6th Framework Programme - Priority 2
"Information Society Technologies"
FP6/2003/IST/2

CogSys
Cognitive Systems

JAST Opening Conference

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Neural Circuits Underlying Action Understanding

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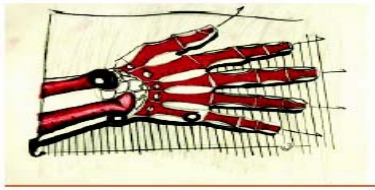


Artefact Structural Learning Through Imitation

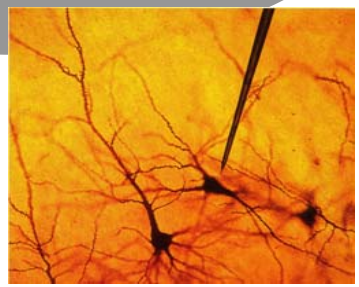
Cognitive Psychology

Reaction Time

H. Bekkering et al
Uni Nijmegen

Electrophysiology

Single Unit Activity, EEG, etc.



G. Rizzolatti et al, Uni Parma
P. Thier et al, Uni Tübingen

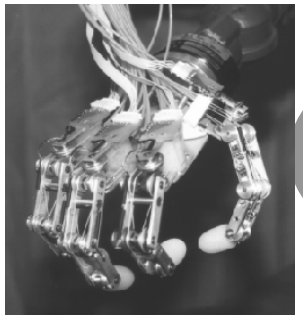
Modeling/Theory

Uni Minho

Dynamic Field Theory, Optimization

Robotics

Control of Arm and Hand Movement,
Goal-directed Imitation
Action Understanding

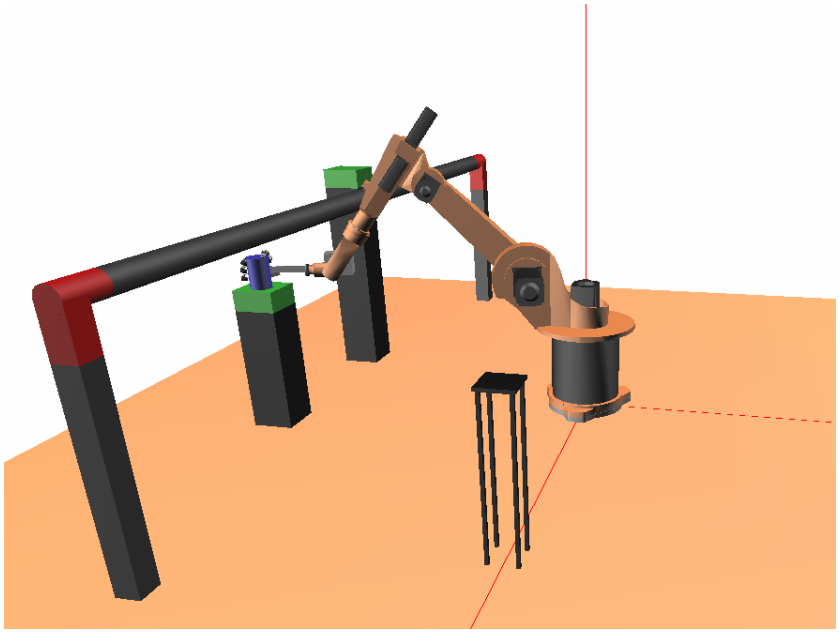


A. Knoll et al,TU München
E. Bicho et al, UMinho

Dutch Bridge Paradigm

- Motor action composed of two motor acts:
  1) grasping an object (*proximate goal*),
  2) placing the object at one of two possible target positions (*ultimate goal*) thereby avoiding an obstacle.

- Trajectory above (AT) or below (BT) the bridge
- Grasping from the side (FG) or from above (PG)



Main hypotheses which guided our work

- Imitation is fundamentally goal-directed,
  as opposed to trajectory-oriented „replay“ over via points.
  (Bekkering and colleagues)

- Action understanding based on “motor simulation”,
  existence of an action observation/execution matching system
  (Rizzolatti and colleagues)

However……

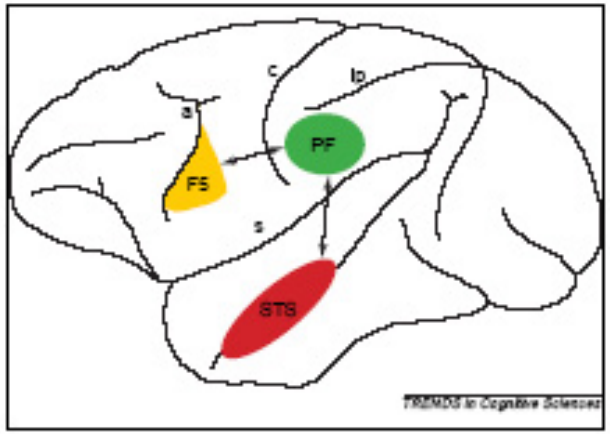
very often, the matching cannot be automatic and direct
due to differences

- in embodiment (child-adult, robot-human)
- environmental constraints (obstacles), and/or
- motor skills.

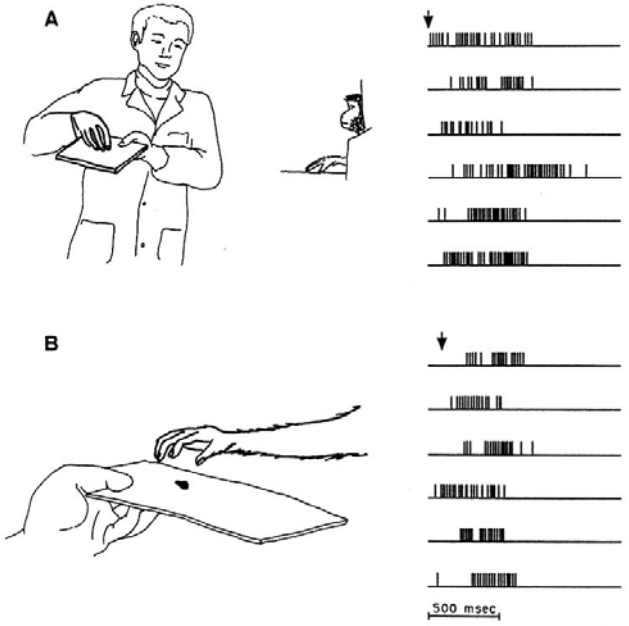
Structure of the talk

- Neural circuits underlying goal inference and imitation
- The dynamic model
- Simulation examples (bridge paradigm)
- The real artifact in action

