

# MOTOR CONTROL

Emmanuel Guigon

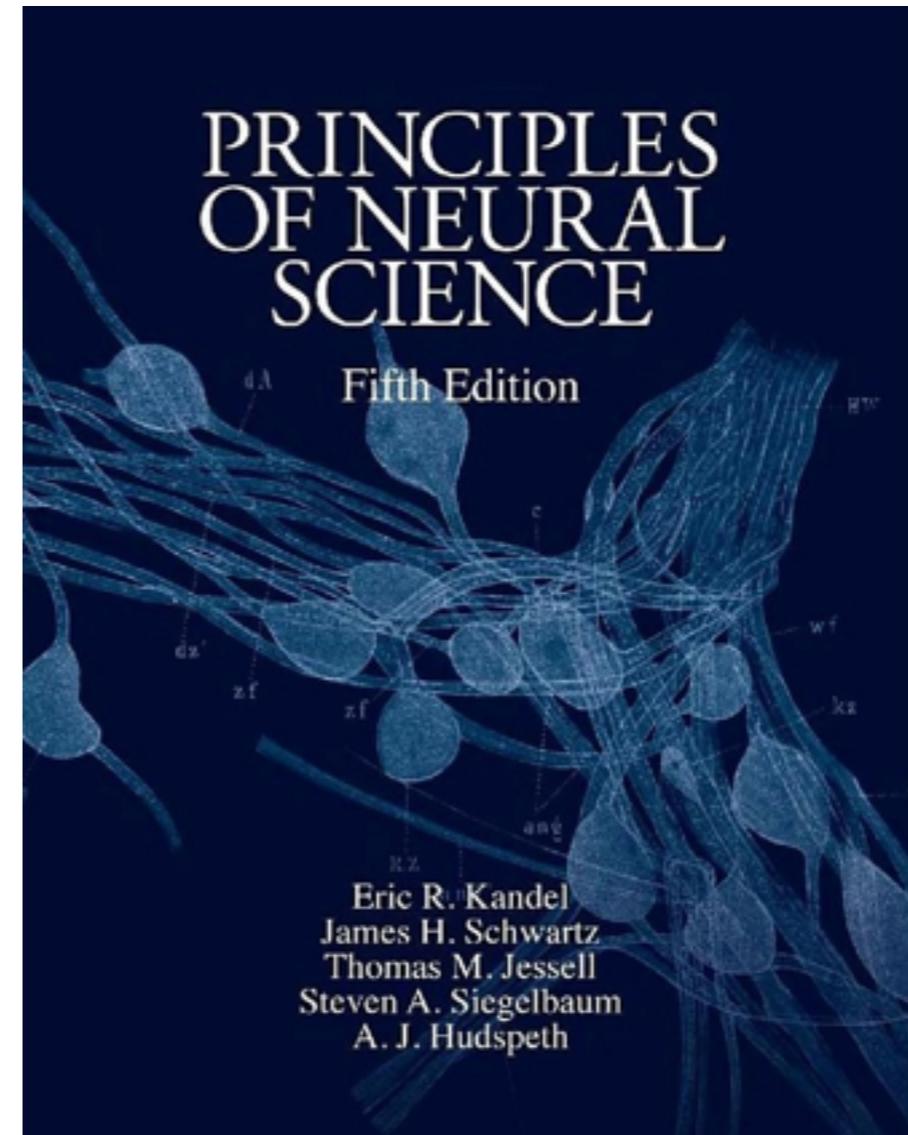
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# DISCLAIMER

## Nothing about

- Biomechanics
- Muscles
- Sensory receptors
- Motoneurons
- Reflexes
- Spinal cord
- Ascending/descending tracts
- Motor cortex
  
- Neurophysiology
- Neuropsychology
- Brain imaging
  
- Motor learning/skills
- Attention
  
- Posture, walking, writing, speaking



# QUESTIONS

1. Why is ACTION an interesting object in the field of Cognitive Sciences?
2. Why robotic artifacts can be useful in the field of Cognitive Science?

# ACTIONS

- Are driven by goals and they can reach these goals or fail to do so;
- Often involve some degree of volitional control;
- Require planning and decisions among alternatives;
- Involve prediction or anticipation of an intended outcome;
- Are often, albeit not always, associated with a sense of agency, that is, the agent's conscious awareness of carrying out the particular action and of its goals.

— Engel et al., 2013, *Trends Cogn Sci* 17:202

# MOTOR CONTROL: « The Cinderella »

## Of Psychology

*“One would expect psychology—the science of mental life and behavior—to place great emphasis on the means by which mental life is behaviorally expressed. Surprisingly, however, the study of how decisions are enacted—the focus of motor control research—has received little attention in psychology.”*

— Rosenbaum, 2005, *Am Psychol* 60:308

## and Cognitive Science

### Brief Contents of Neisser’s (1967) *Cognitive Psychology*

**Table 1**

*Citations of Selected Topics in the Social Science Citation Index From 1986 to 2004*

Topic	Occurrence
Attention	51,946
Cognitive	65,039
Decision or judgment or reasoning	54,367
Language	42,205
Memory	48,867
Motor	17,424
Perception or pattern recognition	34,328

*Note.* All topics except for *Motor* are referred to in Ashcraft’s (2002) *Cognitive Psychology* (3rd ed.; see Appendix B).

1. The Cognitive Approach
2. Iconic Storage and Verbal Coding
3. Pattern Recognition
4. Focal Attention and Figural Synthesis
5. Words as Visual Patterns
6. Visual Memory
7. Speech Perception
8. Echoic Memory and Auditory Attention
9. Active Verbal Memory
10. Sentences
11. A Cognitive Approach to Memory and Thought

# GOOD REASONS

*“To move things is all that Mankind can do ... For such the sole executant is muscle, whether in whispering a syllable or in felling a forest.”*

— Charles Sherrington, 1924, *The Linacre Lecture*

*“The infinite diversity of external manifestation of cerebral activity can be reduced ultimately to a single phenomenon - muscular movement. Whether it's the child laughing at the sight of a toy, or Garibaldi smiling when persecuted for excessive love for his native country, or a girl trembling at the first thought of love, or Newton creating universal laws and inscribing them on paper - the ultimate fact in all cases is muscular movement.”*

*“Absolutely all the properties of external manifestations of brain activity described as animation, passion, mockery, sorrow, joy, etc., are merely results of a greater or lesser contraction of definite groups of muscles, which, as everyone knows, is a purely mechanical act.”*

— Ivan Sechenov, 1863, in *Reflexes of the Brain*

# GOOD REASONS

*“For cognitions to be communicated, they must be physically enacted. It follows from this observation that a complete account of the cognitive system must explain how it transmits information to the environment as well as how it takes information in and retains and elaborates it.”*

— Jordan & Rosenbaum, 1989, in *Foundations of Cognitive Science*

*“The basic idea is that cognition should not be understood as a capacity for deriving world-models, which might then provide a database for thinking, planning, and problem-solving. Rather, it is emphasized that cognitive processes are so closely intertwined with action that cognition would best be understood as 'enactive', as the exercise of skillful know-how in situated and embodied action.”*

*“Cognition is not detached contemplation of the world, but a set of processes that determine possible actions. According to their view, the criterion for success of cognitive operations is not to recover pre-existing features or to construct a veridical representation of the environment. Instead, cognitive processes construct the world by bringing forth action-relevant structures in the environmental niche. In a nutshell, cognition should be understood as the capacity of generating structure by action, that is, of 'enacting' a world.”*

— Engel et al., 2013, *Trends Cogn Sci* 17:202

# COGNITION AND ACTION

## What to move where

*Cognitive science*



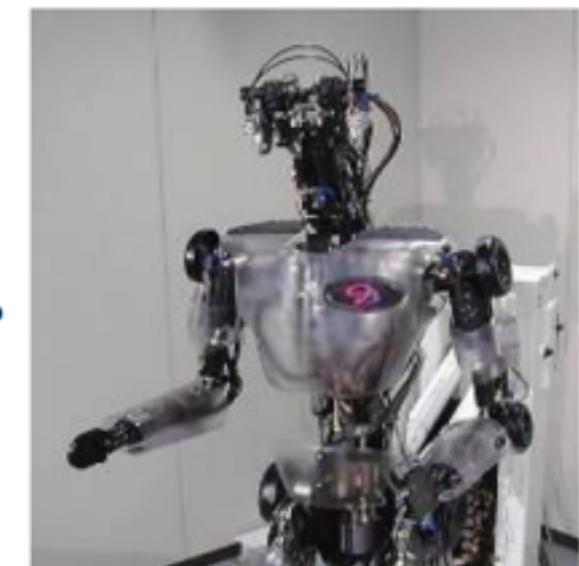
**VS.**



**Moving**



**VS.**



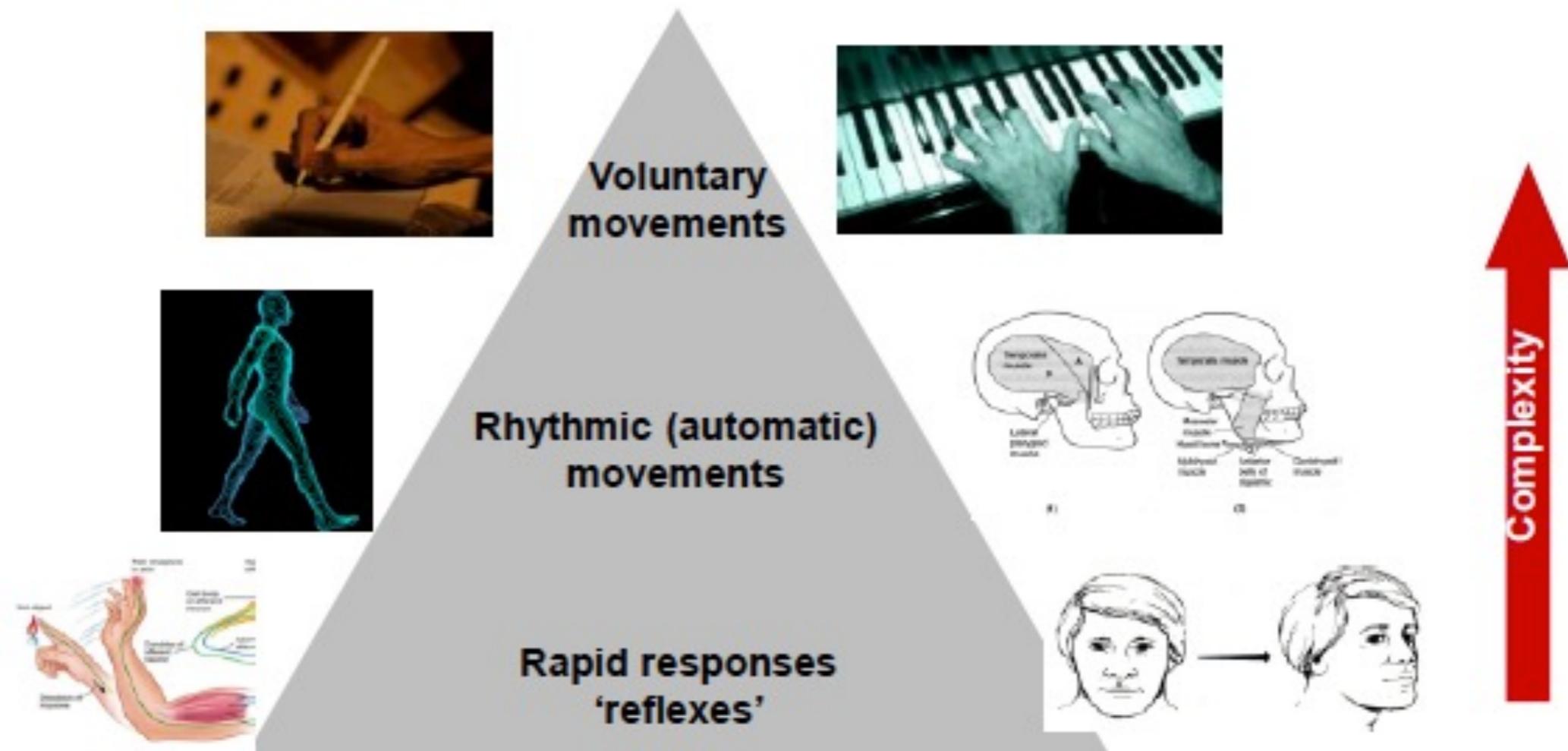
*Motor control*

## « COGNITION IS ACTION »

- Cognition is understood as capacity of generating structure by action;
- The cognitive agent is immersed in his/her task domain;
- System states acquire meaning by virtue of their role in the context of action;
- The functioning of cognitive systems is thought to be inseparable from embodiment;
- A holistic view of the architecture of cognitive systems prevails, which emphasizes the dynamic nature and context-sensitivity of processing;
- Models of cognition take into account the embedded and 'extended' nature of cognitive systems.

— Engel et al., 2013, *Trends Cogn Sci* 17:202

# TYPES OF ACTION



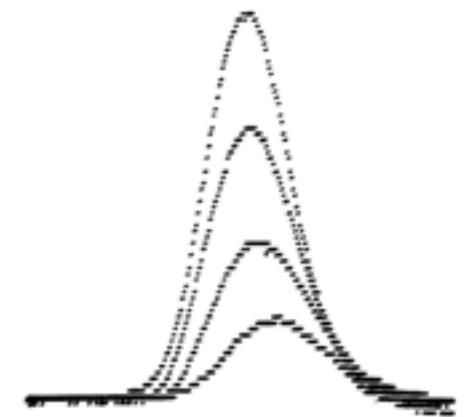
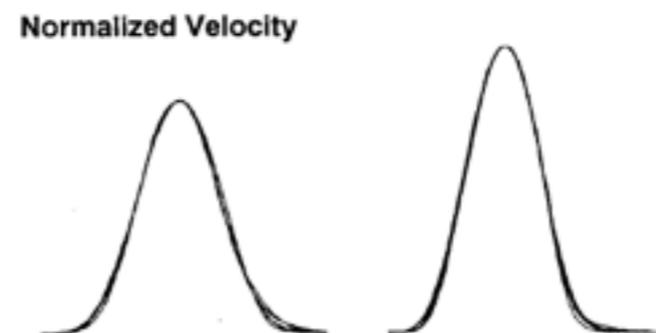
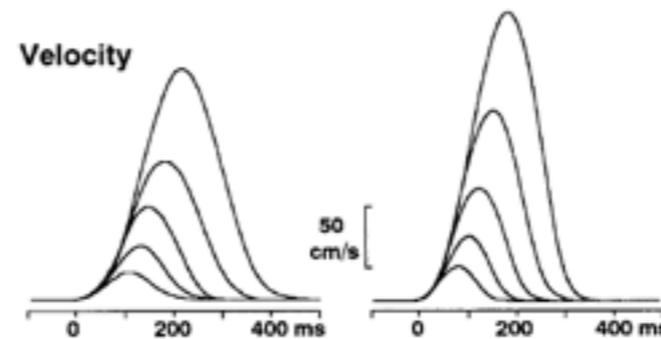
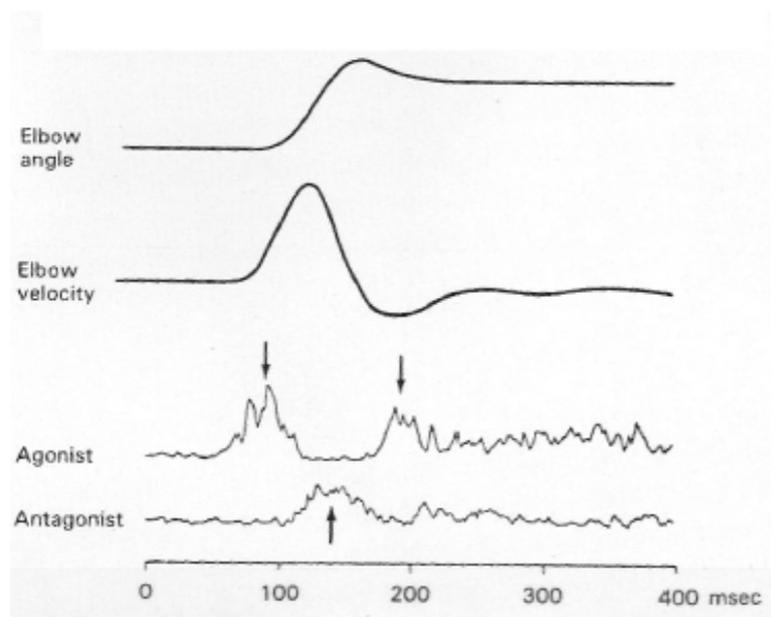
Walking, running, reaching, grasping, speaking, singing, writing, drawing, looking, smiling, keyboarding, ...

# CONTENT OF ACTION

Every action has a specific direction (left/right, toward/away, ...), and intensity (velocity, force, ...)



- Anticipatory electrical activities (EEG, EMG)
- Invariant profiles
- Scaling with task conditions



— Gordon et al., 1994, *Exp Brain Res* 99:112

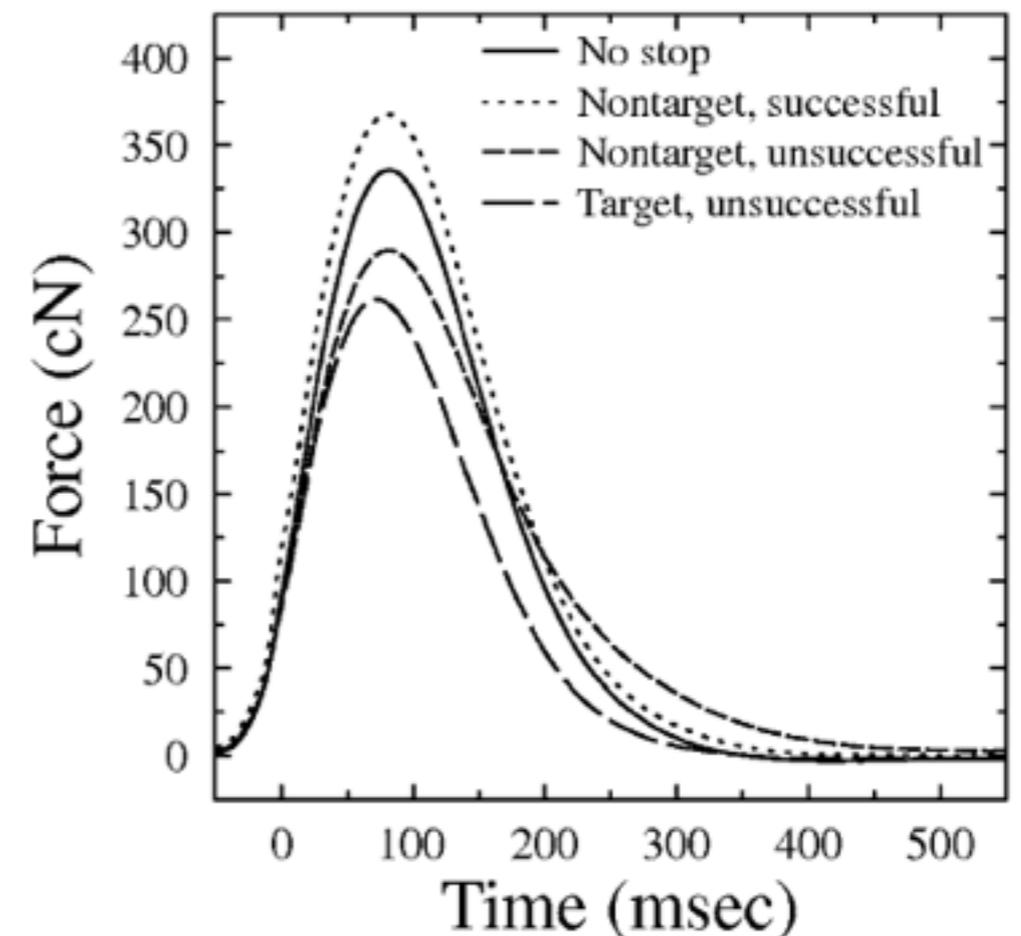
— Angel, 1973,  
*Q J Exp Psychol* 25:193

# ACTION REFLECTS DECISION



## Lexical decision task

Judge the lexical status (word/nonword) of a letter string, and indicate the decision by moving a handle in one direction (word) or in the other direction (nonword)

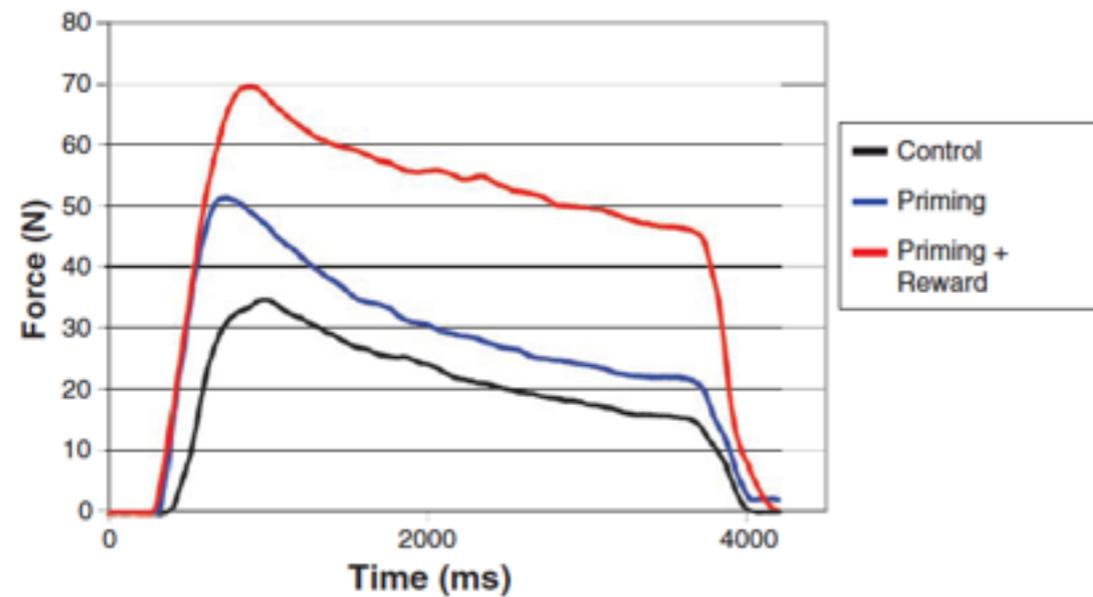


— Ko & Miller, 2011, *Psychon Bull Rev* 18:813

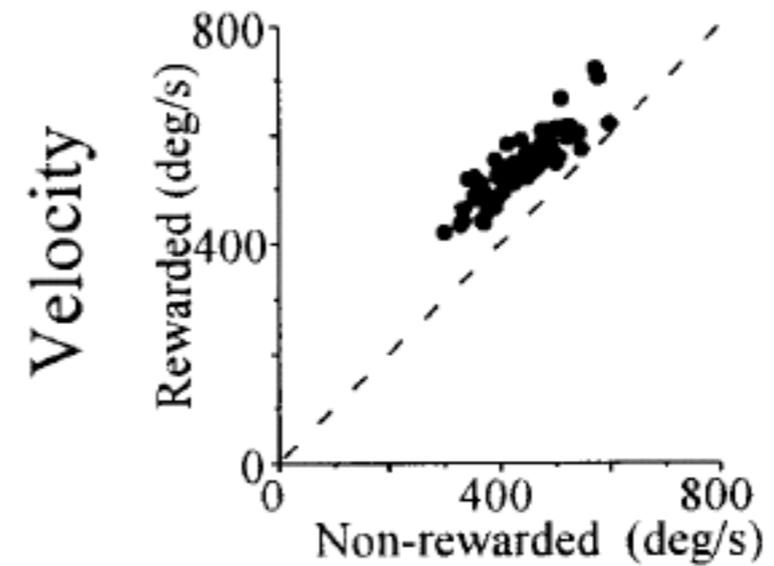
→ Faster movements for words vs nonwords

