Embodied Neural Dynamics

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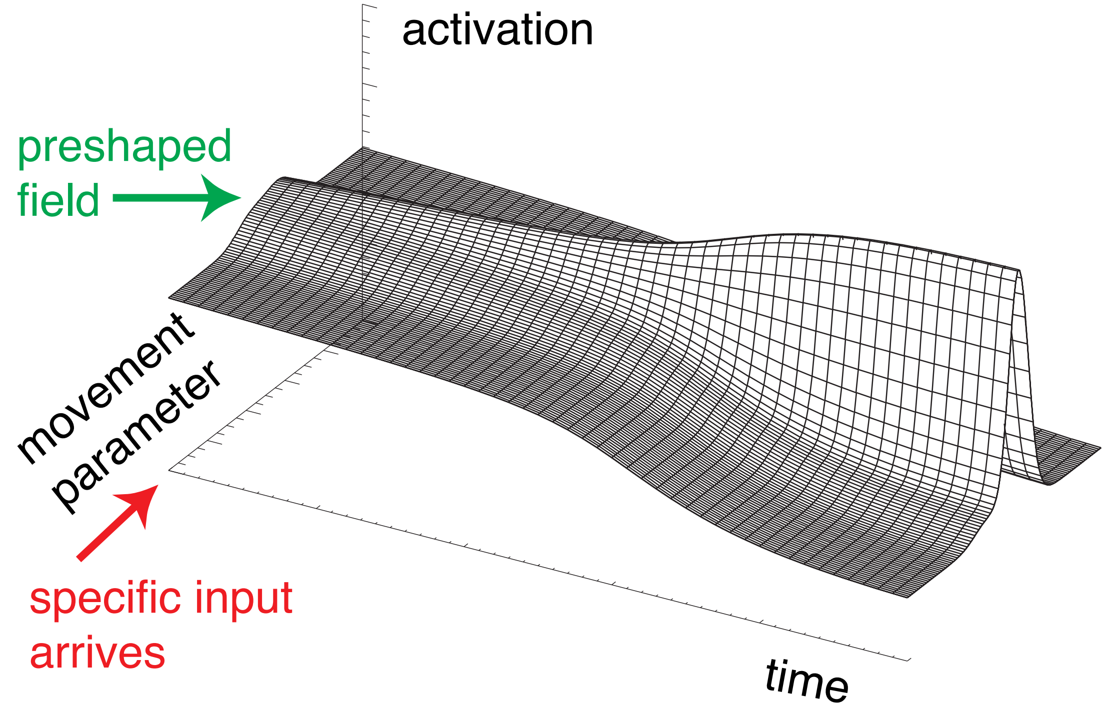
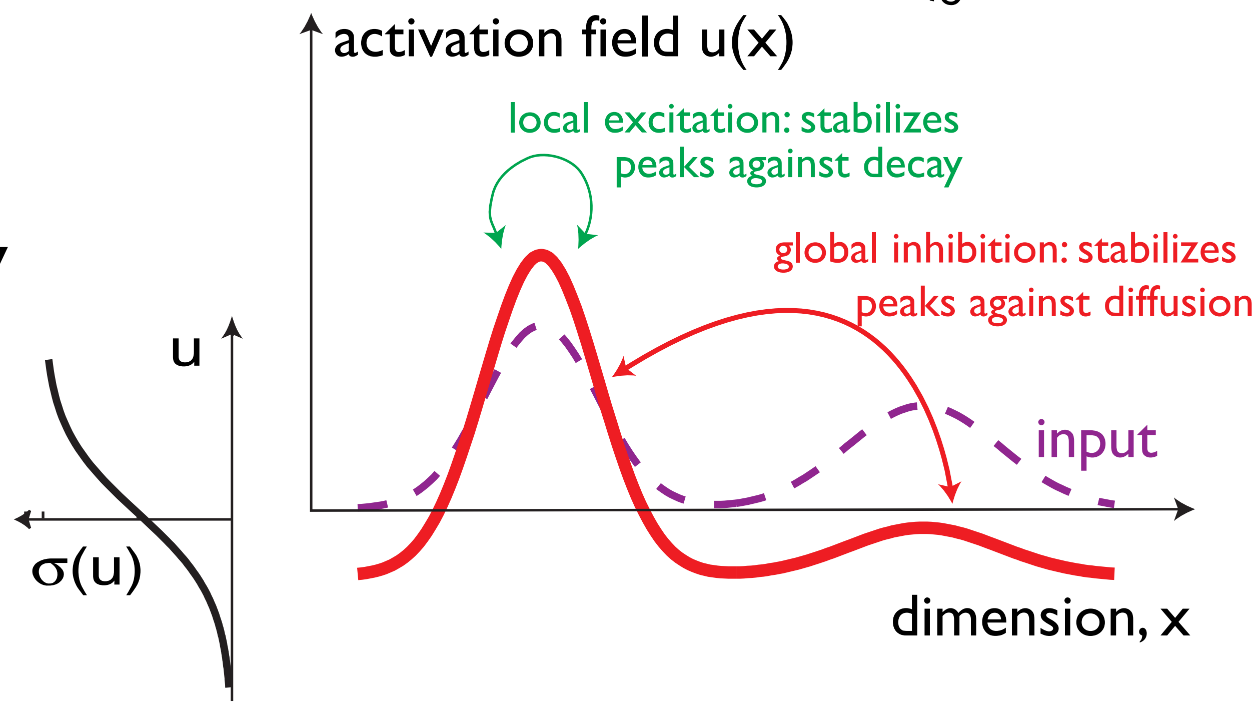
Core of DFT

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





Core of DFT

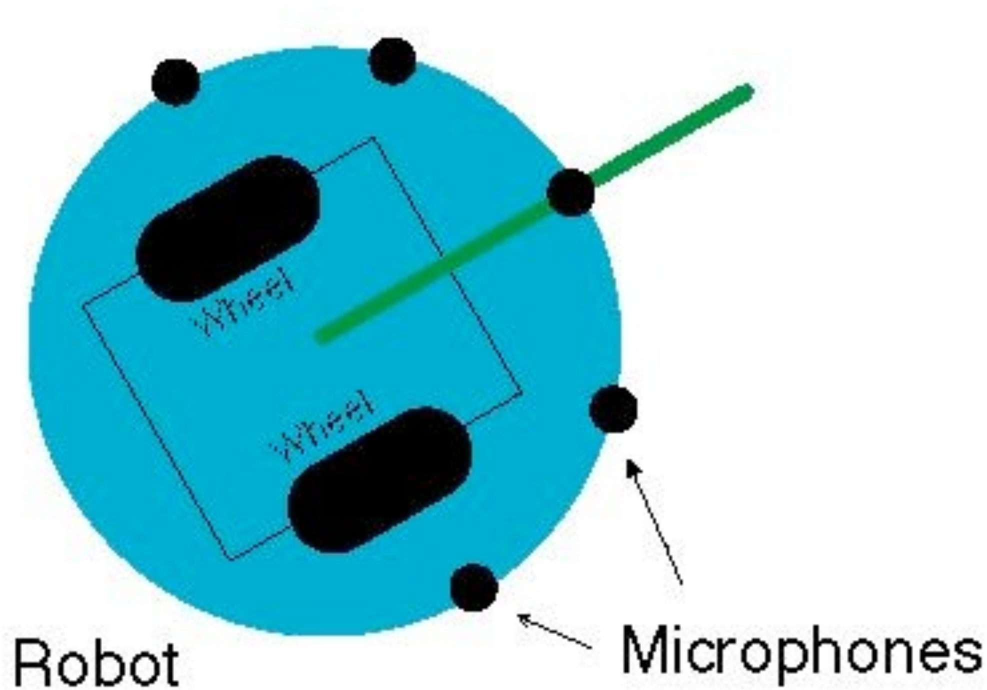
- attractor states
  - input driven solution (sub-threshold)
  - self-stabilized solution (peak, supra-threshold)
- instabilities
  - detection instability (from localize input or boost)
  - reverse detection instability
  - selection instability
  - memory instability

“embodying” DFT

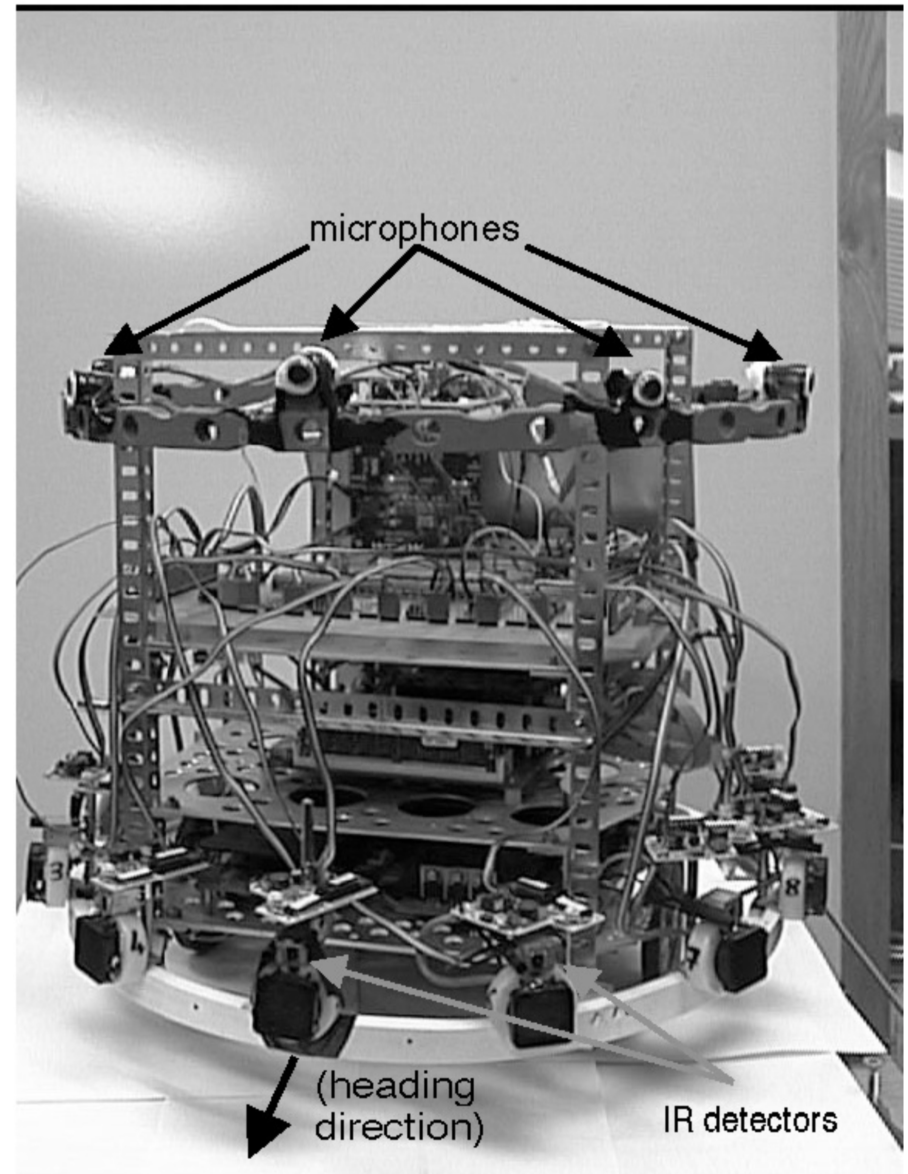
- link to real sensors
- link to real motor systems

Linking fields to sensors

- orientation toward sound sources

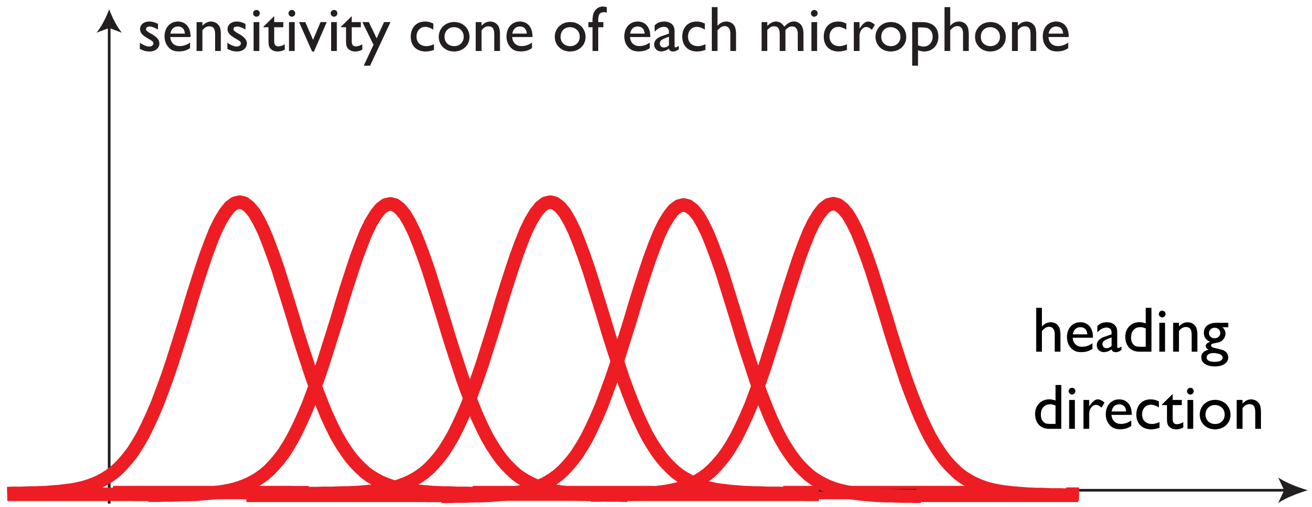


[from Bicho, Mallet, Schöner, Int J Rob Res,2000]