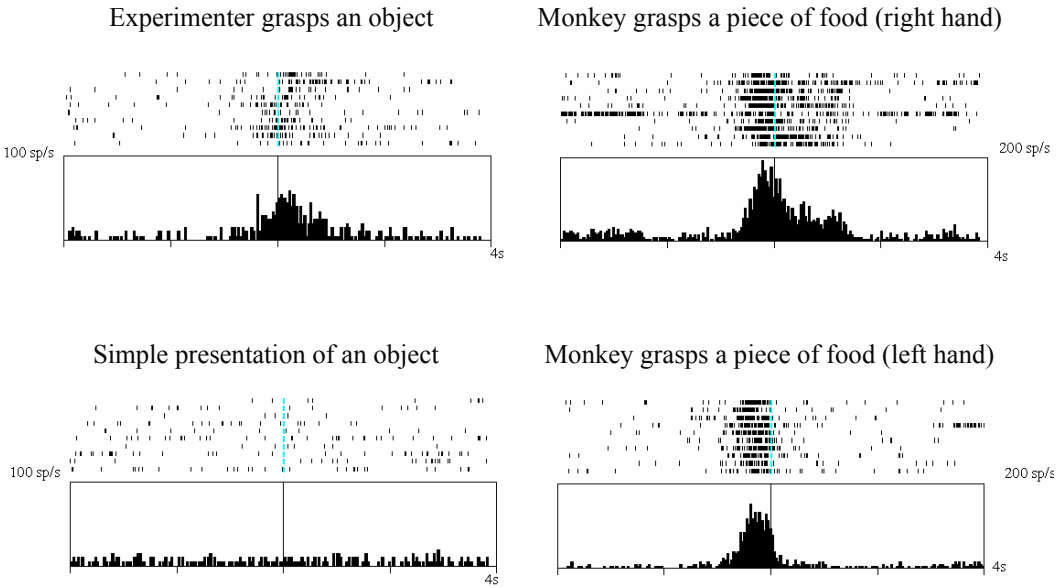
The mirror neuron circuit



Mirror neuron in the premotor cortex



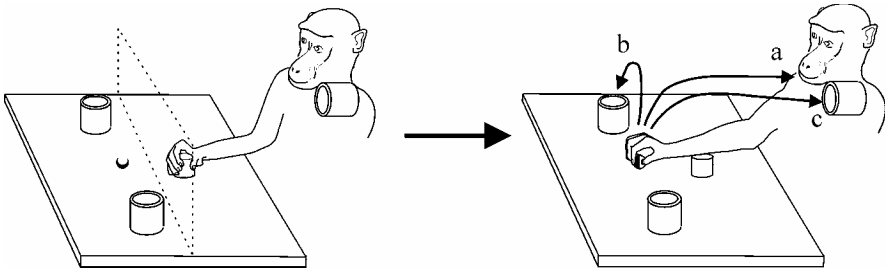
Mirror neuron in the parietal cortex

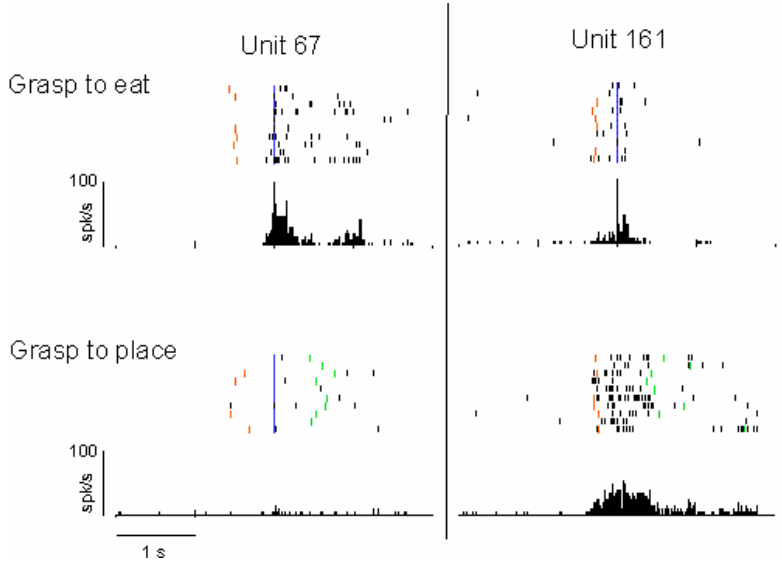


(Rizzolatti et al, 2001)

Motor responses of parietal neurons

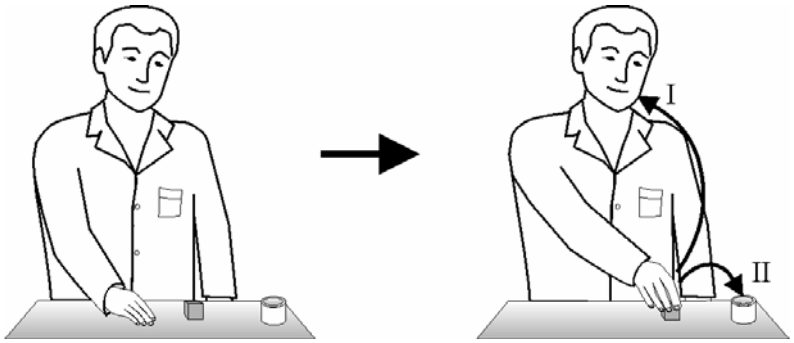
Motor task

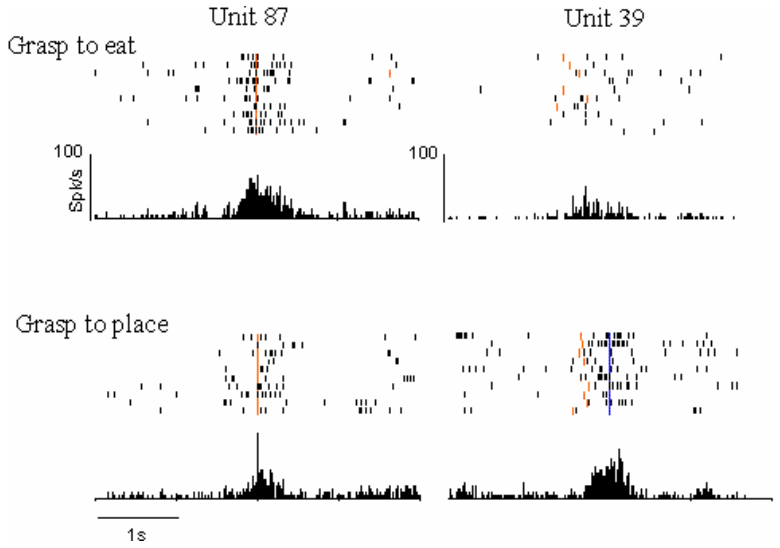




Visual responses of parietal mirror neurons

Observation task

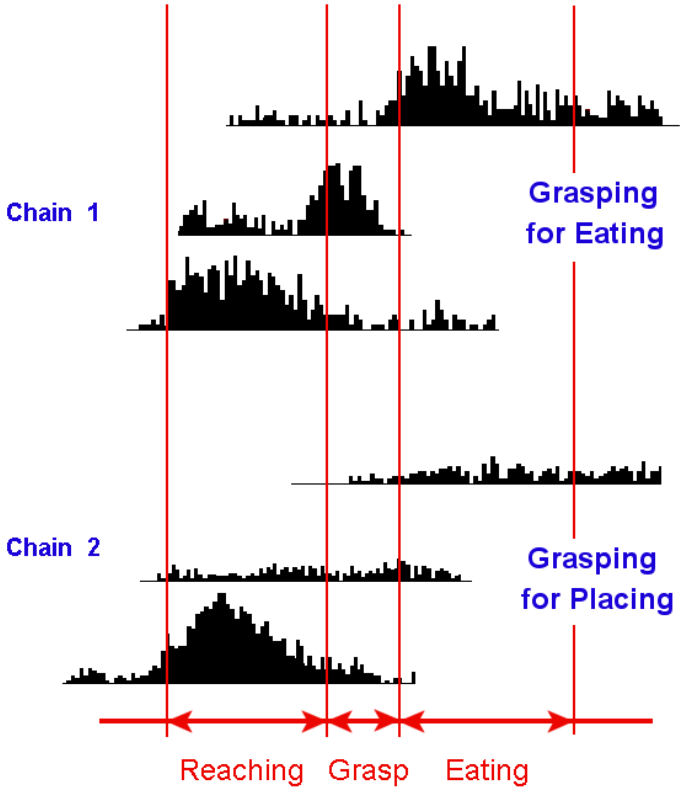




Fogassi et al, *Science*, in press

Action organization in the parietal cortex

- Neurons of inferior parietal cortex appear to be organized in chains, each of which is aimed to a final action goal.



(Fogassi et al, in press)

Beyond the mirror circuit

- Integration of contextual informtion
- Establishing a link between means and goal (physical outcome) of an action sequence.

Role of Prefrontal Cortex (PFC)

- Combine *sensory* and *contextual* information to organize the means represented in other brain areas to achieve an intentional goal.
  $\Rightarrow$ strong connections to IPL (areas PF/PFG)

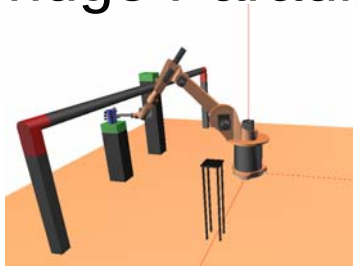
- Cognitive control, for instance, to override prepotent responses (e.g., a direct matching).

- Form associations between events separated in time ("Learning object meaning").

- Learning novel complex actions by combining existing motor primitives.

