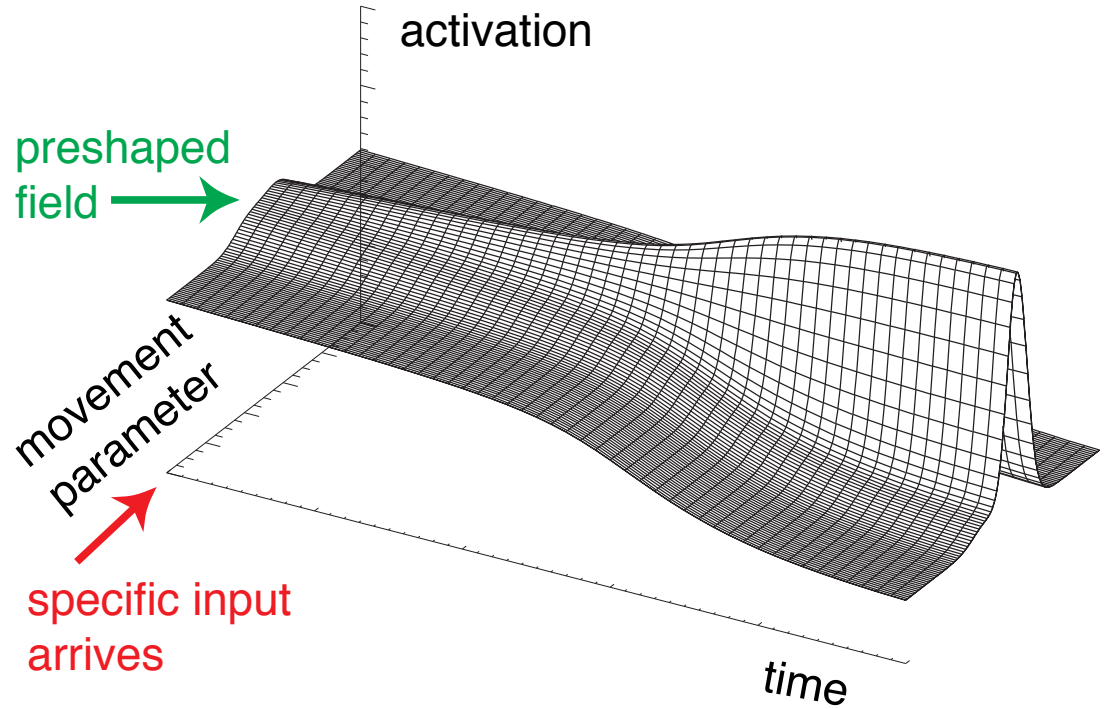
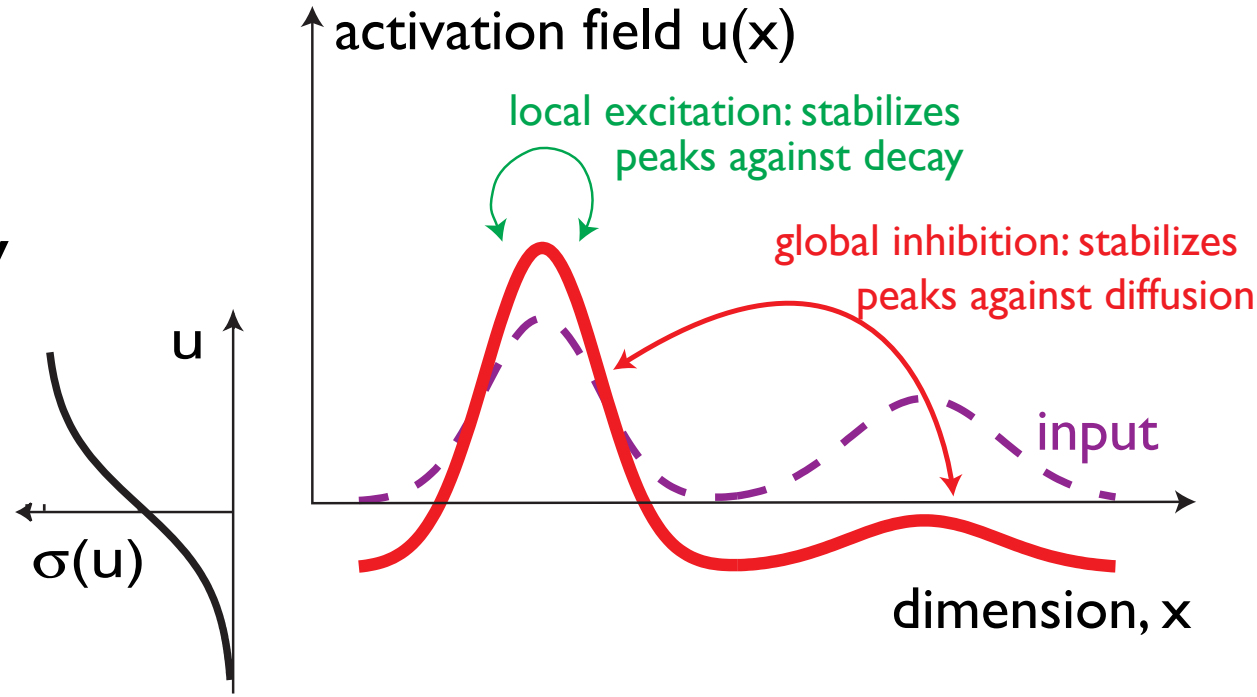
Embodied Neural Dynamics

Gregor Schöner, INI, RUB

The dynamics activation fields

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

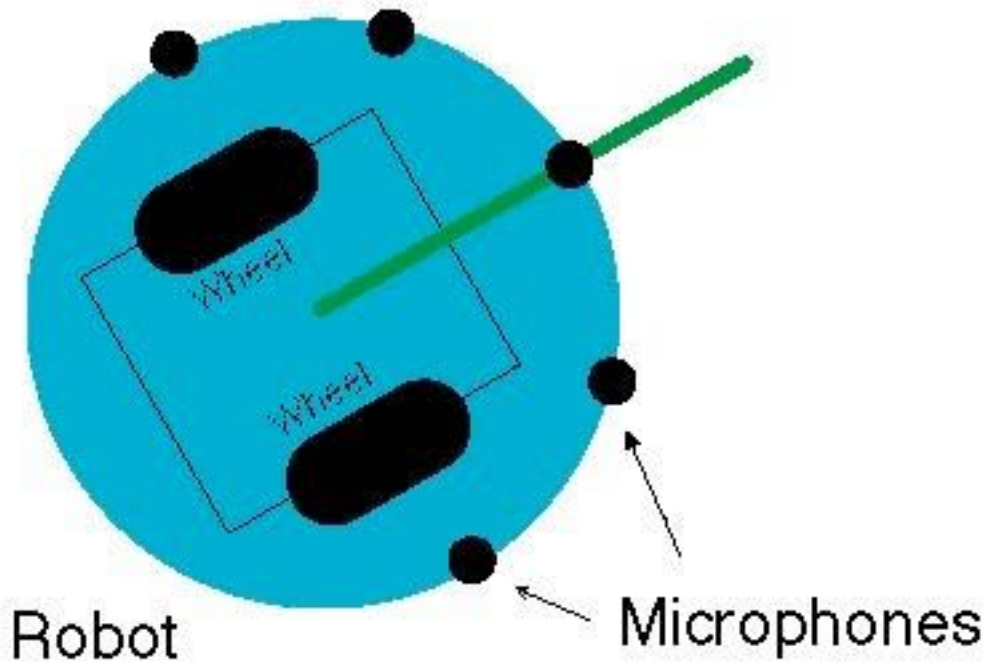




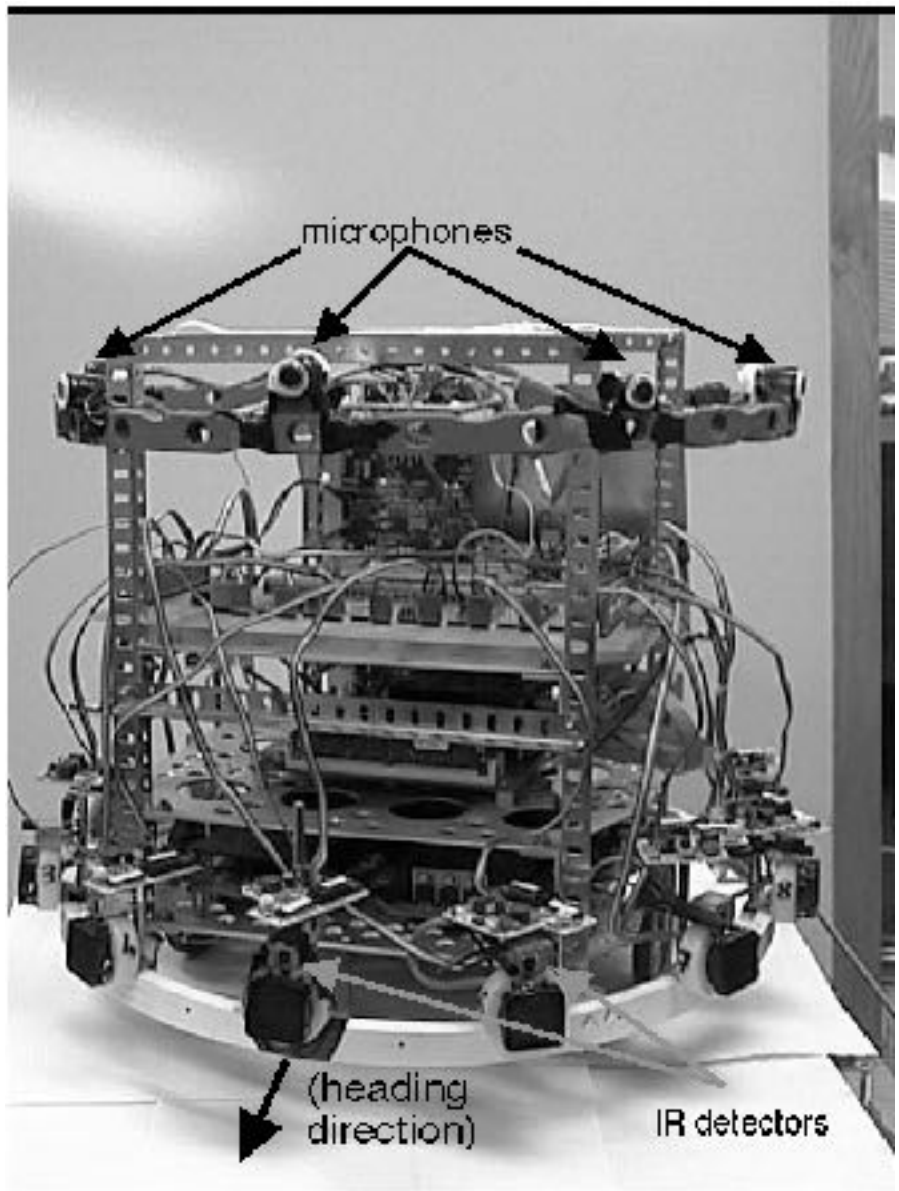
=>

- attractor states
  - input driven solution (sub-threshold)
  - self-stabilized solution (peak, supra-threshold)
- instabilities
  - detection instability (from localize input or boost)
  - reverse detection instability
  - selection instability
  - memory instability

Illustration: linking to sensors

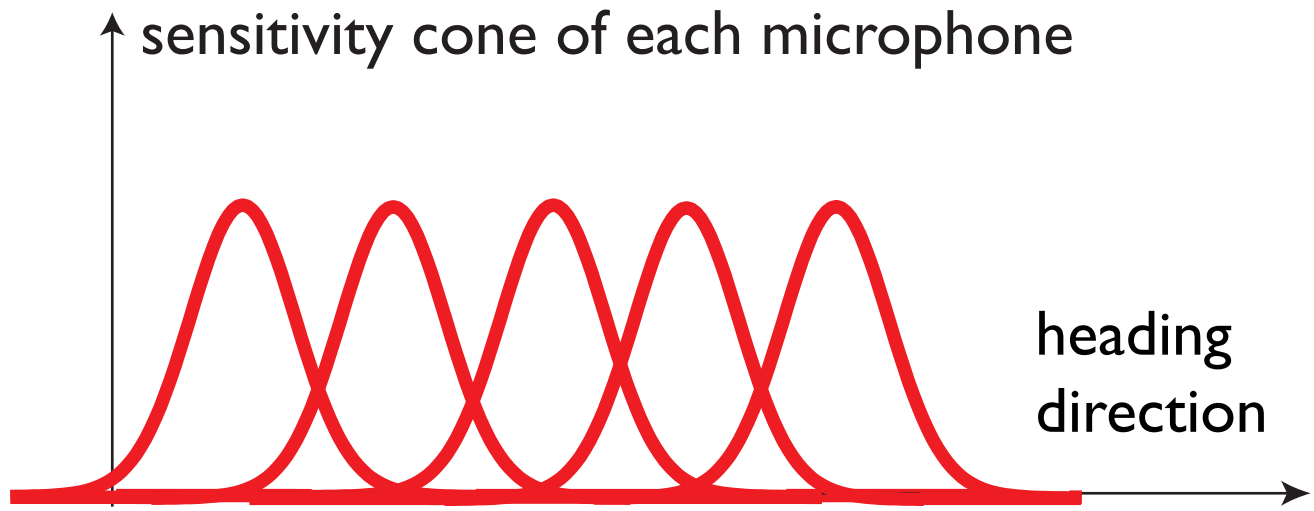


[from Bicho, Mallet, Schöner, Int J Rob Res,2000]

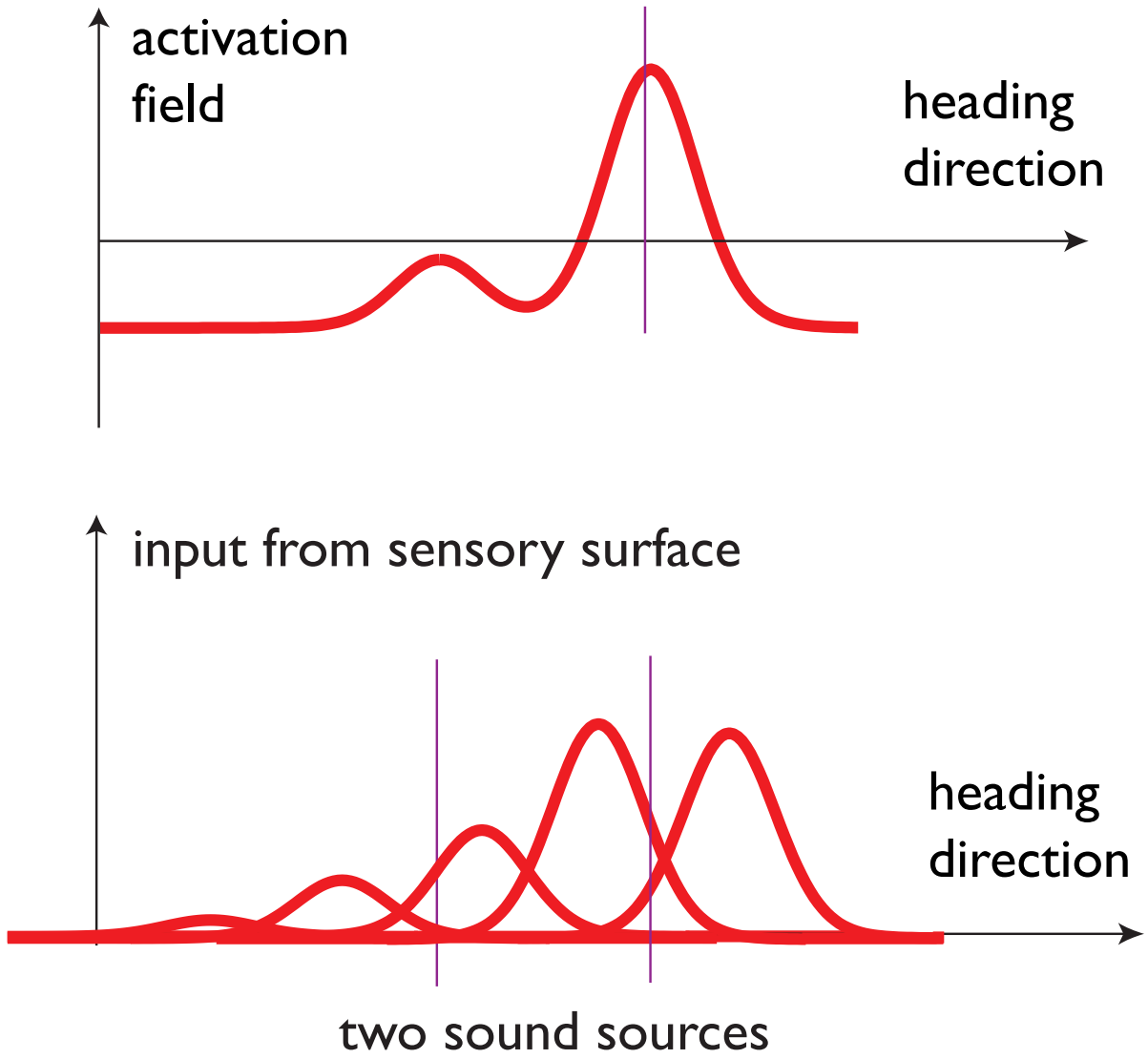


Sensory surface

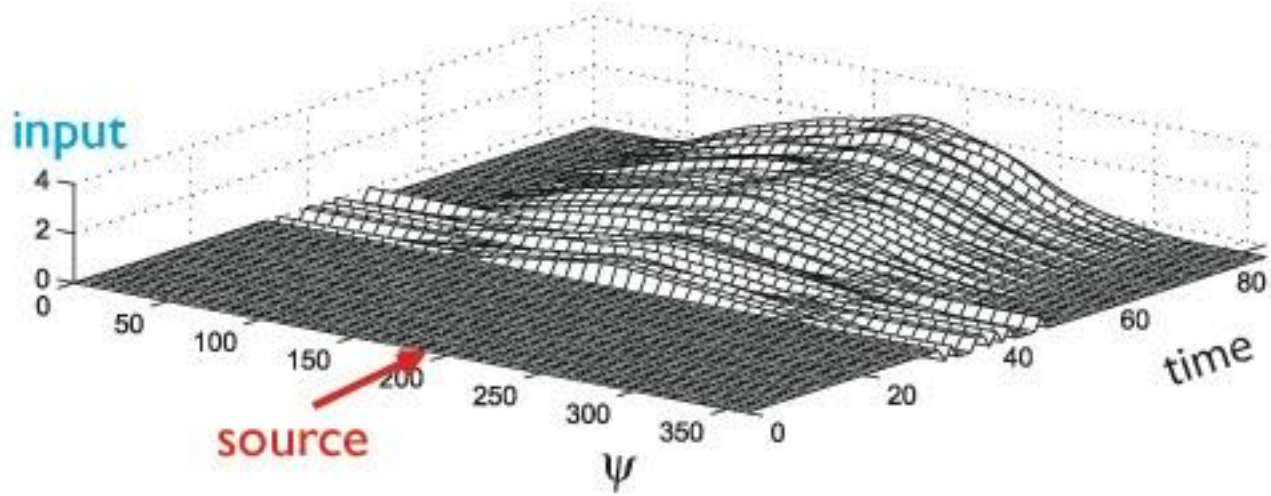
- each microphone samples heading direction

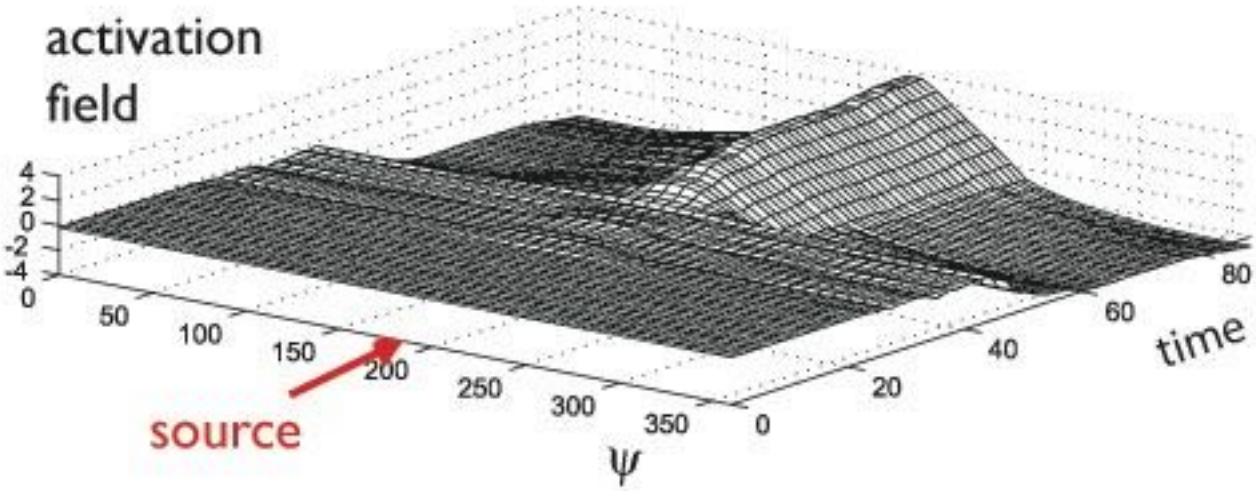


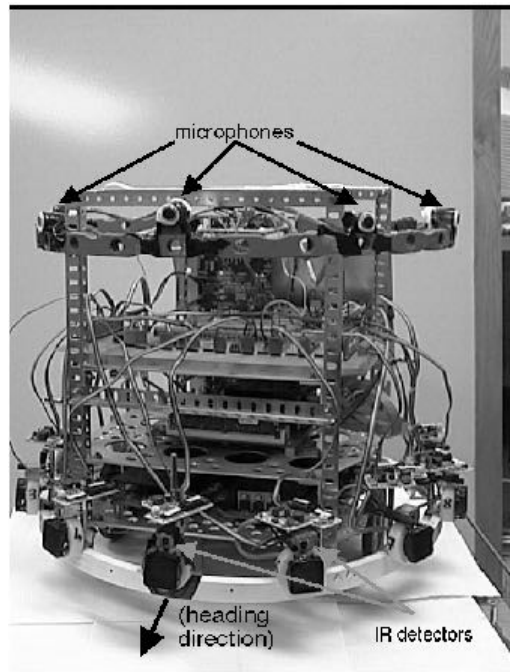
- each microphone provides input to the field



