10 mars 2016

Modèles mathématiques et corrélats anatomiques du mouvement (1/2)

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OUTLINE

1. **Cognition, action and movement**

2. **The organization of action**

3. **Computational motor control**

4. **Neural bases of motor control**

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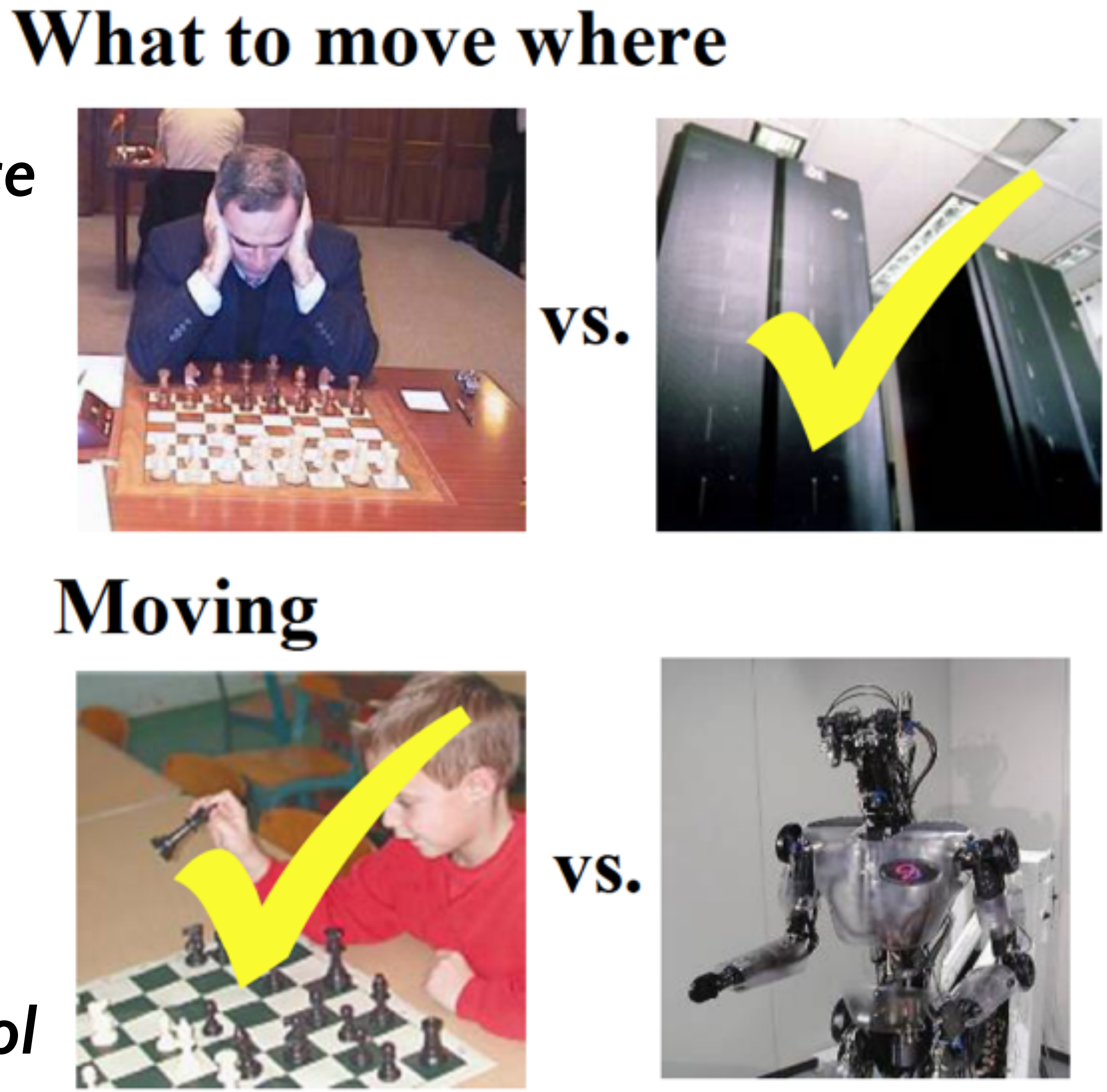
COGNITION AND ACTION

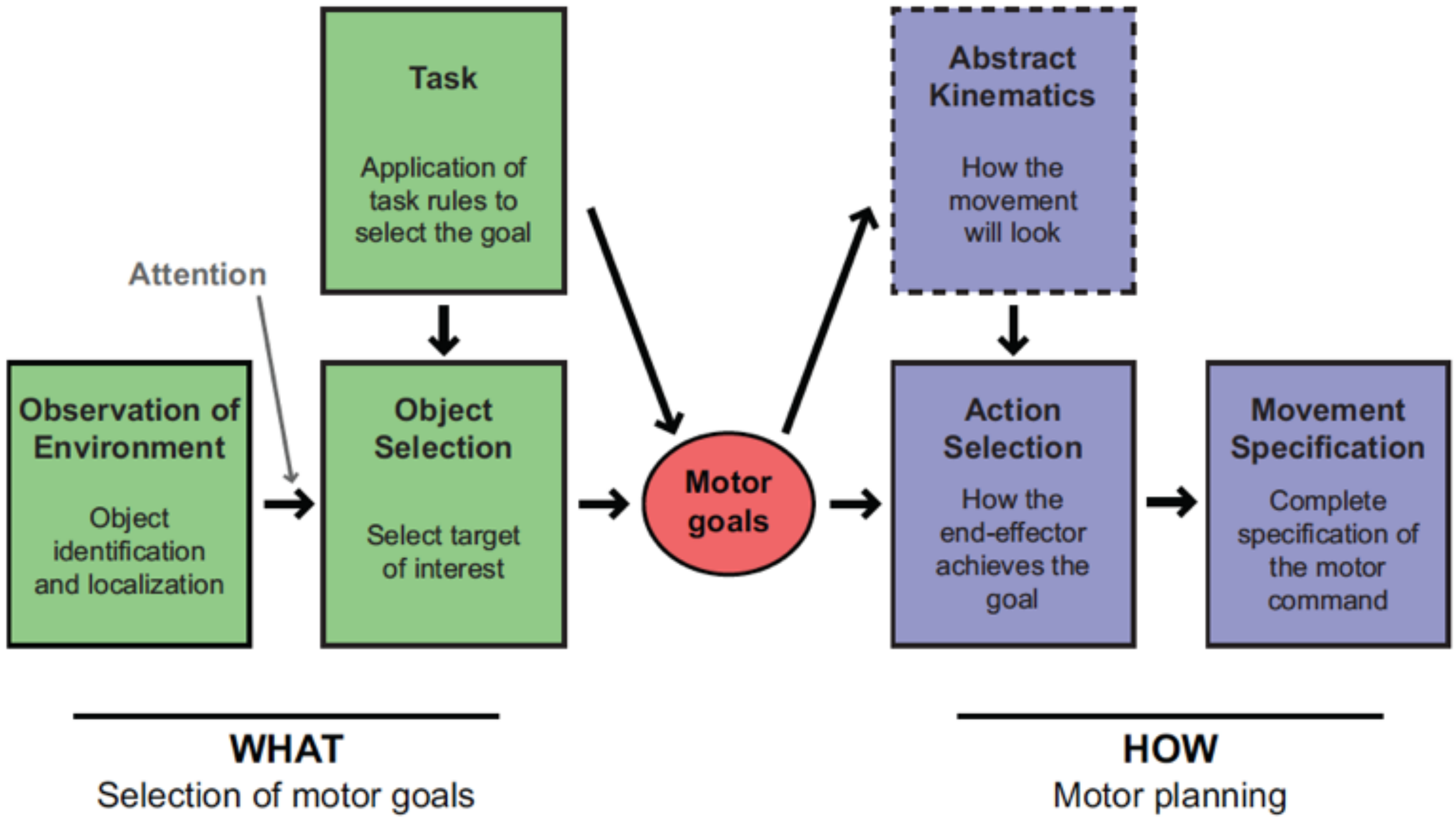
Cognitive science



Motor control

—Wolpert, 2007, *Hum Mov Sci* 26:511

COGNITION AND ACTION

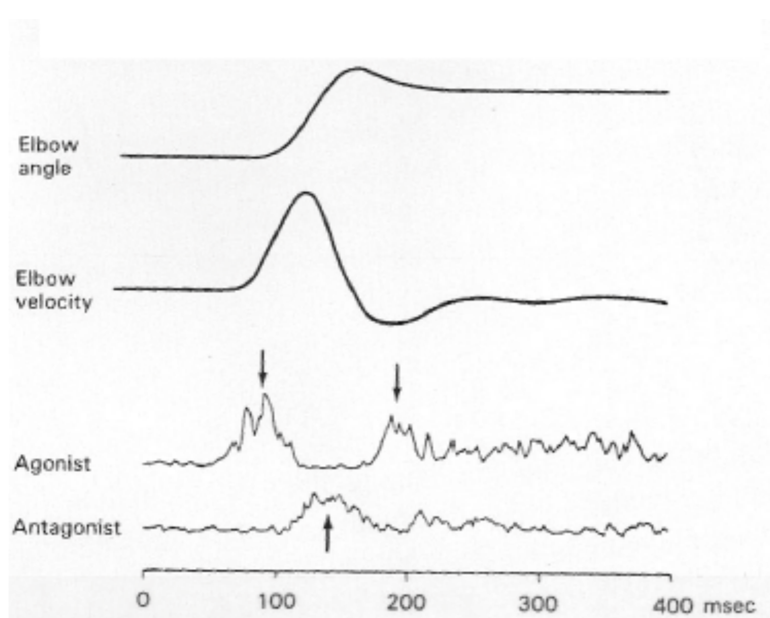


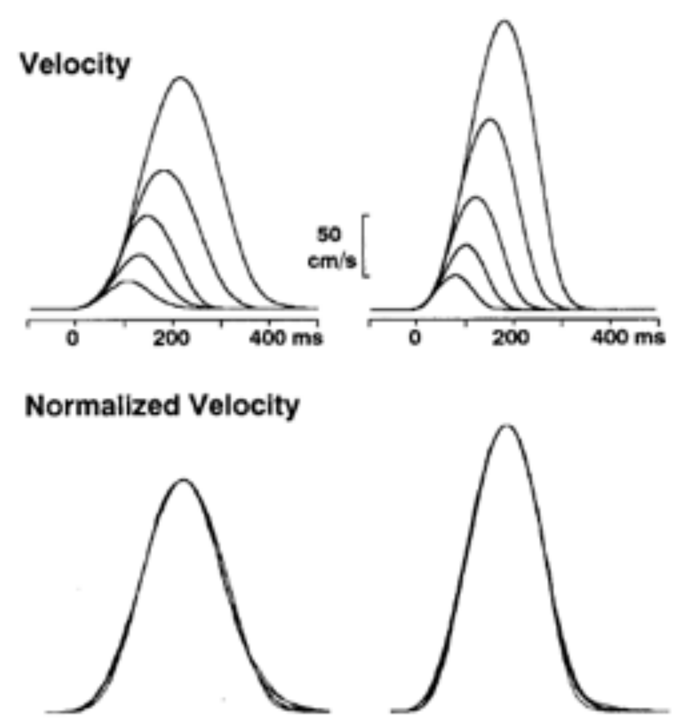
—Wong et al., 2015, *Neuroscientist* 21(4):385

CONTENT OF ACTION

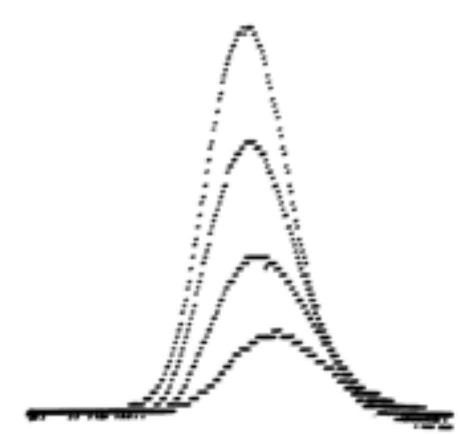
Every action has a specific direction (left/right, toward/away, …), and intensity (velocity, force, …)

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





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

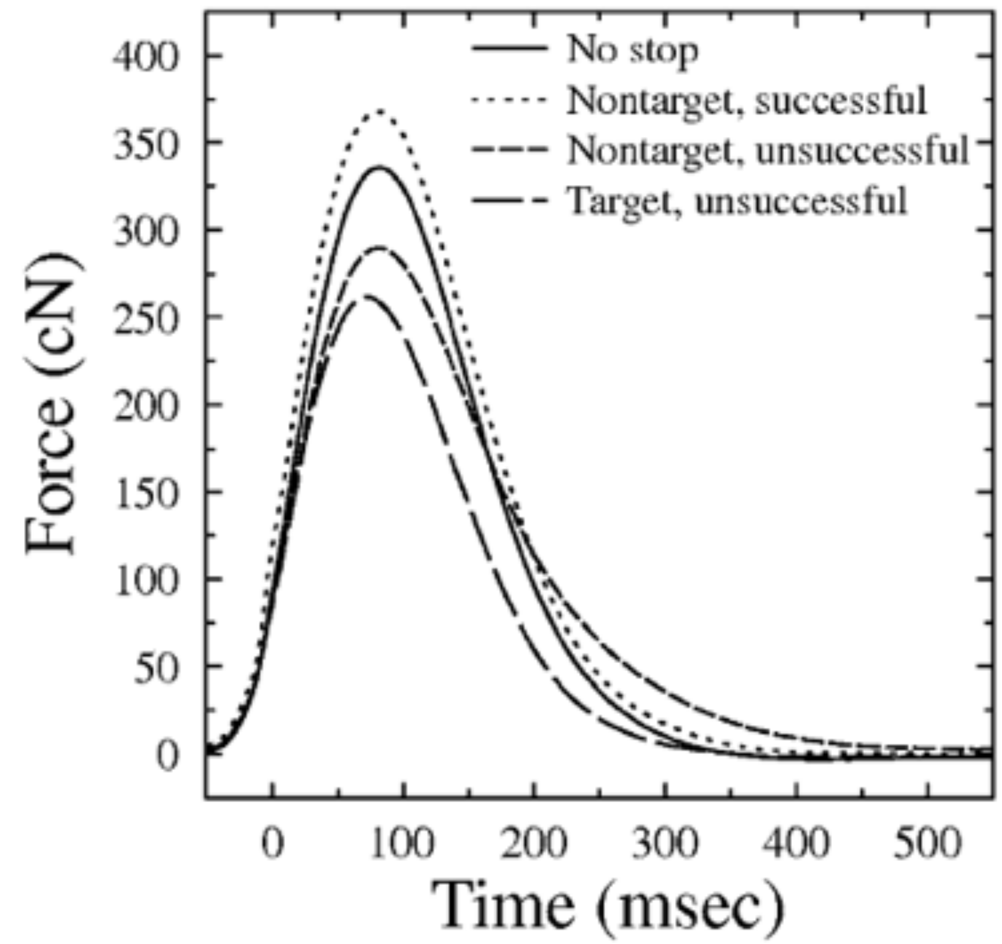


— Angel, 1973, *Q J Exp Psychol* 25:193

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)