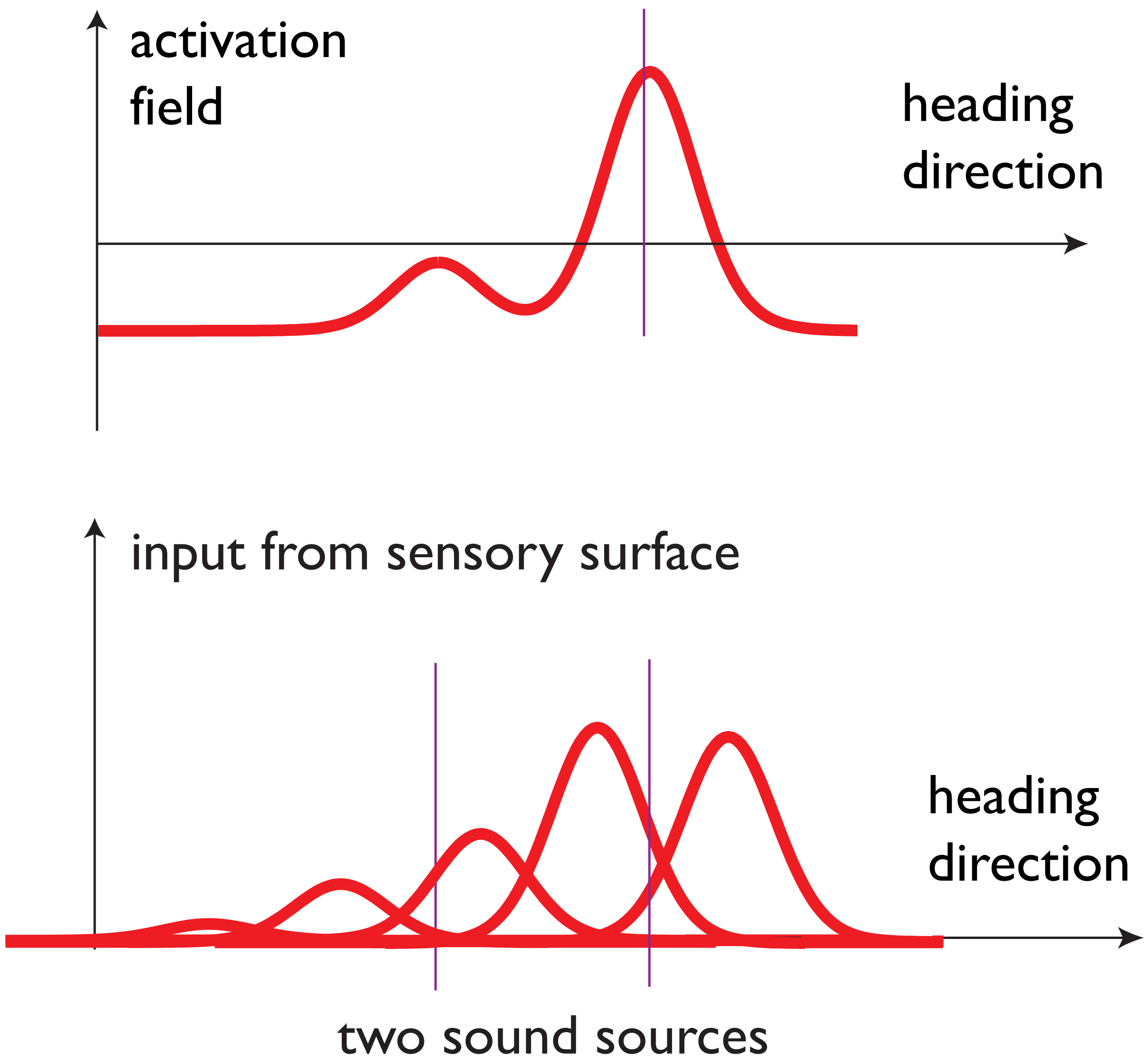
Sensory surface

- each microphone samples heading direction

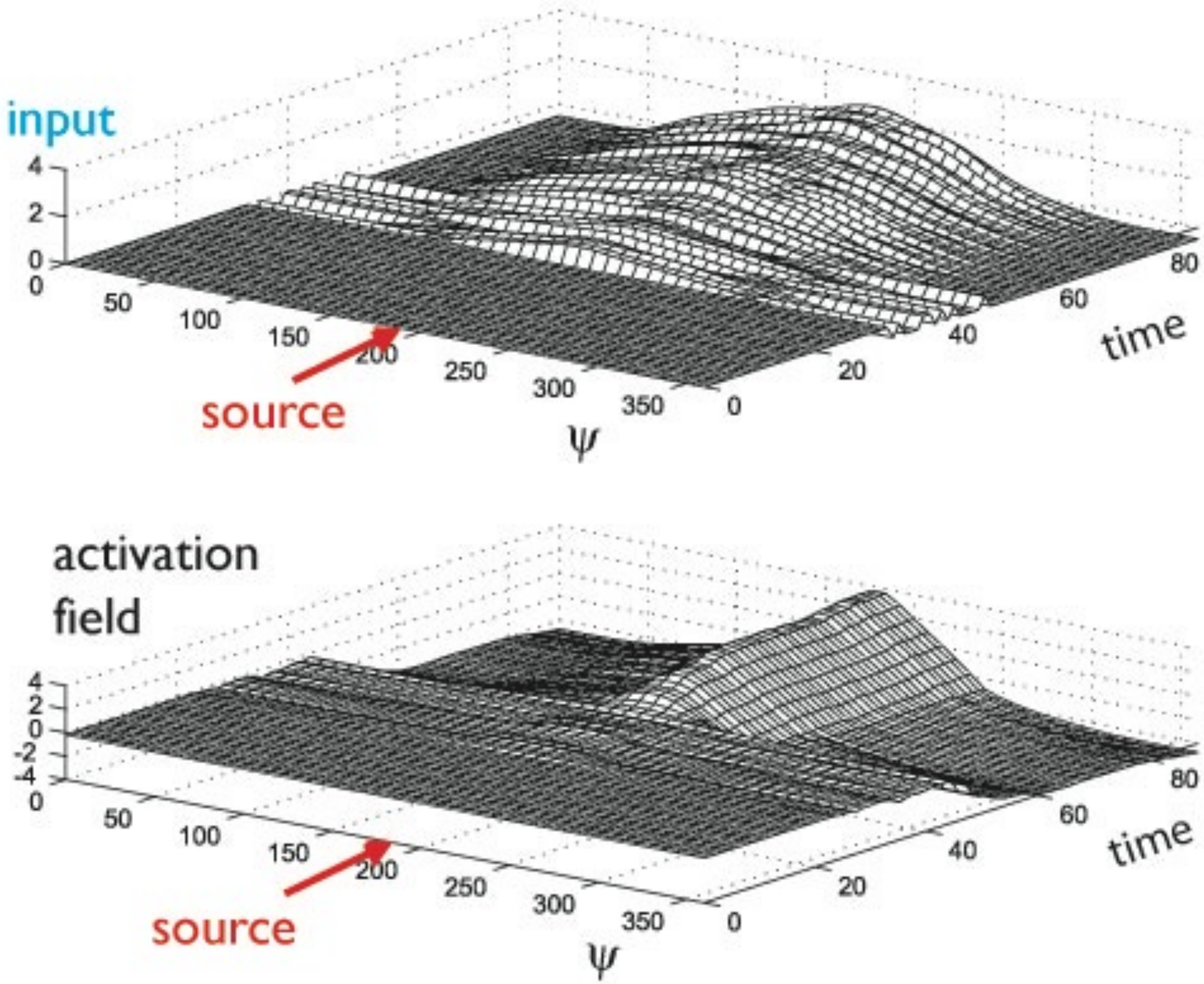


Input to the field

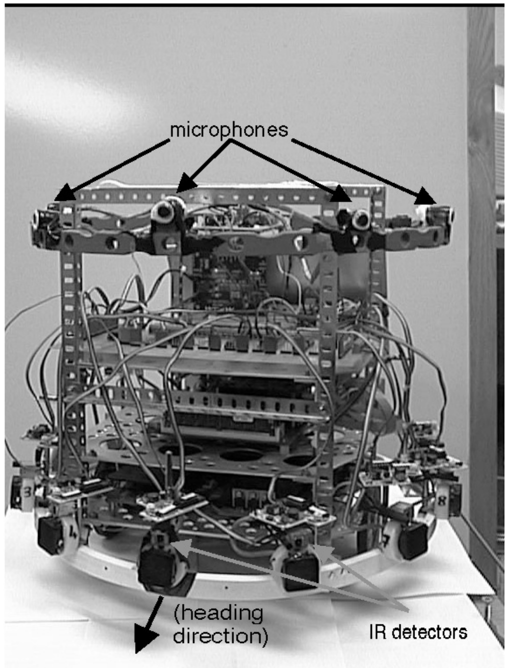
- each microphone provides input to the field



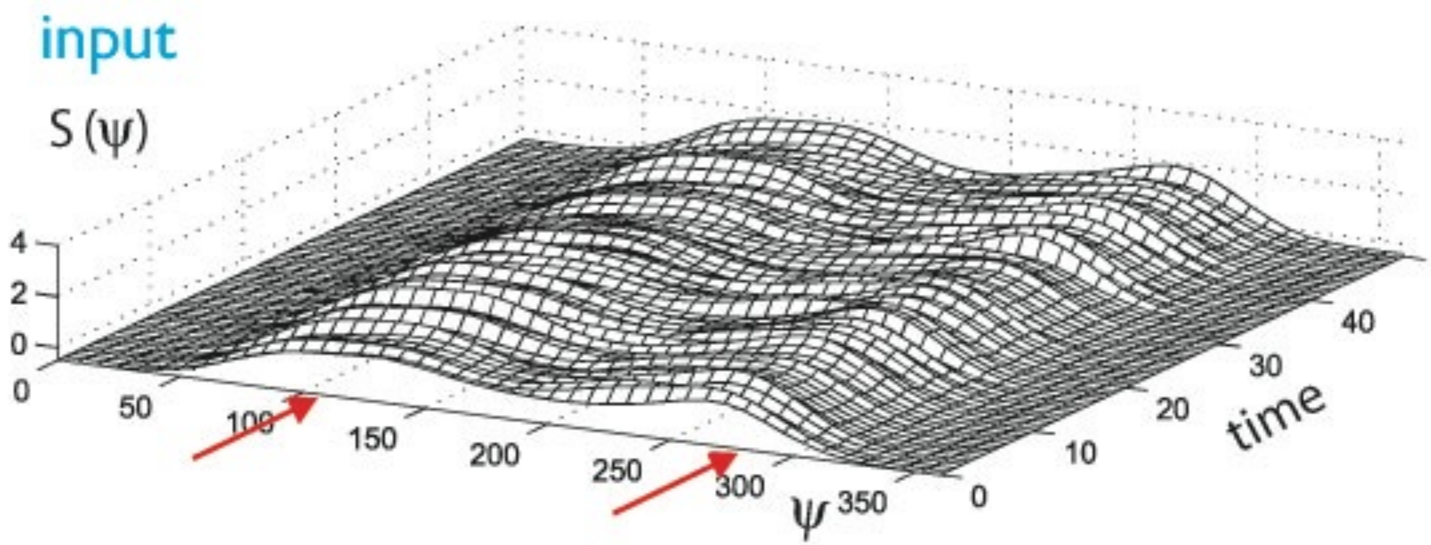
Detection instability induced by increasing intensity of sound source

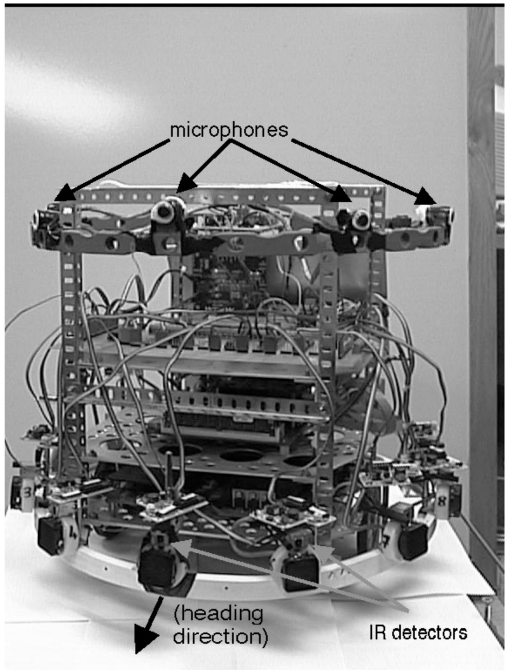


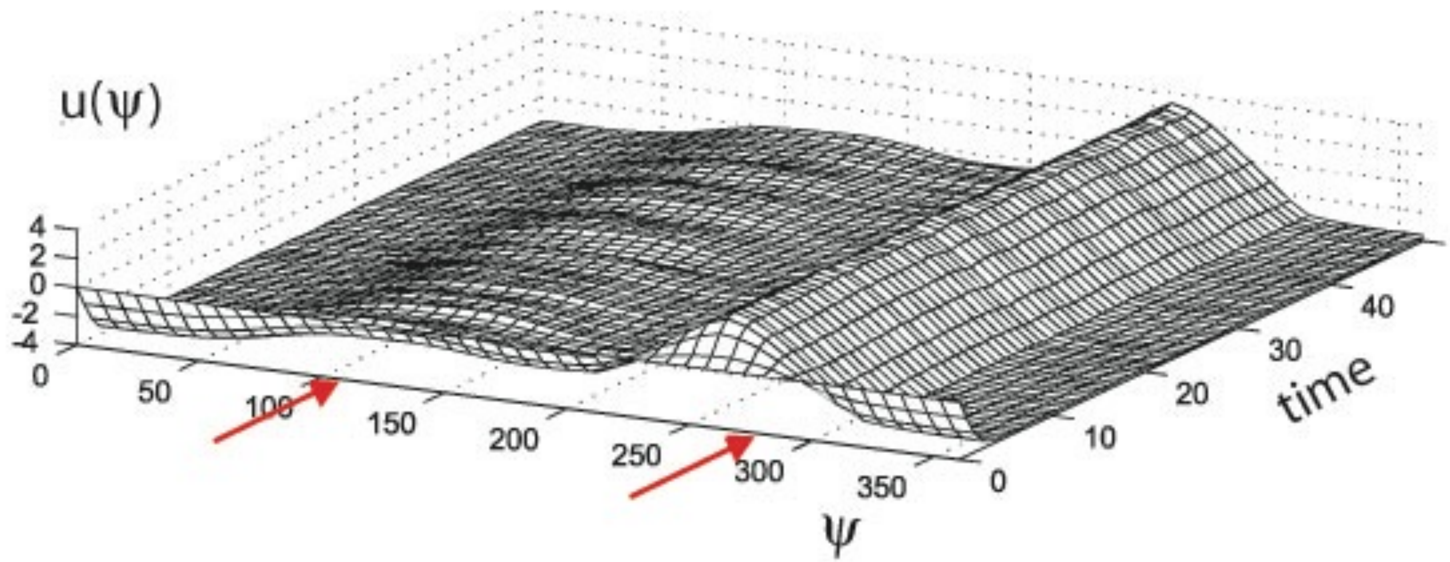
[from Bicho, Mallet, Schöner: Int. J. Rob. Res., 2000]



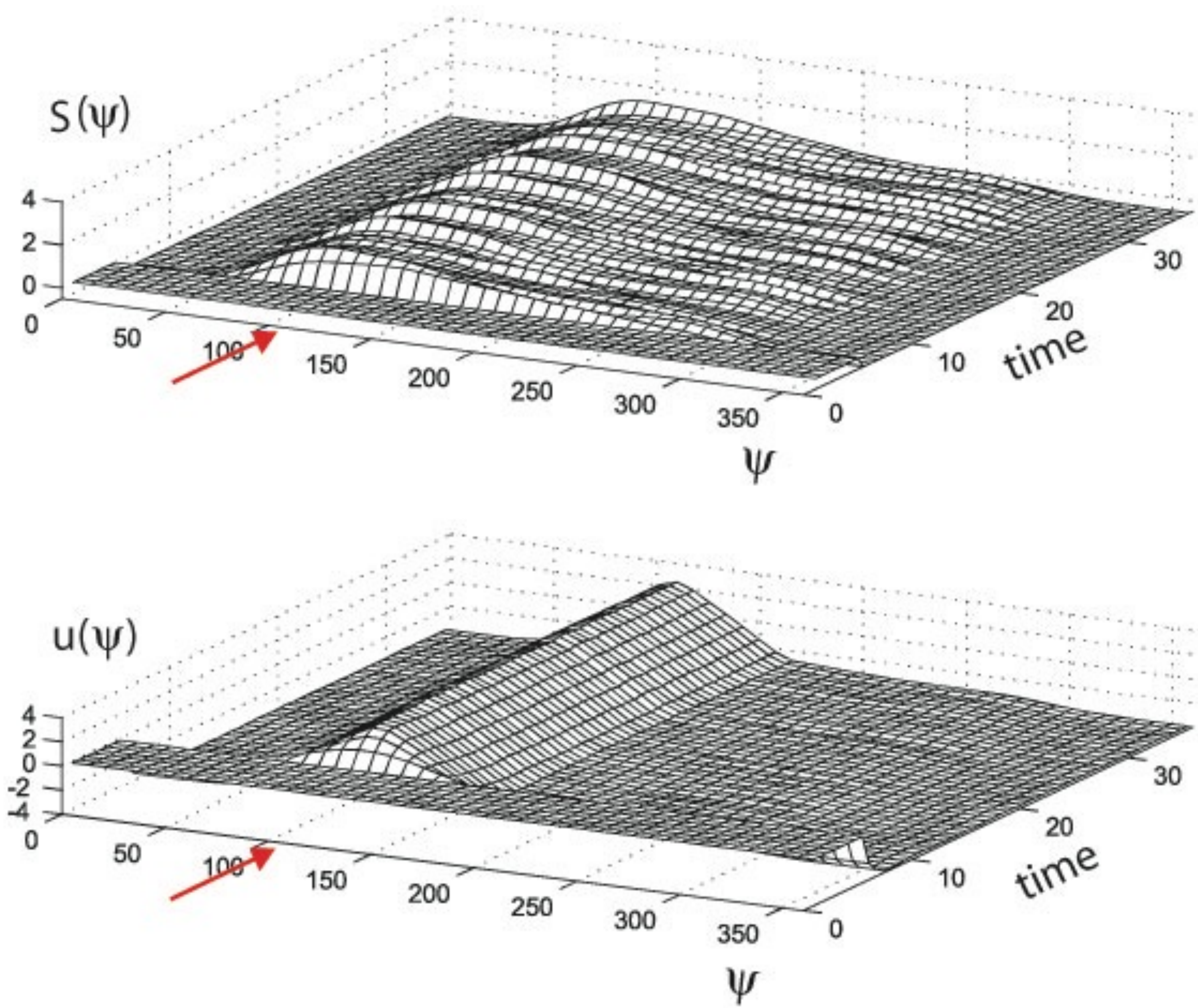
Target selection in the presence of two sources