Detection instability induced by increasing intensity of sound source

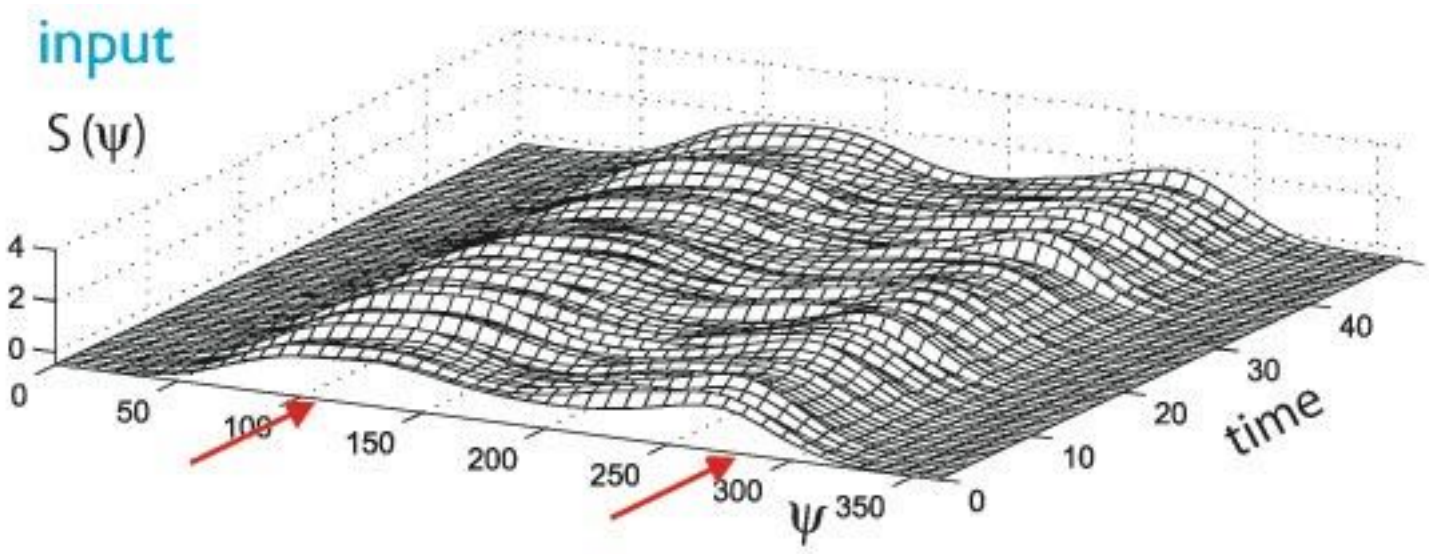


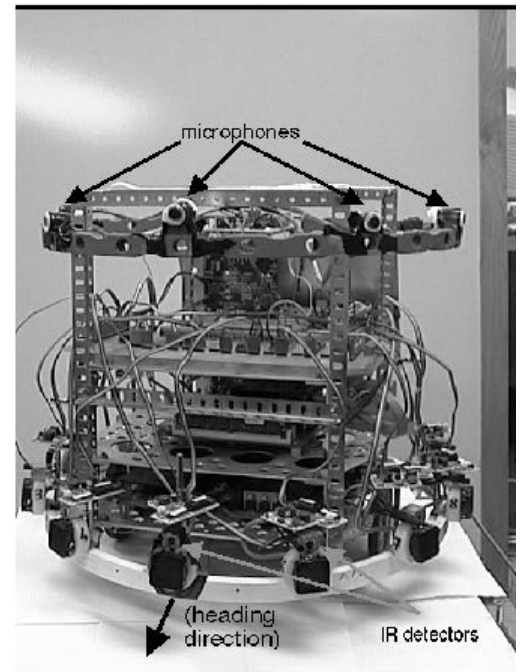


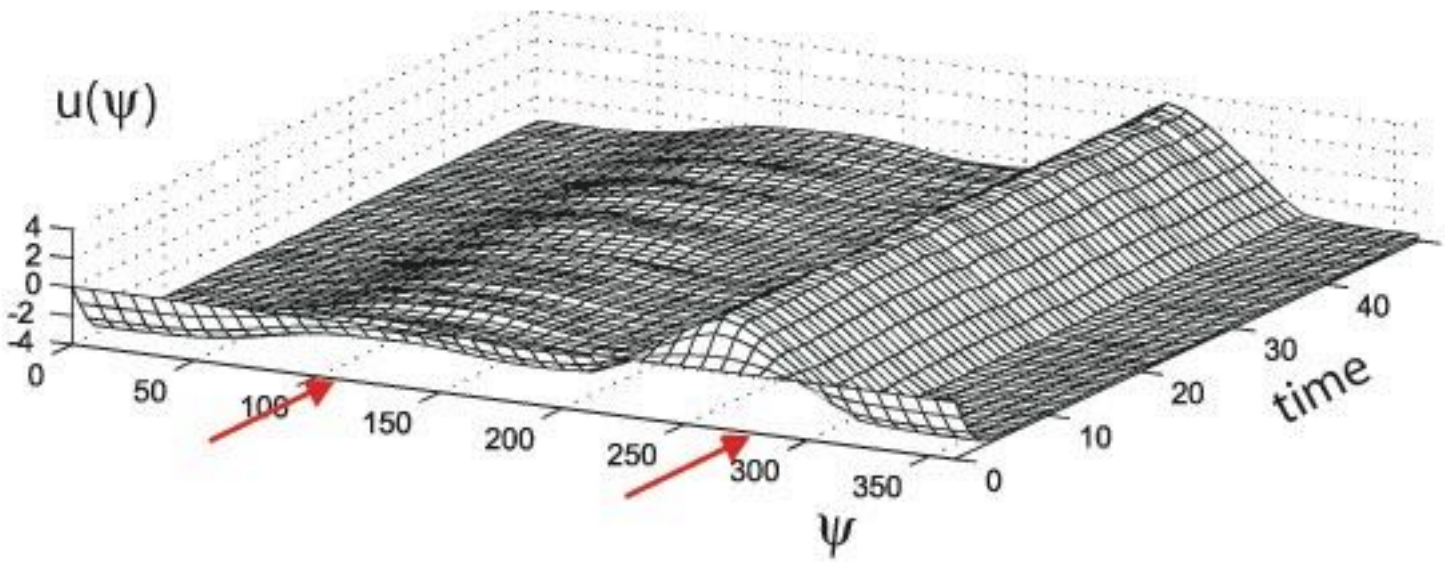


[from Bicho, Mallet, Schöner: Int. J. Rob. Res., 2000]

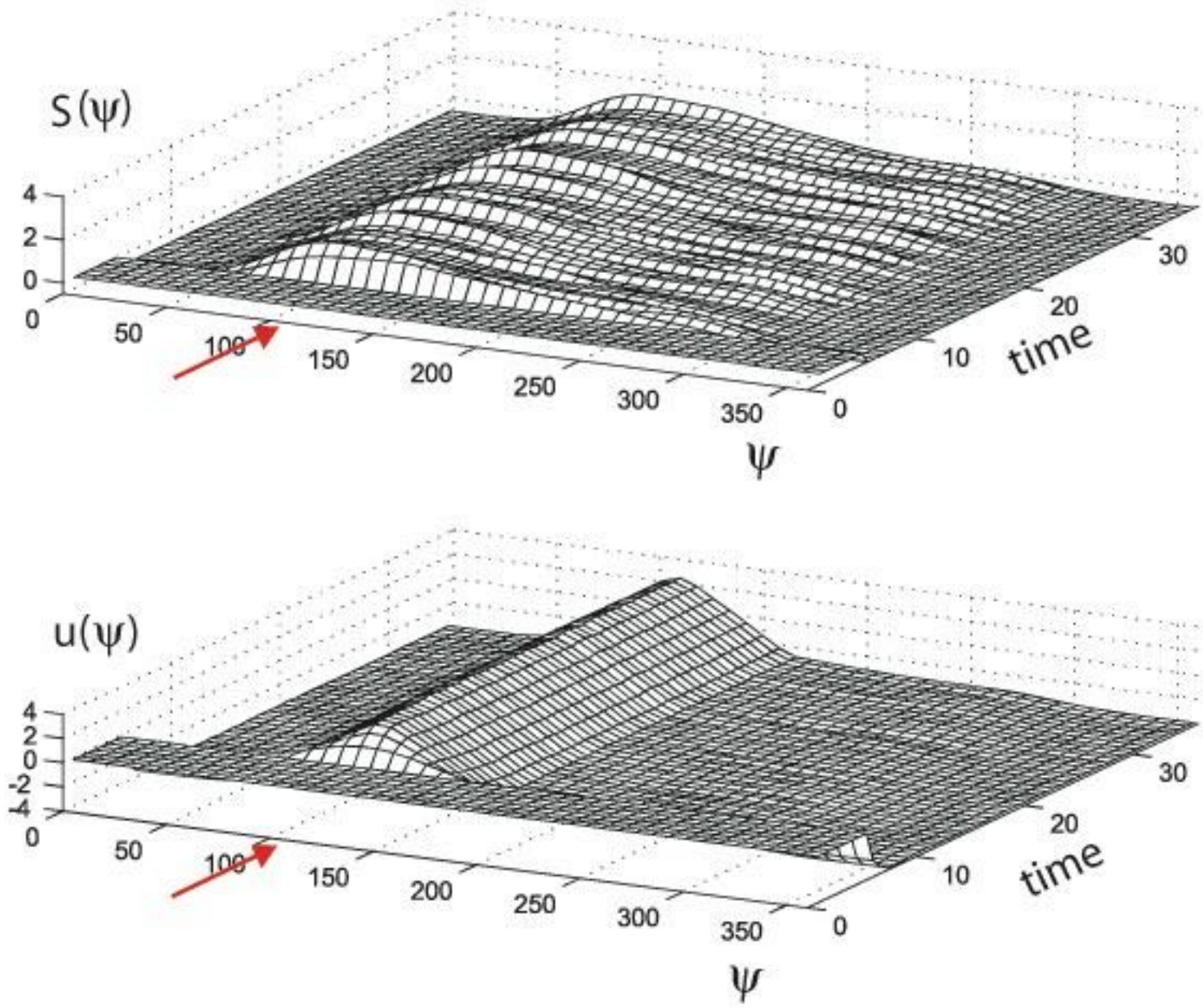
Target selection in the presence of two sources



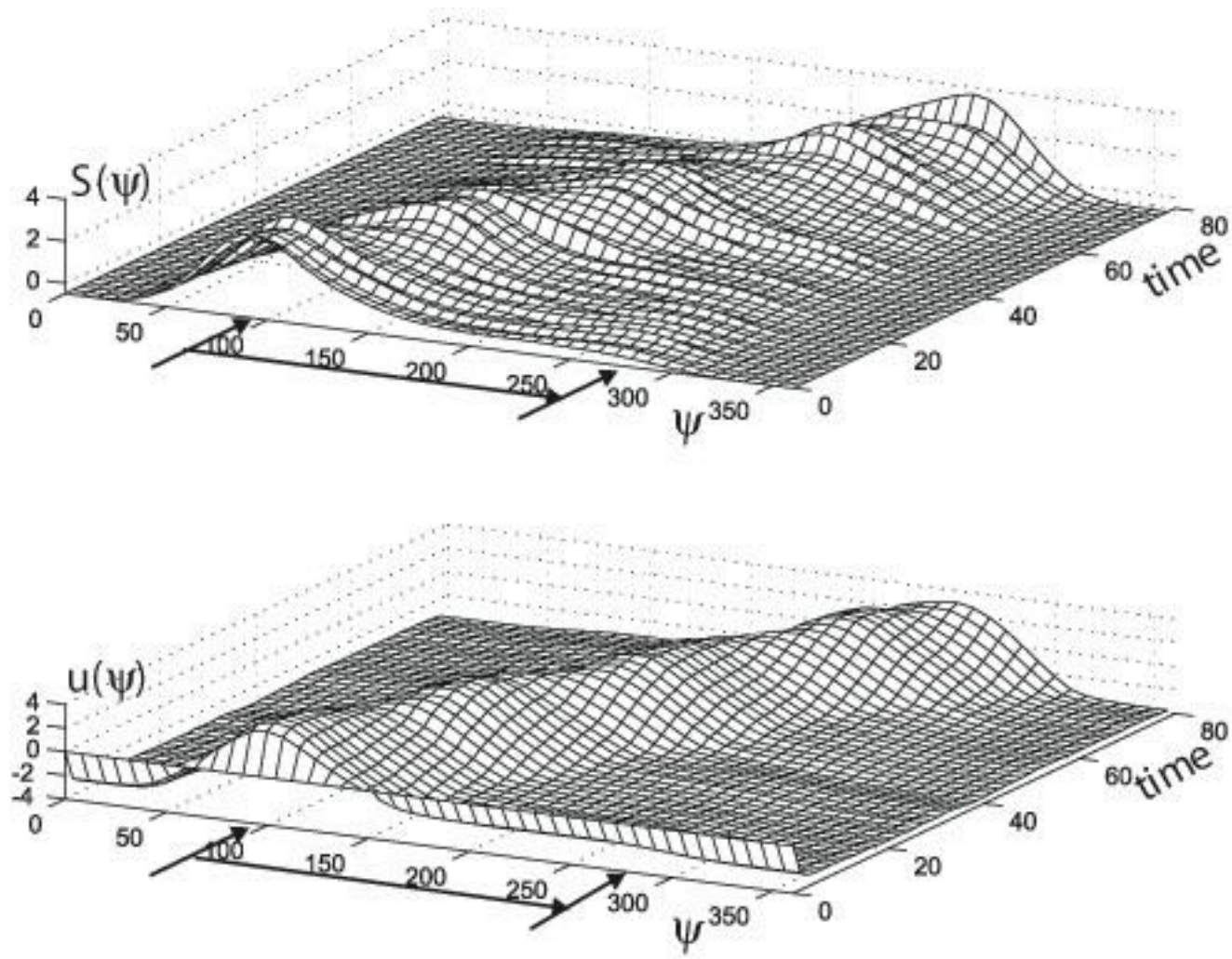




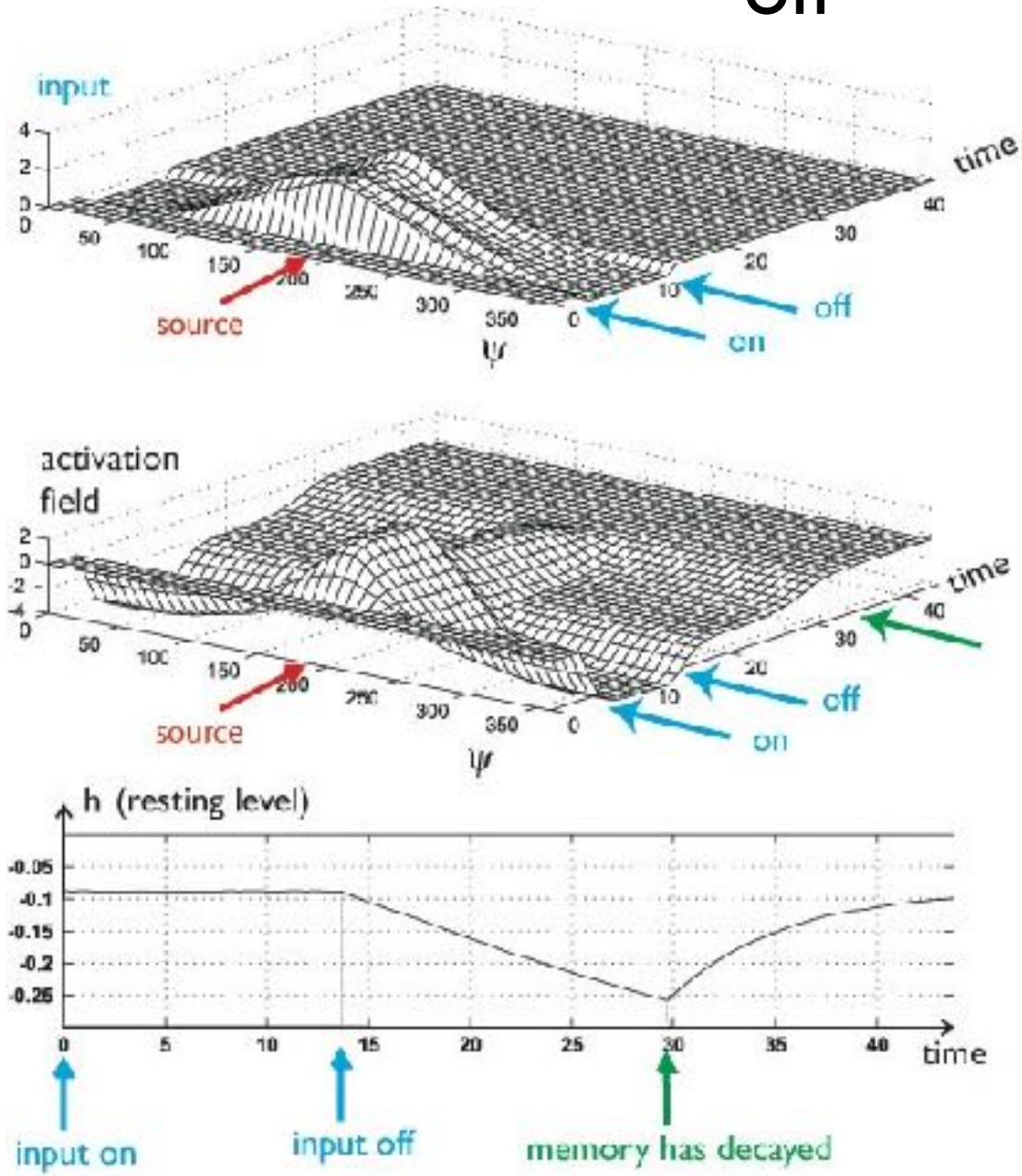
Robust estimation in the presence of outliers

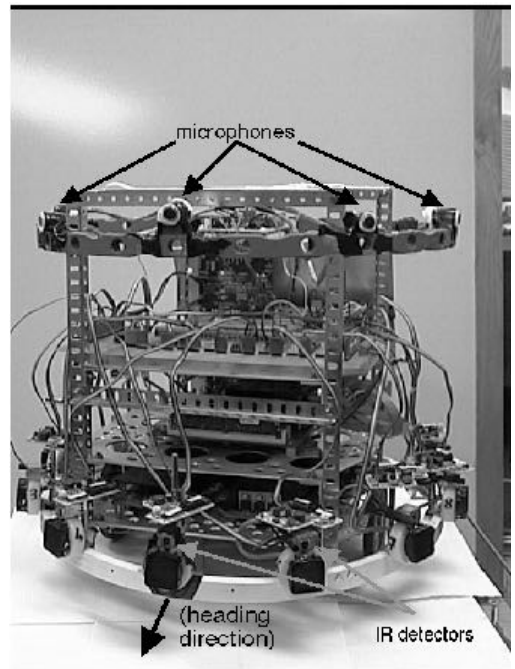


Tracking when sound source moves



Memory (and forgetting) when sound source is turned off





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

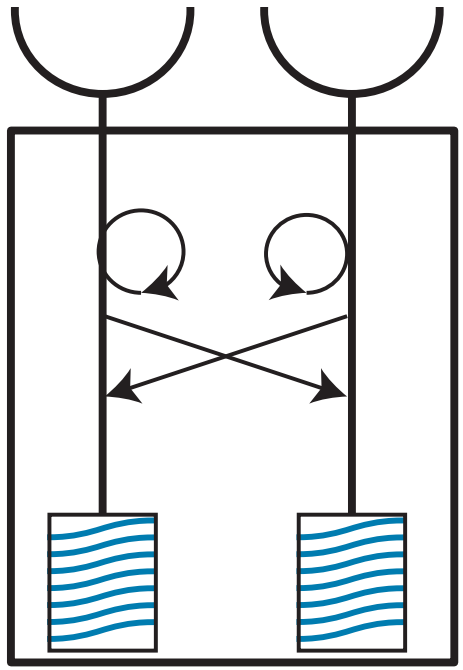
Illustration of instabilities

Motor behavior

- so far, the neural field was in open loop: received input from sensors, but didn't drive around and thus did not influence its own sensor input