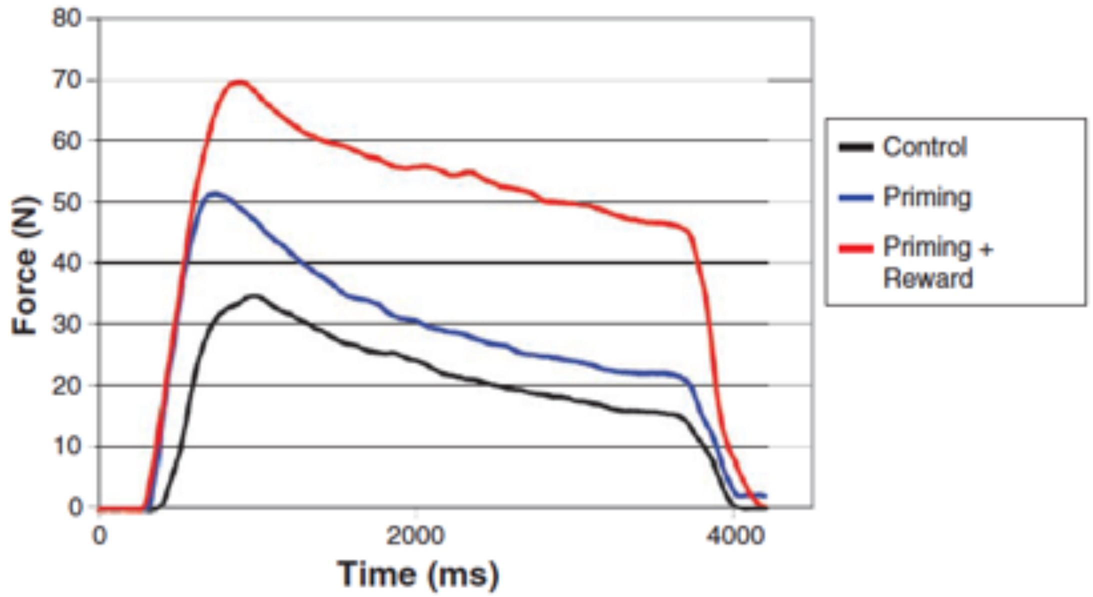


— Ko & Miller, 2011, *Psychon Bull Rev* 18:813

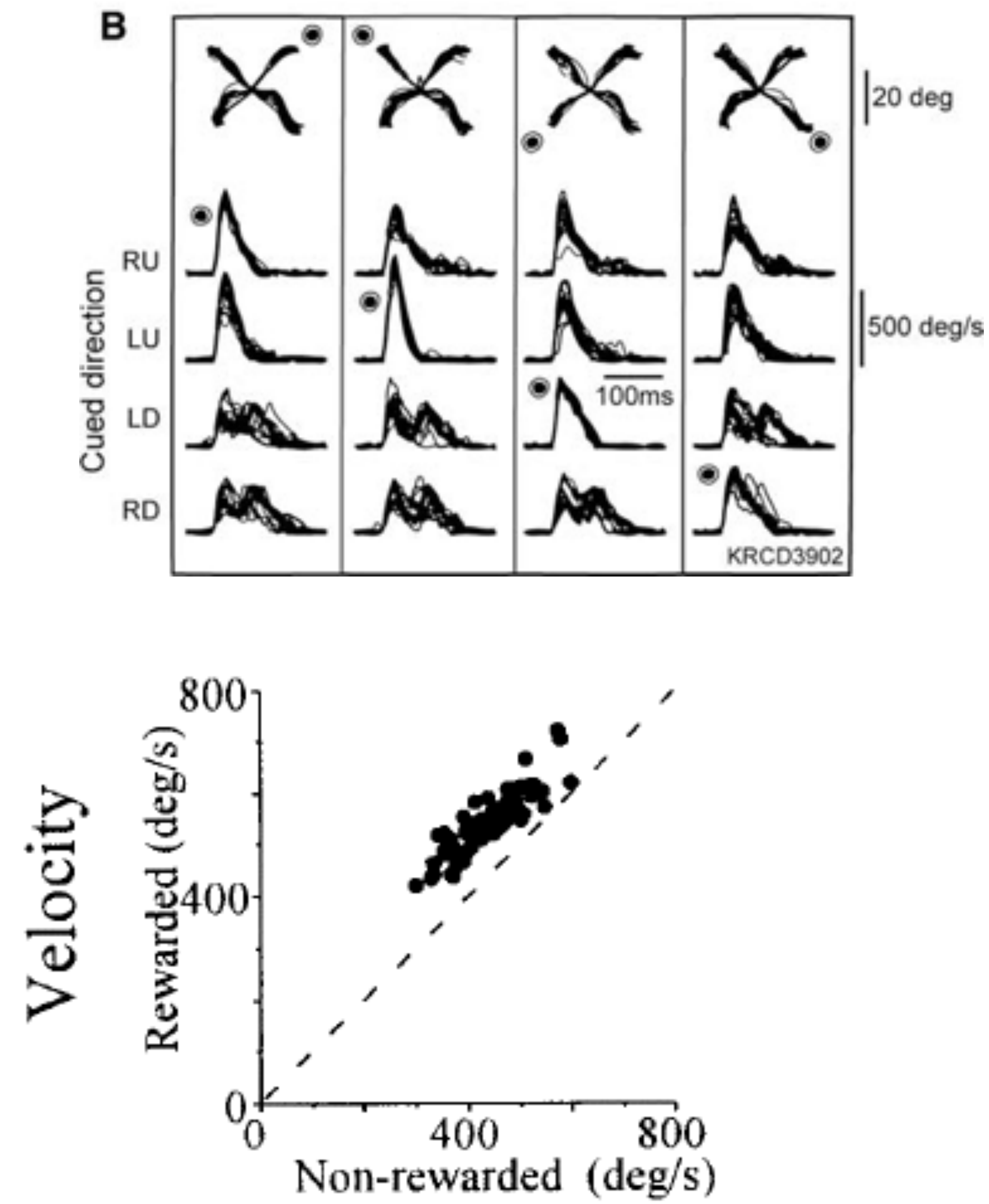
→ Faster movements for words vs nonwords

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

ACTION REFLECTS MOTIVATION

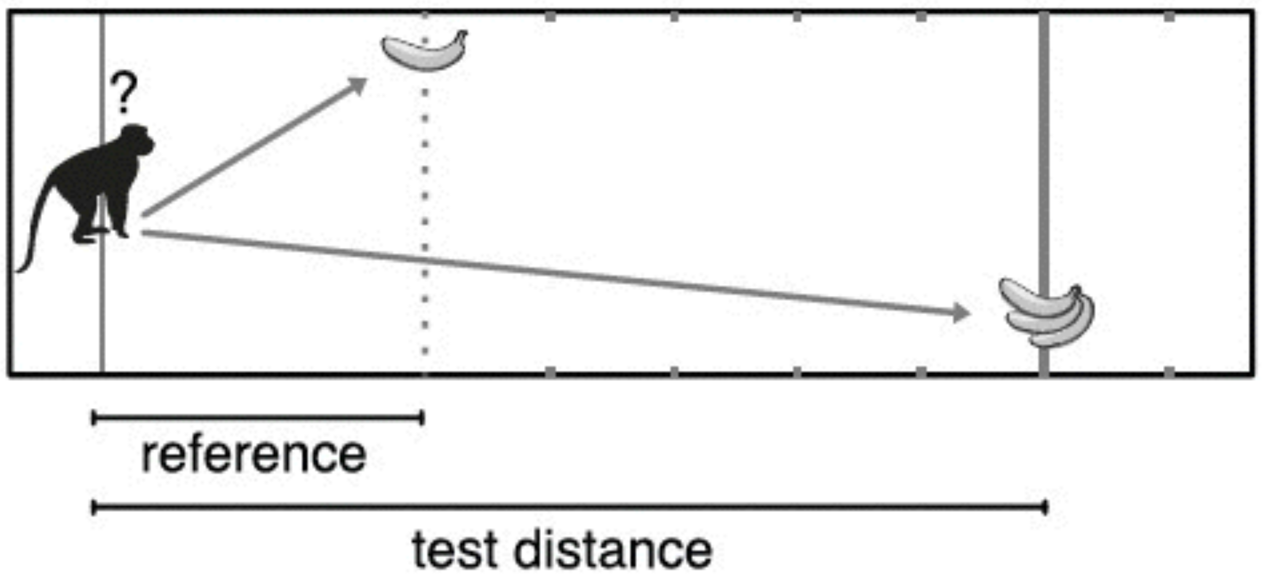


— Aarts et al., 2008, *Science* 19:1639

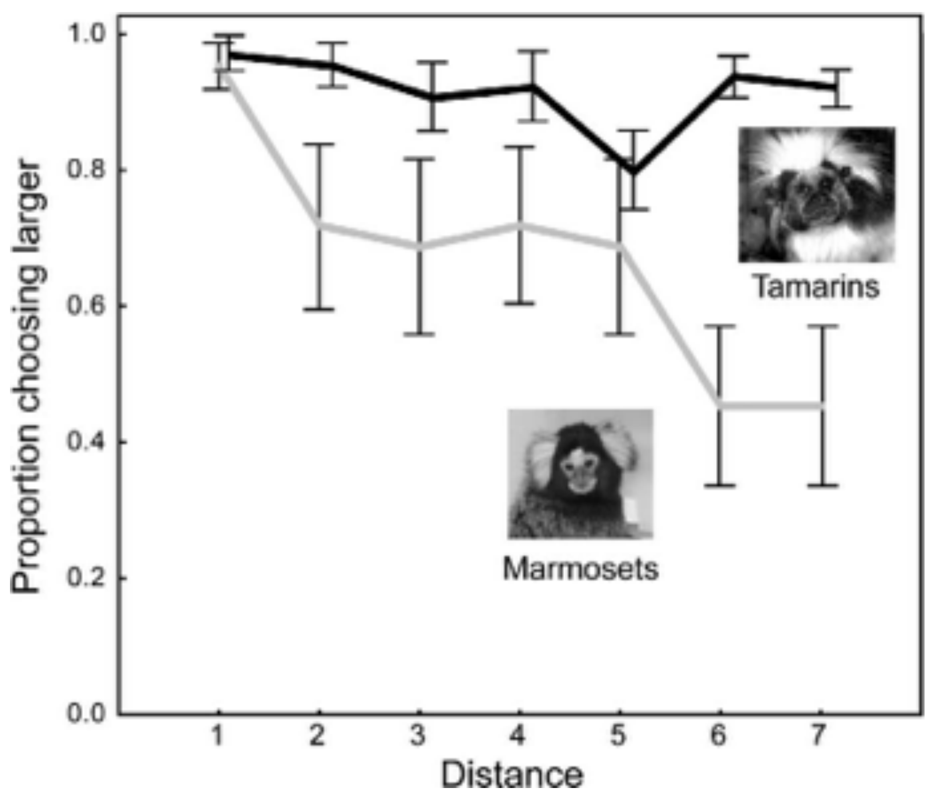


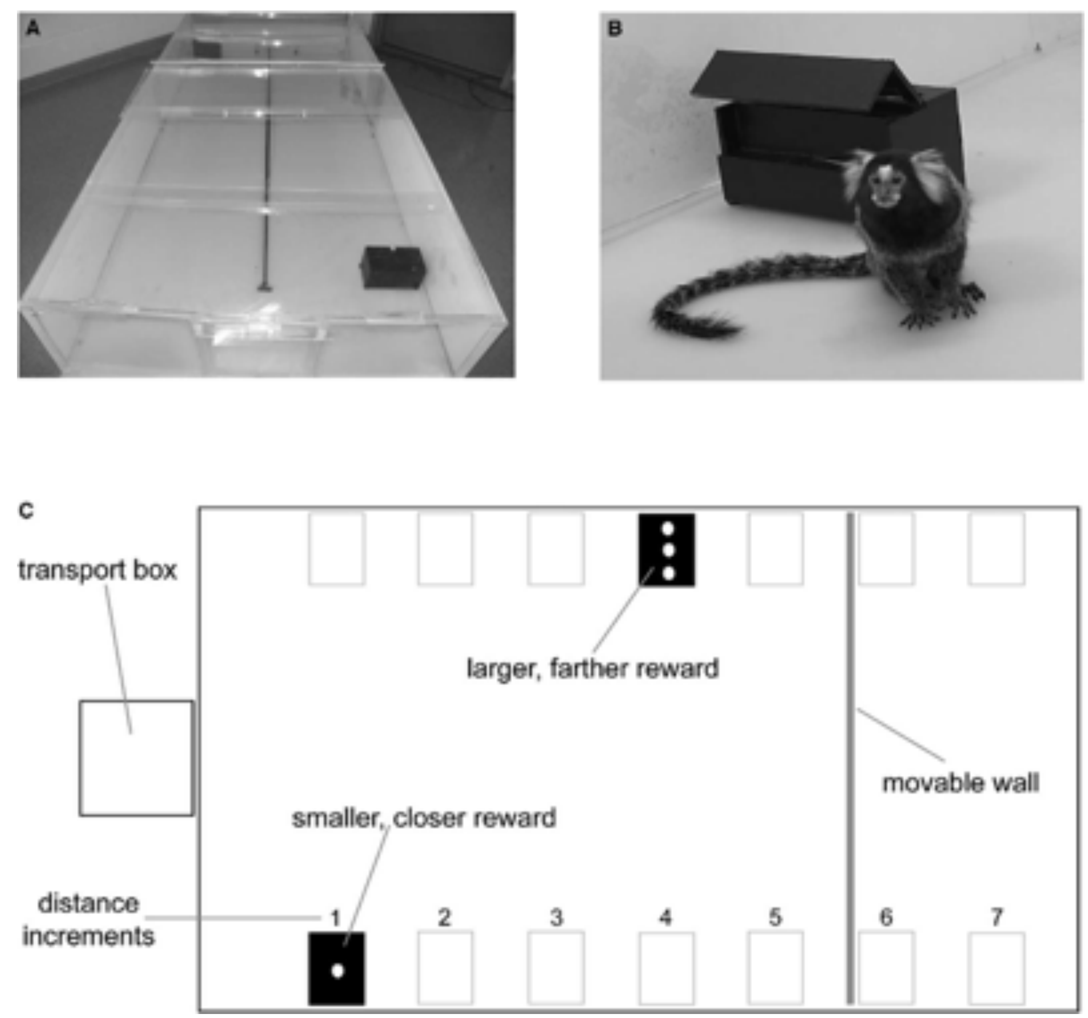
— Takikawa et al., 2002, *Exp Brain Res* 142:284

