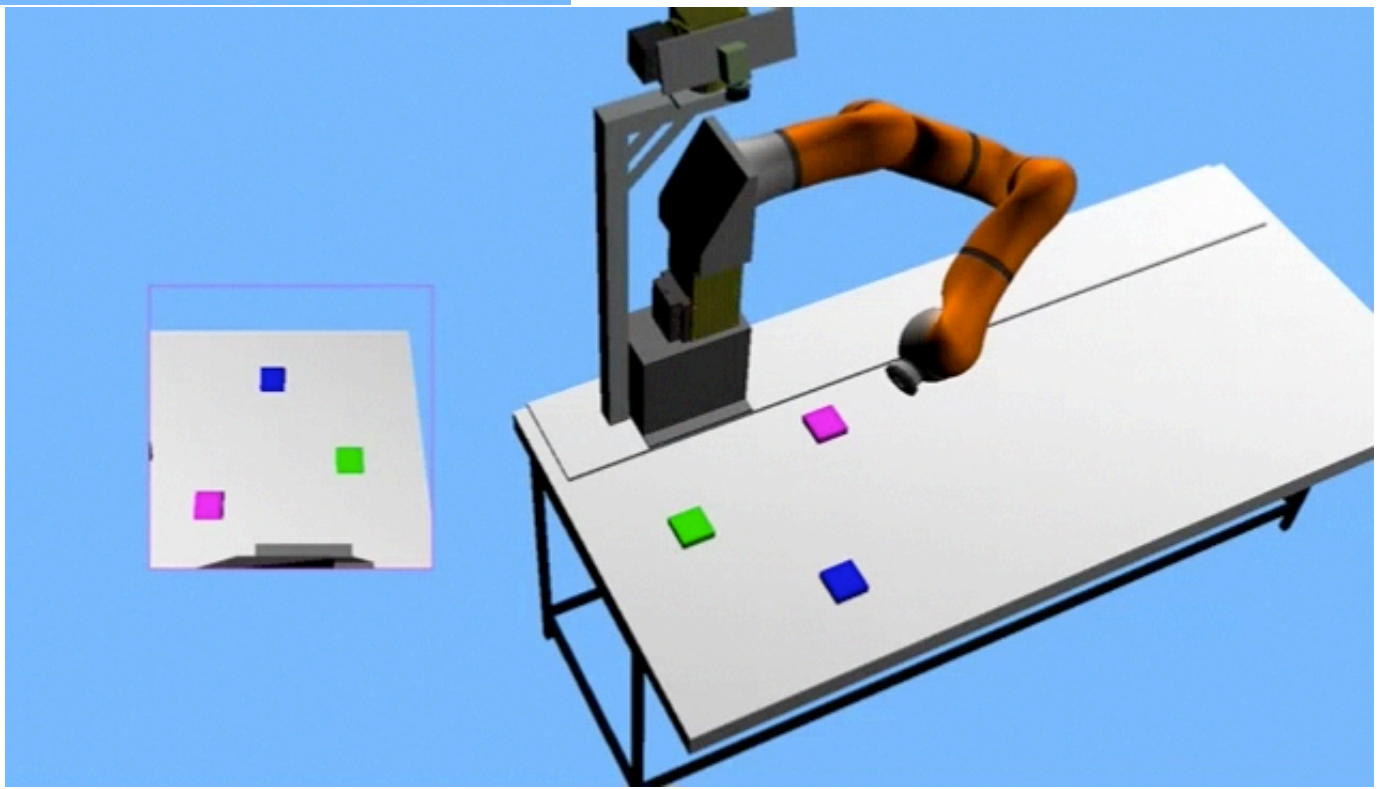
- an illustrative example: the CoS
- the neural/mathematical mechanism of the CoS
- global view of sequence generation
- what state next?
- what if the CoS fails?
- a robotic demo

Serial order demonstrated/enacted



[Tekülve et al., Frontiers in Neurorobotics (2019)]





