



Neuro-IT Workshop

Bonn, 22 June 2004

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FET Bio-I3 Initiative

Bio-inspiration

Why and When is it useful?

It is not sufficient to be bio-inspired.

We should answer to the following questions:

- 1) What could be the potential **advantages** of bio-inspiration, but also what are the **disadvantages** (constraints on the modeling, etc)?
- 2) At **what level of details** can bio-inspiration be successfully implemented?
- 3) Can engineering contribute something back to Biology?



Engineering vs Biology

Engineering solutions are often more efficient.

When is bio-inspiration useful?

Motor Learning



C. Atkeson & S. Schaal, CMU & USC

Excellent engineering approach
General – Reusable in other tasks

Motor Learning

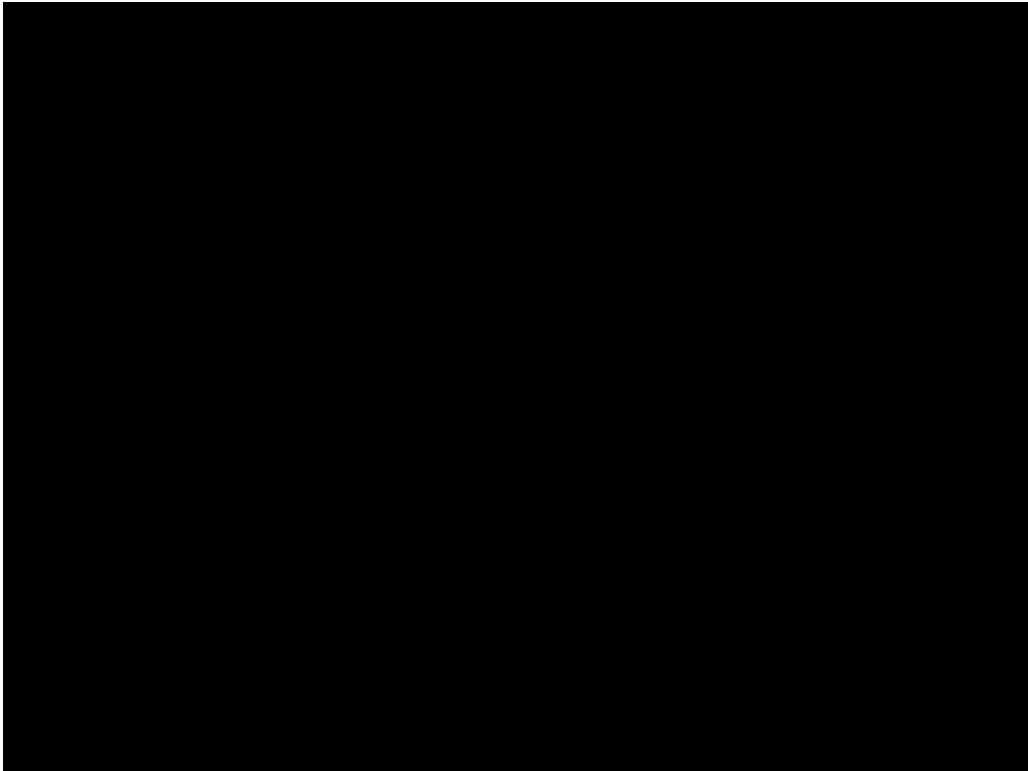


D. Bentevegna, ATR International, Kyoto

The robot achieves rapidly better performance than the human

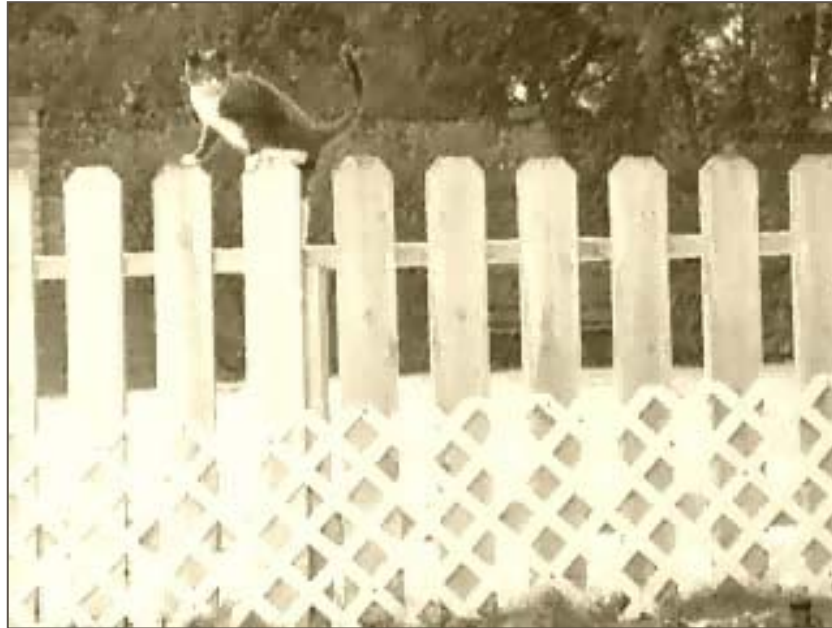
Motor Control – Locomotion

What is missing from state-of-the-art walking machines?



RoboCup 2001, Seattle, USA.

Motor Control – Locomotion



- **Equilibrium**
How is control of balance performed?
- **Robustness to perturbation**
What system is capable to deal with irregular terrains?

Motor Control – Locomotion



➤ Gait generation and transition

How to swap across CPGs?

How to change rapidly speed and direction?

Usefulness of Bio-Inspiration

What is missing from state-of-the-art systems for motor control and motor learning?

- Smooth transition across motor programs

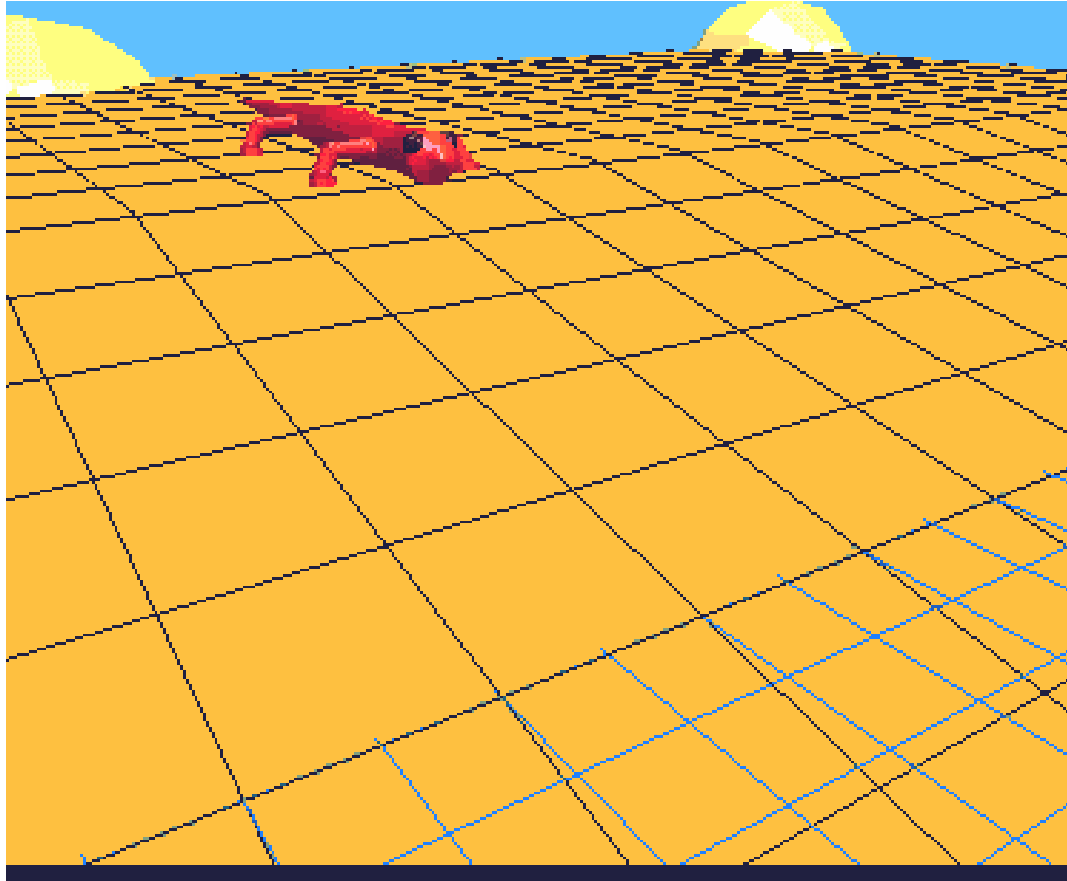
How does Biology solve the problem?

- Transition across CPGs. Network Selection.

How is it implemented?

- Overlap across neural networks?
- Consecutive activation of neural controllers?
- Higher controller?

Motor Control – Locomotion



Auke Jan Ijspeert, EPFL <http://birg.epfl.ch>

Example of work studying the neural mechanisms underlying the smooth transition across motor programs

Usefulness of Bio-Inspiration

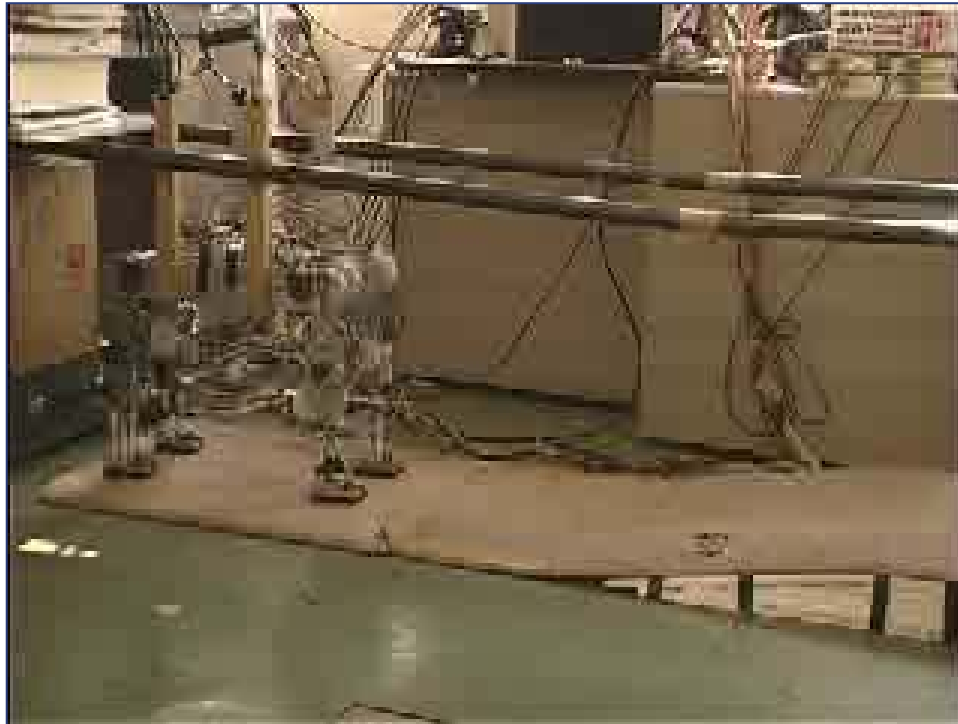
What is missing from state-of-the-art systems for motor control and motor learning?