ACTION IS DECISION MAKING

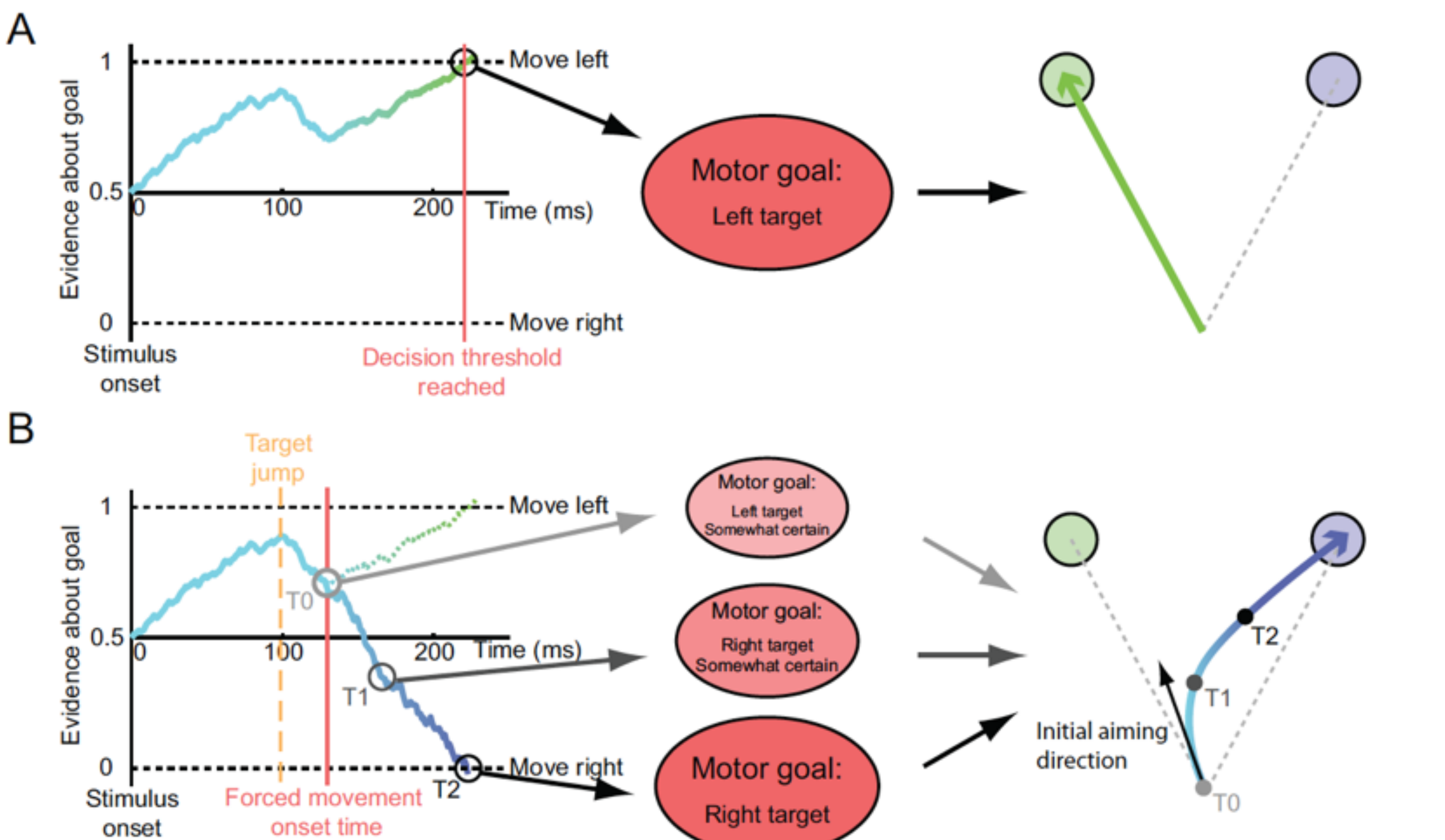


— Stevens et al., 2005, *Curr Biol* 15:1865





ACTION IS DECISION MAKING



—Wong et al., 2015, *Neuroscientist* 21(4):385

OUTLINE

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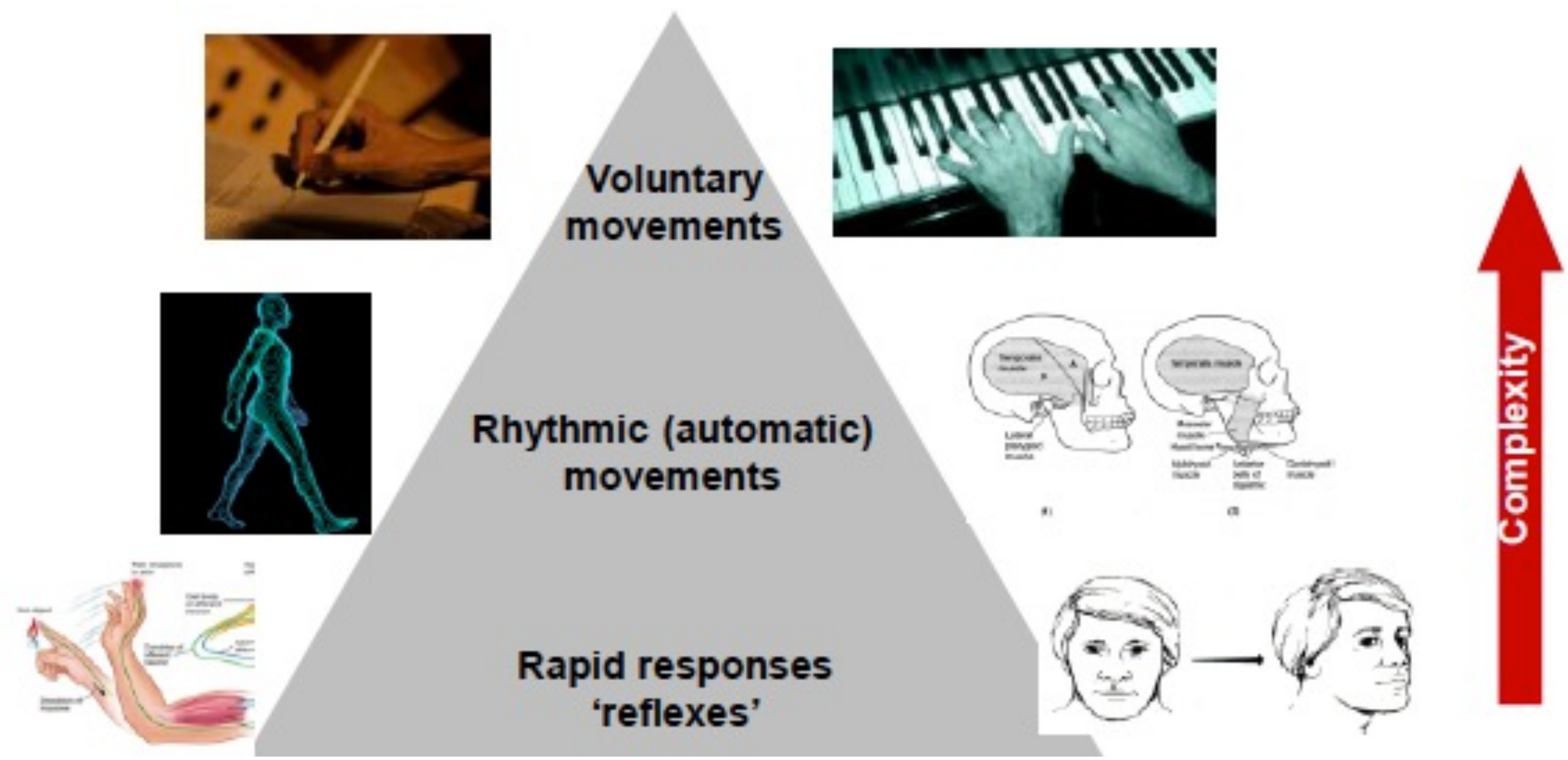
TYPES OF ACTION



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

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

Neural Commands ⇄ Muscle Activations ⇄ Joint motions ⇄ Hand Trajectories ⇄ Task Goals

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

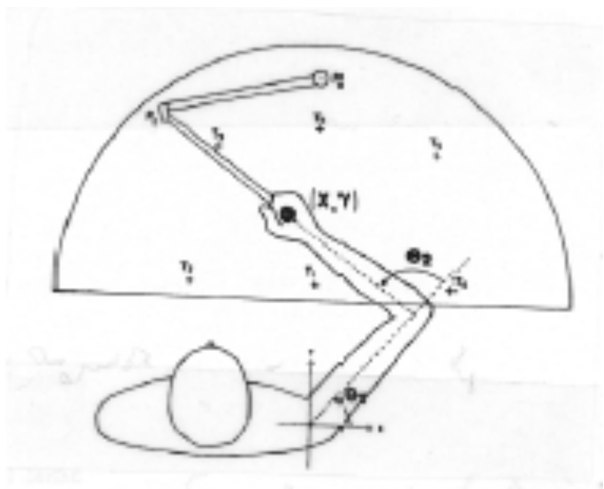
force/torque (Newton's law)