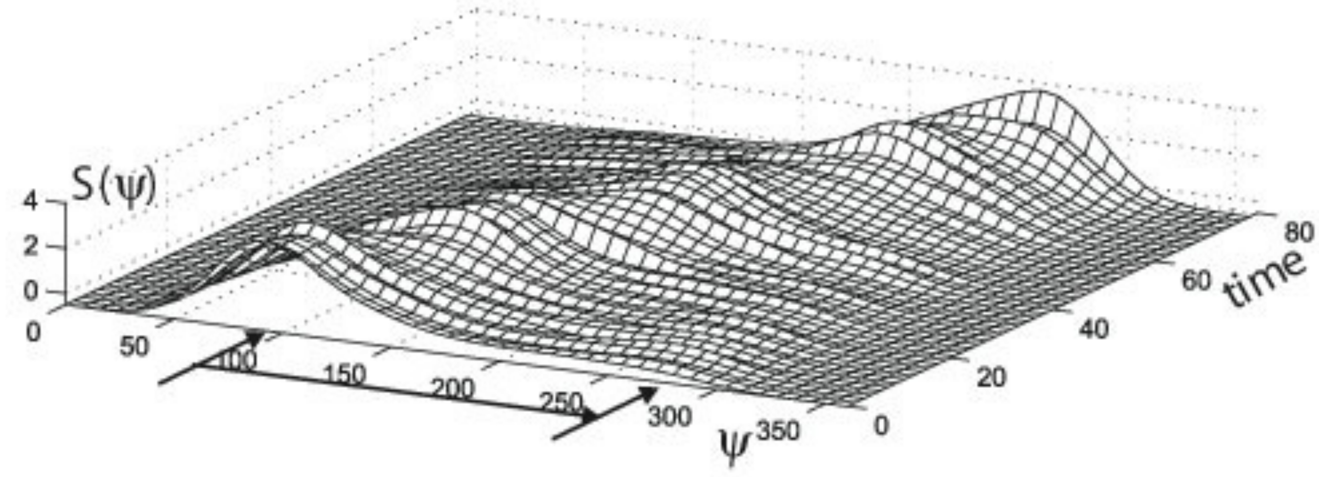


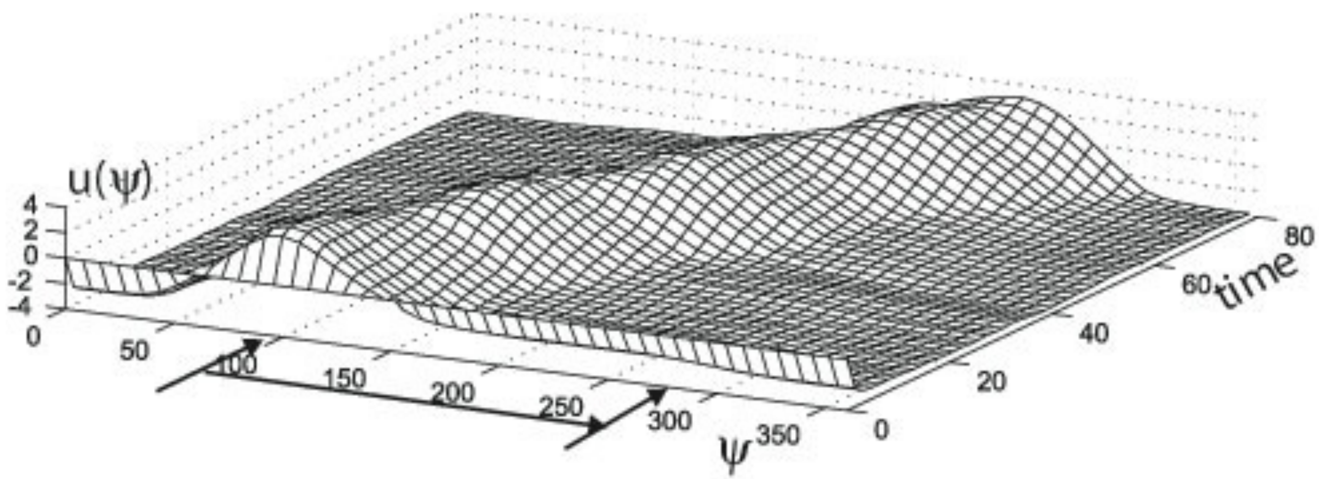


Robust estimation in the presence of outliers

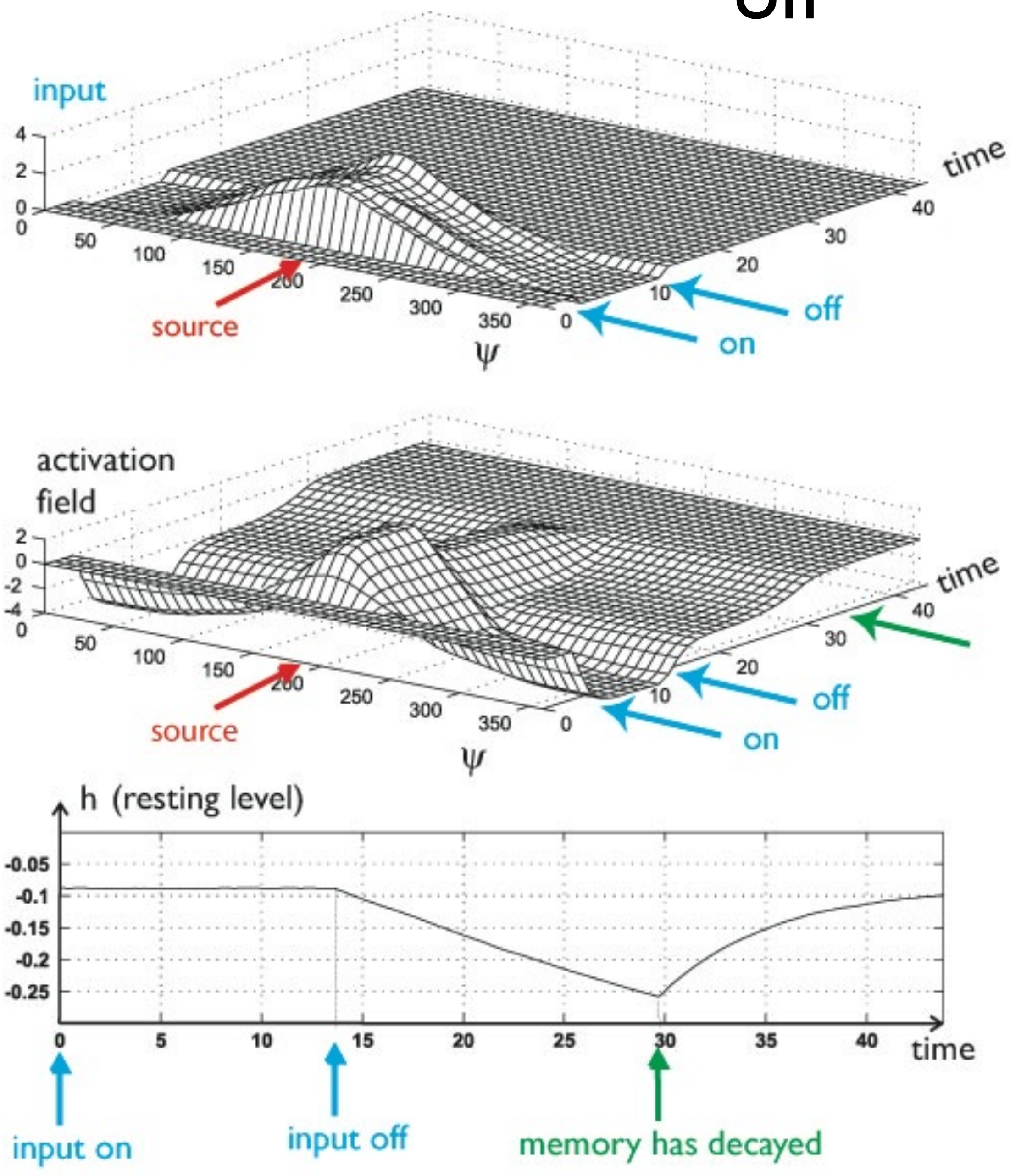


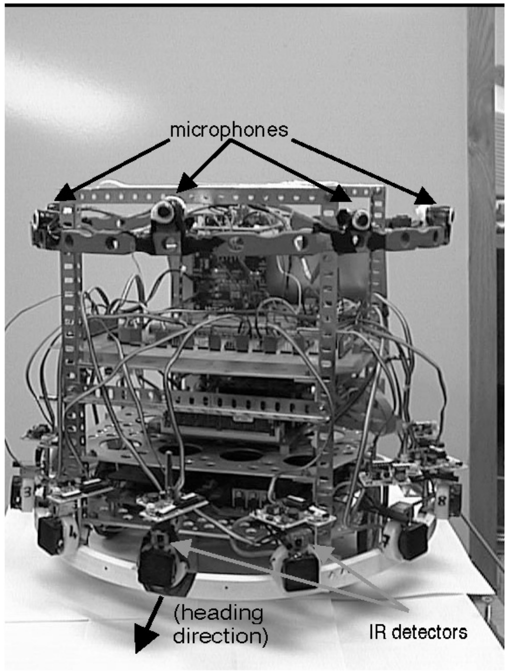
Tracking when sound source moves





Memory (and forgetting) when sound source is turned off





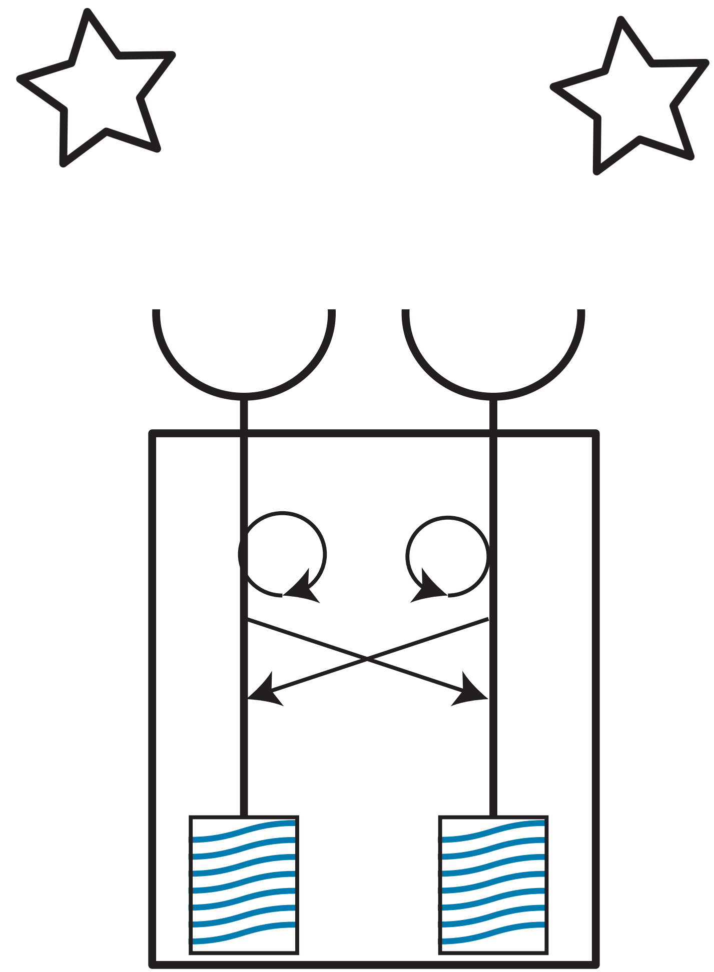
[from Bicho, Mallet, Schöner: Int J Rob Res 19:424(2000)]