— Abrams & Balota, 1991, *Psychol Sci* 2:153

# ACTION REFLECTS MOTIVATION

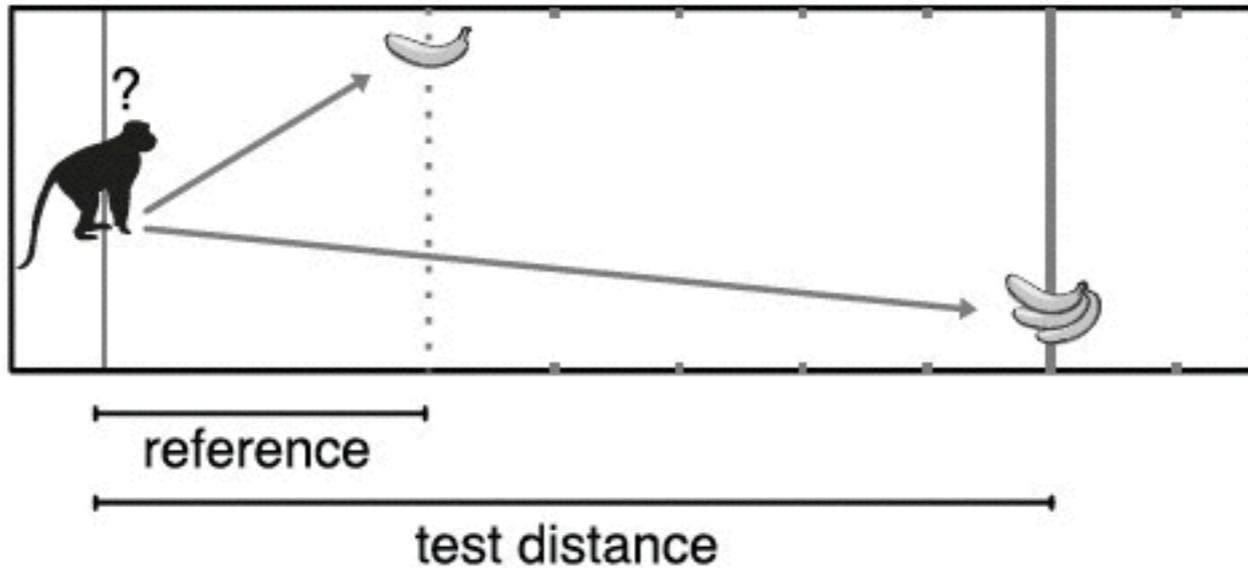


— Aarts et al., 2008, *Science* 19:1639

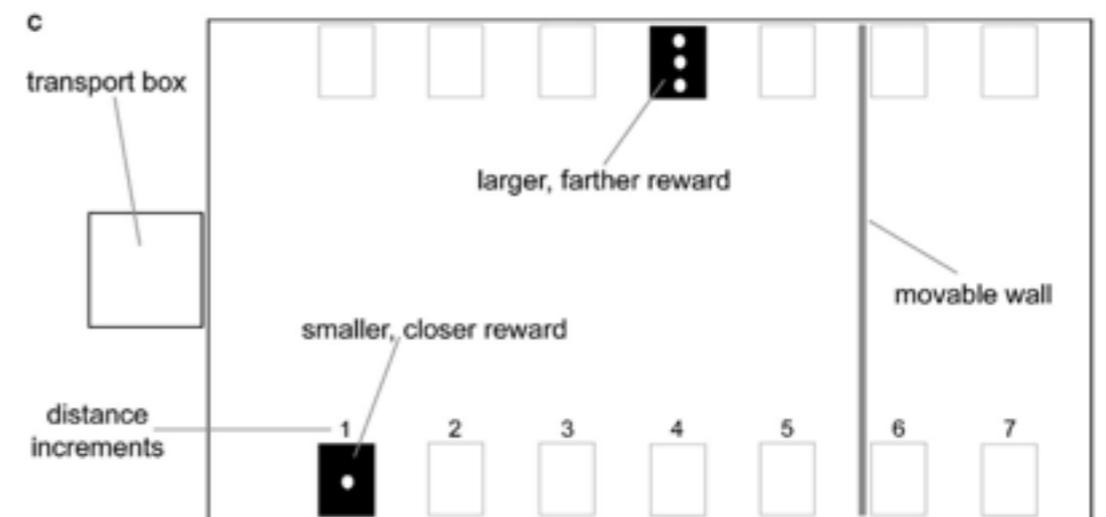
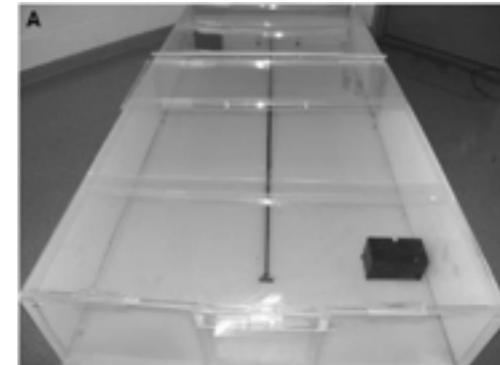
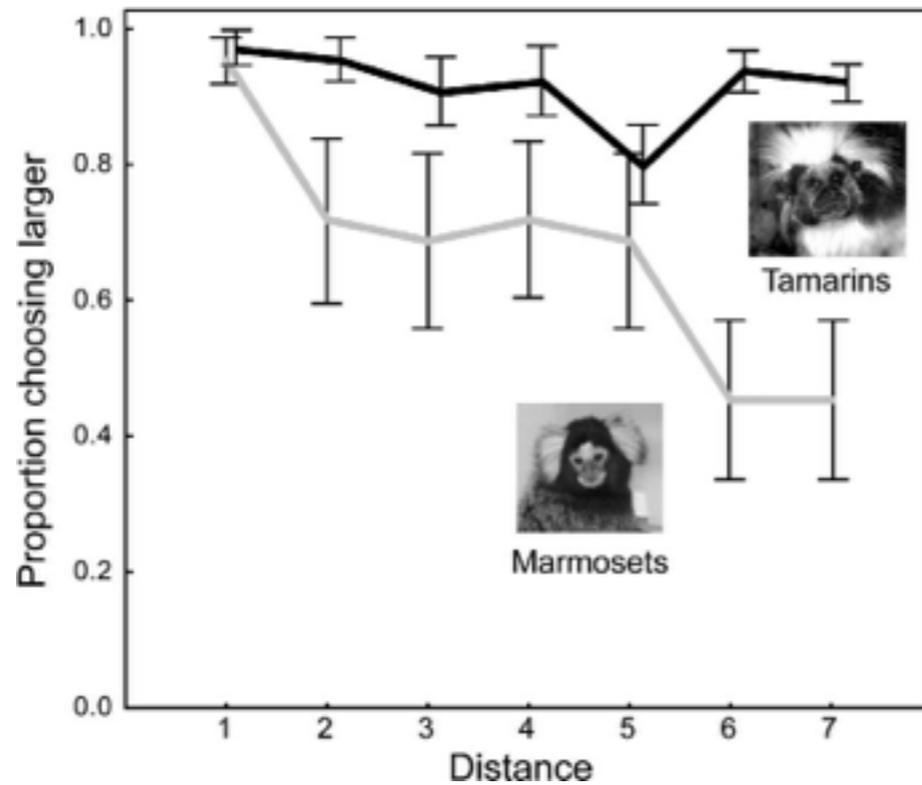


— Takikawa et al., 2002, *Exp Brain Res* 142:284

# ACTION IS DECISION MAKING



— Stevens et al., 2005,  
*Curr Biol* 15:1865



# THE ORGANIZATION OF ACTION

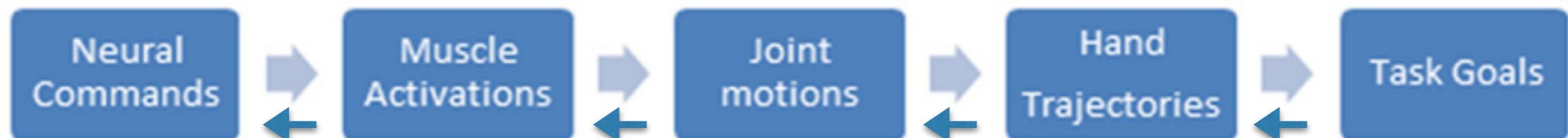
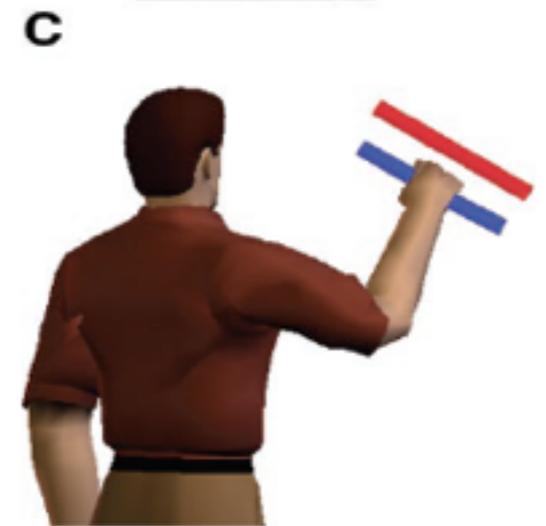
Idea, symbol, object

Space/time displacement/force in task space

Trajectory formation in body space

Joint/muscle force, activations

Neural commands



# LEXICON

## Kinematics

position, velocity, acceleration in task/body space

$$\begin{cases} x = L_1 \cos(\theta_1) + L_2 \cos(\theta_1 + \theta_2) \\ y = L_1 \sin(\theta_1) + L_2 \sin(\theta_1 + \theta_2) \end{cases}$$

## Dynamics

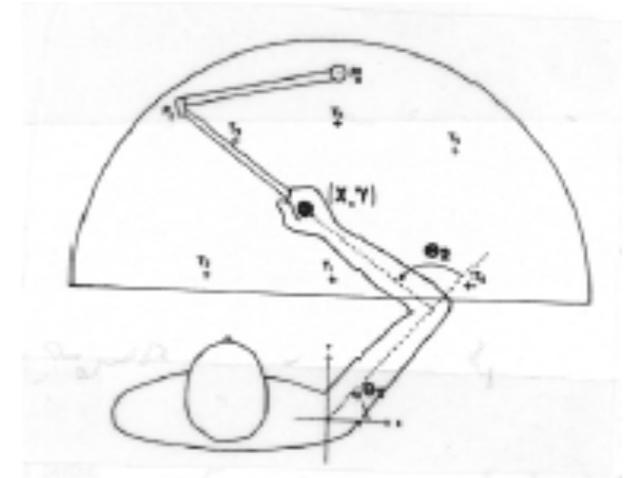
force/torque (Newton's law)

$$\begin{aligned} \tau_1 = & (I_1 + I_2 + m_2 l_1 l_2 \cos \theta_2 + \frac{m_1 l_1^2 + m_2 l_2^2}{4} + m_2 l_1^2) \ddot{\theta}_1 + \\ & (I_2 + \frac{m_2 l_2^2}{4} + \frac{m_2 l_1 l_2}{2} \cos \theta_2) \ddot{\theta}_2 - \\ & \frac{m_2 l_1 l_2}{2} \dot{\theta}_2^2 \sin \theta_2 - m_2 l_1 l_2 \dot{\theta}_1 \dot{\theta}_2 \sin \theta_2 \\ \tau_2 = & (I_2 + \frac{m_2 l_1 l_2}{2} \cos \theta_2 + \frac{m_2 l_2^2}{4}) \ddot{\theta}_1 + \\ & (I_2 + \frac{m_2 l_2^2}{4}) \ddot{\theta}_2 + \frac{m_2 l_1 l_2}{2} \dot{\theta}_1^2 \sin \theta_2 \end{aligned}$$

## Degrees of freedom

« the least number of independent coordinates required to specify the position of the system elements without violating any geometrical constraints »

— Saltzman, 1979, *J Math Psychol* 20:91

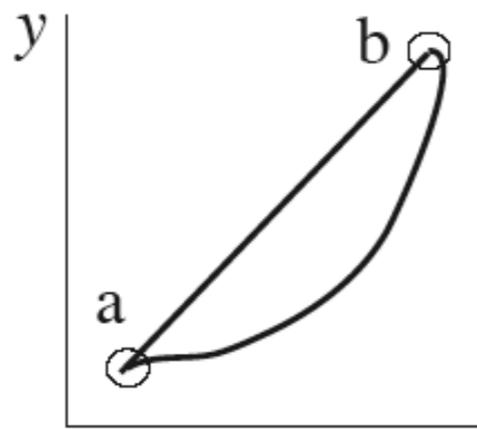


# PROBLEMS

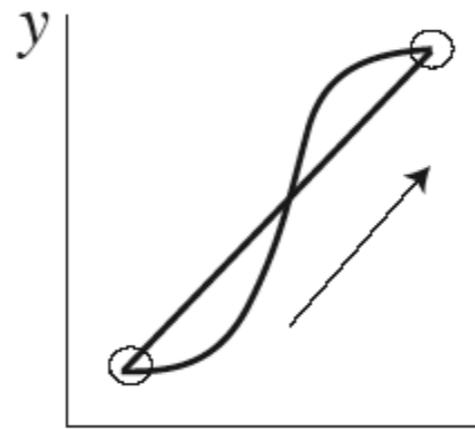
## Redundancy

In task space, body space, muscle space, neural space  
Problem of degrees of freedom (Bernstein's problem)  
600 muscles, 200 joints

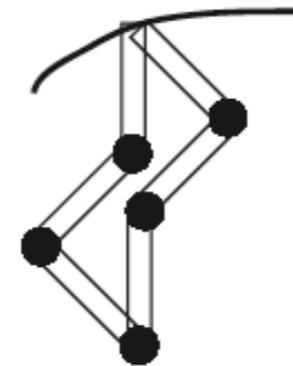
→ *Coordination*



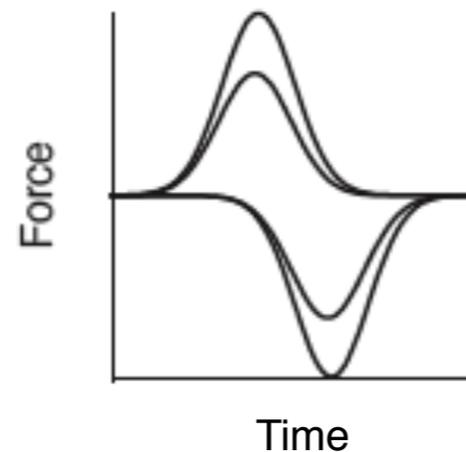
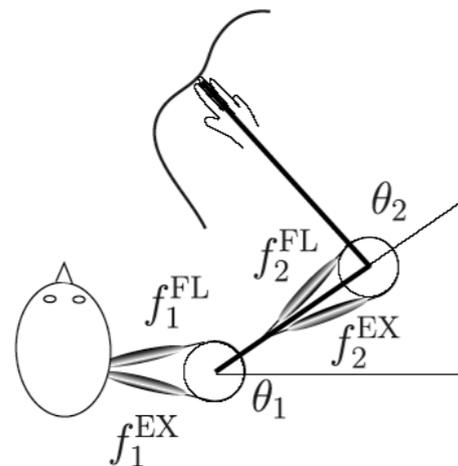
*path in  
task space*



*time  
course*



*body space  
redundancy*



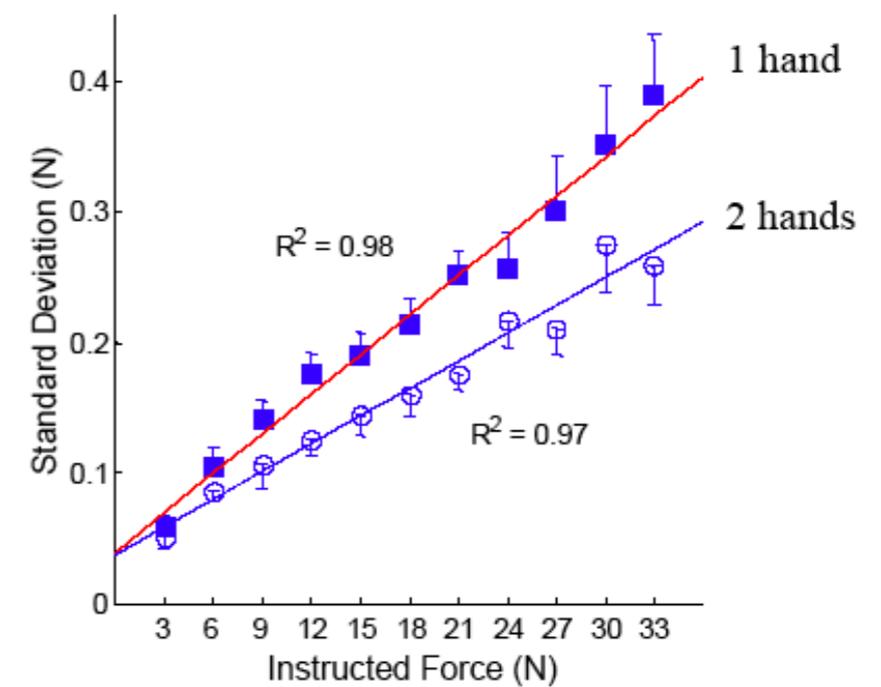
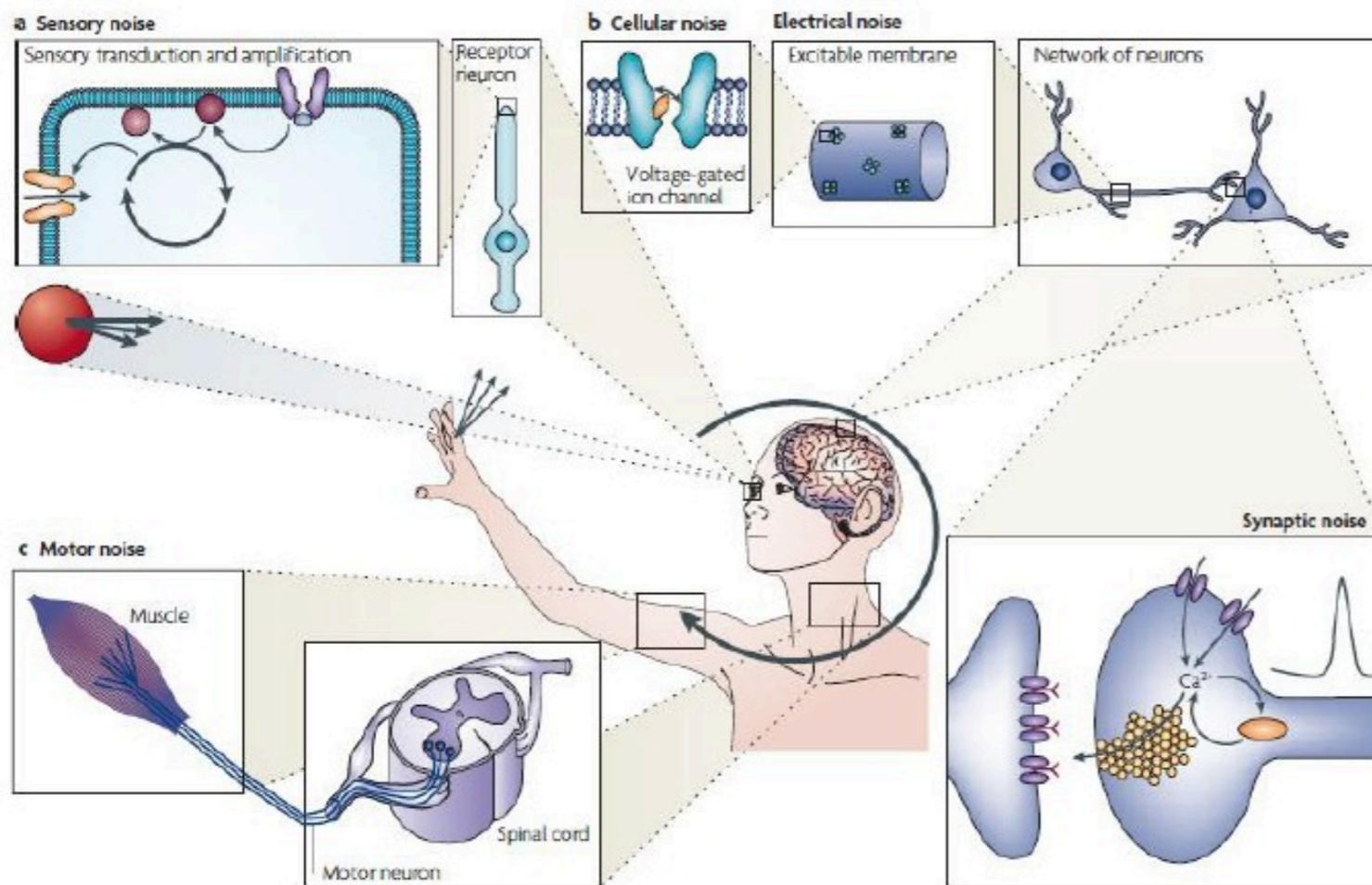
*muscle space  
redundancy*

— Bernstein, 1967, *The Co-ordination and Regulation of Movement*, Pergamon

# PROBLEMS

## Noise

At all stages of sensorimotor processing (sensory, cellular, synaptic, motor)