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

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

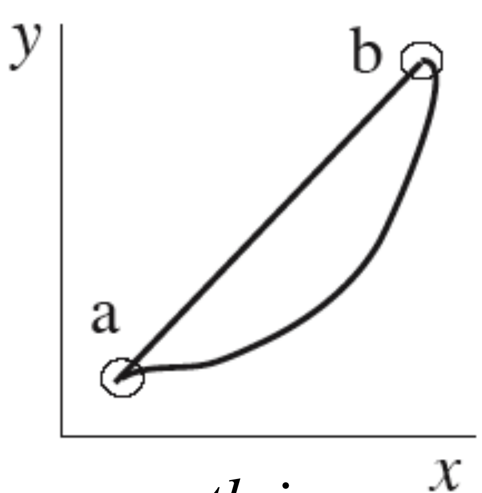


PROBLEMS

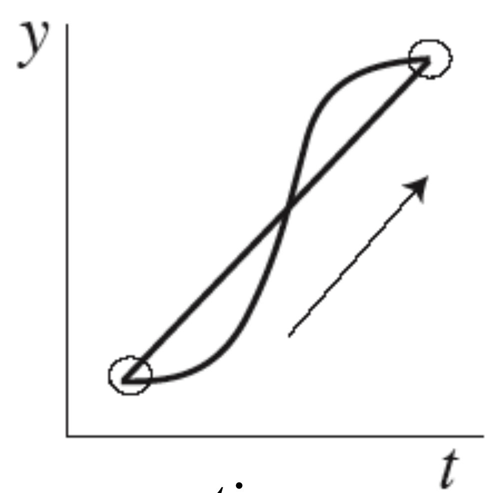
Redundancy

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

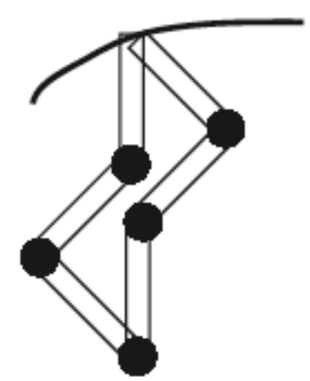
→ *Coordination*



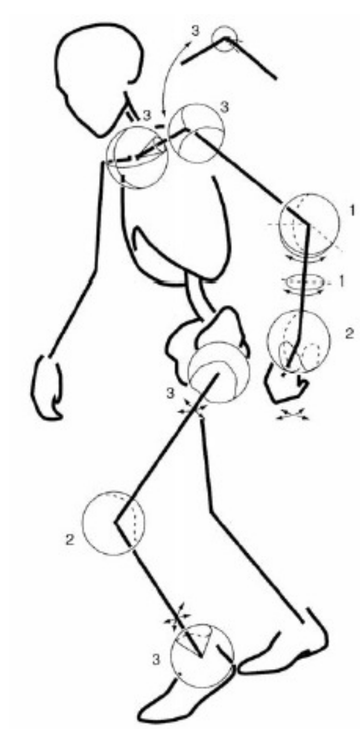
path in task space

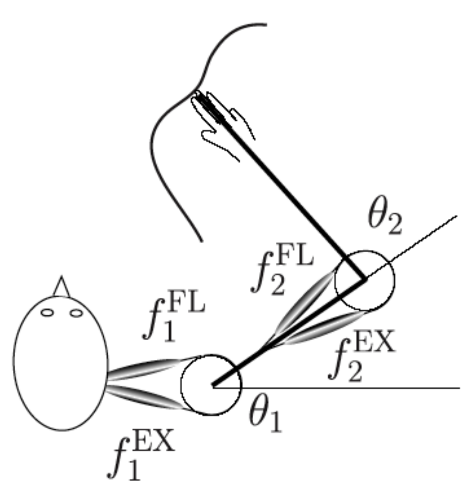


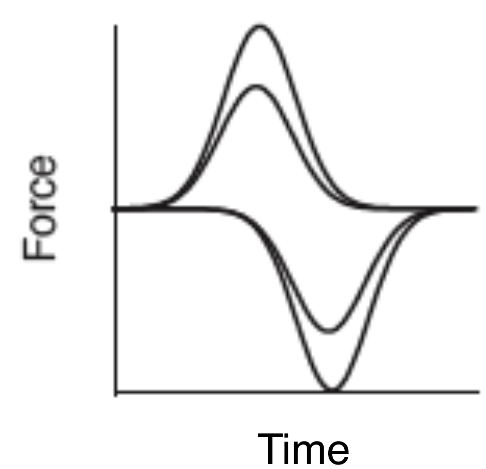
time course



body space redundancy







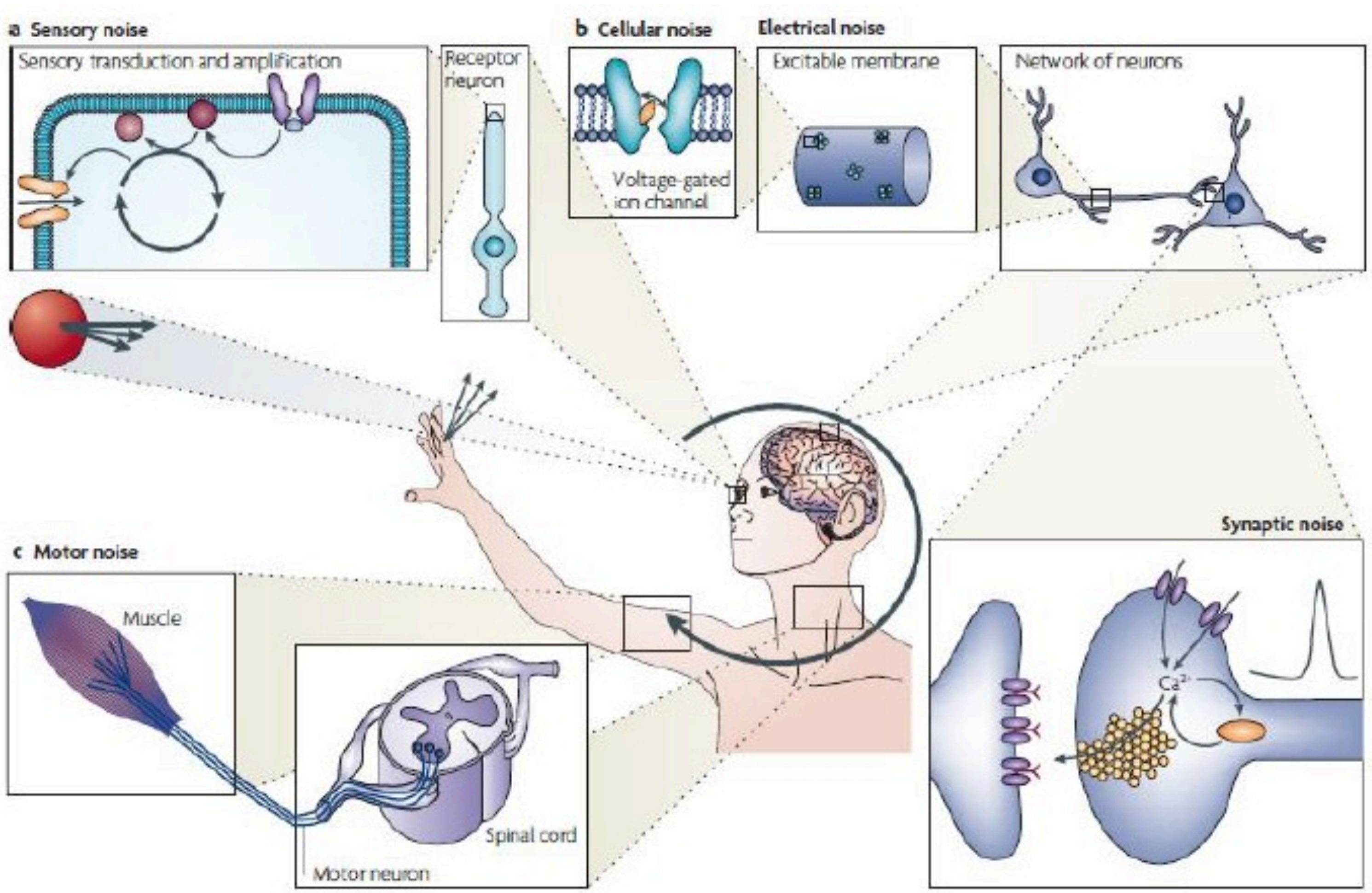
muscle space redundancy

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

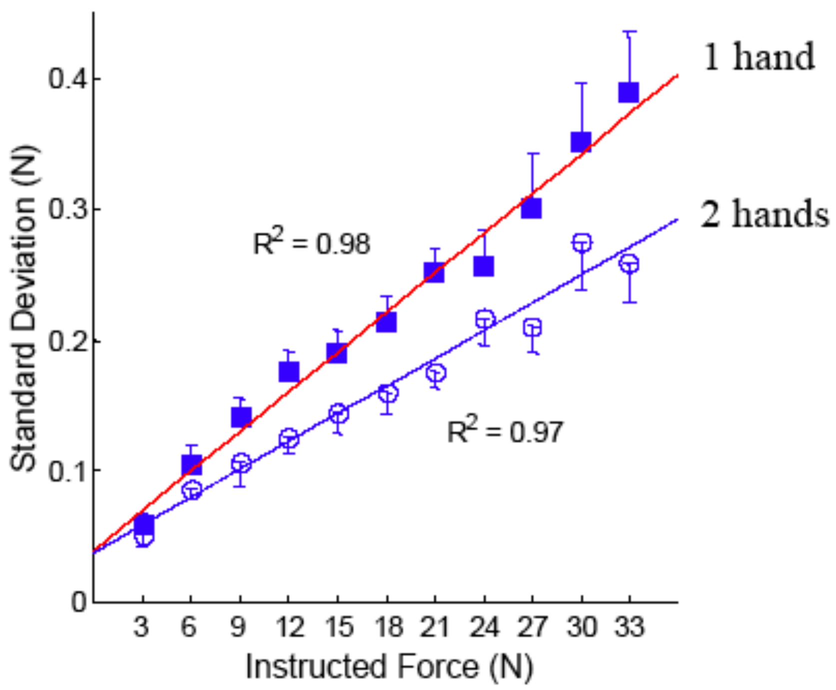
PROBLEMS

Noise

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



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



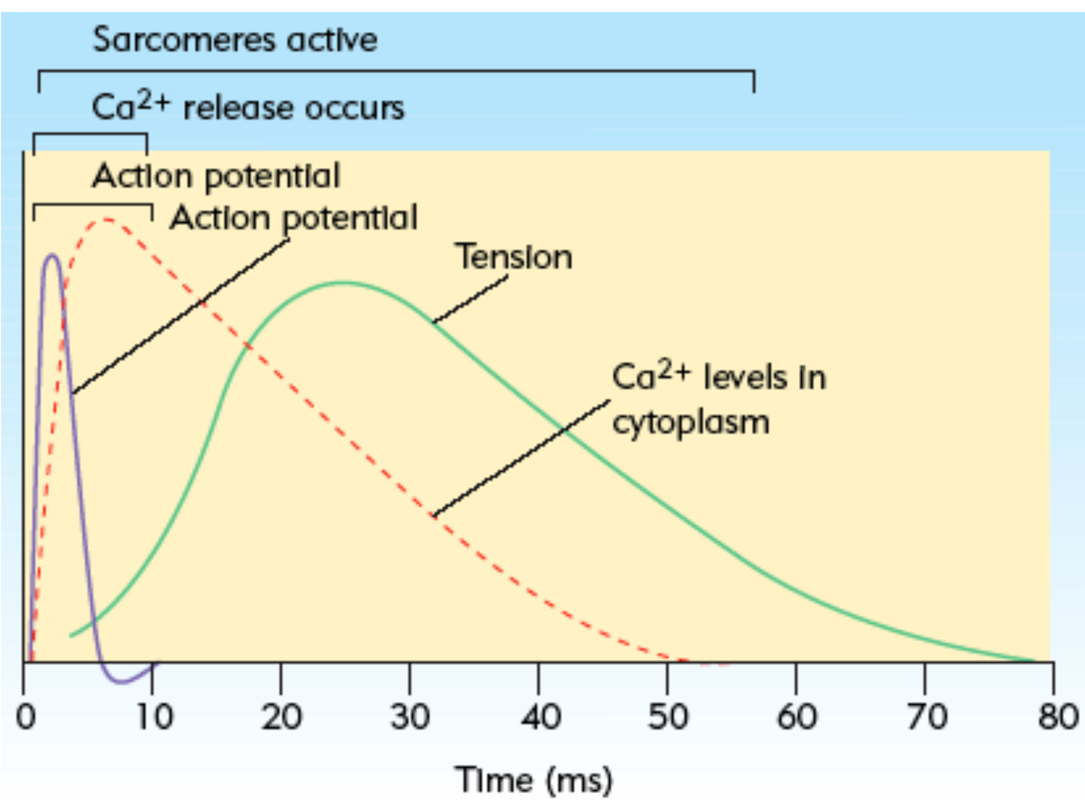
— Todorov, 2002, *Neural Comput* 14:1233