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

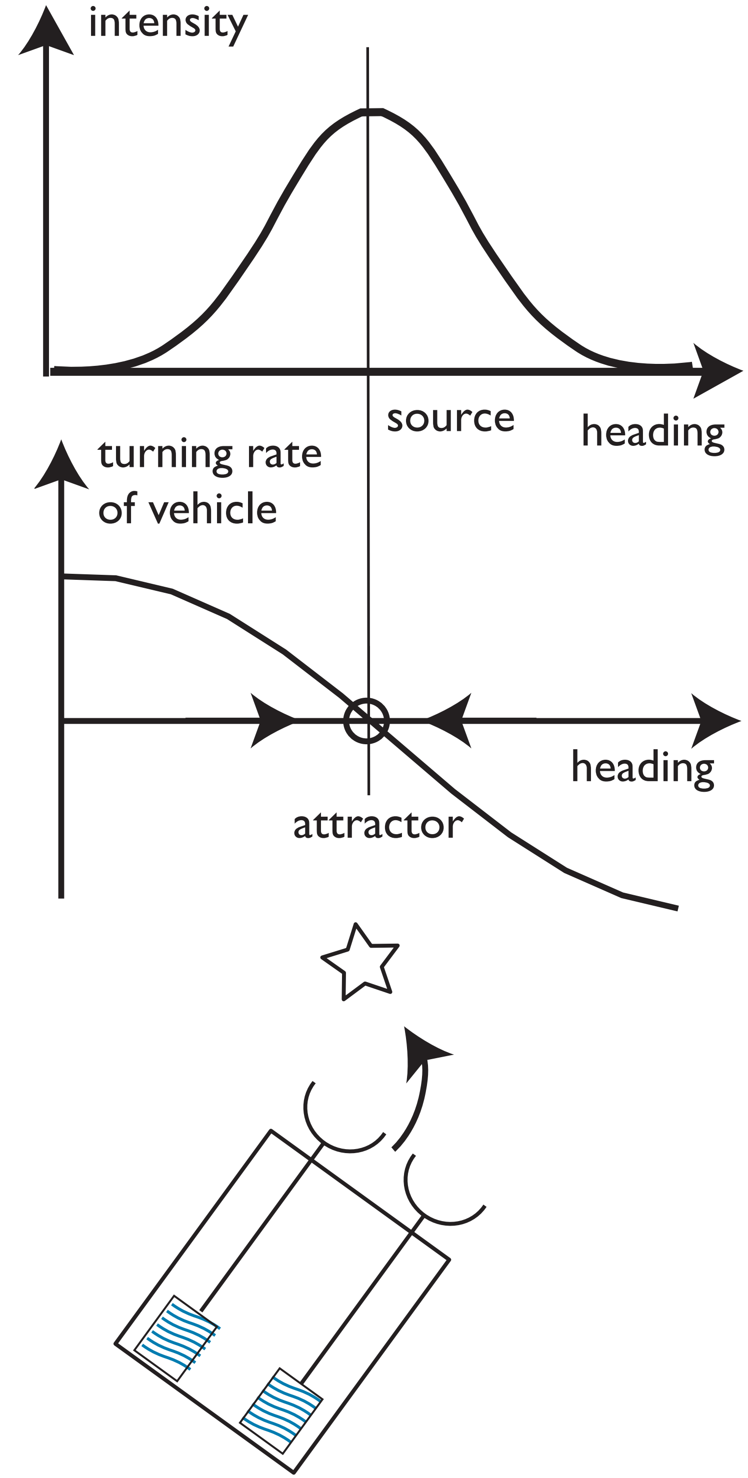
Braitenberg



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

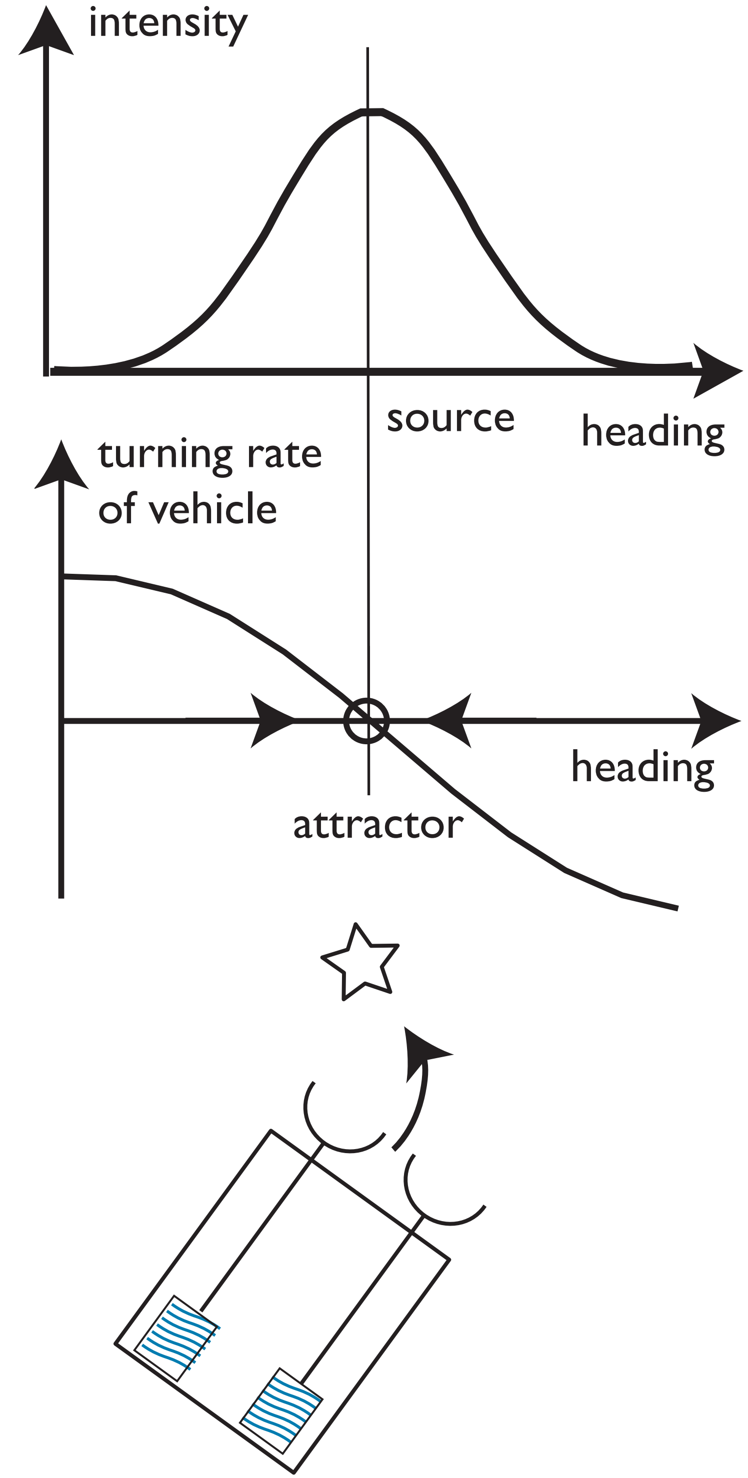
Braitenberg

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



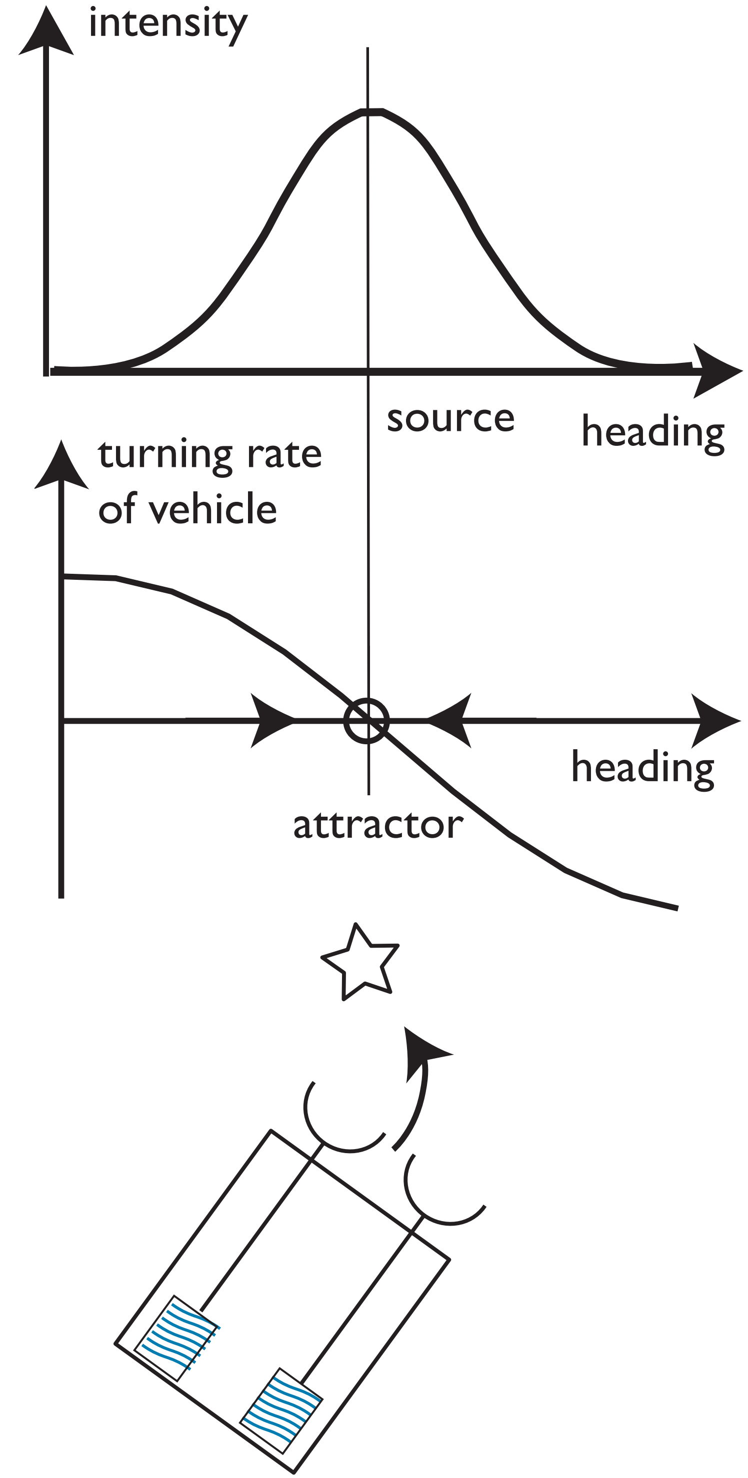
Braitenberg

- 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

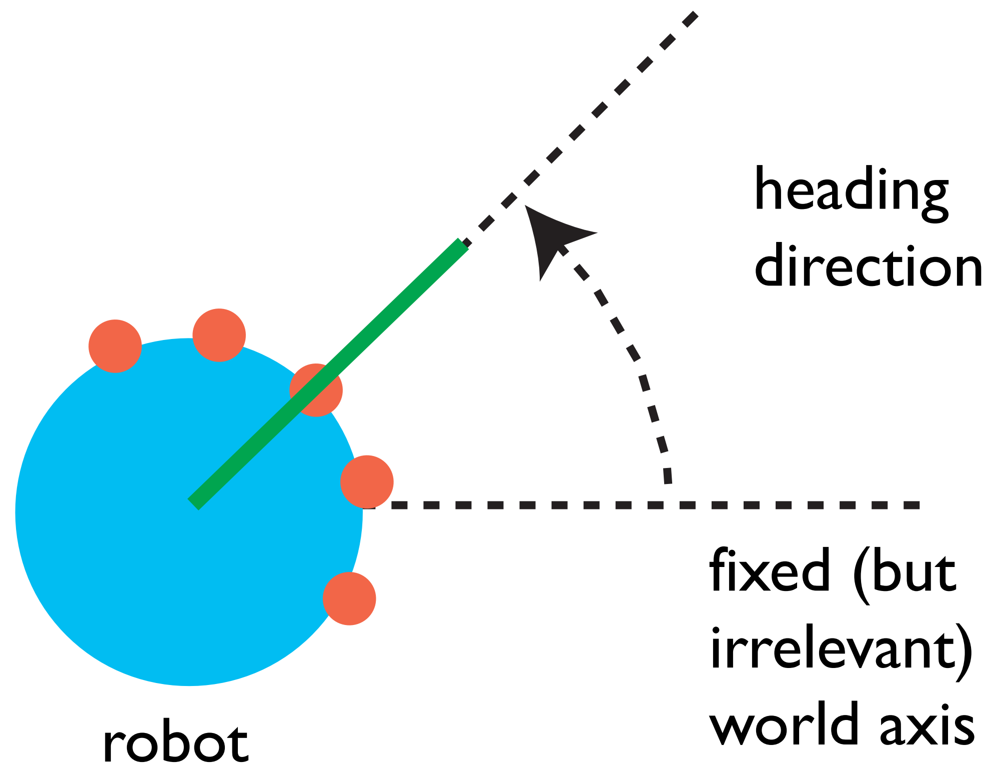


Basic ideas: behavioral dynamics

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

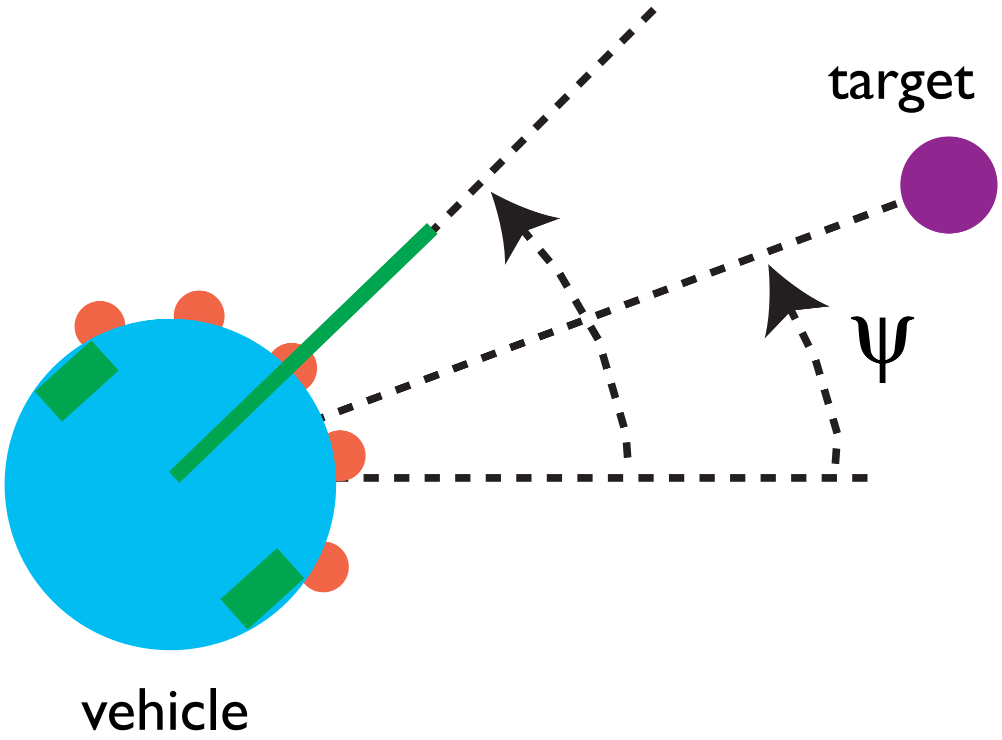
Behavioral variables: example

- vehicle moving in 2D: heading direction



Behavioral variables: example

- constraints as values of the behavioral variable: direction to target



Behavioral variables

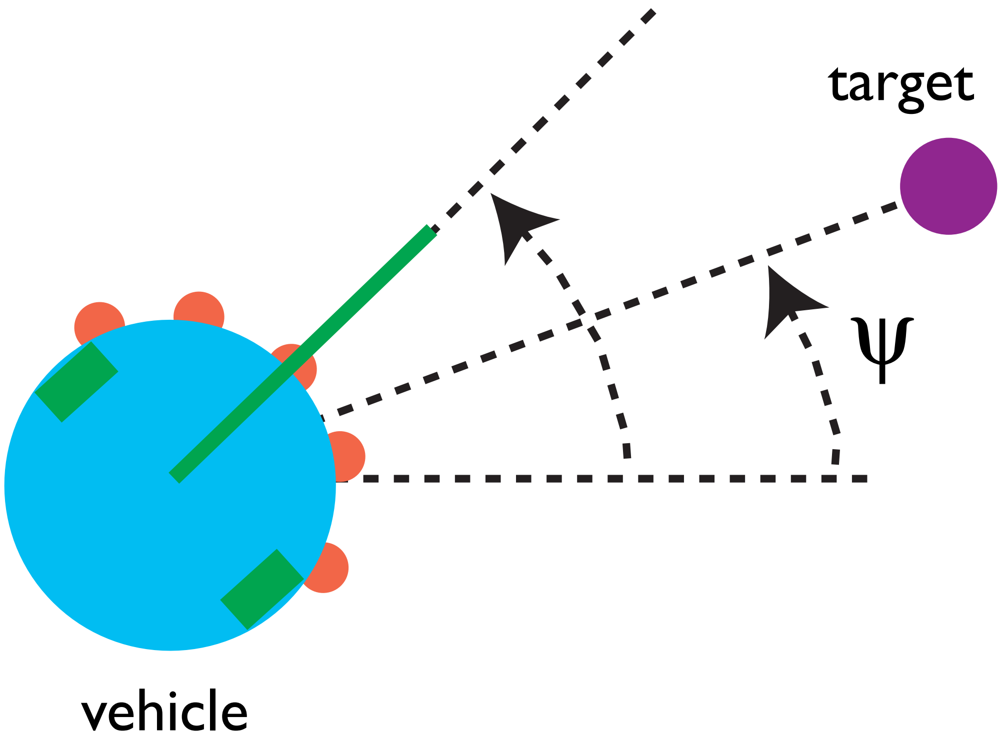
- describe desired motor behavior
- “enactable”
- express constraints as values/value ranges
- appropriate level of invariance

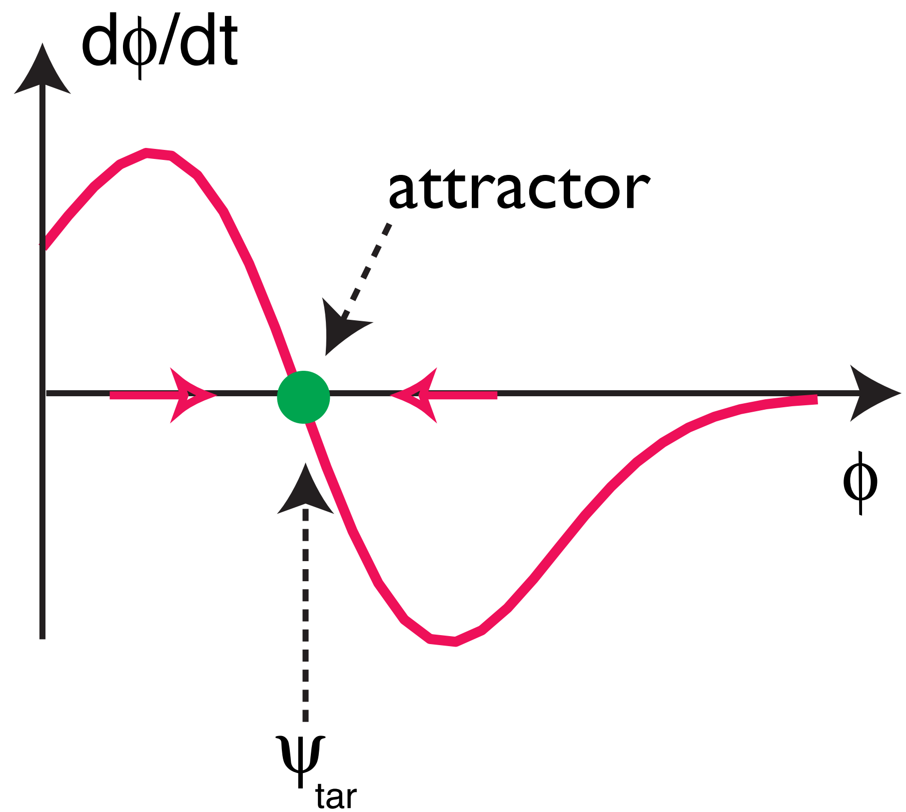
Behavioral dynamics

- 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

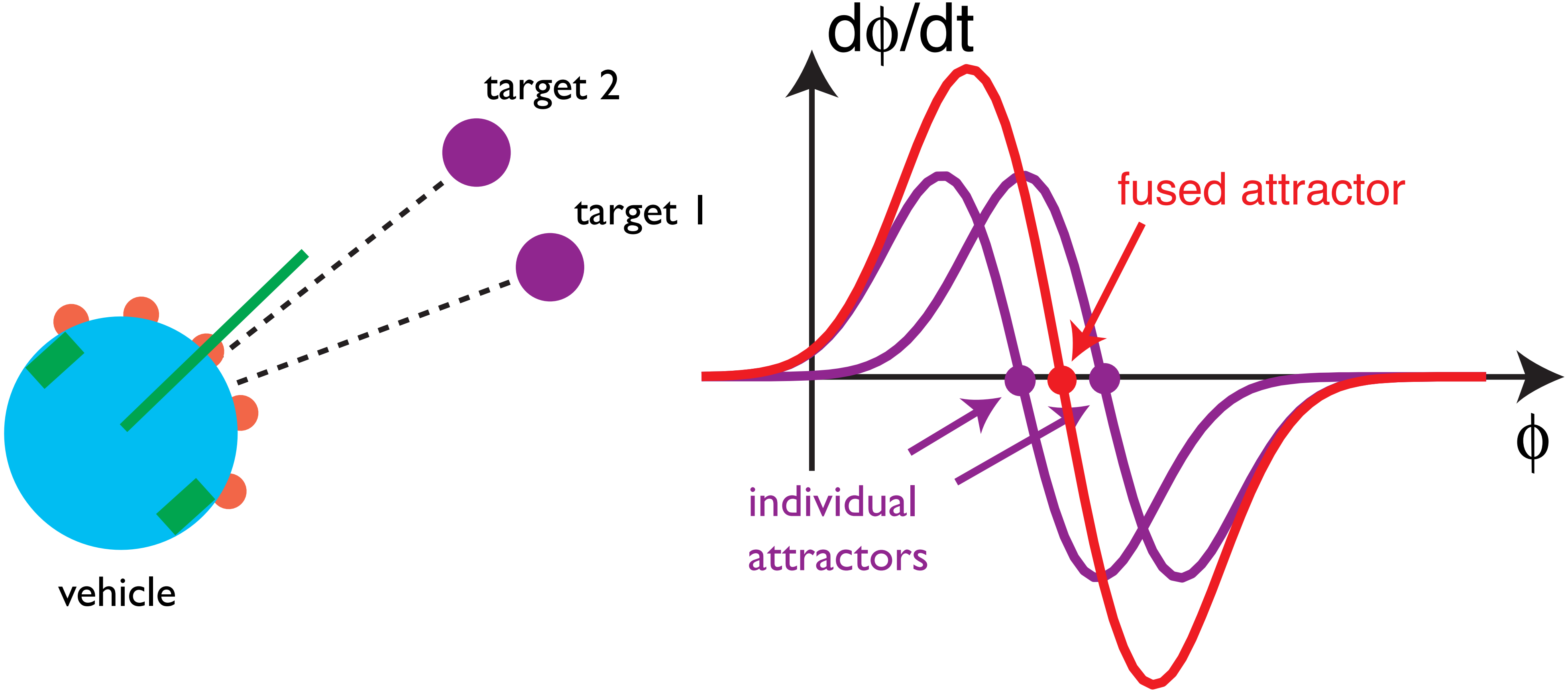
- behavioral constraint: target acquisition





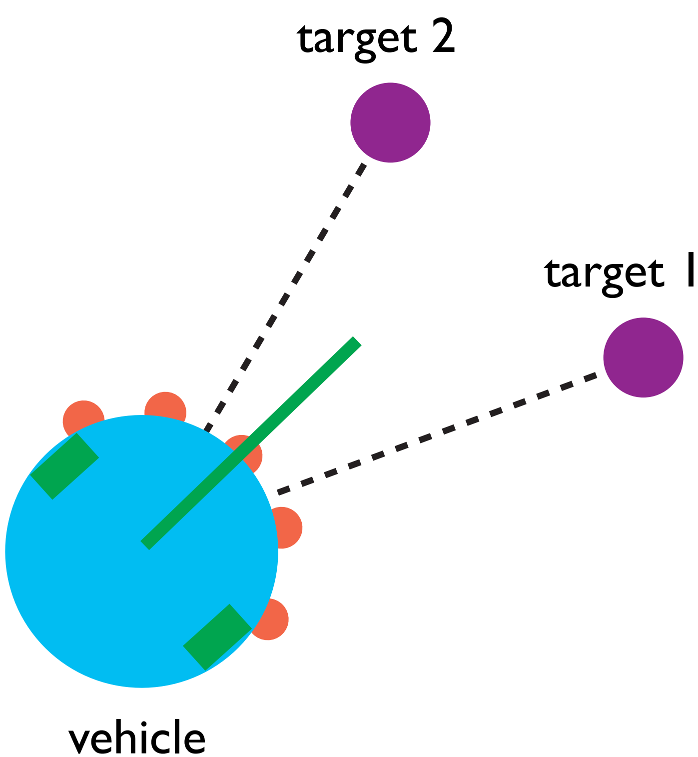
Behavioral dynamics

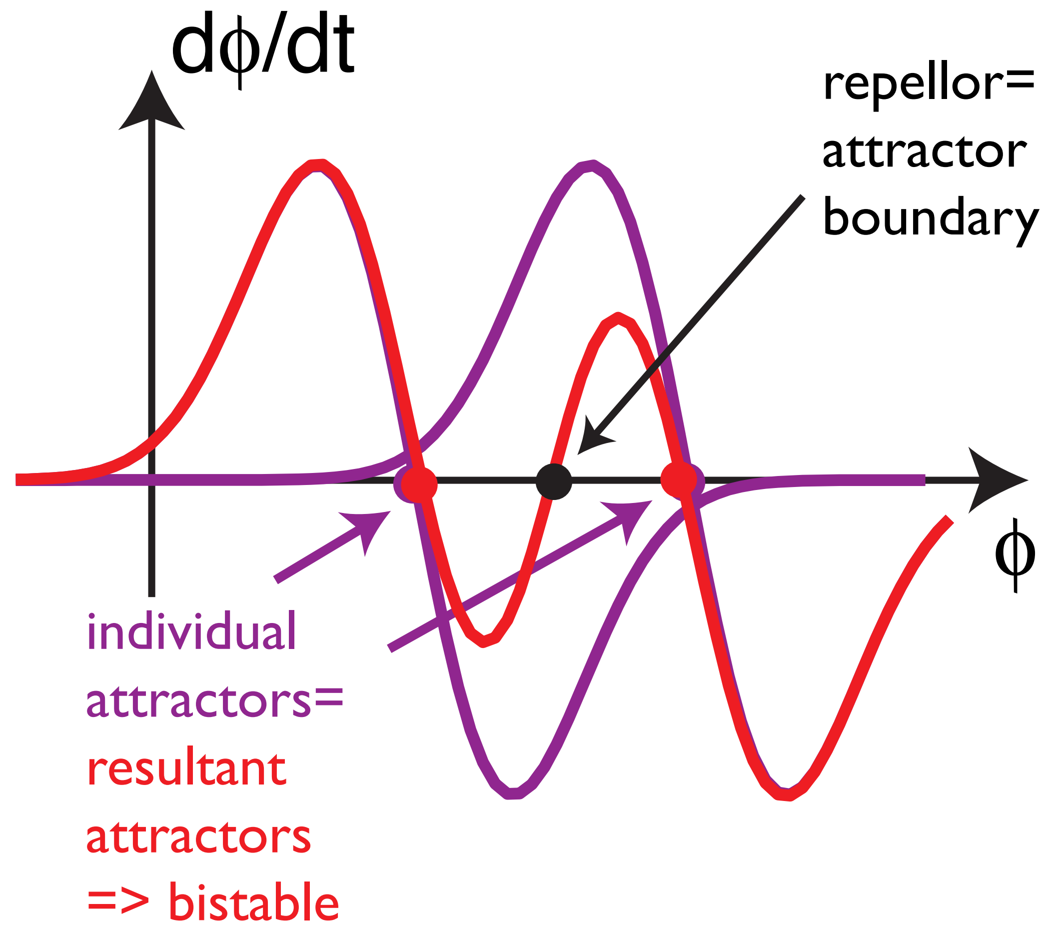
- multiple constraints: superpose “force-lets”
- fusion