— Faisal et al., 2008, *Nat Rev Neurosci* 9:292

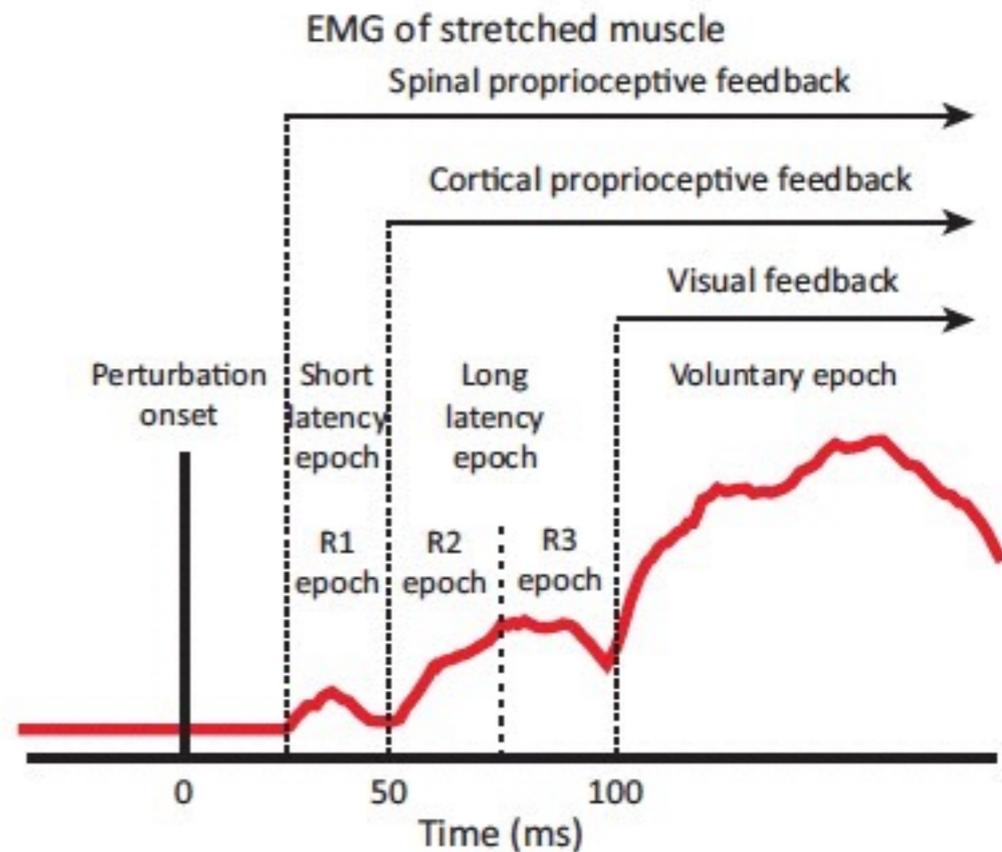
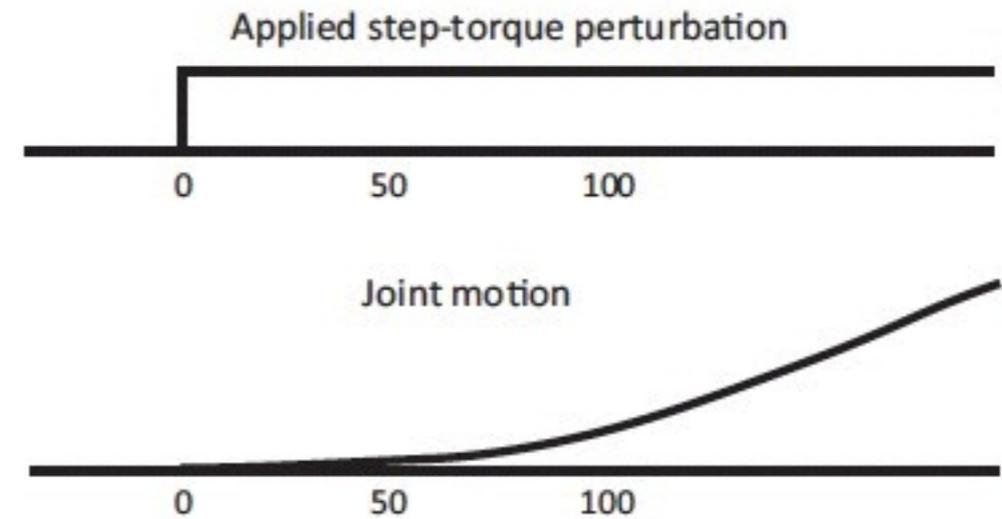
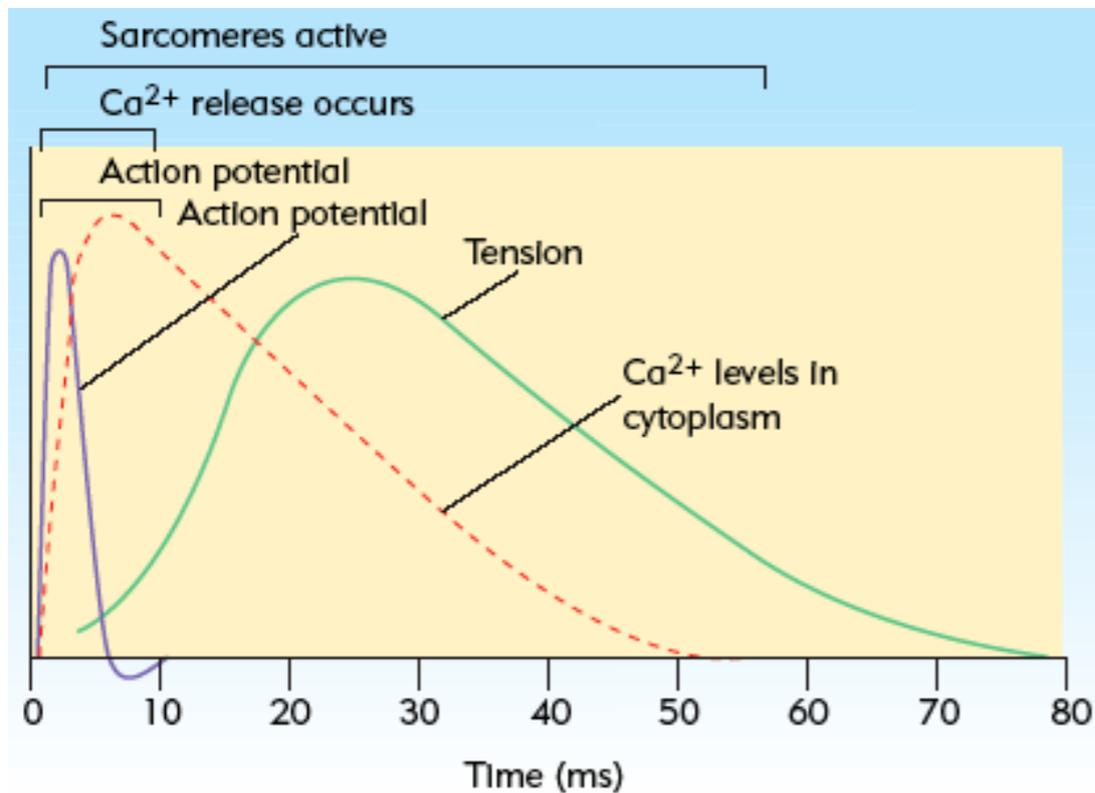
— Todorov, 2002, *Neural Comput* 14:1233

# PROBLEMS

## Delays

In afferent sensory information and efferent motor commands

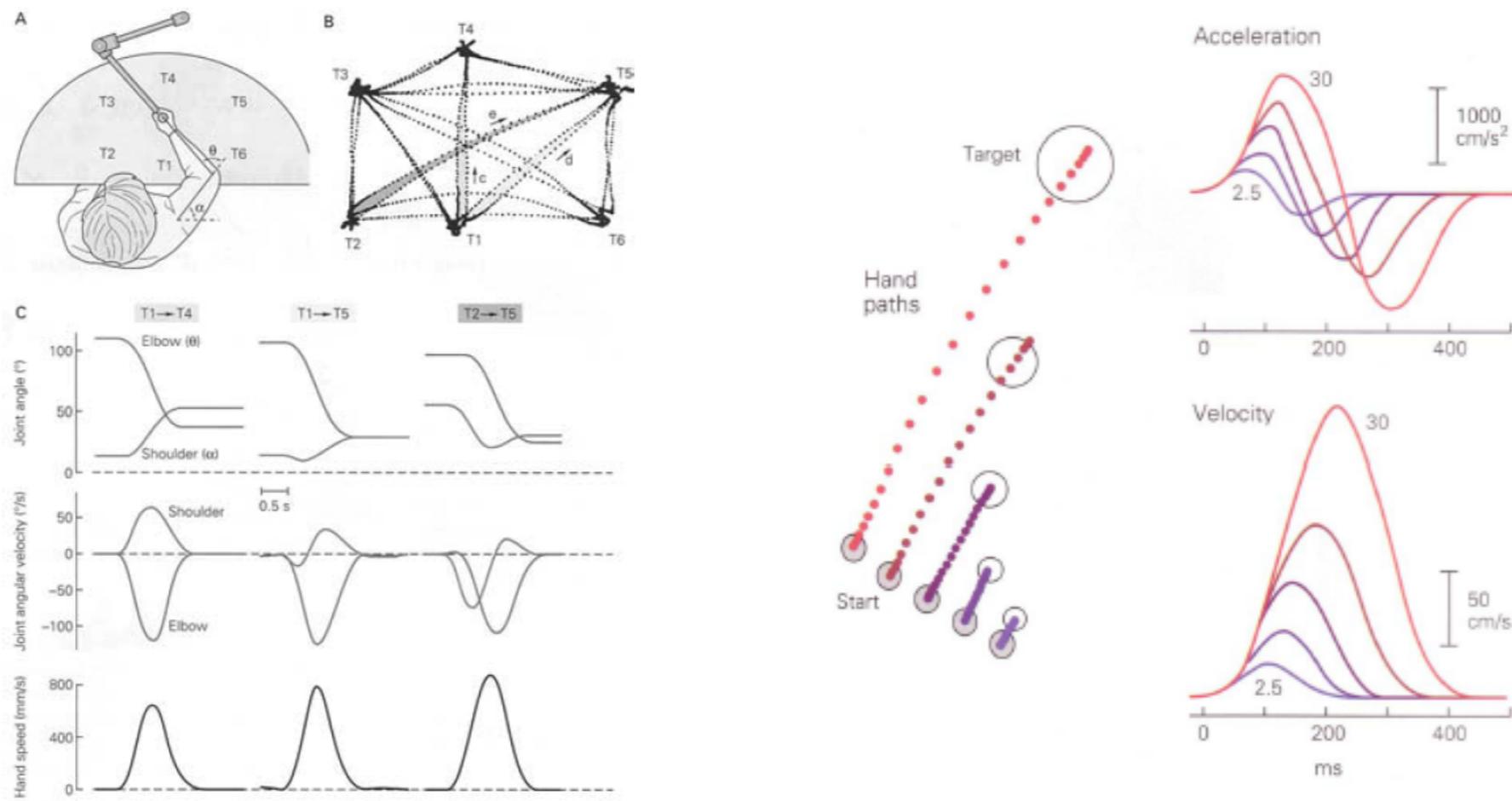
→ “We live in the past”



# MOTOR INVARIANTS

## Trajectories

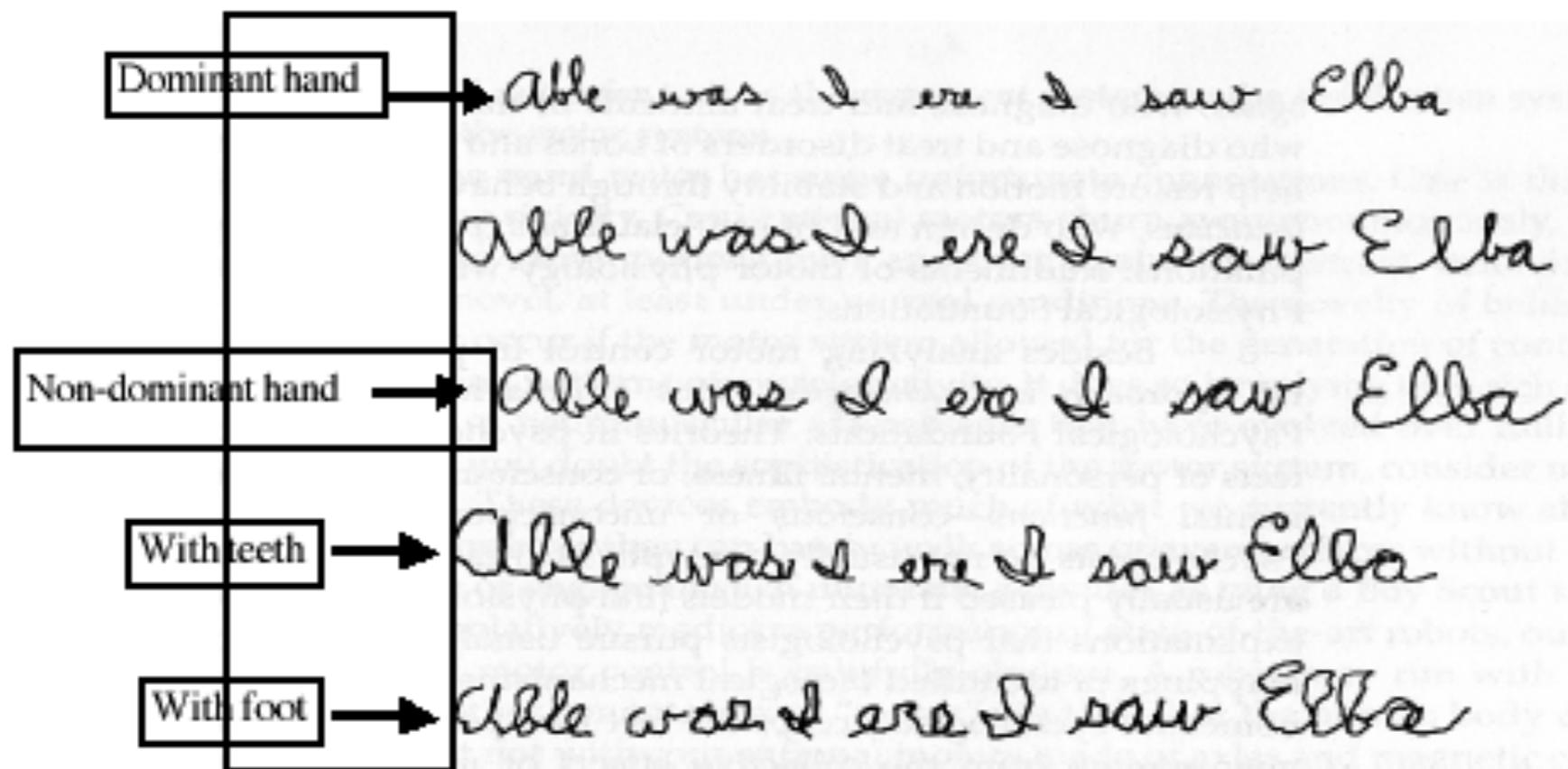
Point-to-point movements are straight with bell-shaped velocity profiles



# MOTOR INVARIANTS

## Motor equivalence

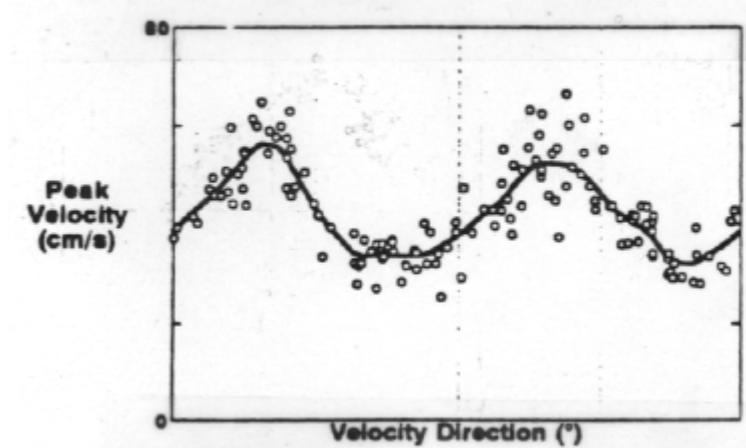
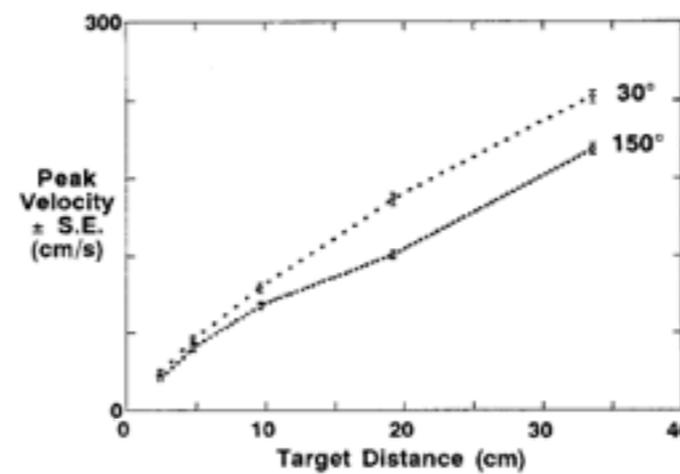
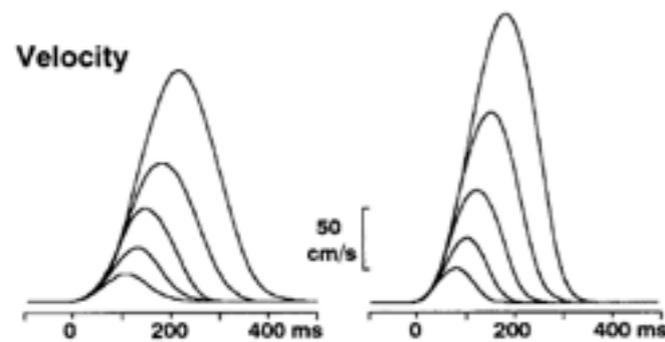
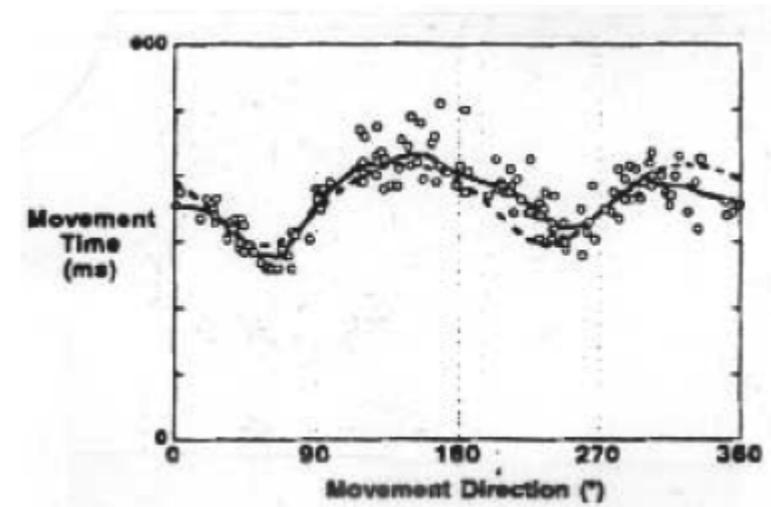
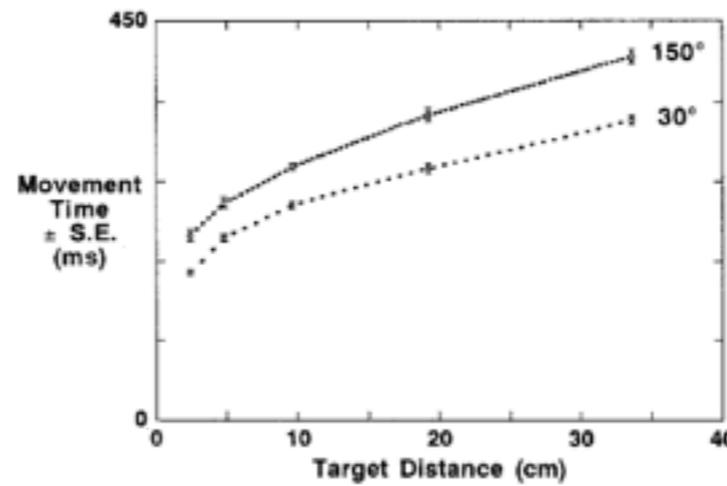
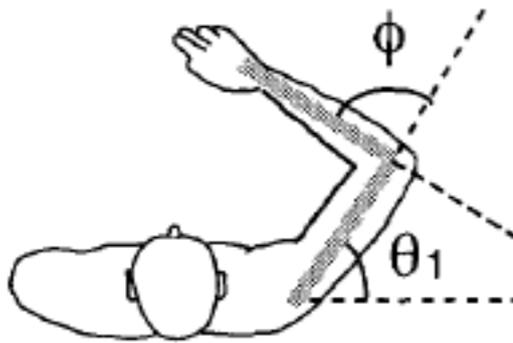
Actions are encoded in the central nervous system in terms that are more abstract than commands to specific muscles



# MOTOR INVARIANTS

## Scaling laws

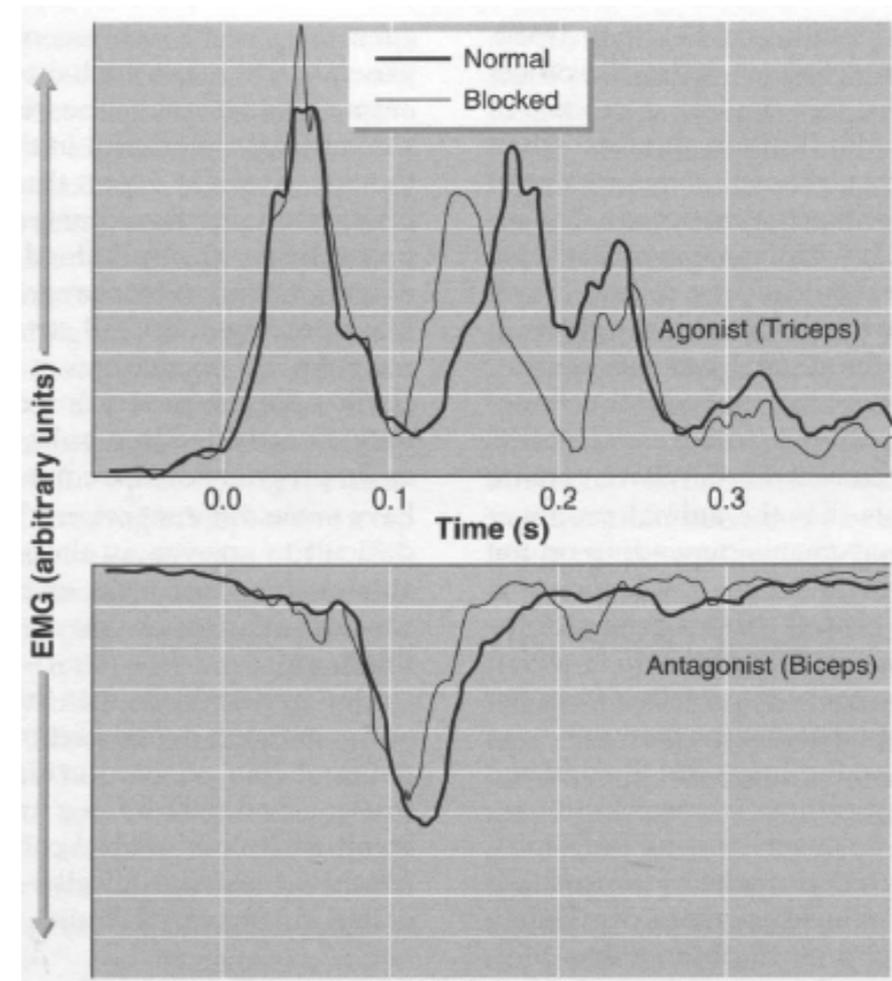
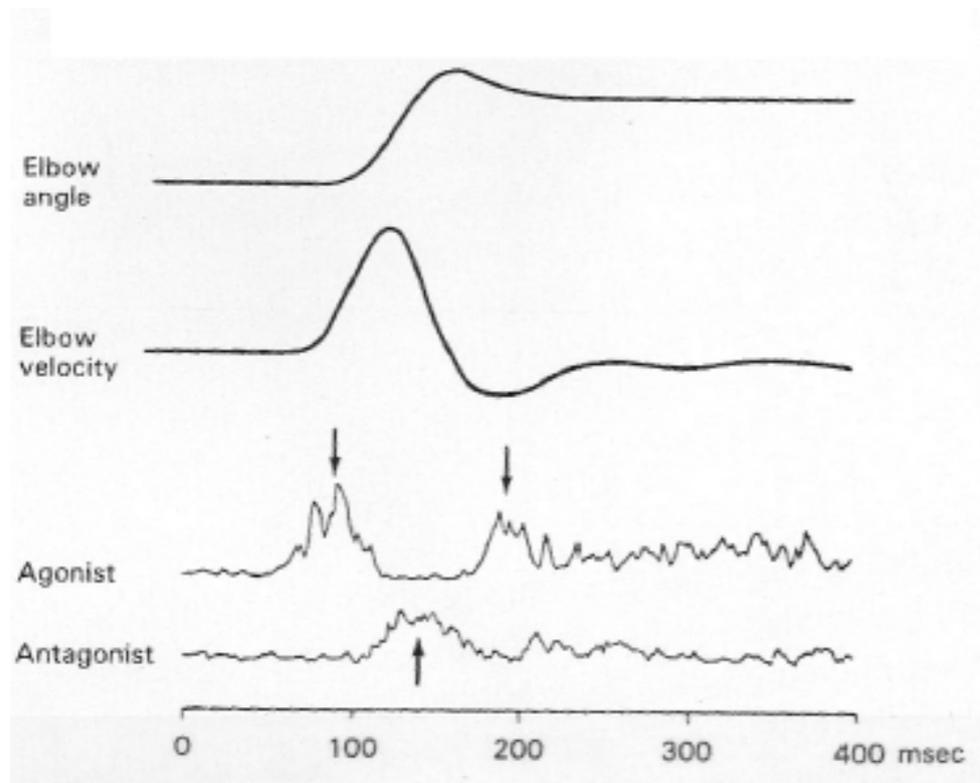
Duration and velocity scale with amplitude and load