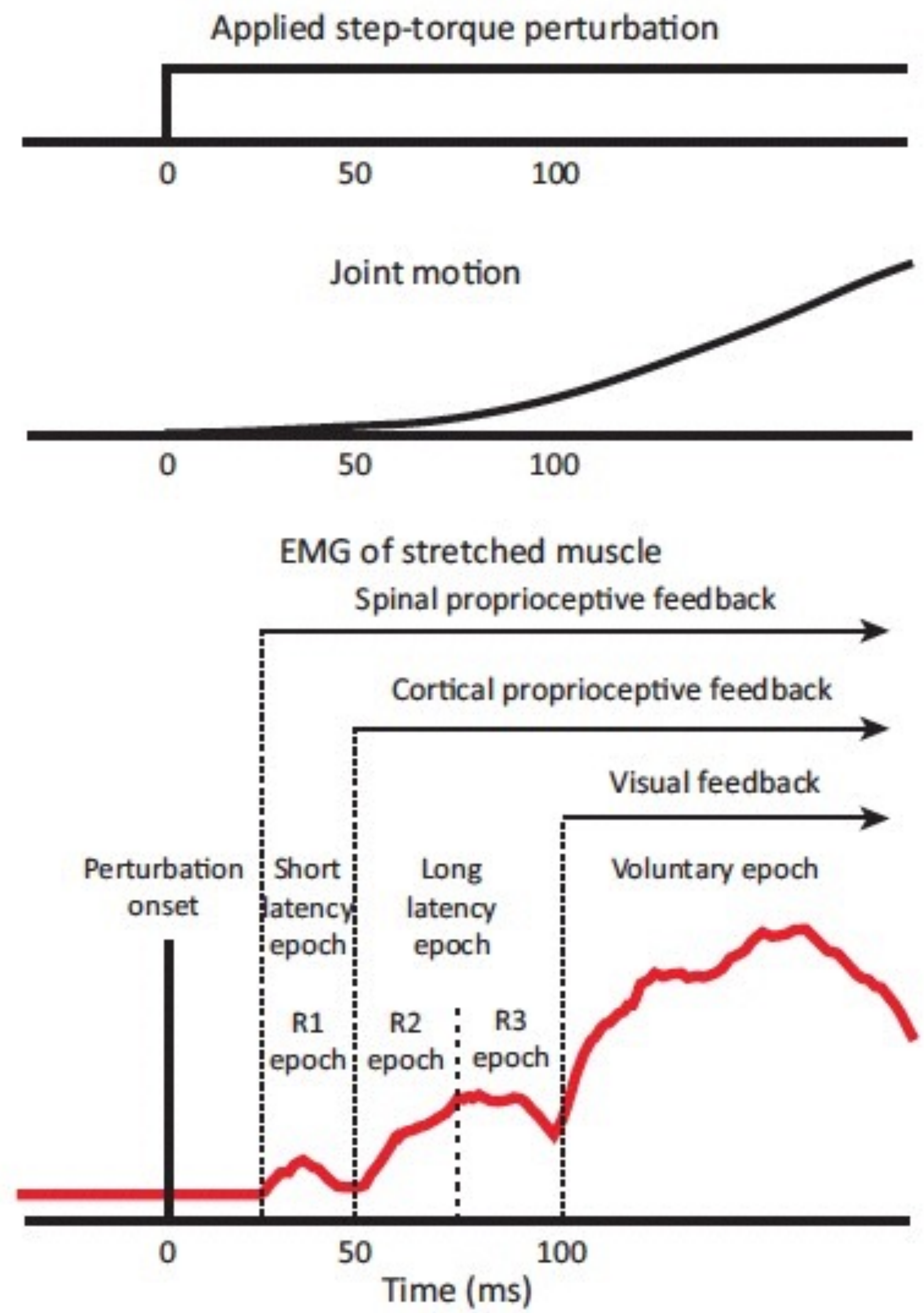
PROBLEMS

Delays

In afferent sensory information and efferent motor commands

→ *"We live in the past"*



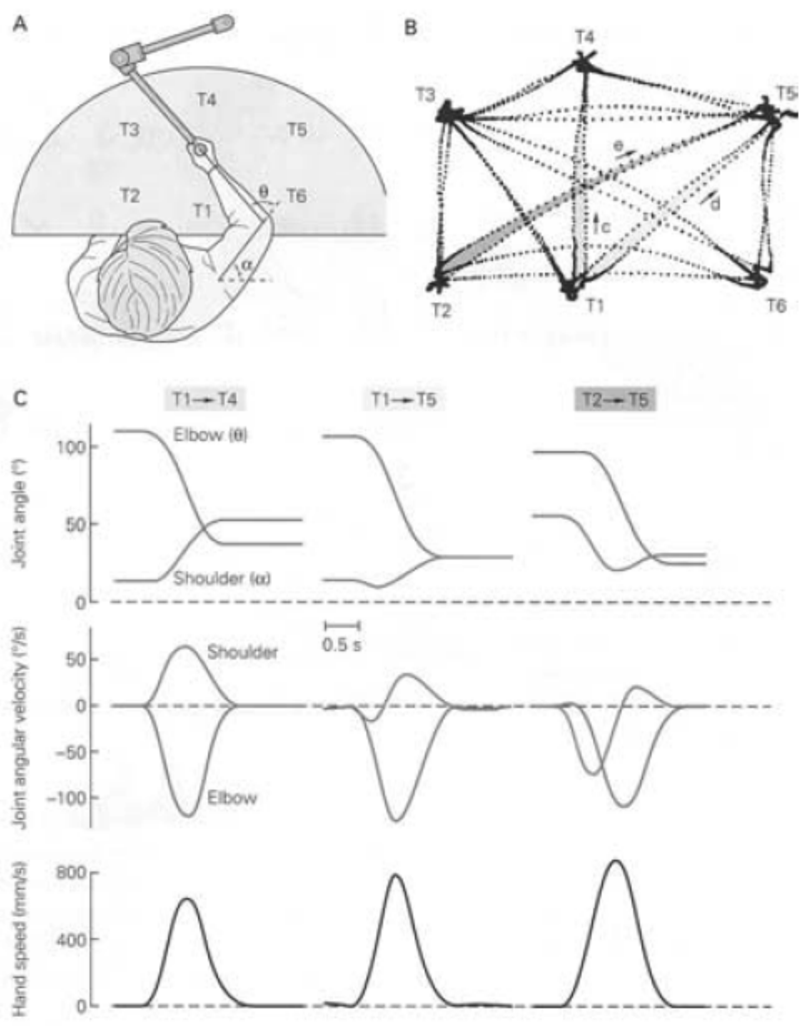


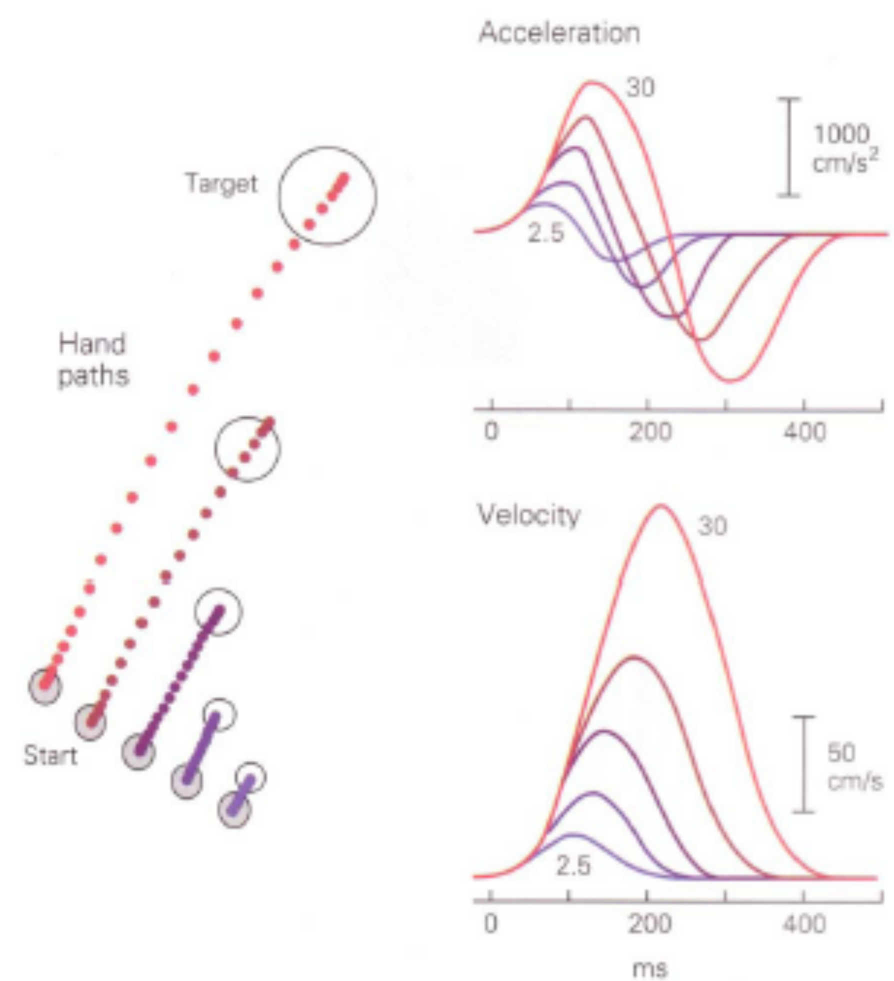
— Scott, 2012, *Trends Cogn Sci* 16:541

MOTOR INVARIANTS

Trajectories

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

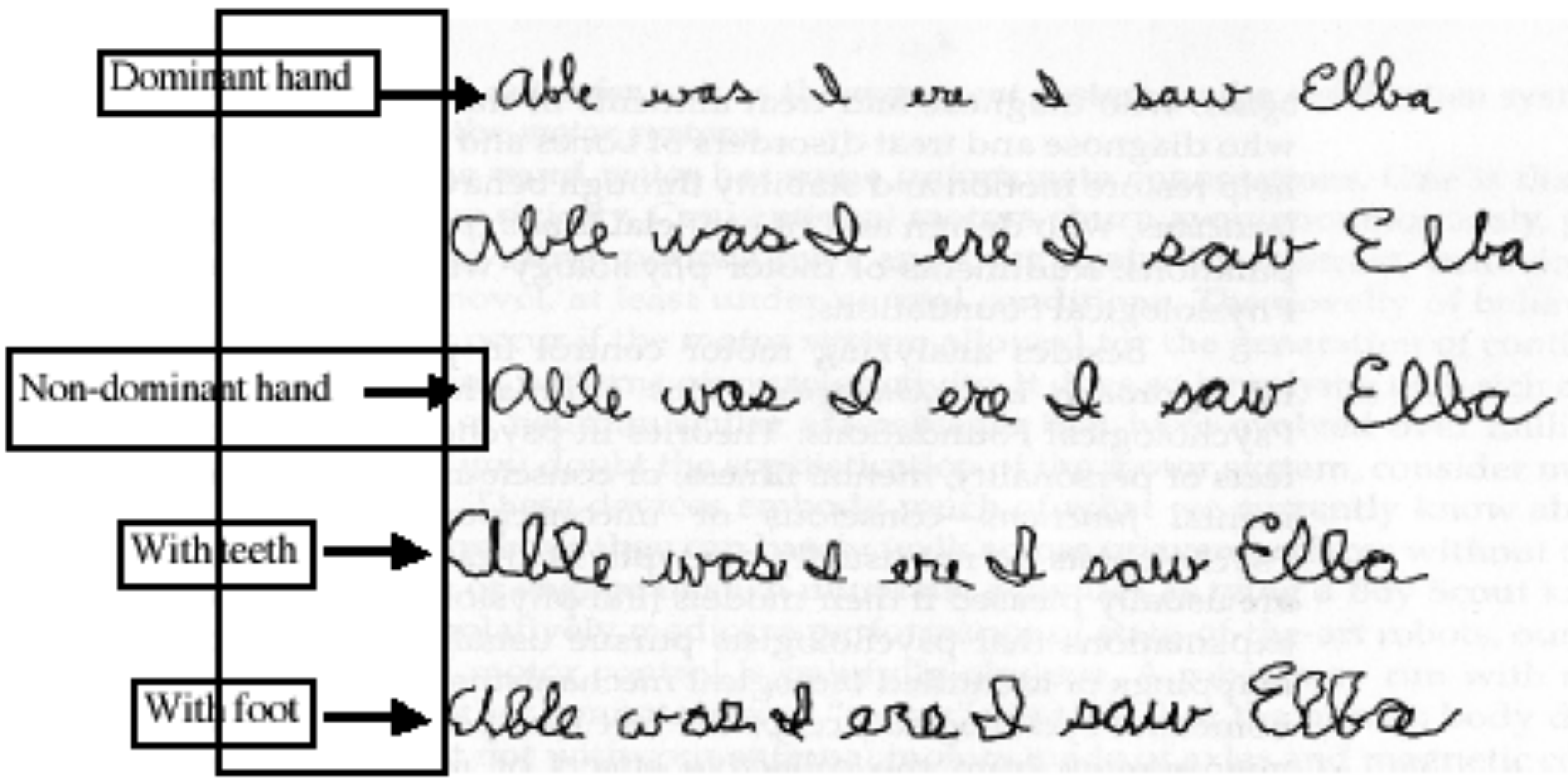




MOTOR INVARIANTS

Motor equivalence

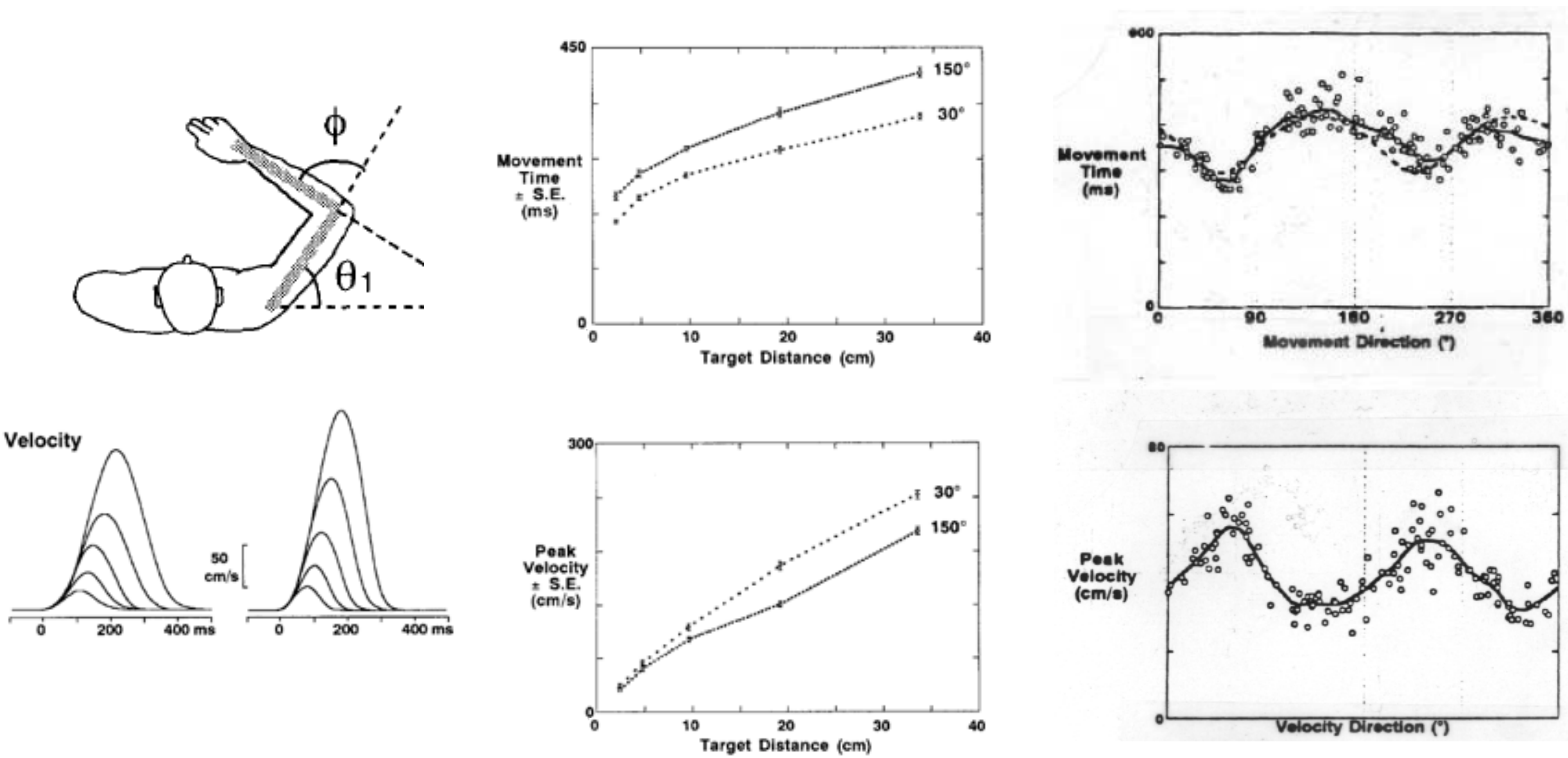
Actions are encoded in the central nervous system in terms that are more abstract than commands to specific muscles



MOTOR INVARIANTS

Scaling laws

Duration and velocity scale with amplitude and load

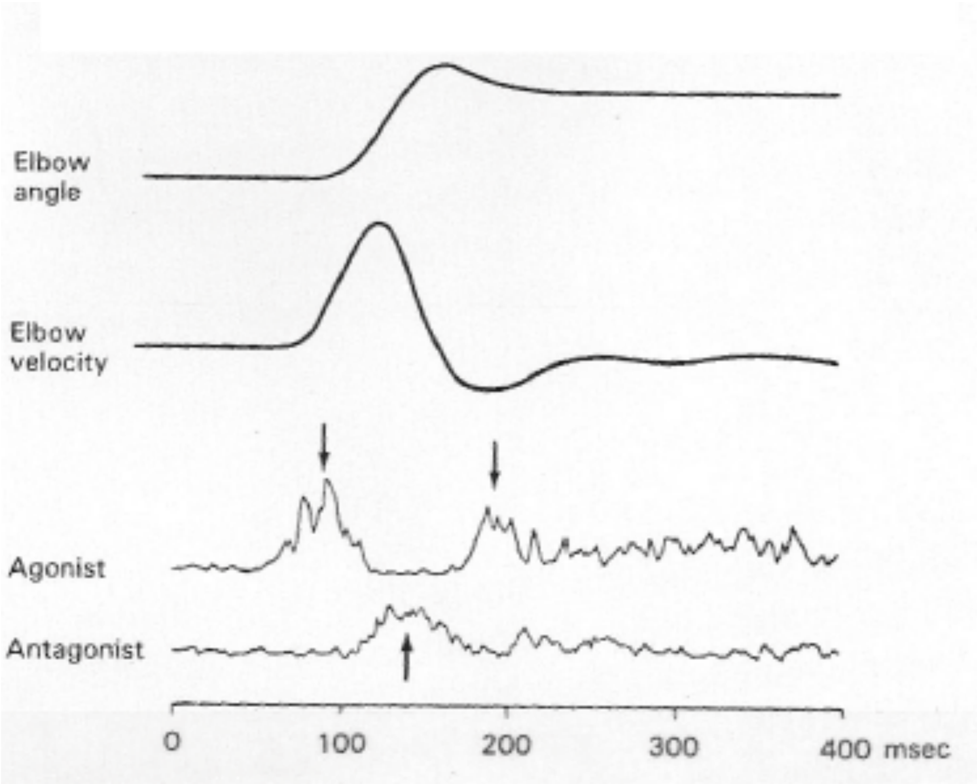


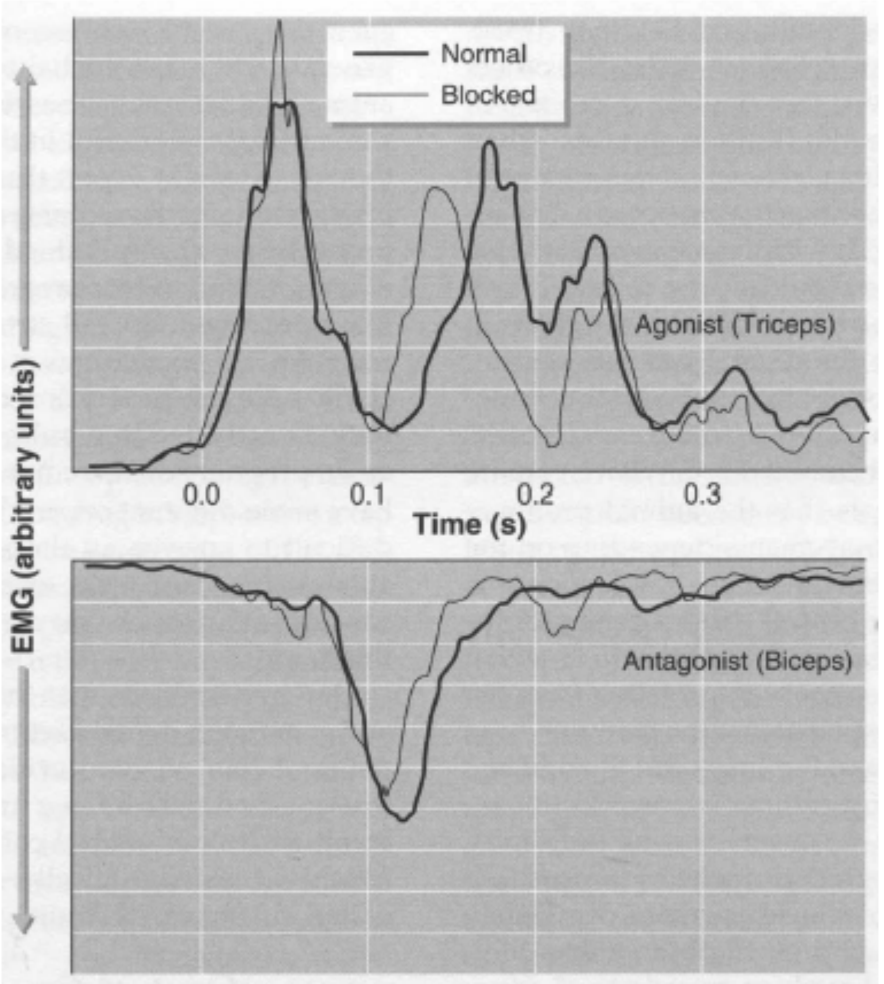
— Gordon et al., 1994, *Exp Brain Res* 99:112

MOTOR INVARIANTS

EMG

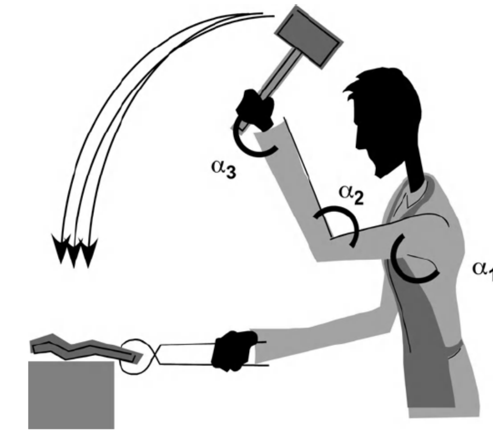
Triphasic pattern during fast movements





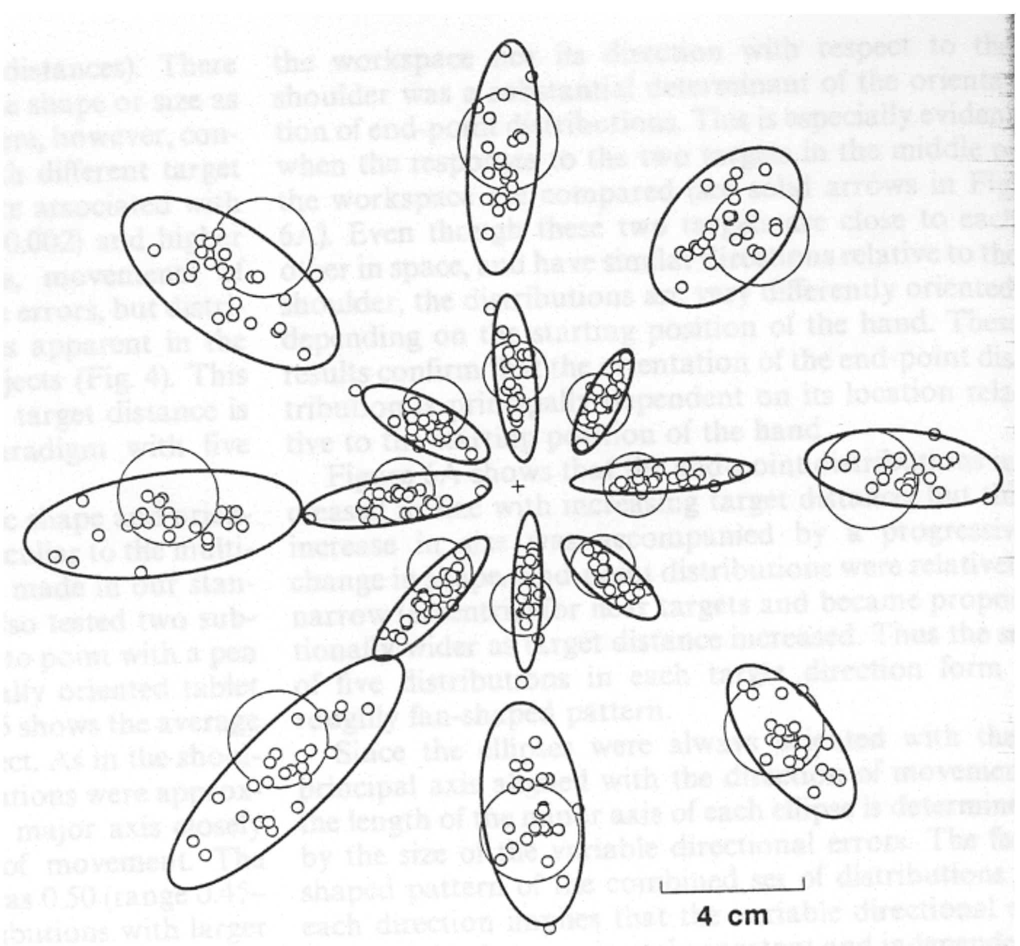
—Wadman et al., 1979, *J Hum Mov Stud* 5:3

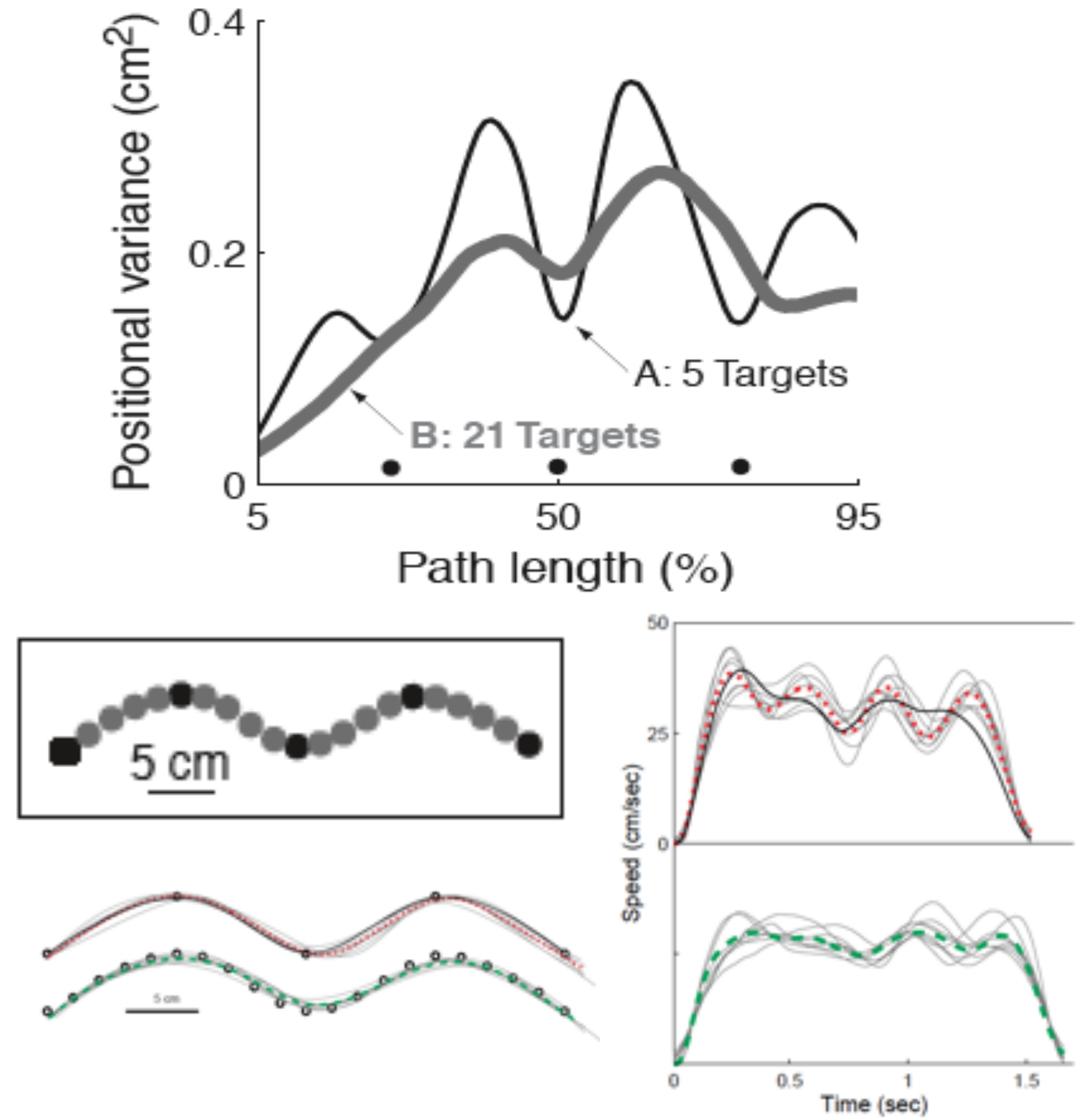
MOTOR VARIABILITY



Uncontrolled manifold, structured variability

« Repetition without repetition » (Bernstein)