Model architecture

Bridge Paradigm



PFC:

Goal representations
Task input
Object properties (e.g. colour)

STS:

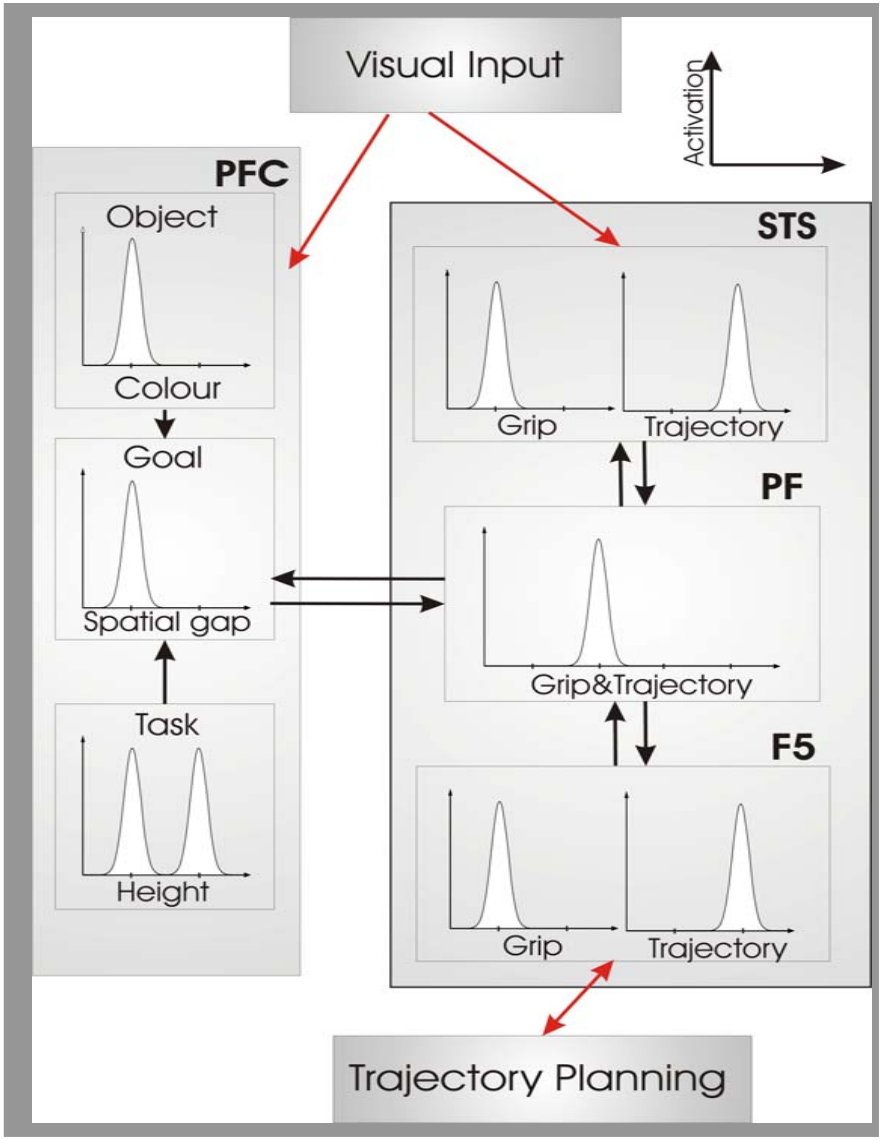
Visual desciption of grip and trajectory

PF:

Sequence of means

F5:

Movement primitives

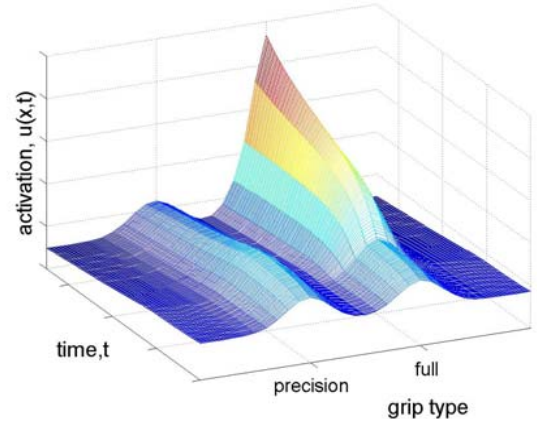


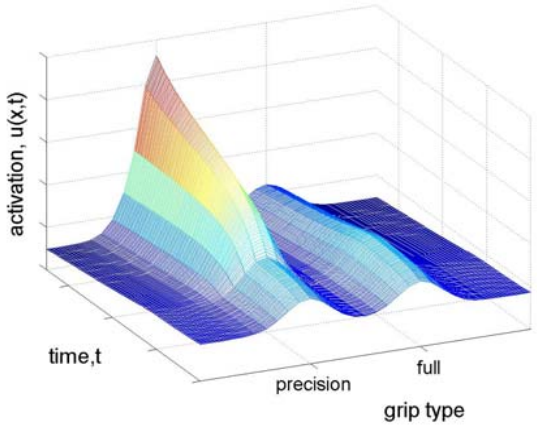
(Erlhagen et al., 2005)

Basic Concepts of the Dynamic Model

- in each layer, neuronal activation patterns encode task relevant information

Type of grasping behaviour





Mean-Field Rate Model

$$\frac{du(x,t)}{dt} = -u(x,t) + G\big(u(x,t)\big)\int W_u(x-x')F\big(u(x',t)\big)dx' + h + S(x,t) - v(x,t)$$

$$\frac{dv(x,t)}{dt} = -v(x,t) + \int W_v(x-x')F\big(u(x',t)\big)dx'$$

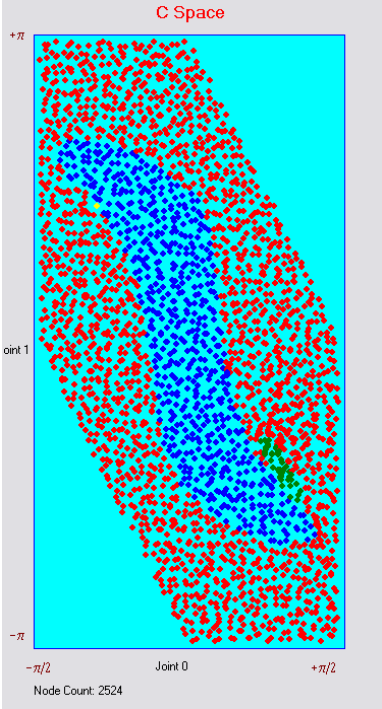
- Integration: representations evolve under the influence of multiple information sources *S(x,t)* (visual input, input from other layers...)

- Decision making in ambigious situations through recurrent inhibition

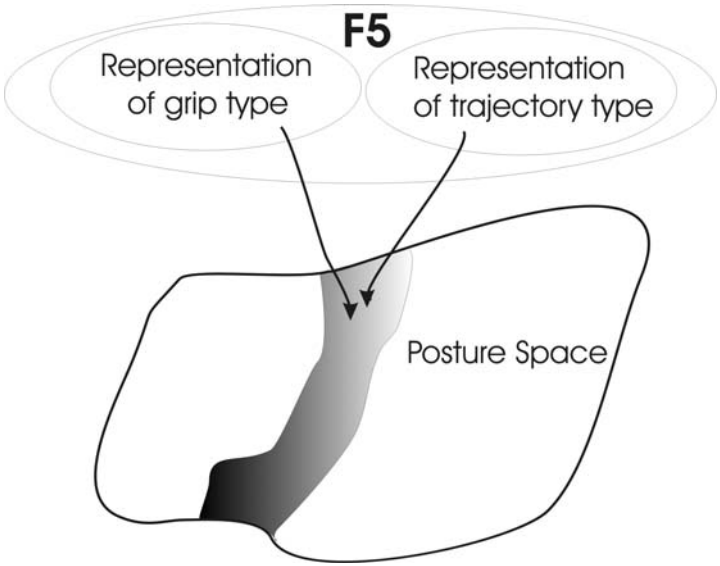
(e.g., Erlhagen & Schöner, 2002)

Path planning in posture space

- Planning provides a posture sequence linking the initial posture to the desired end-posture.
- Movement primitives in F5 serve to pre-select relevant parts of the posture space.
- Obstacles are mapped into posture space.