- Robustness in the face of perturbation

How does Biology solve the problem?

- Neural controller generic and flexible
- Adaptation of neural controllers to incorporate new knowledge

Motor Control – Locomotion



Hiroshi Kimura, National Univ of Electro-Communication, Tokyo,

Example of work studying neural controllers robust to perturbations

Engineering versus biological solutions

- Bio-inspiration is no use when the task cannot be performed by biological systems (flying to the moon!)
- Bio-inspiration should not constrain us to reproduce exactly the same capabilities / limitations (laser, arrays of microphones)
- Engineering solutions are performing better when the environment can be modeled entirely
- Biological solutions are more robust in the face of highly variable and dynamic environments

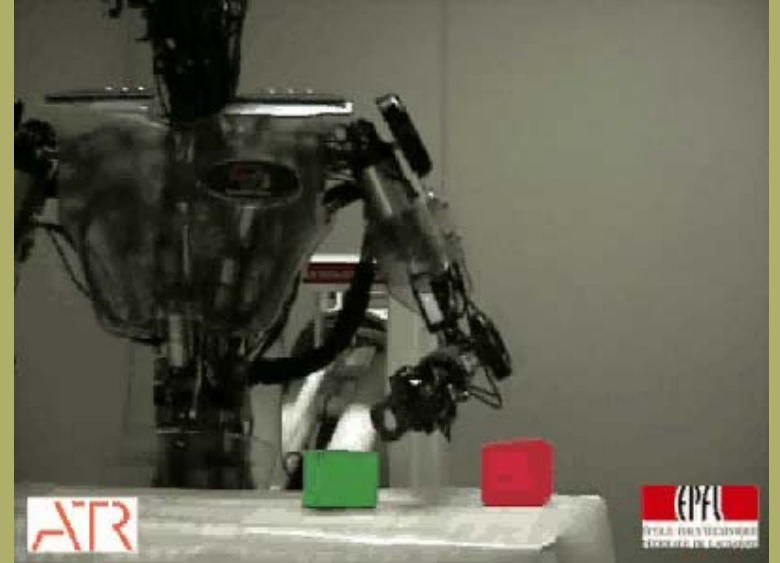
Imitation Learning

An Example of a Research Area in which
Engineering and Biology seek similar answers

Demonstration (human)



Reproduction (robot)



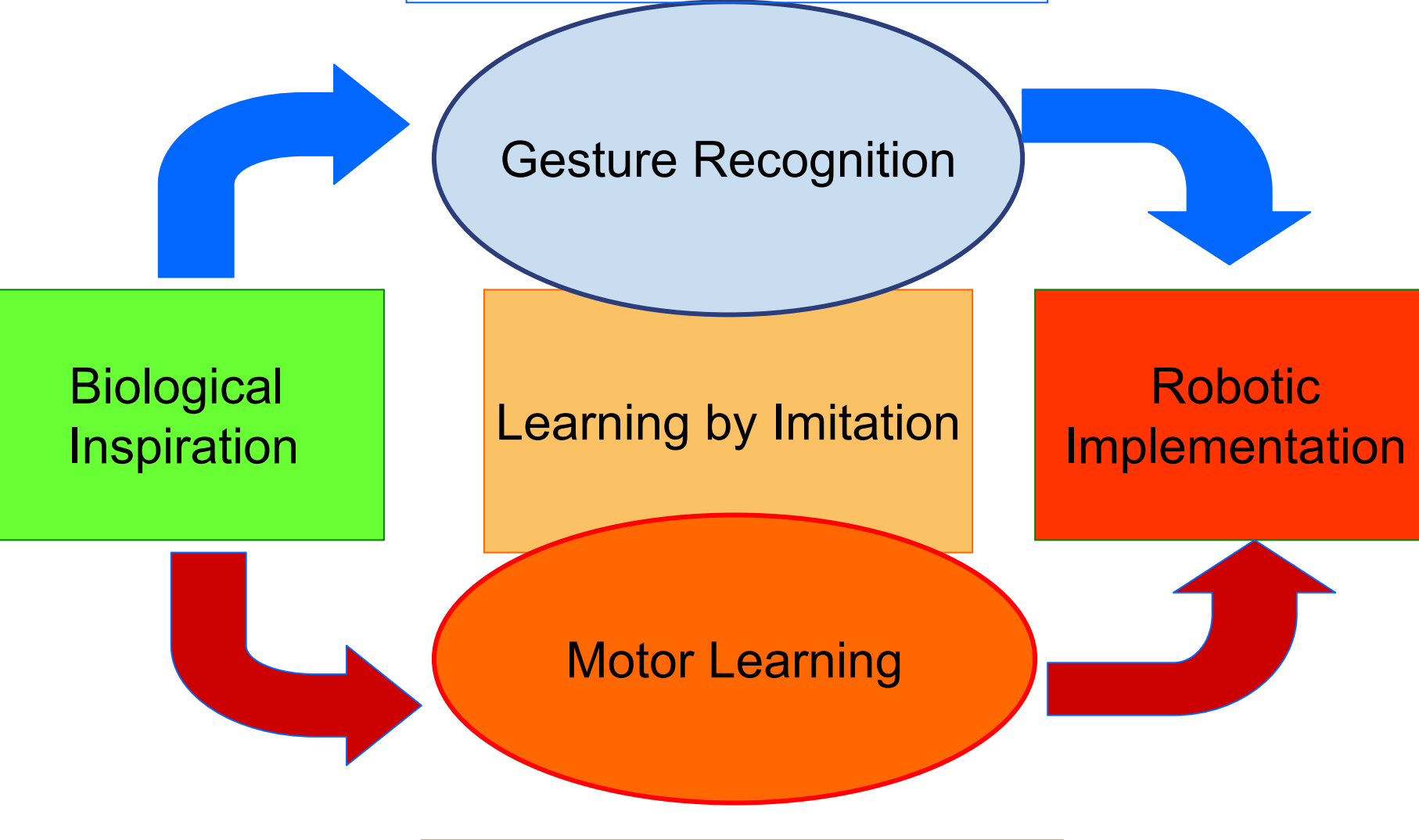
observation

learning

retrieval

Motor command

What to Imitate?



How to Imitate?

Imitation Learning

Developmental Stages of Imitation

- Innate Facial Imitation (newborns → 3 months)
- Delayed imitation 9-12 months
- Imitation of sequences of gestures (18 months)



Biological
Inspiration

- Piaget, *Play, Dreams and Imitation in Infancy*, 1962
- Meltzoff & Moore, *Developmental Psychology*, 1989
- Nadel et al, *Cambridge Univ Press*, 1999

Cognitive Abilities and Neural Correlates

- Imitation is hierarchical and goal-directed
- Mirror Neuron System – locus of visuo-motor transformation (STS, PM, Broca)



Biological
Inspiration

- Bekkering, Wolschlagel & Prinz, *Psychologia* 2000
- Rizzolatti et al, *Cog. Brain Res.*, 1996
- Iacoboni et al, *Science* 1999
- Decety et al, *Neuroimage*, 2002

Imitation Learning

Imitation Capabilities in Animals

- Copying and Mimicry: Rats, Monkeys
- Vocal Imitation: Dolphins, Parrots



- Moore, *Behaviour*, 1999.
- Heyes, *Trends in Cog. Sciences*, 2001

Biological
Inspiration

Imitation Learning

Imitation Capabilities in Animals

- “True” imitation: Ability to learn new actions not part of the usual repertoire
- The appanage of humans only, and possibly great apes

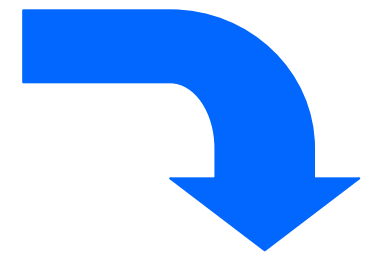
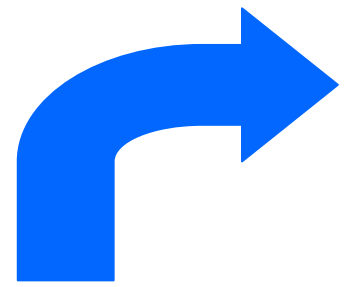
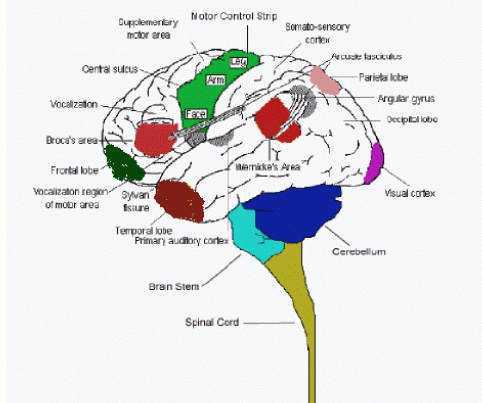


- Whiten & Ham, *Advances in the Study of Behaviour*, 1992
- Savage & Rumbaugh, *Child Devel*, 1993

Biological
Inspiration

Neural Modeling

What brain mechanisms?

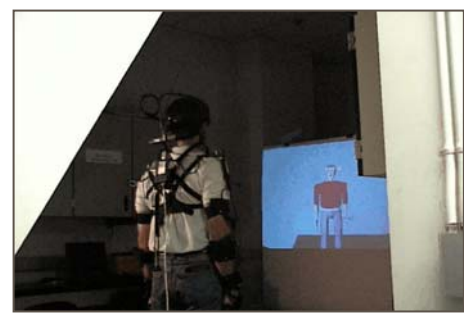


Motion Studies

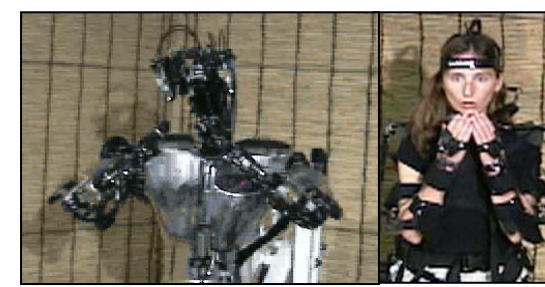
How do humans imitate?

Robotics

What controllers?

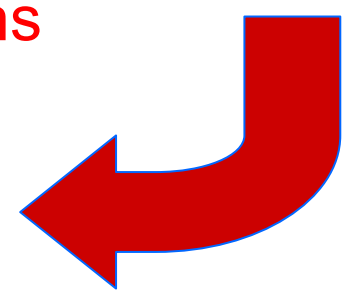
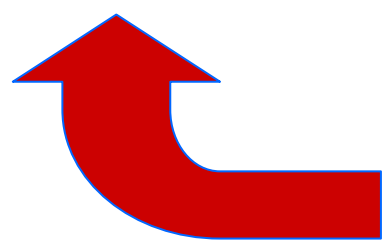


Learning by Imitation



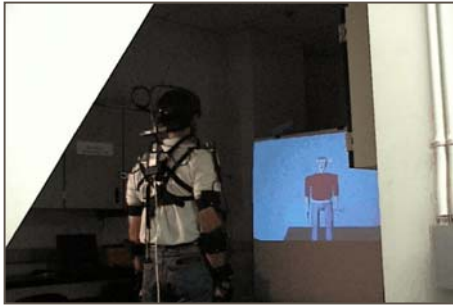
Human-Robot Interactions

Applications?