# MOTOR INVARIANTS

## EMG

Triphasic pattern during fast movements

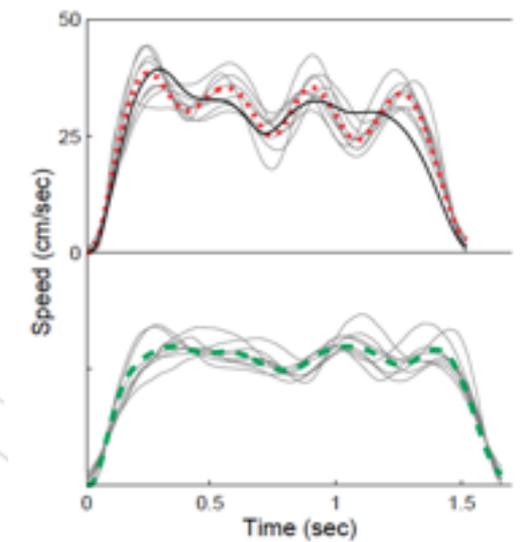
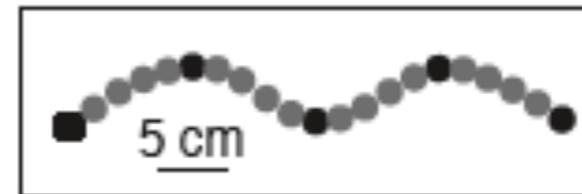
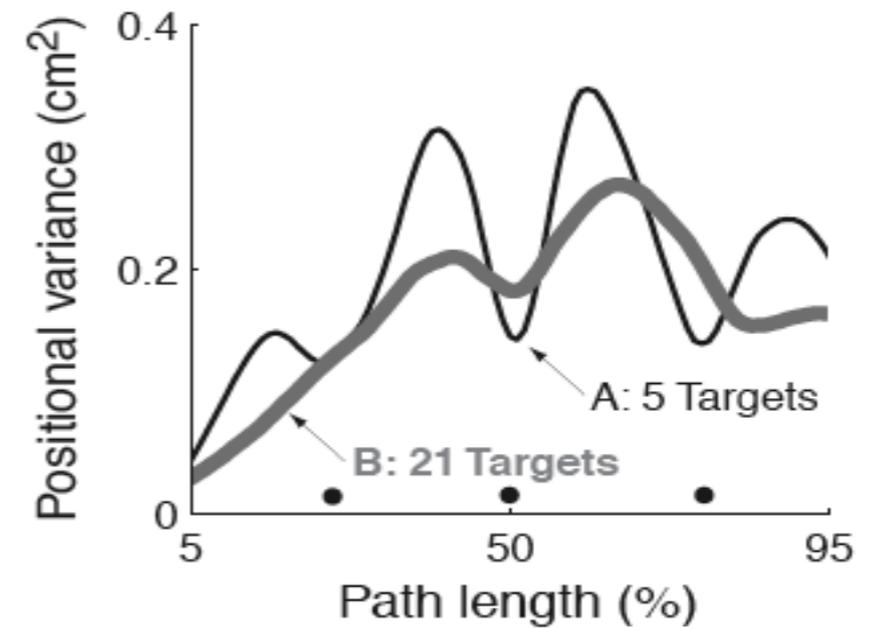
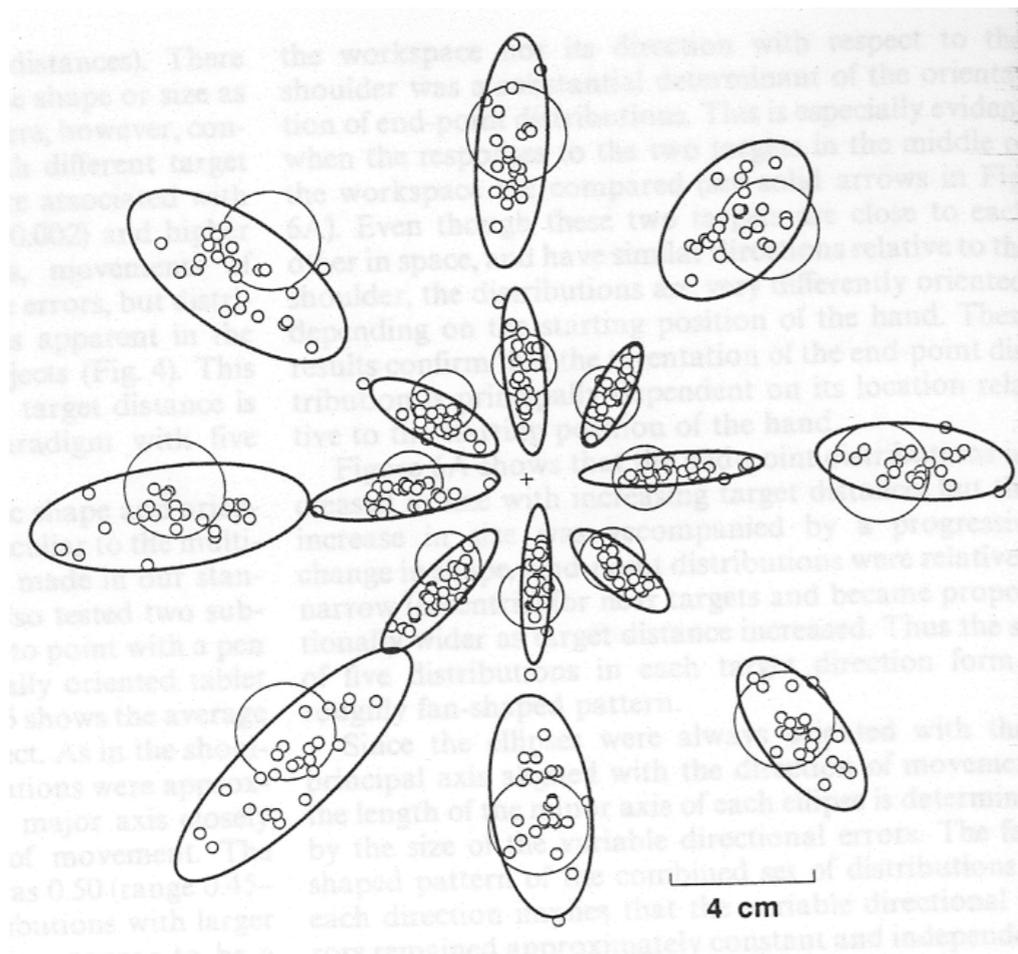
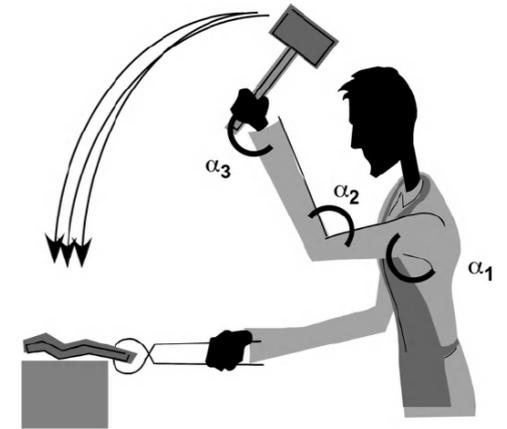


— Wadman et al., 1979, *J Hum Mov Stud* 5:3

# MOTOR VARIABILITY

## Uncontrolled manifold, structured variability

« Repetition without repetition » (Bernstein)



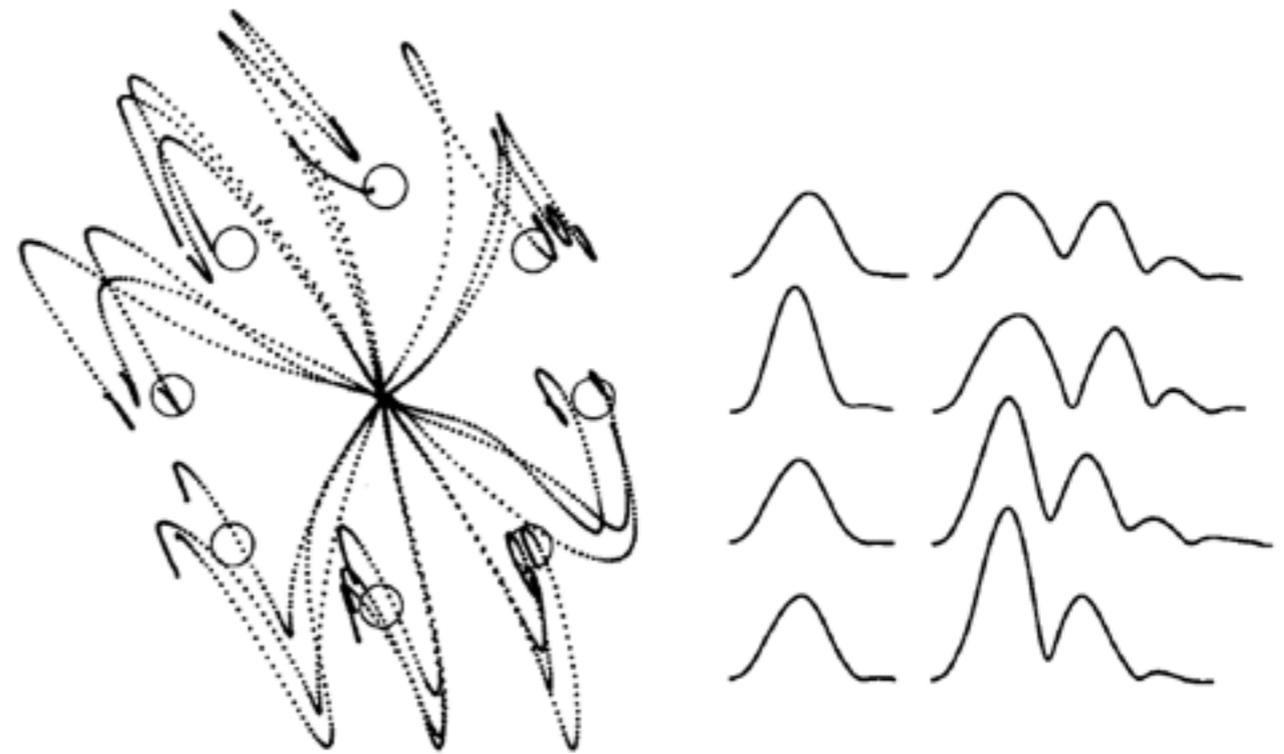
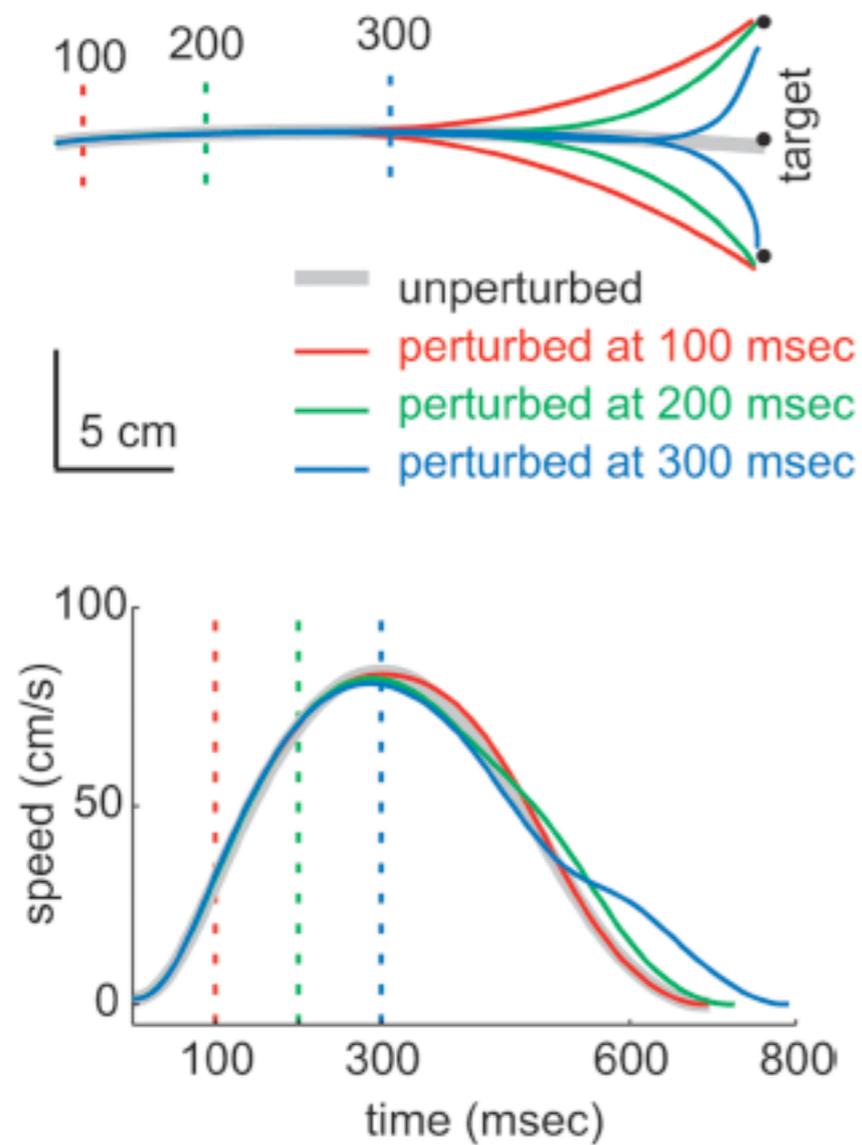
# MOTOR INVARIANTS AND VARIABILITY

**Are motor invariants are really invariants  
or simply by-products of control?**

**Motor variability is as important as  
motor invariants (structure of variability)**

# FLEXIBILITY

Motor control is highly flexible in space and time



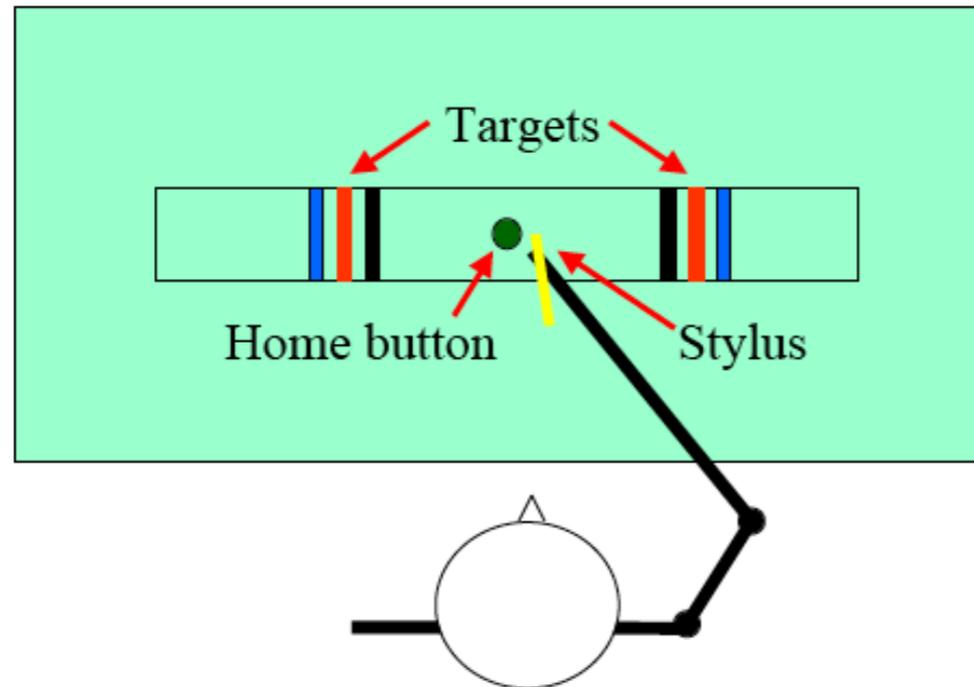
— Shadmehr & Mussa-Ivaldi, 1994, *J Neurosci* 14:3208

— Liu & Todorov, 2007, *J Neurosci* 27:9354

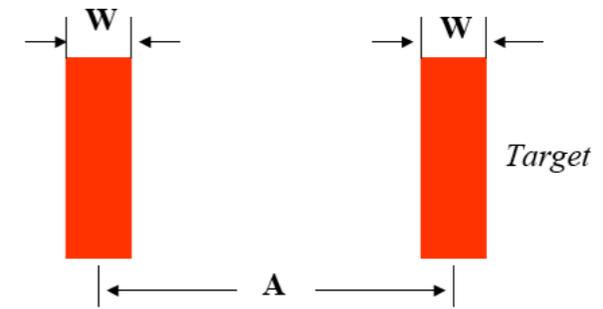
# LAWS OF MOVEMENT

## Fitts' law

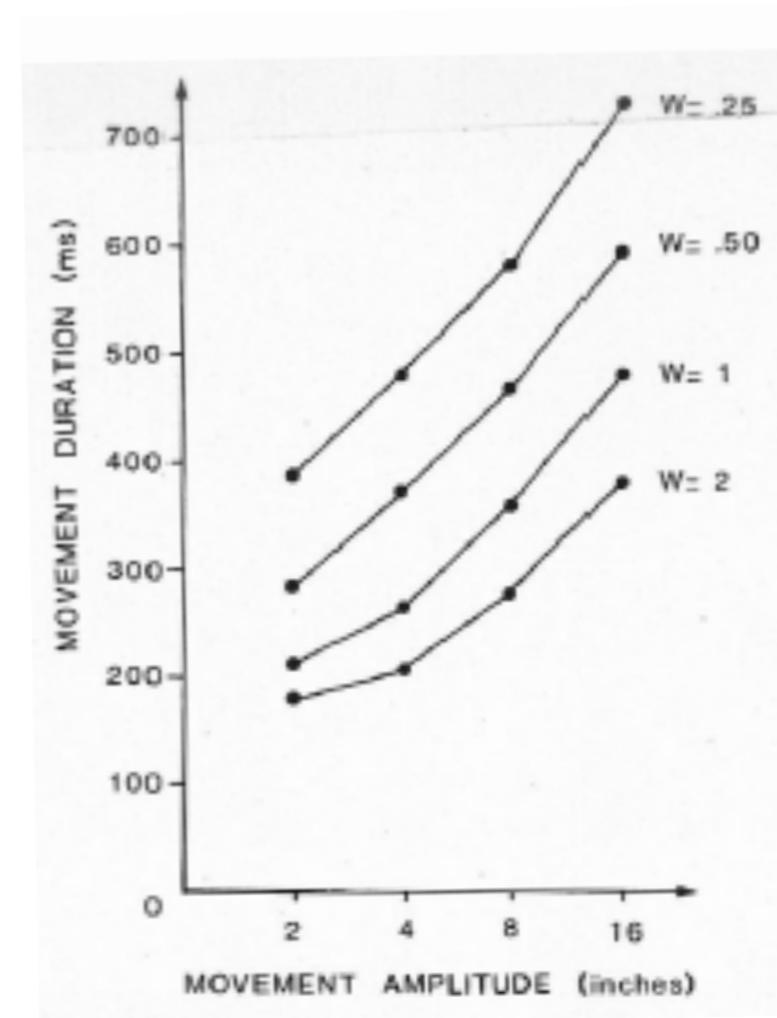
Speed/accuracy trade-off



— Fitts, 1954, *J Exp Psychol* 47:381



$$MT = a + b \underbrace{[\text{Log}_2 (2A/W)]}_{\text{ID (index of Difficulty)}}$$



# COMPUTATIONAL MOTOR CONTROL

## Descriptive (mechanistic) vs normative models

- Descriptive statements present an account of how the world is
- Normative statements present an evaluative account, or an account of how the world should be



*Action characteristics result from properties of synapses, neurons, neural networks, muscles, ...*



*Action characteristics result from principles, overarching goals, ...*

**Problems: planning, control, estimation, learning**

# THEORETICAL BASES

## Dynamical systems theory

Describes the behavior in space and time of complex, coupled systems.

$x[n]$  state  $y[n]$  output (observation)

$u[n]$  input (control)

$x[n + 1] = f(x[n], u[n])$  state equation

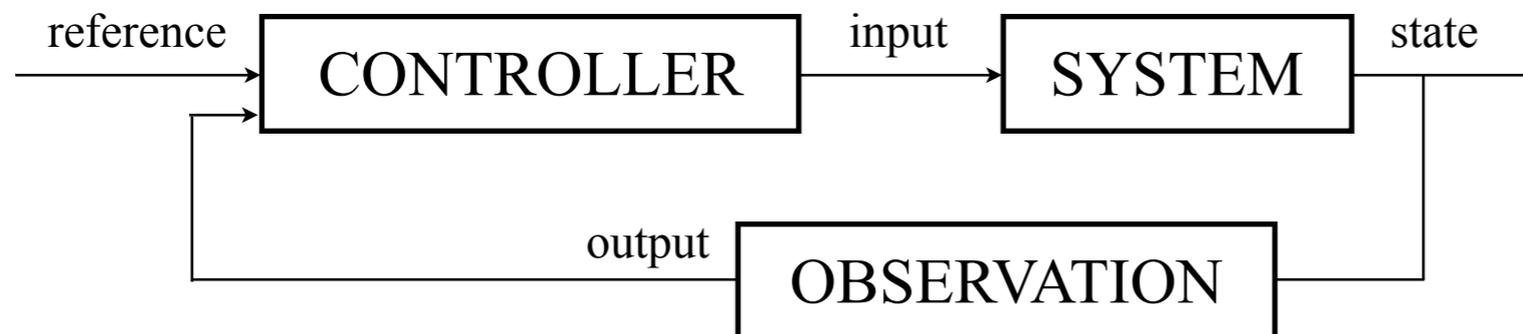
$y[n] = g(x[n])$  output equation

$y[n + 1] = h(x[n], u[n])$

**state:** « the smallest possible subset of system variables that can represent the entire state of the system at any given time »

## Control theory

Deals with the behavior of dynamical systems with inputs, and how their behavior is modified by feedback.



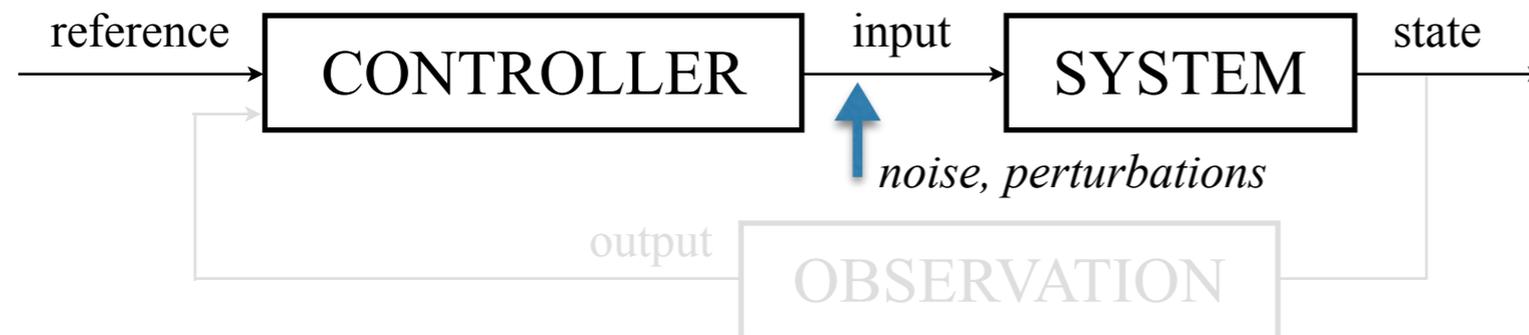
**reference**

- desired trajectory
- fixed point

# TWO CONTROL PRINCIPLES

## Open-loop (feedforward)

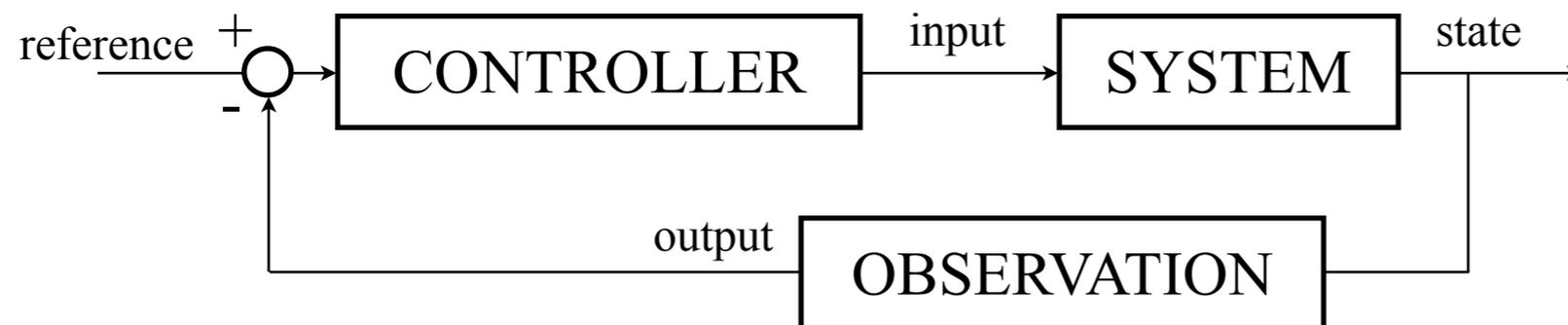
The controller is an *inverse* model of the system.



- Predictive control
- Model-based
- Sensitive to modeling uncertainty
- Sensitive to unexpected, unmodeled perturbations

## Closed-loop (feedback)

The controller is a function of an error signal.