- Active Node
- Inhibited Node
- Target Node

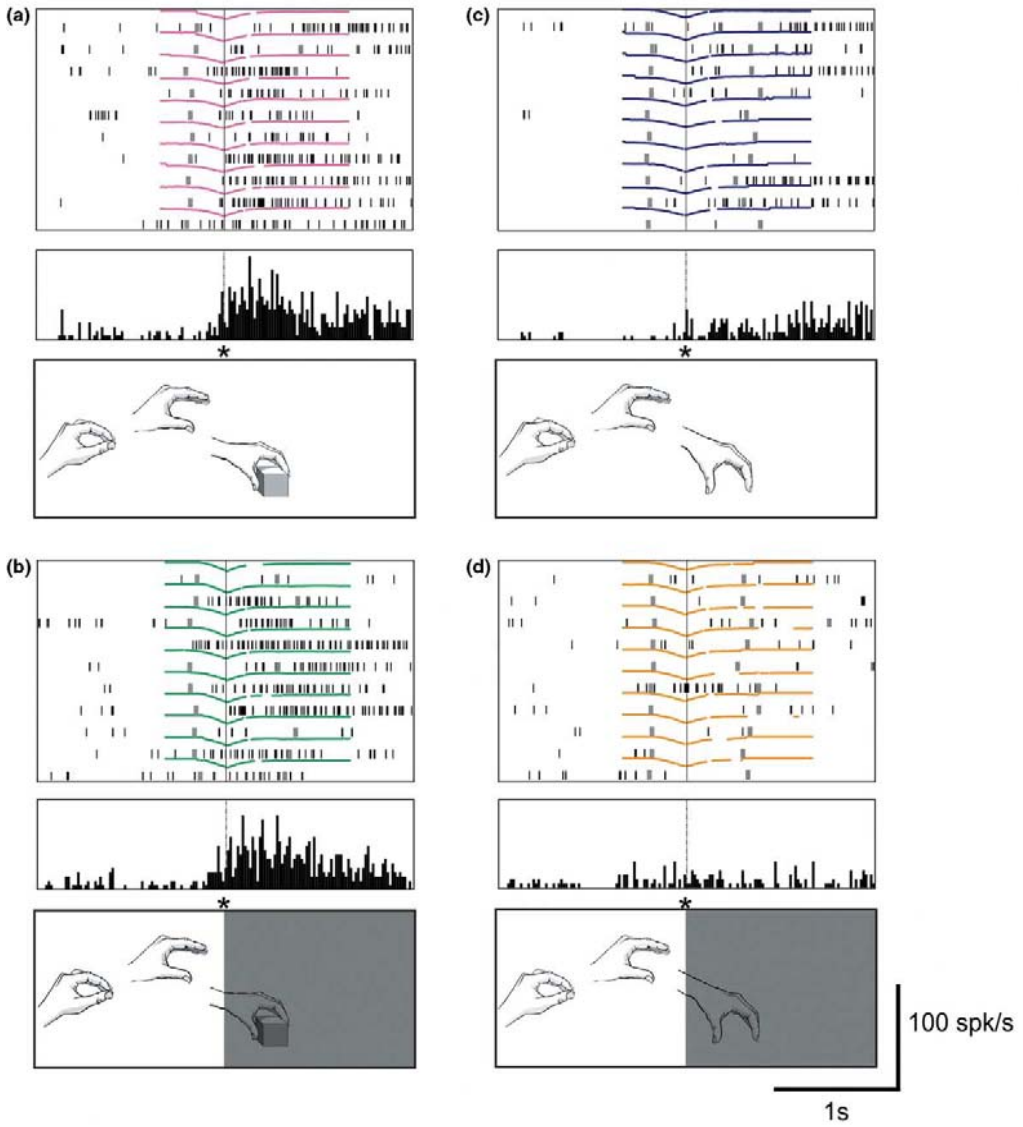


Model Simulations

- Goal inference and choice of means
- Growth of cognitive skills through learning

“I know what you are doing”

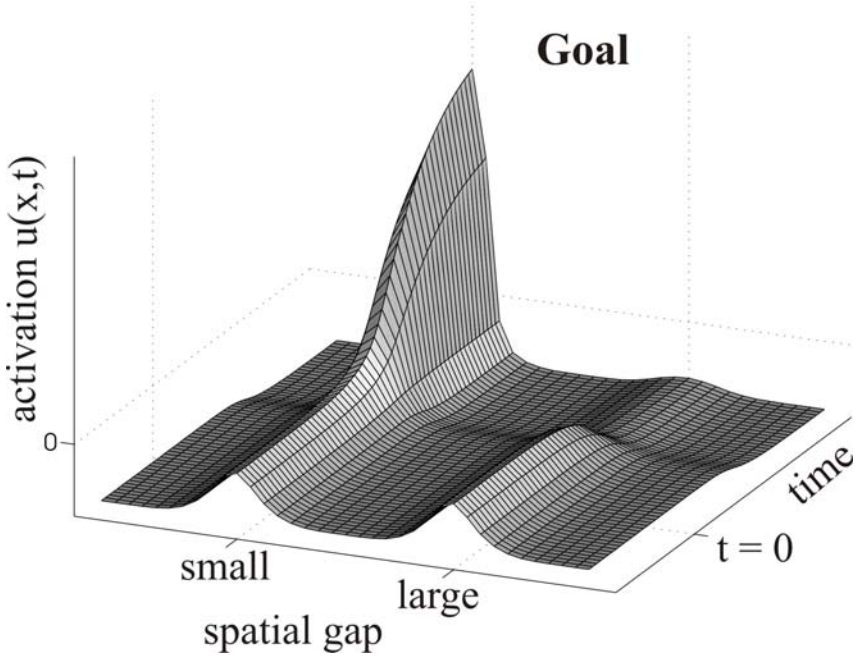
(Umiltà et al, 2001)