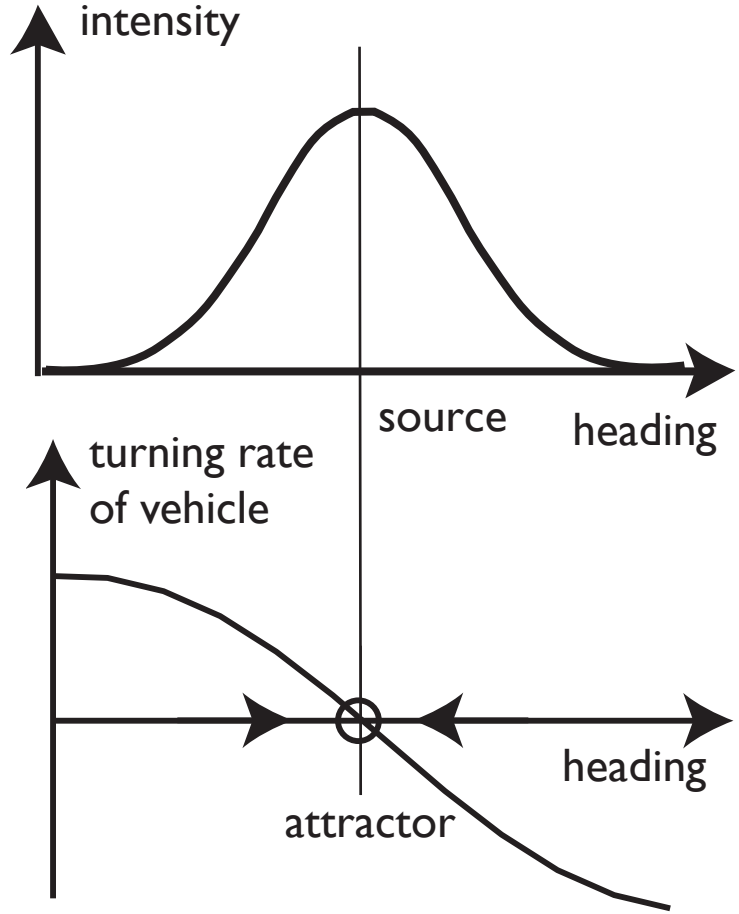
Braitenberg

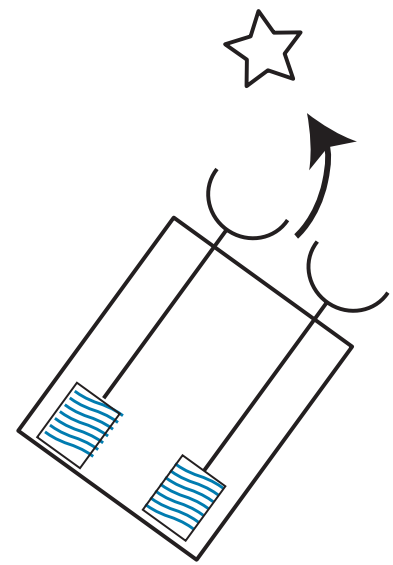
- in terms of the Braitenberg vehicle, we only looked at the “inner” neural dynamics



Braitenberg

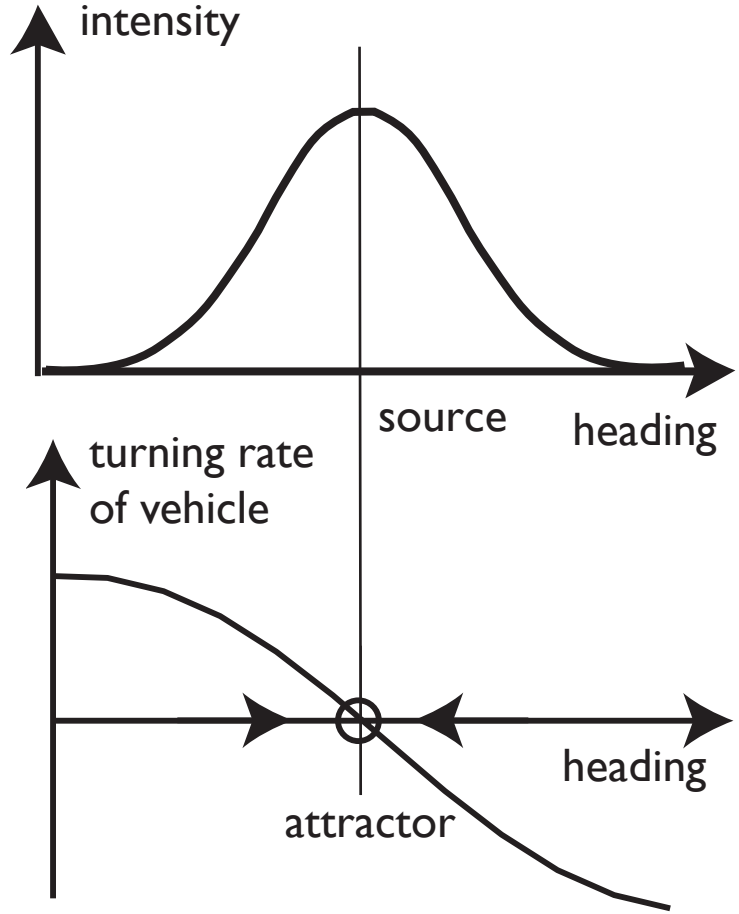
- we did not yet look at the emergence of (motor) behavior given a representation of sensory information

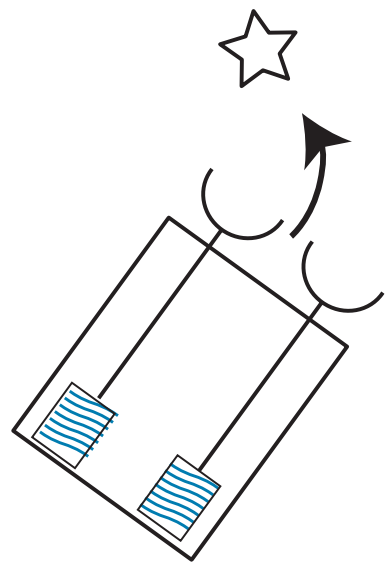




Braitenberg

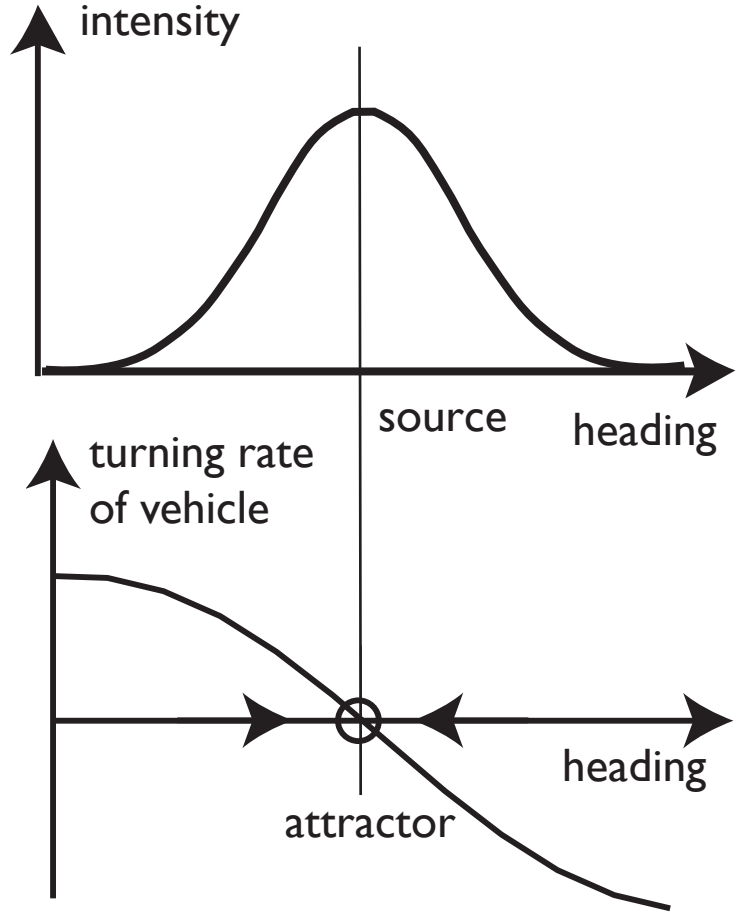
- overt movement behavior is generated by a behavioral dynamics
- how may the neural representations of DFT couple into behavioral dynamics "standing in for" sensory inputs?

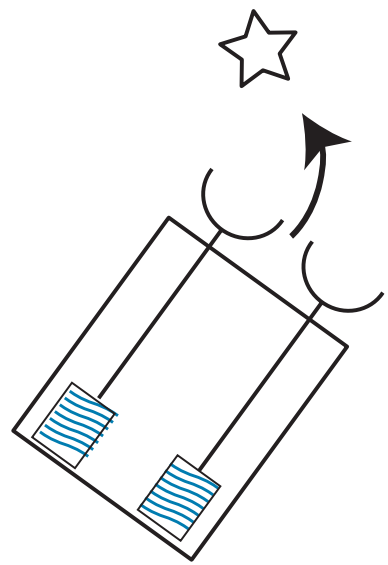




Braitenberg

- two problems
  - how do we go from a field to an attractor dynamics? => space to rate code issue
  - how does the field emulate "closed loop" behavior? => coordinate transforms



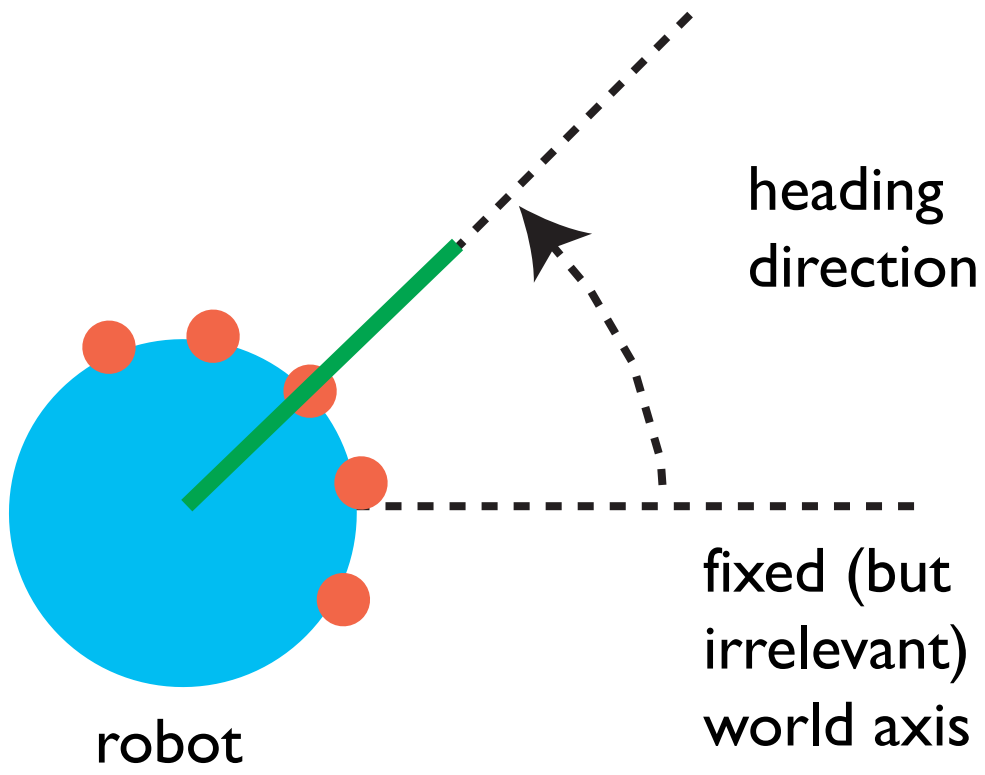


Basic ideas: behavioral dynamics

- behavioral variables
- time courses from dynamical system: attractors
- tracking attractors
- bifurcations for flexibility

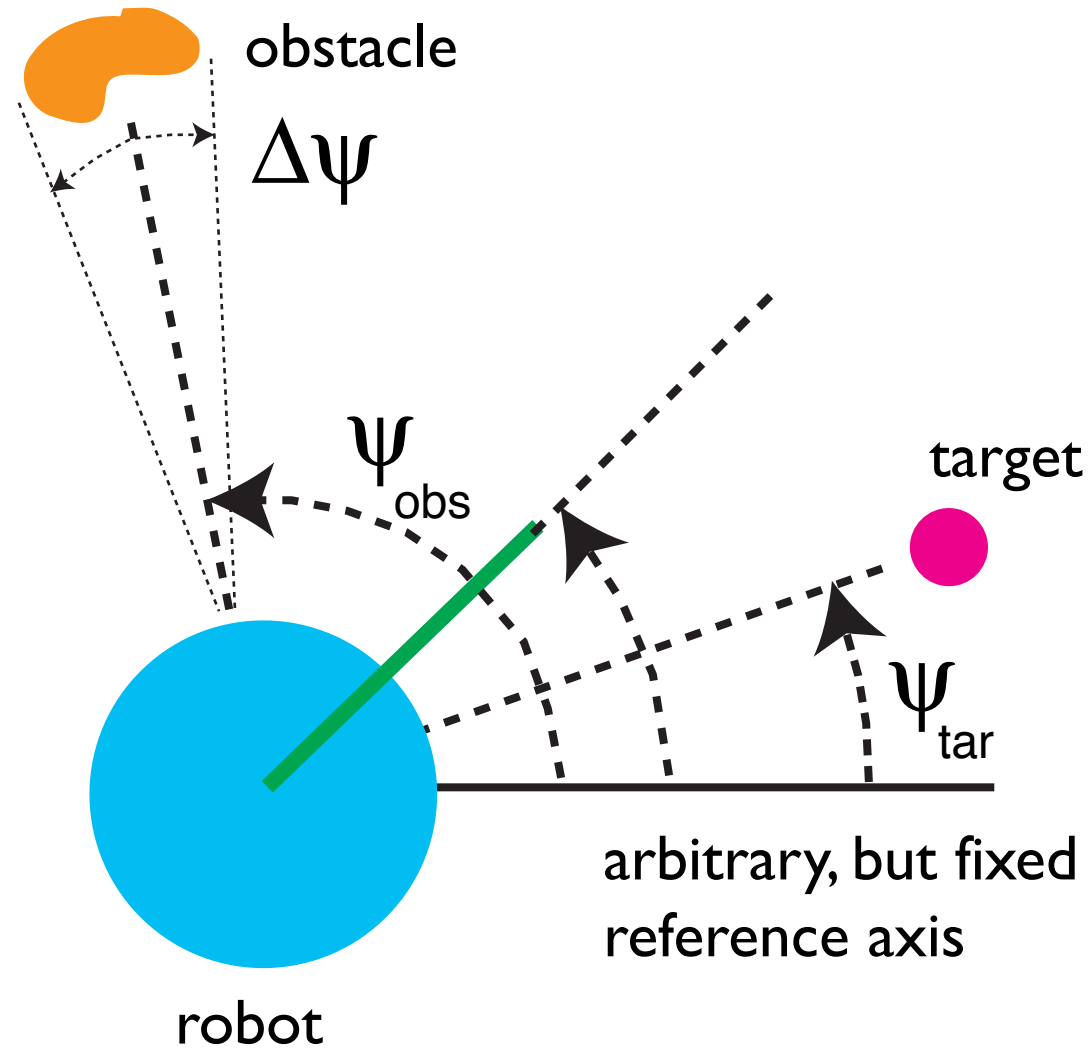
Behavioral variables: example

- vehicle moving in 2D: heading direction



Behavioral variables: example

- constraints: obstacle avoidance and target acquisition



Behavioral variables

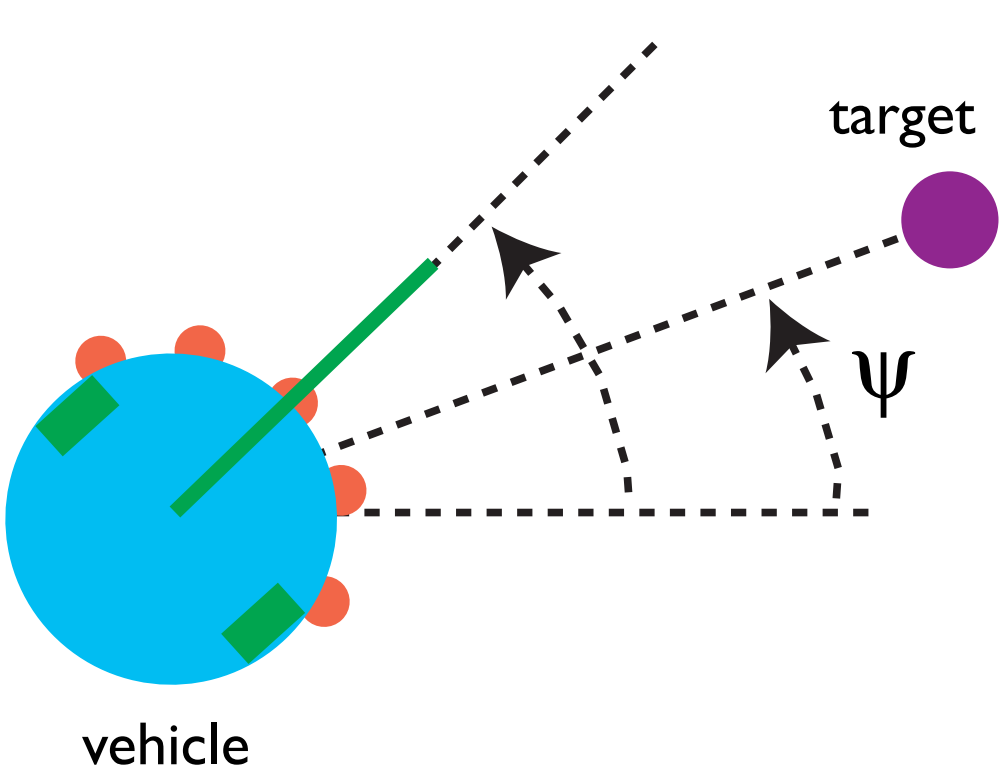
- describe desired motor behavior
- “enactable”
- express constraints as values/value ranges
- appropriate level of invariance

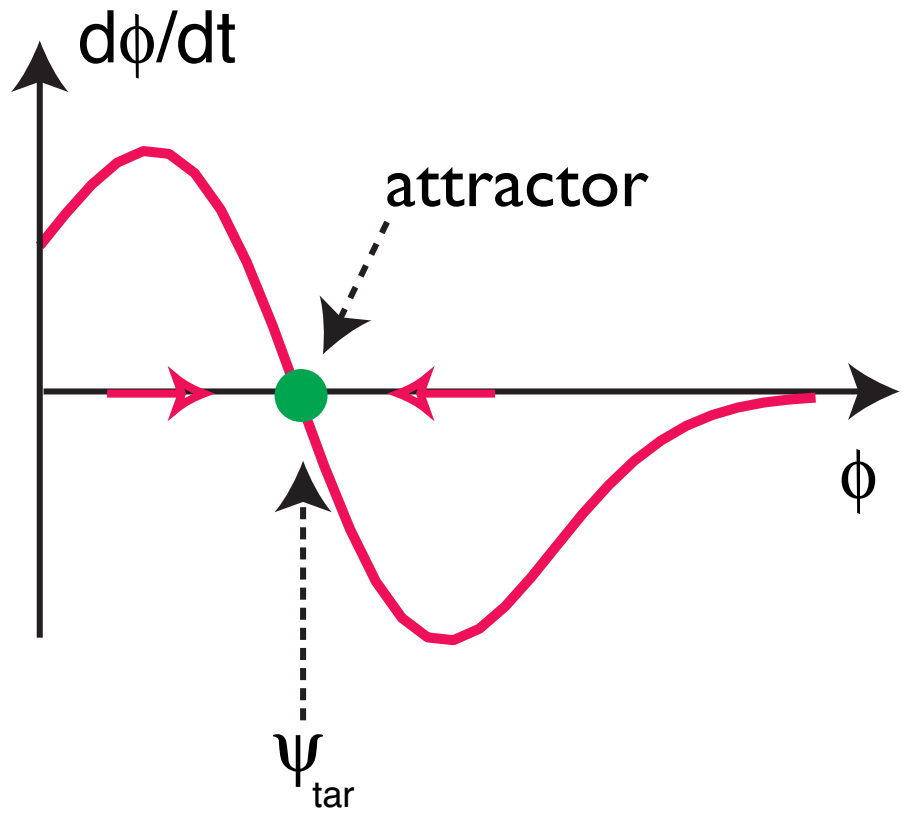
Behavioral dynamics

- generate behavior by generating time courses of behavioral variables
- generate time course of behavioral variables from attractor solutions of a (designed) dynamical system
- that dynamical system is constructed from contributions expressing behavioral constraints