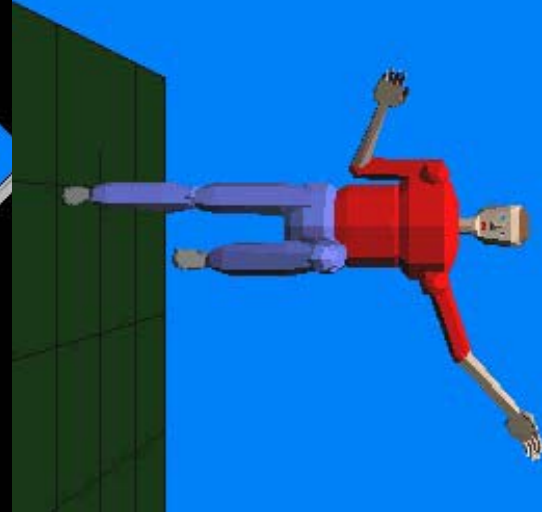
Motion Studies

How do humans imitate?



Learning by Imitation

Motion studies on human imitation



Variables manipulated:

Imitation type: ipsilateral/crosslateral

Handedness: Left and right handers

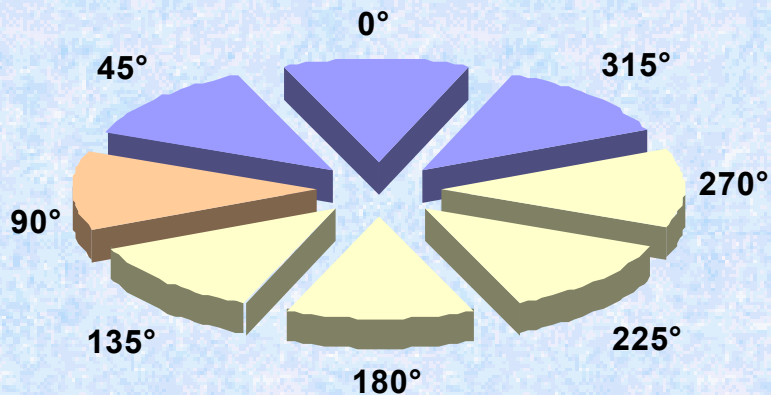
Limb choice: Left/right arm/leg

Rotation of the display: 0, 45, ..., 315

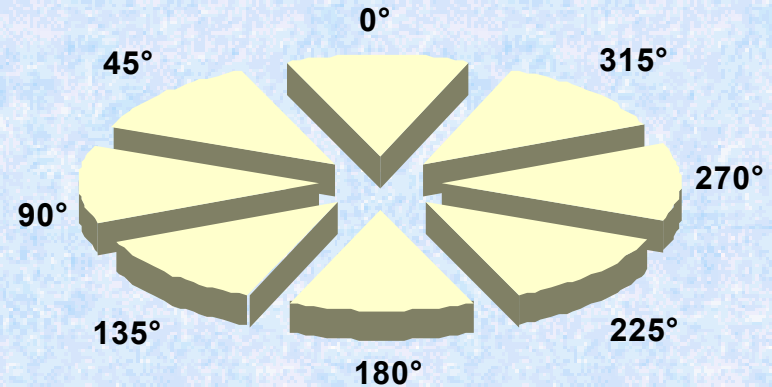
Orientation of the body: facing forward or away




Motion studies on human imitation

Right-Handed



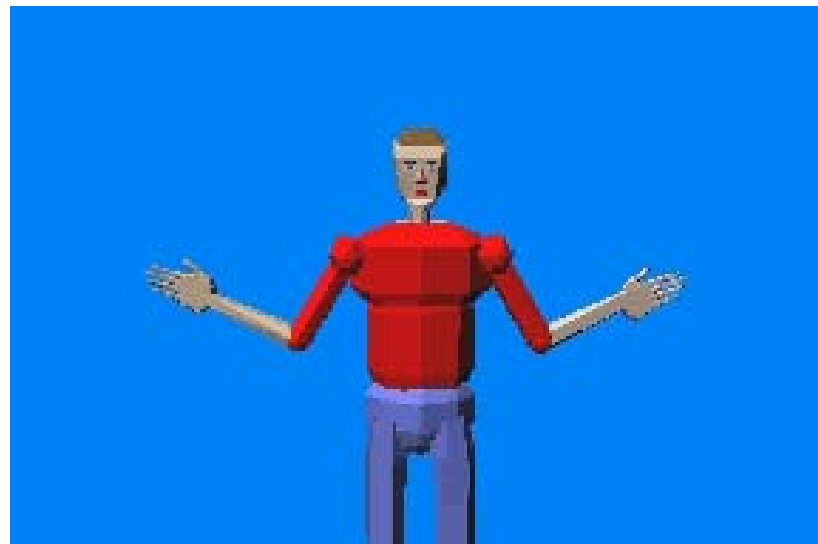
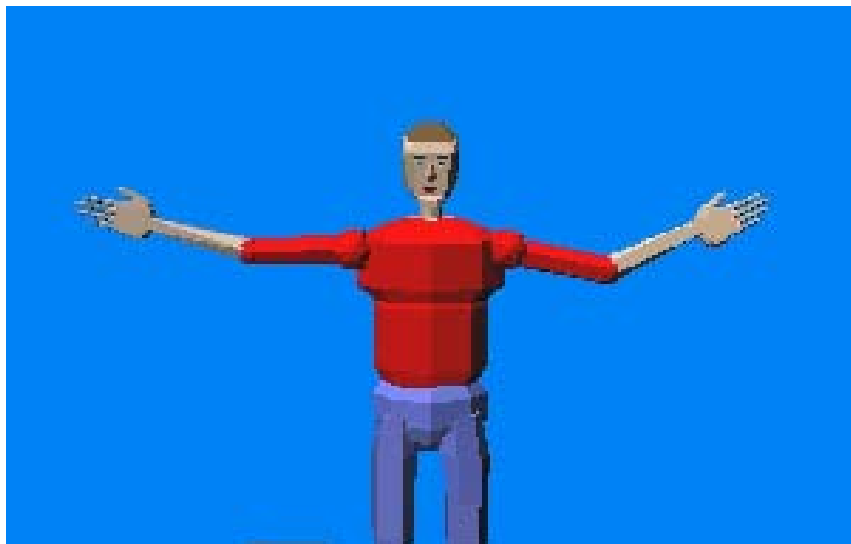
Left-Handed



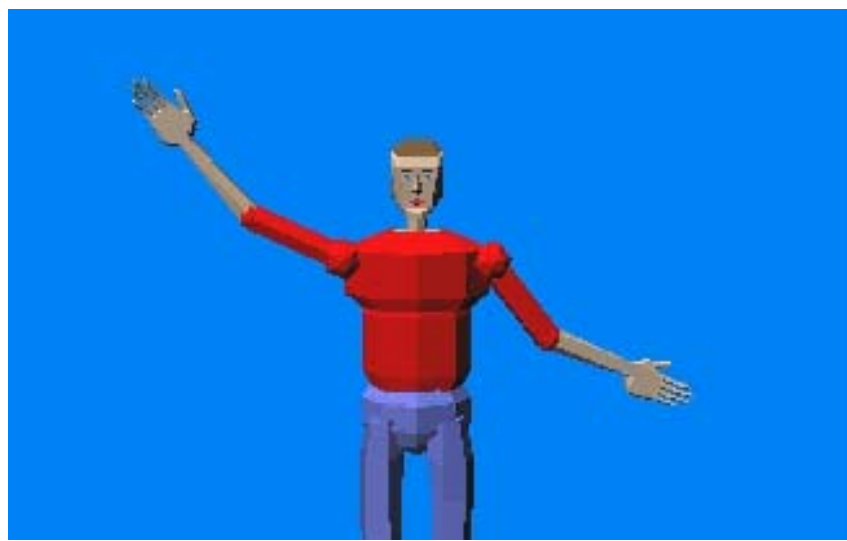
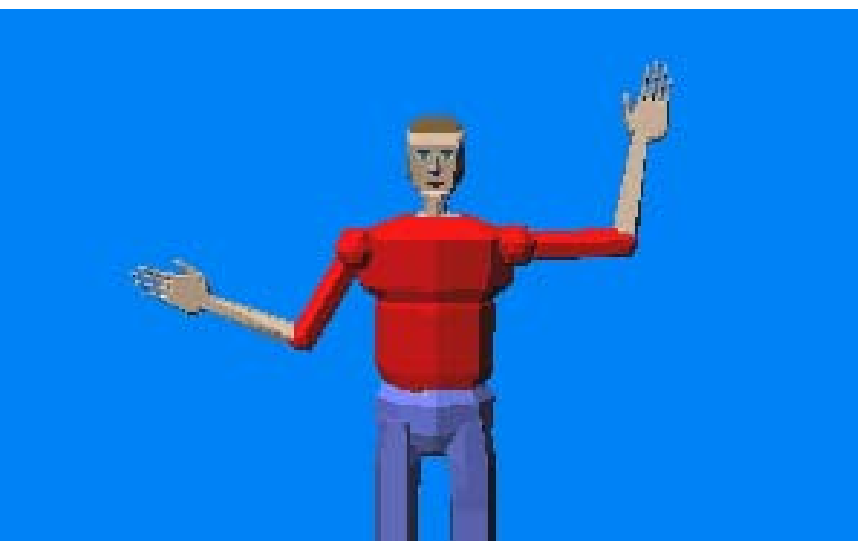
 Preference for Identical
 Preference for Mirror
 No preference

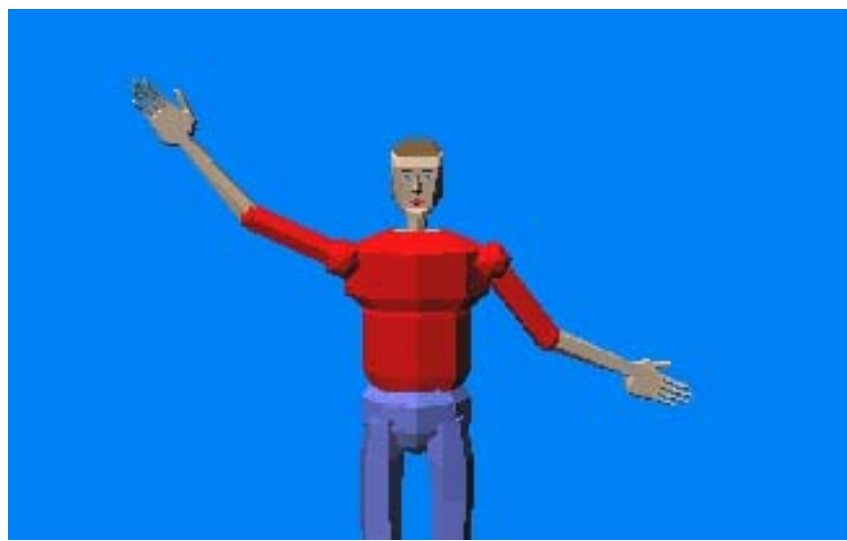
- Left and right-handed apply different imitation strategies
- Right-handed strategy is affected by the number of transformations of frame of reference