Behavioral dynamics

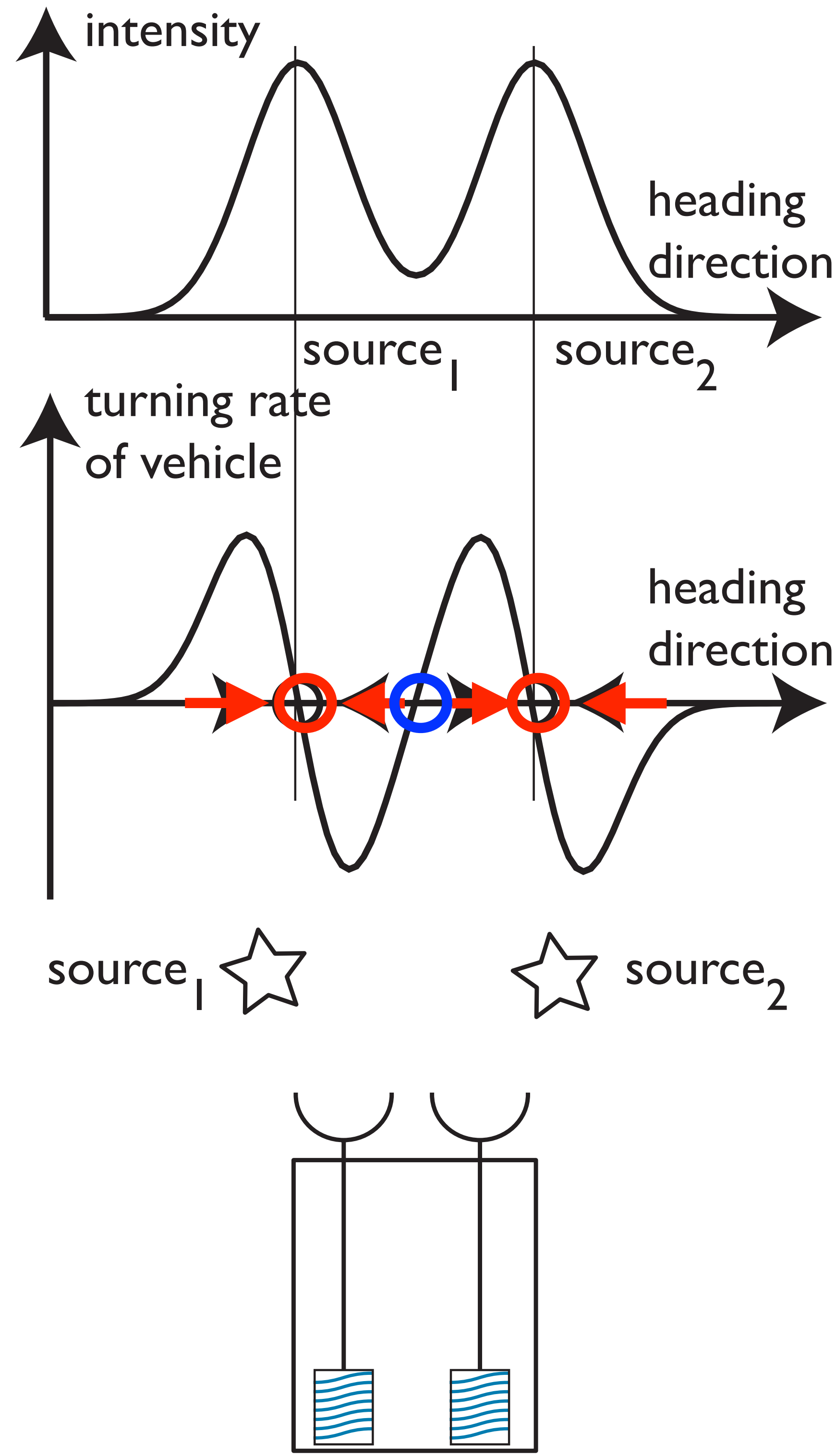
- decision making





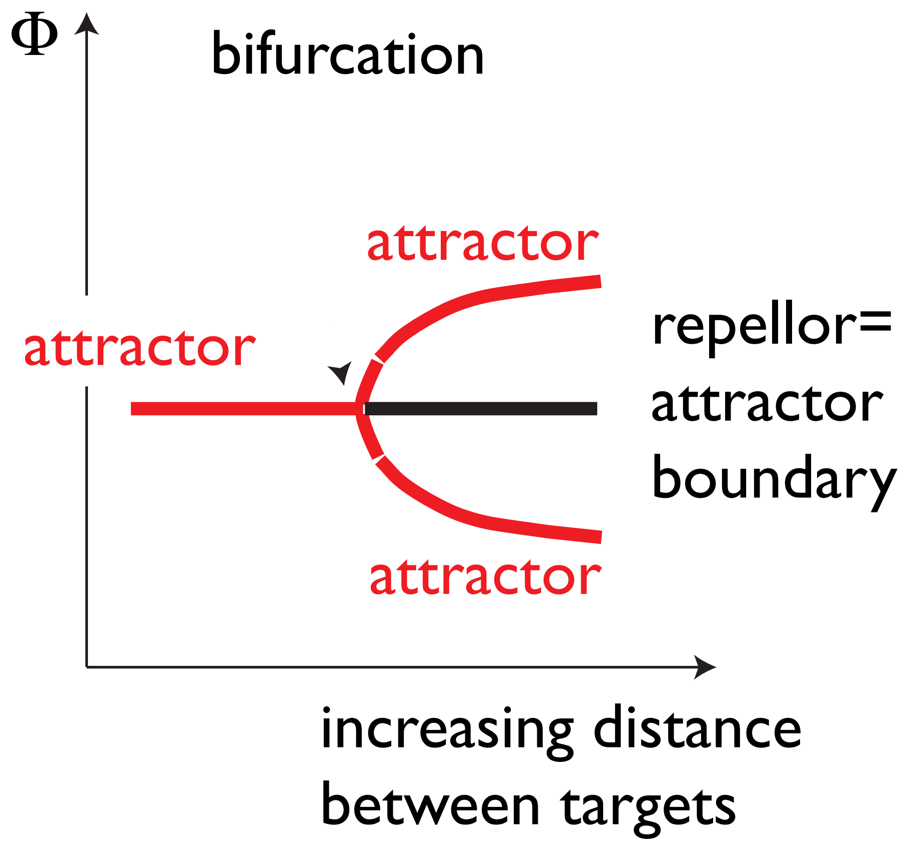
Braitenberg

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



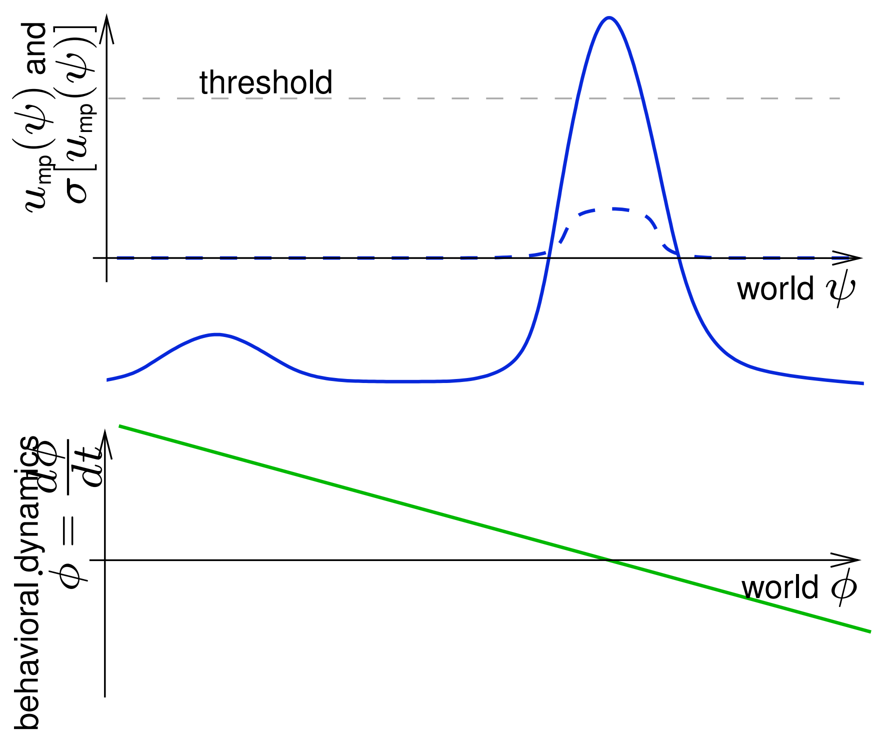
Behavioral dynamics

- Bifurcations switch between fusion and decision making



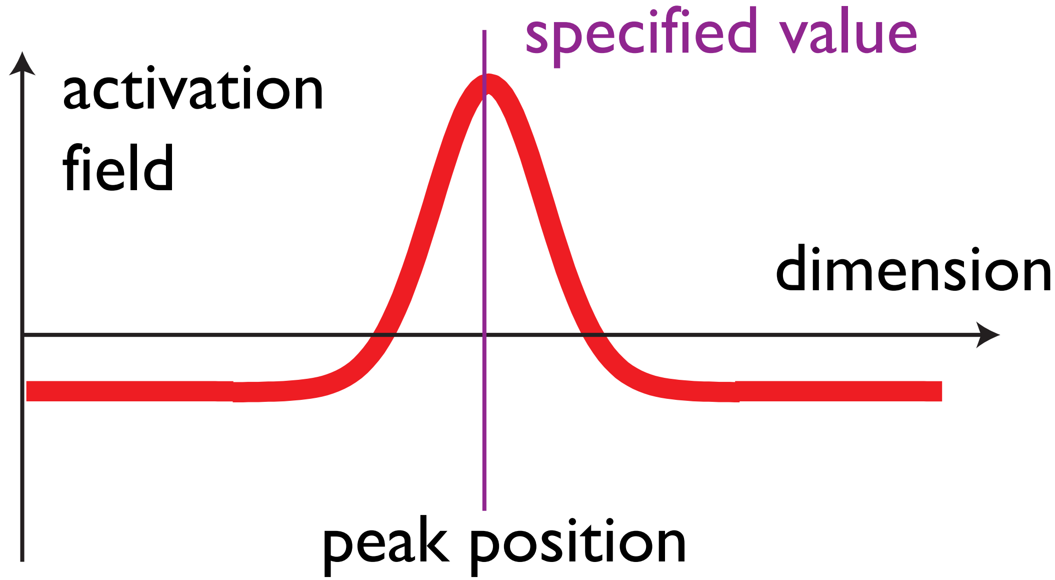
Steering the behavioral dynamics

- 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?

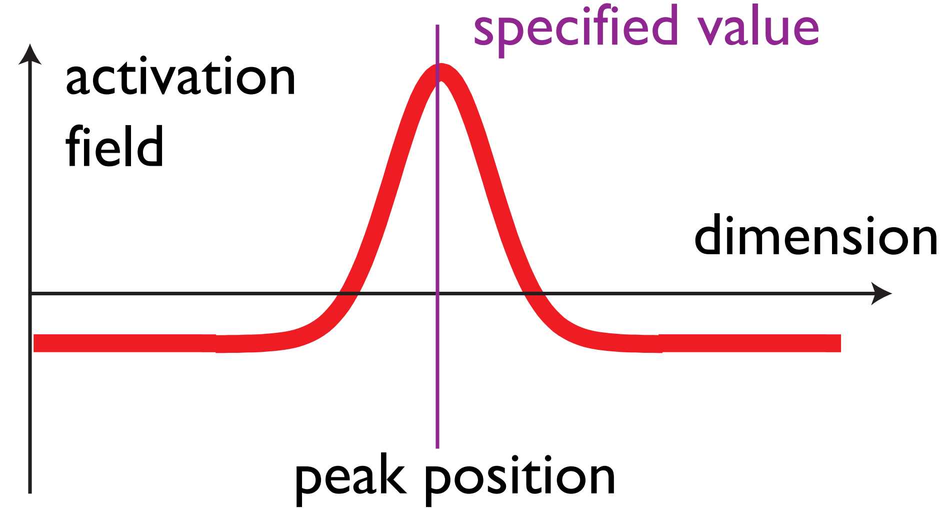
- peak specifies value of the field dimension over which it is located…
- but how to "read out" that value?

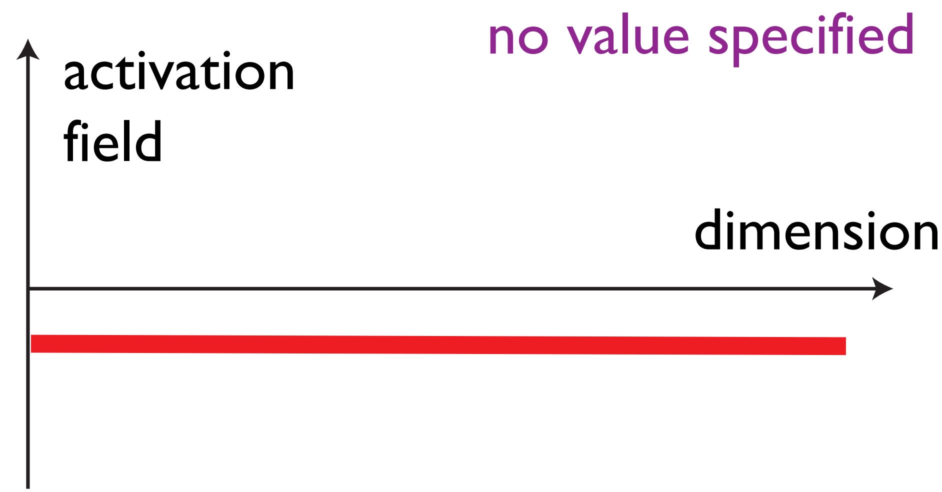


“reading out” from the neural field?

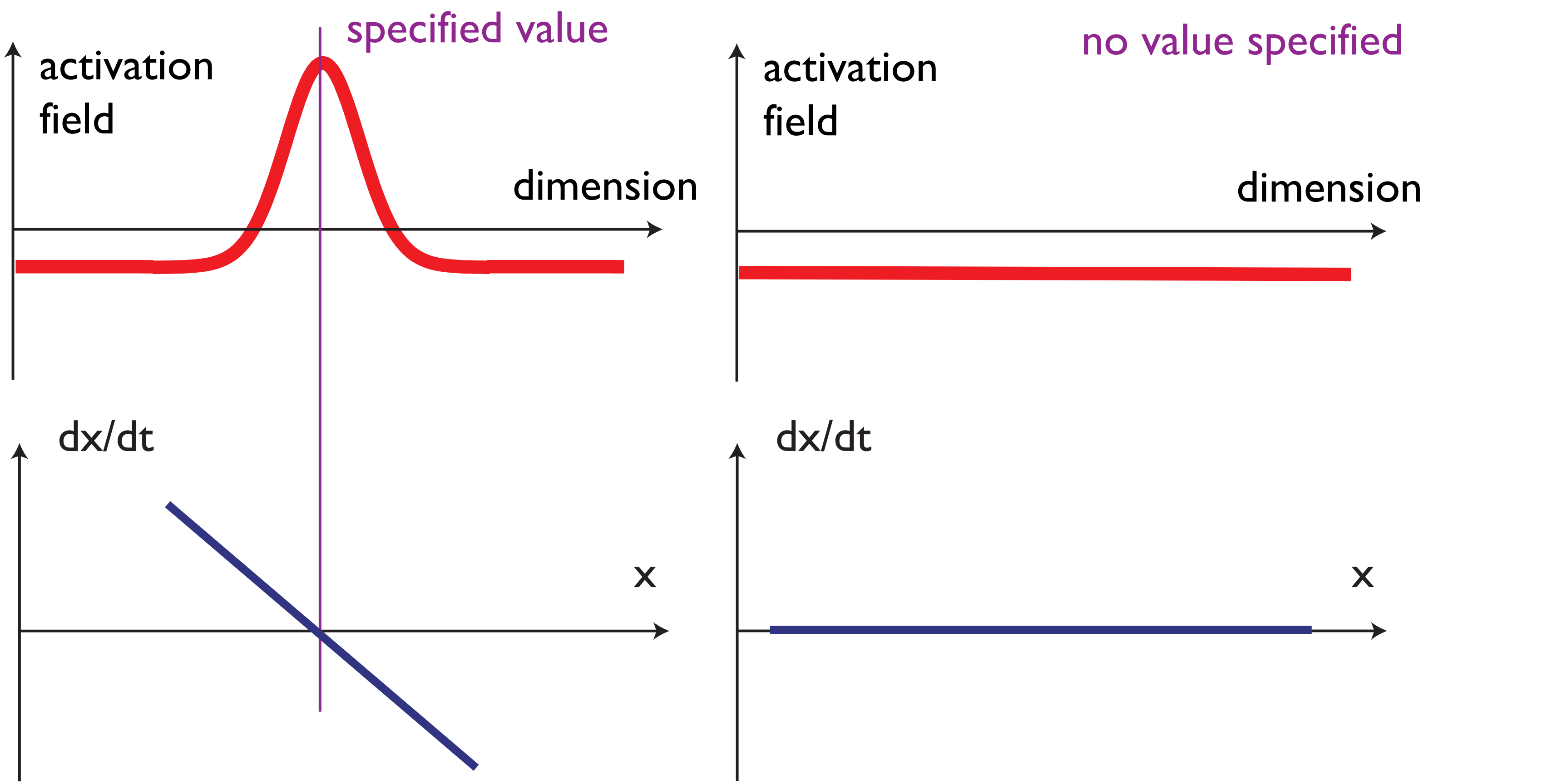
- standard idea: treat supra-threshold field as a probability density
- but: need to normalize the activation pattern
- => problem when there is no peak: divide by zero!