Behavioral dynamics: example

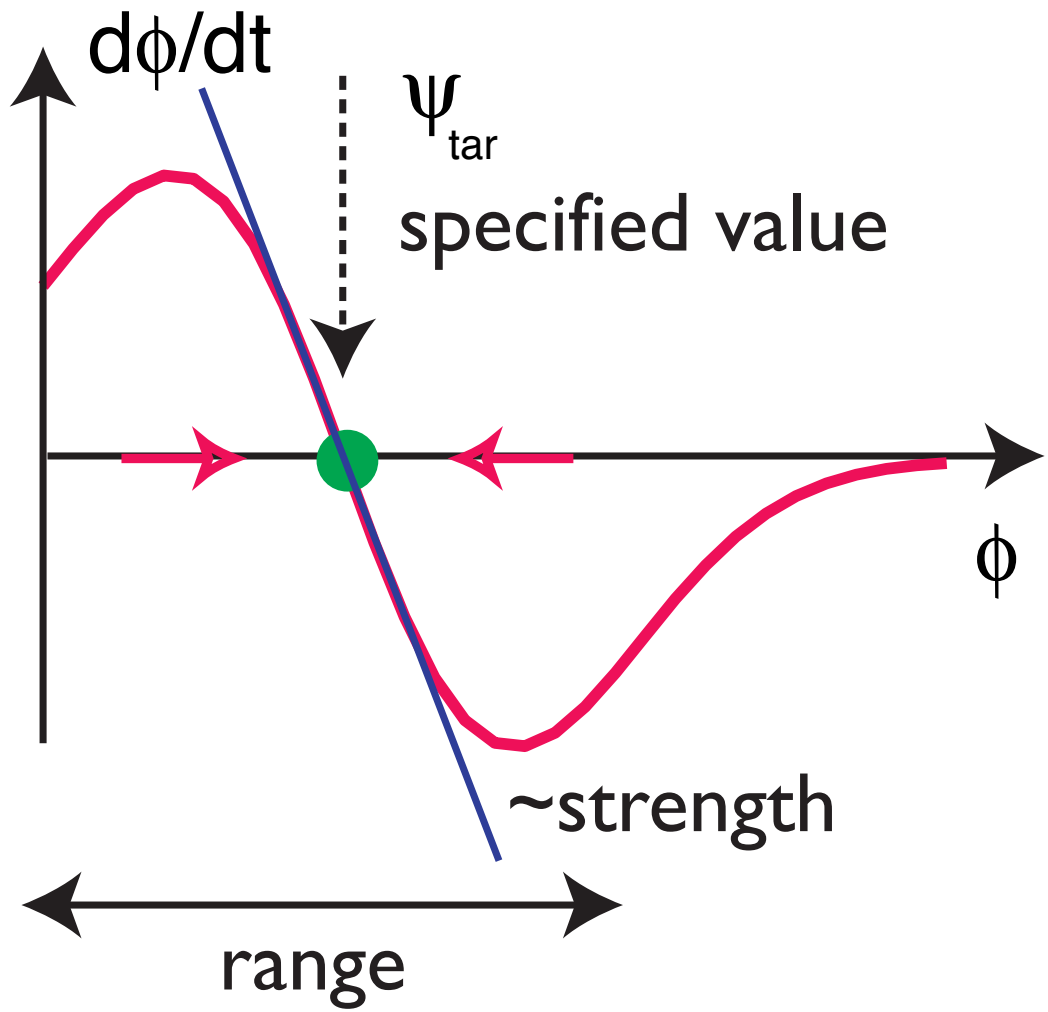
- behavioral constraint: target acquisition





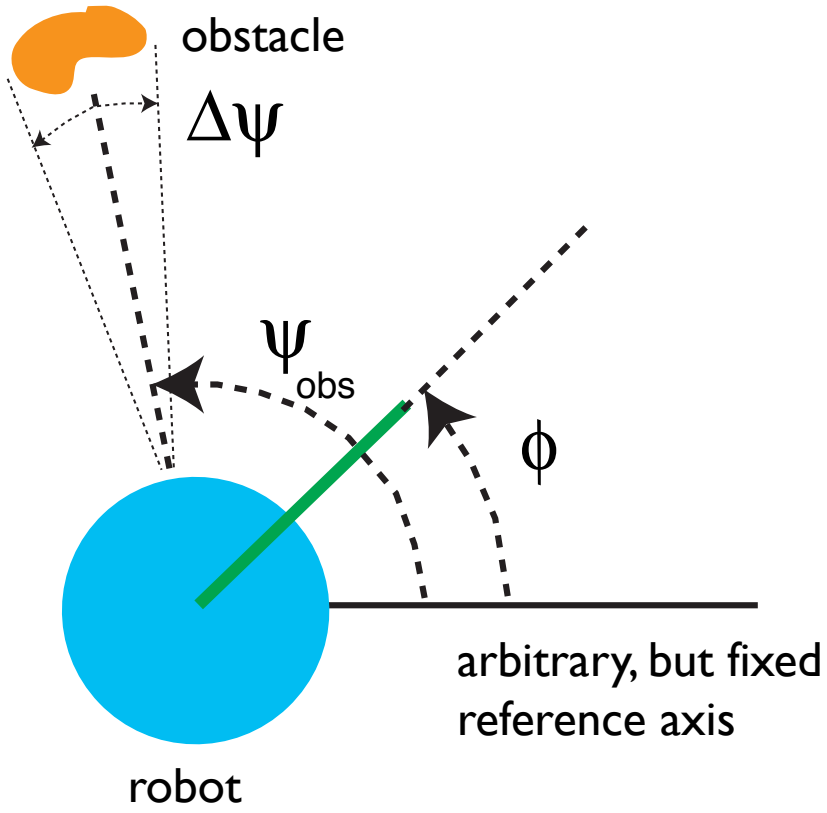
Behavioral dynamics

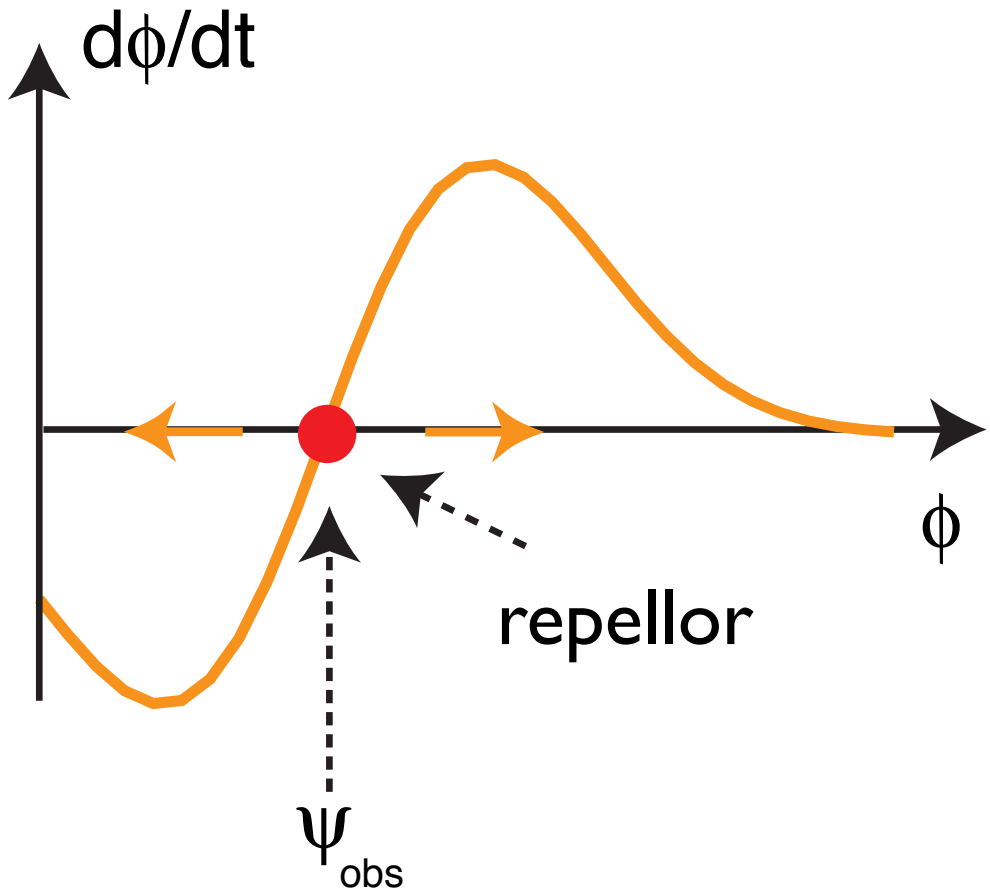
- each contribution is a "force-let" with
  - specified value
  - strength
  - range



Behavioral dynamics: example

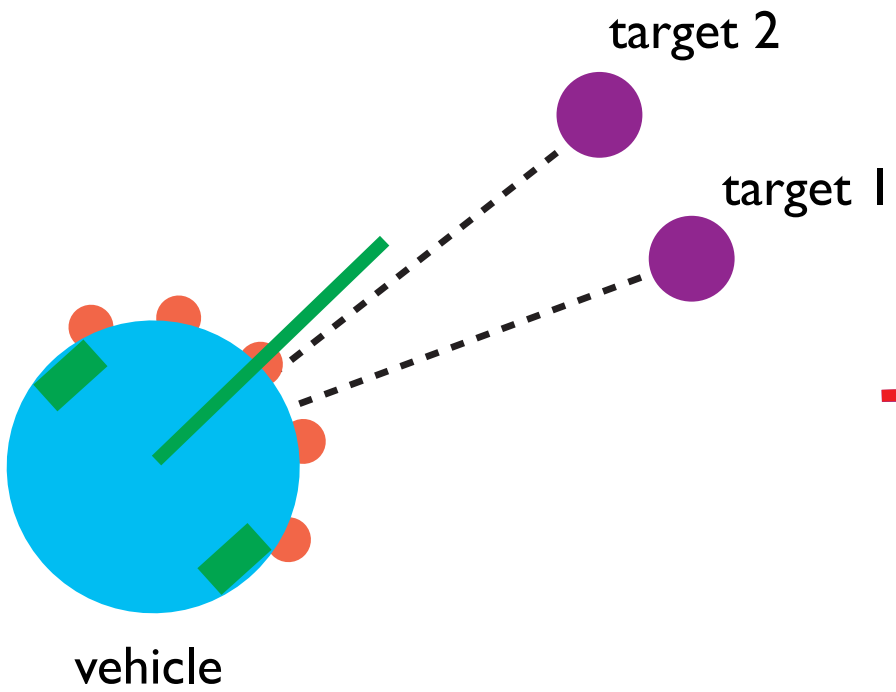
- behavioral constraint: obstacle avoidance

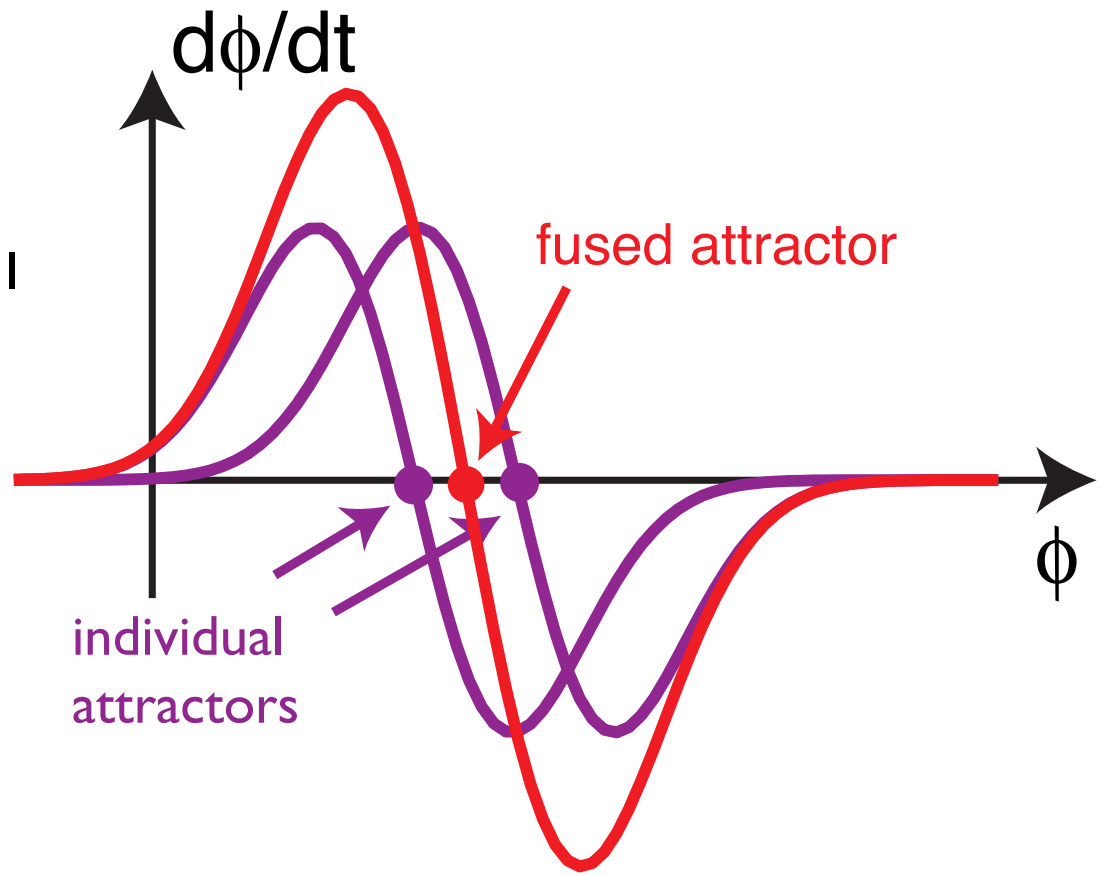




Behavioral dynamics

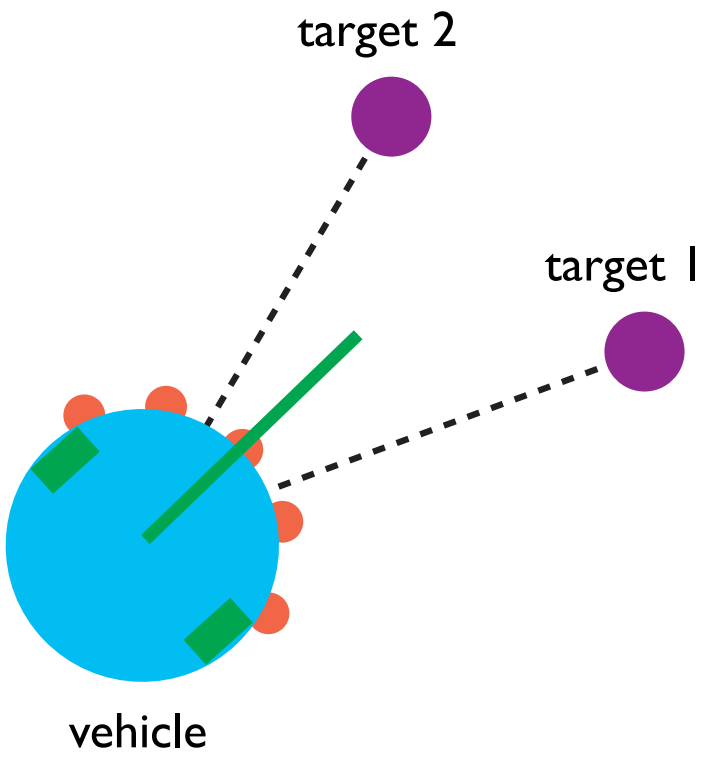
- multiple constraints: superpose "force-lets"
- fusion

