Modèles de l'apprentissage et du contrôle sensori-moteur

The organization of movement

1st course

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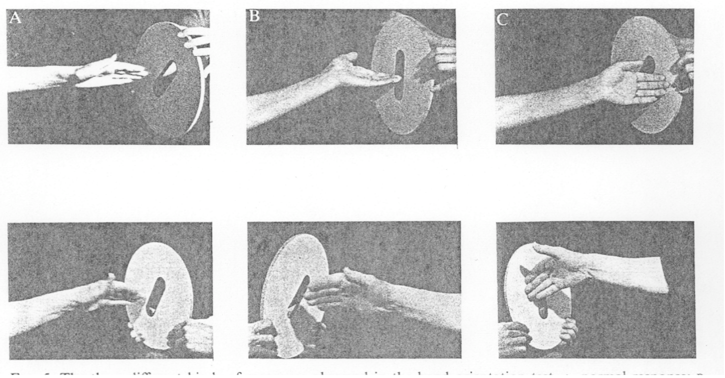
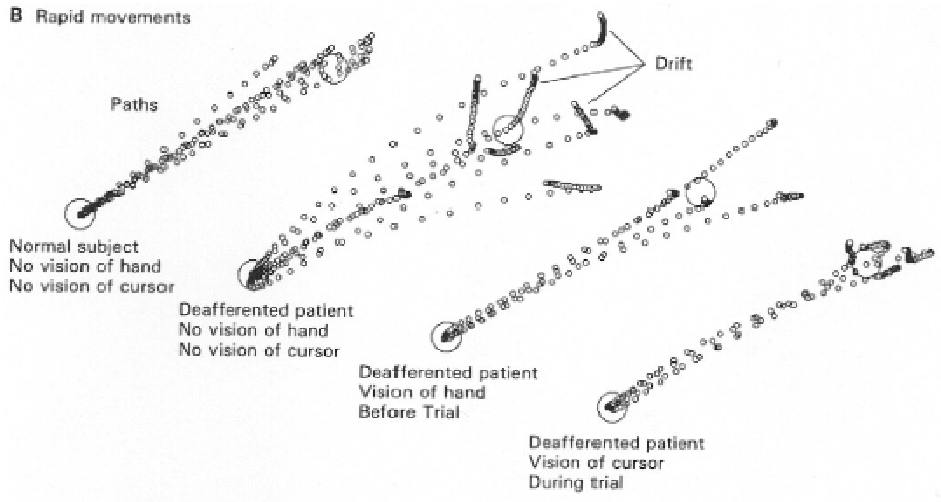
I would like a coffee …

- Where is the cup? Where is my arm?
  - Multisensory integration
  - Reference frame, coordinate systems
- How to reach the cup?
  - Choice of trajectory and trajectory formation
  - Motor equivalence, kinematic redundancy
- How to calculate the motor command?
  - Choice of muscles and muscular activations
  - Dynamic redundancy
- Is the command correct?
  - Online corrections: sensory feedback
  - Open or closed loop?
- How to do better at the next trial?
  - Adaptation, motor learning

Where is the cup? Where is my arm?

- Modalities: vision, audition, proprioception, …
  - Multimodal integration
- Reference frames
  - Target position: in fixed frame (earth), but perceived in moving frame (body)
  - Arm position: in body-related frame
  - In which frame is the movement represented?
- e.g. optic ataxia
- e.g. deafferentation

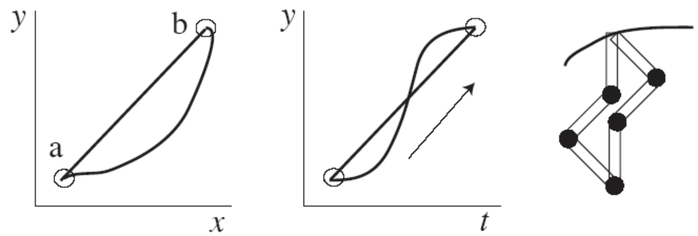




Perenin & Vighetto (1988)

