# *Neuro-IT Workshop*

Bonn, 22 June 2004

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# FET Bio-I3 Initiative

## Bio-inspiration

## Why and When is it useful?

EPFL

# Bio-Inspiration

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

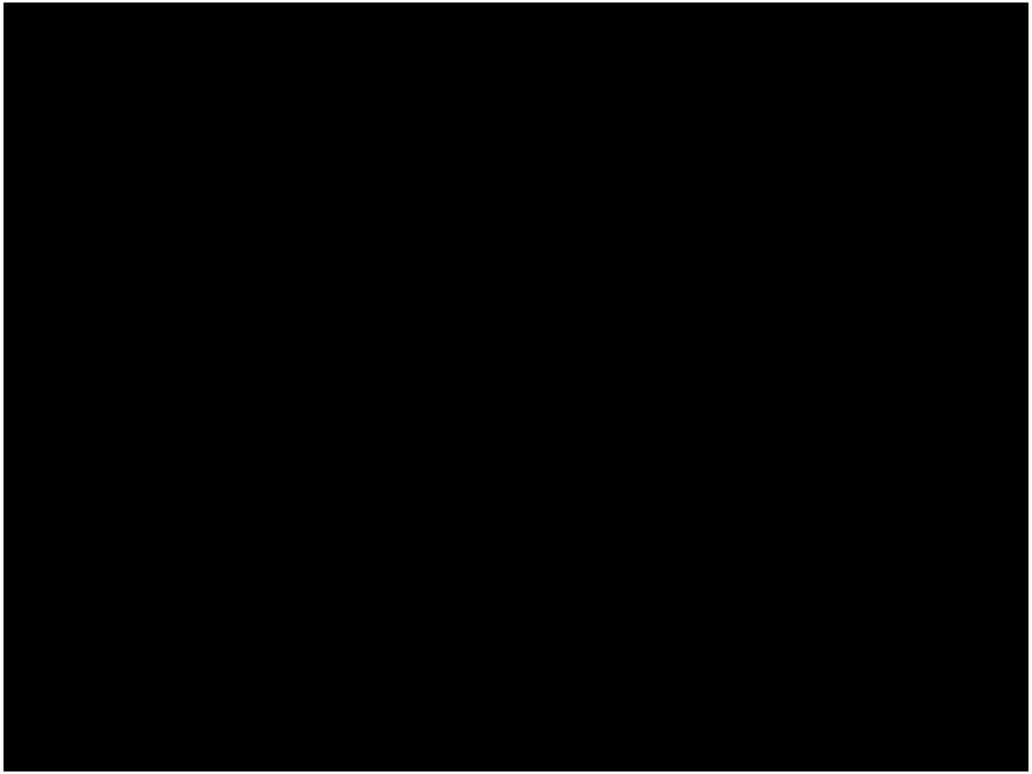
Excellent engineering approach
General – Reusable in other tasks

# Motor Learning

D. Bentivegna, ATR International, Kyoto

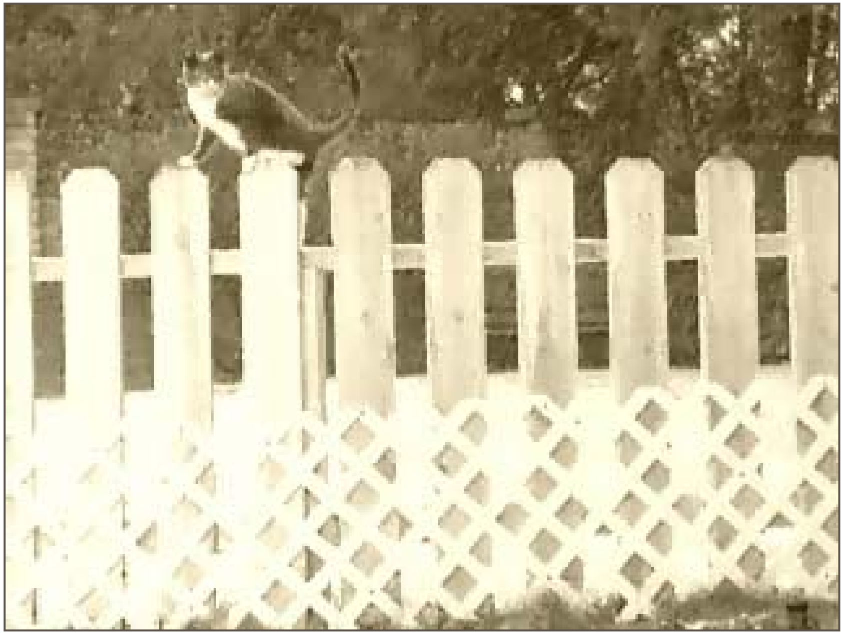
The robot achieves rapidly better performance than the human

## 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

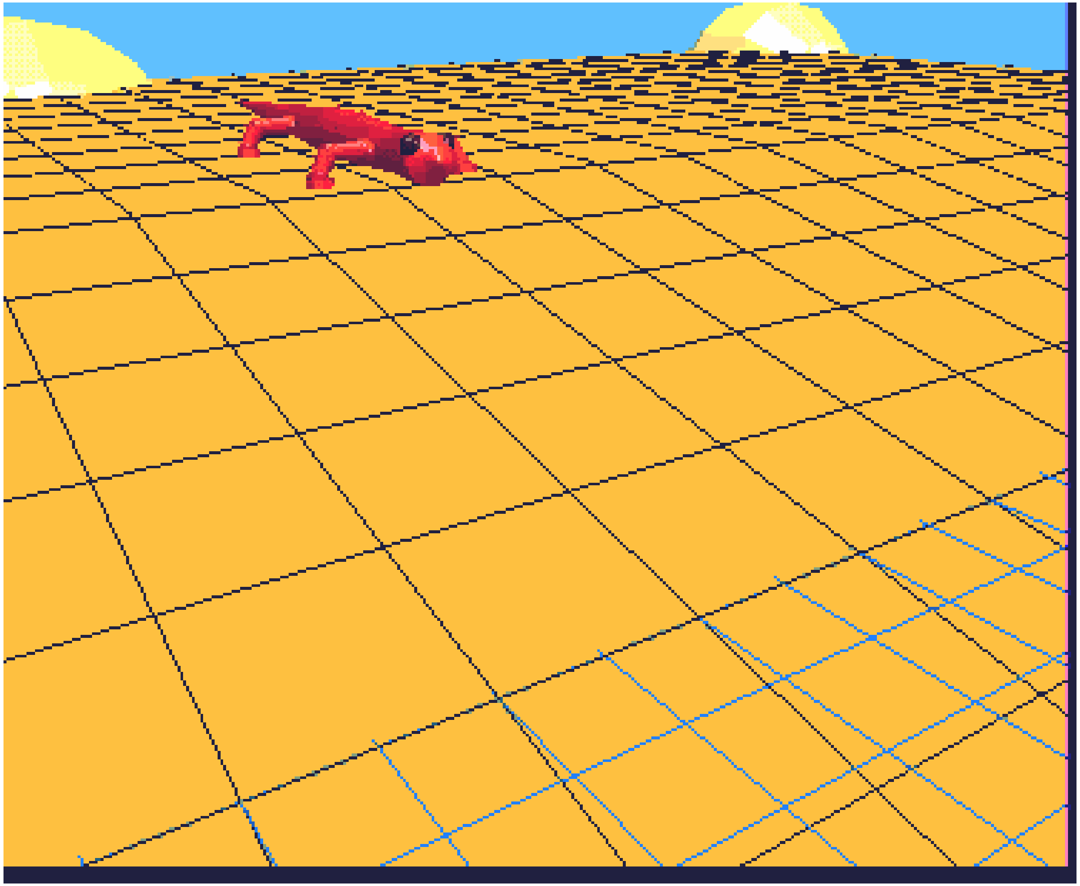
How does Biology solve the problem?

- 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

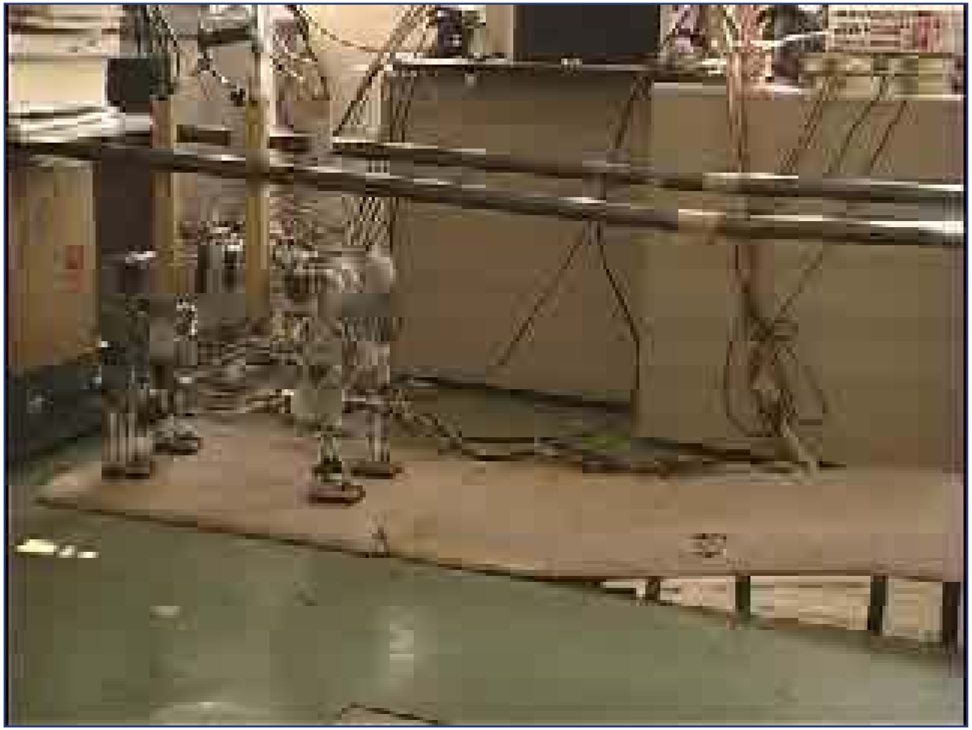
What is missing from state-of-the-art systems for motor control and motor learning?