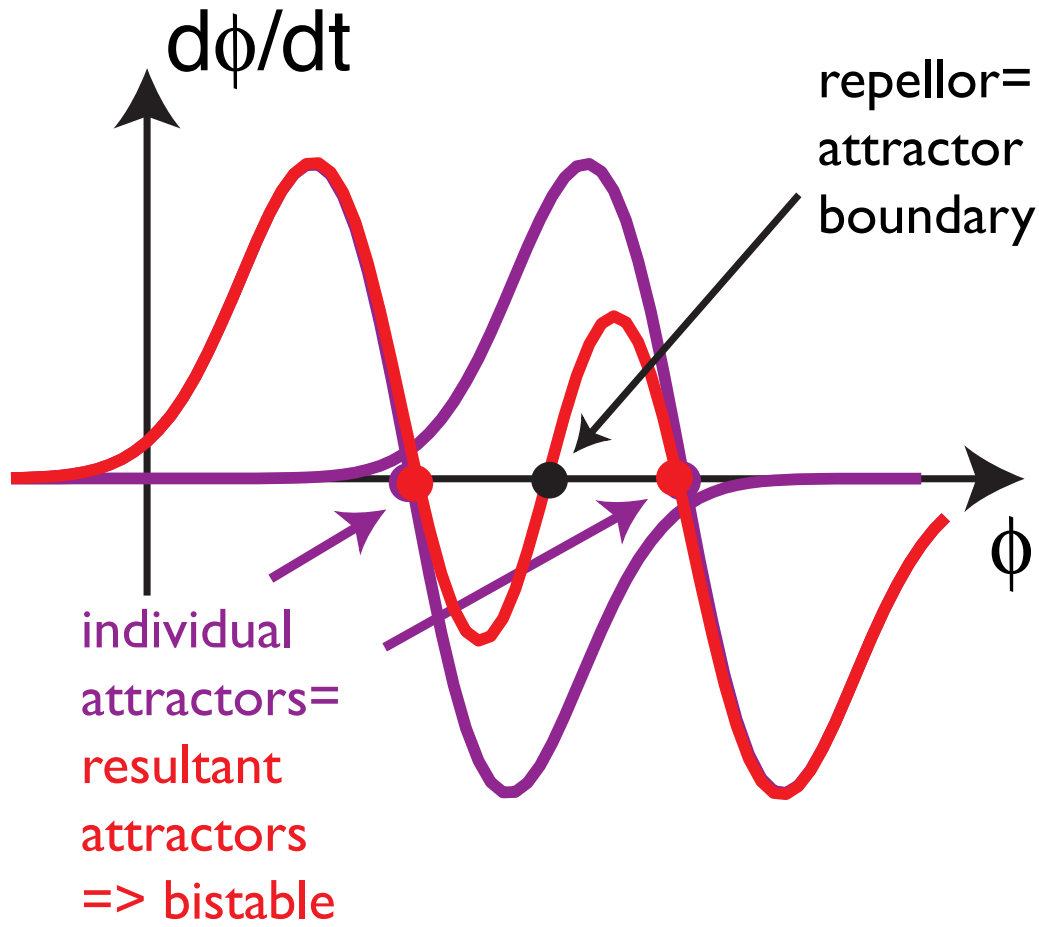




Behavioral dynamics

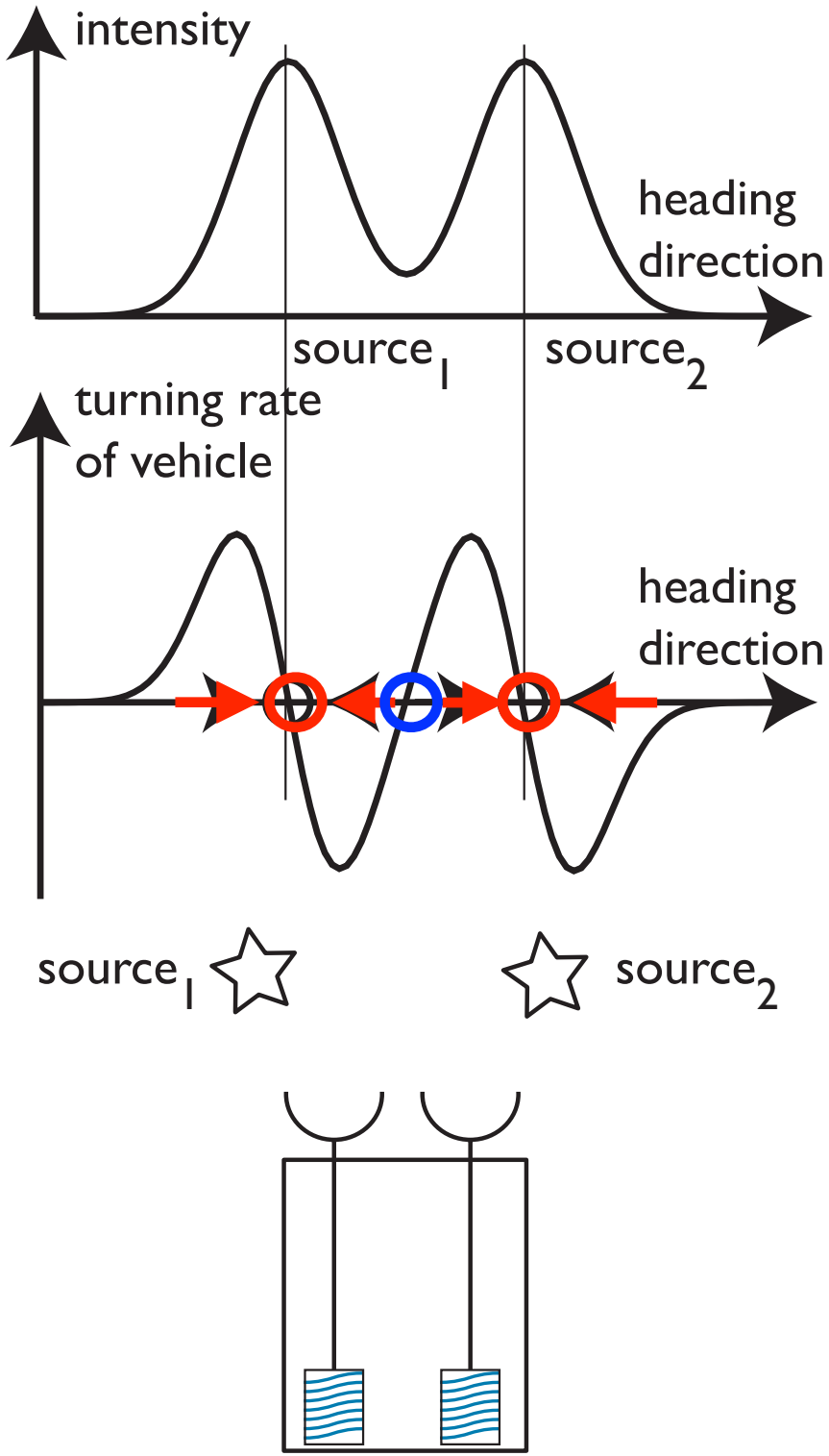
- decision making





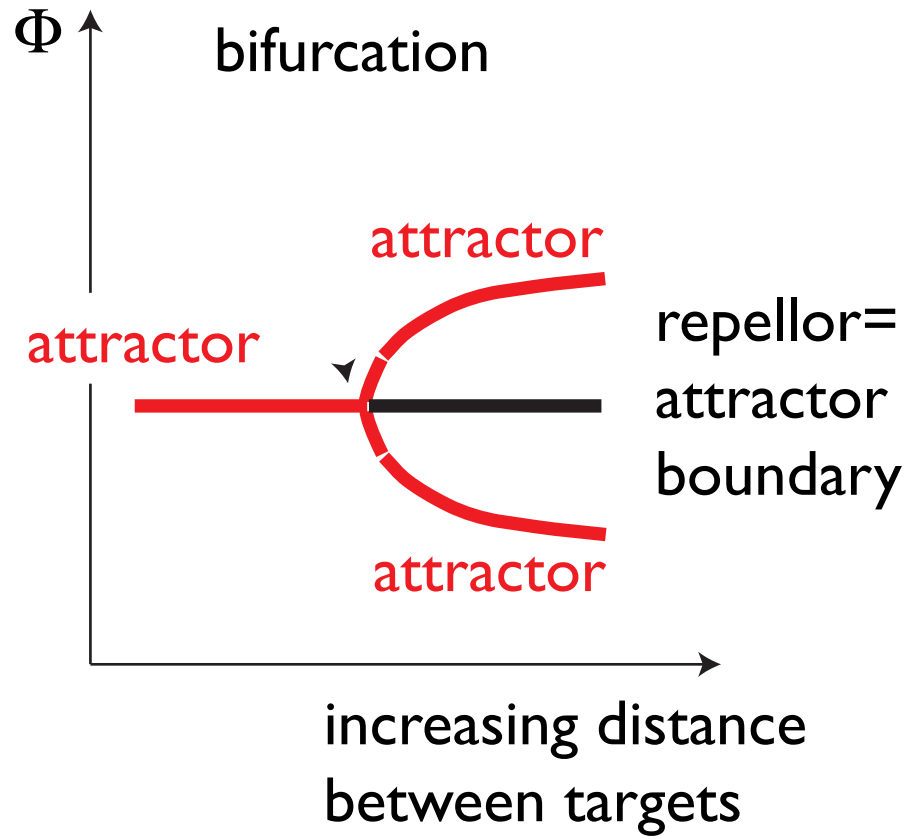
Braitenberg

- bistable dynamics for bimodal intensity distribution
- => nonlinear dynamics makes selection decision



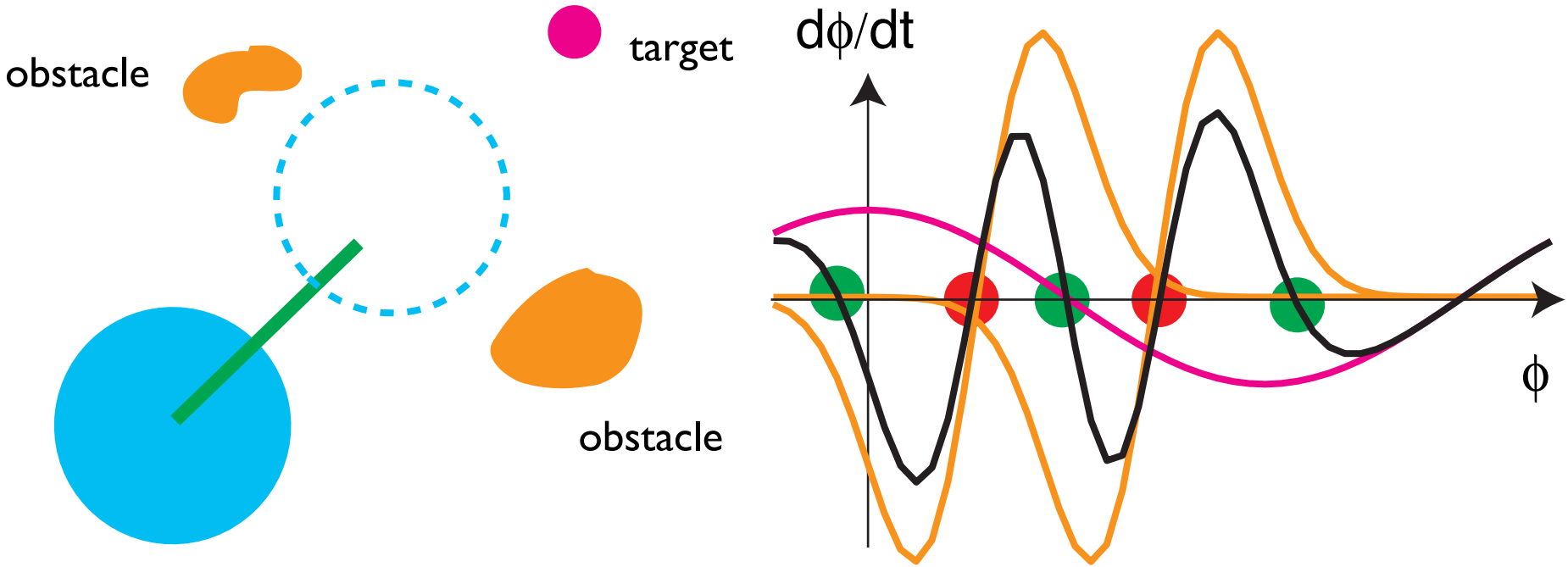
Behavioral dynamics

- Bifurcations switch between fusion and decision making



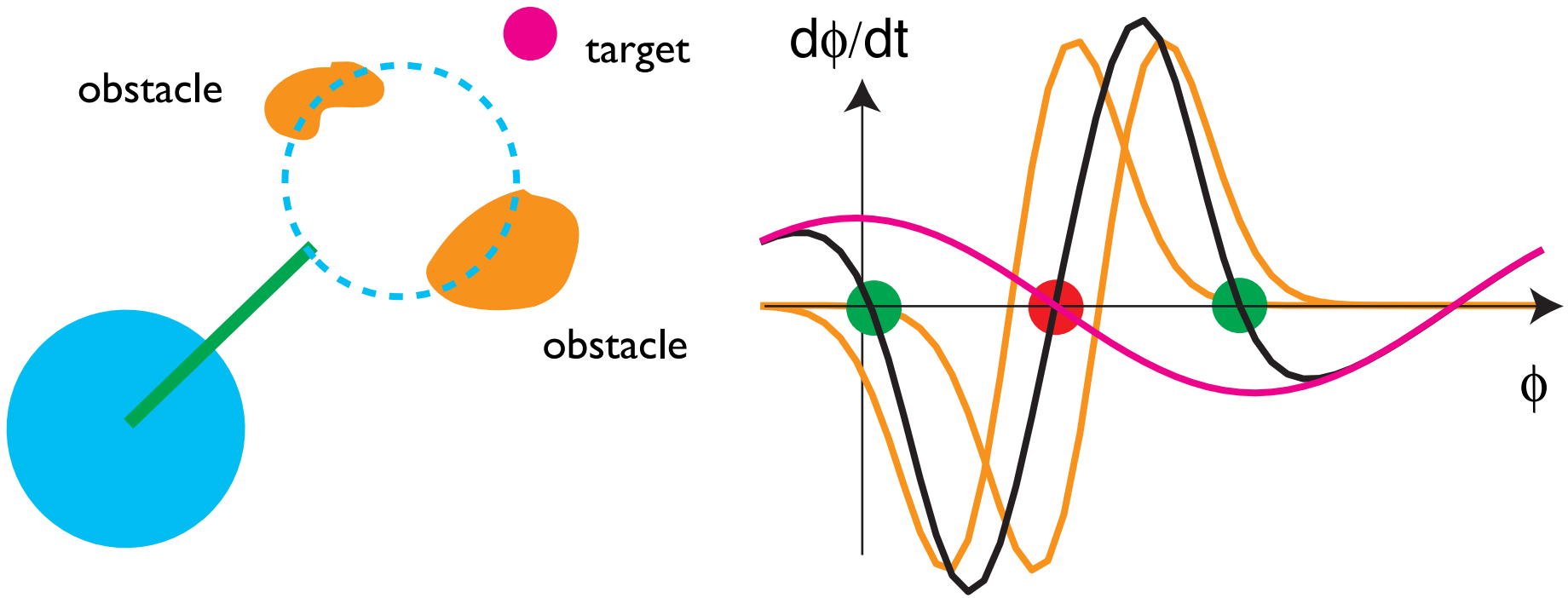
Behavioral dynamics

- an example closer to "real life": bifurcations in obstacle avoidance and target acquisition
- constraints not in conflict



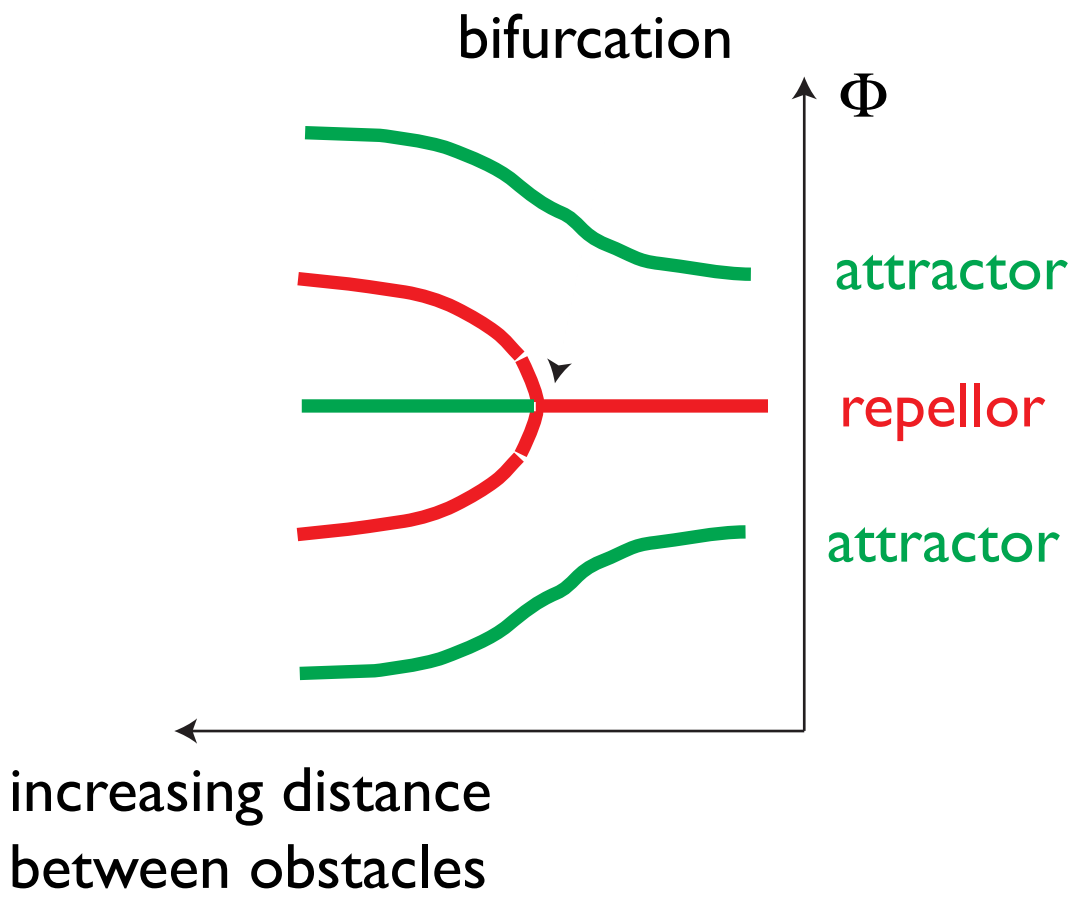
Behavioral dynamics

- constraints in conflict

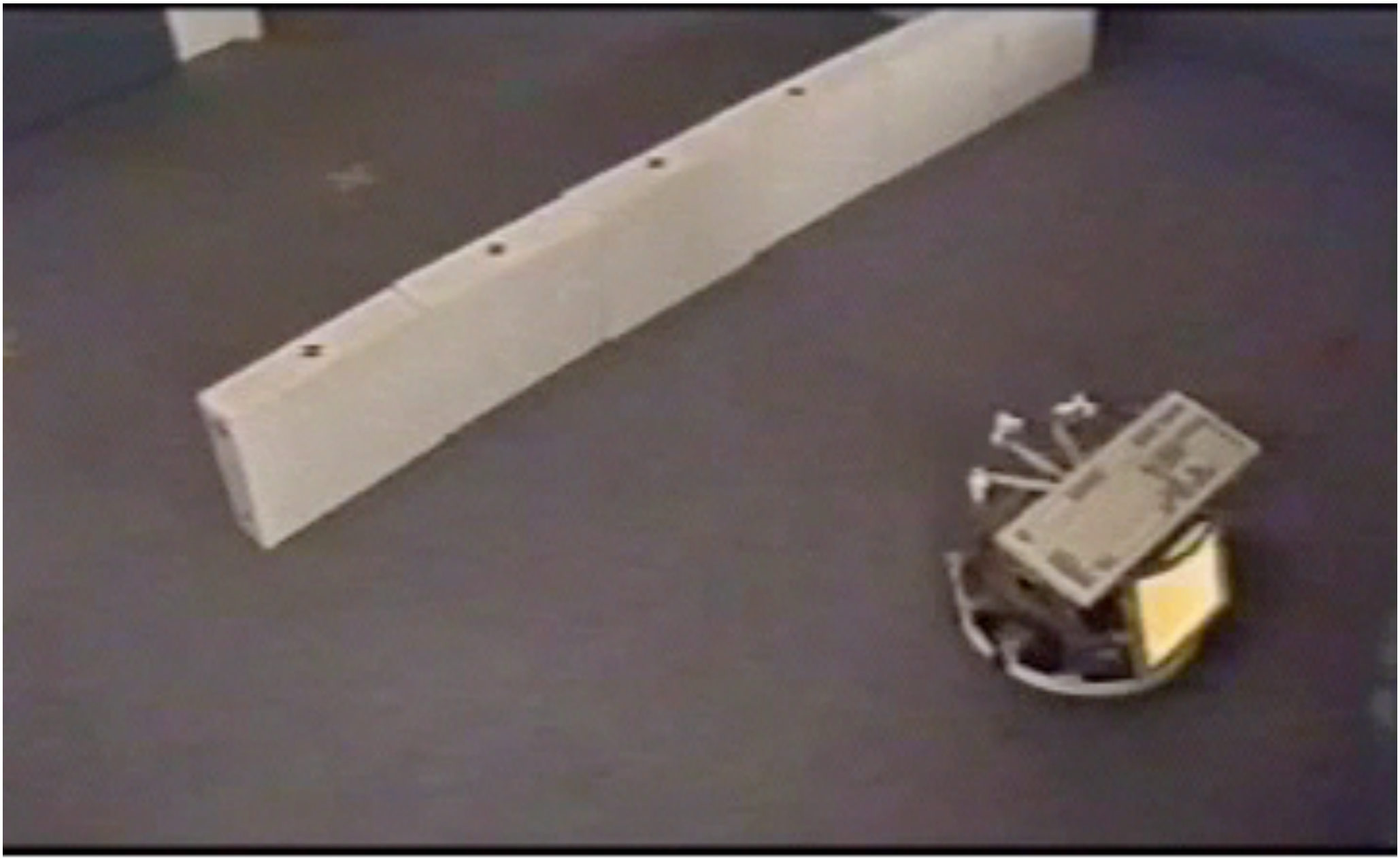


Behavioral dynamics

- transition from "constraints not in conflict" to "constraints in conflict" is a bifurcation

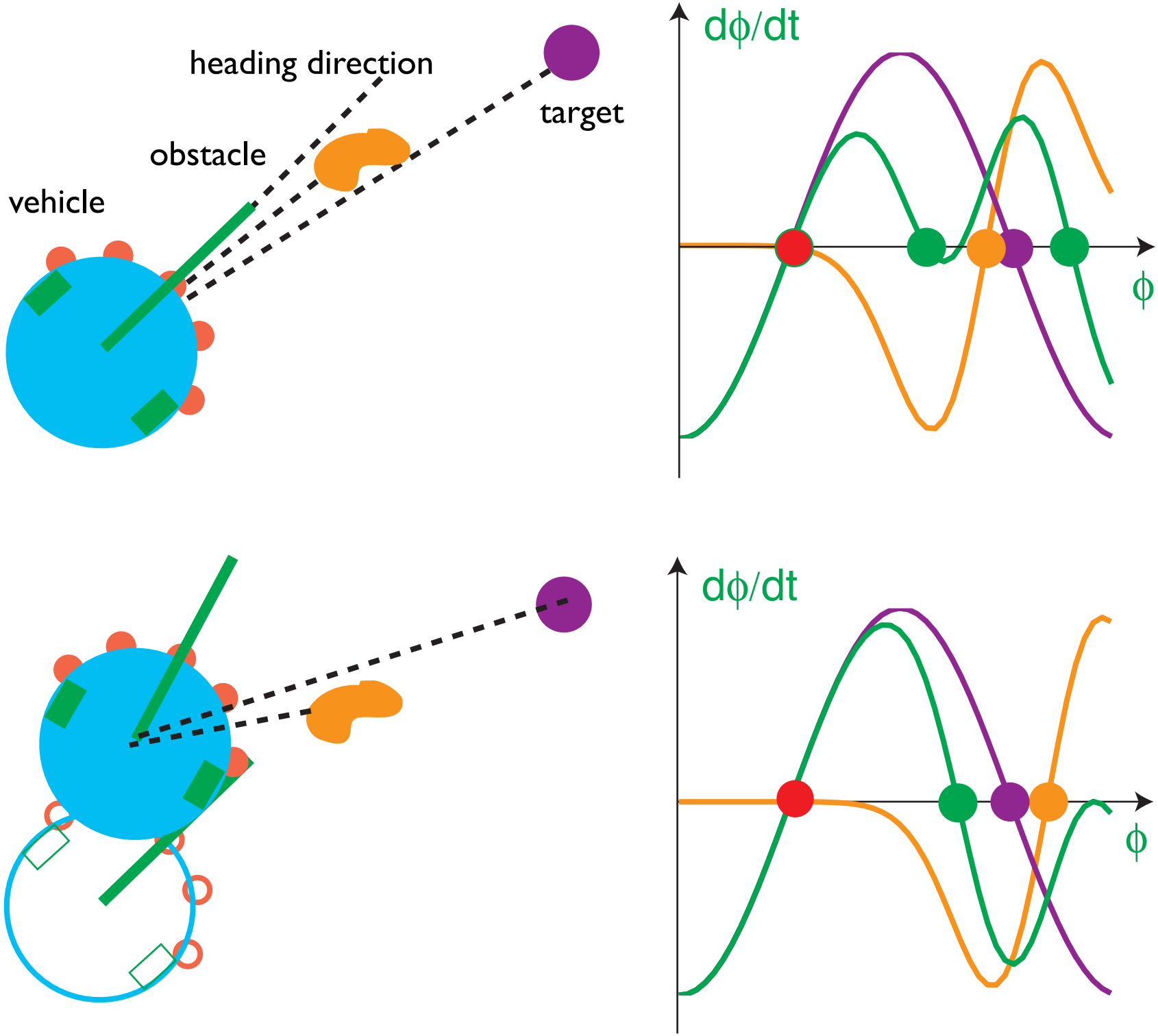


Bifurcations

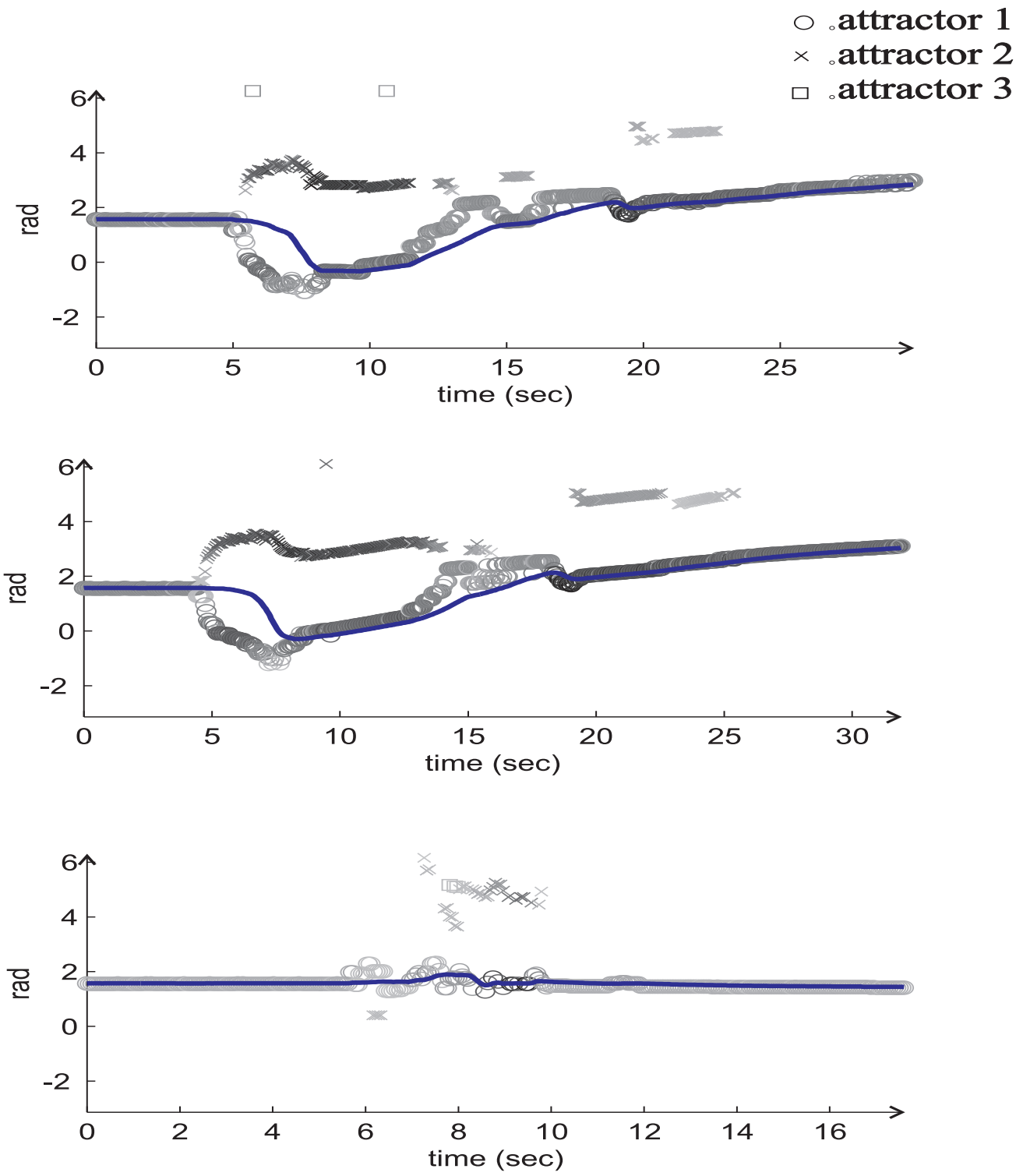


Behavioral dynamics

- heading direction is always in or close to attractor… which is why bifurcations matter…
- But how may complex behavior be generated while "sitting" in an attractor?