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





“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

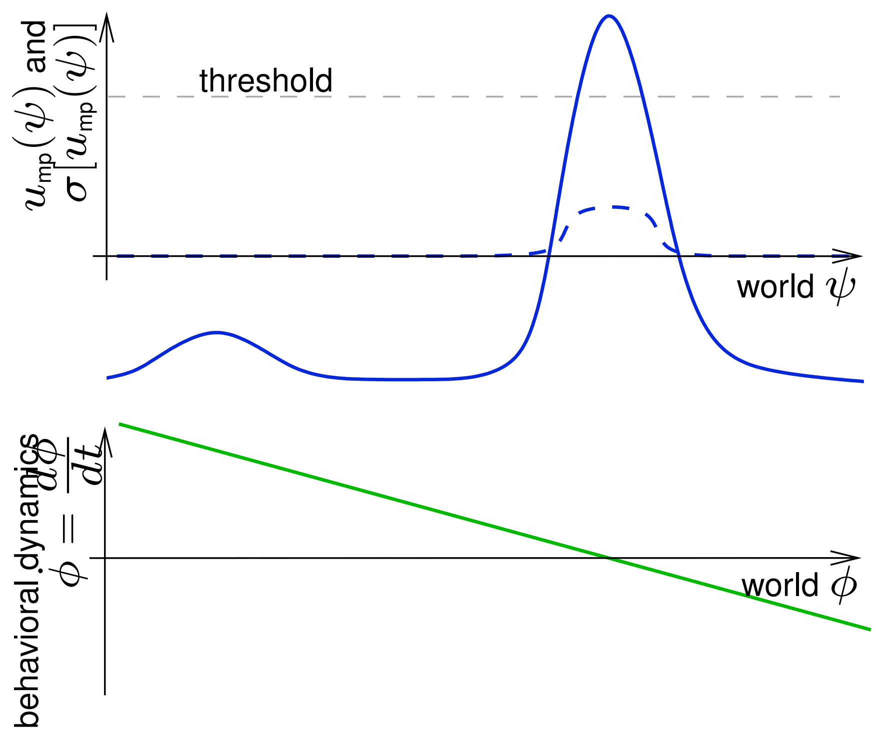
$$\dot{x} = -\int dx' \; g(u(x',t)) \; (x - x_{\text{peak}}) \qquad x_{\text{peak}} = \frac{\int dx \; x \; g(u(x,t))}{\int dx' \; g(u(x',t))}$$

$$\dot{x} = -\int dx' \; g(u(x',t)) \; x + \int dx' \; g(u(x',t)) \, \frac{\int dx'' \; x'' g(u(x'',t))}{\int dx''' \; g(u(x''',t))}$$

$$\dot{x} = -\int dx' \; g(u(x',t)) \; (x - x')$$

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?



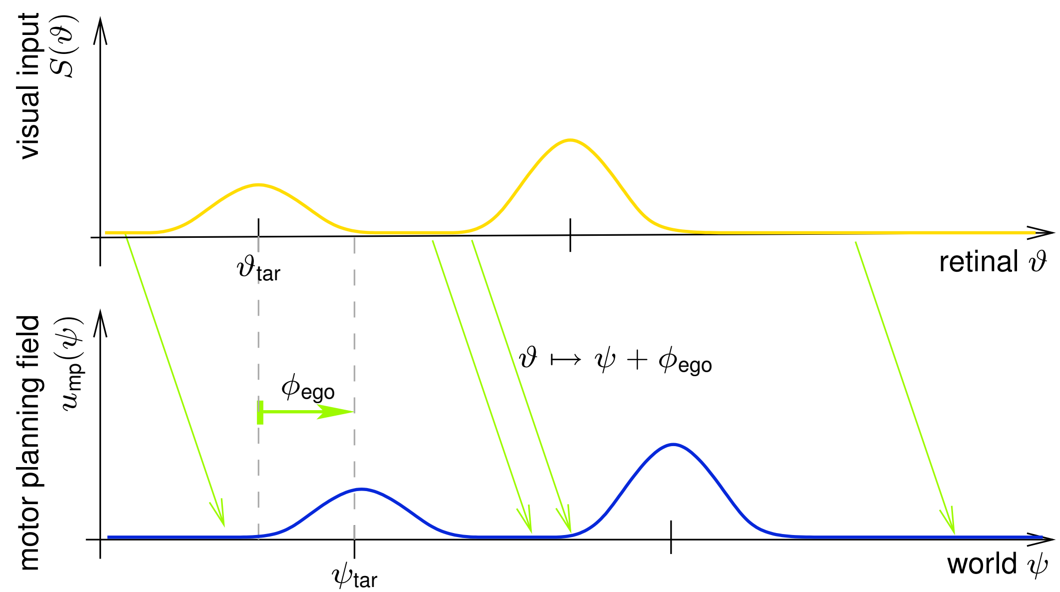
Answer

- the target representation must be invariant under a change of 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

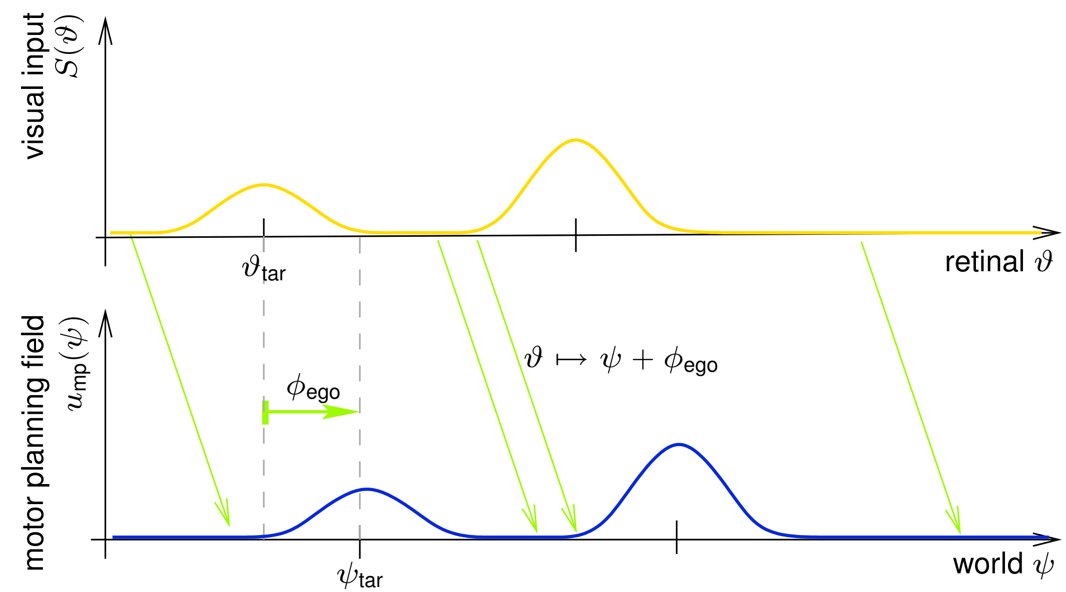
- to makes this consistent with coupling to sensory information, we must perform a a coordinate transform from the sensory surface (“retina”) to the invariant world frame!

- and that requires knowing the heading direction in the world…



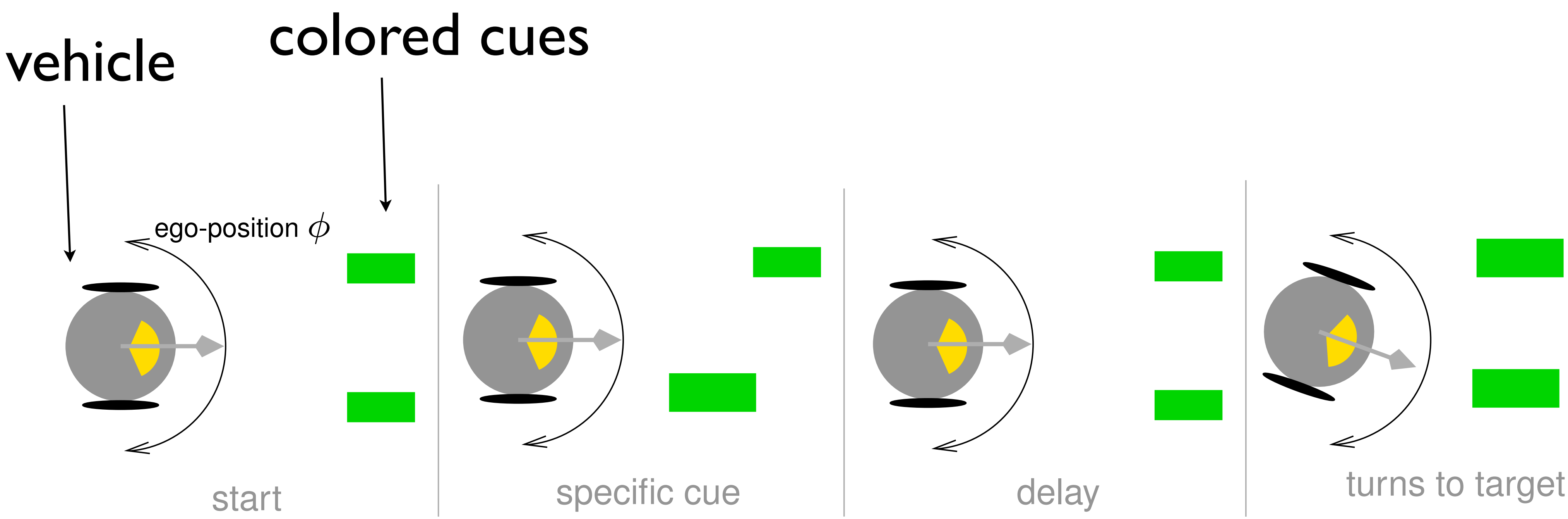
Answer

- this is a steerable neural map…
- => lecture later in the course



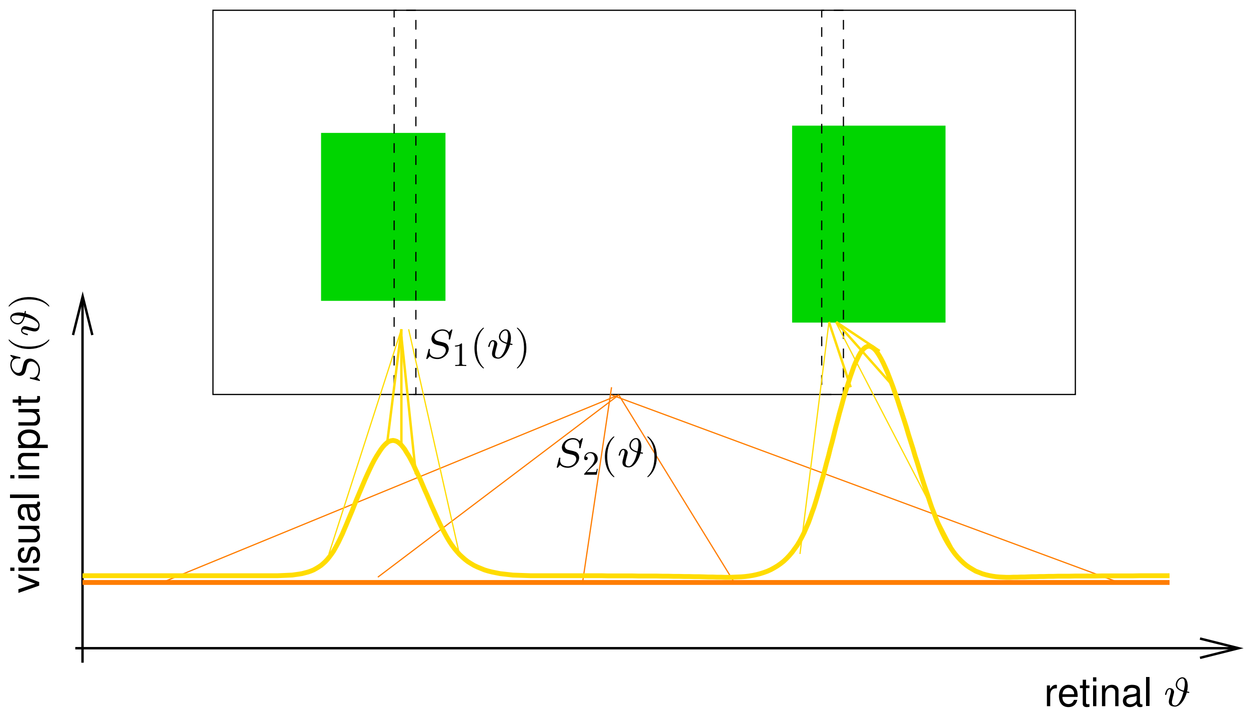
Embodied A not B

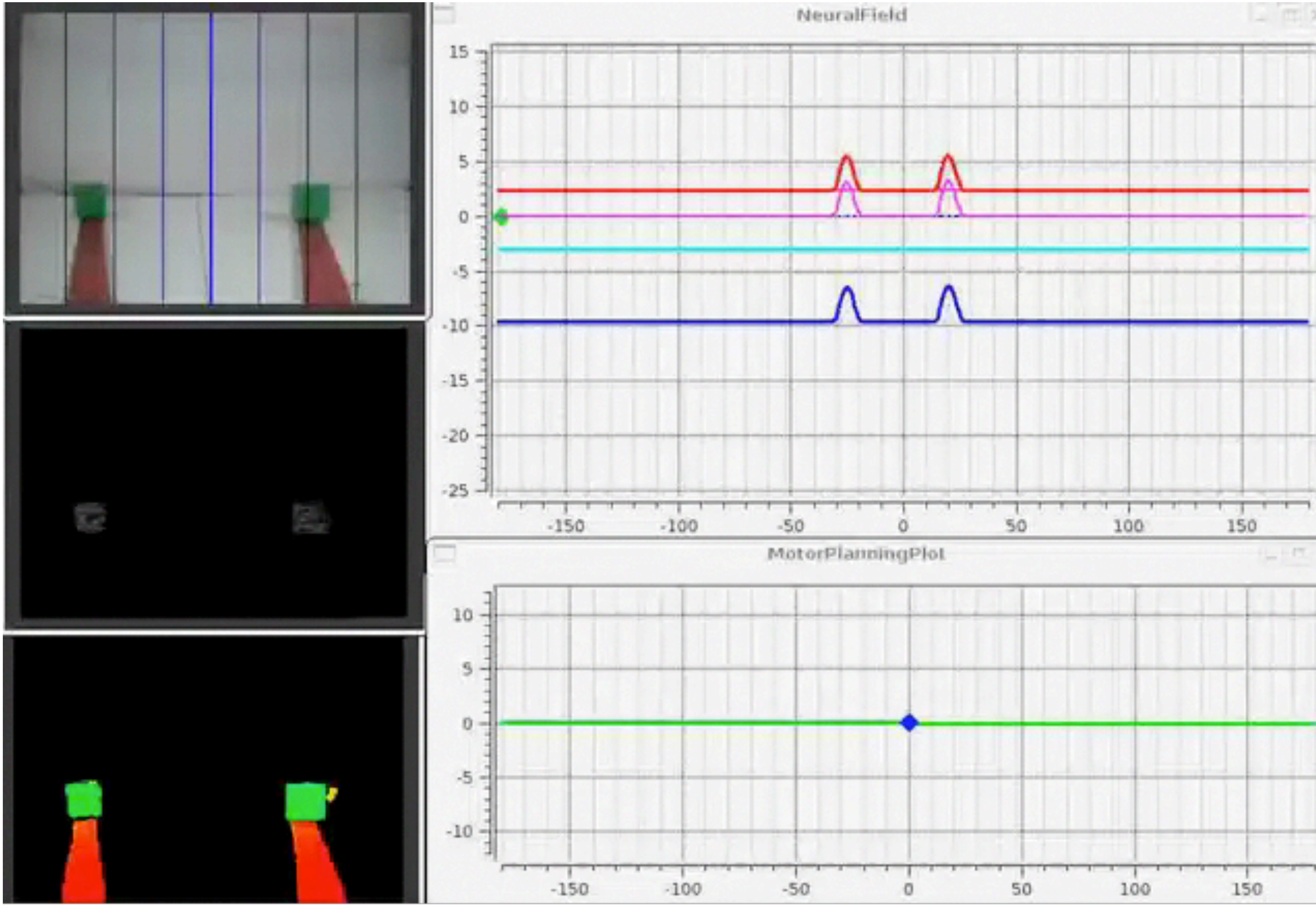
- implementing the A not B model on a autonomous robot with continuous link to sensory and motor surfaces...