- 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

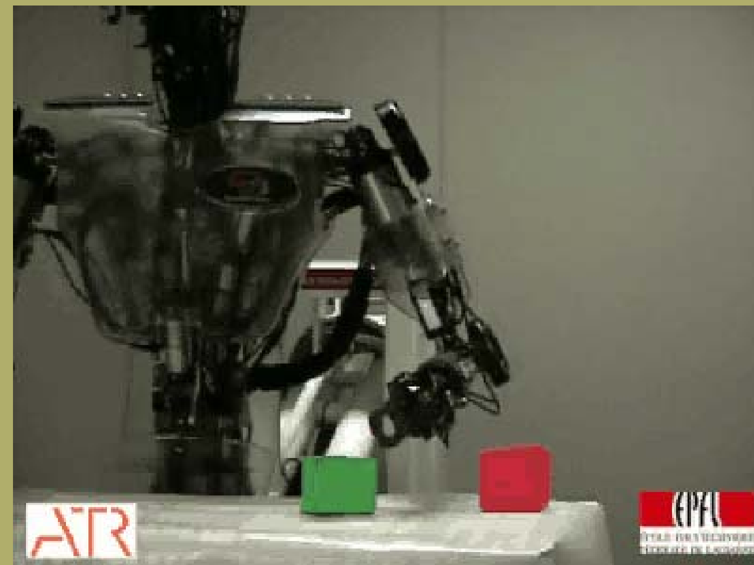
- Bio-inspiration is no use when the task cannot be performed by biological systems (flying to the moon!)
- Bio-inspiration should not constrain us to reproduce exactly the same capabilities / limitations (laser, arrays of microphones)
- Engineering solutions are performing better when the environment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

# Imitation Learning

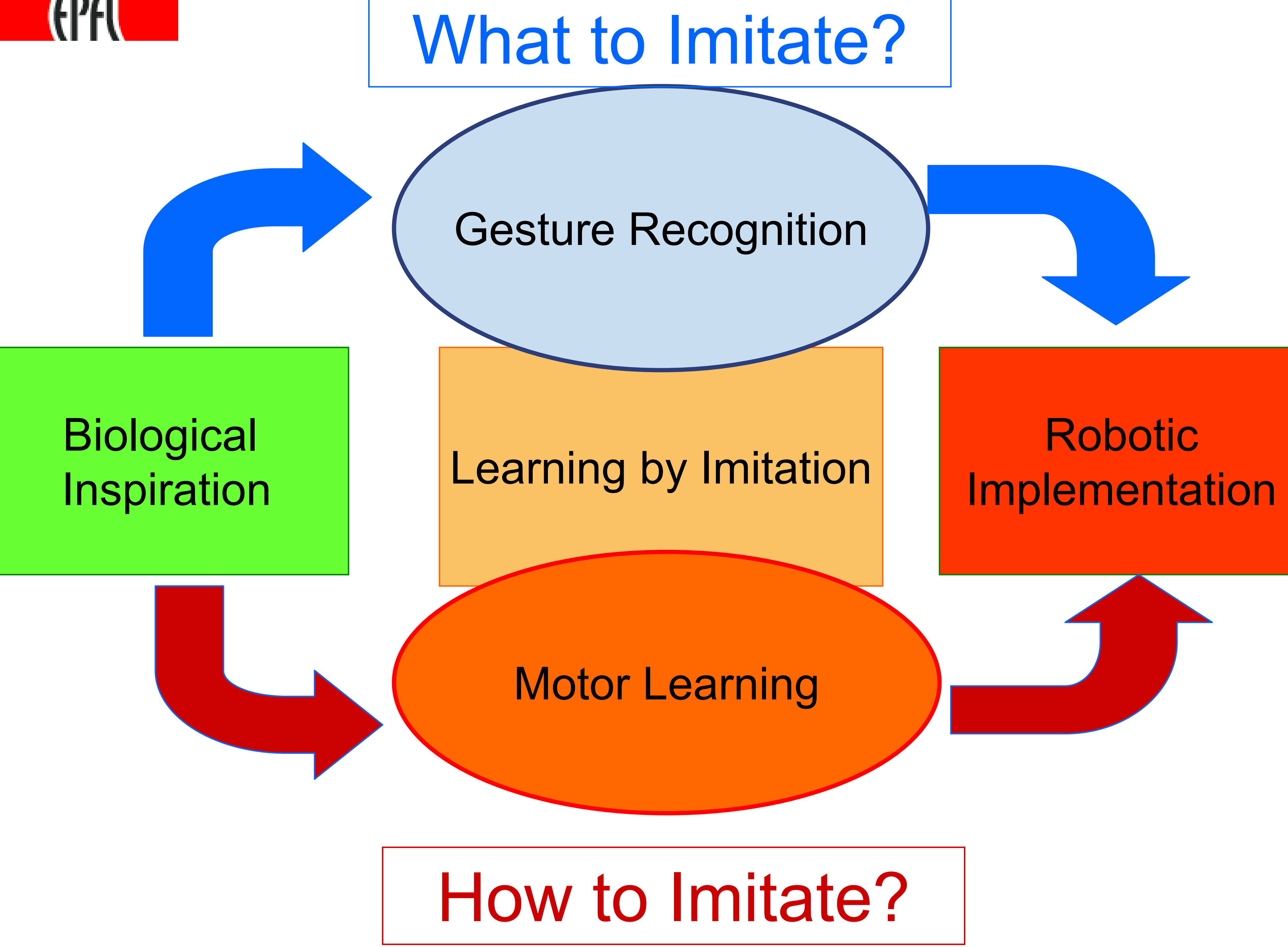
An Example of a Research Area in which Engineering and Biology seek similar answers

**Demonstration (human)**

**Reproduction (robot)**



observation → learning → retrieval → Motor command


What to Imitate?
Gesture Recognition
Biological Inspiration
Learning by Imitation
Robotic Implementation
Motor Learning
How to Imitate?

Biological Inspiration

## Developmental Stages of Imitation

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


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

Biological Inspiration

## Cognitive Abilities and Neural Correlates

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

- Bekkering, Wolschlager & Prinz, *Psycholoquia* 2000
- Rizzolatti et al, *Cog. Brain Res.,* 1996
- Iacobonni et al, *Science* 1999
- Decety et al, *Neuroimage, 2002*

## Imitation Capabilities in Animals

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

Biological Inspiration

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

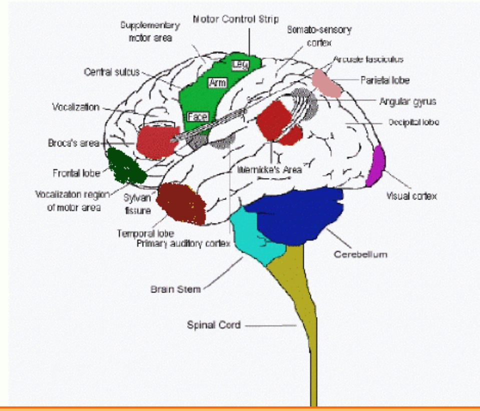
Biological Inspiration

## Imitation Capabilities in Animals

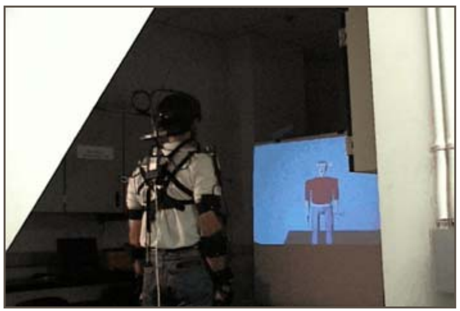
- "True" imitation: Ability to learn new actions not part of the usual repertoire
- The appanage of humans only, and possibly great apes

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

## Neural Modeling
What brain mechanisms?

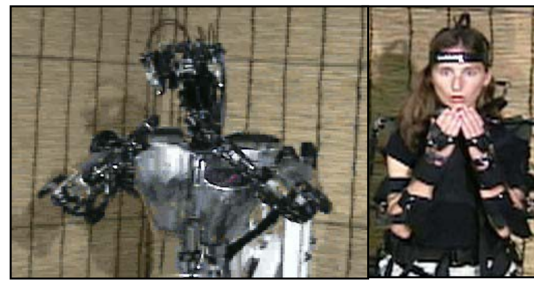



## Motion Studies
low do humans imitate?



## Learning by Imitation

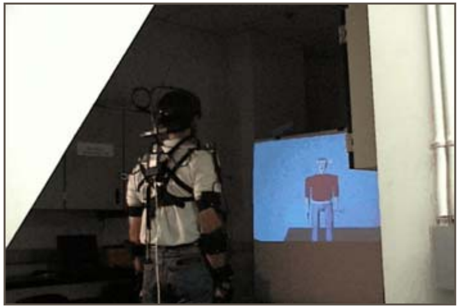
## Robotics
What controllers?



## Human-Robot Interactions
Applications?

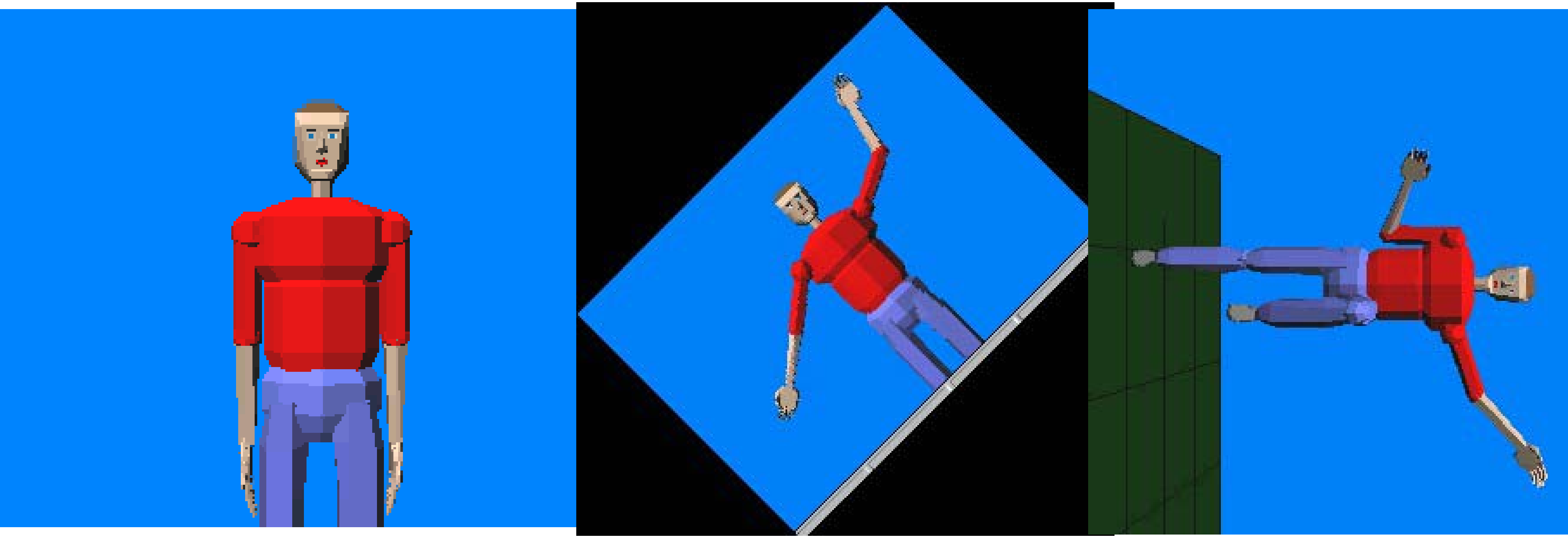
Motion Studies

low do humans imitate?