heading direction
target
obstacle
vehicle
dϕ/dt
ϕ
dϕ/dt
ϕ

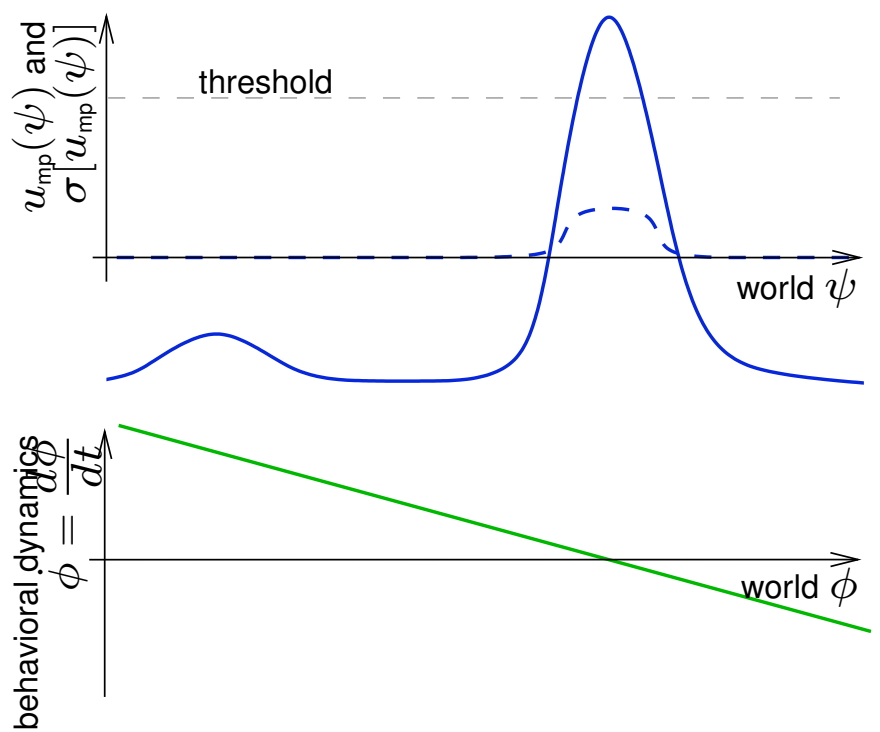
Tracking attractors



[Bicho, 2000]

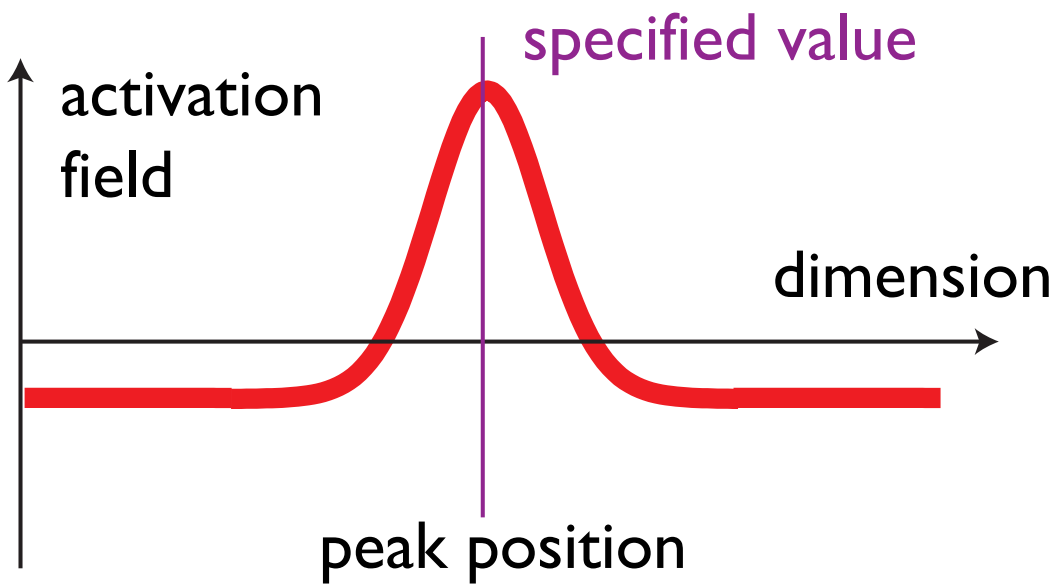
Steering the behavioral dynamics

- so far, we took for granted that there is perceptual information about the constraints: targets, obstacles
- these constraints emerge from a neural dynamics: couple a peak in the neural field of target bearing into the dynamics of heading direction as an attractor



Problem number 1:
"Reading out" from the neural field?

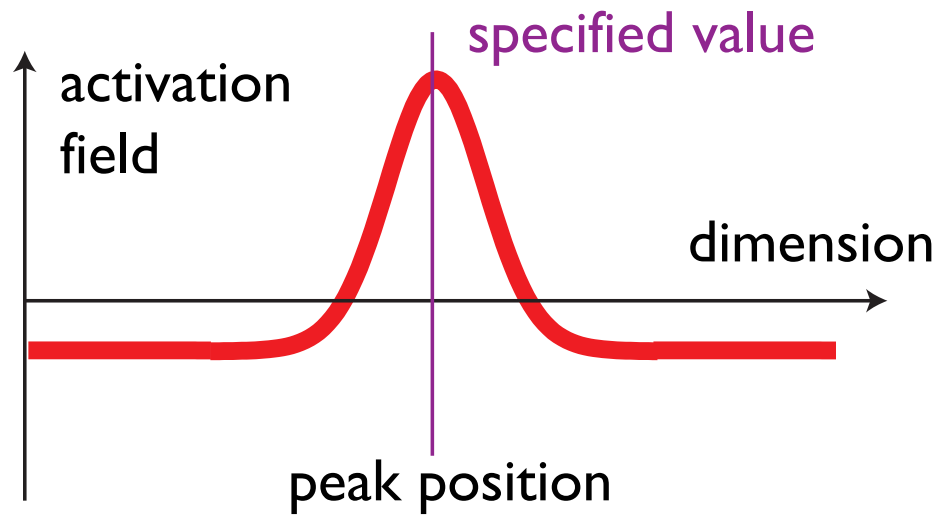
- peak specifies value of the field dimension over which it is located…
- but how to "read out" that value?

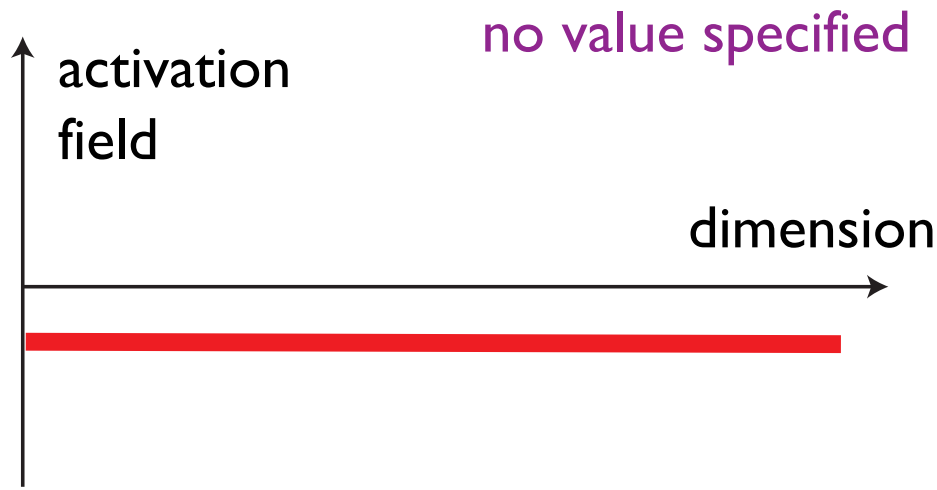


"reading out" from the neural field?

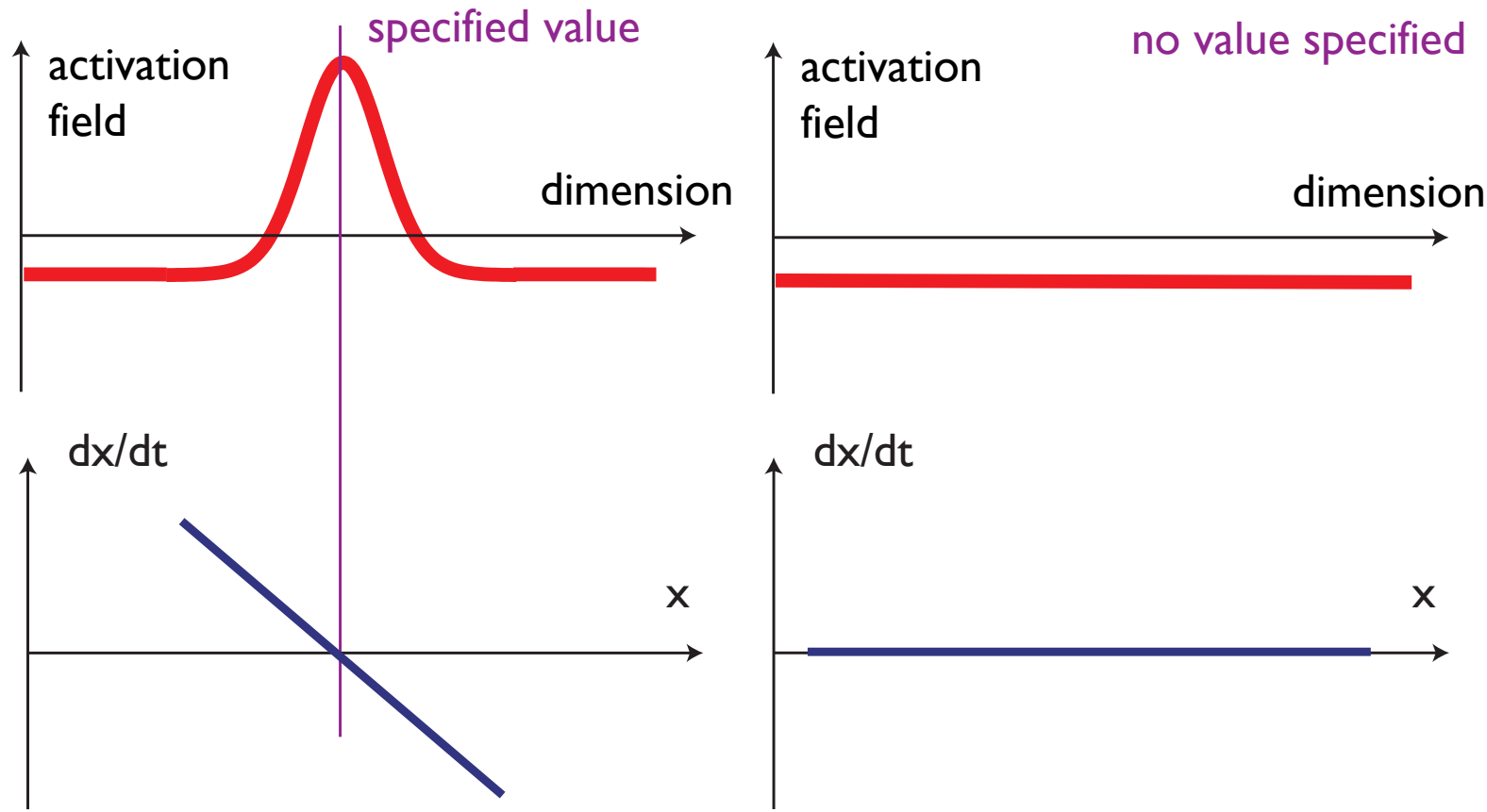
- standard idea: treat supra-threshold field as a probability density
- but: need to normalize the activation pattern
- => problem when there is no peak: divide by zero!

$$x_{\text{peak}} = \frac{\int dx \; x \; \sigma(u(x,t))}{\int dx \; \sigma(u(x,t))}$$





“reading out” from the neural field?



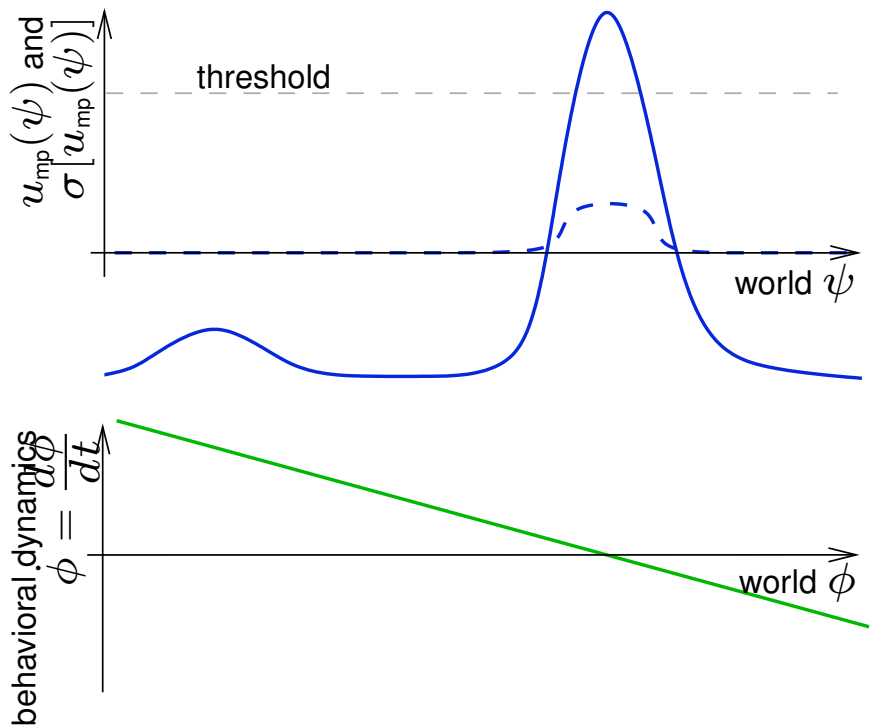
from DFT to DST

- solution: peak sets attractor
  - location of attractor: peak location
  - strength of attractor: summed supra-threshold activation

$$
\begin{aligned}
x_{\text{peak}} &= \frac{\int dx\ x\ \sigma(u(x,t))}{\int dx\ \sigma(u(x,t))} \\
\dot{x} &= -\left[\int dx\ \sigma(u(x,t))\right](x - x_{\text{peak}}) \\
\Rightarrow \dot{x} &= -\left[\int dx\ \sigma(u(x,t))\right]\ x + \left[\int dx\ x\ \sigma(u(x,t))\right]
\end{aligned}
$$

Problem number 2: closed loop

- the target representation is invariant in space, defined over heading direction
- and so is the motor dynamics…
- how does the "heading direction" then capture the physical state of the body in the world ~ behavioral dynamics?

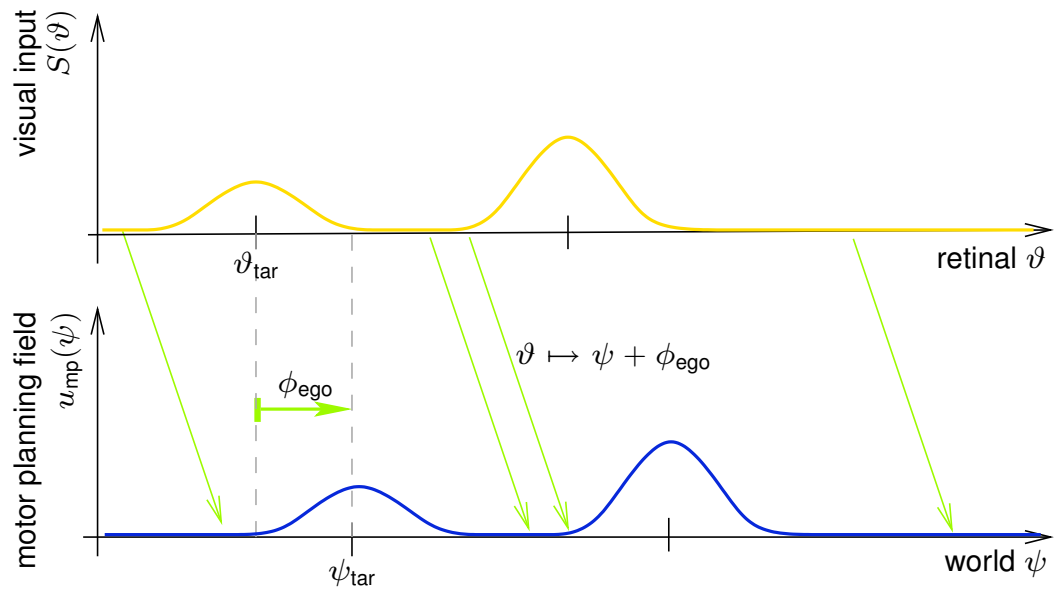


Answer

- the target representation must be invariant under a change in heading because it is in that frame that working memory about the target and neural state about target selection is meaningful… this is a property of the world
- and the same argument applies to the motor dynamics: only when the dynamics is invariant under change of heading is it a meaningful dynamics

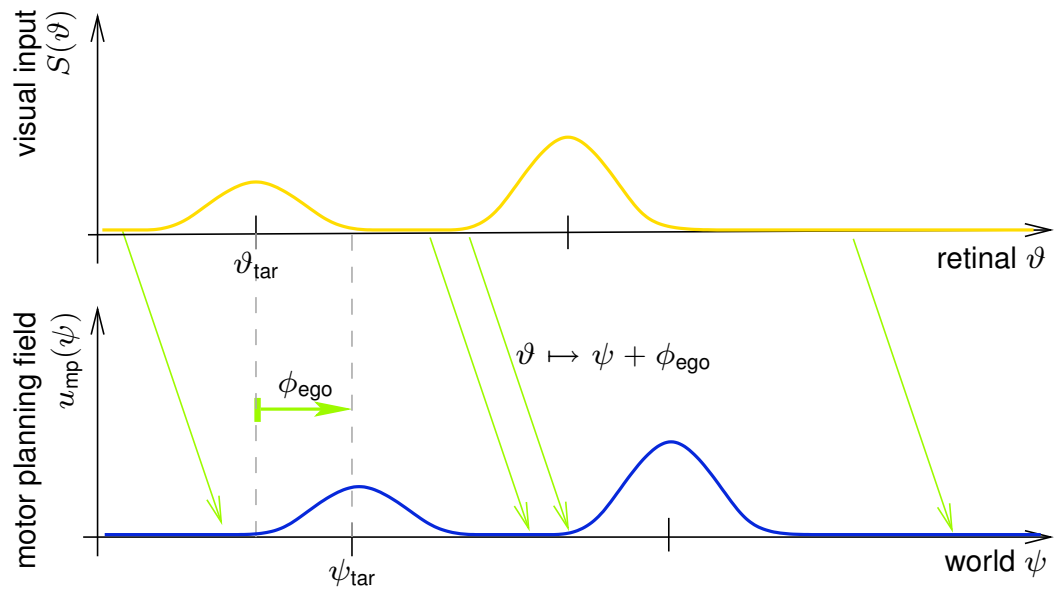
Answer

- to makes this consistent with coupling to sensory information, we must perform a a coordinate transform from the sensory surface (“retina”) to the invariant world frame!
- and that requires knowing the heading direction in the world…