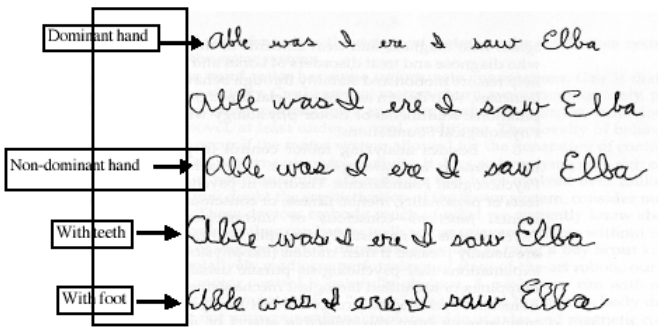
How to reach the cup?

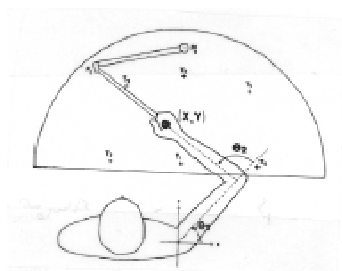
- Choice of a trajectory
  - Path in task space
  - Time course along the path



- Trajectory formation
  - Effector (***DEGREES OF FREEDOM, MOTOR EQUIVALENCE***)
  - Joint space trajectory (***REDUNDANCY***)

- Mathematics: inverse kinematics
  - Coordinate transformation
  - Ill-posed problem





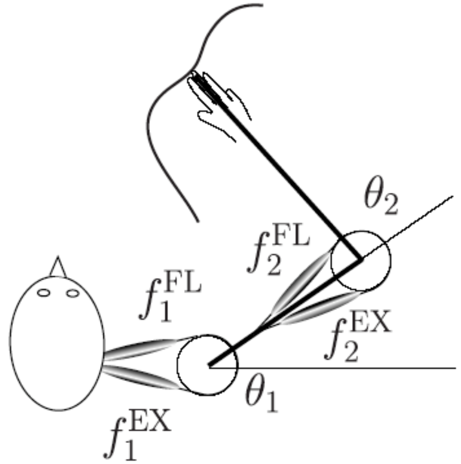
$$\begin{cases} x = L_1 \cos(\theta_1) + L_2 \cos(\theta_1 + \theta_2) \\ y = L_1 \sin(\theta_1) + L_2 \sin(\theta_1 + \theta_2) \end{cases}$$

$$\theta_2 = \arccos\left(\frac{x^2 + y^2 - L_1^2 - L_2^2}{2L_1L_2}\right)$$

$$\theta_1 = \arctan\left(\frac{y}{x}\right) - \arctan\left(\frac{L_2 \sin(\theta_2)}{L_1 + L_2 \cos(\theta_2)}\right)$$

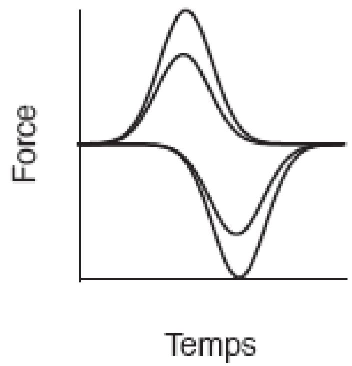
How to calculate the command?

- Joint torques
  - To produce a desired joint space trajectory



- Force distribution
  - Dynamic redundancy

- Mathematics: inverse dynamics



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

$$\tau_2 = (I_2 + \frac{m_2 l_1 l_2}{2}\cos\theta_2 + \frac{m_2 l_2^2}{4})\ddot{\theta}_1 + (I_2 + \frac{m_2 l_2^2}{4})\ddot{\theta}_2 + \frac{m_2 l_1 l_2}{2}\dot{\theta}_1^2 \sin\theta_2$$

$$\begin{cases} \tau_1 = \mu_1^{\mathrm{FL}} f_1^{\mathrm{FL}} - \mu_1^{\mathrm{EX}} f_1^{\mathrm{EX}} \\ \tau_2 = \mu_2^{\mathrm{FL}} f_2^{\mathrm{FL}} - \mu_2^{\mathrm{EX}} f_2^{\mathrm{EX}} \end{cases}$$

Is the command correct?