Learning by Imitation

# Motion studies on human imitation

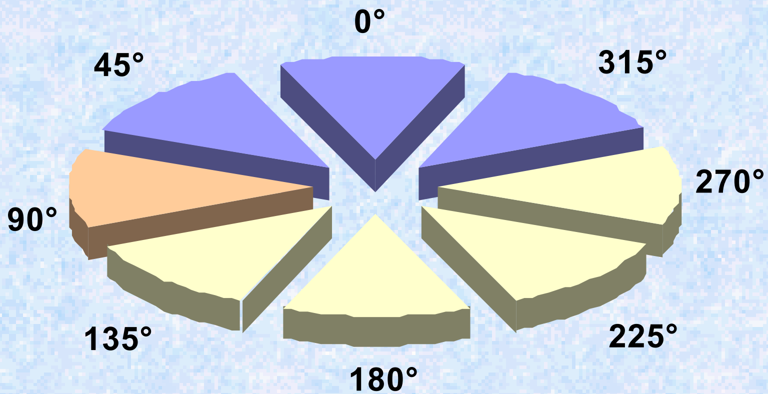


**Variables manipulated:**

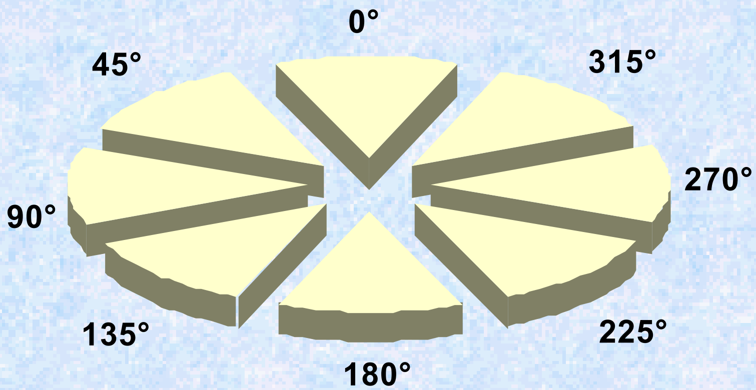
**Imitation type:** ipsilateral/crosslateral
**Handedness:** Left and right handers
**Limb choice:** Left/right arm/leg
**Rotation of the display:** 0, 45, …, 315
**Orientation of the body:** facing forward or away

# Motion studies on human imitation

## Right-Handed




## Left-Handed

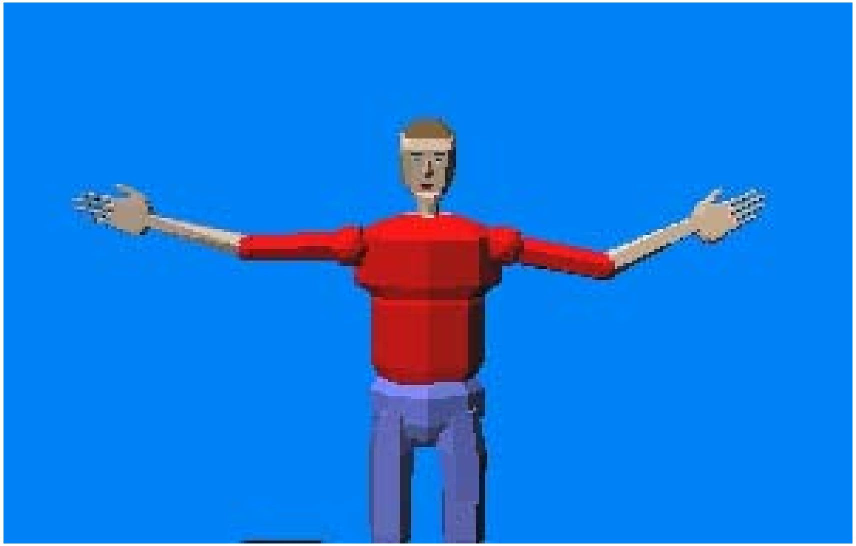


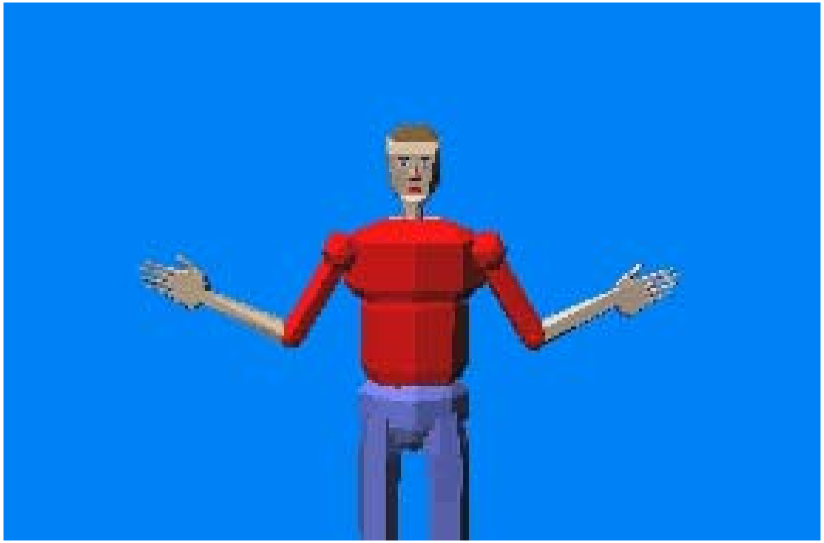

- Preference for Identical
- Preference for Mirror
- No preference

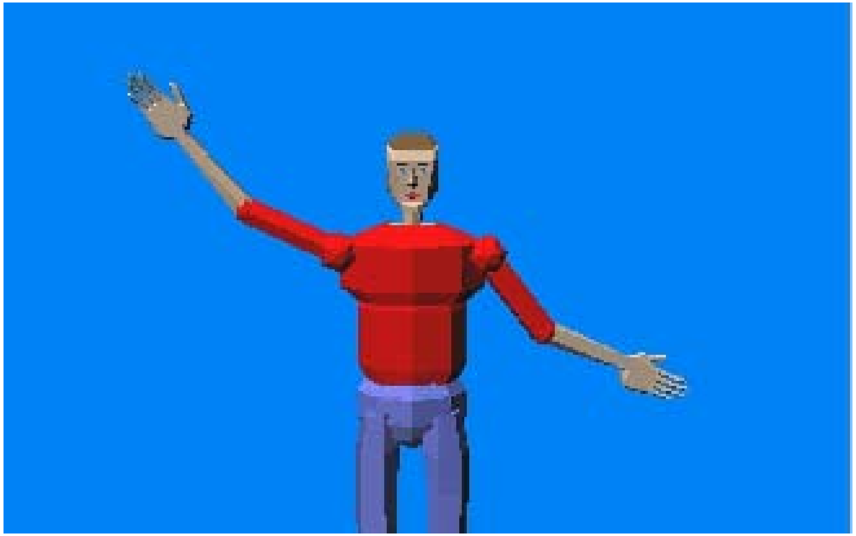
- Left and right-handed apply different imitation strategies
- Right-handed strategy is affected by the number of transformations of frame of reference

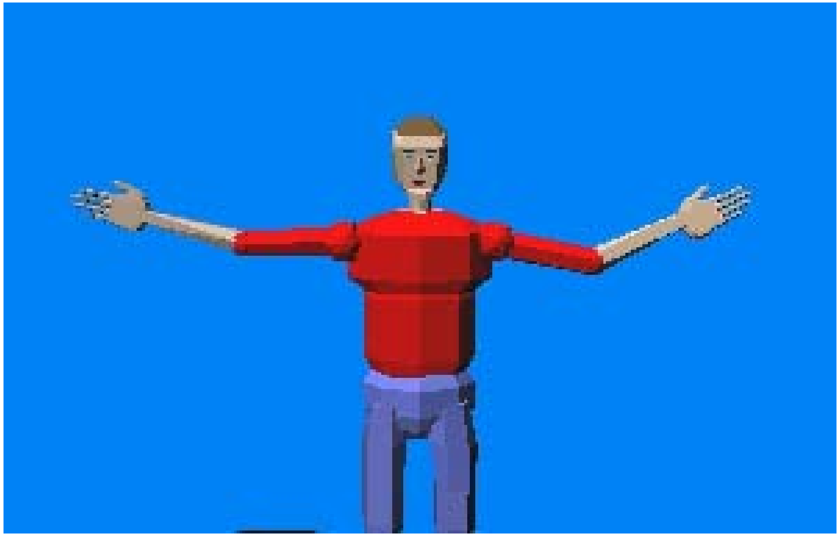
Billard, Todesco, Gordon, Exp. Brain Res., Submitted 2004