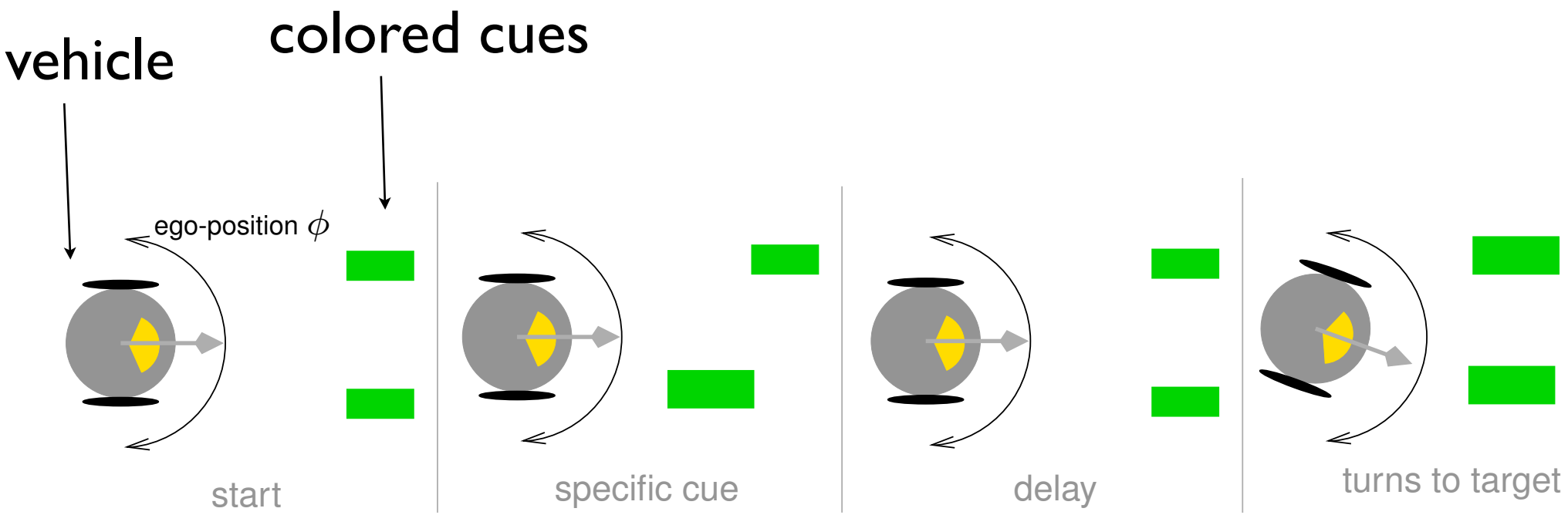
Answer

- this is a steerable neural map… and we'll cover that in the next lecture



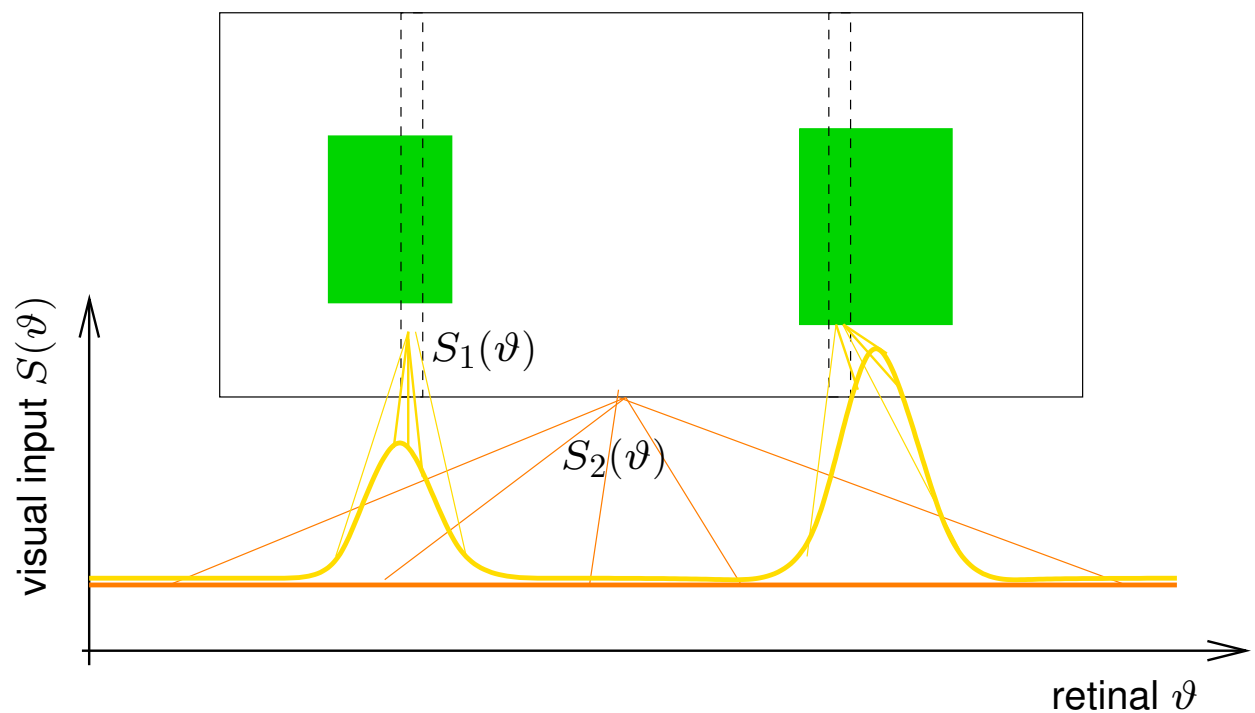
Embodied A not B

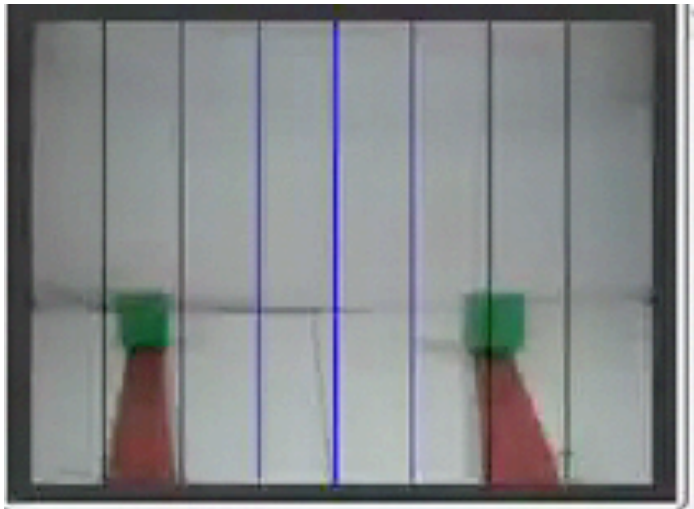
- implementing the A not B model on a autonomous robot with continuous link to sensory and motor surfaces...

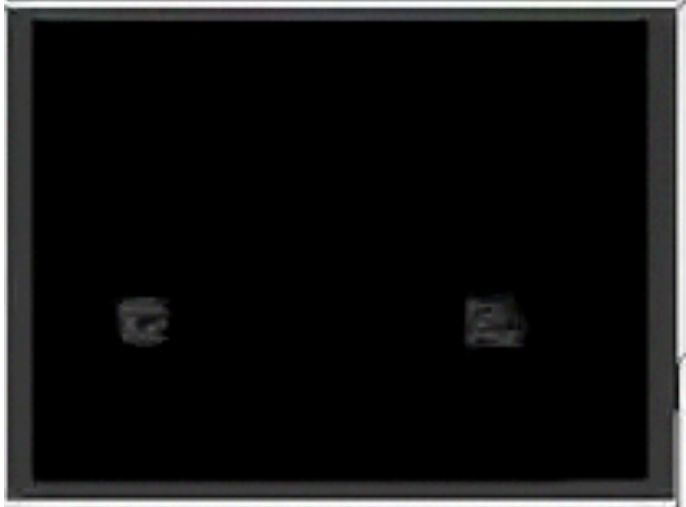


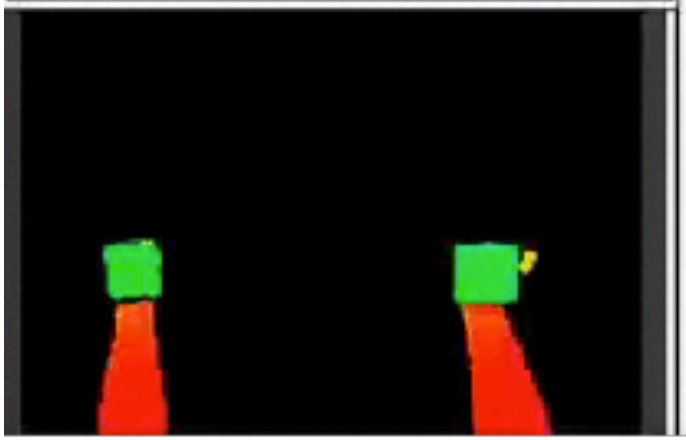
Visual input

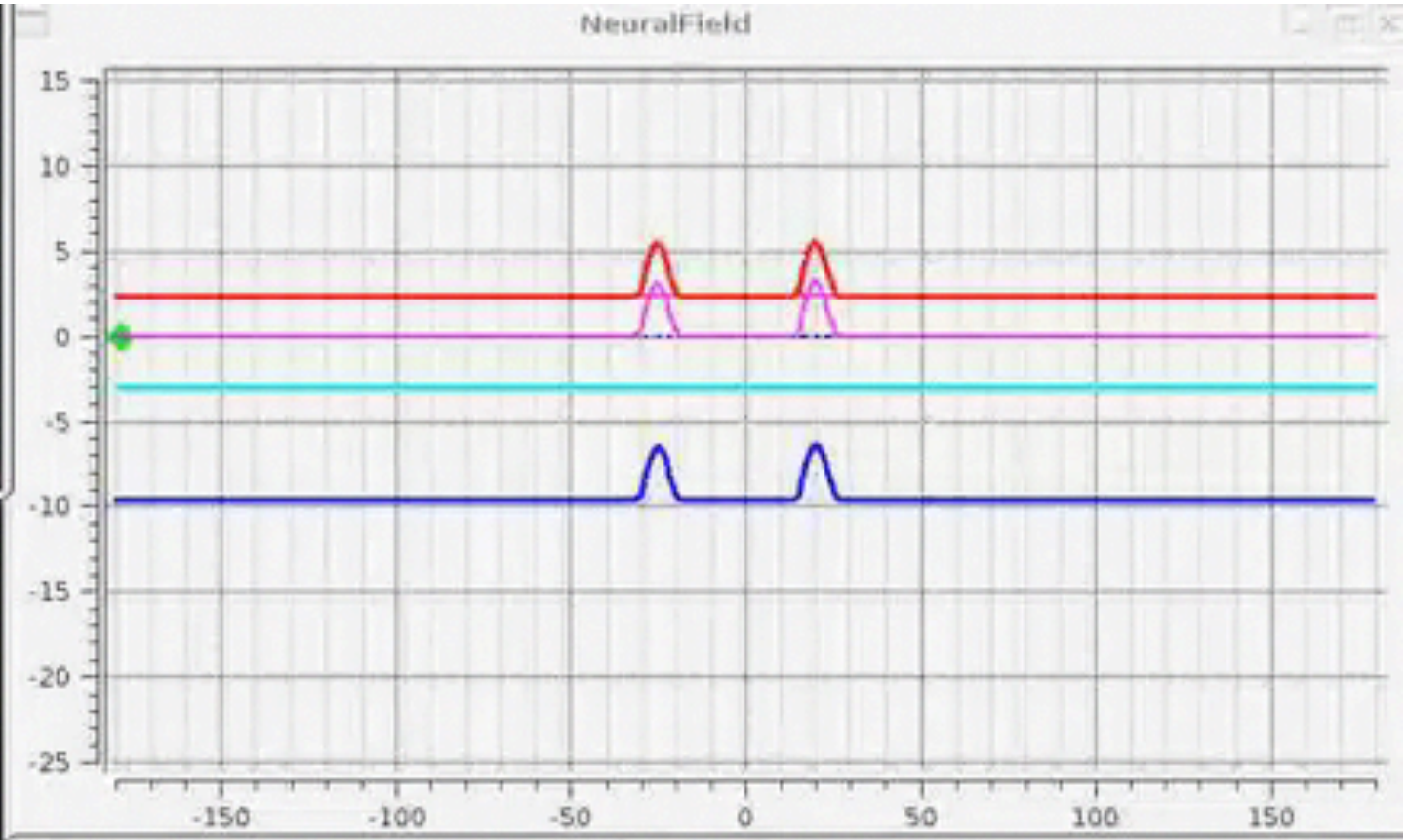
- color-based segmentation
- summing color pixels within color slot along the vertical
- spatially filter at two resolutions