COORDINATED PATTERNS OF ARM MOVEMENTS

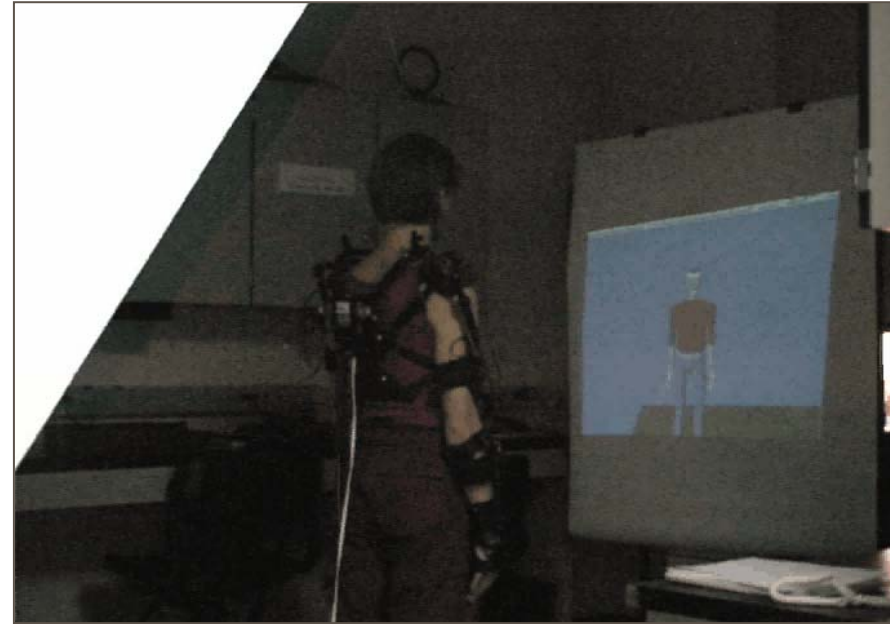
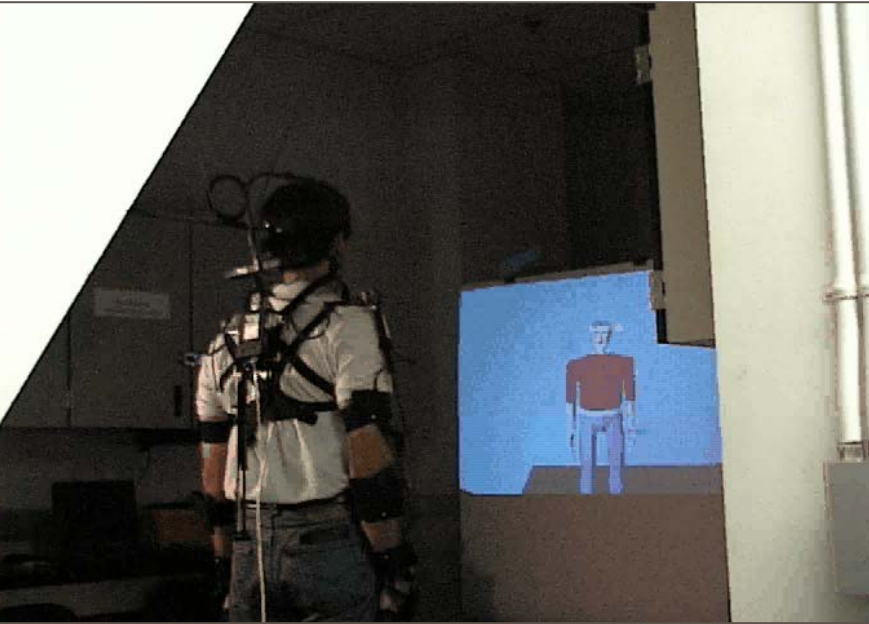








IMITATION OF COORDINATED PATTERN OF ARM MOTION

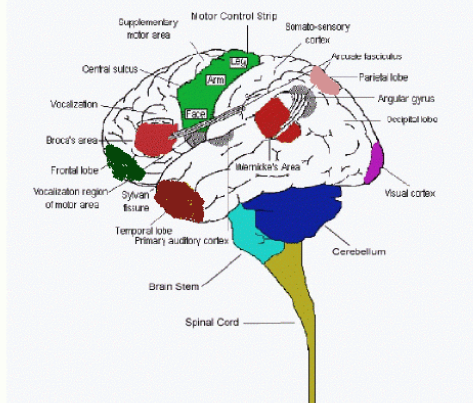
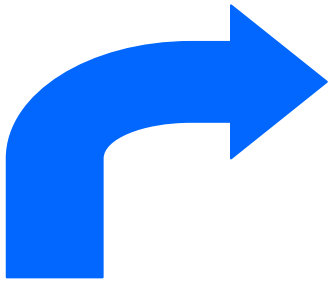


RESULTS and HYPOTHESES

Motions in anti-phase are more difficult to reproduce and to recognize because they result from correlated neural mechanisms leading to bimanual coordination

Neural Modeling

What brain mechanisms?



Motion Studies
How do humans imitate?



Learning by Imitation

Pre-Motor Cortex / Broca's area:
Visuo-motor transformation / Mirror Neurons

Motor Cortex
Somatotopic control

SMA:
Sequence learning

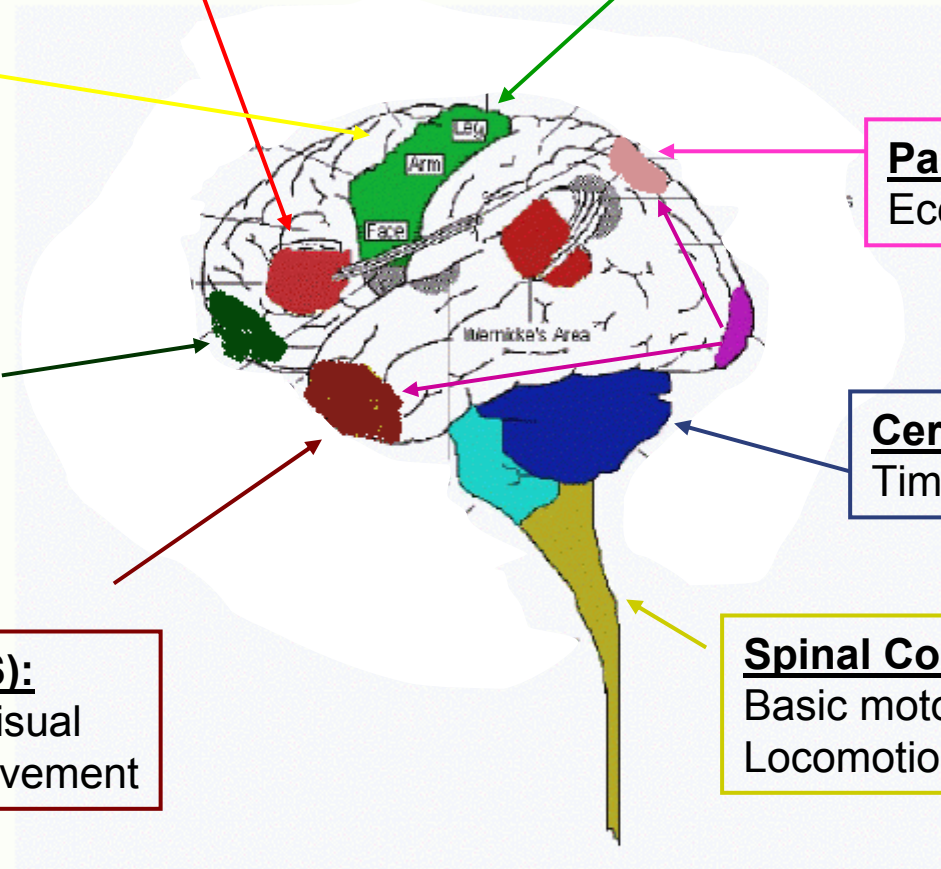
Parietal Lobe:
Eccentric visual coding

Frontal Lobe:
Decision Center
Inhibition of motion

Cerebellum:
Timing, Sequencing

Temporal Lobe (STS):
Eccentric – Intrinsic visual
Representation of movement

Spinal Cord + Brain Stem:
Basic motor patterns, CPG
Locomotion, Reflexes



High-Level representation of the brain mechanisms underlying imitation
Functional and abstract model of the brain areas and their connection