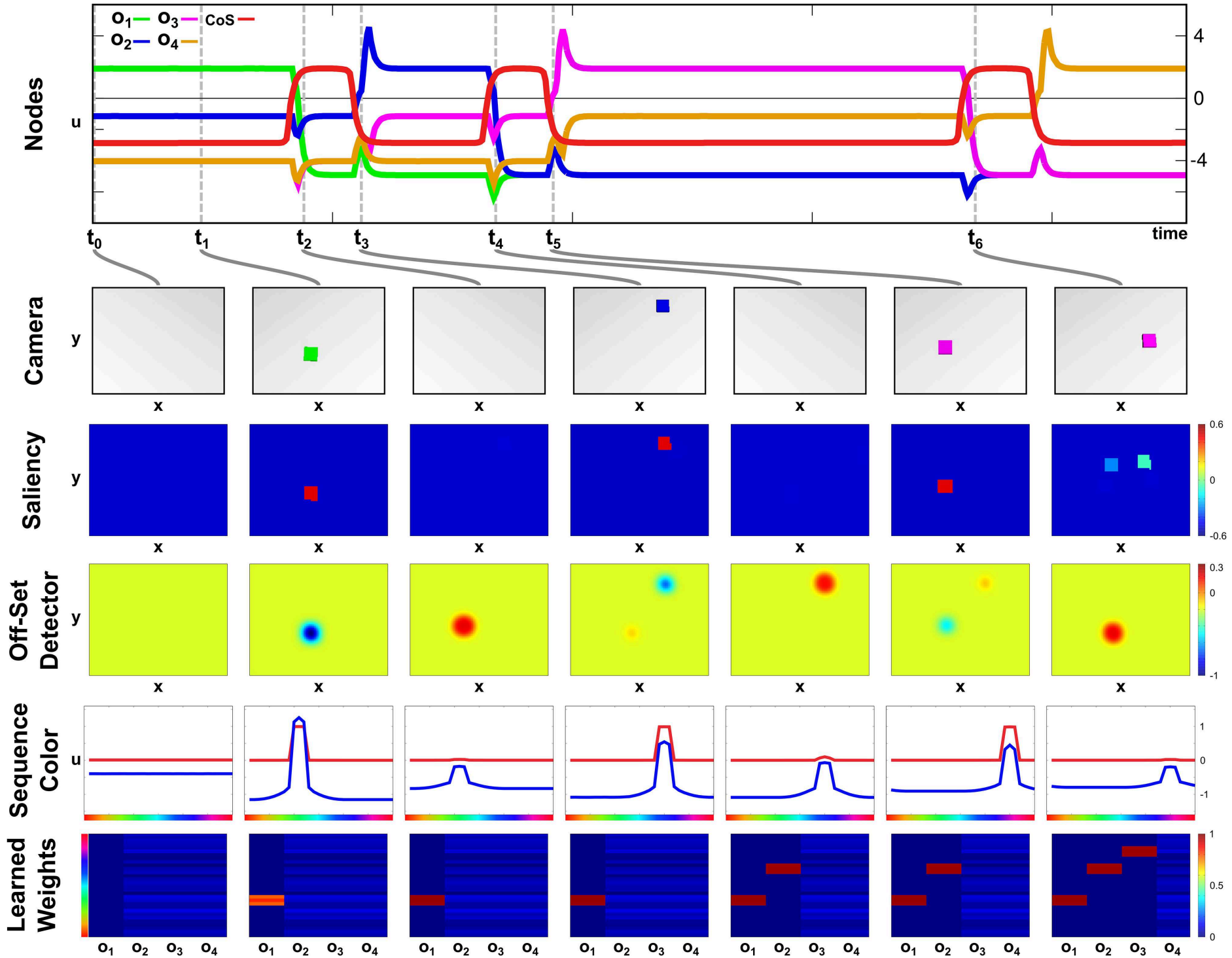


FIGURE 5 | Time course of learning a three element sequence with varying presentation time.