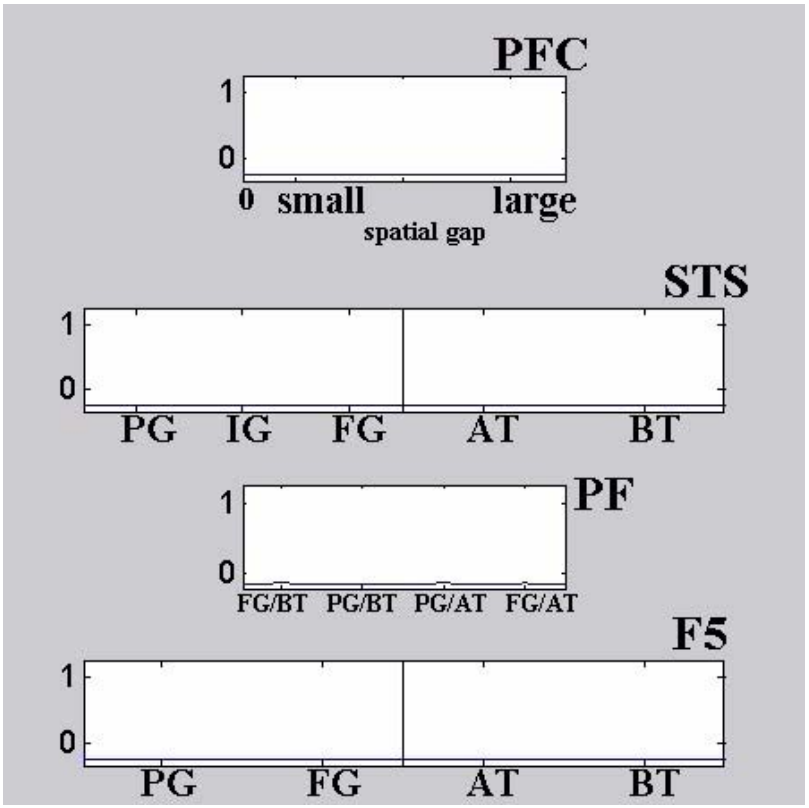
Goal Inference: Bridge Paradigm

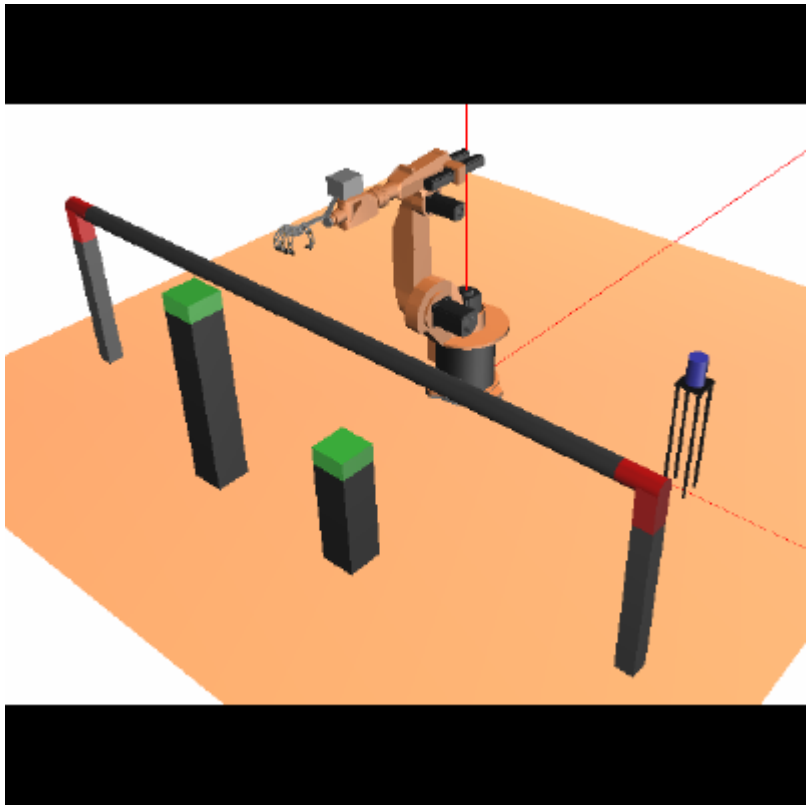
- Combination of partial visual information (grasping) with prior task information.

- Constant task input results in a "preshaping" of neural populations representing goals (in PFC) and associated sequences of means (in PF).

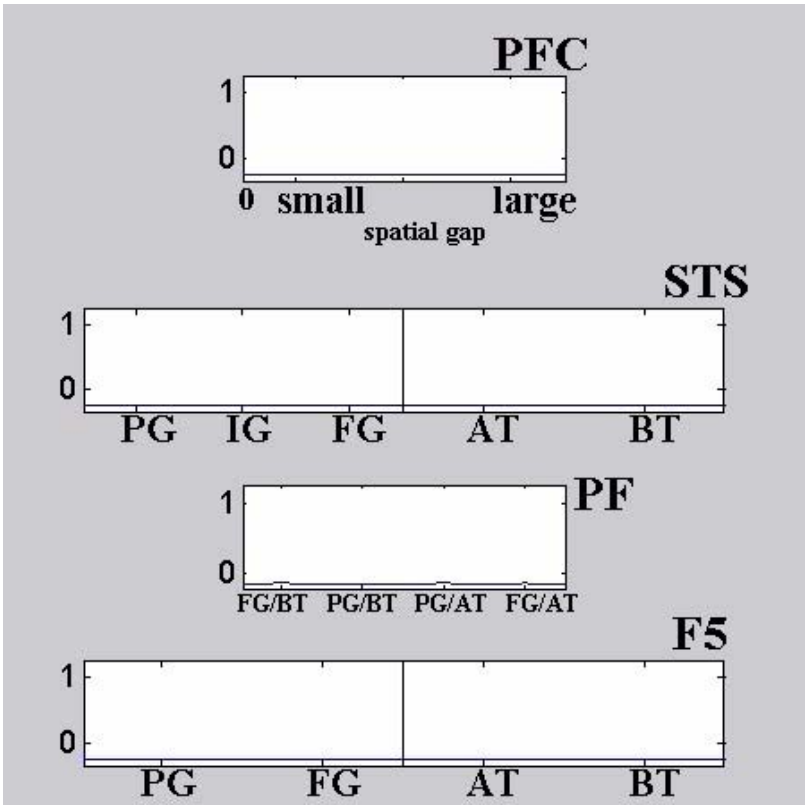


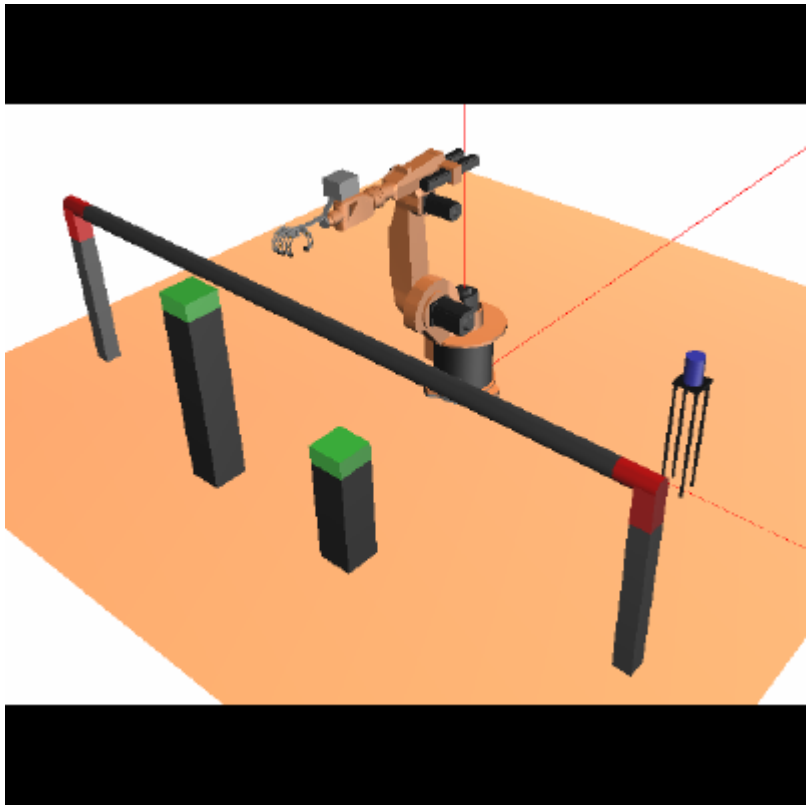
Goal Inference Task



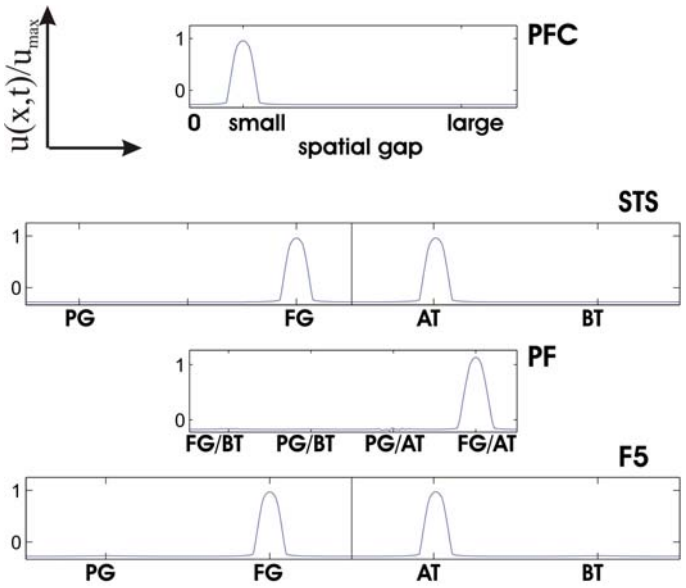


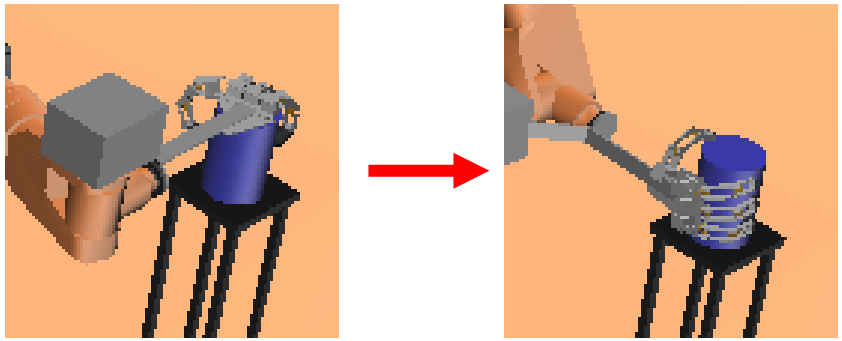
Goal-directed imitation: Conflict in the grip type