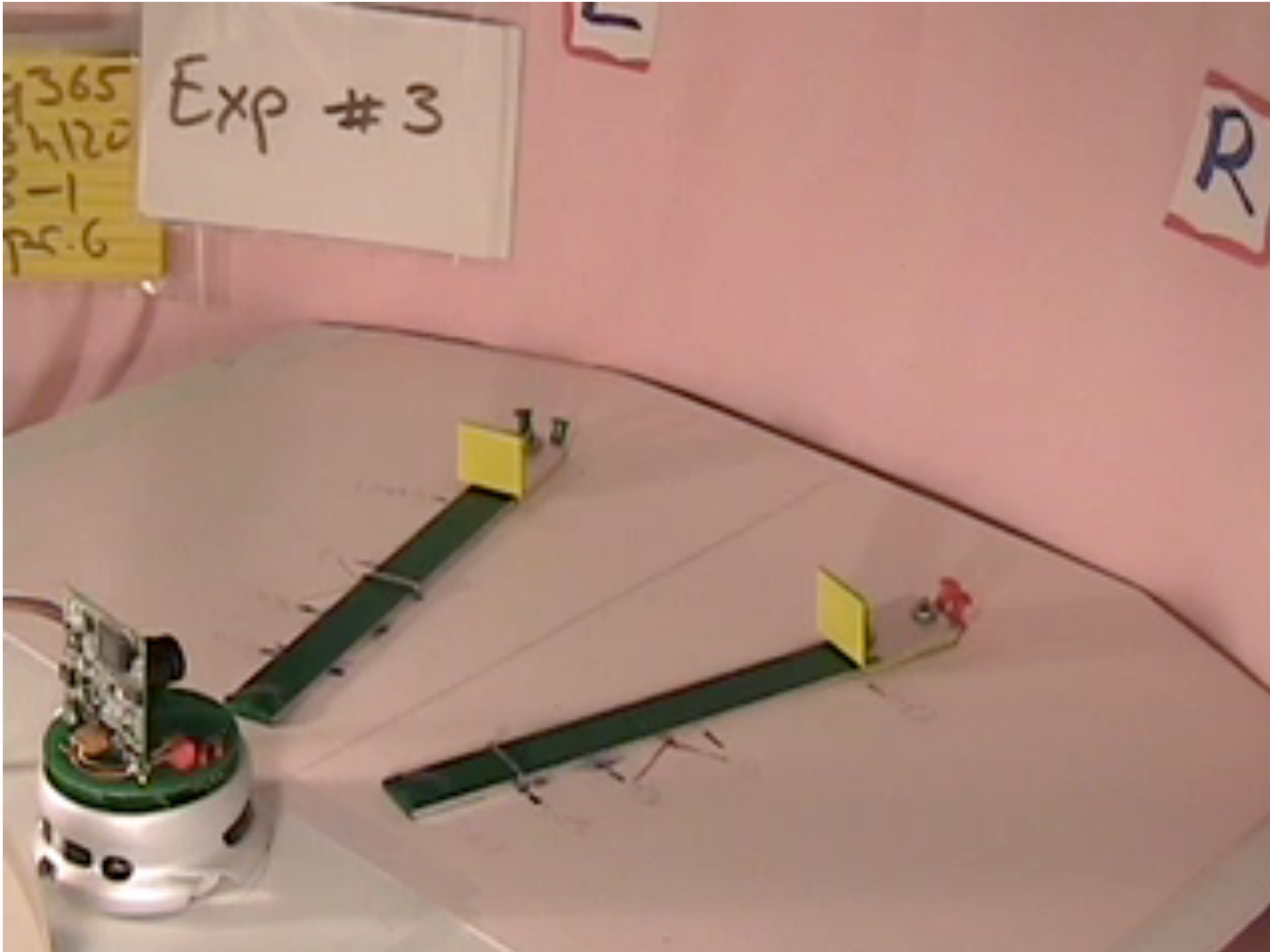
Visual input

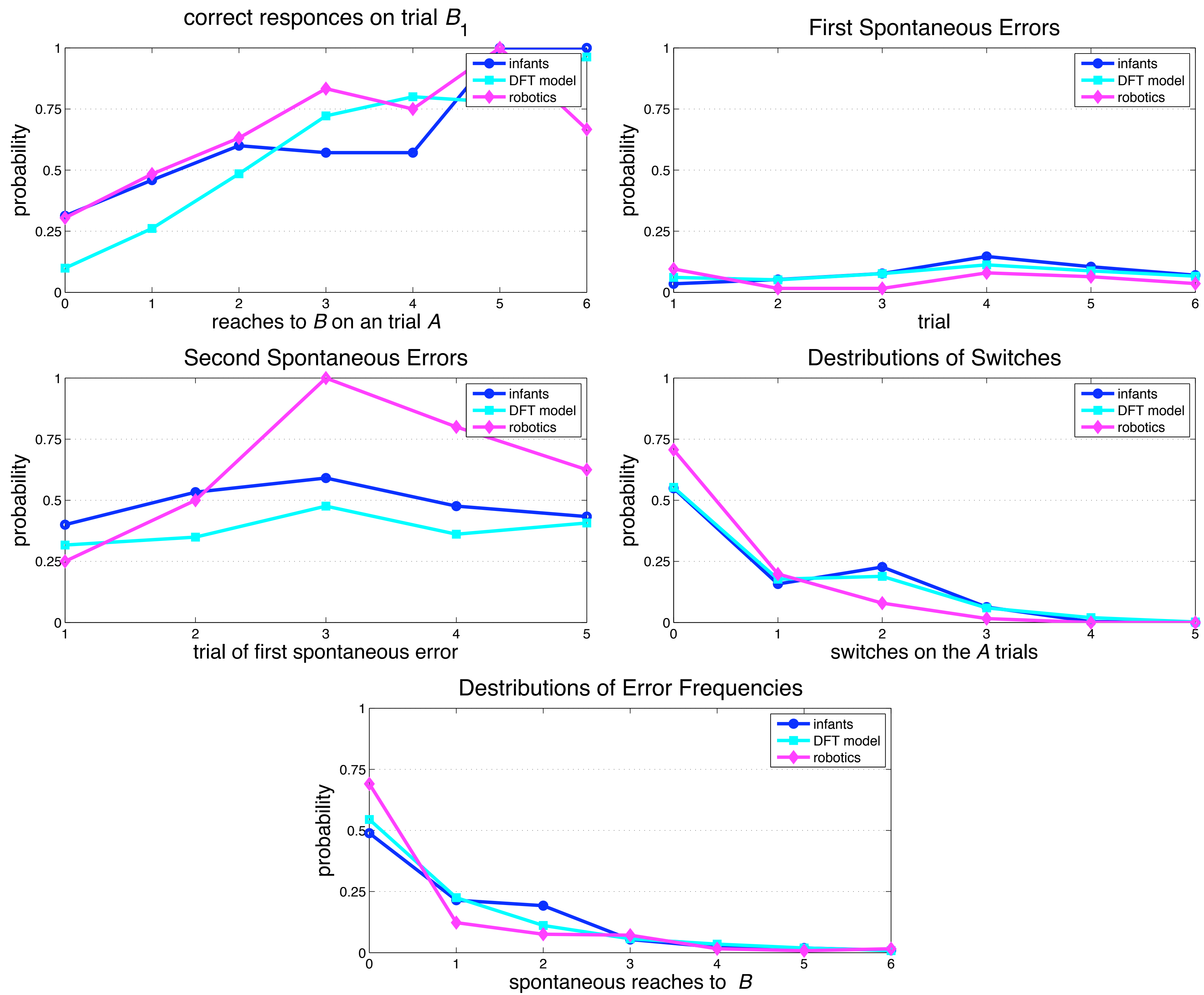
- color-based segmentation
- summing color pixels within color slot along the vertical
- spatially filter at two resolutions



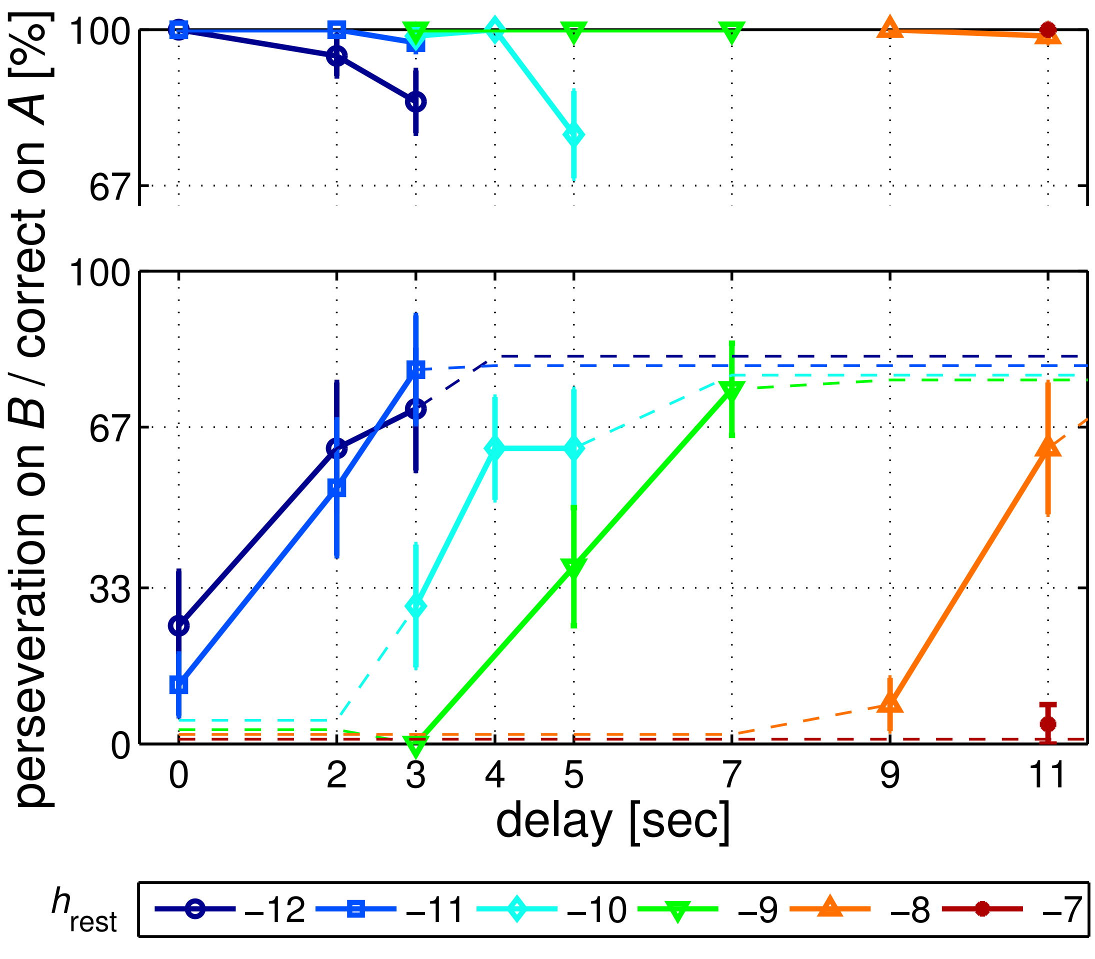


NeuralField
MotorPlanningPlot


Exp #3
R


correct responces on trial B_1
reaches to B on an trial A
First Spontaneous Errors
trial
Second Spontaneous Errors
trial of first spontaneous error
Destributions of Switches
switches on the A trials
Destributions of Error Frequencies
spontaneous reaches to B
probability
infants
DFT model
robotics
0
0.25
0.5
0.75
1
1
2
3
4
5
6