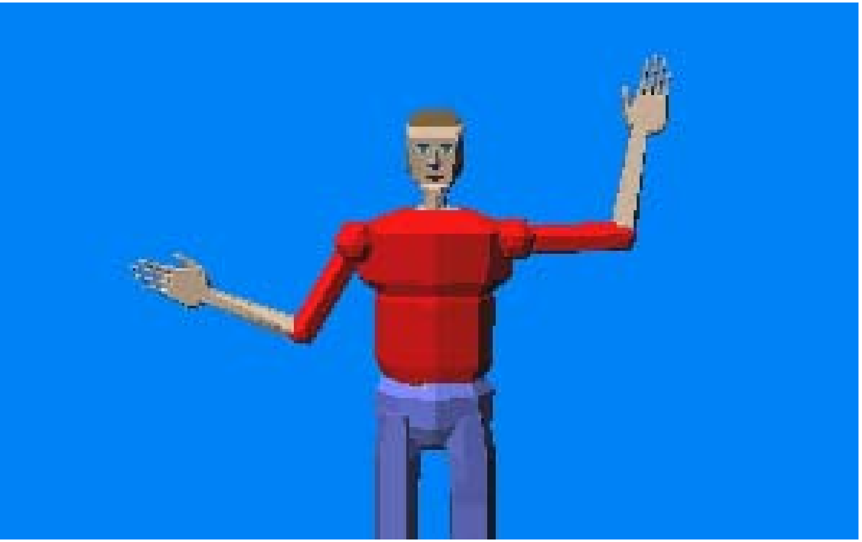
# COORDINATED PATTERNS OF ARM MOVEMENTS

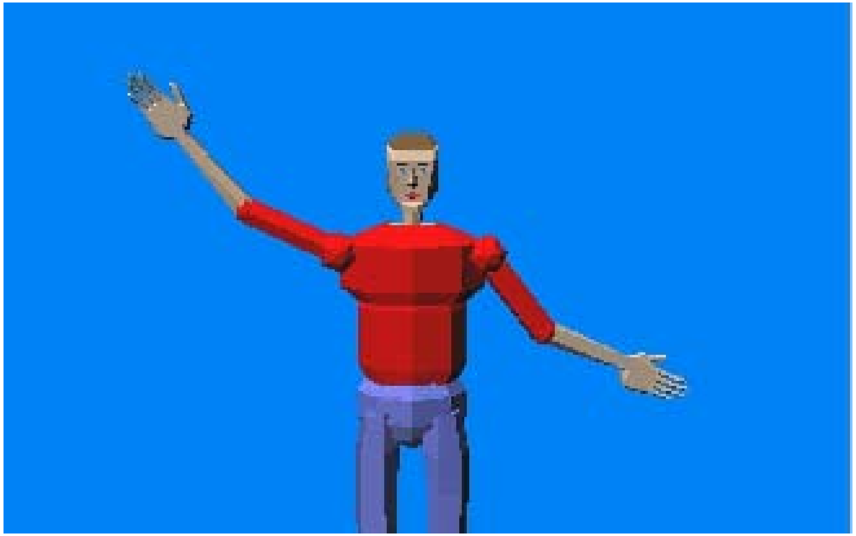


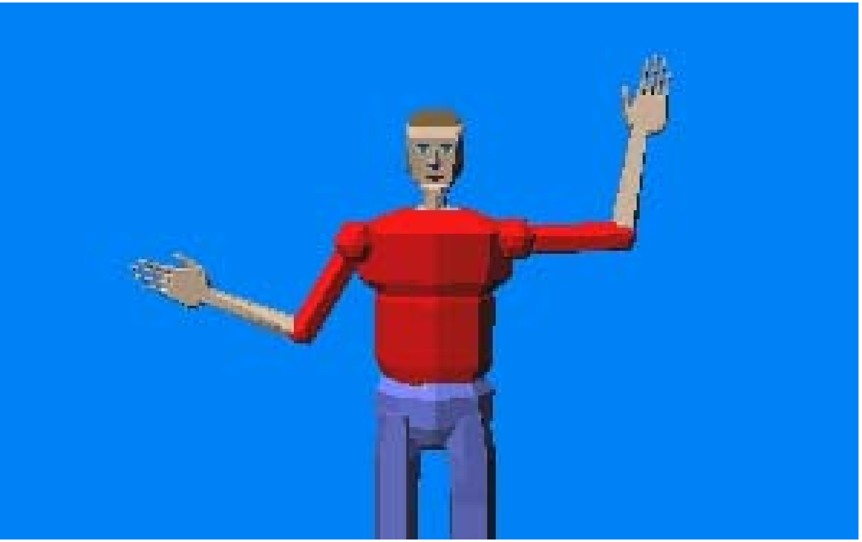


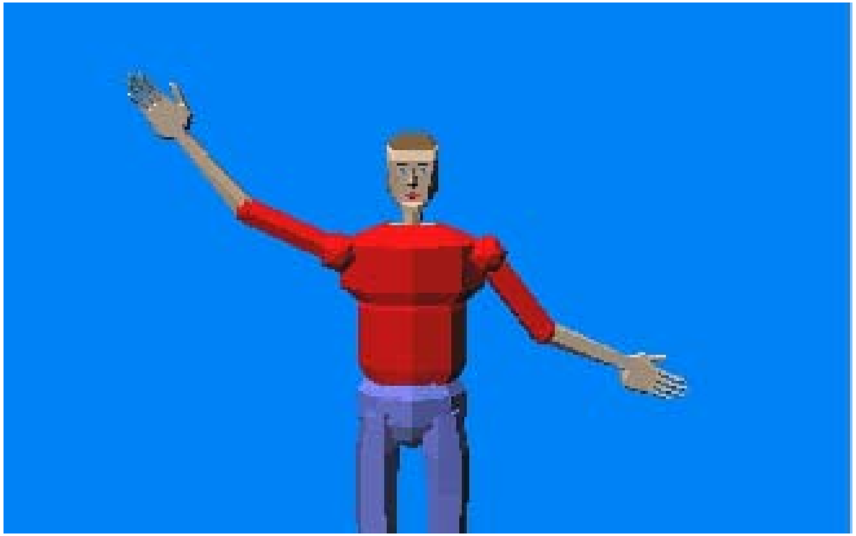




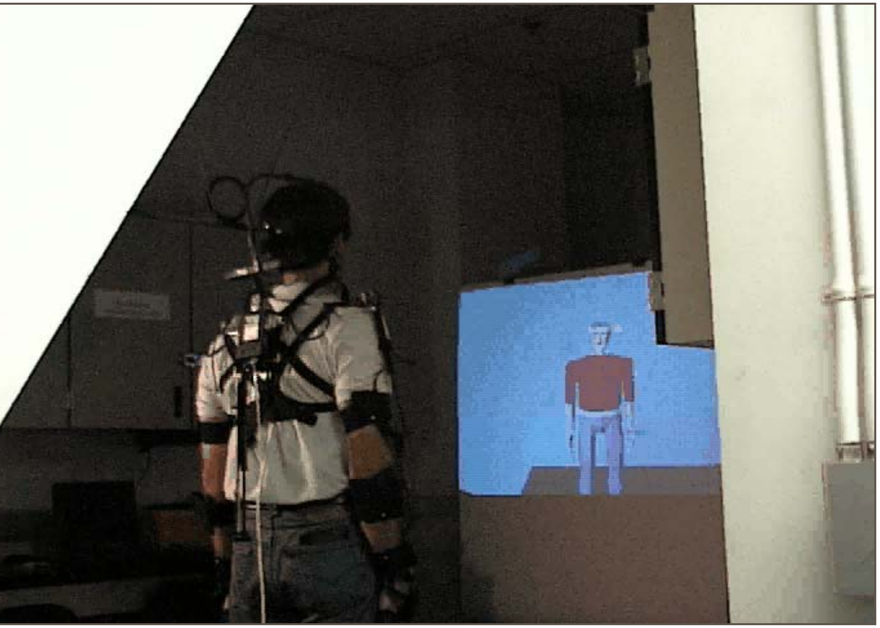


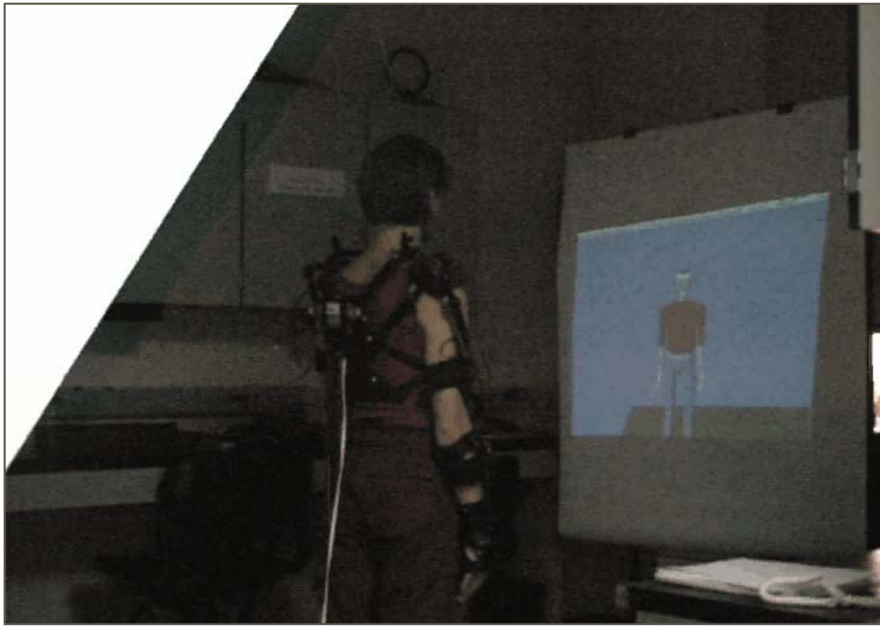






# IMITATION OF COORDINATED PATTERN OF ARM MOTION



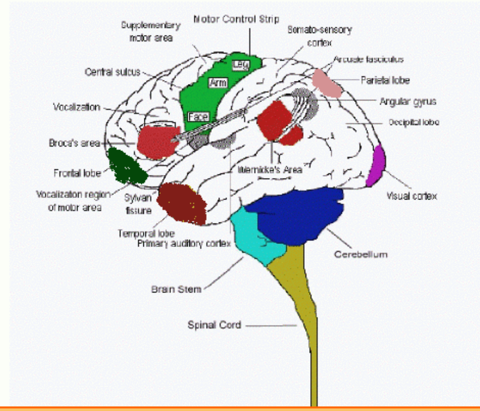


## RESULTS and HYPOTHESES

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

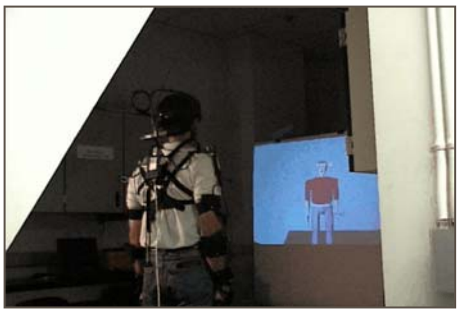
# Neural Modeling

## What brain mechanisms?

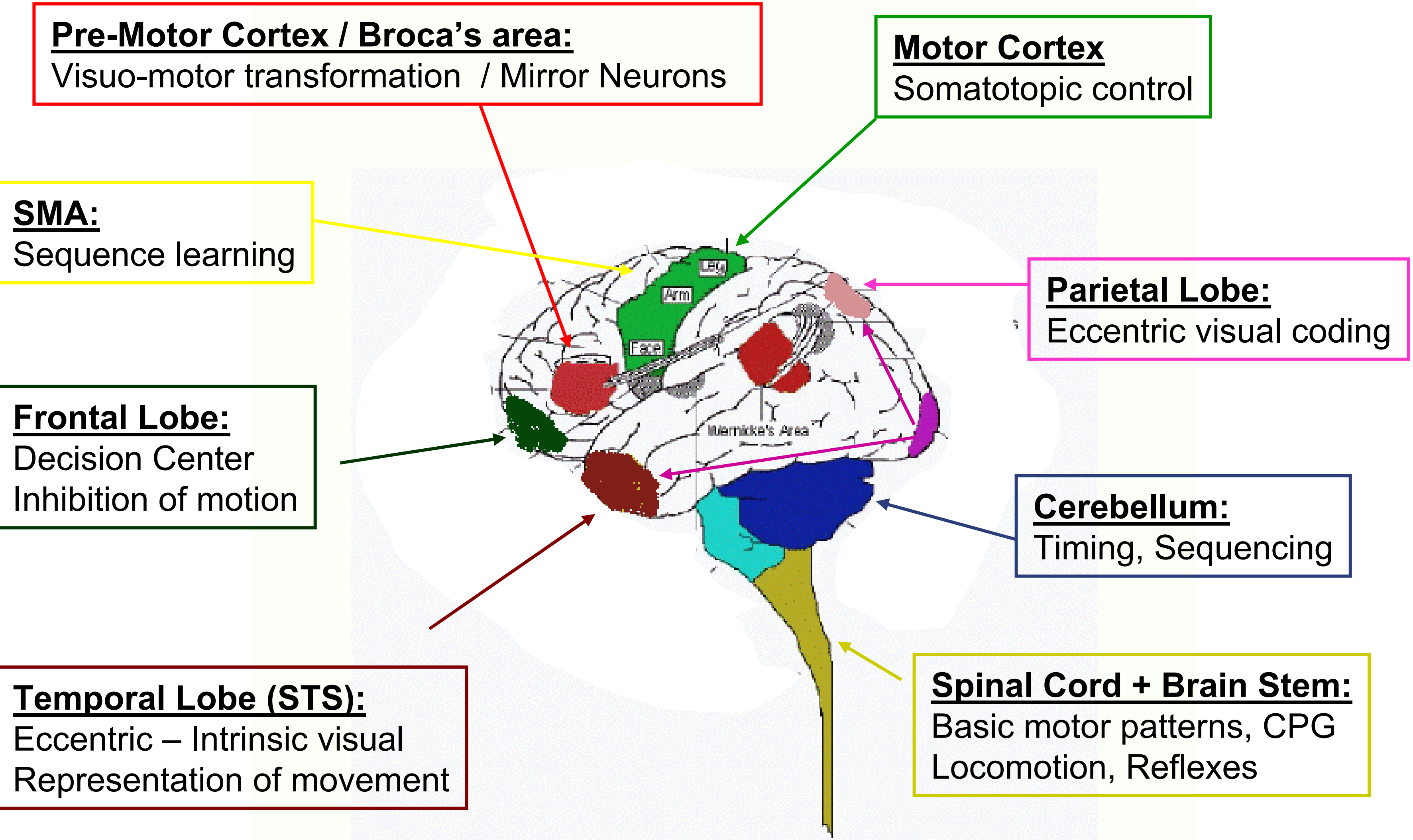