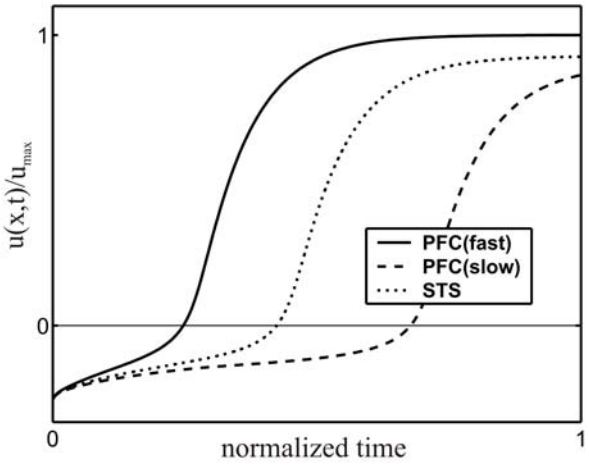


Constraints allow to copy the means





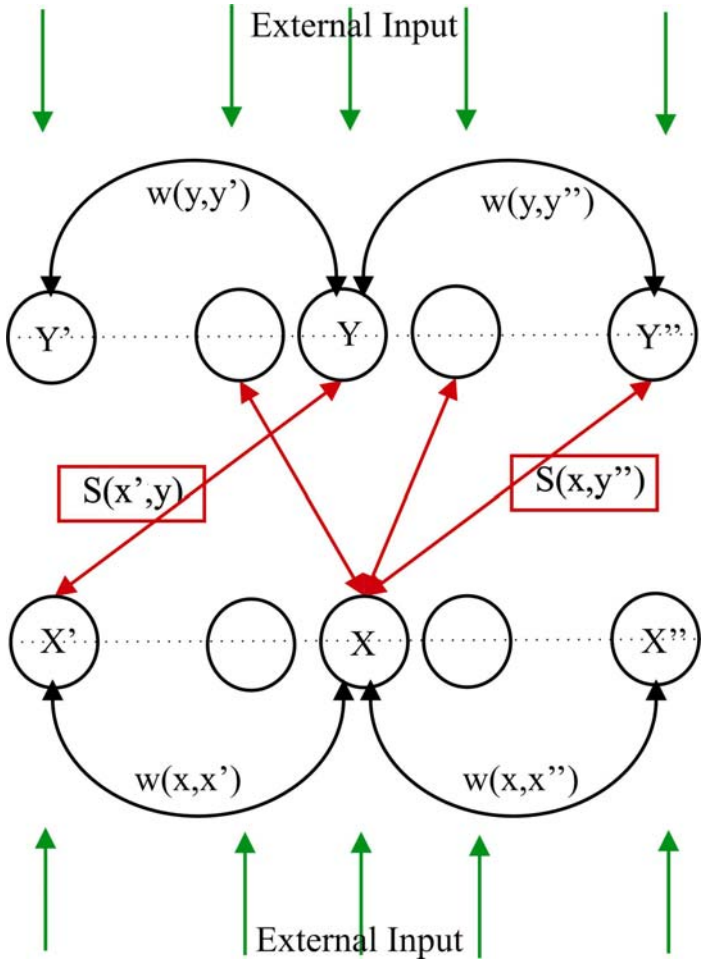
Time course in PFC



<u>Purely</u> <u>temporal mechanism:</u>
Change in baseline firing rate
affects time course
(e.g., *Asaad, Rainer & Miller, 2000*)

Learning the synaptic links between Dynamic Fields

- Learning results from modifying synaptic connections between neurons (Hebb 1949).
- The modification of synapses is slow compared with the caracteristic time scale of neuronal dynamics.
- Internally generated reinforcement signal representing a successful planning defines epoches of learning (goal-directed).



Mathematical formalization

- Learning the connections between *Field* [1] and *Field* [2]

$$\frac{\partial s(x,y,\tau)}{\partial \tau} = -s(x,y,\tau) + \alpha \int g(\tilde{u}_1(y-y'))\, f(\tilde{u}_2(x-y'))dy'$$

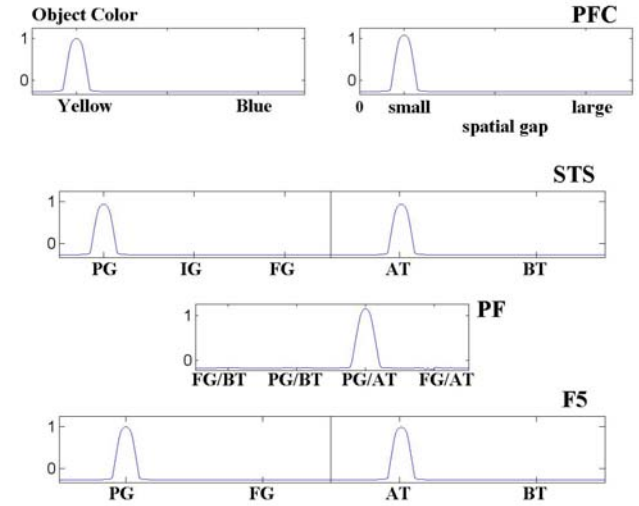
with $\alpha = const.$ and $\tilde{u}_1, \tilde{u}_2$ equilibrium solutions of the relaxation phase.

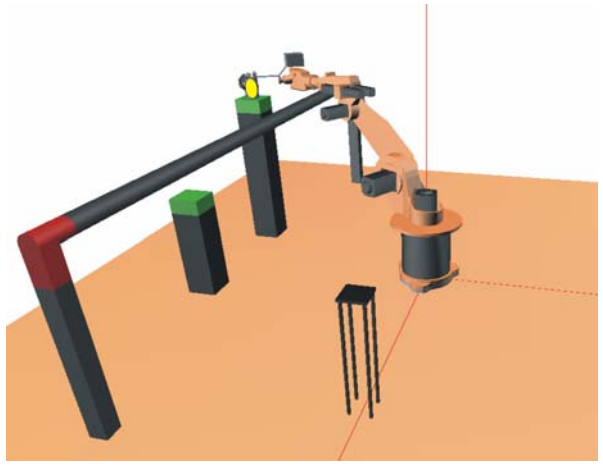
- Total input to *Field* [2] after learning (equivalent for *Field* [1]):

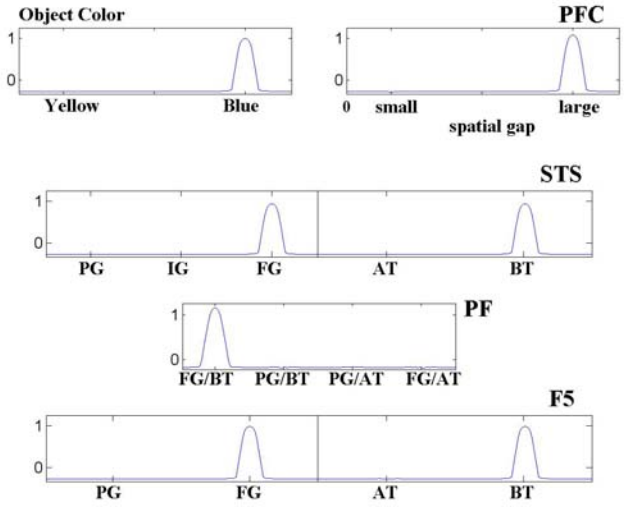
$$\bar{S}(x,y) = \int g(\tilde{u}_1(y-y'))s(x,y')dy'$$

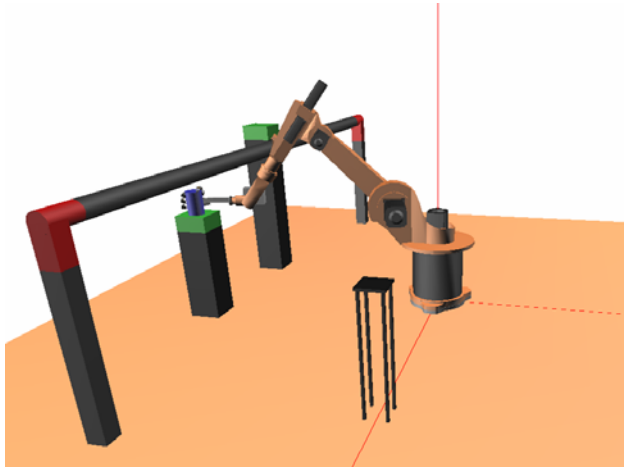
Learning object meaning

Example: color ↔ goal









A Hebbian perspective on how mirror properties evolve

- First learning phase (correct alignment):
  Pay attention to your own arm/hand,
  motor system provides stimulus for the visual system.