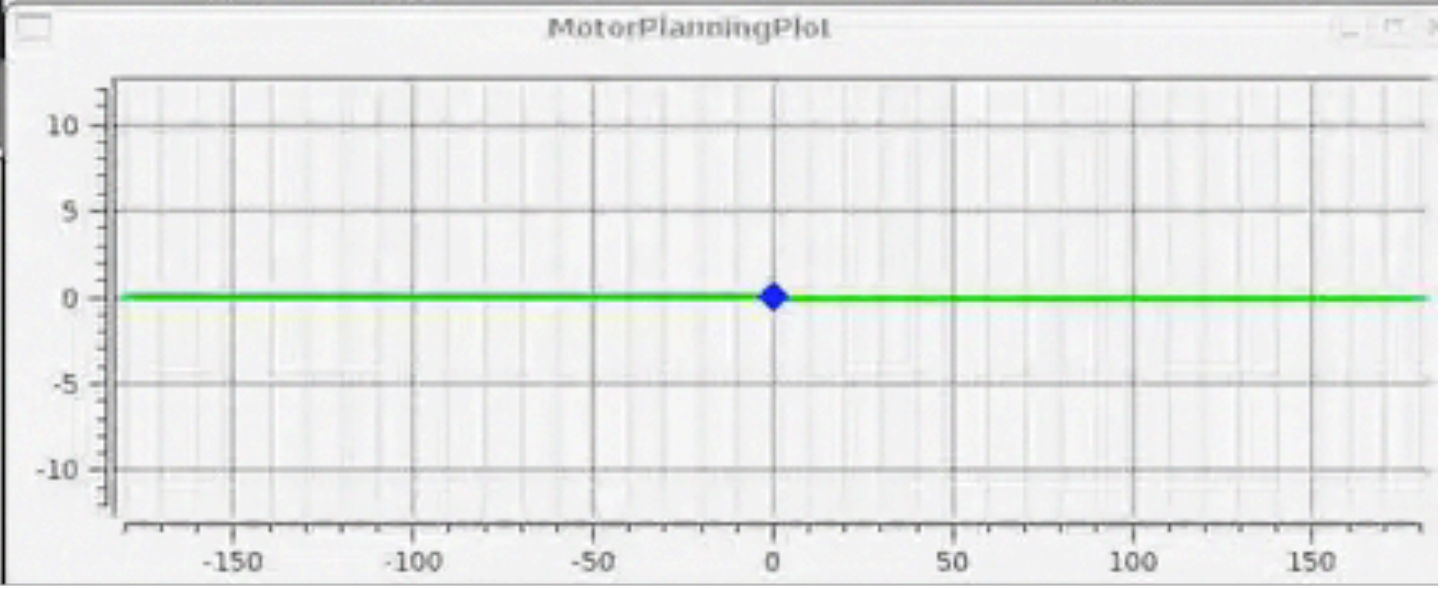


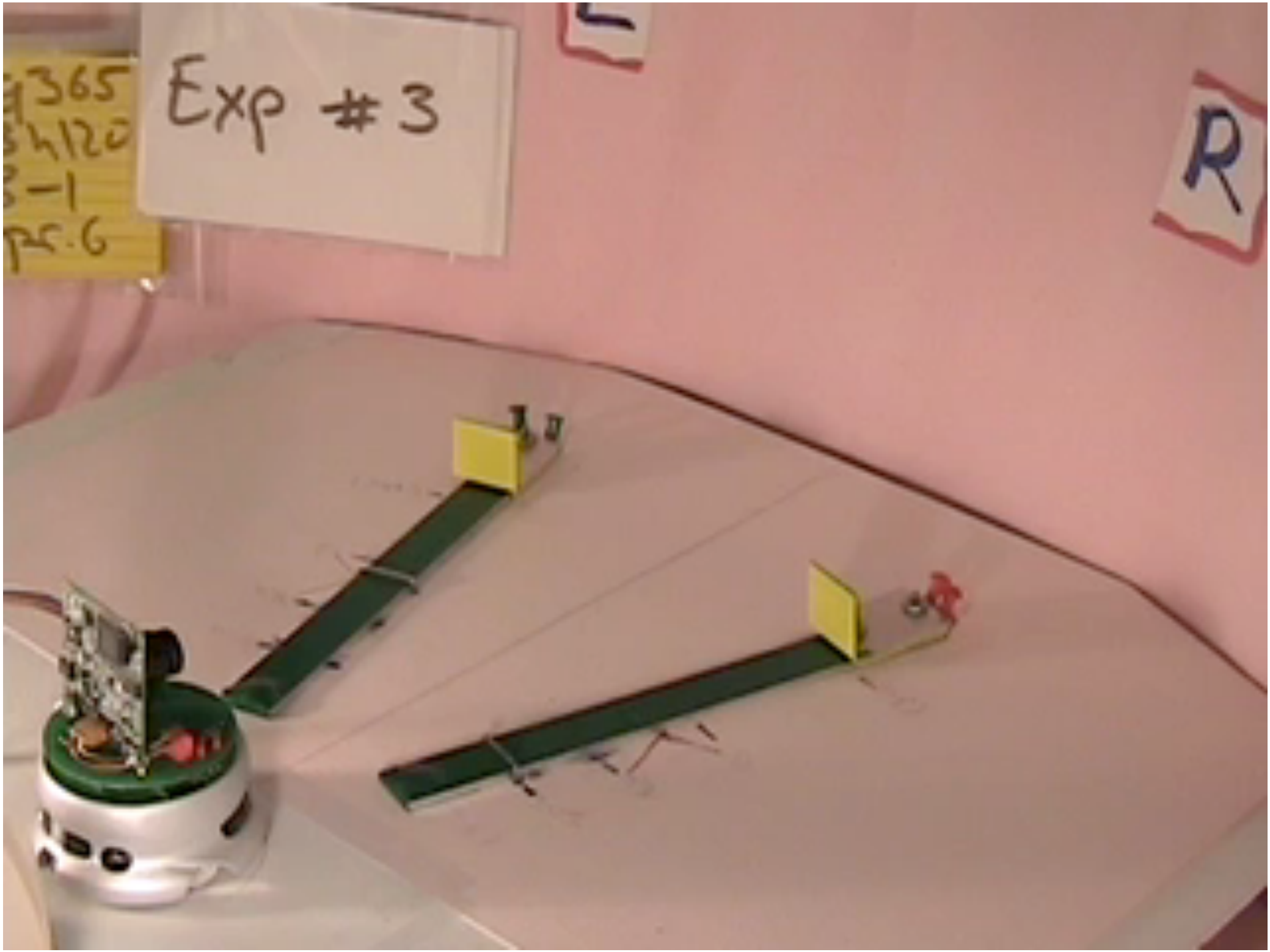


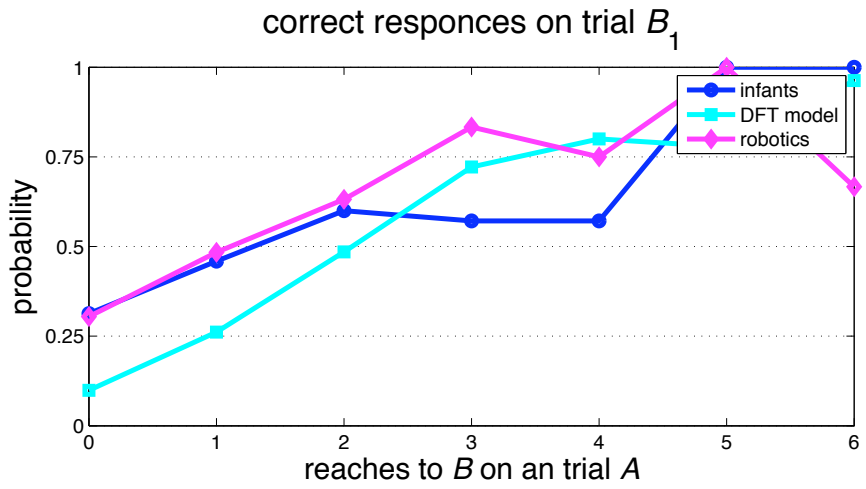




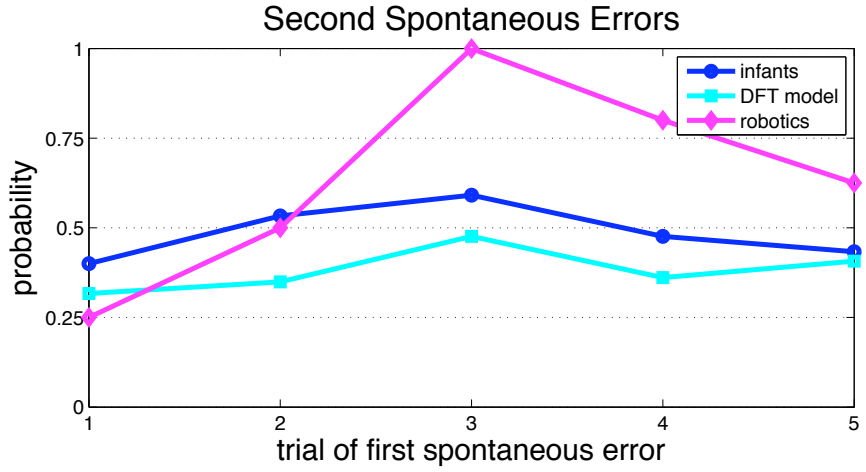

NeuralField
15
10
5
0
-5
-10
-15
-20
-25
-150
-100
-50
0
50
100
150

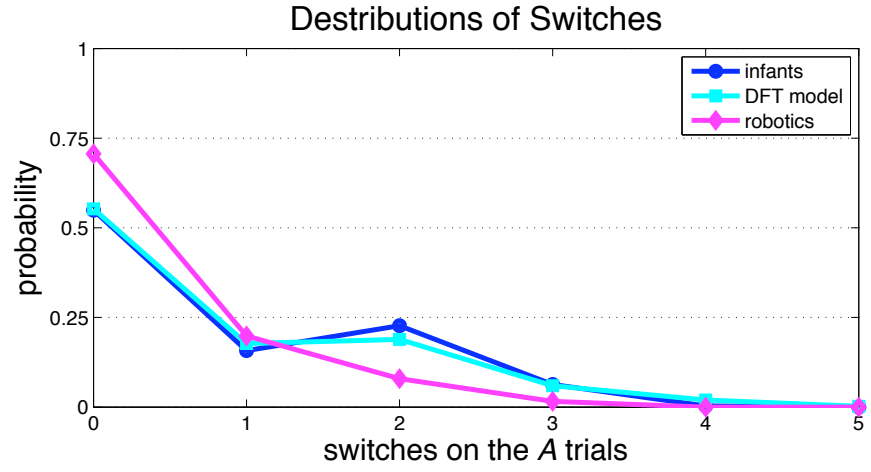

MotorPlanningPlot
10
5
0
-5
-10
-150
-100
-50
0
50
100
150

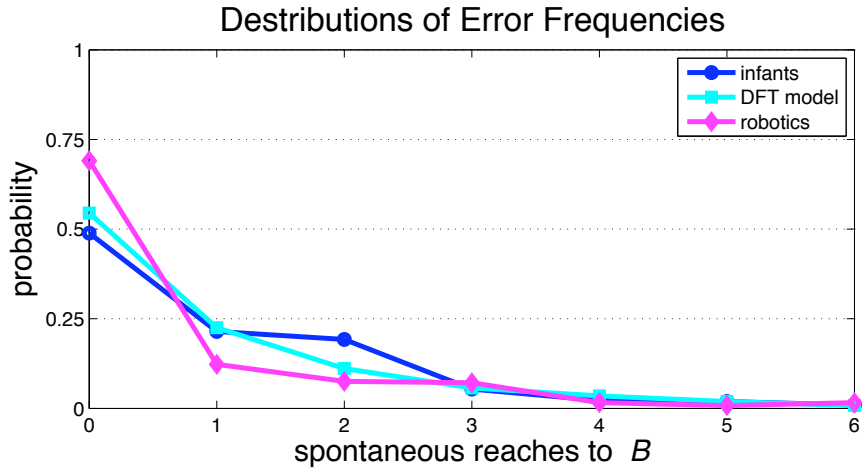

Exp #3
R


correct responces on trial B_1
probability
reaches to B on an trial A
infants
DFT model
robotics

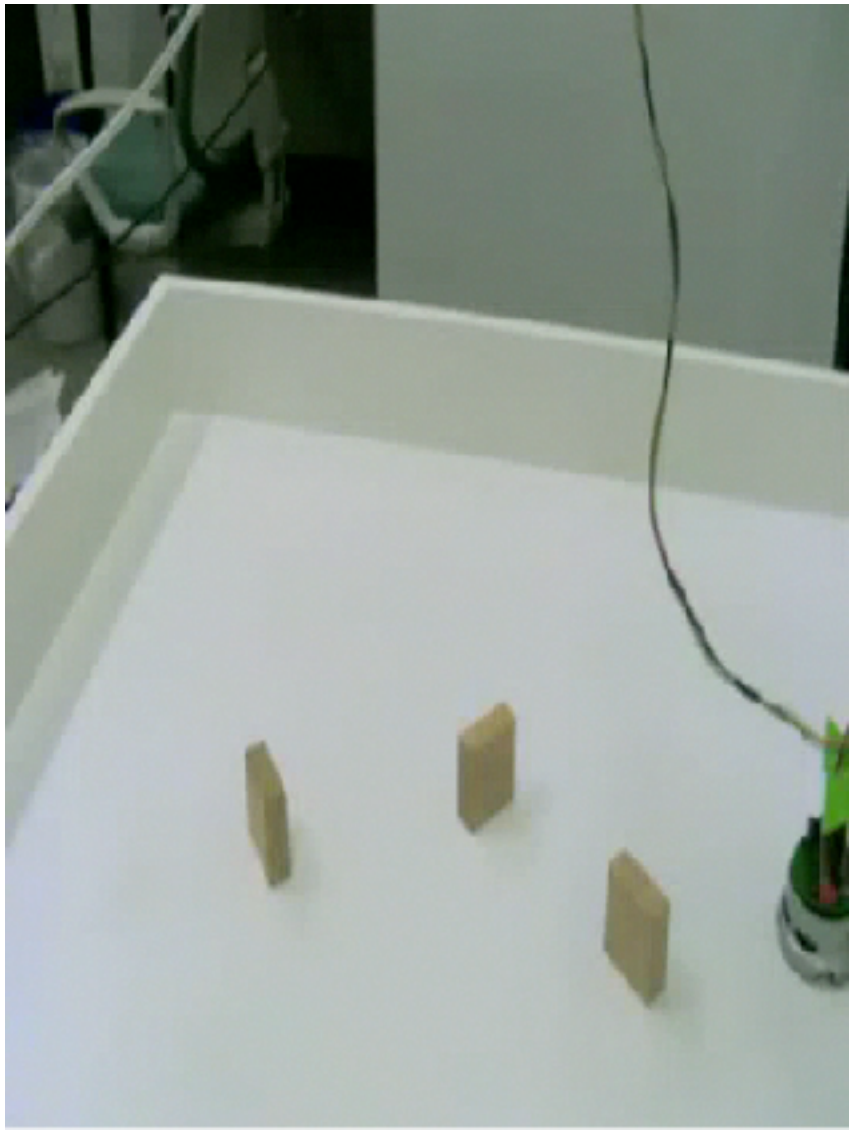

First Spontaneous Errors
probability
trial
infants
DFT model
robotics


Second Spontaneous Errors
probability
trial of first spontaneous error
infants
DFT model
robotics

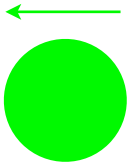

Destributions of Switches
probability
switches on the A trials
infants
DFT model
robotics


Destributions of Error Frequencies
probability
spontaneous reaches to B
infants
DFT model
robotics

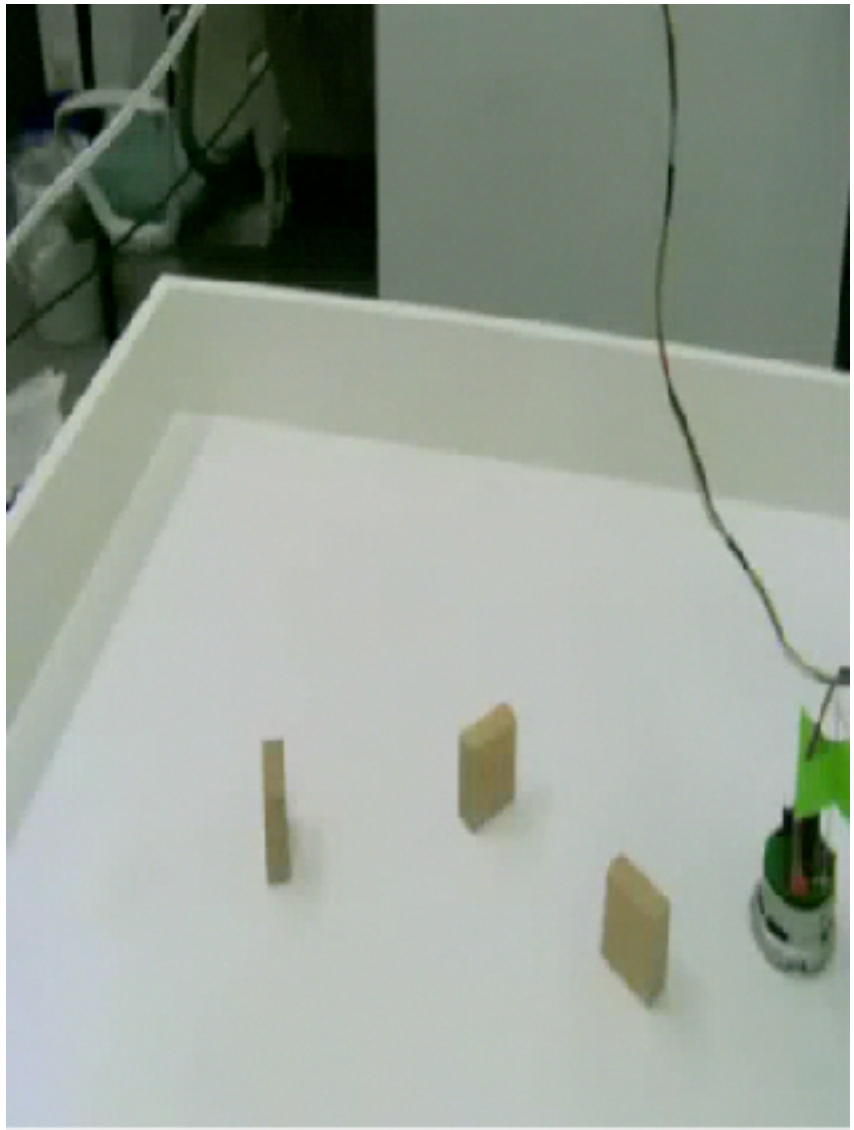
"young" robot



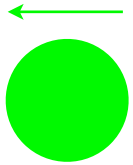
target



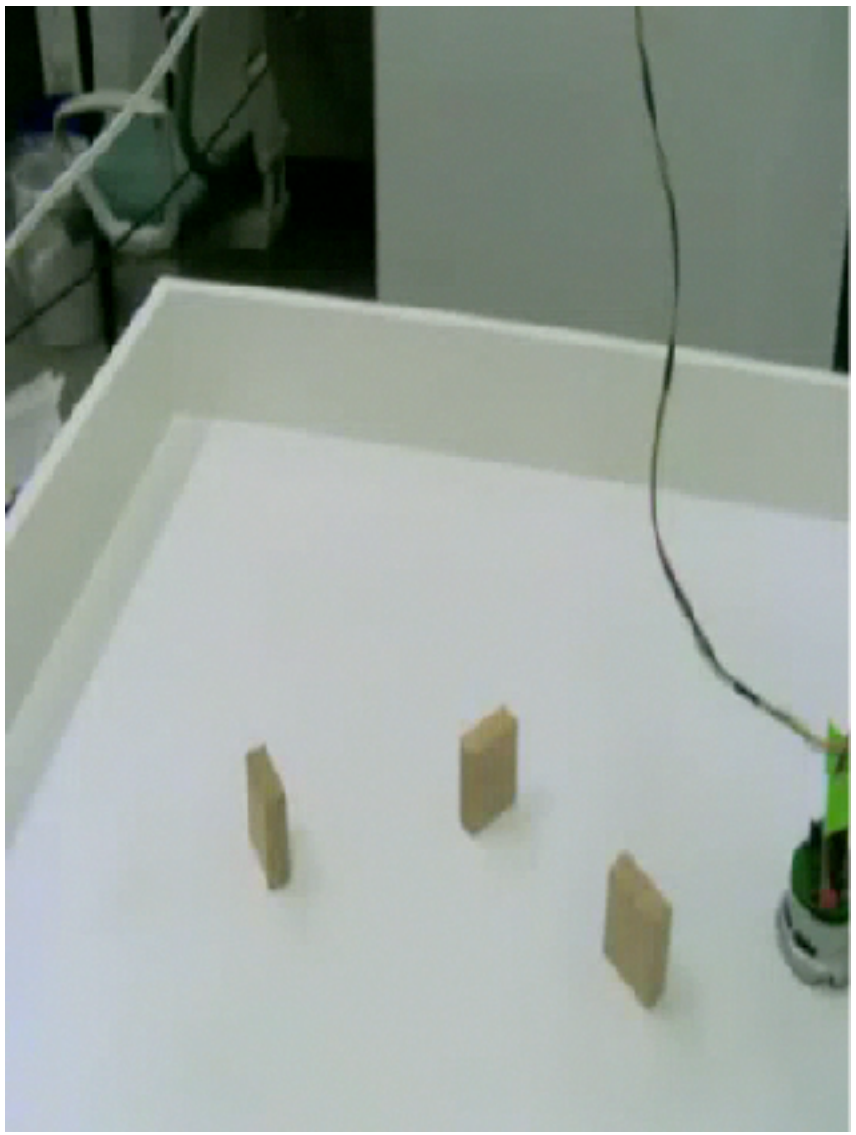
"old" robot



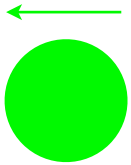
target



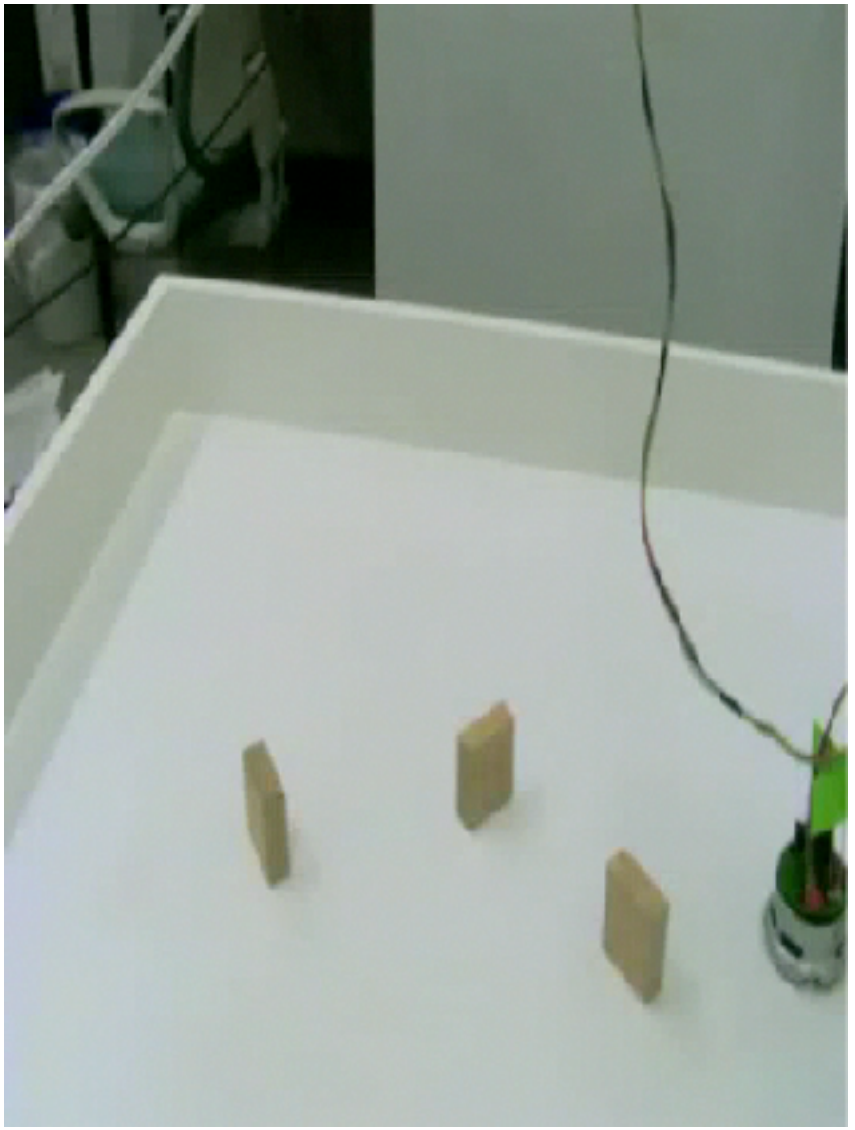
"young" robot



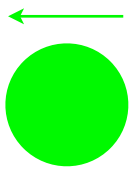
target



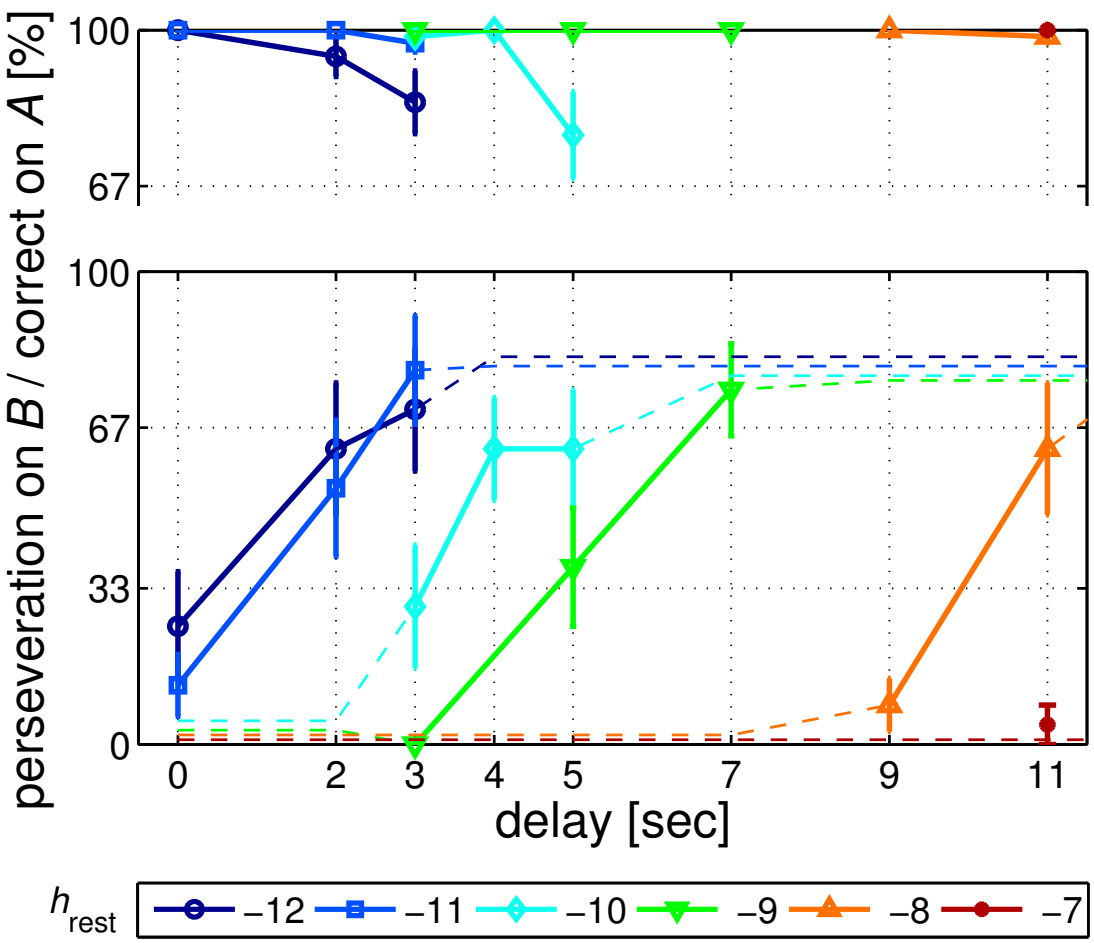
"young" robot with memory trace



target



result: reproduce fundamental age-delay trade-off in A not B



young

old

Conclusion

- neural dynamics directly driven by sensory input
- attractor dynamics all the way down to behavioral variables
- fields couple into behavioral dynamics by setting attractors => no more "read-out" of neural dynamics