# Motion Studies

## ow do humans imitate?

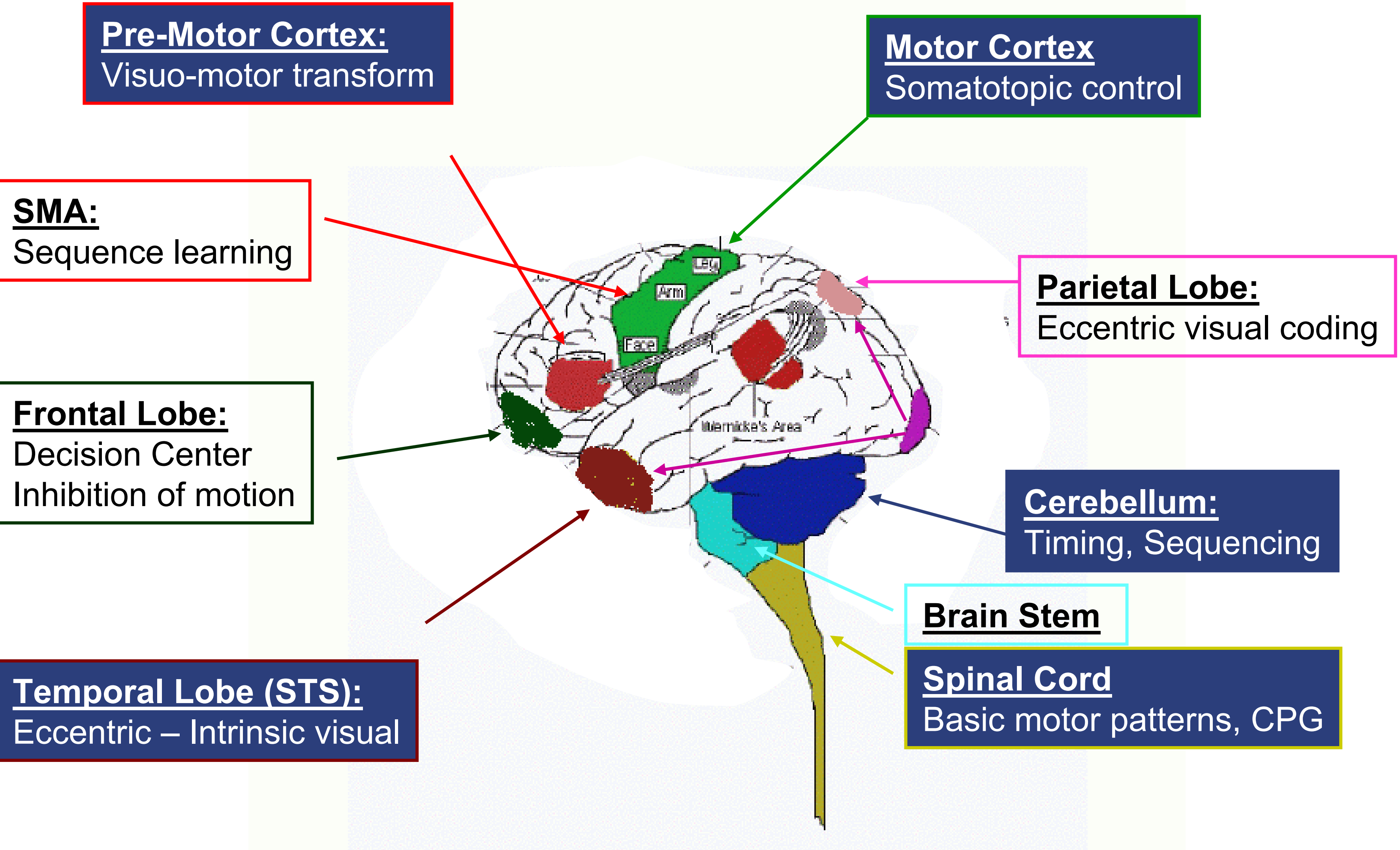


Learning by Imitation




**High-Level representation of the brain mechanisms underlying imitation**

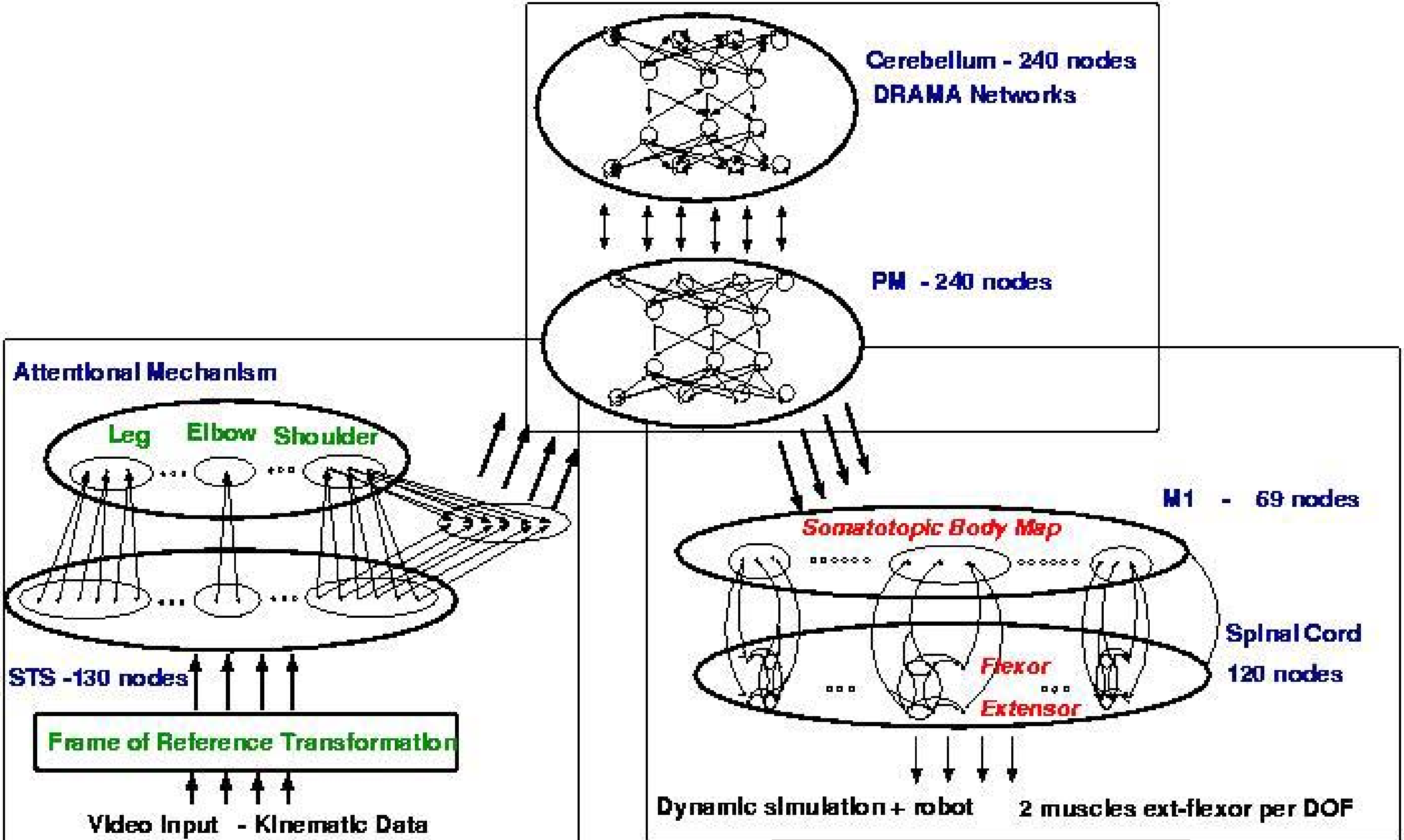
**Functional and abstract model of the brain areas and their connection**




**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

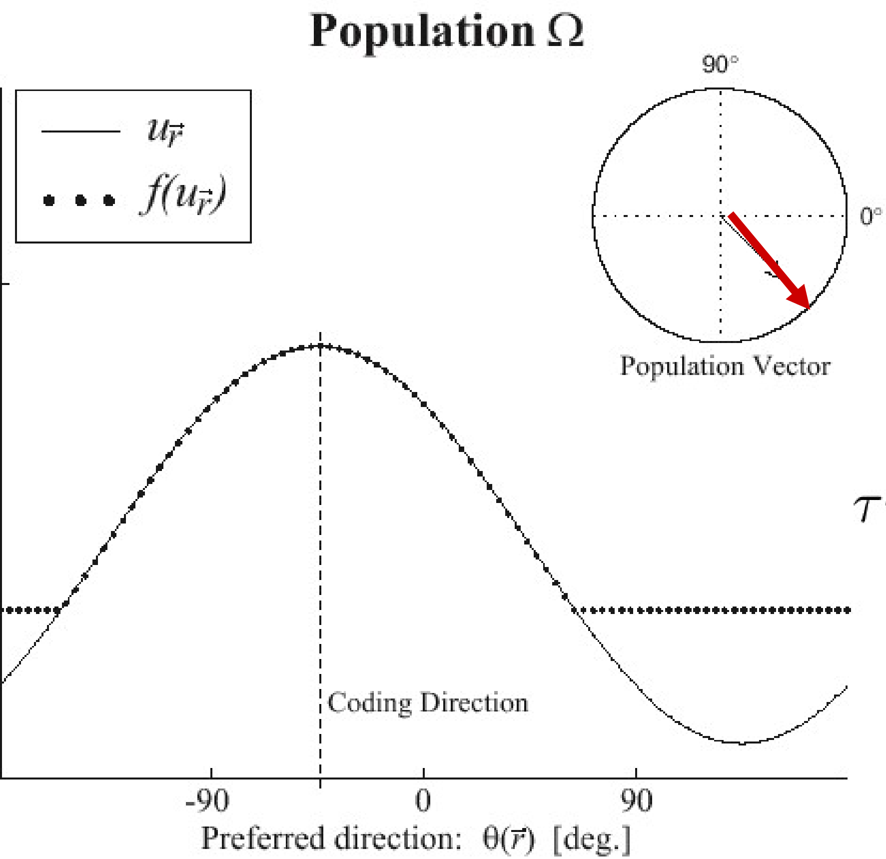
When performing visually-guided movements, the brain faces the task of transferring information across different frames of reference.