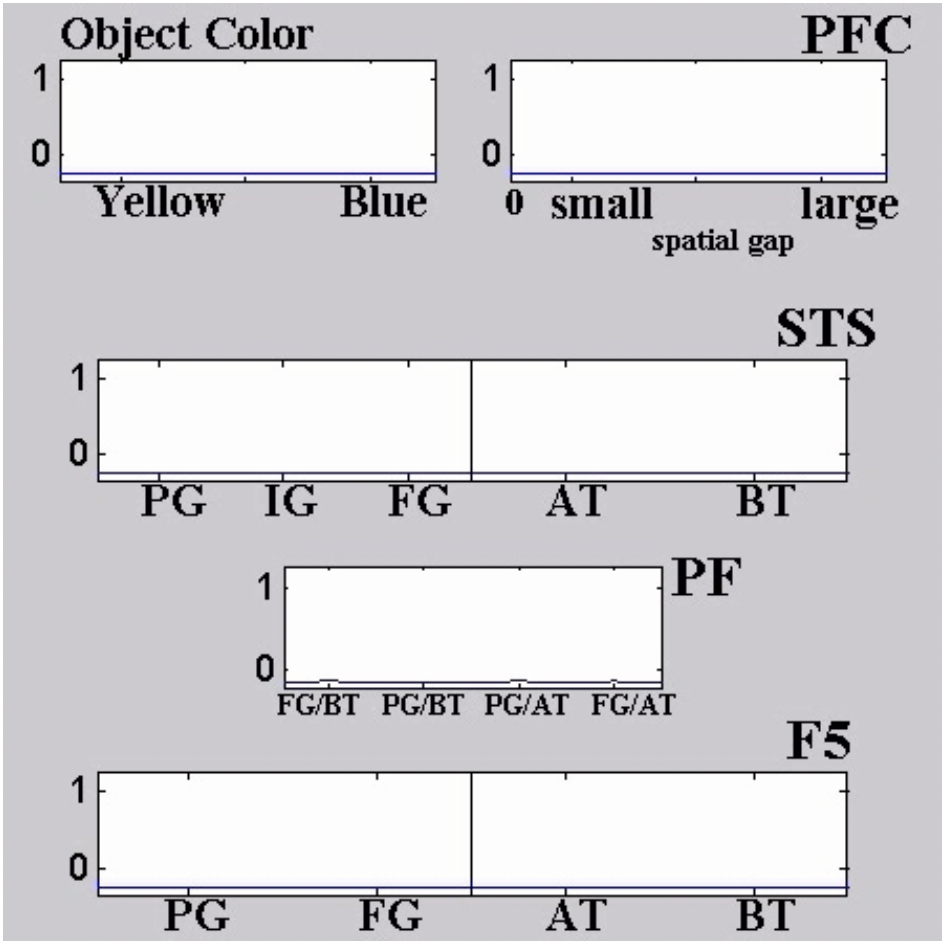
- Second learning phase (mirror properties):
  Generalization to goal-directed actions of others.

⇒Action understanding requires high level of abstraction
⇒Learning a goal-directed matching

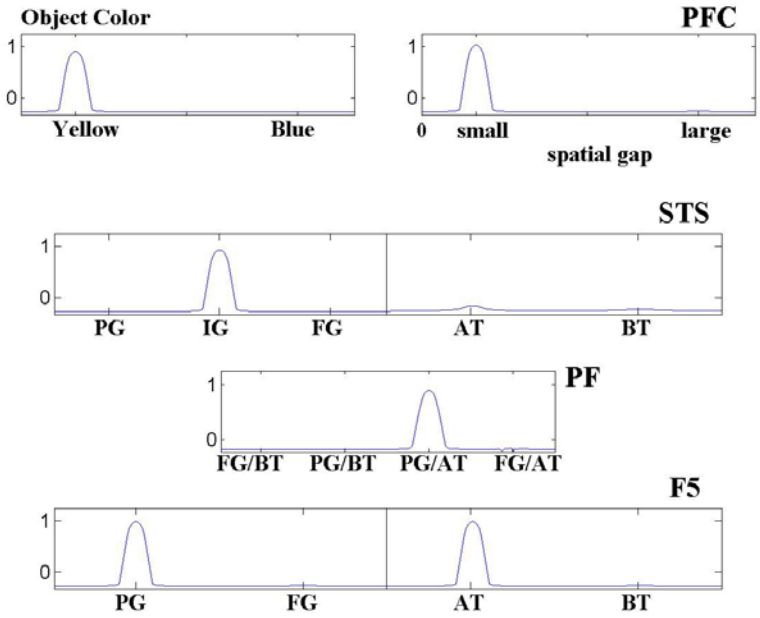
Understanding actions made with tools

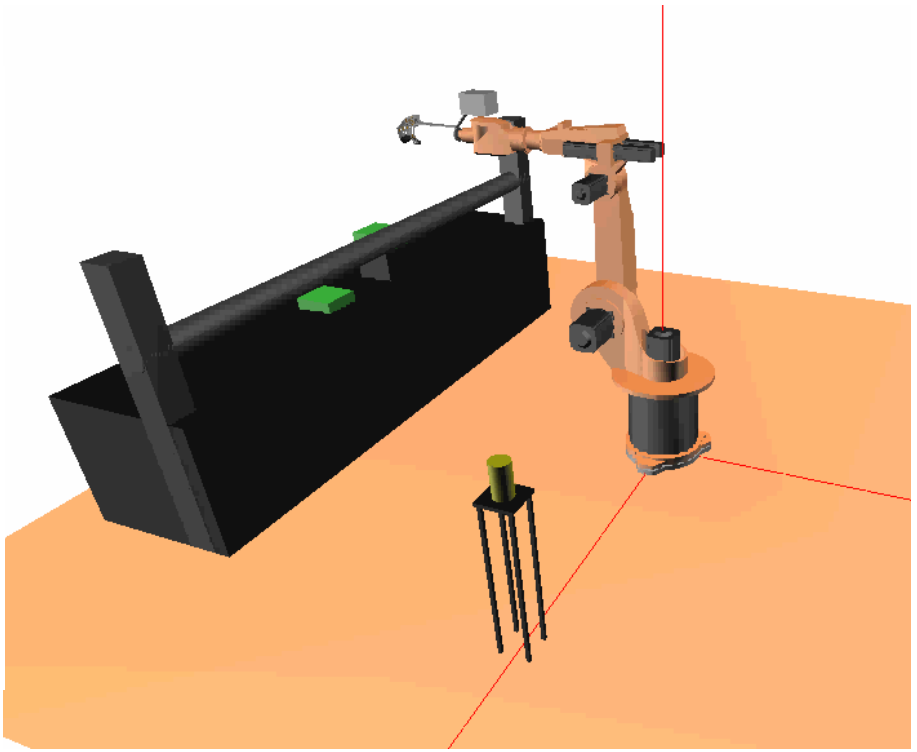
- Tool-use not in the repertoire of the observer
- Long visual exposure to represent the hand-tool motion in STS
- End-state/goal should be observable

Inference task:
Only the tool-grip “IG” is observable,
color information is ambigious.