Time course of attention selection and building of scene memory

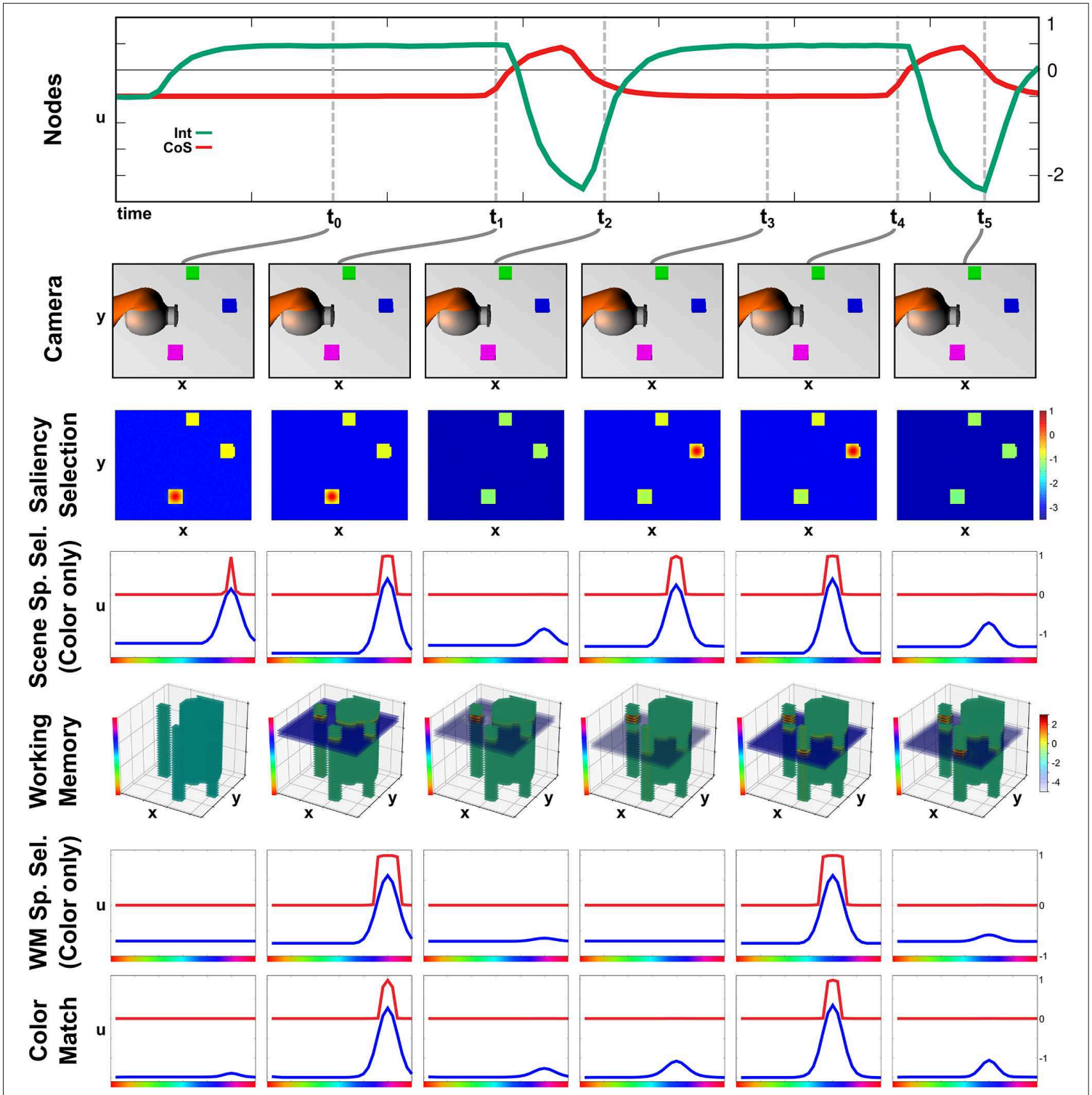


FIGURE 4 | Time course of building a scene memory.