- Error correction
- No model
- Not sensitive to modeling uncertainty
- Robust to perturbations

# INTERNAL MODELS

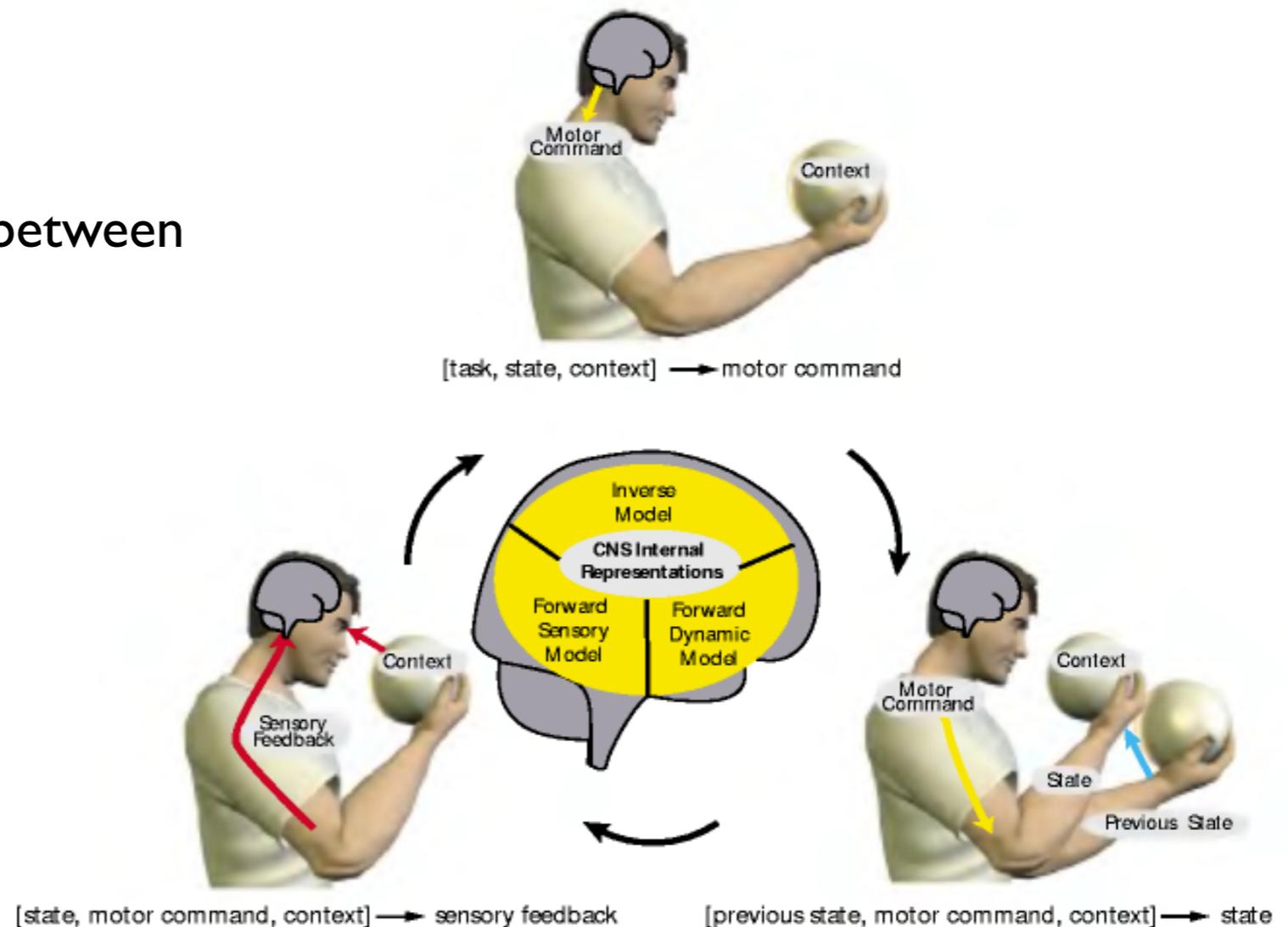
## Direct (forward) model

Model of the causal relationship between inputs and their consequences (states, outputs).

## Inverse model

Model of the relationship between desired consequences and corresponding inputs.

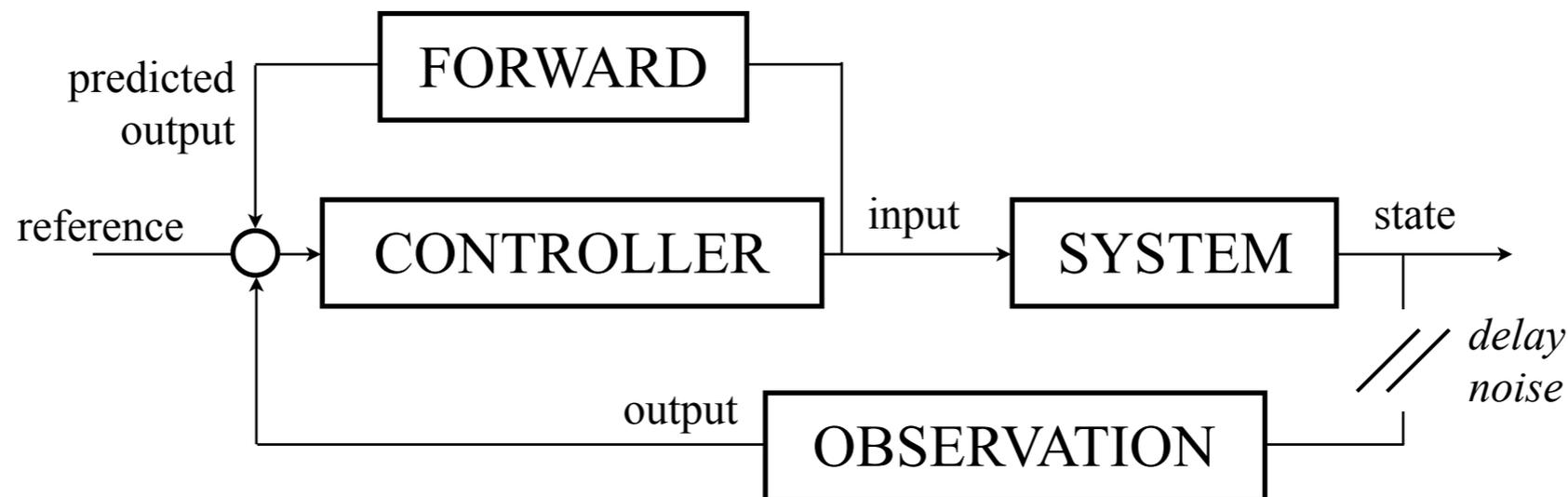
*! Ill-defined model*



# ROLE OF FORWARD MODELS

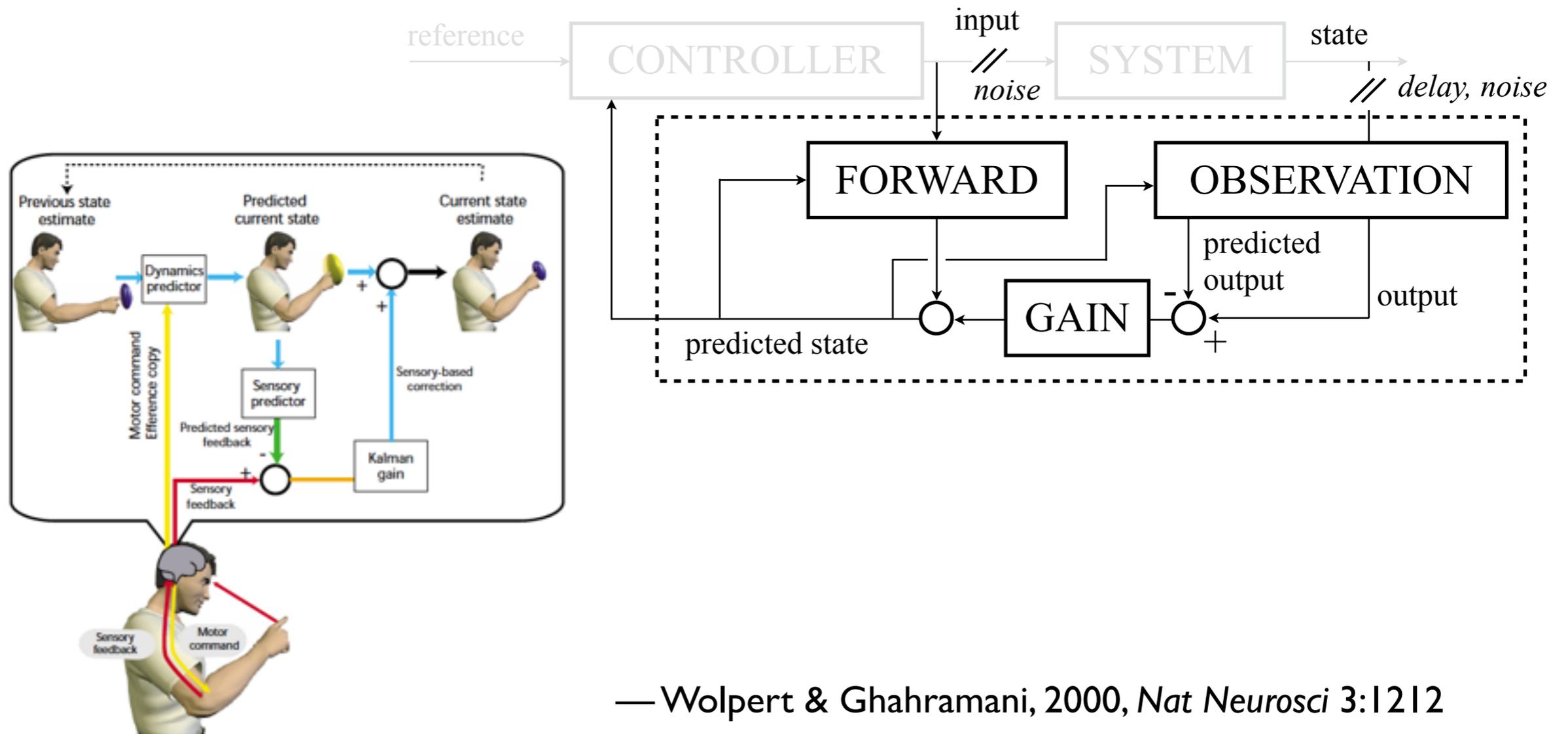
A system can use a direct model rather than an external feedback to evaluate the effect of command and its associated error.

Avoid the instability due to delays in feedback loops.



# THE KALMAN FILTER

Combines a forward model and a state observation to obtain the best state prediction in the presence of delays and noise



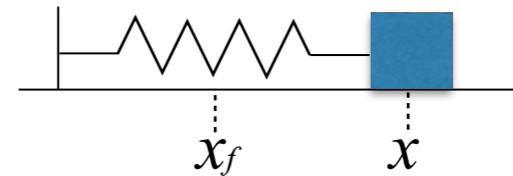
— Wolpert & Ghahramani, 2000, *Nat Neurosci* 3:1212

# TWO MAIN THEORIES

## Task-dynamics approach

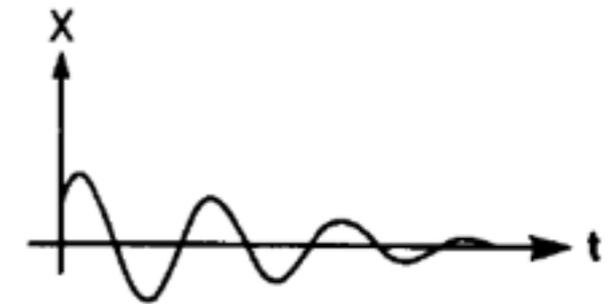
Generalized closed-loop systems.  
Movements result from convergence to attractors of a dynamical system.

*Action systems approach*  
*Dynamical systems*  
*Ecological psychology*



$$m\ddot{x} + b\dot{x} + k(x - x_f) = 0$$

$$x = x(t, m, b, k)$$

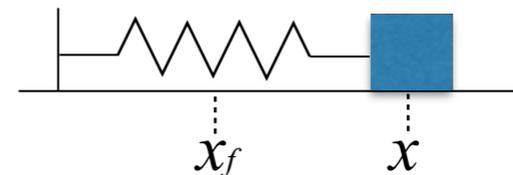


Saltzman & Kelso (1987)

## Internal model approach

Builds an inverse model of the system to follow a prescribed trajectory or match some constraints (e.g. optimization).

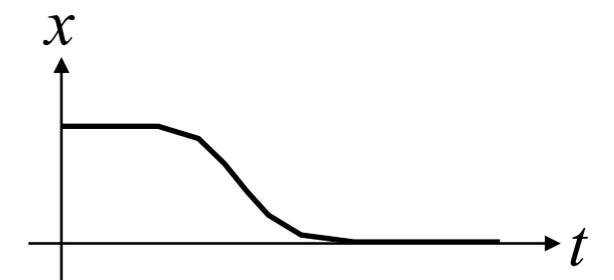
*Information processing approach*  
*Cognitive approach*  
*Motor programs*



$$m\ddot{x} + b\dot{x} + k(x - x_f) = u$$

$$u = u(t, m, b, k)$$

$$x = x(t, u)$$



# OPTIMALITY PRINCIPLE\*

The interaction between the behavior and the environment leads a better adaptation of the former to the latter. The tendency could lead to an optimal behavior, i.e. the best behavior corresponding to a goal, according to a given criterion.

The idea is to describe a movement not in terms of its characteristics (kinematics, dynamics), but in an abstract way, using a global value to be maximized or minimized.

E.g. smoothness, energy, variability, ...

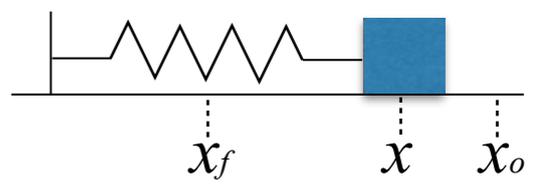
**\*Debated issue (e.g. — Schoemaker, 1991, *Behav Brain Sci* 14:205)**

# OPTIMAL MOTOR CONTROL

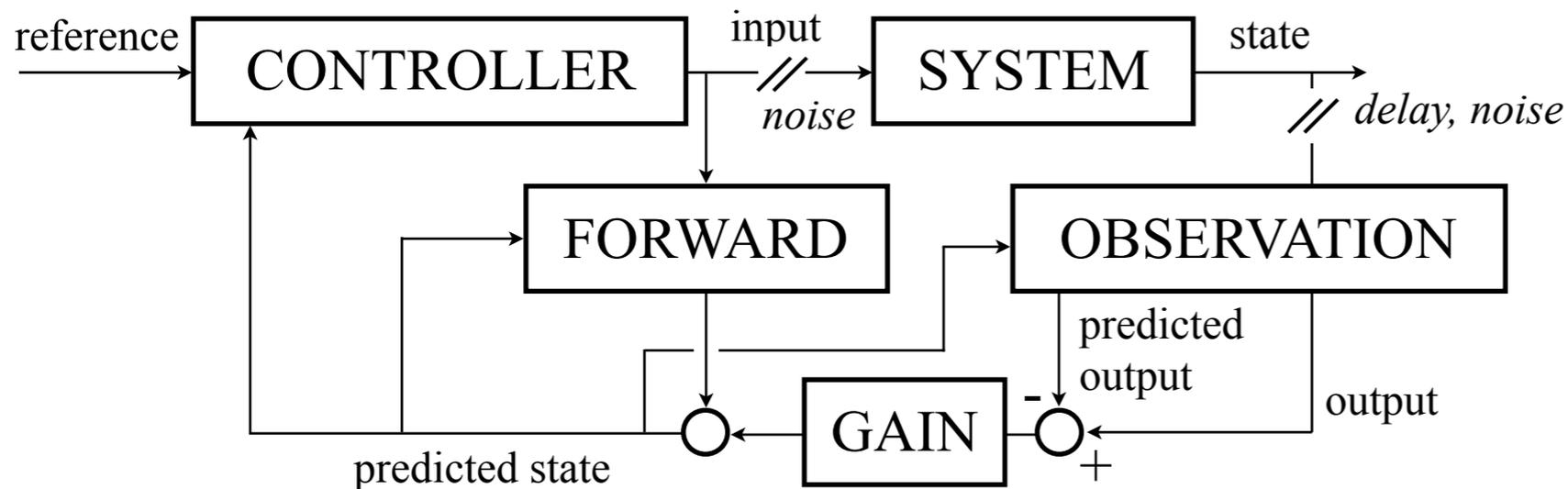
## Extension of the internal model approach

control theory → optimal control theory

Define an « objective function »: minimization/  
maximization of task and action related quantities  
(*cost, utility*)

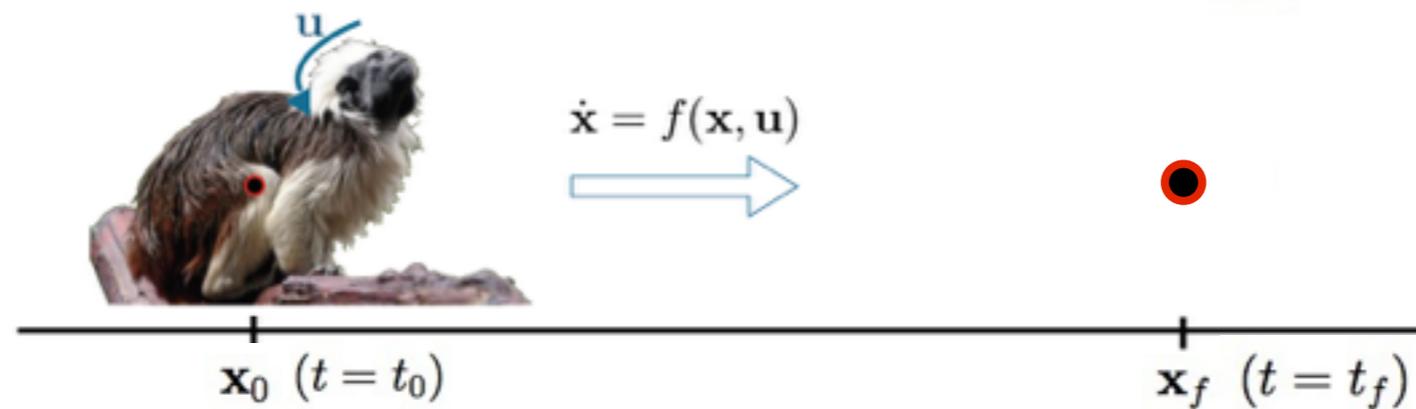


Find the smallest  $u(t)$   
( $t$  in  $[t_o; t_f]$ ) such that  
 $x(t_o) = x_o, x(t_f) = x_f$   
and  
 $m\ddot{x} + b\dot{x} + k(x - x_f) = u$



# FROM MOVEMENT TO ACTION

## Movement

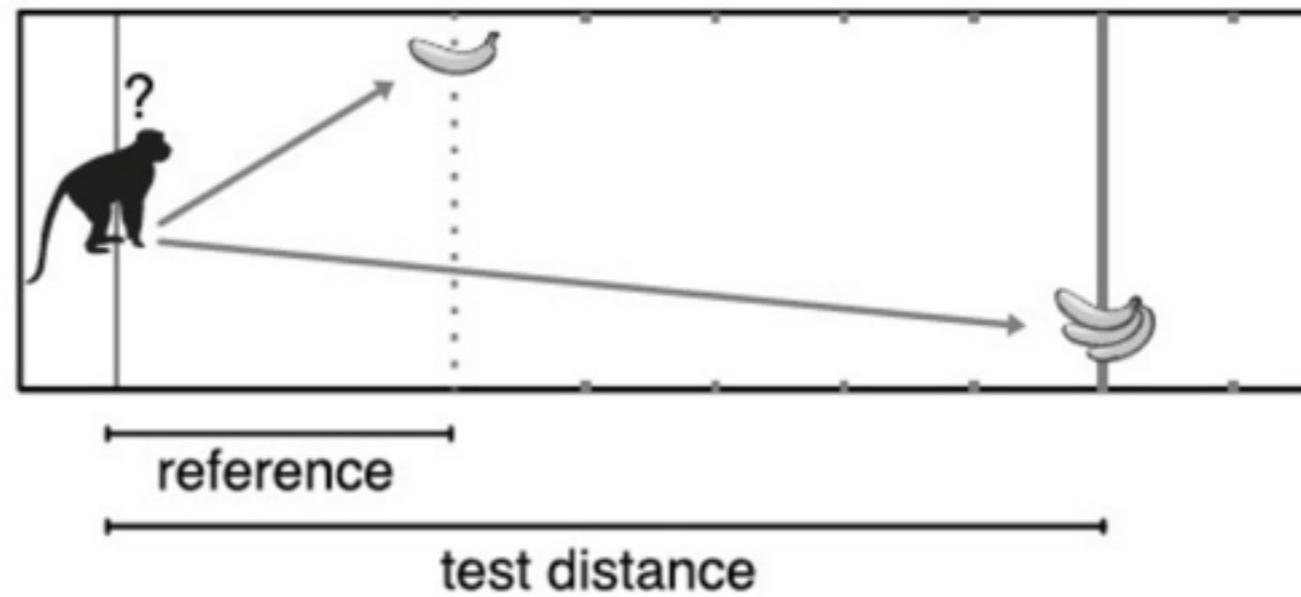
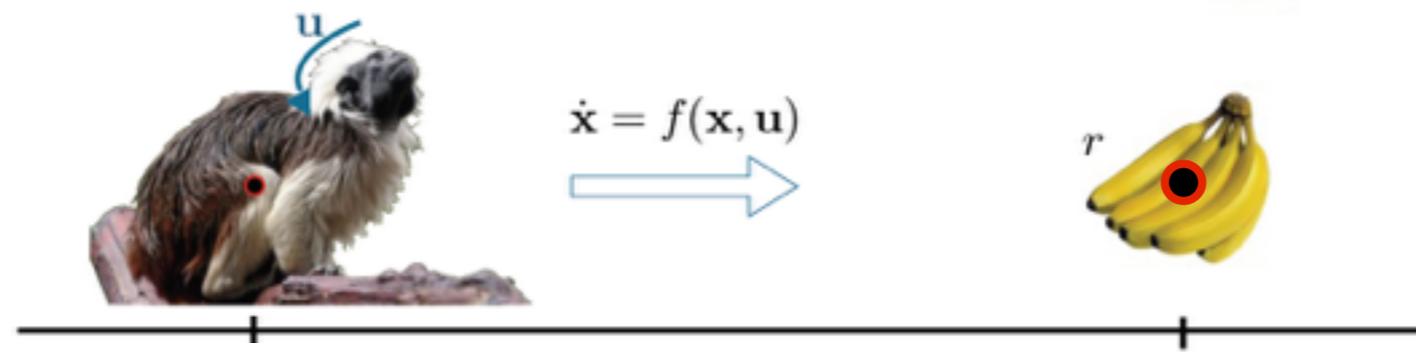


$$J^* = \min_{\mathbf{u}} \int_{t_0}^{t_f} \|\mathbf{u}(t)\|^2 dt$$

*Minimizing costs, fixed time*

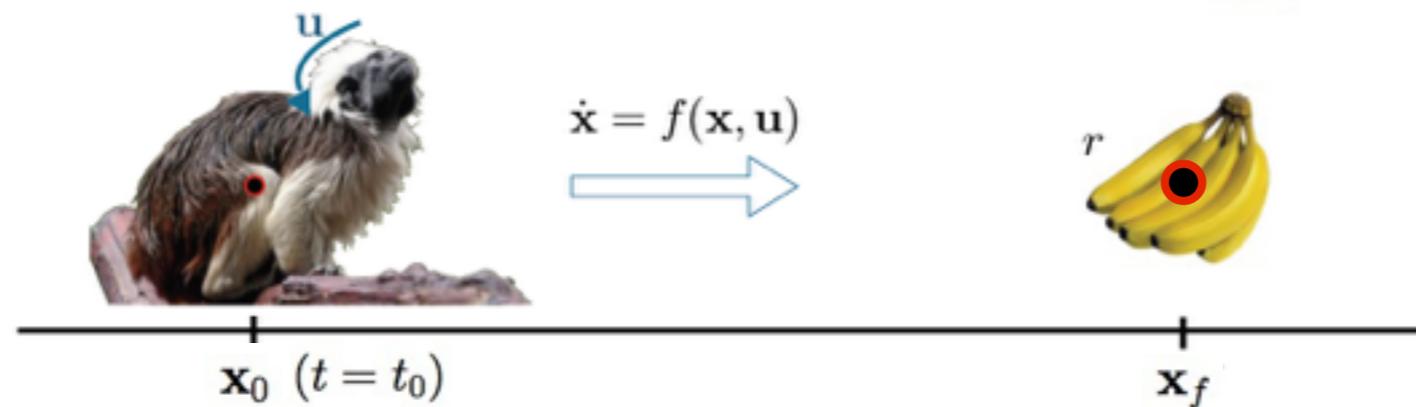
# FROM MOVEMENT TO ACTION

## Action



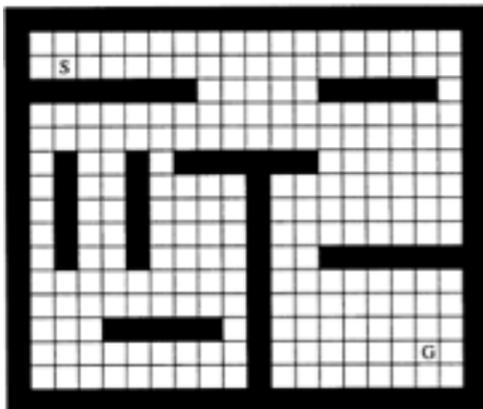
# FROM MOVEMENT TO ACTION

## Reinforcement learning



$$V(\mathbf{x}_t) = E[r_t + \gamma r_{t+1} + \gamma^2 r_{t+2} + \dots | \mathbf{x}_t]$$