Tool-use task: Overt behavior

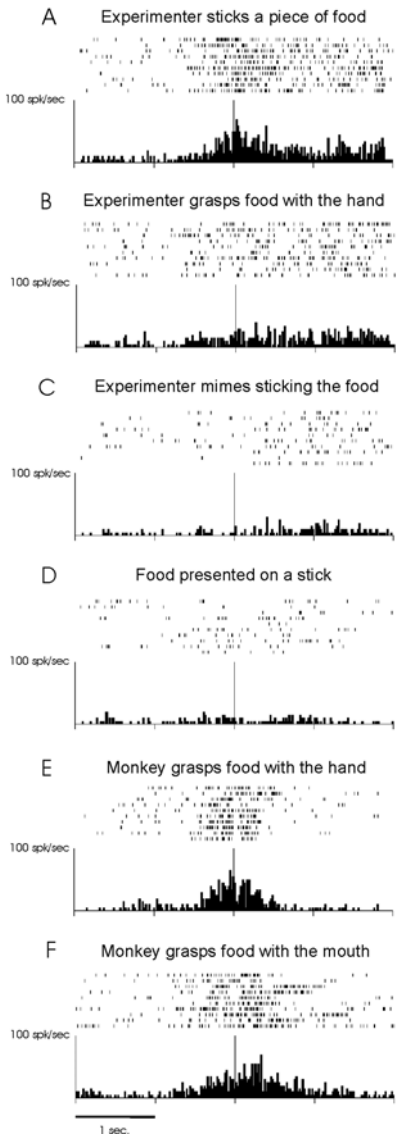




Tool-responding mirror neurons

UNIT 088 **F5**

(Ferrari et al., 2005)



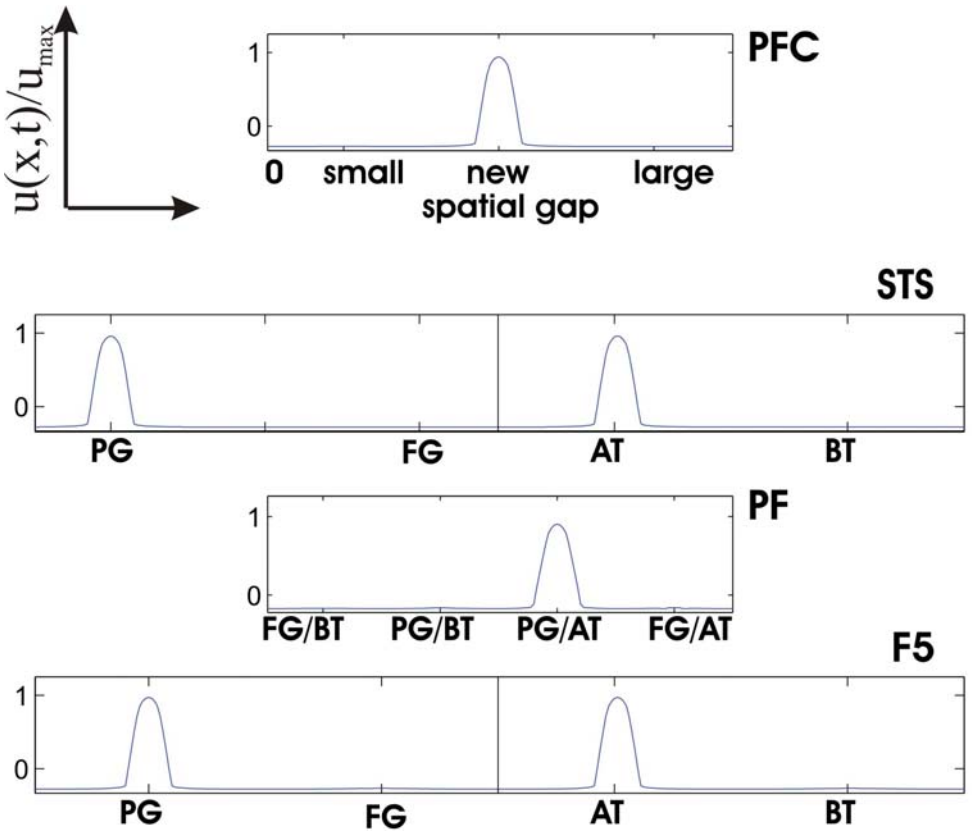
Experimental conditions:

- Long exposure to actions made with tools.
- Tool can be associated by the monkey to the possibility to receive food.

Learning the link between goal and means
(PFC-PF)

Copying the organizational structure of actions

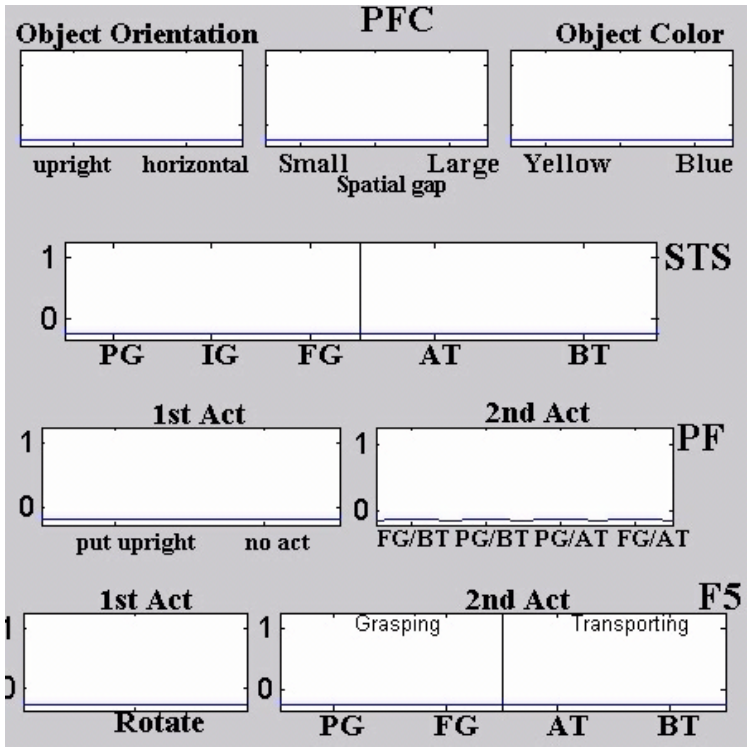
- New goal parametrized by an intermediate gap.
- Trying to copy the demonstrator's means (covert planning).
- If sucessful, association is learned between PFC and PF.

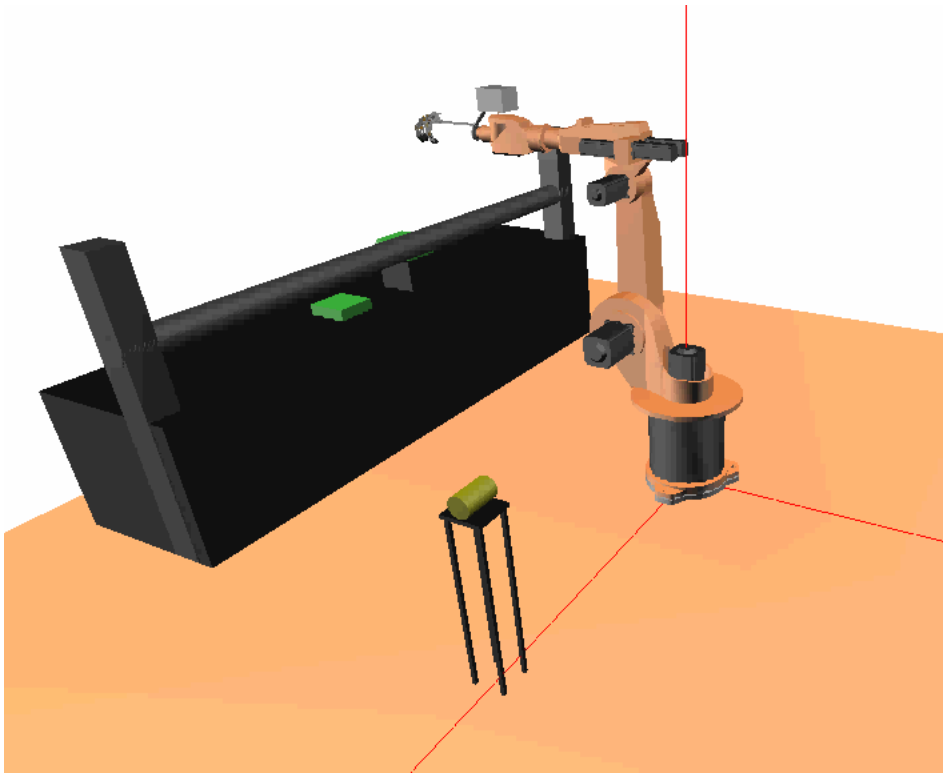


Learning of a new action sequence

Example: object not in upright position

After learning (no teacher)





Conclusions

Experimental and modelling results suggest that

- *action understanding* is a continuous process which combines sensory evidence, prior task knowledge and a goal-directed matching,

- a *goal-directed matching* between action observation and action execution may develop during practice using a *biologically plausible learning rule*.

The model architecture may be extended to allow also for inferring higher intentional goals.

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