Pre-Motor Cortex:
Visuo-motor transform

Motor Cortex
Somatotopic control

SMA:
Sequence learning

Frontal Lobe:
Decision Center
Inhibition of motion

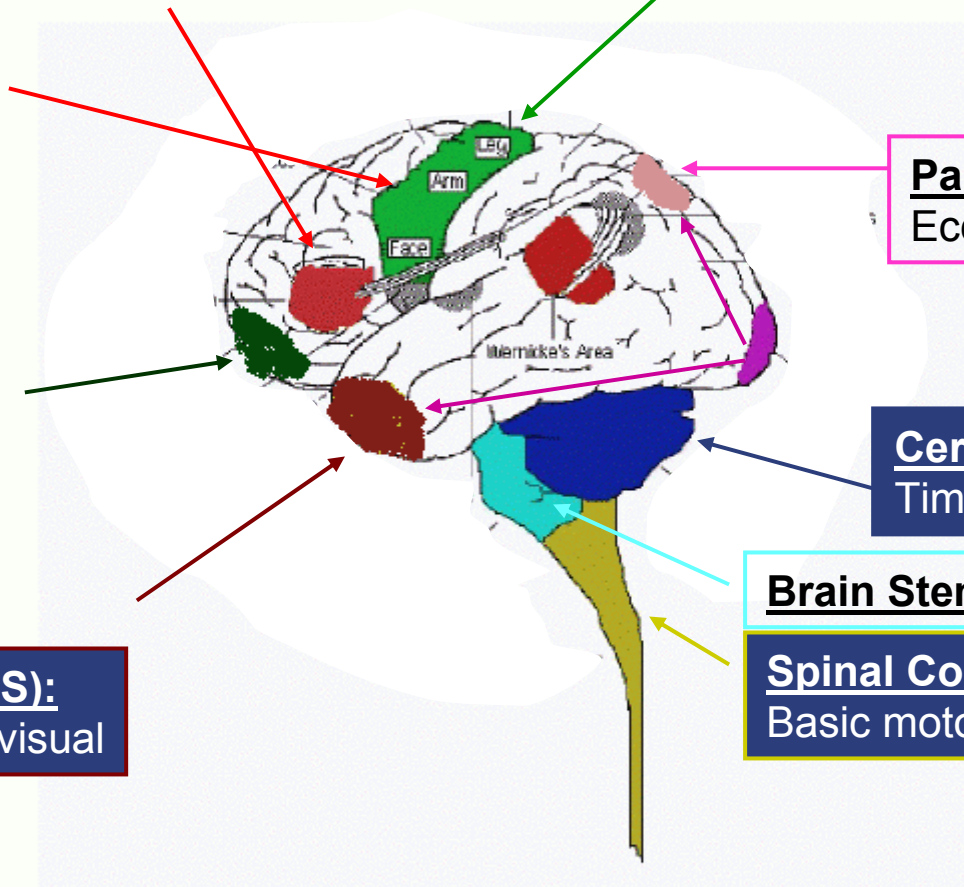
Temporal Lobe (STS):
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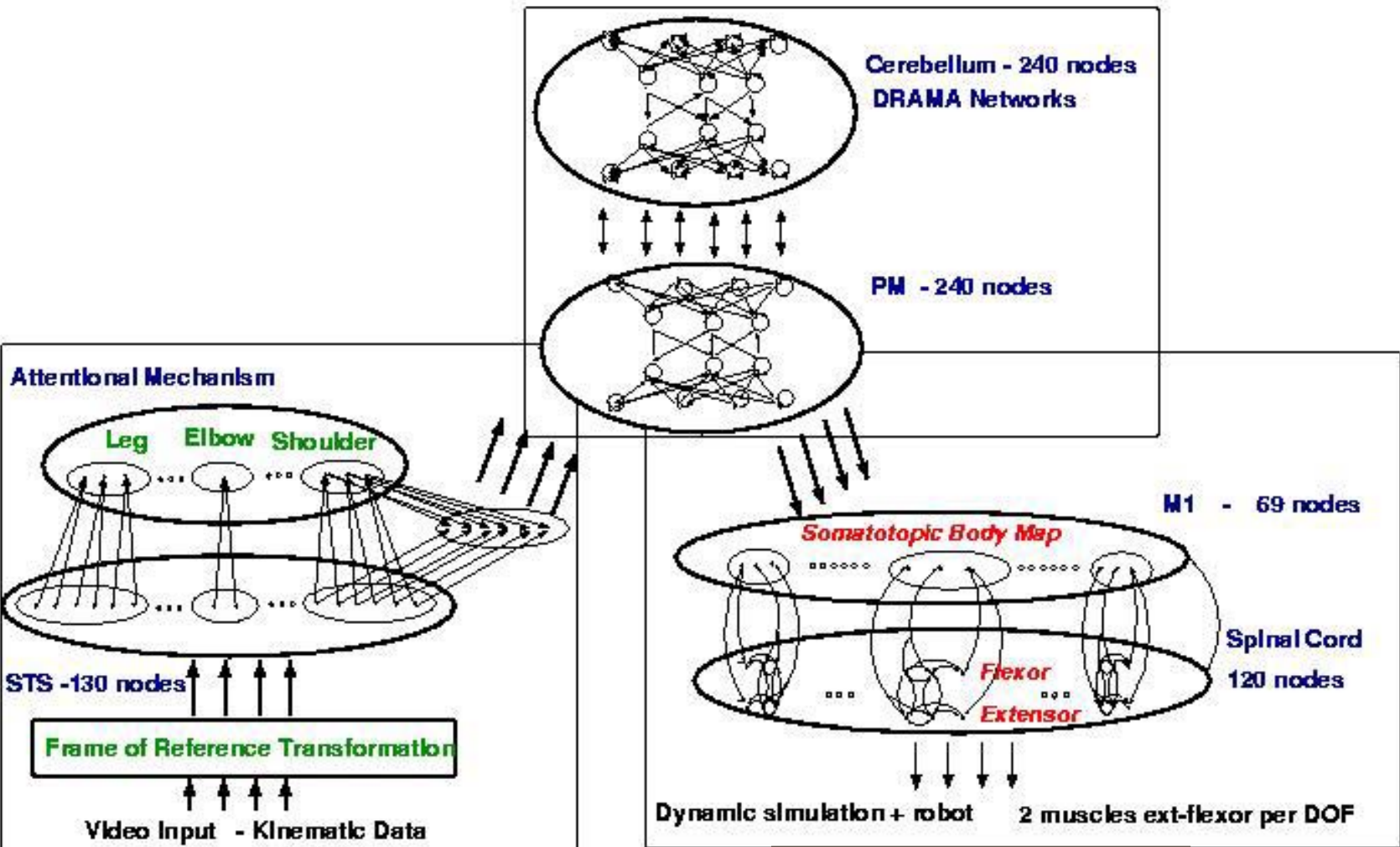
Brain Stem

Spinal Cord
Basic motor patterns, CPG



High-Level representation of the brain mechanisms underlying imitation
Functional and abstract model of the brain areas and their connection

Computational Model of Imitation Learning



Basic Neural Mechanism of Imitation

3-D Frames of Reference Transformations using Gain Modulated Populations of Neurons

When performing visually-guided movements, the brain faces the task of transferring information across different **frames of reference**.

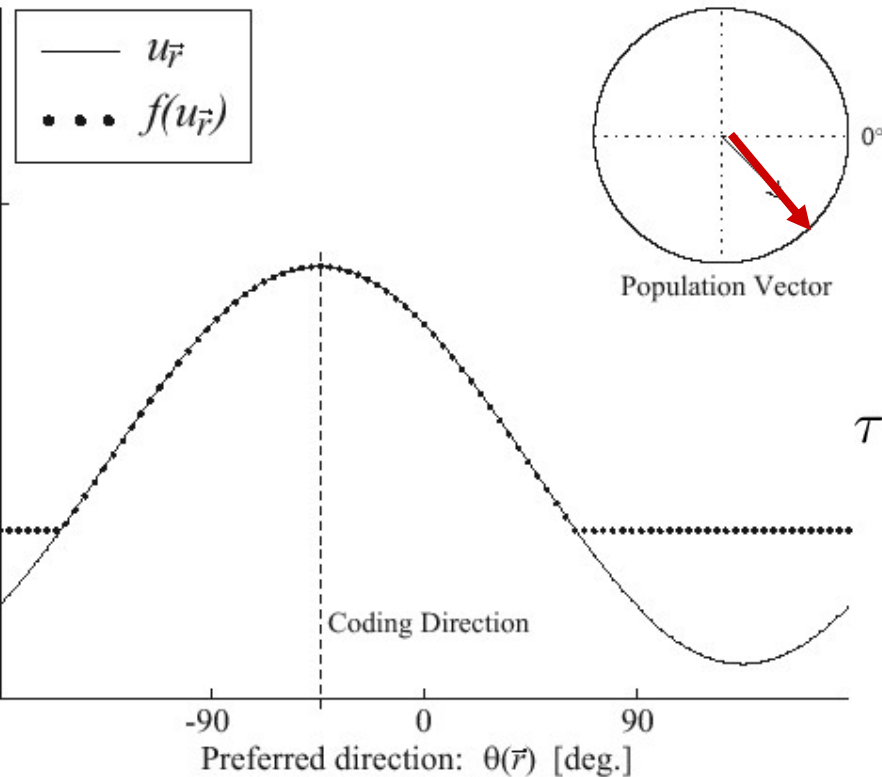
How does the brain compute these FR transformations?

Population vector coding appears to be a principle mechanism through which different neural populations share information, by integrating multi-modal information for distributed control across the whole body.

How can population vector coding be used as principle mechanism to accomplish FR transformation?

3-D Frames of Reference Transformations using Gain Modulated Populations of Neurons

Population Ω



Let Ω be a population of neurons with preferred direction r and uniformly distributed along a 3-D subspace

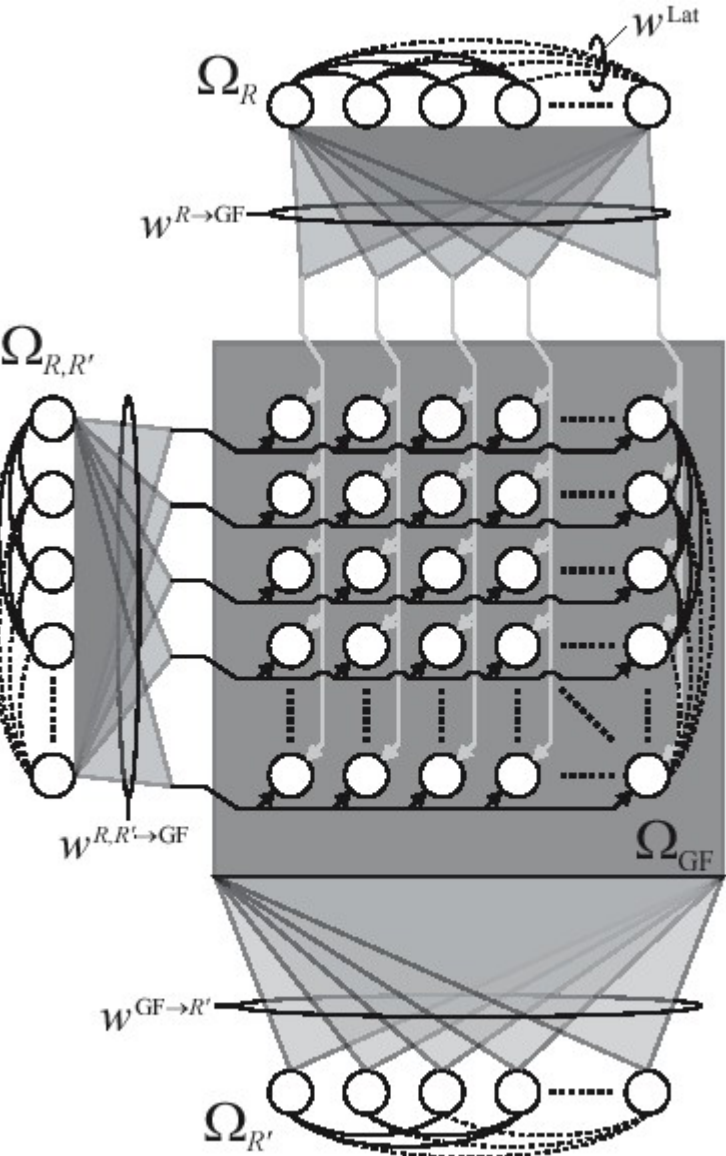
Each unit membrane potential is regulated by:

$$\tau \dot{u}_{\vec{r}} = -u_{\vec{r}} + \int_{\Gamma} w_{\vec{r}' \rightarrow \vec{r}}^{\text{Lat}} f(u_{\vec{r}'}) d\vec{r}' + x_{\vec{r}}$$

$$w_{\vec{r}' \rightarrow \vec{r}}^{\text{Lat}} = \gamma (\vec{r} \cdot \vec{r}')$$