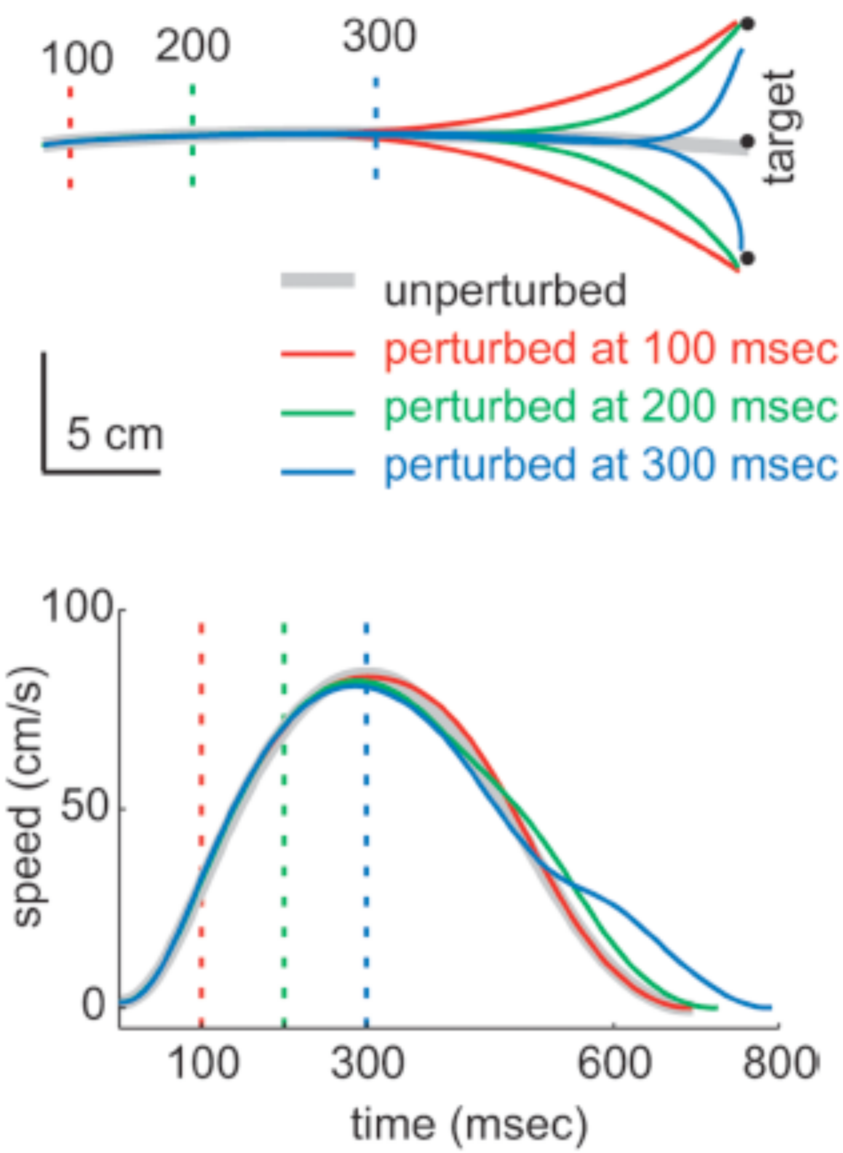


— Gordon et al., 1994, *Exp Brain Res* 99:97

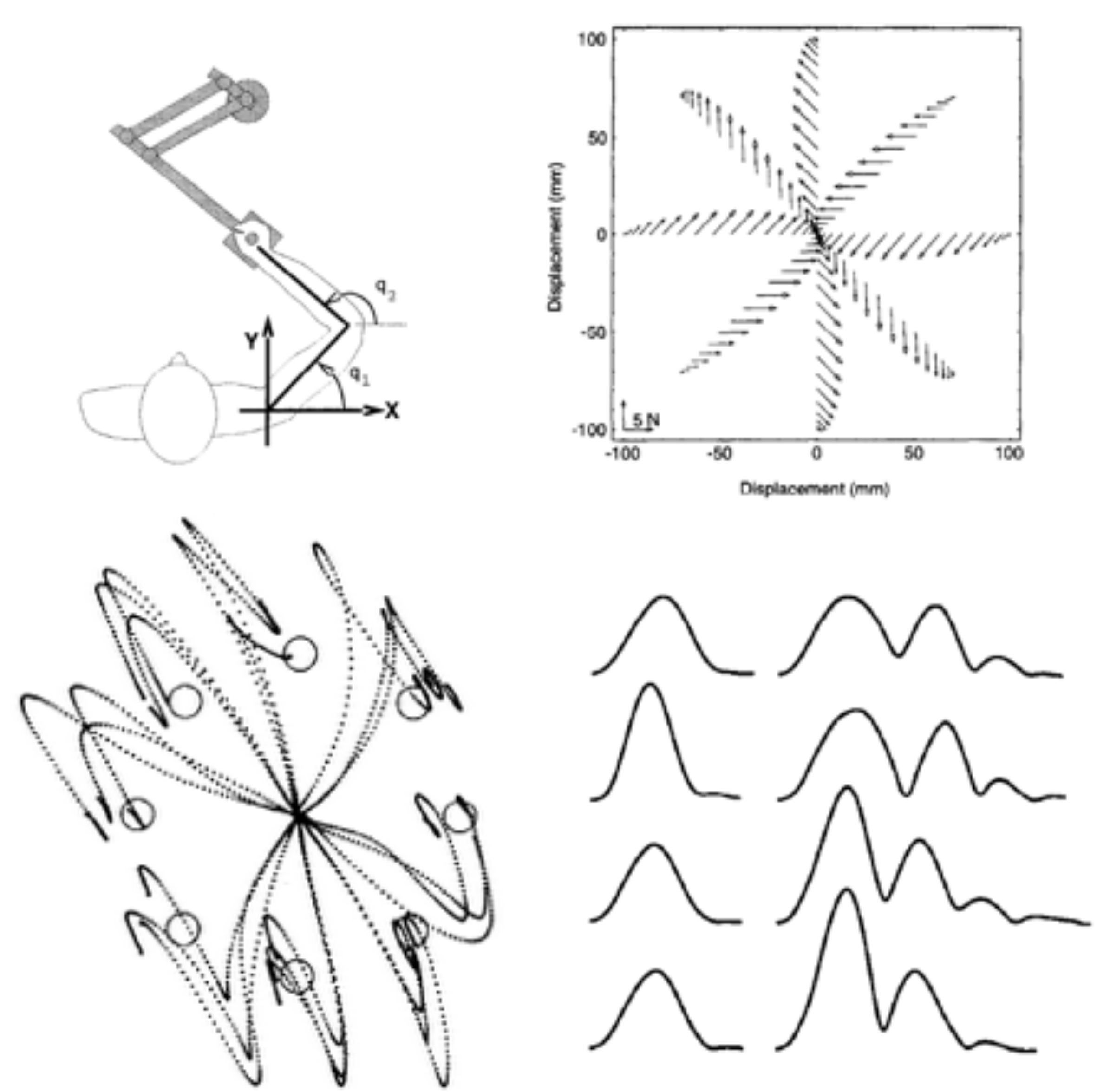
— Todorov & Jordan, 2002, *Nat Neurosci* 5:1226

FLEXIBILITY

Motor control is highly flexible in space and time



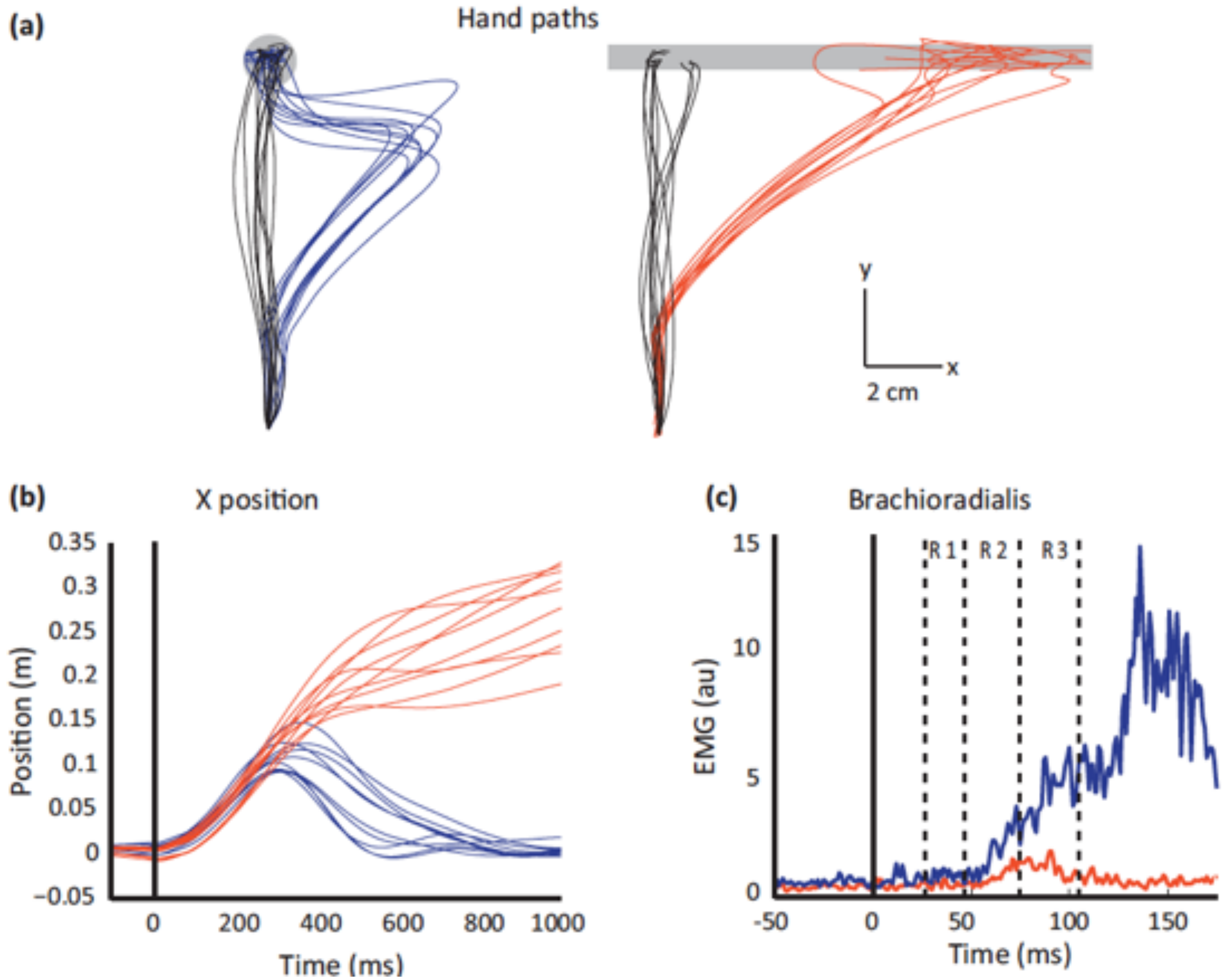
— Liu & Todorov, 2007, *J Neurosci* 27:9354

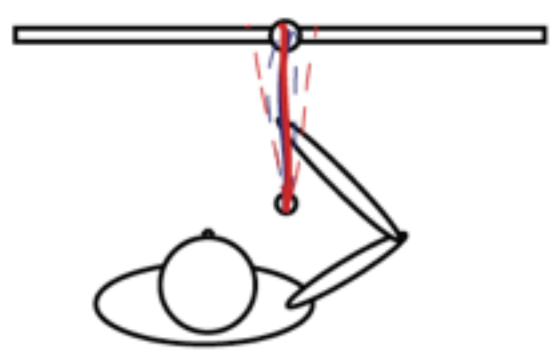


— Shadmehr & Mussa-Ivaldi, 1994, *J Neurosci* 14:3208

FLEXIBILITY

Errors are only corrected if they affect the behavioral goal and are ignored if they do not





Corrective responses are directed back to the circular target, whereas responses for the rectangular bar are redirected to a new location along the bar.

→

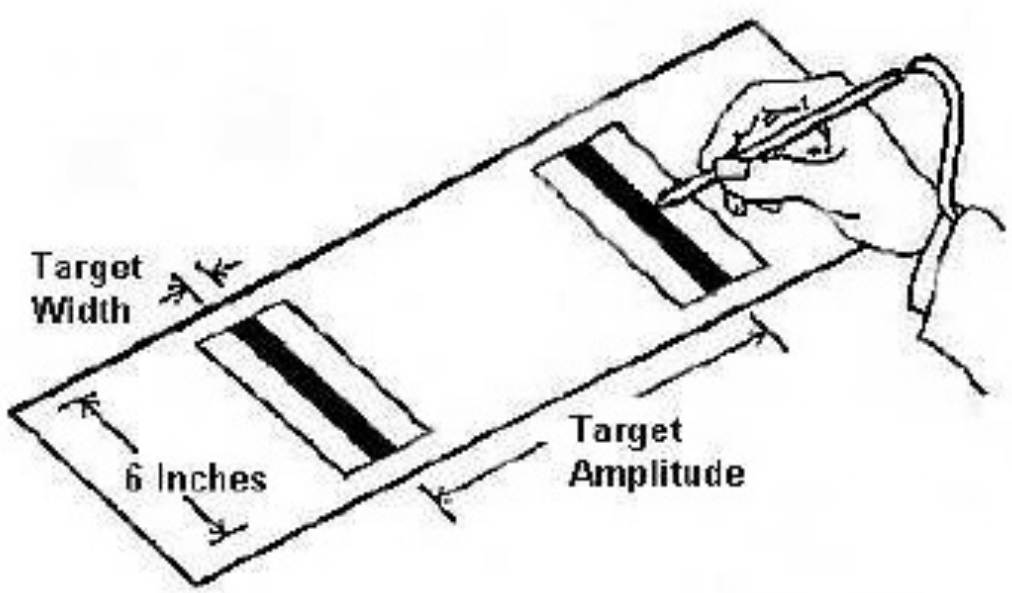
Corrective responses do not return to a desired trajectory