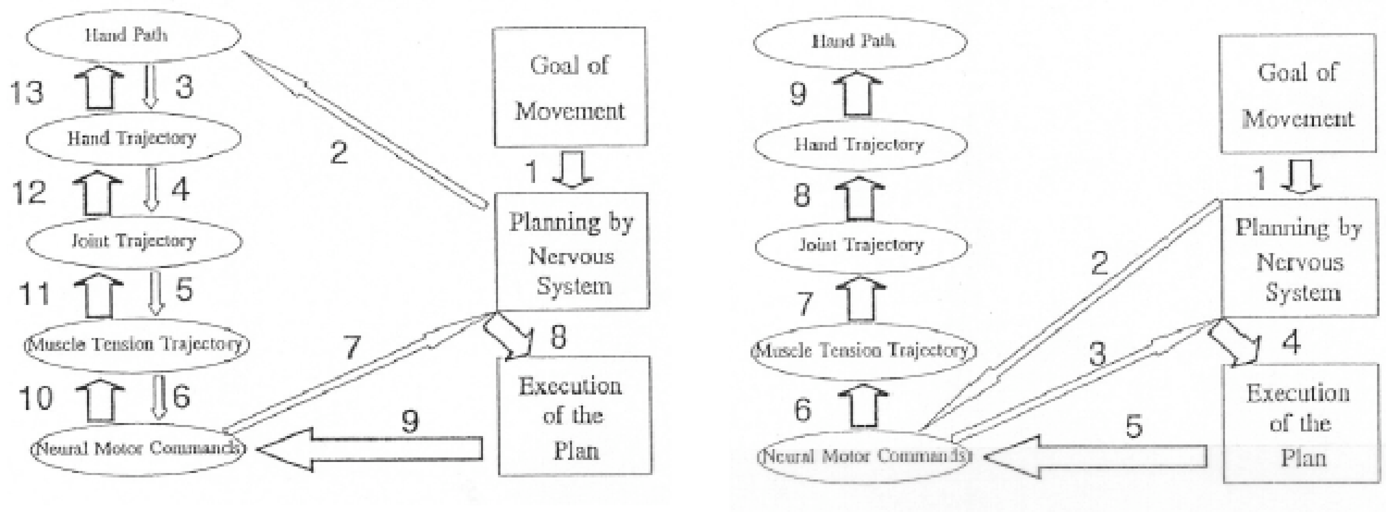
- Origin of errors
  - Localization of the target (target/eye, eye/head, head/trunk)
  - Localization of hand and arm (vision or not)
  - Estimation of physical characteristics (length, mass, inertia)
  - Approximation in transformations
  - Perturbations (e.g. the target has been displaced)
  - Noise
- Solution: online correction
  - Using vision and proprioception
  - Delays in feedback pathways
- Key points
  - Unsolved issues: open or closed loop?
  - « Motor program » vs online programming
  - Reflex vs voluntary

How to do better …

- Adaptation, motor learning
  - Biomechanical interface: tools, telemanipulation
  - Visuomotor transformations (gains, rotations, …)
  - Dynamic transformations (inertia, viscosity, stiffness)
- Nature of learning
  - Temporary / permanent
  - Interferences
  - Learning vs development
- Construction
  - Error signals
  - Learning step

But …

- Difference between idea, plan and execution?
- Separate representation of kinematics and dynamics?
- Level of details necessary to generate a motor act?
- Biological motor control = control of a robot?