\vec{r}_v is the population vector

$$u_{\vec{r}} = \alpha + \beta (\vec{r} \cdot \vec{r}_v)$$

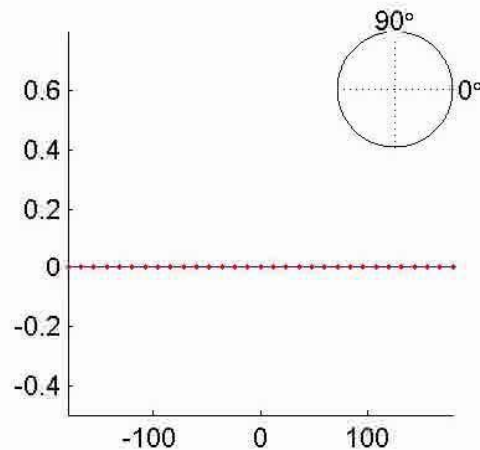
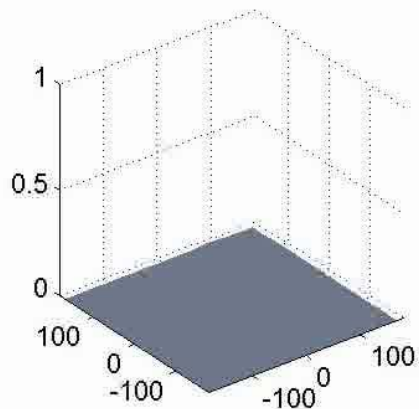
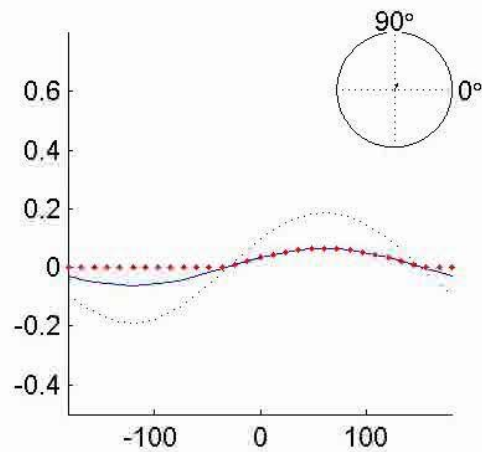
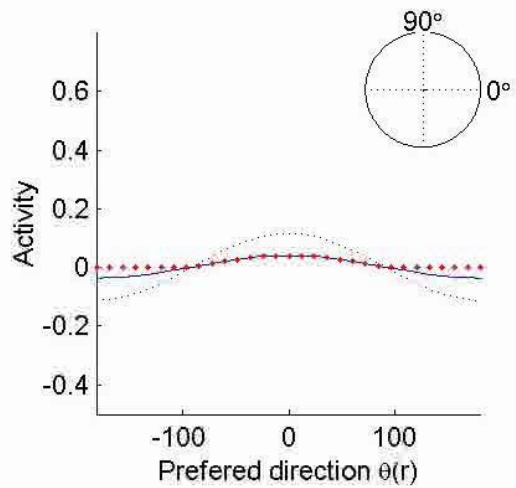


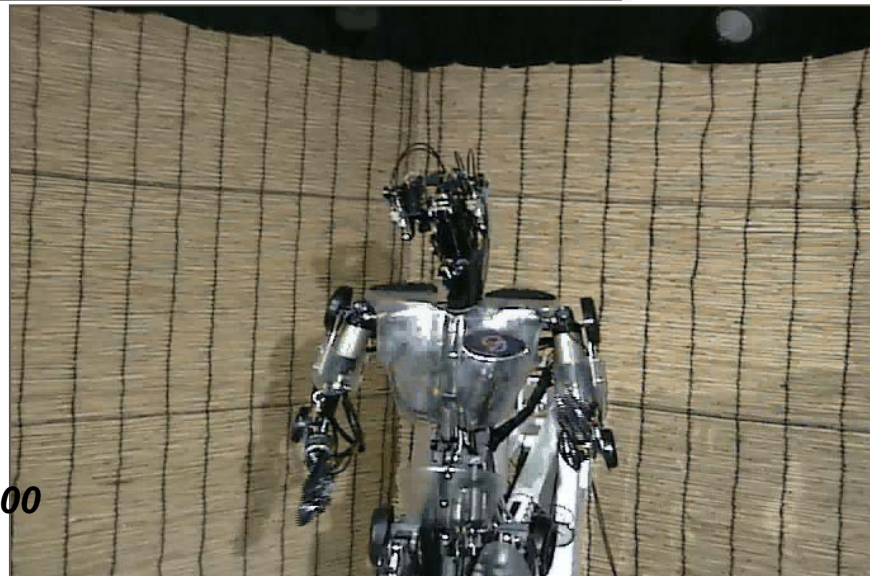
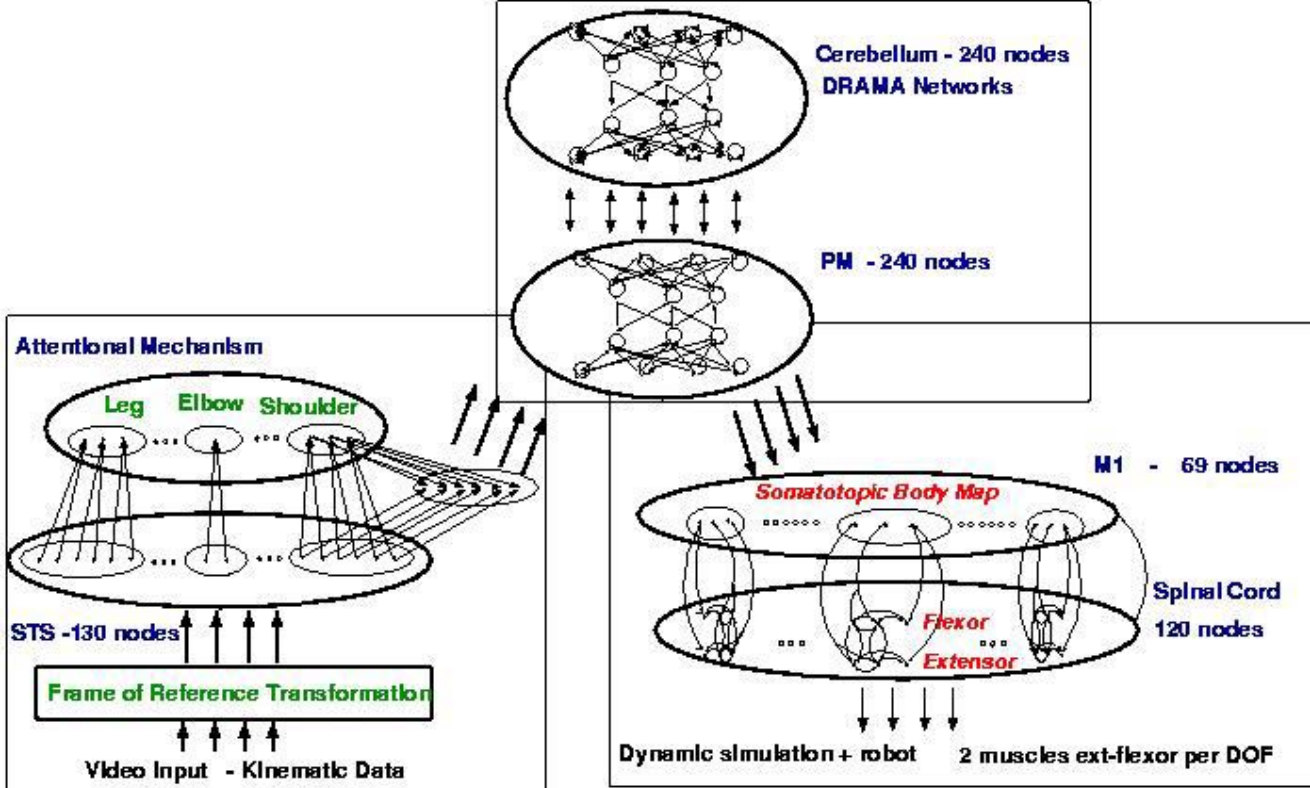
Construction of a network of population performing 2D rotations:

Let Ω_R , and $\Omega_{R'}$ the populations coding, respectively, for V in referential R and V' the projection of V in R' .

Let $\Omega_{R,R'}$ the populations coding for the vector V^T , s.t. $V' = V^T - V$

Let Ω_{GF} an intermediary population coding for the projection of V on V^T .

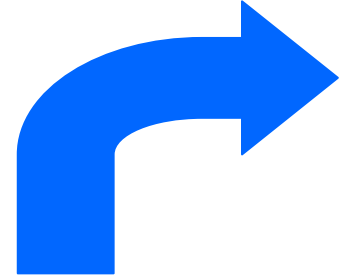




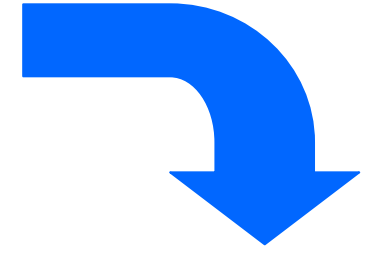
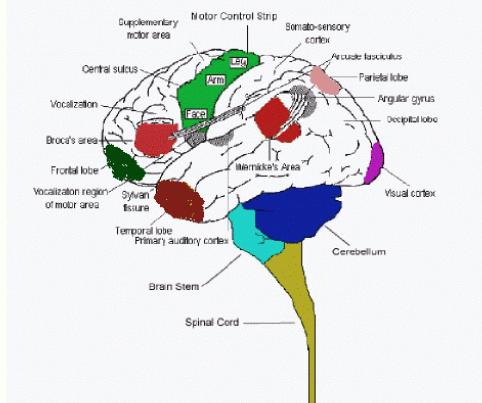
Arbib, Billard, Iacoboni, Oztop, *Neural Networks*, 2001
 Billard & Mataric, *Robotics & Autonomous Systems*, 2000
 Billard, *Cybernetics Systems*, 1999

Neural Modeling

What brain mechanisms?

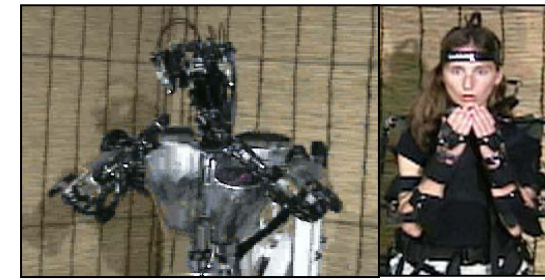
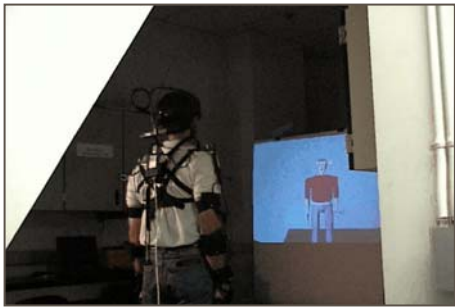


Motion Studies How do humans imitate?



Robotics What controllers?

Learning by Imitation



What should the robot imitate?

Which features of the demonstration are relevant?

What should it pay attention to?

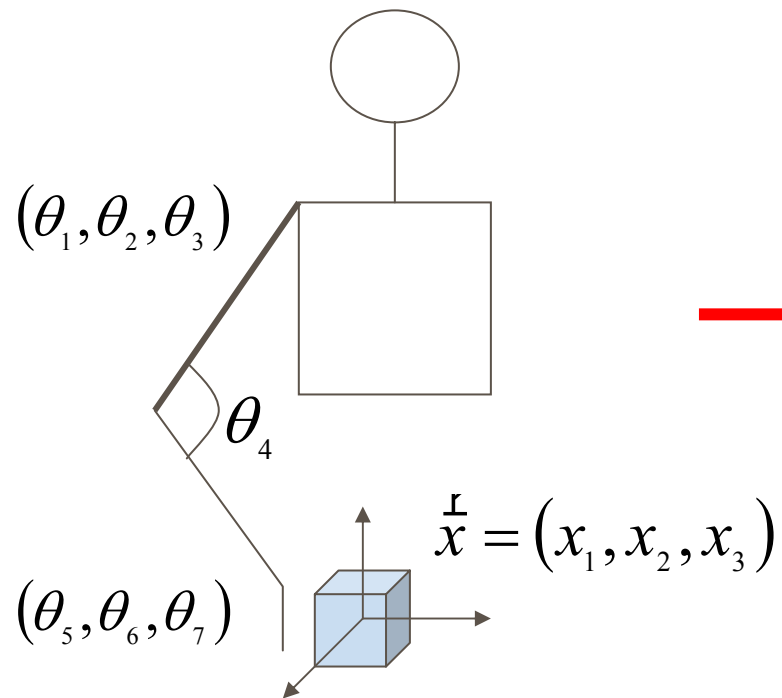
What are the task constraints?