— Nashed et al., 2012, *J Neurophysiol* 109:999

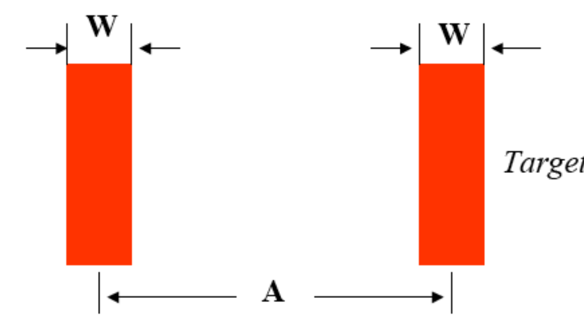
LAWS OF MOVEMENT

Fitts' law

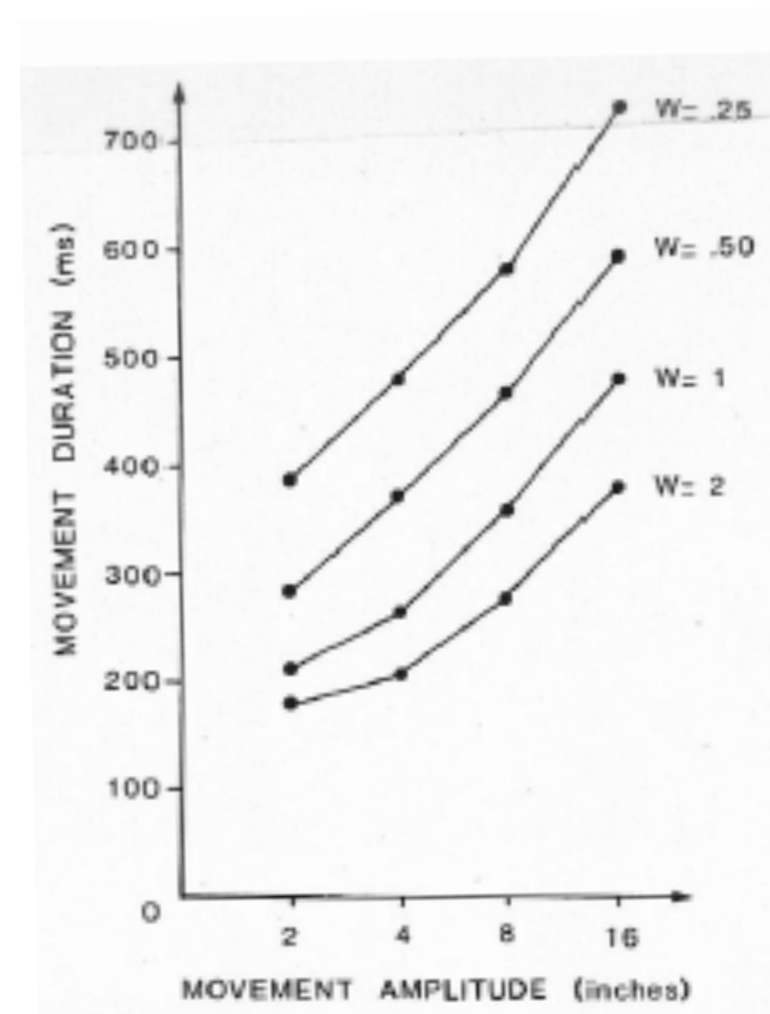
Speed/accuracy trade-off



— Fitts, 1954, *J Exp Psychol* 47:381



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



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COMPUTATIONAL MOTOR CONTROL

Descriptive (mechanistic) vs normative models

- Descriptive statements present an account of how the world is

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

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

  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*

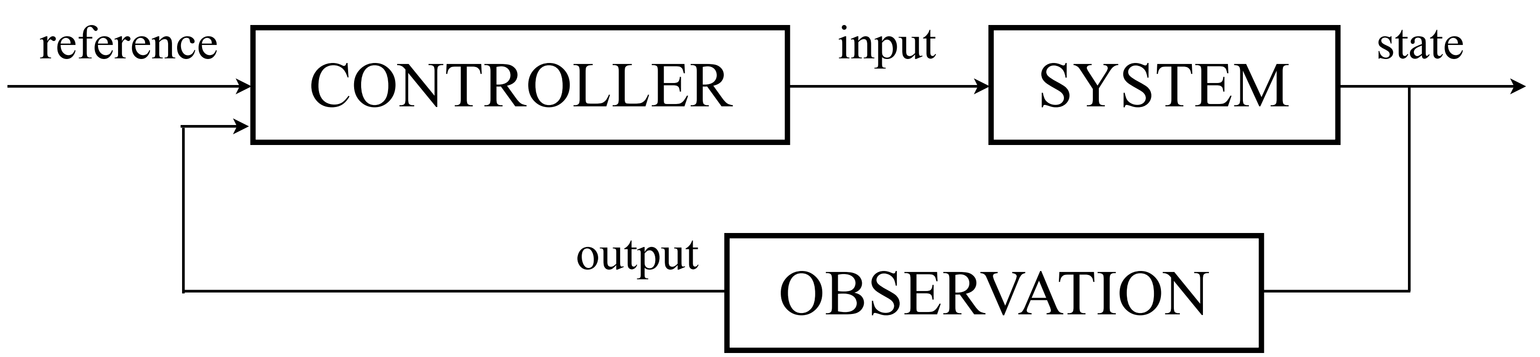
$y[n] = g(x[n])$ *output equation*

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

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

Control theory

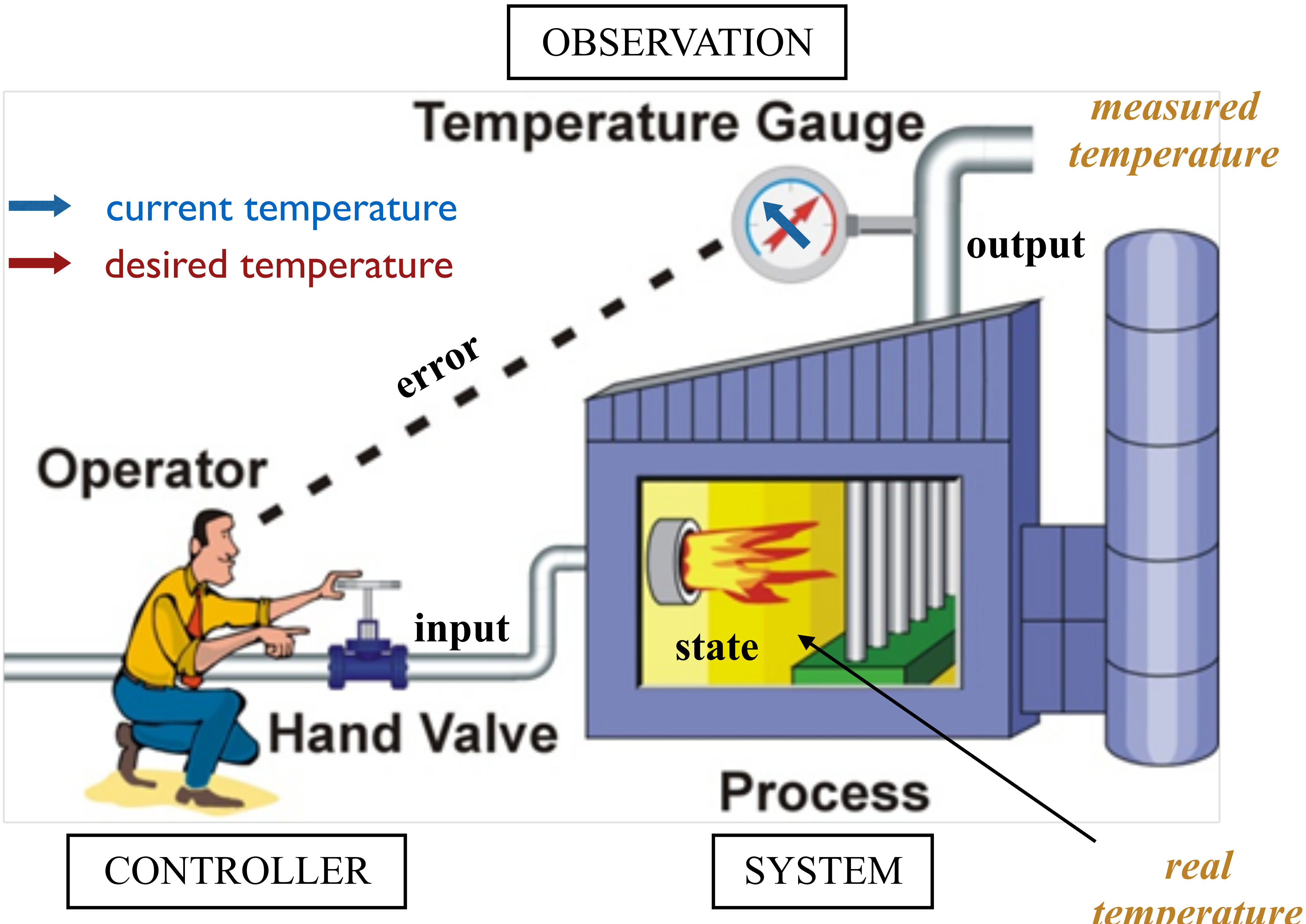
Deals with the behavior of dynamical systems with inputs, and how their behavior is modified by feedback.



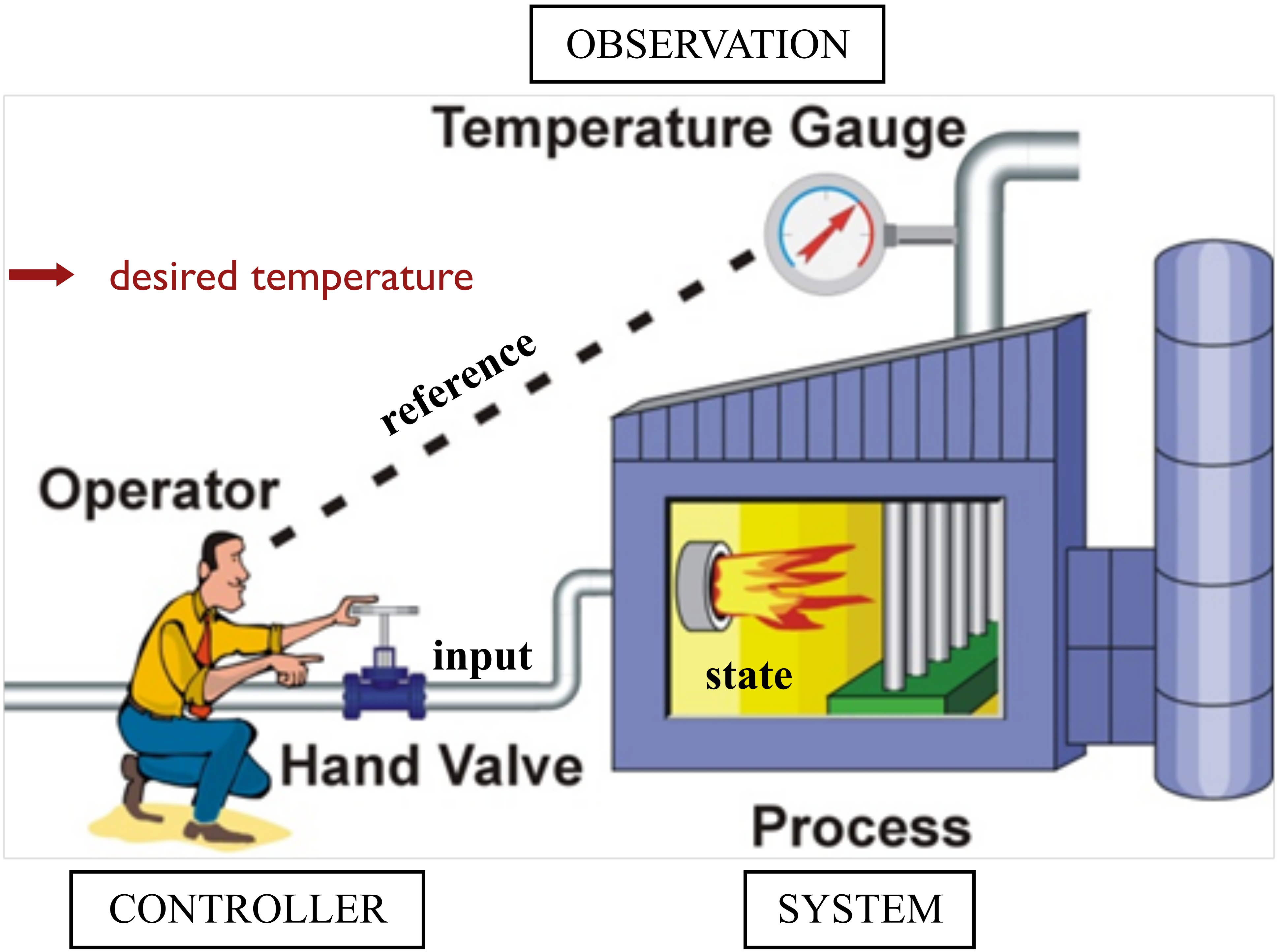
reference

- desired trajectory
- fixed point

TWO CONTROL PRINCIPLES — CLOSED LOOP



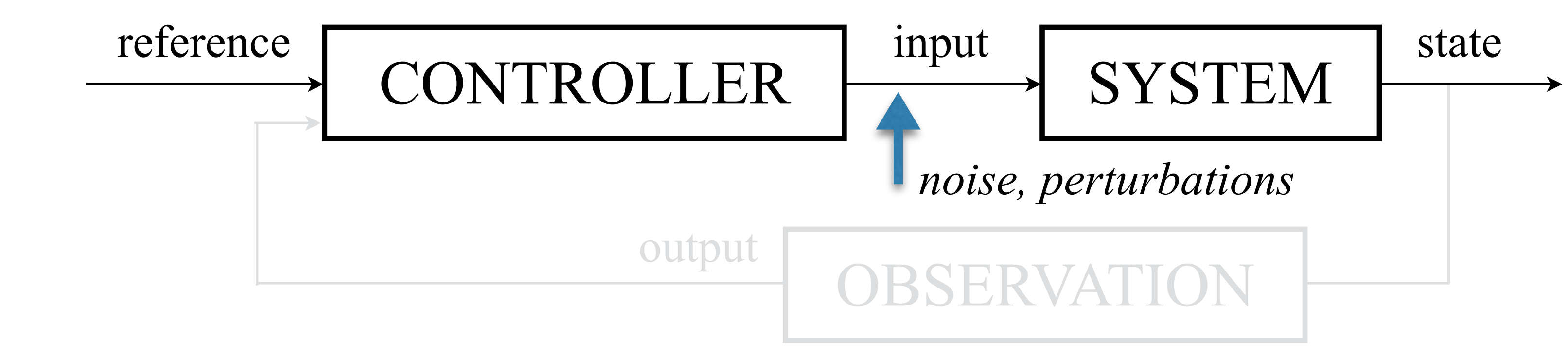
TWO CONTROL PRINCIPLES — OPEN LOOP



TWO CONTROL PRINCIPLES

Open-loop (feedforward)

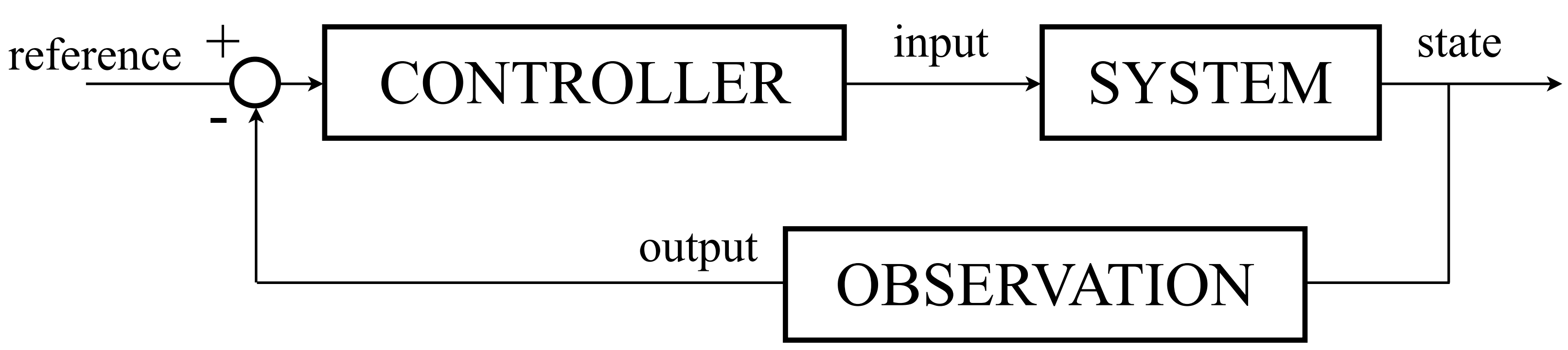
The controller is an *inverse* model of the system.