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




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

Each unit membrane potential is regulated by:

$$\tau \dot{u}_{\vec{r}} = -u_{\vec{r}} + \oint_{\Gamma} w^{\text{Lat}}_{\vec{r}' \to \vec{r}} f\left(u_{\vec{r}'}\right) \mathrm{d}\vec{r}' + x_{\vec{r}}$$

$$w^{\text{Lat}}_{\vec{r}' \to \vec{r}} = \gamma \left(\vec{r} \cdot \vec{r}'\right)$$

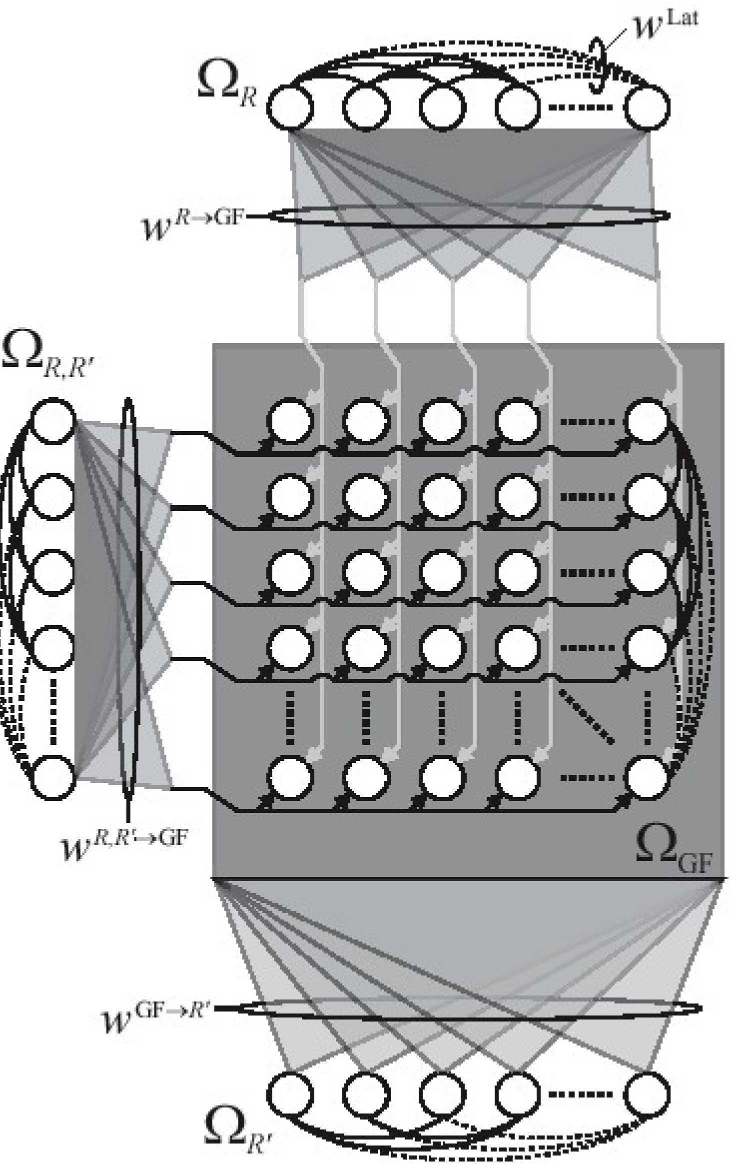
$r_V$ is the population vector

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

Sauser & Billard, *12th European Symposium on Artificial Neural Networks*, ESANN, Bruges, April 28-30, 2004

Sauser & Billard, *NeuroComputing* in preparation, 2004

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

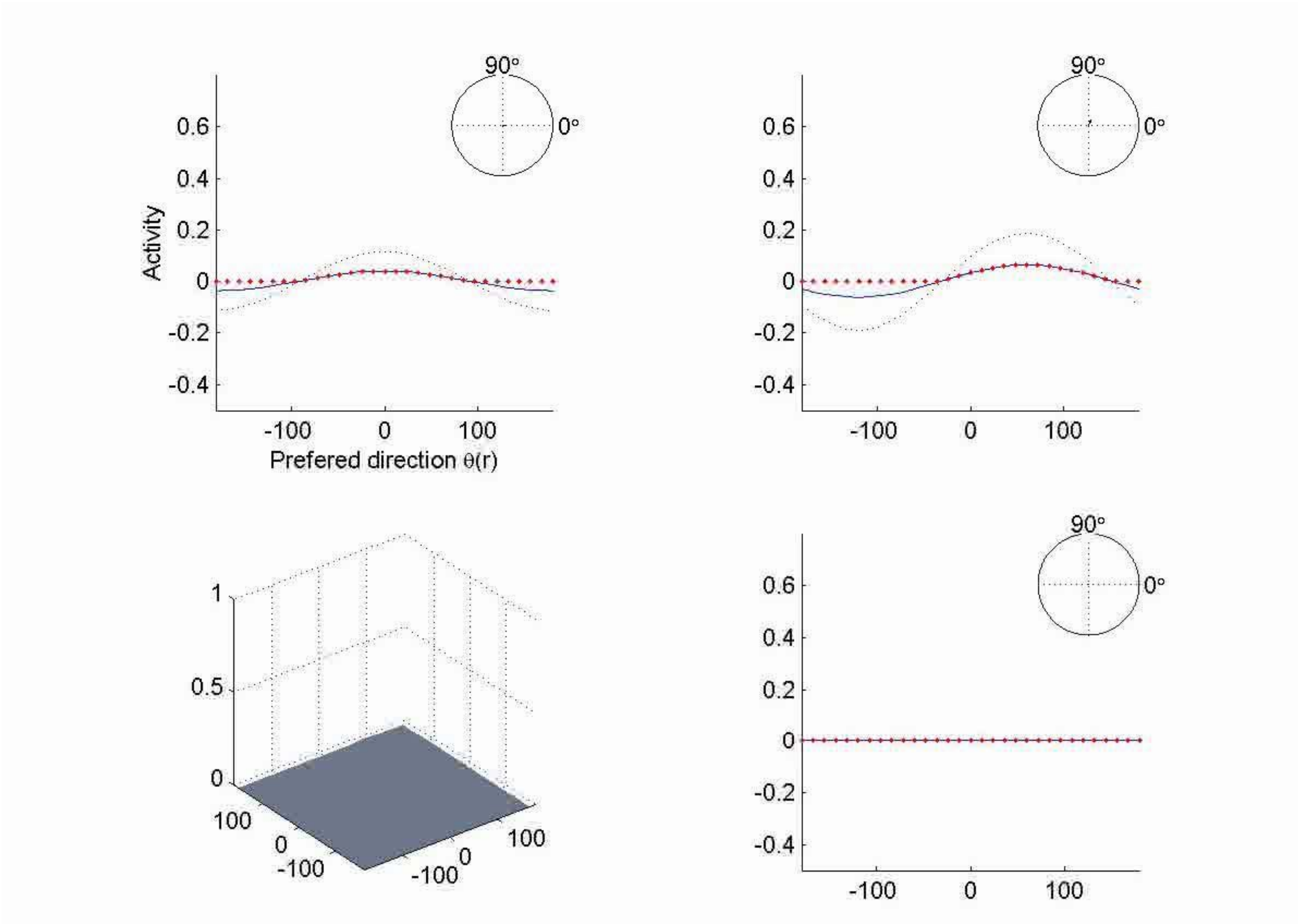



Construction of a network of population performing 2D rotations:

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

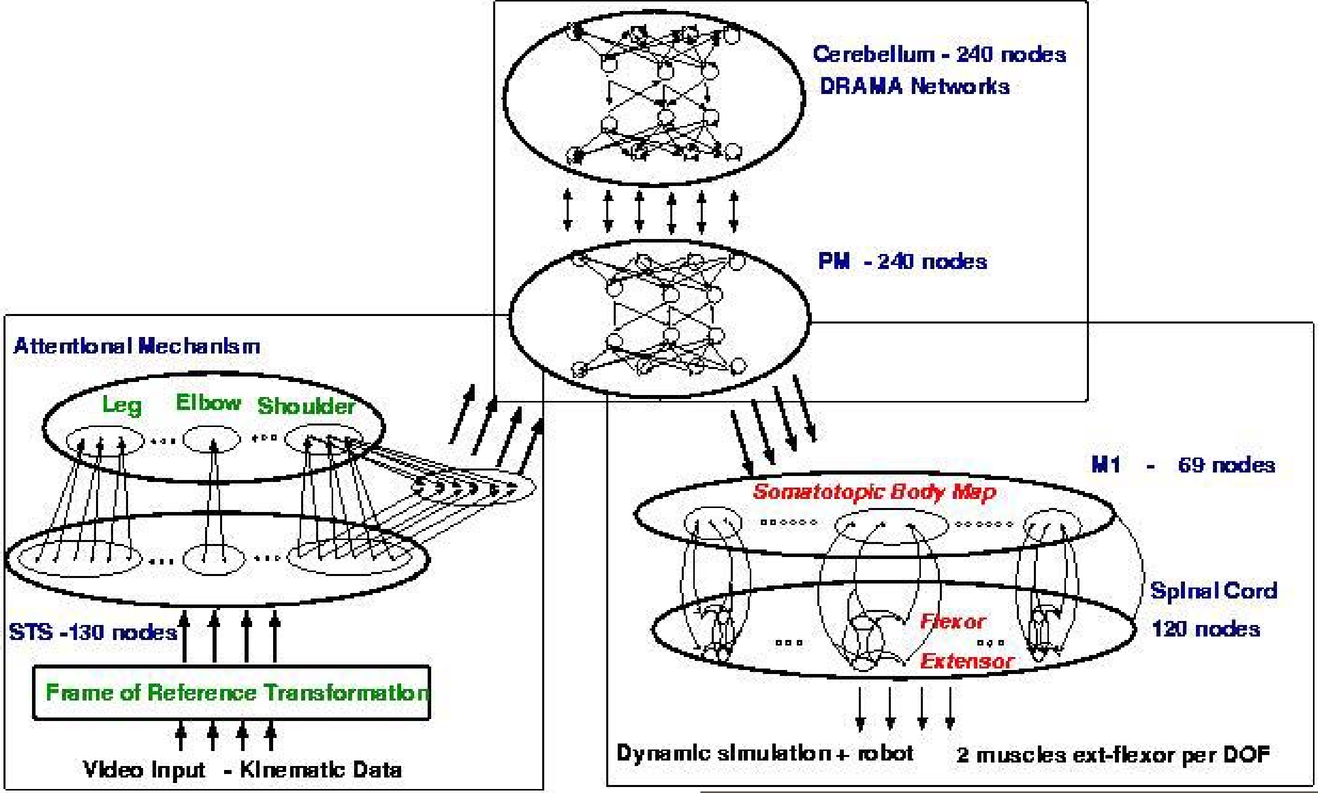
Let $\Omega_{R,R'}$ the populations coding for the vector $V^T$, s.t. $V' = V^T - V$