Invariants are the relevant parts of the demonstration

→ To determine a metric of imitation performance

The transfer problem

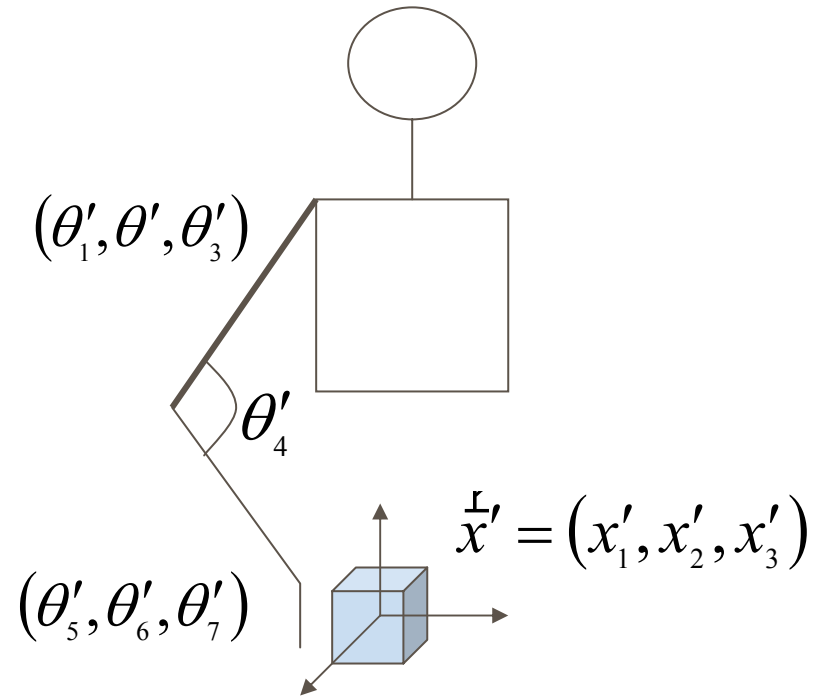
Demonstrator



forward kinematics $\mathbf{x} = f(\dot{\theta})$



Imitator



$\mathbf{x}' = f'(\dot{\theta}')$

Constraints specified by imitation

$$\overset{\perp}{x} = \overset{\perp}{x}'$$

Same Object, same target location

$$\overset{\perp}{d} = \overset{\perp}{d}'$$

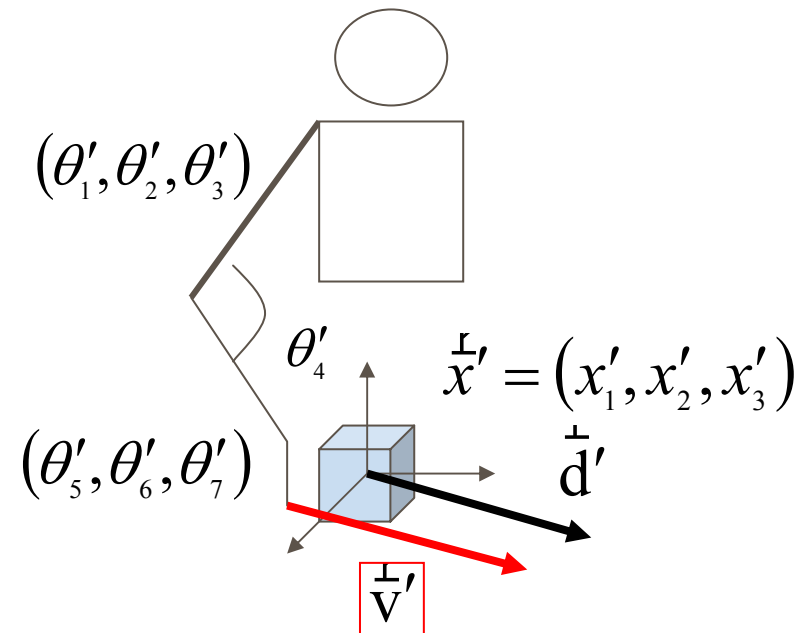
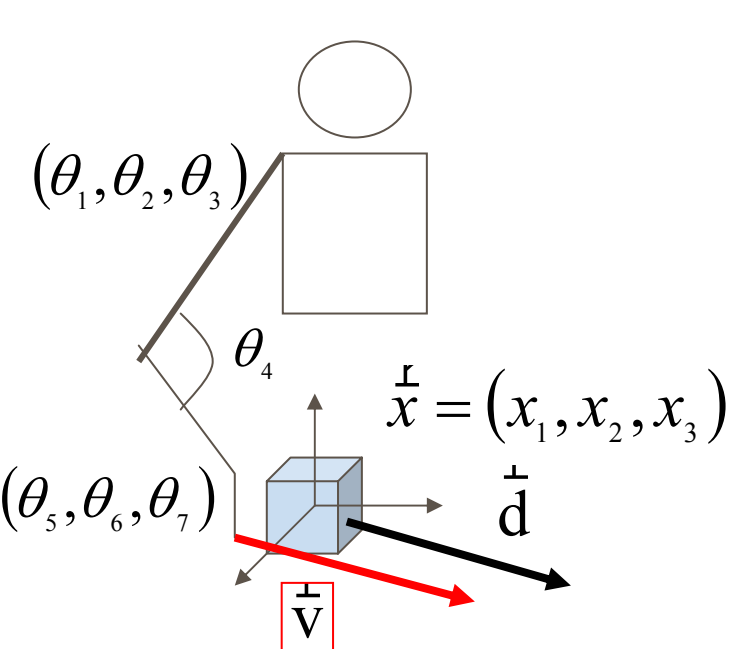
Same direction of motion

$$\overset{\perp}{v} = \overset{\perp}{v}'$$

Same speed, same force

$$\overset{\perp}{\theta} = \overset{\perp}{\theta}'$$

Same posture

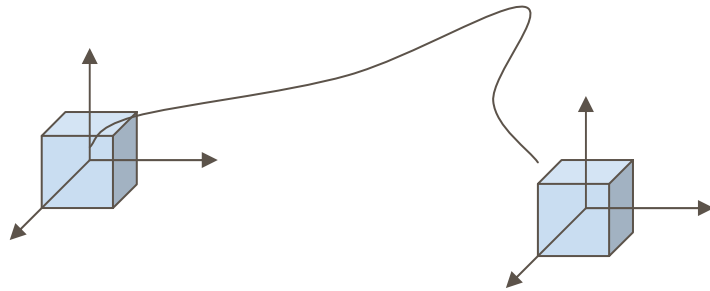


The transfer problem

Trajectory imitation

Demonstration

$$\dot{\theta} = f^{-1}(\dot{x})$$

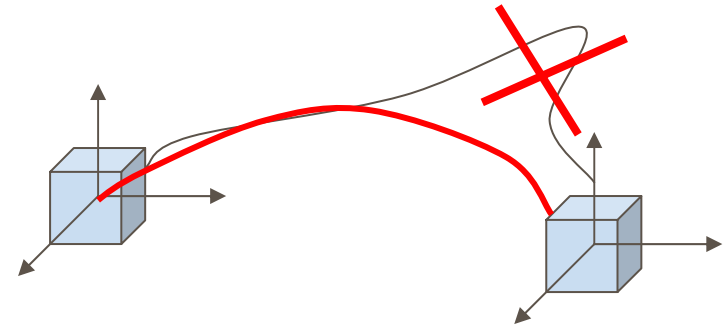


?

→

Imitation

$$\dot{\theta}' = f'^{-1}(\dot{x}')$$



No solutions (smaller range of motion)

$$\dot{\theta} \neq \dot{\theta}' \Rightarrow \dot{x} \neq \dot{x}'$$

→ Find the closest solution according to a metric

Tracking the direction of motion of the hand

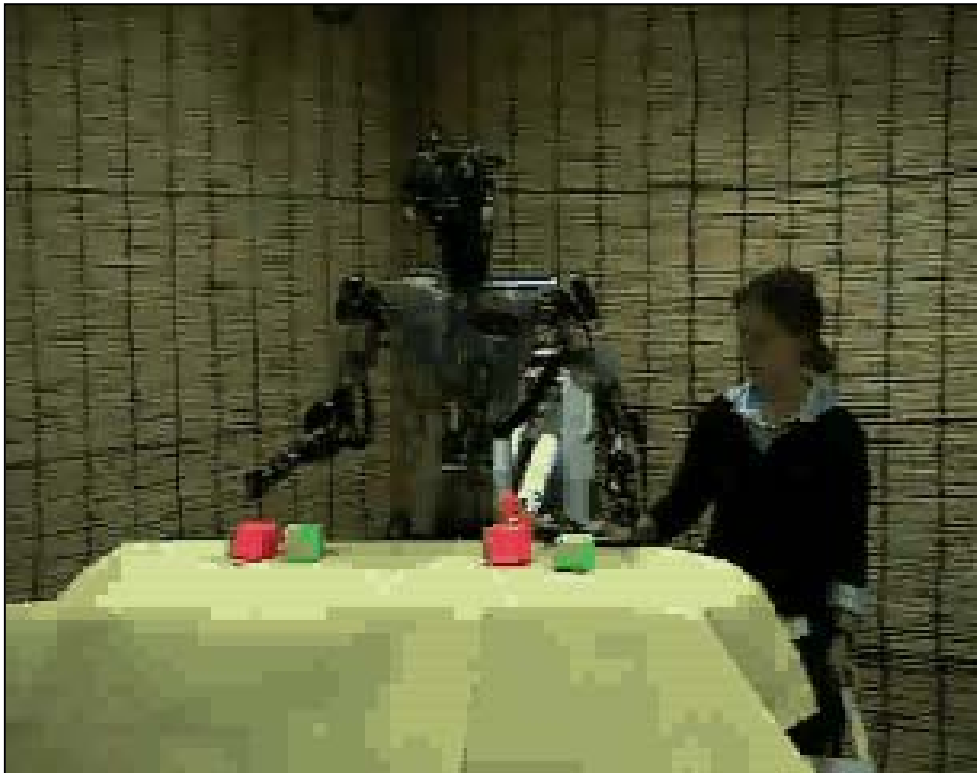
$$\text{Data Set : } D(U) = \{\dot{\bar{X}}, \dot{\bar{X}}_o\}$$

$$\text{Constraint : } \dot{\bar{X}}'_o = \dot{\bar{X}}_o \quad \& \quad \dot{\bar{X}}' = \dot{\bar{X}}$$

Cost function :

$$J = J_1(\overset{r}{x}, \overset{r}{x}') + J_2(\overset{r}{x}, \overset{r}{x}_o, \overset{r}{x}_o')$$

$$J_2(\overset{r}{x}, \overset{r}{x}_o, \overset{r}{x}_o') = \sum_i (x^{i_o'} - x^i - x^{i_o})^2$$



Controller :

Calculate distance from hand to object : $(X - X_o)$

Define the target point : $X_T = X'_o - X - X_o$

Go to that point (Inv. Kinematics) : $\Theta' = f^{-1}(X'_T)$

Imitation Level 2 – second strategy:

Follows the speed of motion of the arm

$$\text{Data Set : } D(U) = \{ \overset{\perp}{X}, \overset{\perp}{X}_o \}$$

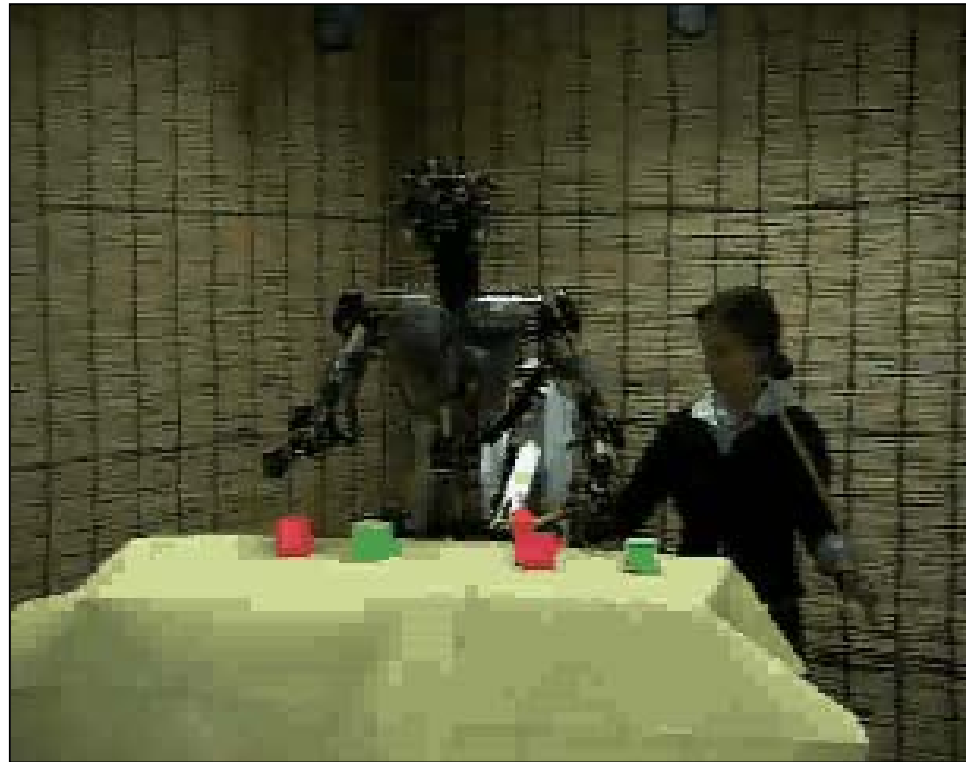
$$\text{Constraint : } \overset{\perp}{X}'_o = \overset{\perp}{X}_o \quad \& \quad \overset{\perp}{X}' = \overset{\perp}{X}$$

$$\& \quad \overset{\perp}{X}'_{\'} = \overset{\perp}{X}_{\'}$$

Cost Function :

$$J = J_1 \left(\overset{\perp}{x}_o, \overset{\perp}{x}'_o \right) + J_2 \left(\overset{\perp}{x}, \overset{\perp}{x}' \right) + J_3 \left(\overset{\perp}{\'}, \overset{\perp}{\'}' \right)$$

$$J_3 \left(\overset{\perp}{\'}, \overset{\perp}{\'}' \right) = \overset{\perp}{\'} - \overset{\perp}{\'}'$$



Controller :

Calculate distance from hand to object : $(X - X_o)$

Define the target point : $X_T = X'_o - X - X_o \quad \& \quad \overset{\perp}{X}_T = \overset{\perp}{X}$

Go to that point (Inv. Kinematics) : $\Theta' = f^{-1}(X'_T, \overset{\perp}{X}'_T)$

Recognition & Reproduction of Angular Trajectories of the Arm using HMMs

Sylvain Calinon & Aude Billard,
Swiss Federal Institute of Technology Lausanne,
Autonomous Systems Lab,
ASL3-EPFL (<http://asl.epfl.ch>)

in collaboration with:

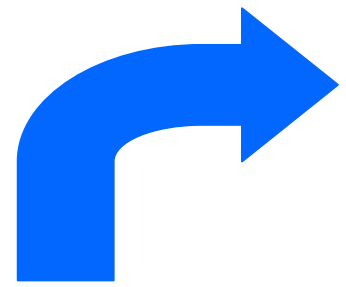
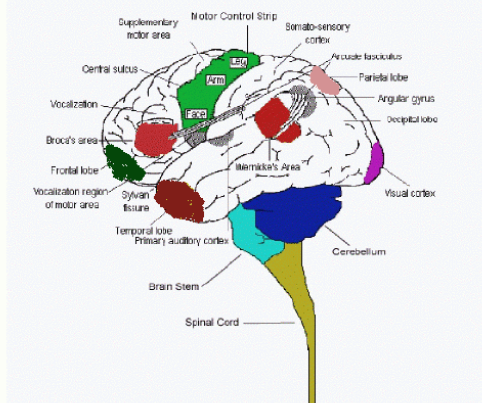
Gordon Cheng, Mitsuo Kawato
Advanced Telecommunication Research Institute,
HRCN-ATR (<http://www.cns.atr.co.jp>)

Stefan Schaal,
University of Southern California,
CLMC-USC (<http://www-clmc.usc.edu>)



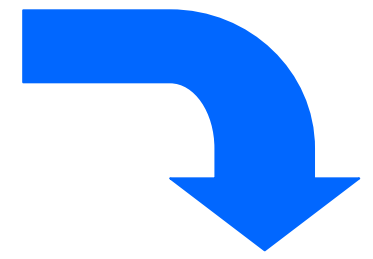
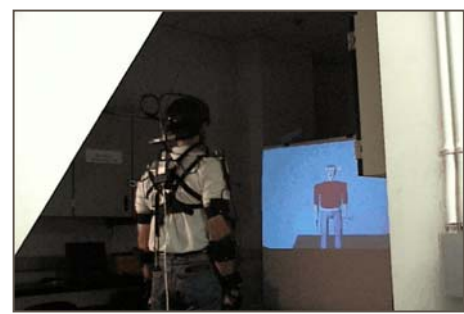
Neural Modeling

What brain mechanisms?



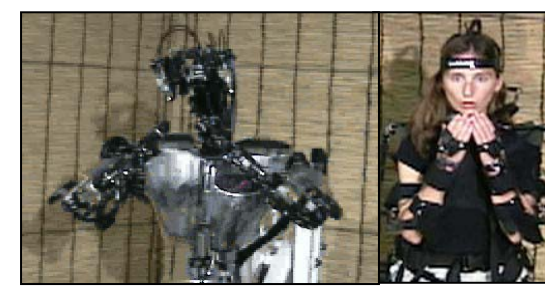
Motion Studies

How do humans imitate?



Robotics

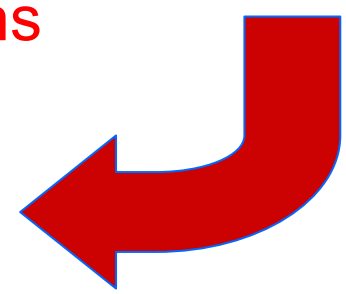
What controllers?



Learning by Imitation

Human-Robot Interactions

Applications?



Robota *Clever Toy and Educational Toy*



An application of Imitation Learning in Educational and
Therapeutic Set-Ups

ROBOTA Project



**Imitation Game
using vision**

**Sylvain Calinon, Aude Billard, ASL3
Swiss Institute of Technology Lausanne**

ROBOTA:

A tool to test the imitation capabilities of autistic children

**In collaboration with
Kerstin Dautenhahn, University of Hertfordshire
Jaqueline Nadel, Hopital de la Salpetriere, Paris, France**



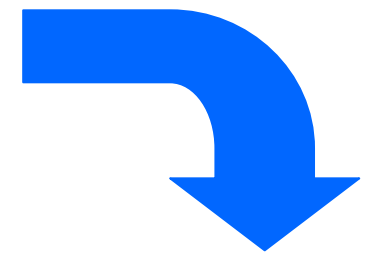
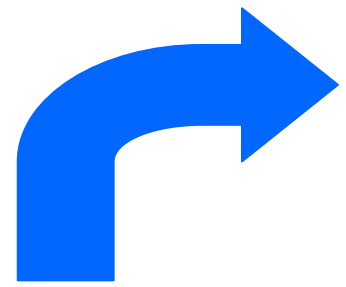
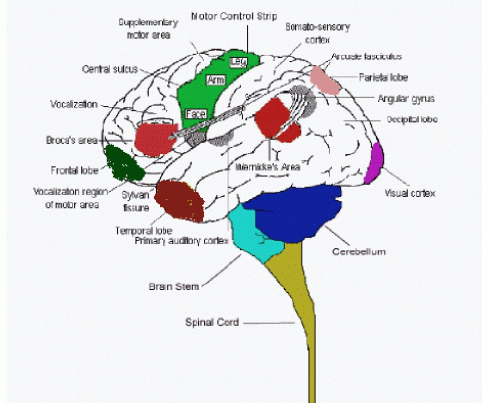
The educator demonstrates
The imitation game



The autistic child is let free to
play with the robot

Neural Modeling

What brain mechanisms?

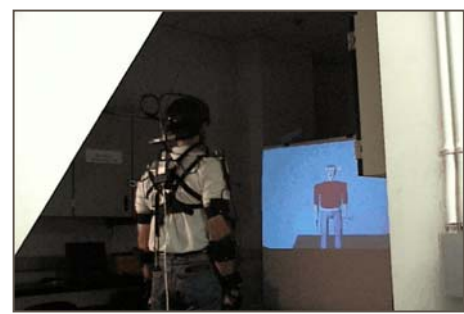


Motion Studies

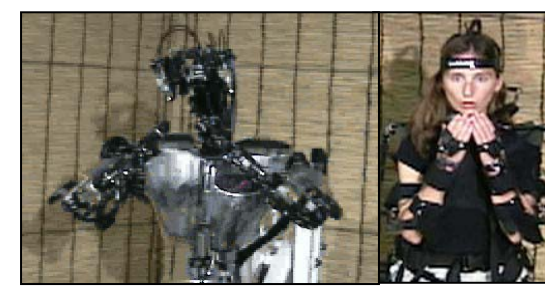
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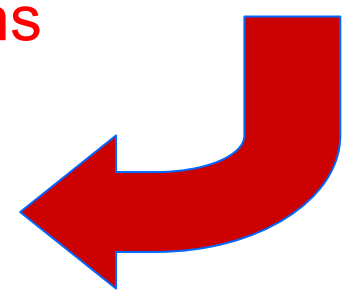
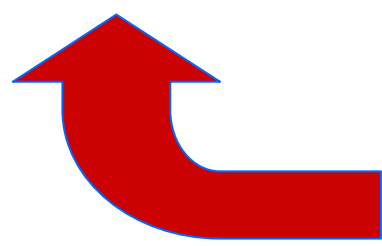


Learning by Imitation



Human-Robot Interactions

Applications?



How can we contribute to Biology?

Computational models can help decipher the minimal underlying mechanisms

Robotic models can help understand how the interaction of such systems with the environment constrain the underlying mechanisms

Artifacts that mimic specific human capacities can also be used to help people with disabilities in these capacities