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

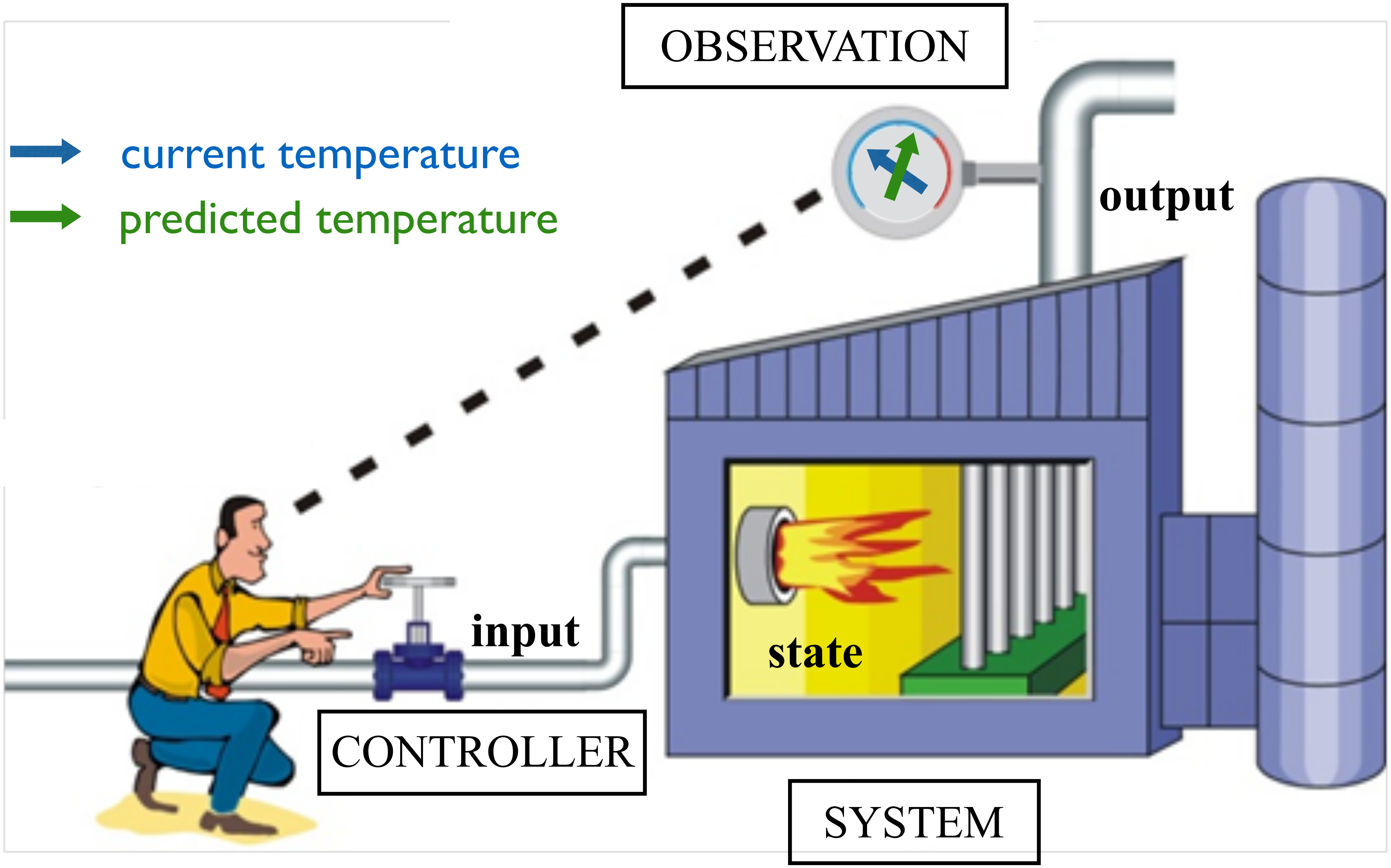
Closed-loop (feedback)

The controller is a function of an error signal.



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

FORWARD MODEL

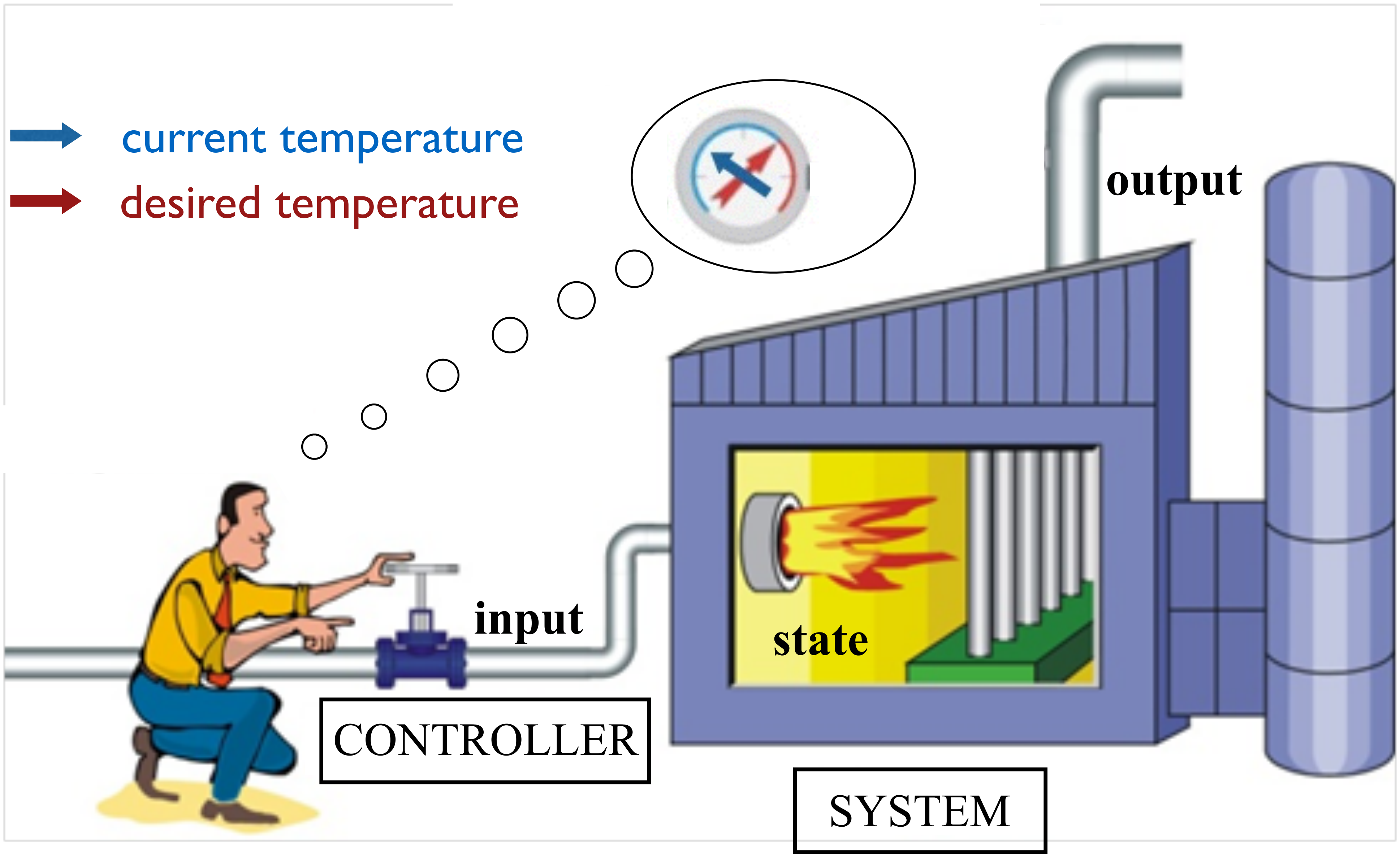


Model of the causal relationship between inputs and their consequences (states, outputs)

input → predicted output

input → predicted state

INVERSE MODEL



Model of the relationship between desired consequences (outputs, states) and corresponding inputs

desired state → input

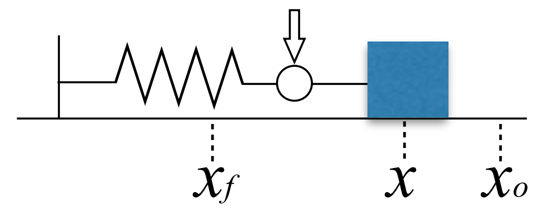
desired output → input

TWO MAIN THEORIES

Task-dynamics approach

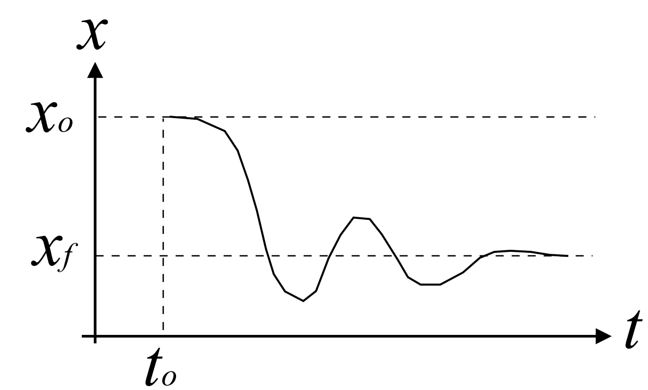
Generalized closed-loop systems.
Movements result from convergence to attractors of a dynamical system.

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



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

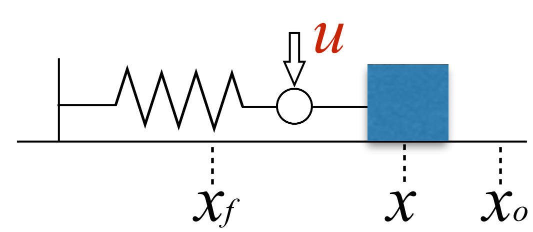
$$x=x(t,m,b,k)$$



Internal model approach

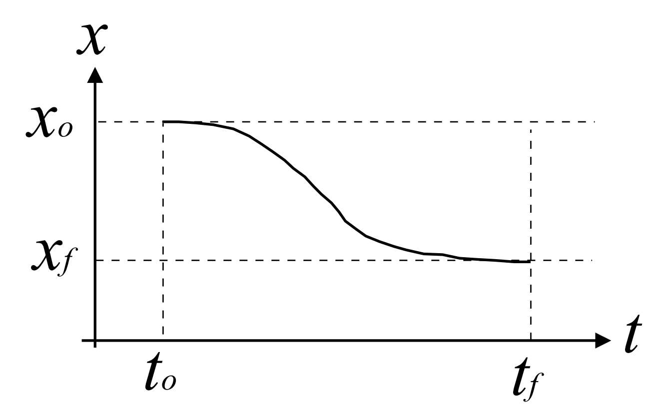
Builds an inverse model of the system to follow a prescribed trajectory or match some constraints (e.g. optimization).

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

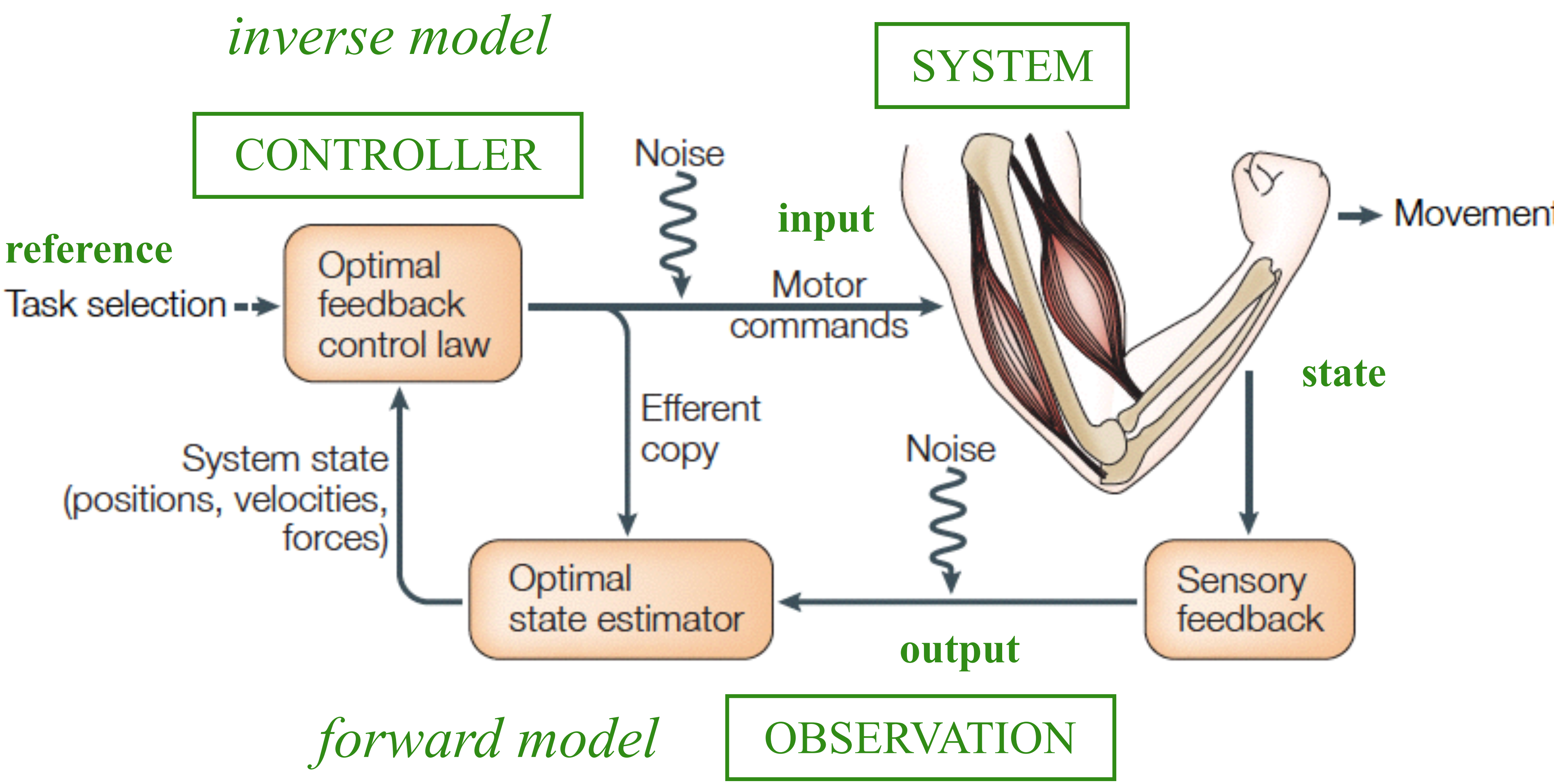


$$m\ddot{x}+b\dot{x}+k(x-x_f)=u$$

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



PROPOSED ARCHITECTURE

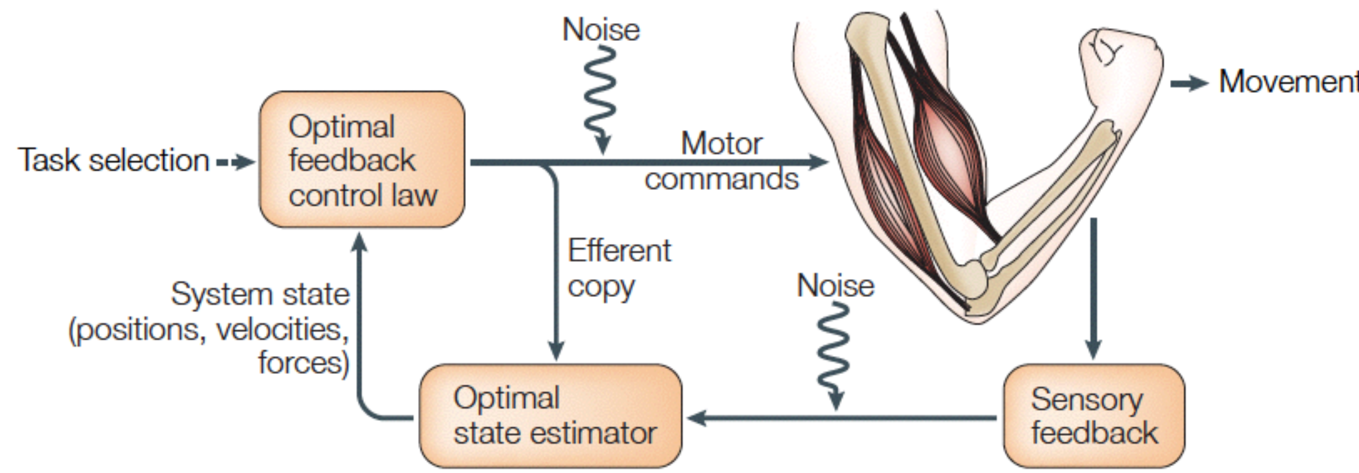


— Scott, 2004, *Nat Rev Neurosci* 5:534

PROPOSED ARCHITECTURE

Optimality principle

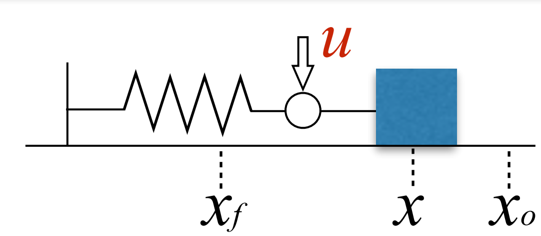
The interaction between the behavior and the environment leads a better adaptation of the former to the latter. The tendency could lead to an optimal behavior, i.e. the best behavior corresponding to a goal, according to a given criterion.



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

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