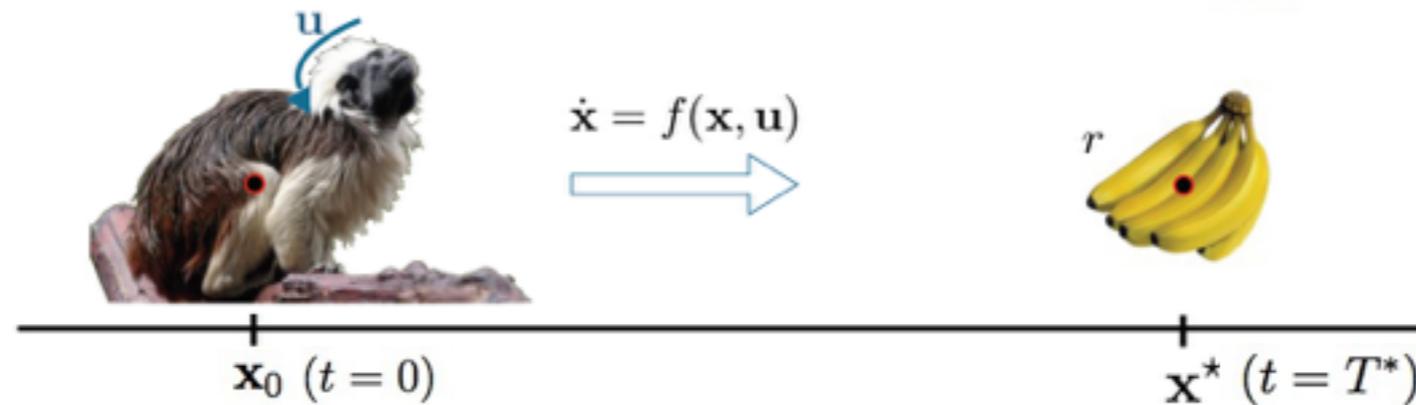
*Maximizing benefits, open time*



— Sutton & Barto, 1998, *Reinforcement Learning*, MIT Press

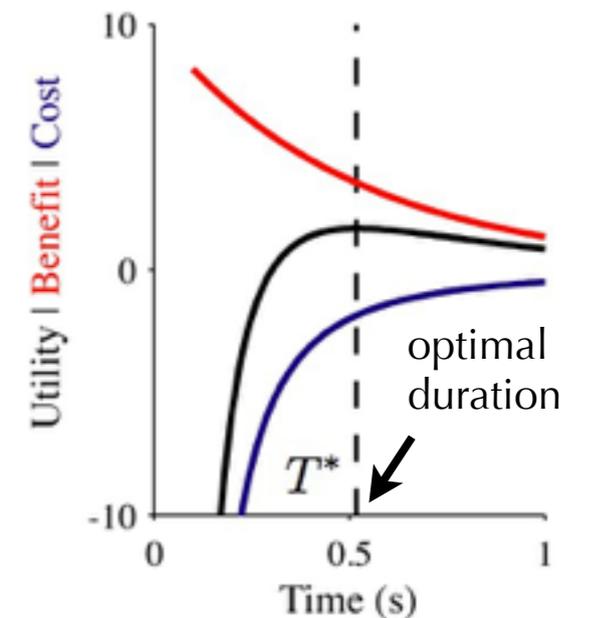
# FROM MOVEMENT TO ACTION

## Reward/effort trade-off



$\mathbf{x}$	state
$\mathbf{u}$	control
$r$	reward
$\gamma$	discount factor
$\rho$	benefit scaling
$\varepsilon$	cost scaling
$\mathbf{x}^*$	target state

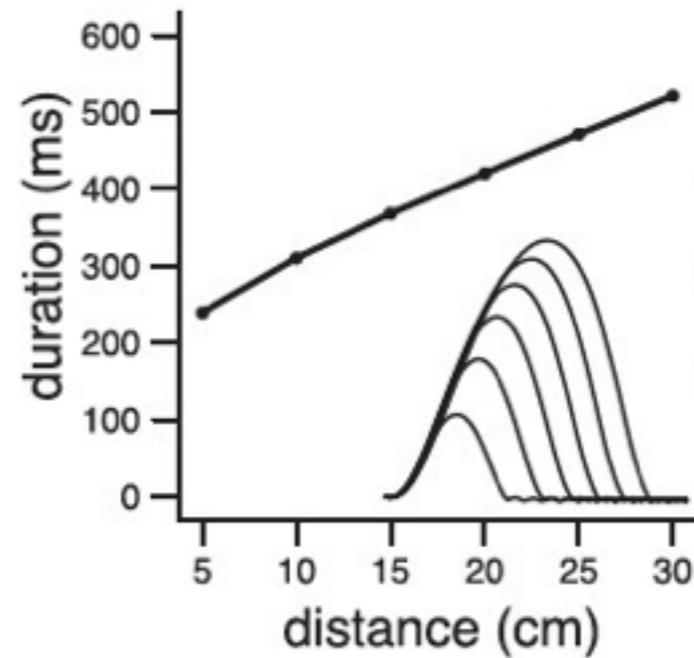
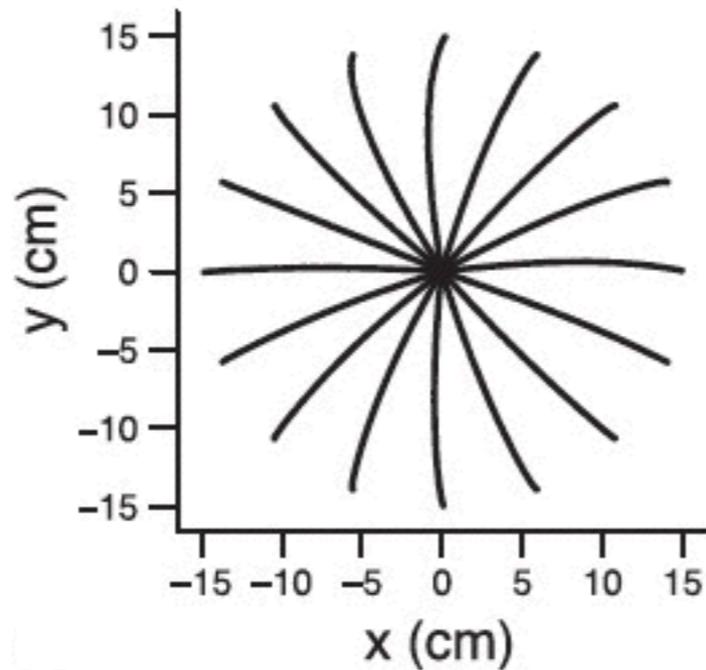
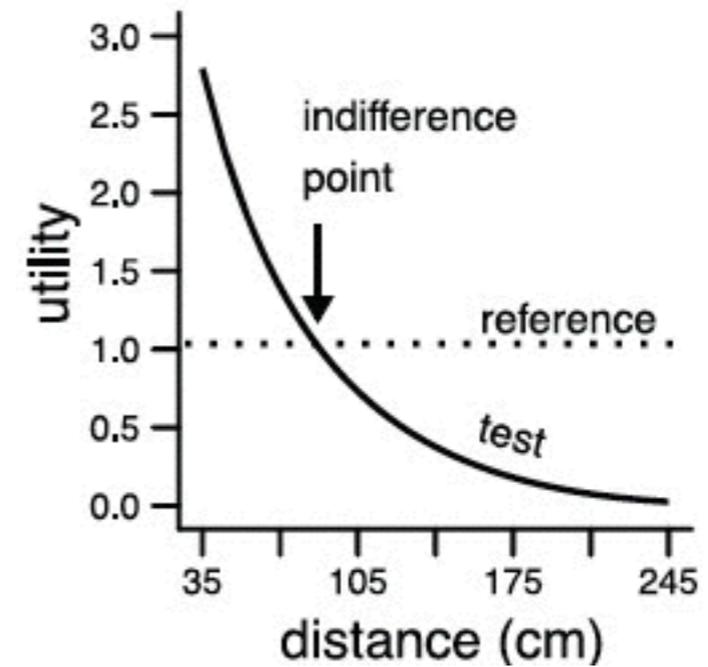
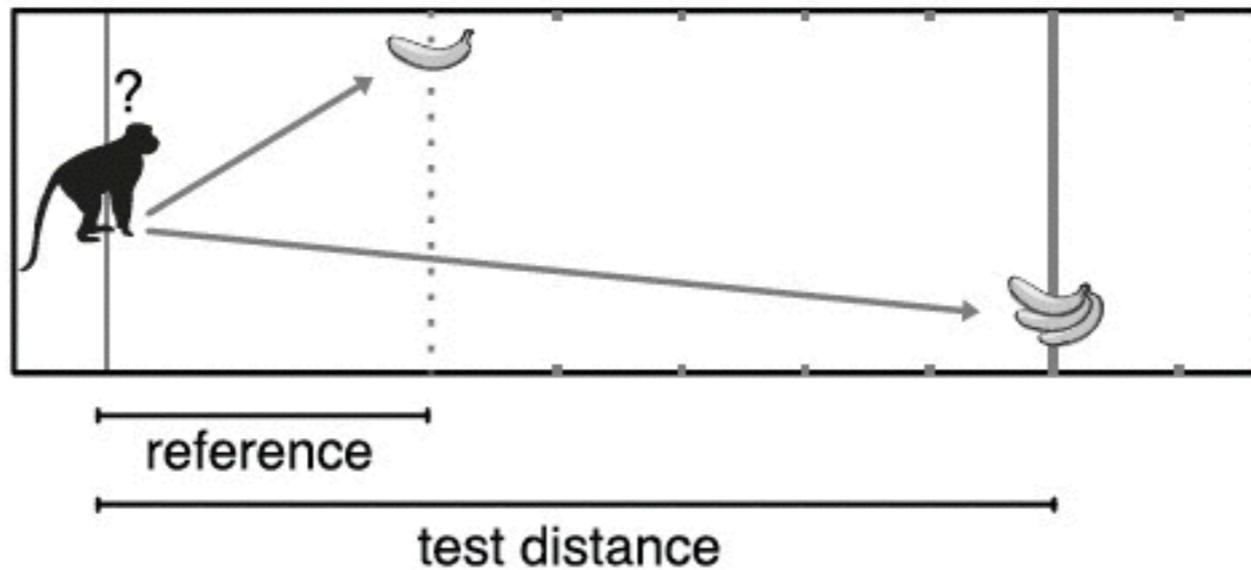
$$J^* = \max_{\mathbf{u}} \int_0^{\infty} e^{-t/\gamma} [\underbrace{\rho r \delta(\|\mathbf{x}^* - \mathbf{x}(t)\|)}_{\text{Benefit}} - \underbrace{\varepsilon \|\mathbf{u}(t)\|^2}_{\text{Cost}}] dt$$



— Rigoux & Guigon, 2012, *PLoS Comput Biol* 8:e1002716

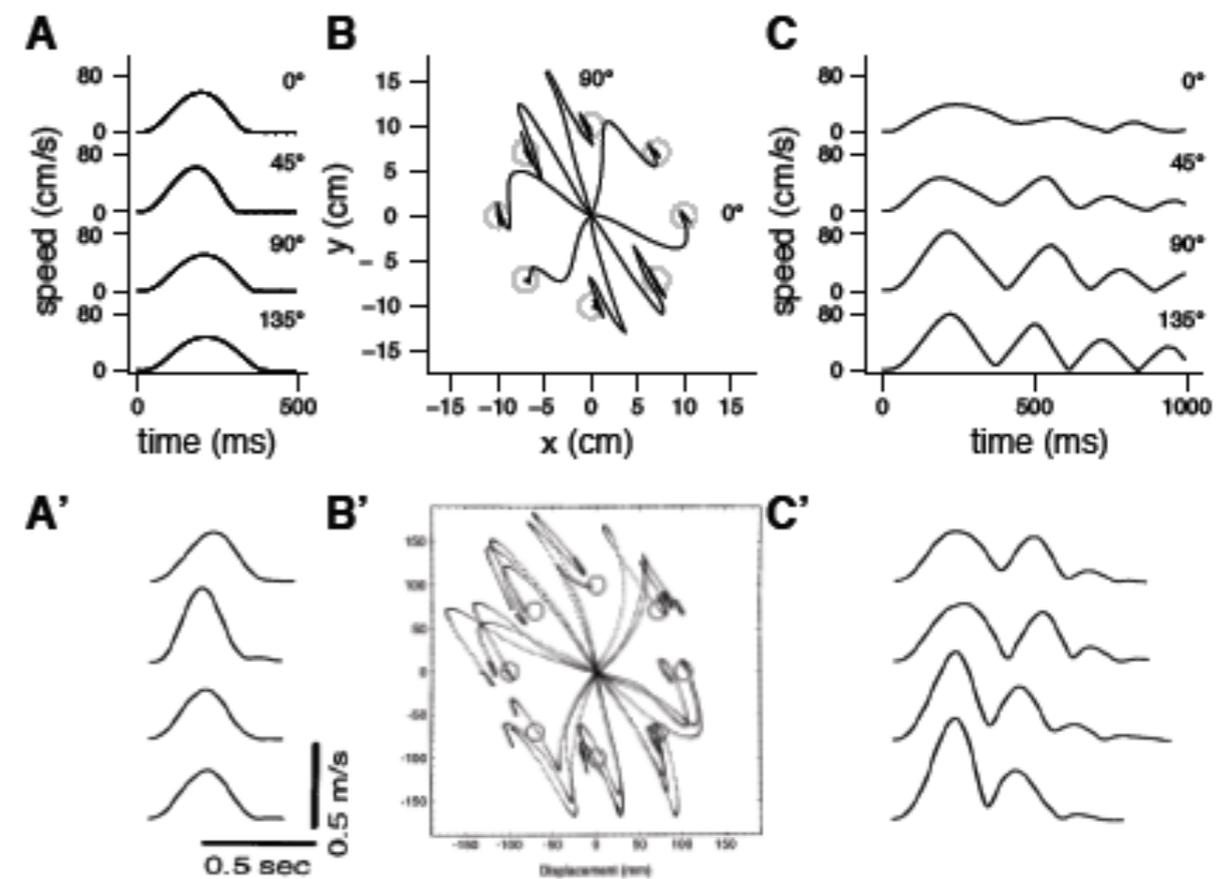
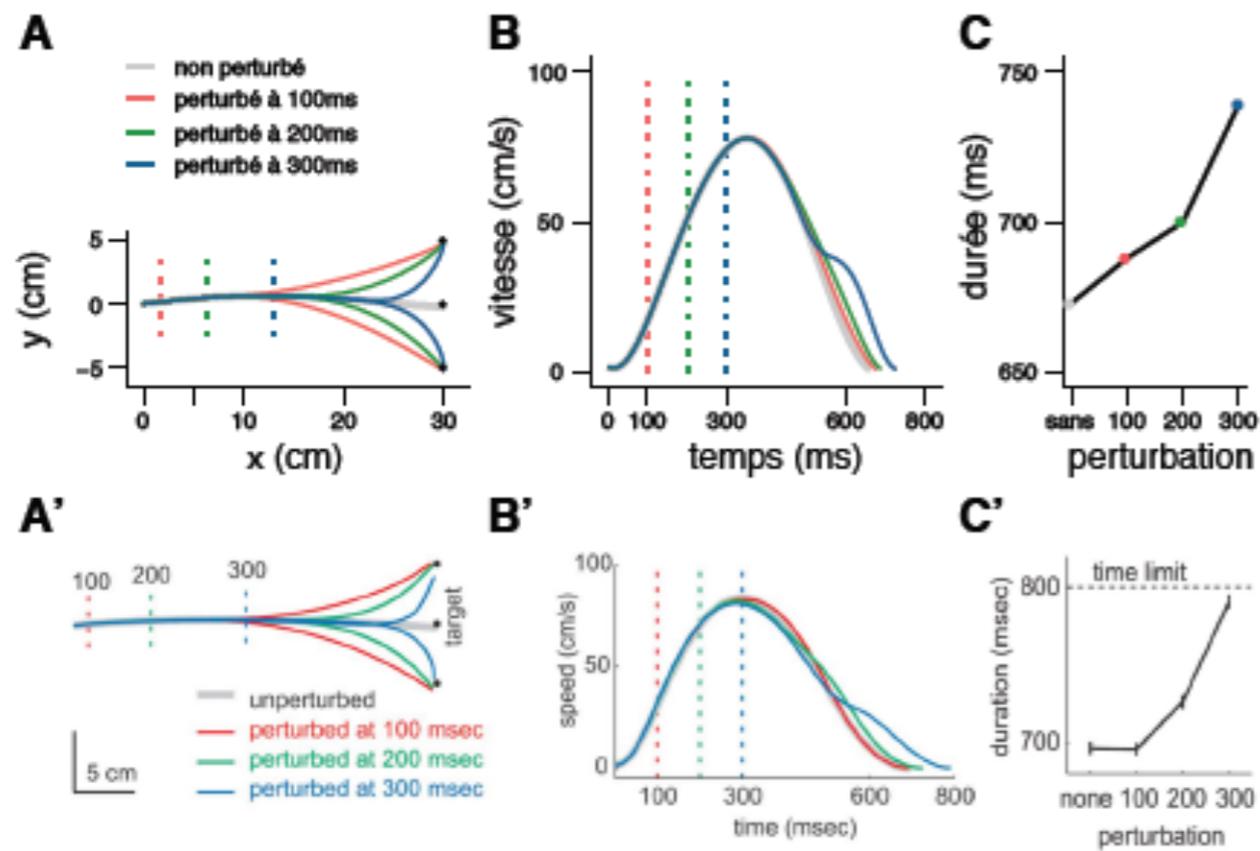
# FROM MOVEMENT TO ACTION