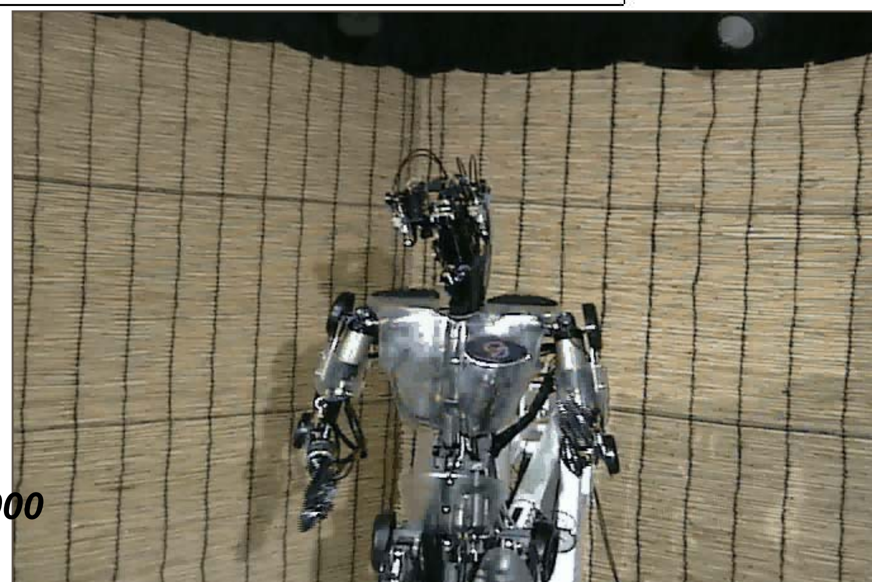
Let $\Omega_{GF}$ an intermediary population coding for the projection of *V* on $V^T$ .




auser & Billard, *12th European Symposium on Artificial Neural Networks*, ESANN'04

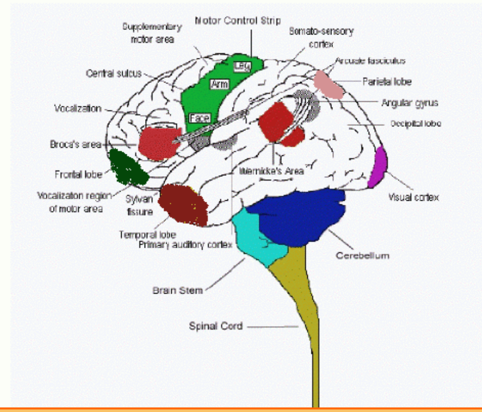
auser & Billard, *Neuro Computing*, in preparation, 2004



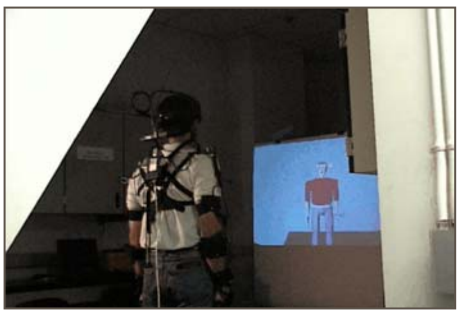



rbib, Billard, Iacobonni, Oztop, *Neural Networks, 2001*
illard & Mataric, *Robotics & Autonomous Systems, 2000*
illard, *Cybernetics Systems, 1999*