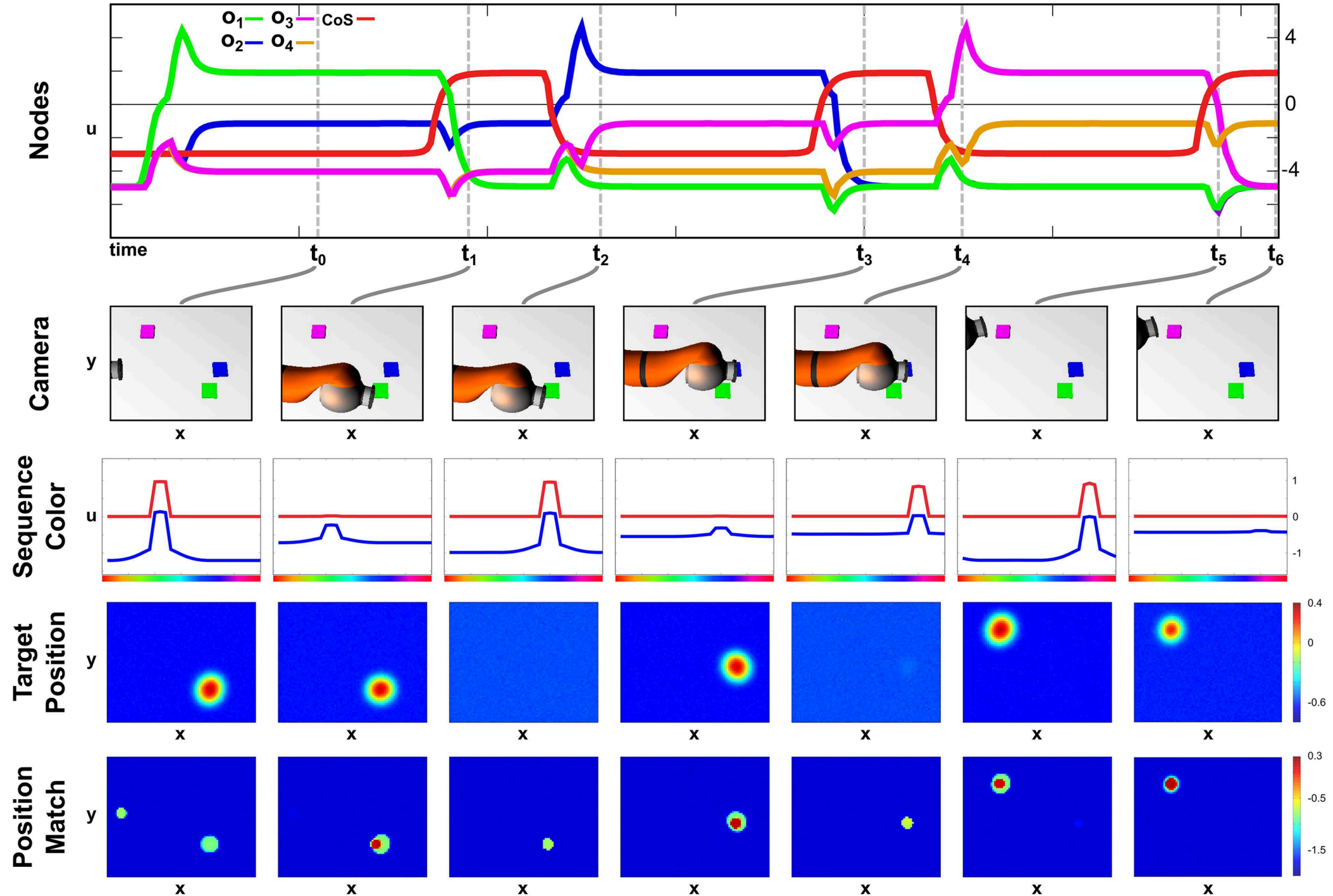
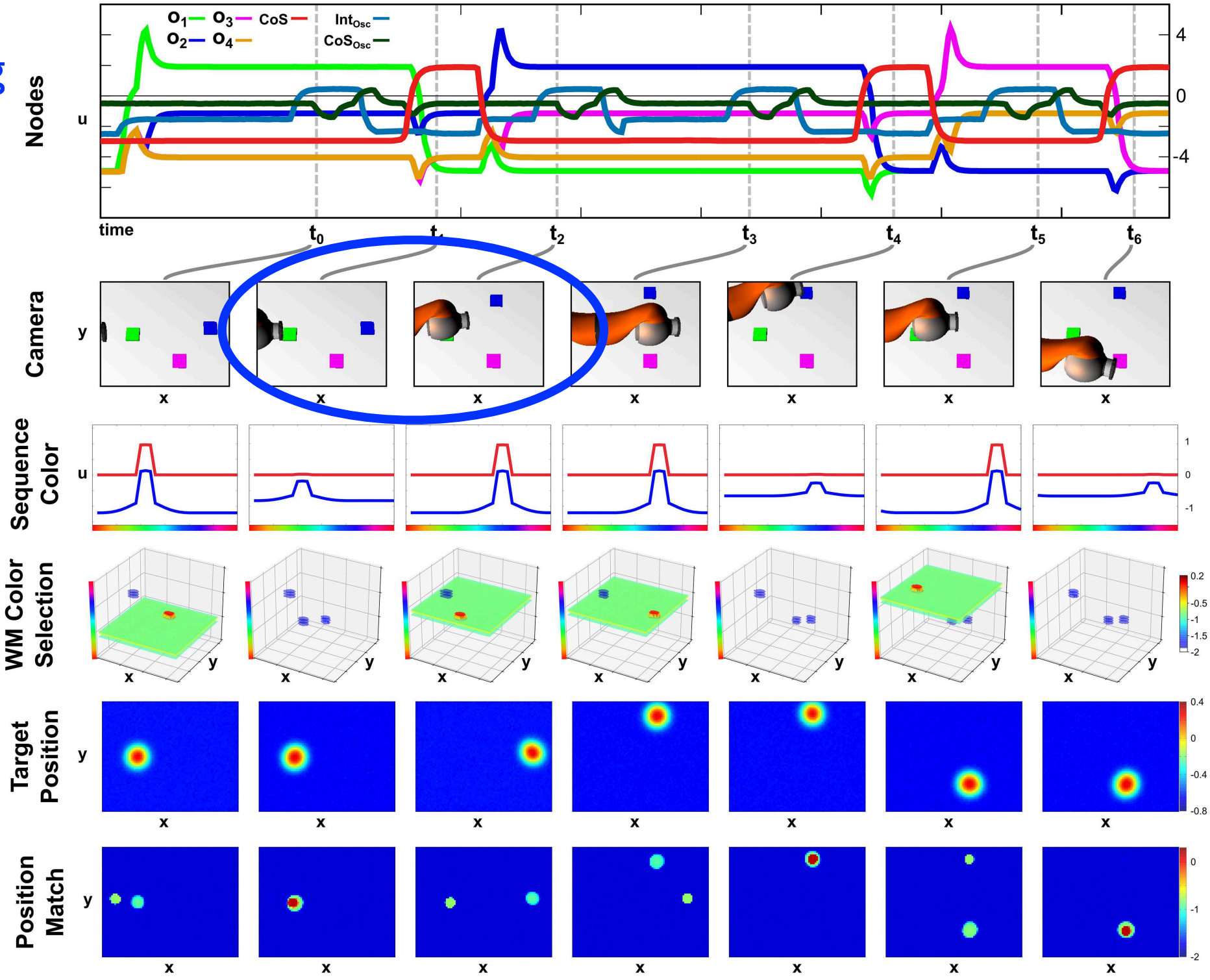


FIGURE 6 | Time course of recalling a three element sequence through pointing at colored objects.

online updating



Roadmap

Sequence generation

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Conclusion

- the principles of DFT
  - localist representations for stable states
  - that may become unstable in a controlled way
  - through the "condition of satisfaction"
- enable the autonomous generation of sequences of mental states or action
  - critical step toward higher cognition

Outlook

- are all neural states of the "intentional" kind… with a CoS?
  - "direction of fit"
- frontier: goals… true autonomy