## Reward/effort trade-off



# FROM MOVEMENT TO ACTION

## Reward/effort trade-off

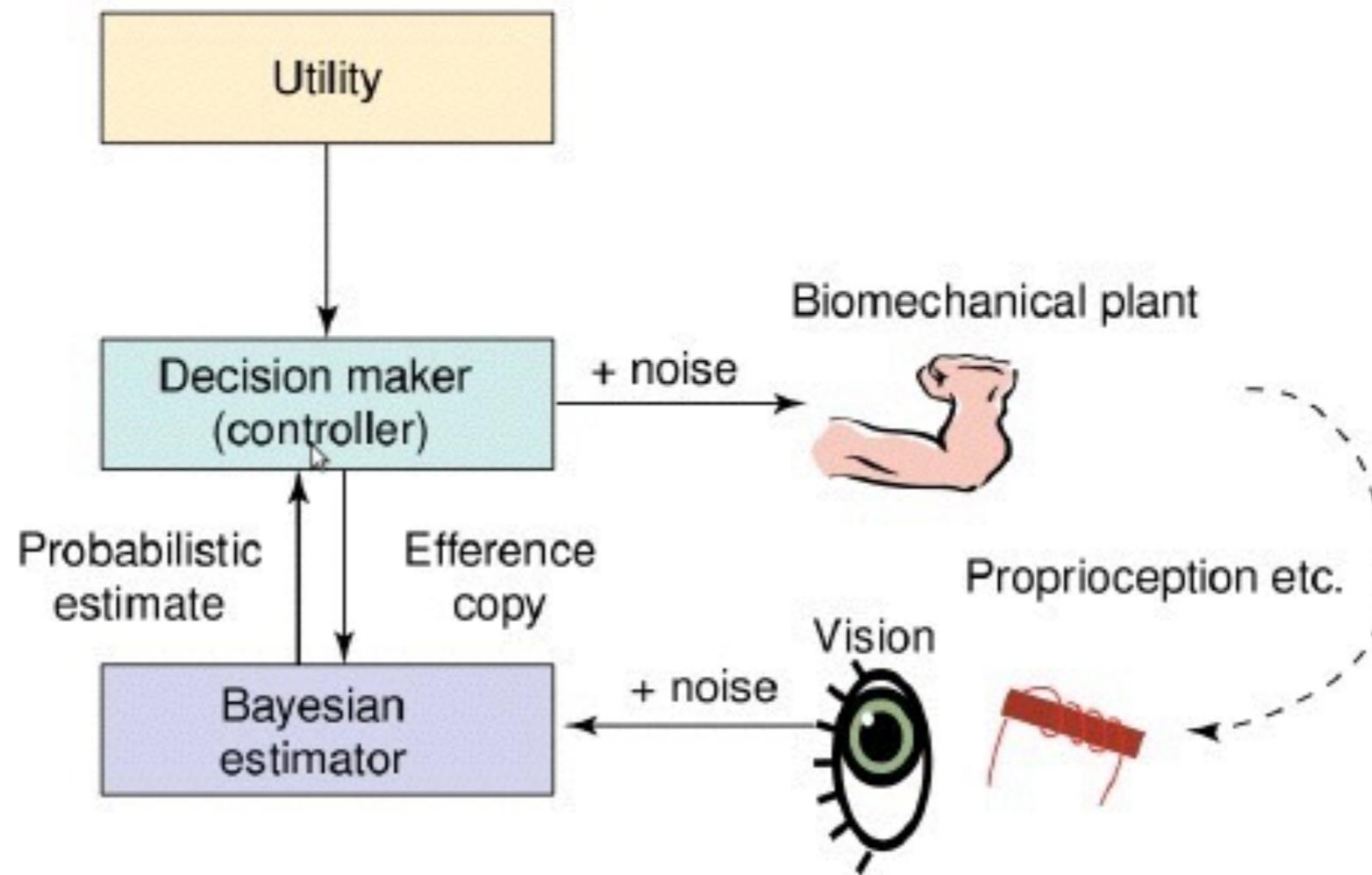


— Liu & Todorov, 2007, *J Neurosci* 27:9354

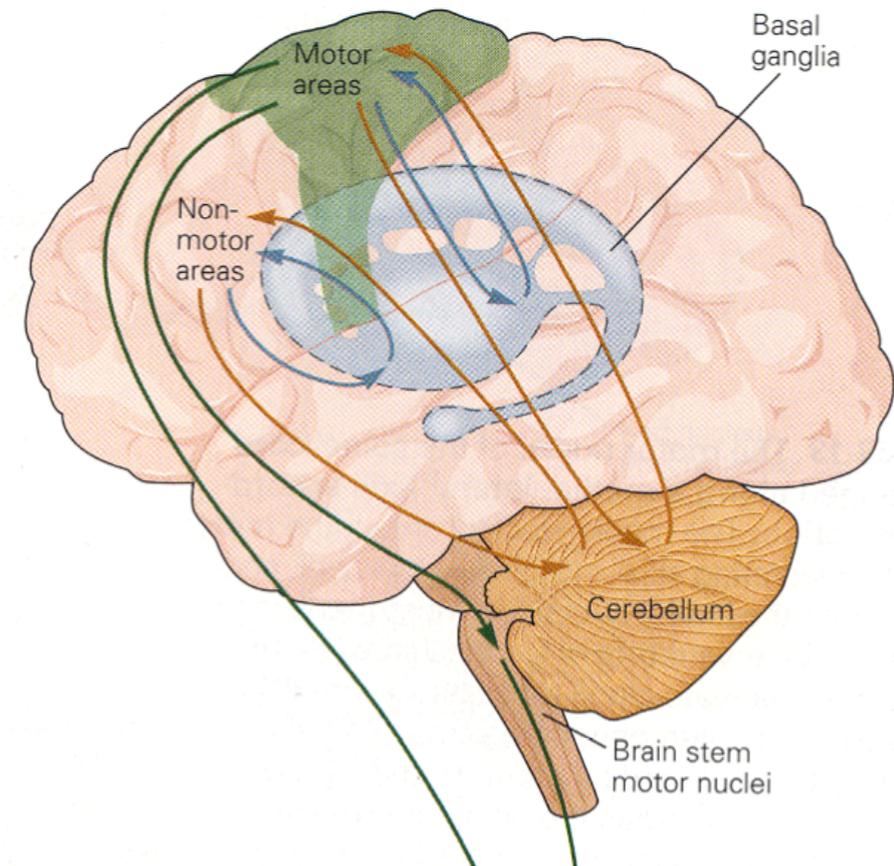
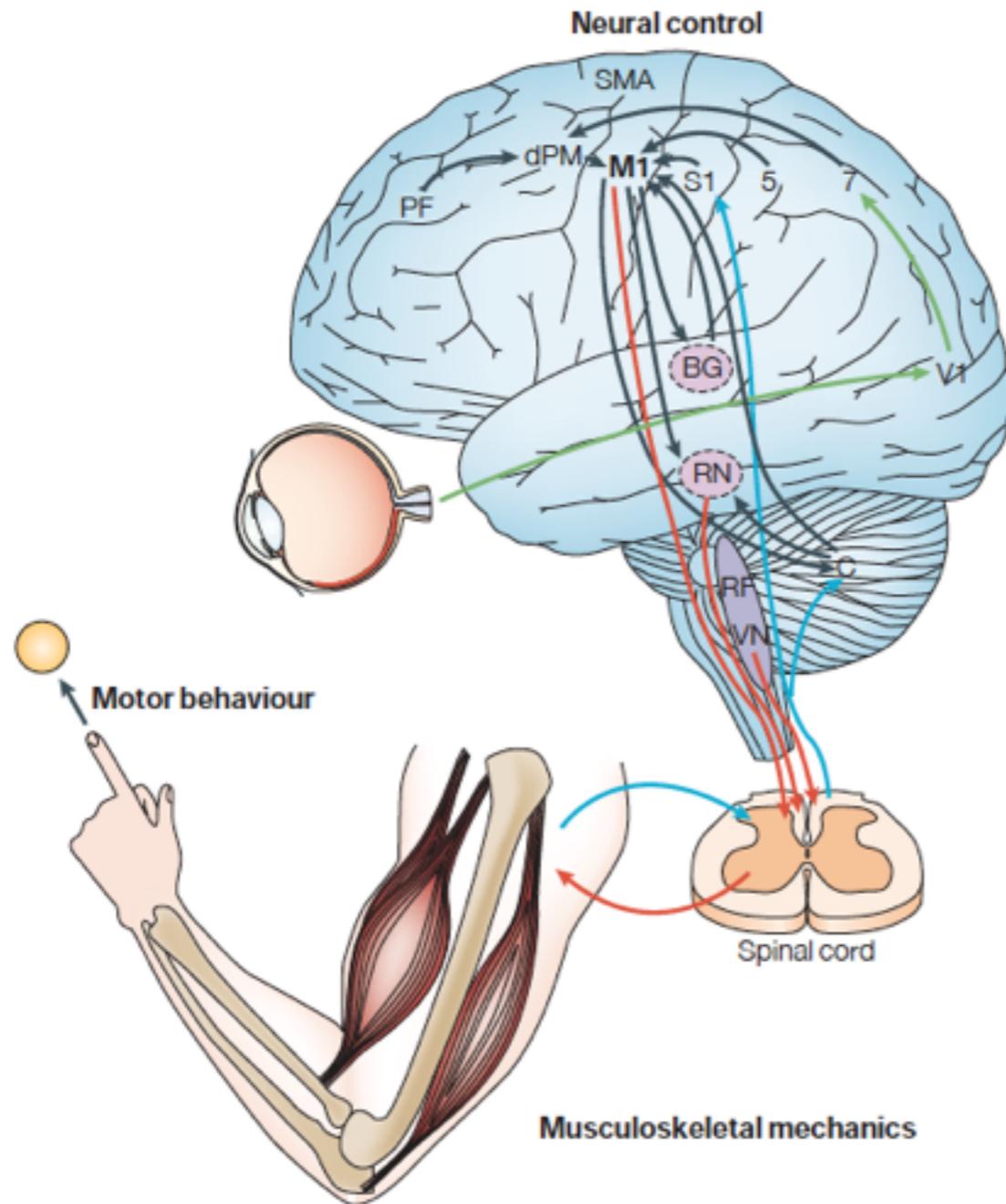
— Shadmehr & Mussa-Ivaldi, 1994, *J Neurosci* 14:3208

# EXTENSION

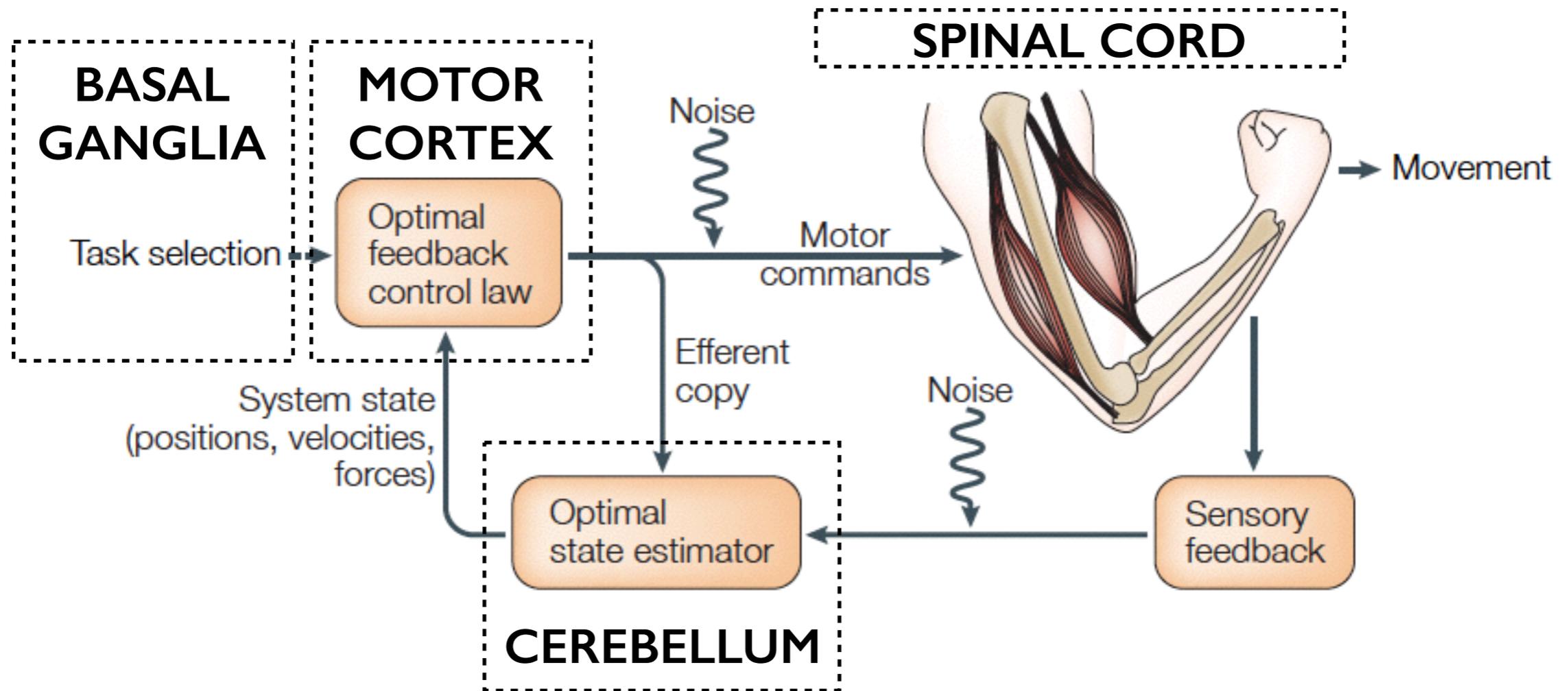
## Bayesian inference



# ANATOMICAL ARCHITECTURE



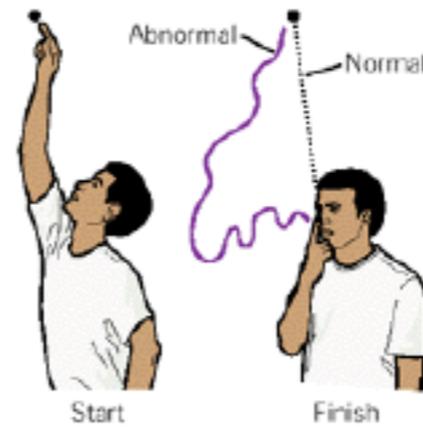
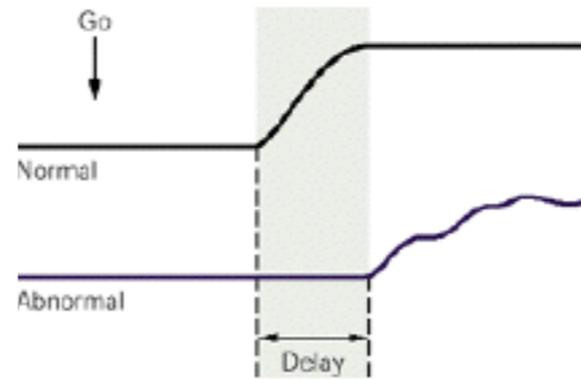
# COMPUTATIONAL ARCHITECTURE



- Scott, 2004, *Nat Rev Neurosci* 5:534
- Guigon et al., 2007, *Eur J Neurosci* 26:250
- Shadmehr & Krakauer, 2008, *Exp Brain Res* 185:359

# CEREBELLAR DEFICITS

## Ataxia



dysmetria

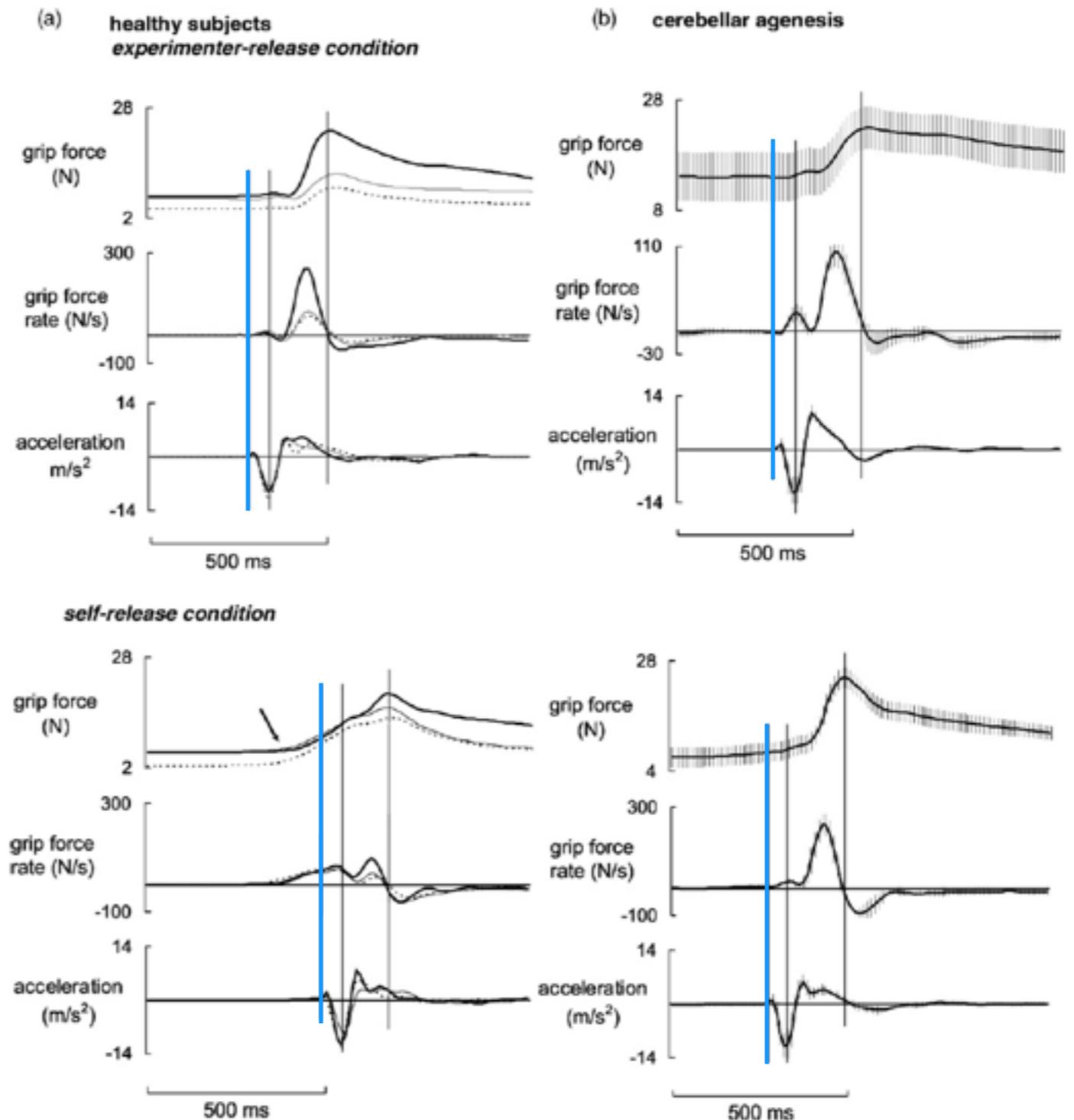
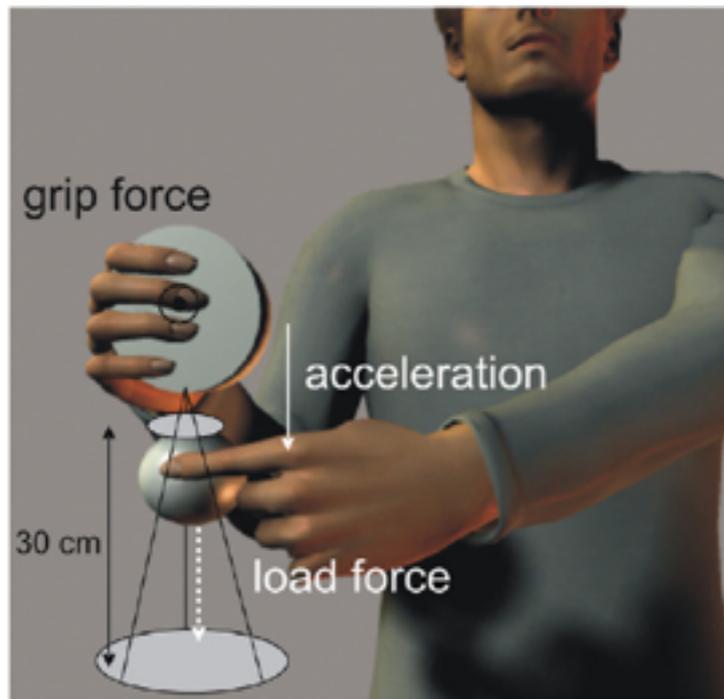


dysdiadochokinesia



# CEREBELLAR DEFICIT

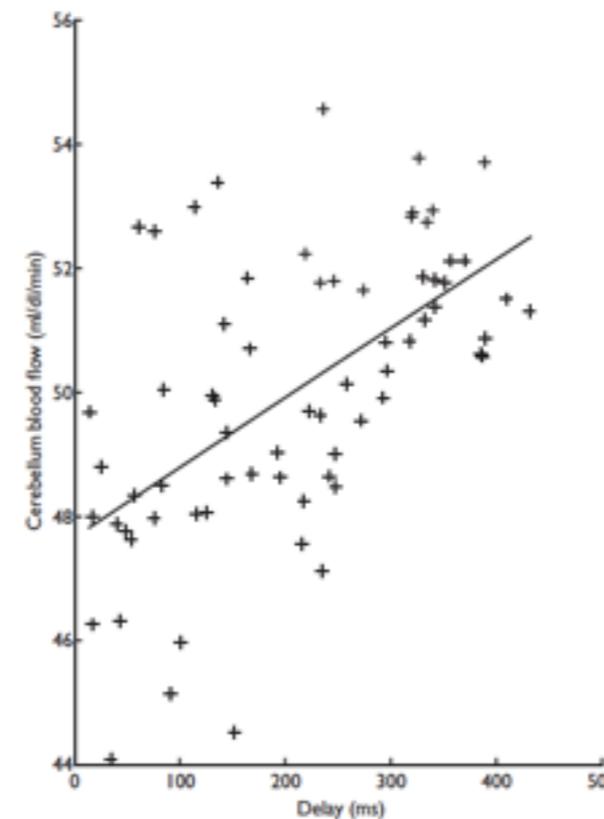
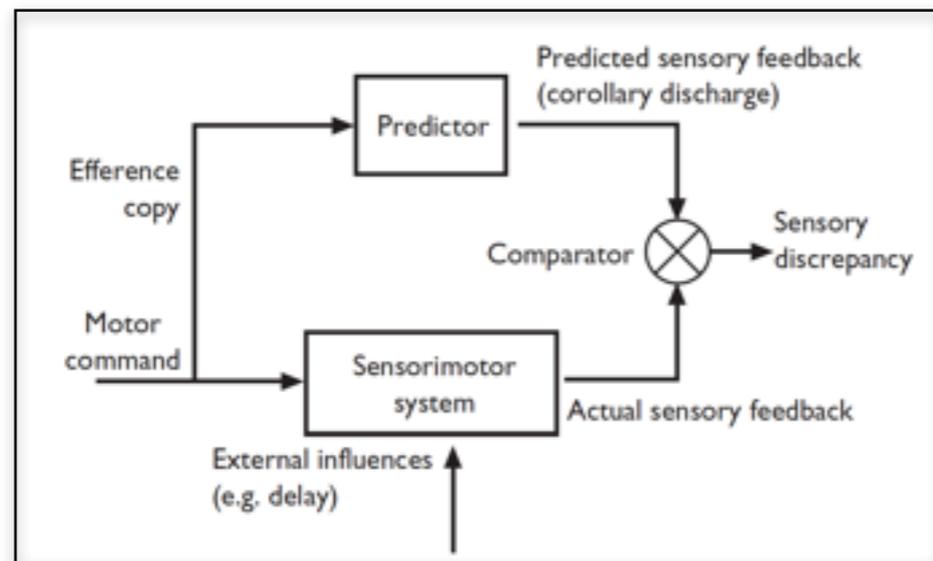
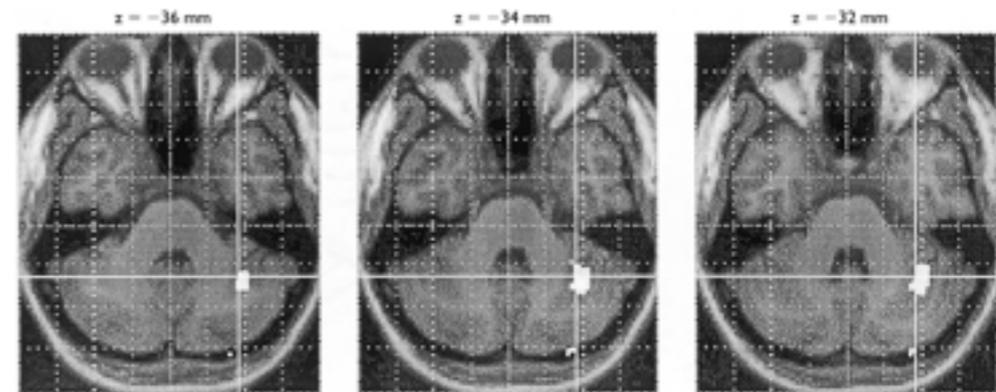
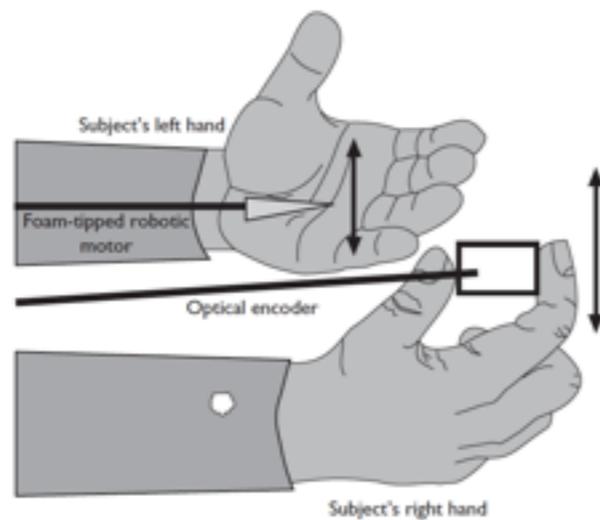
## Deficit in predictive grip force control



— Nowak et al., 2007,  
*Neuropsychologia* 45:696

# PREDICTING SENSORY CONSEQUENCES

The cerebellum is involved in predicting the sensory consequences of action

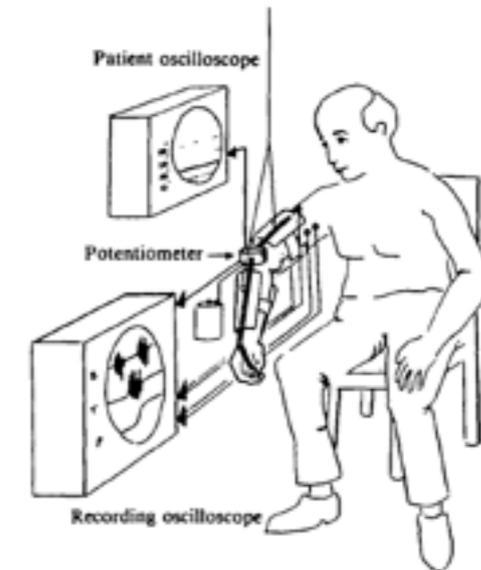
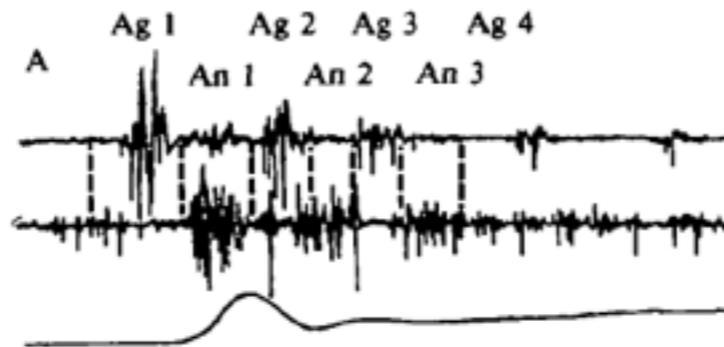
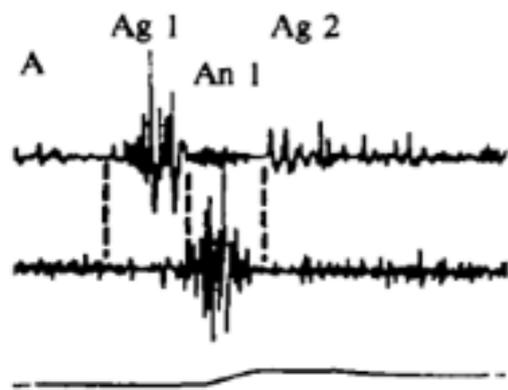


Activity in the right lateral cerebellar cortex shows a positive correlation with delay.