# Neural Modeling
## What brain mechanisms?

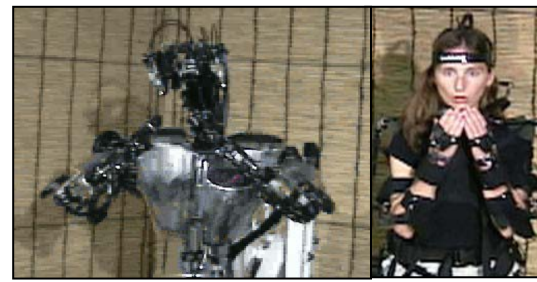



# Motion Studies
## low do humans imitate?



# Learning by Imitation

# Robotics
## What controllers



# What should the robot imitate?

**Which features of the demonstration are relevant?**

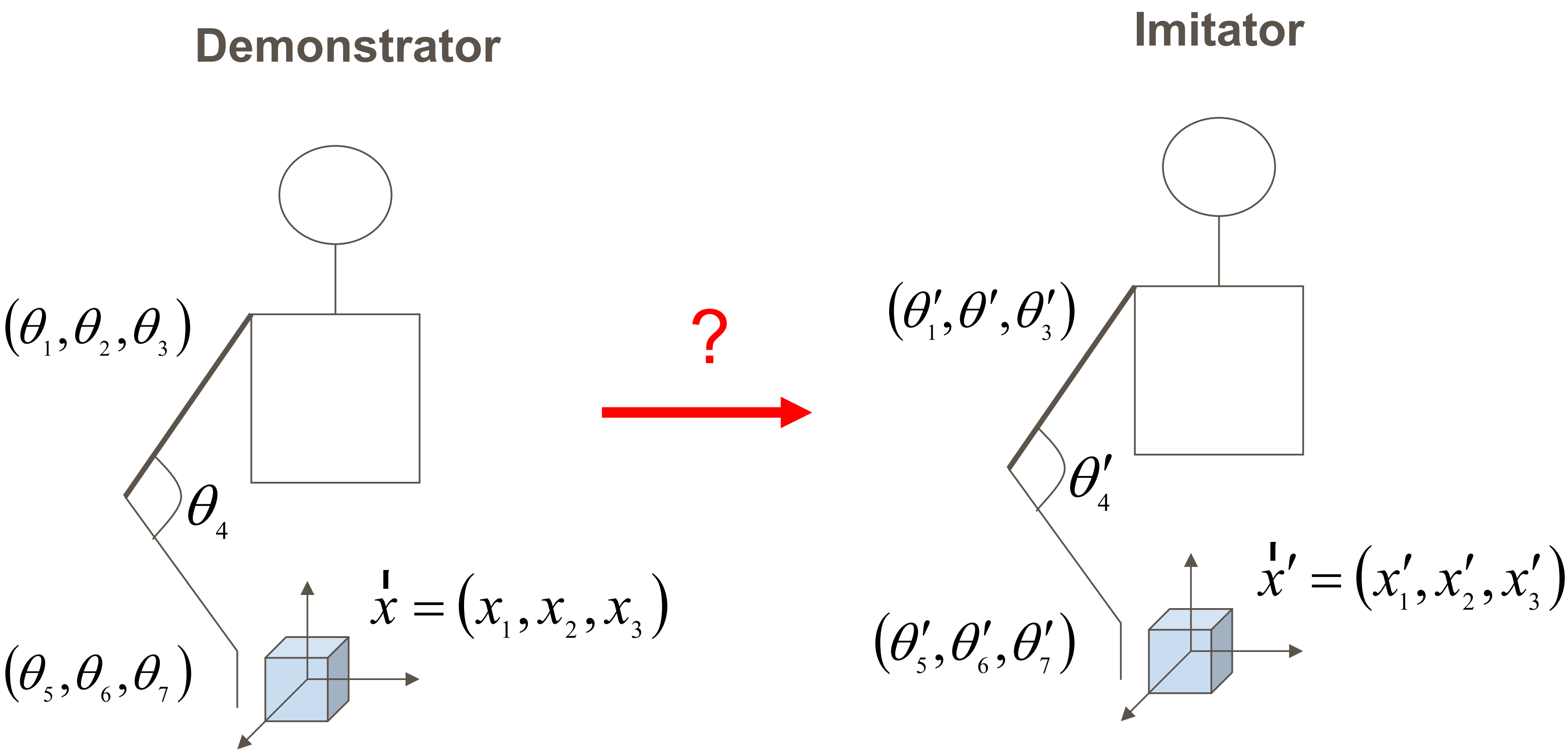
**What should it pay attention to?**

**What are the task constraints?**

**Invariants are the relevant parts of the demonstration**

**→ To determine a metric of imitation performance**

# The transfer problem




orward kinematics $\vec{x} = f(\vec{\theta})$ $\vec{x}' = f'(\vec{\theta}')$

EPFL

# The transfer problem

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

Demonstrator — Imitator

**Inverse Kinematics Problem:** $\dot{\theta}' = f'^{-1}(\dot{\vec{x}}')$

**7 DOFs , 3 independent equations, Multiple solutions**

**→Additional constraints (minimum torque, minimum energy, preferred posture, etc.)**

**Imitation provides additional constraints**

**→ restricts the space of solutions**

**Imitation provides optimal solutions**

**→ speeds up the learning process**

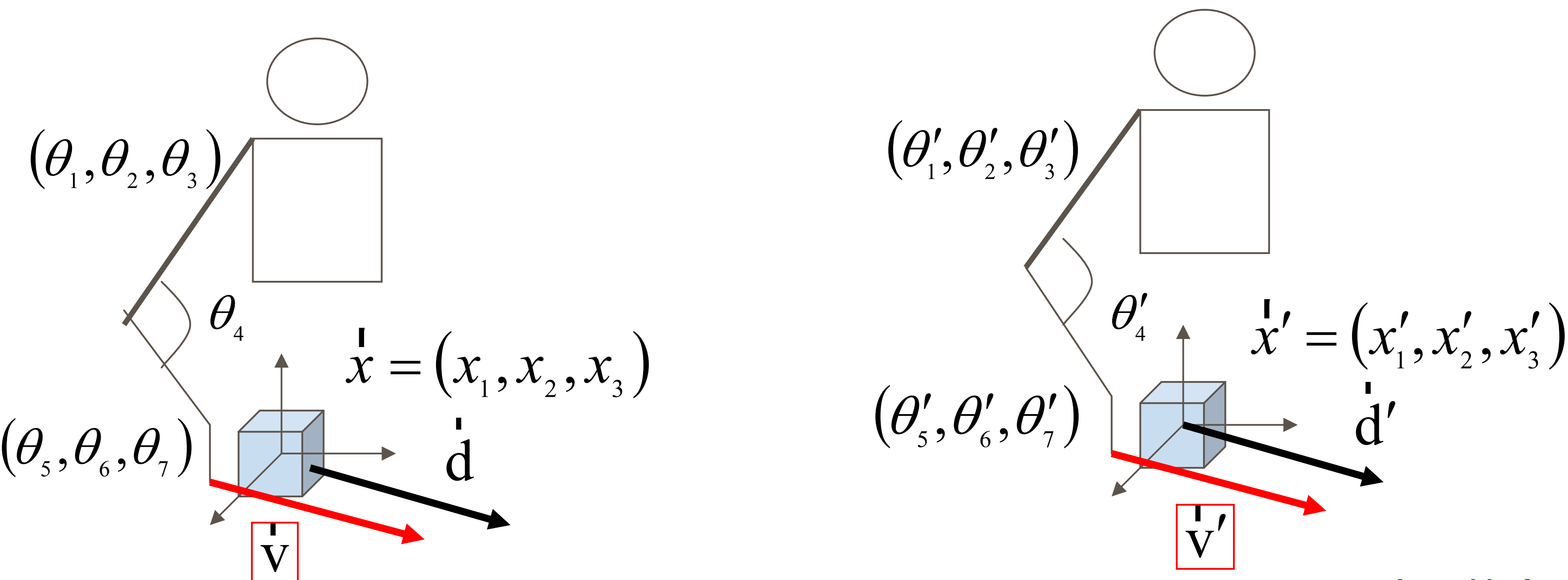
# Constraints specified by imitation

$\vec{x} = \vec{x}'$ **Same Object, same target location**

$\vec{d} = \vec{d}'$ **Same direction of motion**

$\vec{v} = \vec{v}'$ **Same speed, same force**

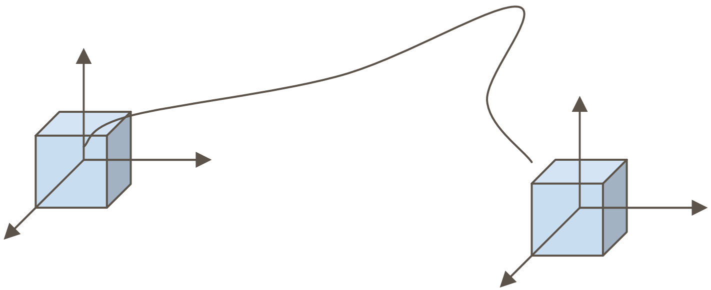
$\vec{\theta} = \vec{\theta}'$ **Same posture**



# The transfer problem
# Trajectory imitation

Demonstration

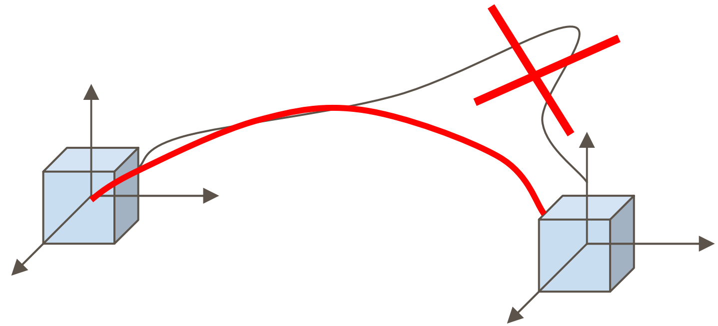
$$\dot{\theta} = f^{-1}(\dot{\vec{x}})$$



? →

Imitation

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



**No solutions (smaller range of motion)** $\dot{\theta} \neq \dot{\theta}' \Rightarrow \dot{\vec{x}} \neq \dot{\vec{x}}'$

**→ Find the closest solution according to a metric**

# Imitation Level 2 – first strategy: Tracking the direction of motion of the hand

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

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

Cost function :

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

$$J_2(\vec{x}, \vec{x}_o, \vec{x}_o') = \sum_i \left(x^i{}_o' - x^i - x^i{}_o\right)^2$$

Controller :

Calculate distance from hand to object : $(X - X_0)$

Define the target point : $X_T = X'_0 - X - X_0$

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

# Imitation Level 2 – second strategy: Follows the speed of motion of the arm

Data Set : $D(U) = \{\vec{X}, \vec{X}_o\}$

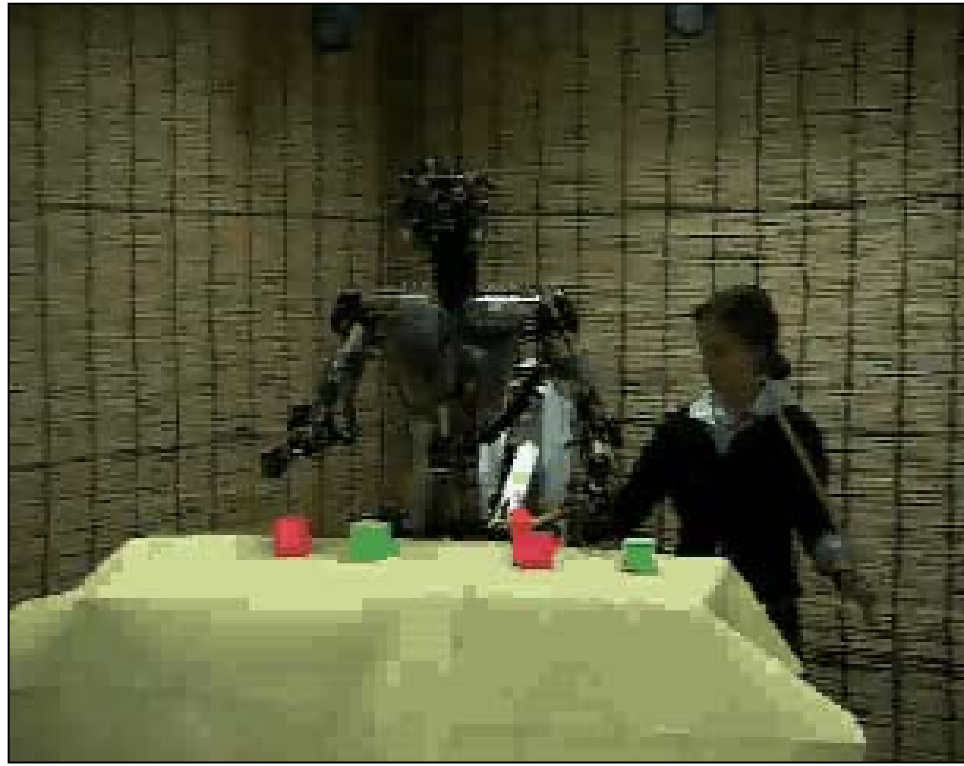
Constraint : $\vec{X}'_o = \vec{X}_o$ & $\vec{X}' = \vec{X}$

& $\dot{\vec{X}}' = \dot{\vec{X}}$

Cost Function :

$$J = J_1(\vec{x}_o, \vec{x}'_o) + J_2(\vec{x}, \vec{x}') + J_3(\dot{\vec{x}}, \dot{\vec{x}}')$$

$$J_3(\dot{\vec{x}}, \dot{\vec{x}}') = \dot{\vec{x}} - \dot{\vec{x}}'$$



Controller :

Calculate distance from hand to object : $(X - X_0)$

Define the target point : $X_T = X'_0 - X - X_0$ & $\dot{X}_T = \dot{X}$

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

# 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)

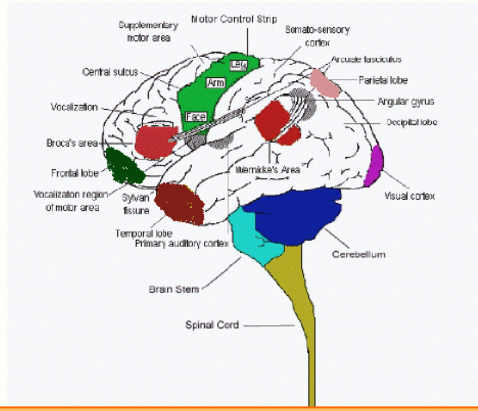
in collaboration with:

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)

Billard & Schaal, *IROS* 2001, Billard et al, *IROS* 2003, Calinon & Billard, IROS 2004
Billard et al, *Robotics & Autonomous Systems*, 47, 69-77, 2004

# Neural Modeling
## What brain mechanisms?




# Motion Studies
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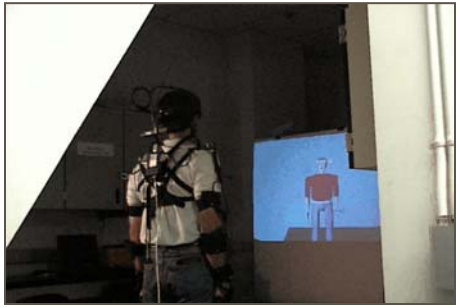
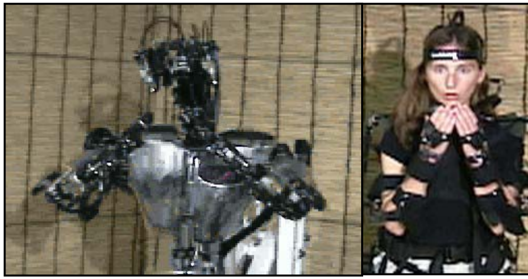


# Robotics
## What controllers?



**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

# ROBOTA:

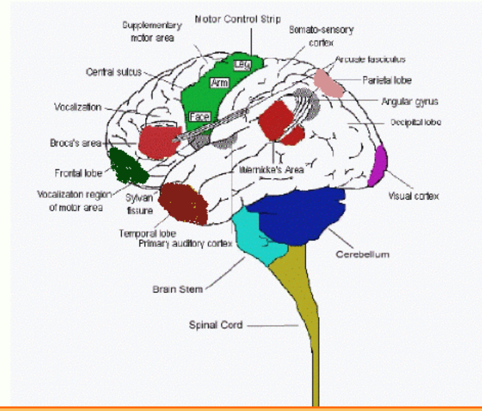
## A tool to test the imitation capabilities of autistic children

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

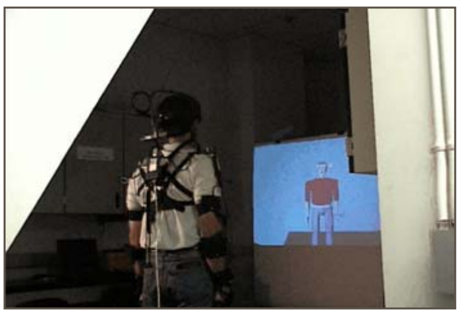
The educator demonstrates
The imitation game

The autistic child is let free to
play with the robot

## Neural Modeling
What brain mechanisms?

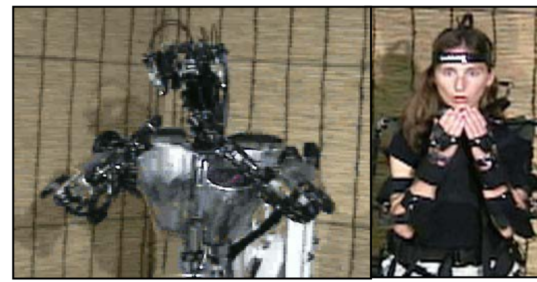



## Motion Studies
How do humans imitate?



## Learning by Imitation

## Robotics
What controllers?



## Human-Robot Interactions
Applications?


http://asl.epfl.ch

# Contribution to Biology

## 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