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

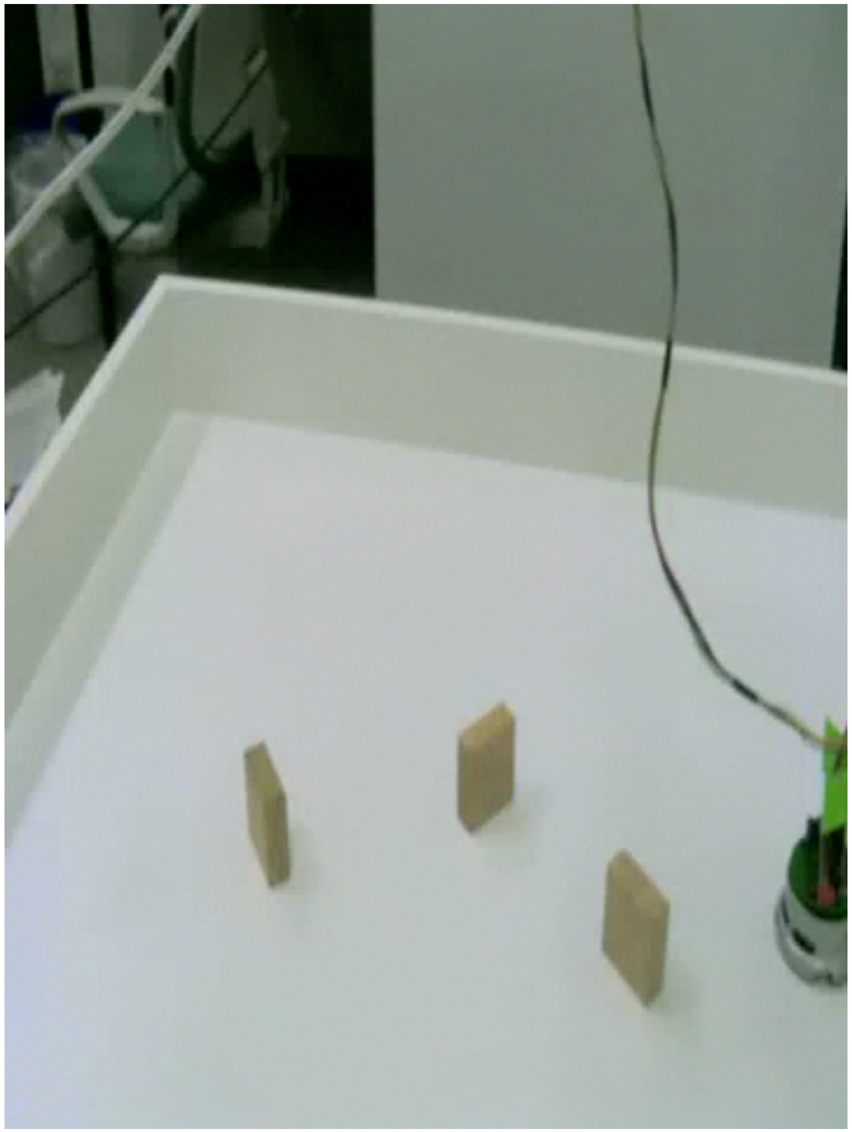


young

old

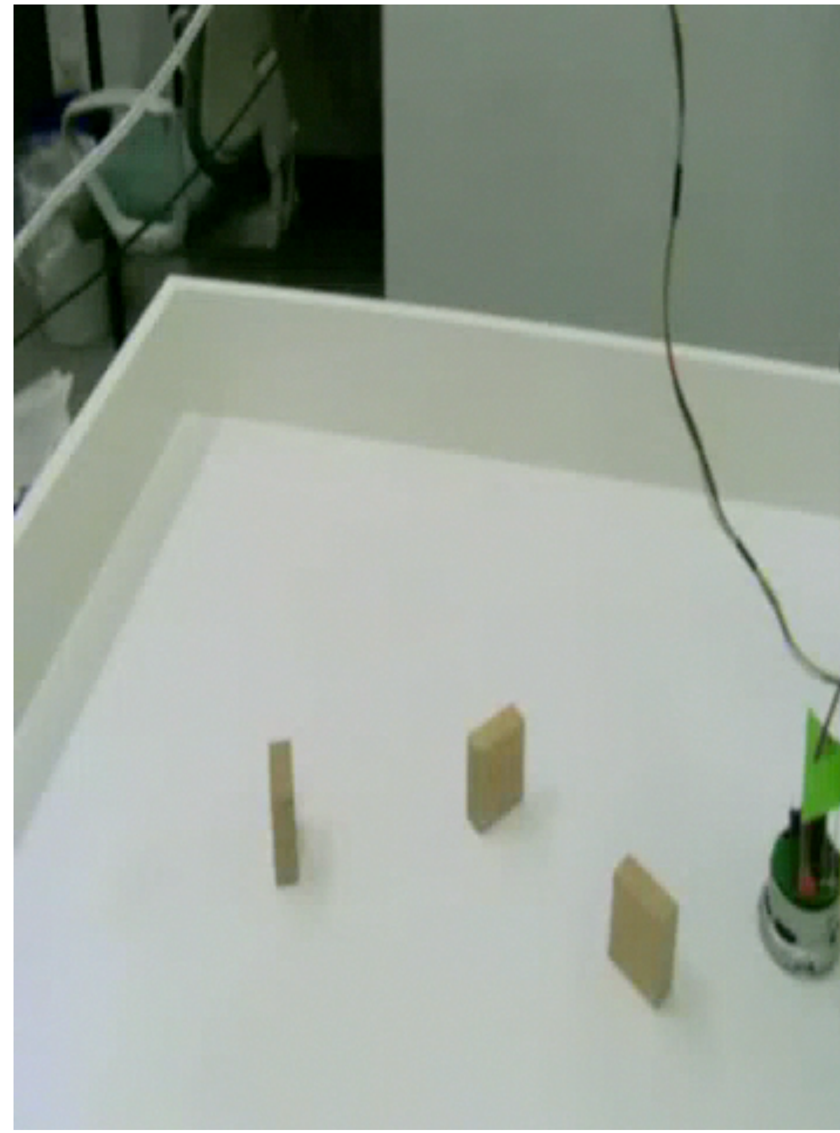
“young” robot

target



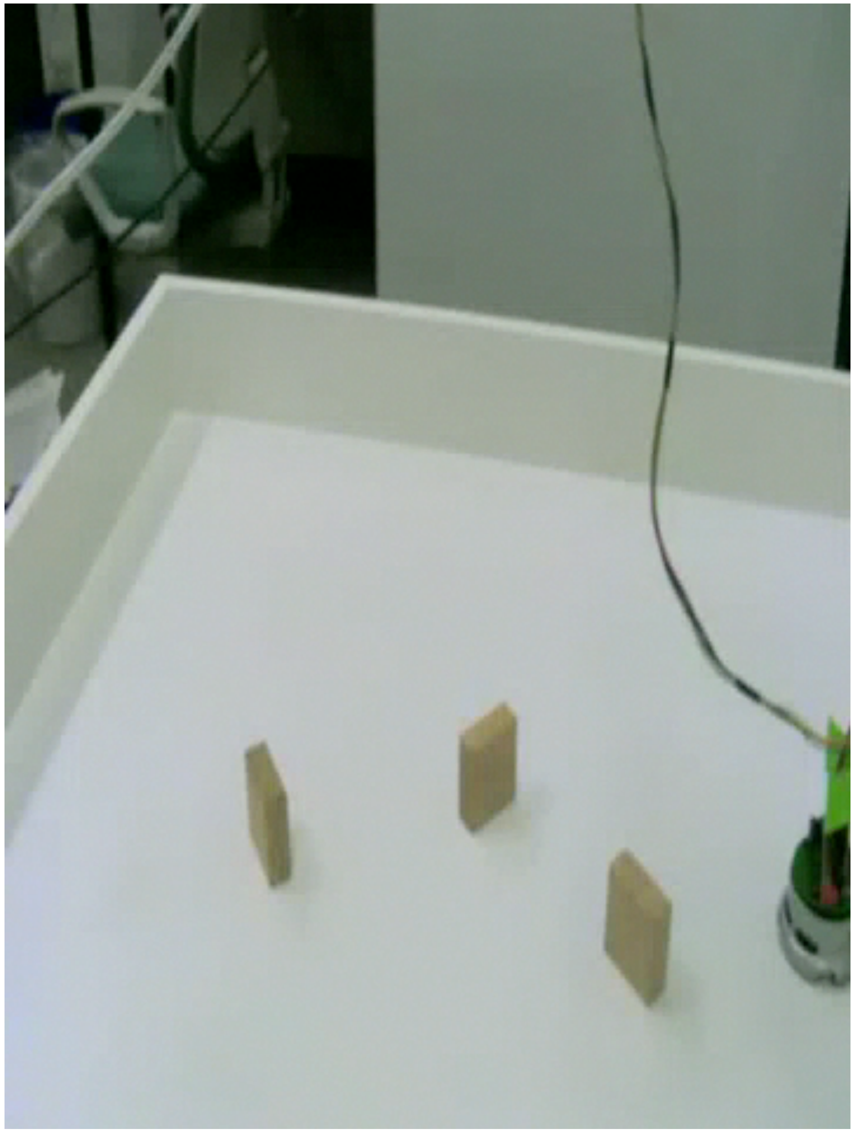
“old” robot

target



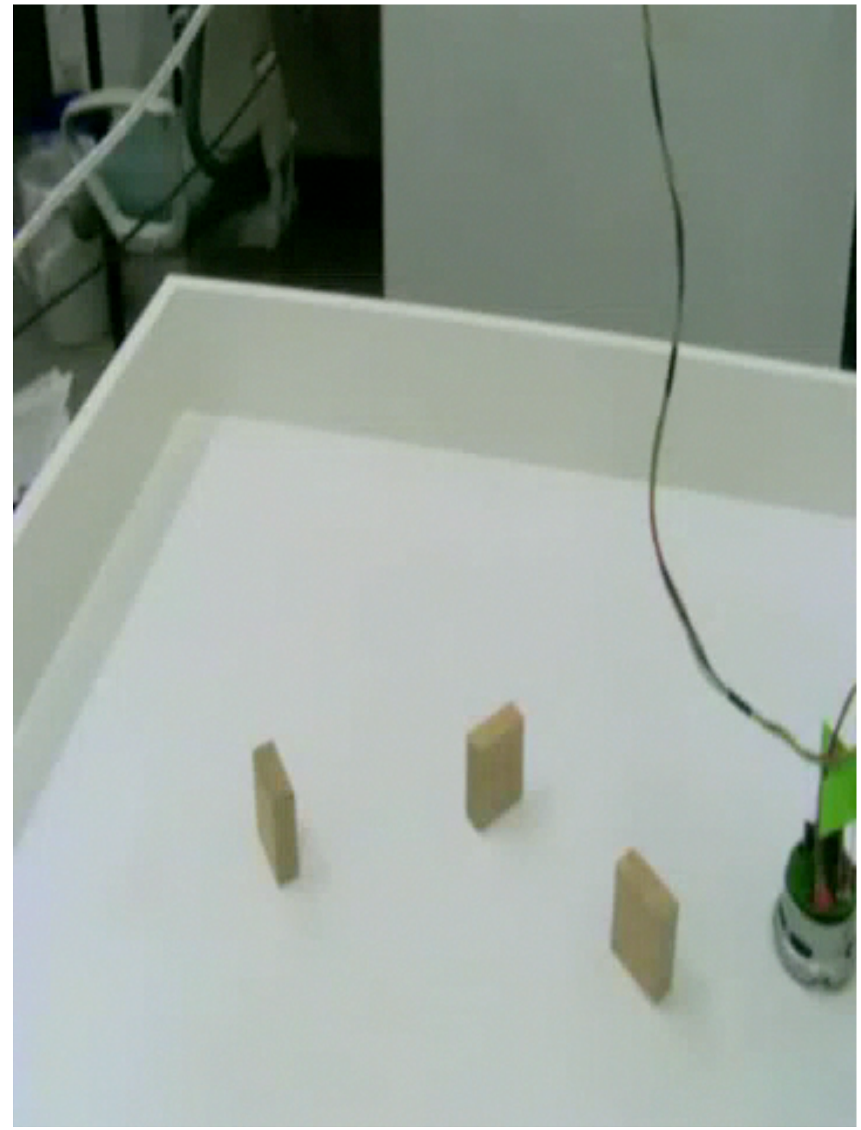
“young” robot

target



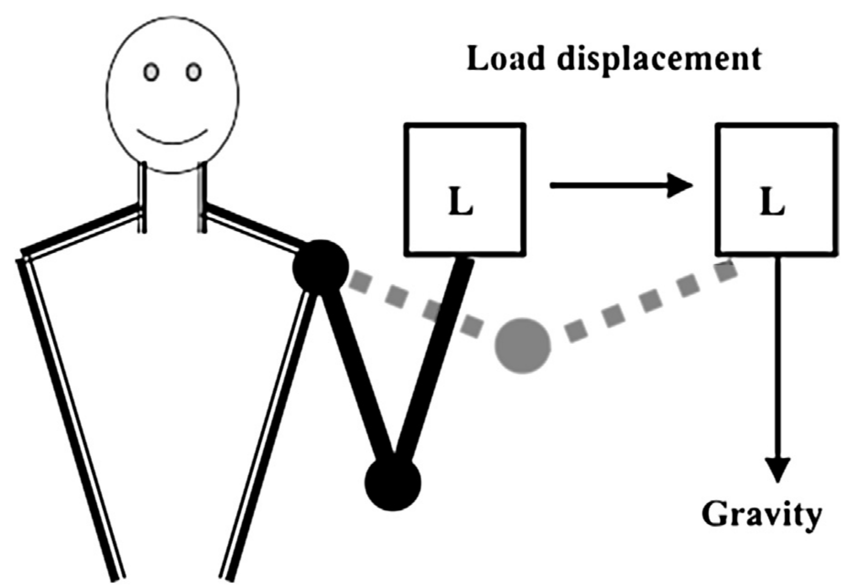
“young” robot with memory trace

target



How generic is “behavioral dynamics”?

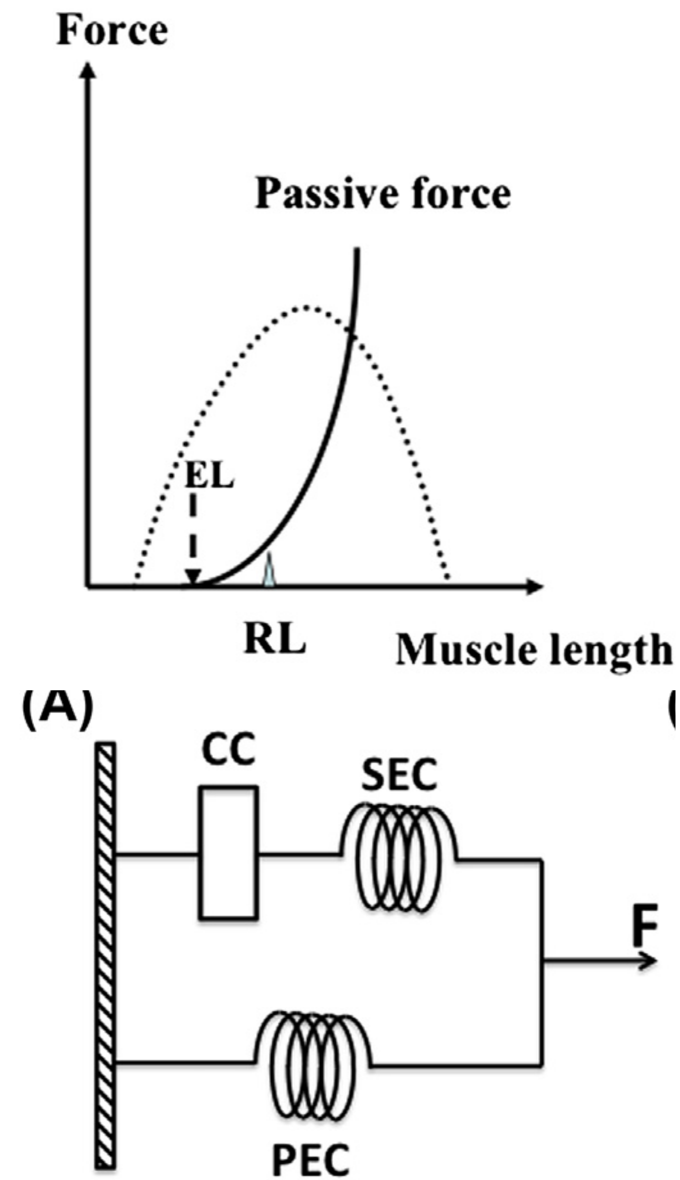
- physically, all actuator systems are dynamical systems: they have mechanical state driven by forces (stable, but not asymptotically stable



[Latash, Zatsiorksy 2016]

How generic is "behavioral dynamics"?

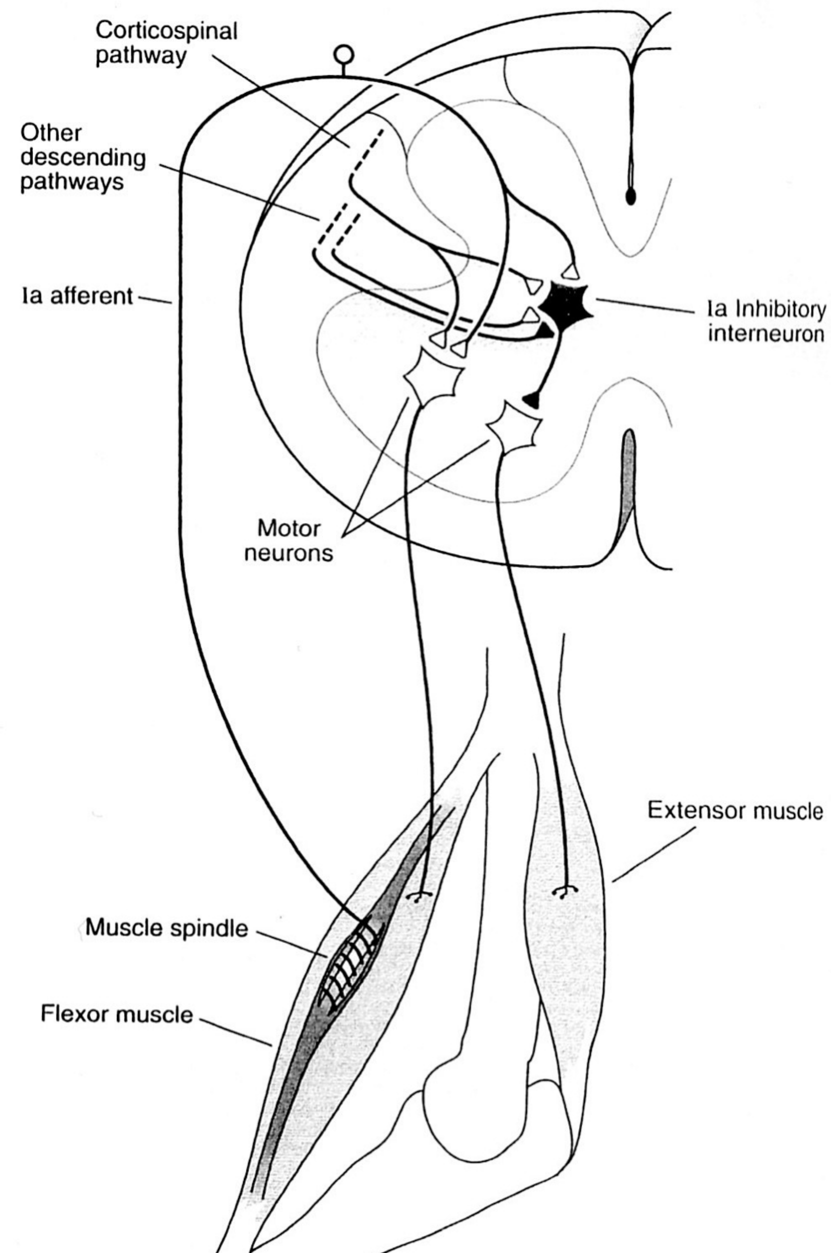
- the forces are generated by muscles, which are dynamical systems, generating force dependent on current physical state… attractor states in velocity space (but only stable transiently)



[Latash, Zatsiorksy 2016]

How generic is "behavioral dynamics"?

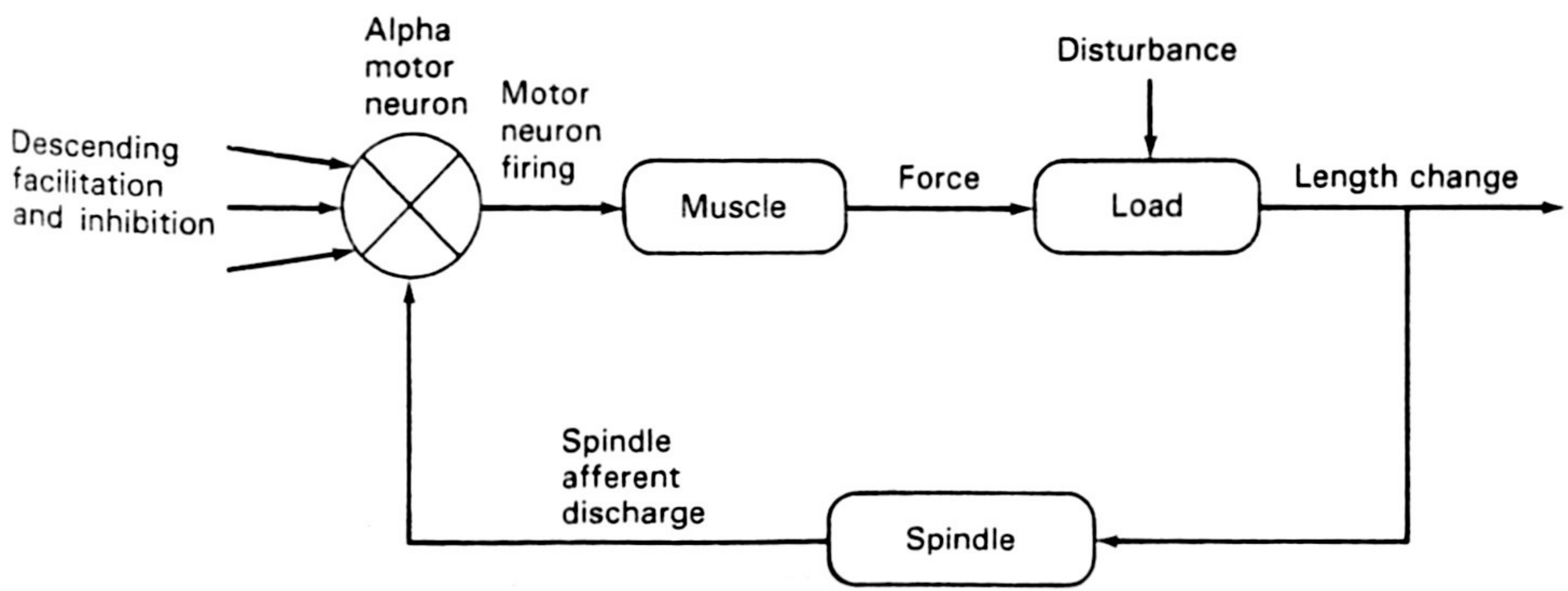
- muscle force generation is controlled in closed loop by peripheral feedback
- e.g. the stretch reflex



[Kandel, Schartz, Jessell, Fig. 38-2]

How generic is “behavioral dynamics”?

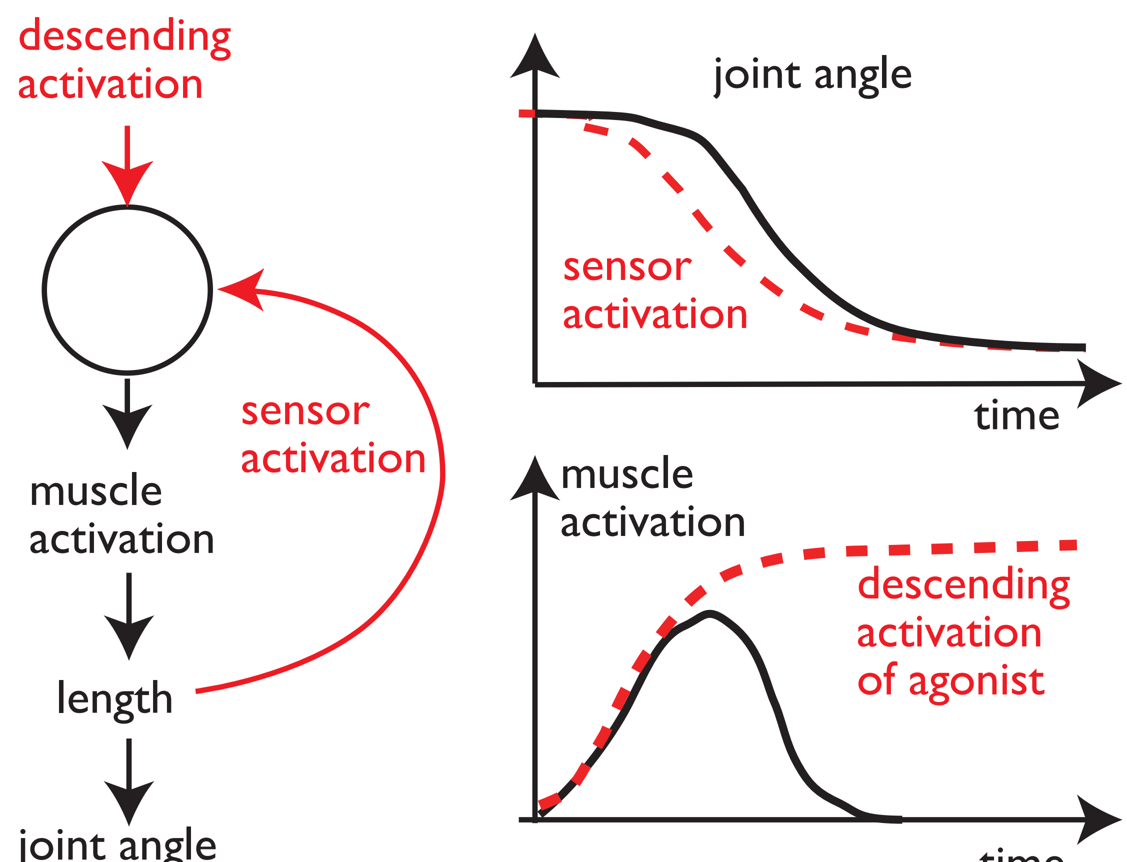
- the stretch reflex erects a dynamical system with a fixed point attractor at an equilibrium length of the muscle
- => Feldman’s equilibrium hypothesis…



[Kandel, Schartz, Jessell, Fig. 31-12]

How generic is "behavioral dynamics"?

- such peripheral dynamics changes what descending activation time courses are need to generate movement
- => summer semester course....



Conclusion

- neural dynamics can be directly driven by sensory input
- fields couple into behavioral dynamics by setting attractors => no more "read-out" of neural dynamics
- coordinate systems are important!