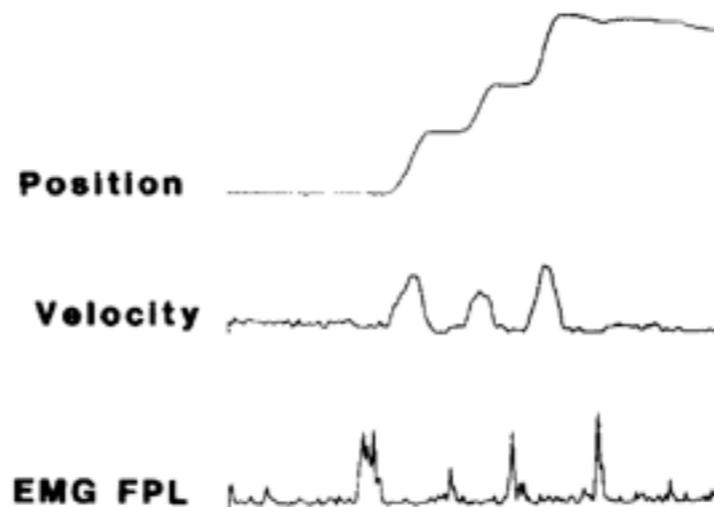
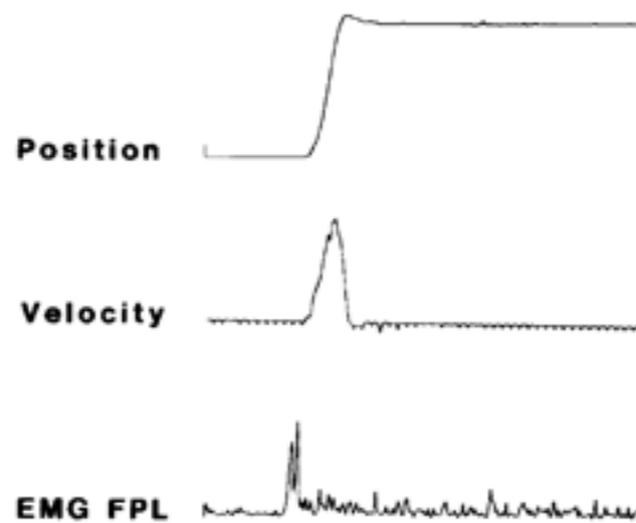
The cerebellum is involved in signalling the sensory discrepancy between the predicted and actual sensory consequences of movements

# BASAL GANGLIA DEFICITS

Movements and EMG are segmented

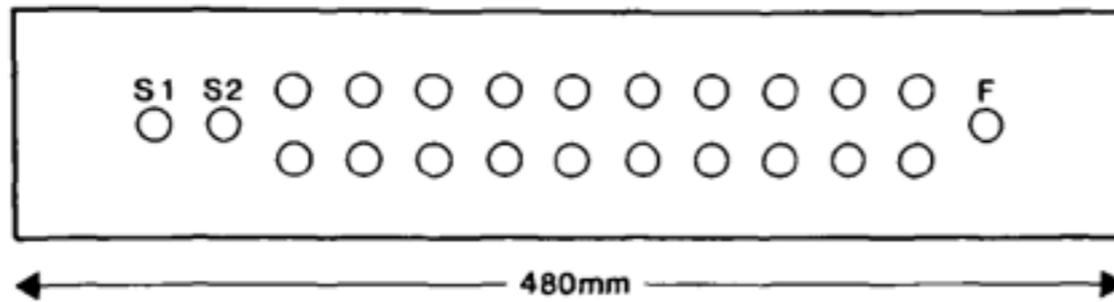


— Hallett & Khoshbin, 1980, *Brain* 103:301

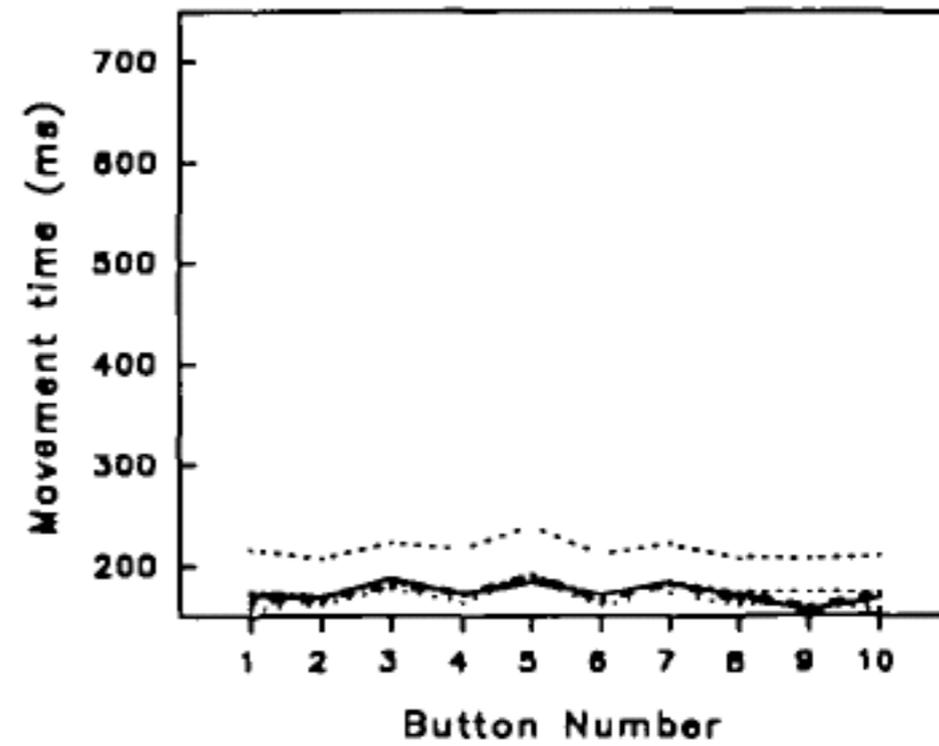
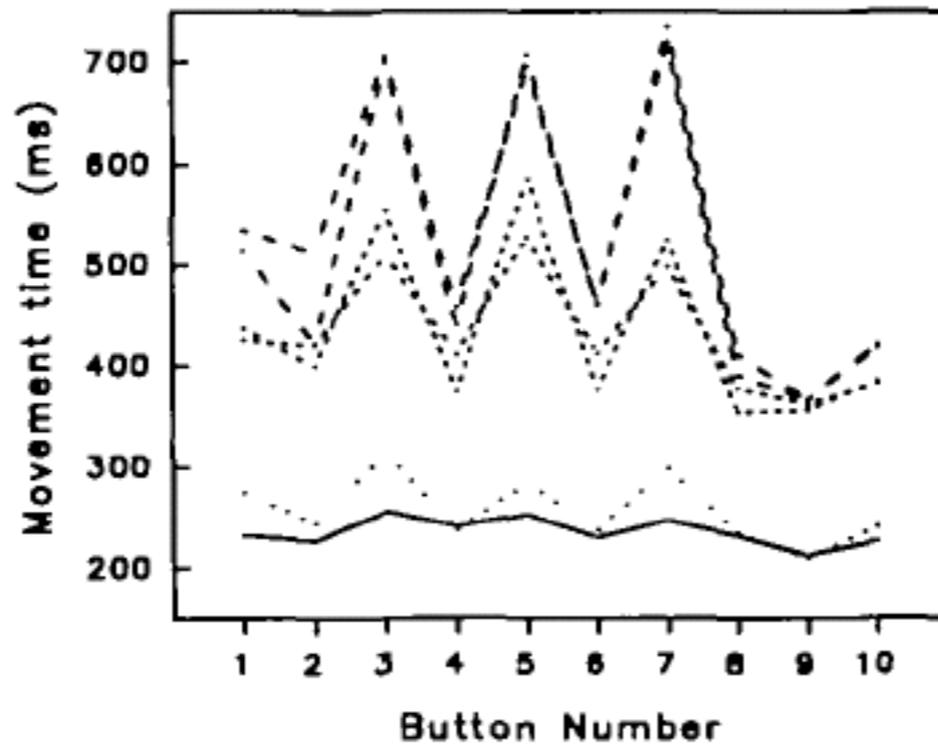
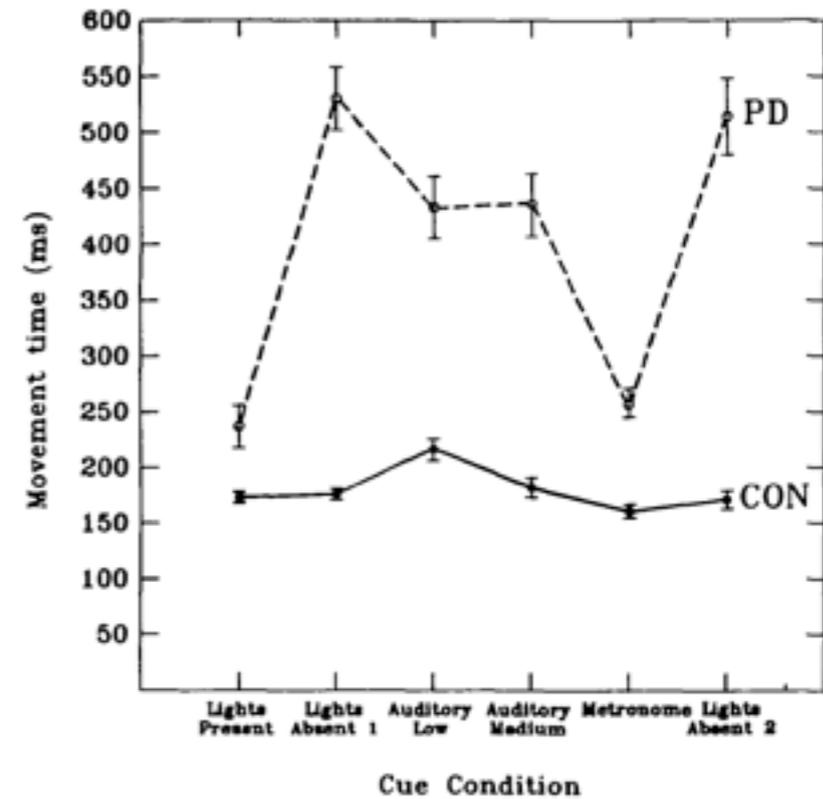


— Berardelli et al.,  
1984, *Neurosci Lett* 47:47

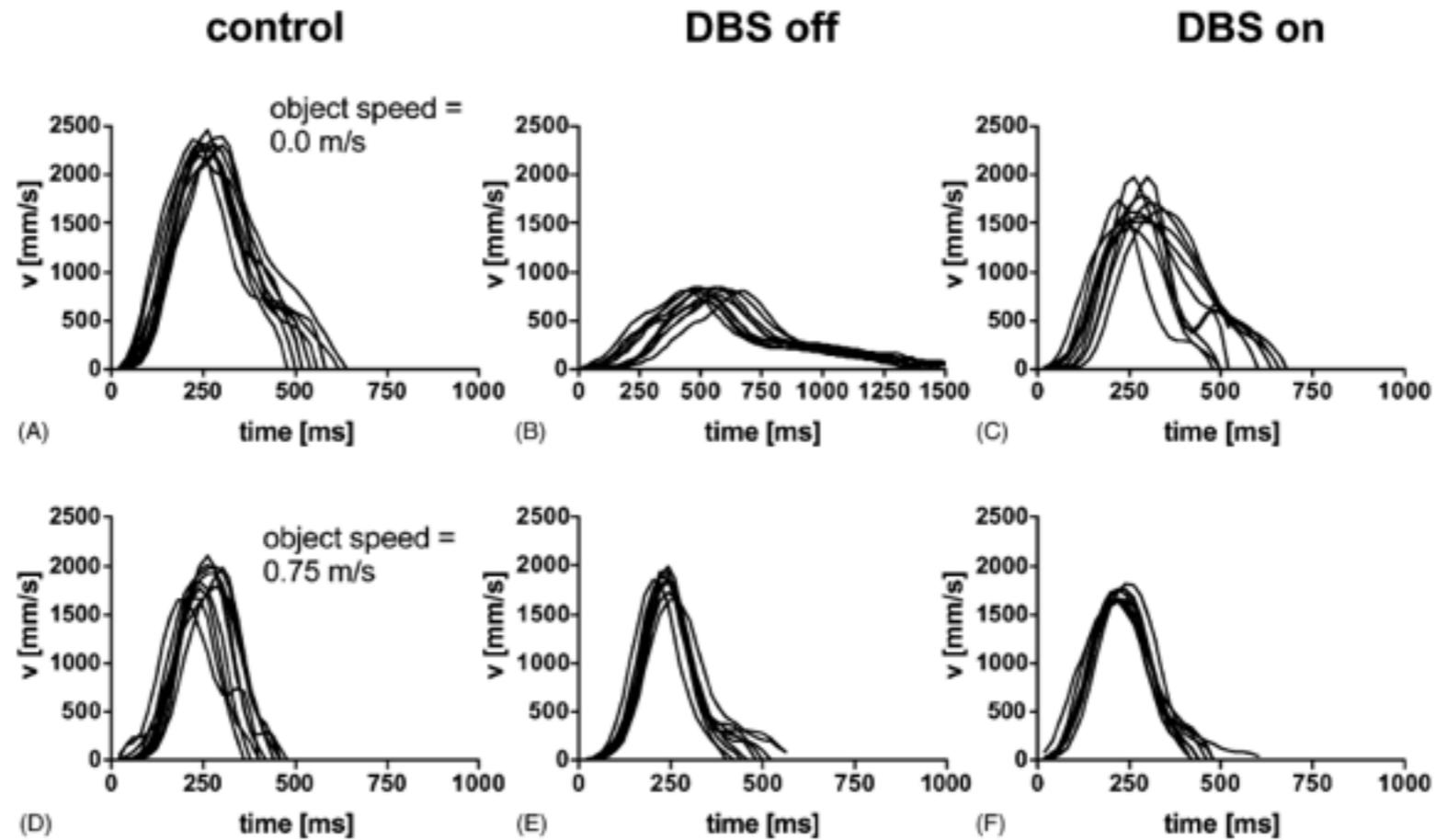
# BASAL GANGLIA DEFICITS



— Georgiou et al.,  
1993, *Brain* 116:1575



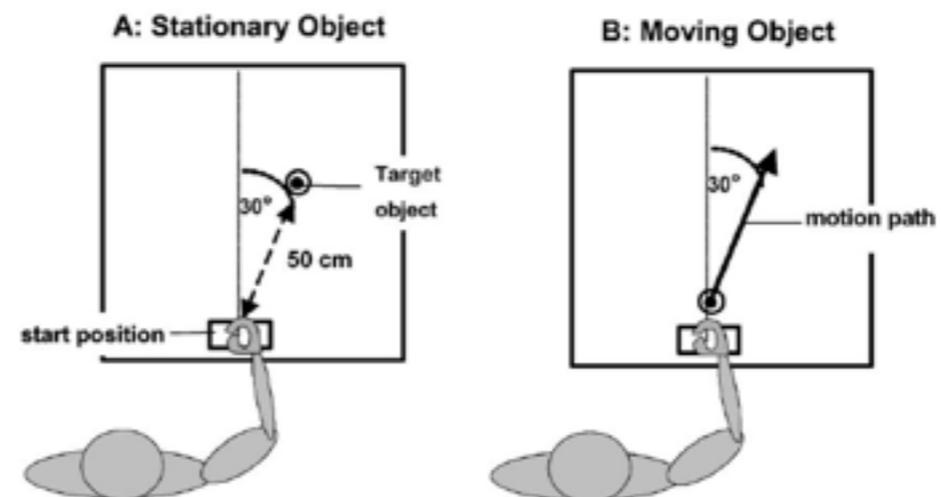
# BASAL GANGLIA DEFICITS



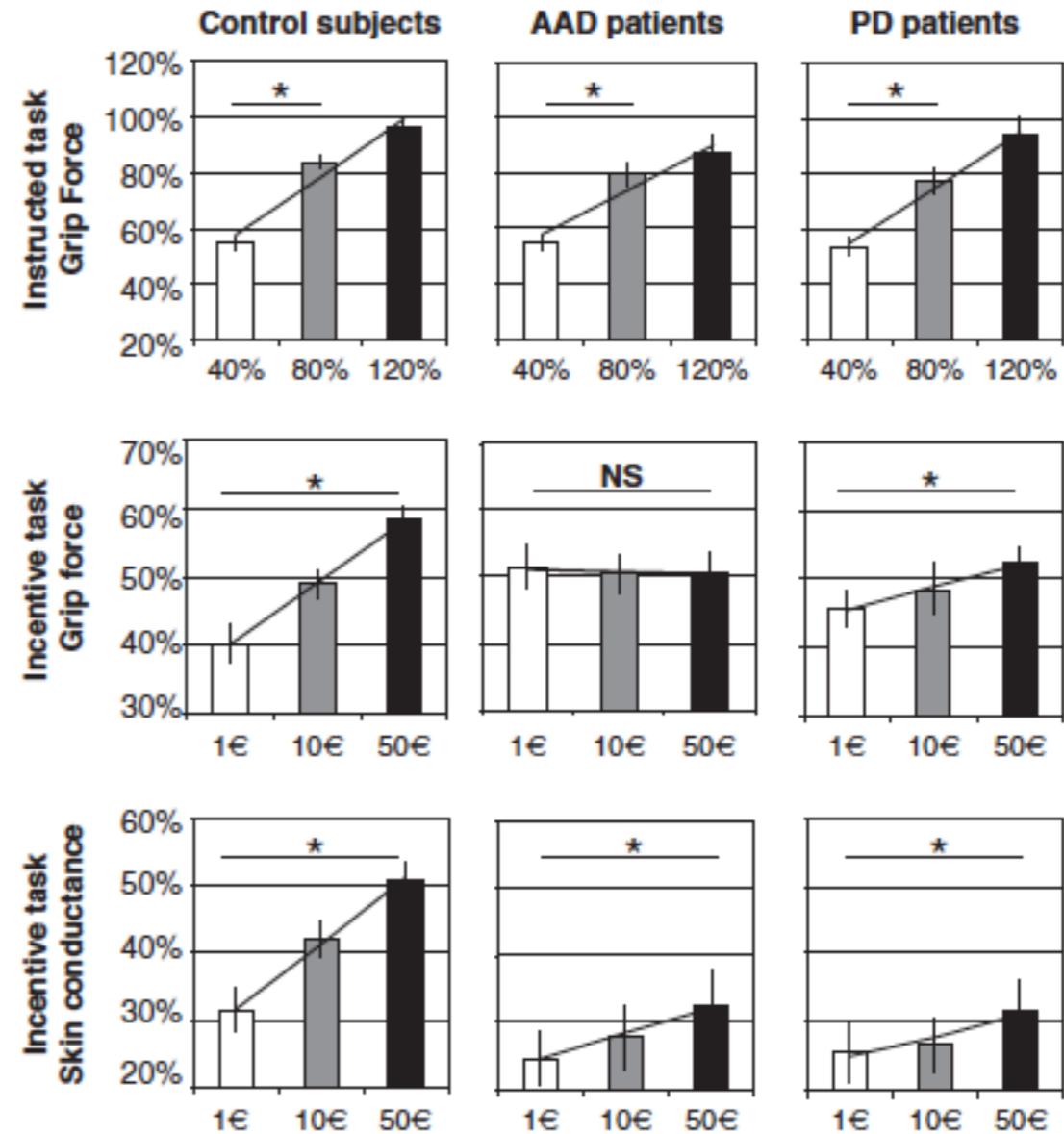
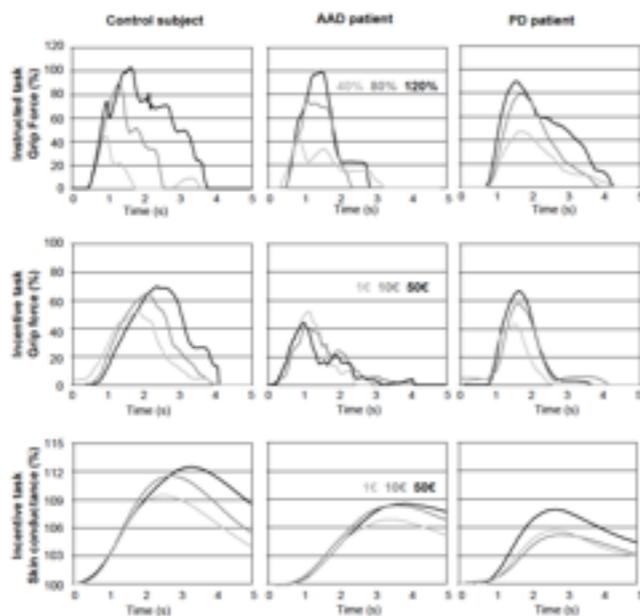
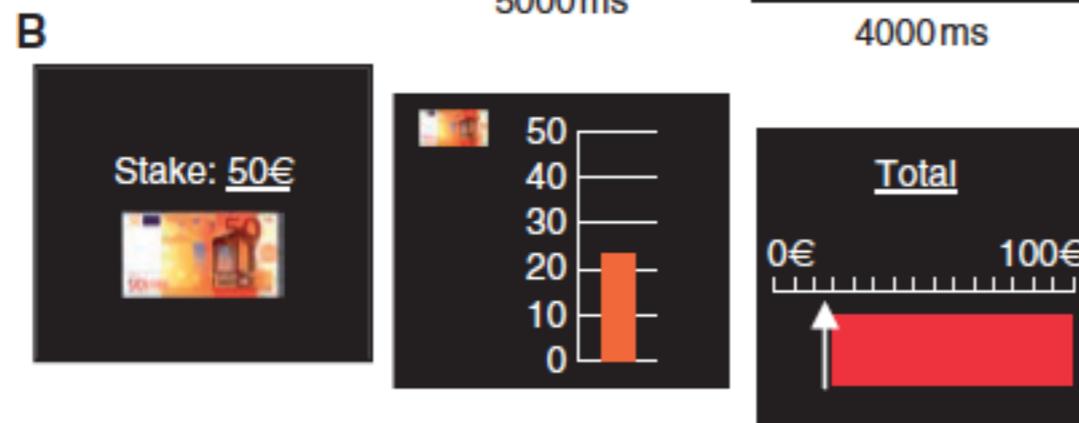
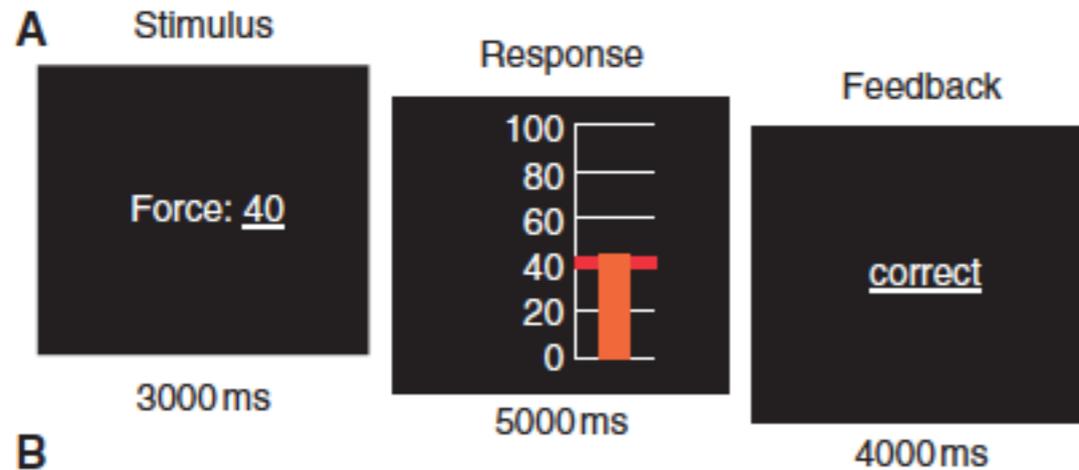
Reaching to moving targets

Paradoxical kinesis in PwPD

— Schenk et al., 2003, *Neuropsychologia* 41:783



# PARKINSON'S DISEASE AND MOTIVATION



— Schmidt et al., 2008, *Brain* 131:1303

# ROBOTICS

The field of robotics is heavily inspired by biology; a clearer understanding of how nature accomplishes efficient and precise motor control is critical to the development of advanced robotic systems.

As human interaction with technology continues to expand, ergonomic design and intuitive control based on the principles of human movement and motor control will also become increasingly important.



*Da Vinci surgical system*



*Chihira Aico*

# REFERENCES