Long ago …

- Early in the 20th century, *Woodworth* wrote :
« When I voluntarily start to walk, my intention is not of alternately moving my legs in a certain manner; my will is directed toward reaching a certain place. I am unable to describe … what movements my arms or legs are going to make; but I am able to state what result I design to accomplish. »

Difficulties and paradoxes

- Interweaving of processes
  - No « elementary » movements which would be equivalent to elementary sensory stimuli
  - Parallel/sequential elaboration and convergence in the « final common pathway »
  - Multiple loops

- Complexity of problem / apparent ease in the control of movement
  - Complex problems to solve even for the simplest motor acts
  - Problem of degrees of freedom (*Bernstein*): how does the CNS choose among an infinity of solutions
  - Yet: stereotyped behaviors (invariants)

Study of motor control

- Computational approach
  - What is the problem to be solved?
  - Reveals the nature of constraints that the physical world puts on the solution of problem
  - *Hildreth and Hollerbach* : « It is often true that before we can understand how a biological system solves an information processing problem, we must understand in sufficient detail at least one way that the problem can be solved, whether or not it is a solution for the biological system. »

- Experimental approach: observe, measure, quantify
  - Search for « regular » patterns (**invariants**)
    - Kinematic, dynamic, neuronal variables; errors (constant, variable); parametric relationships task/performance; simple/complex, slow/fast movements; vision, proprioception, touch; pathologies
  - Hypothesis that invariants are actually controlled by the CNS
  - Description in terms of « laws »

Methods

- Psychophysics
  - Time course of physical quantities (e.g. position, velocity, force, …)
  - *e.g. a human subject points with his hand toward a target - the experimenter measures characteristics of movement*
- Neurophysiology
  - Neural substrat of sensorimotor transformations
  - *e.g. a monkey points with his hand toward a target - the experimenter records single neuron activity in the motor cortex*
- Brain imaging
  - Neural bases of motor control
  - *e.g. a human subject points with his hand toward a target - the experimenter measures electrical, metabolic, …, activity of the brain*
- Neuropsychology
  - Quantify sensorimotor deficits
  - *e.g. a patient points with his hand toward a target - the experimenter tries to define the nature of the deficit*

Otherwise

Neural networks

Neuroscience

Anatomy

Physiology

Psychology

Engineering
Control theory

Neurology

Physical education
Sport

Biomechanics

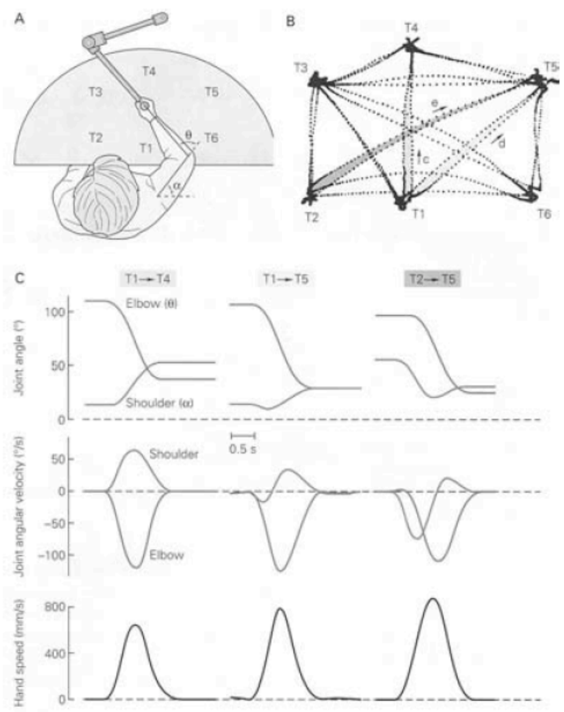
Ergonomy

Physiotherapy

Invariants of movement

- Trajectories
  - Approximately straight, bell-shaped velocity profiles, independent of movement conditions (e.g. load)

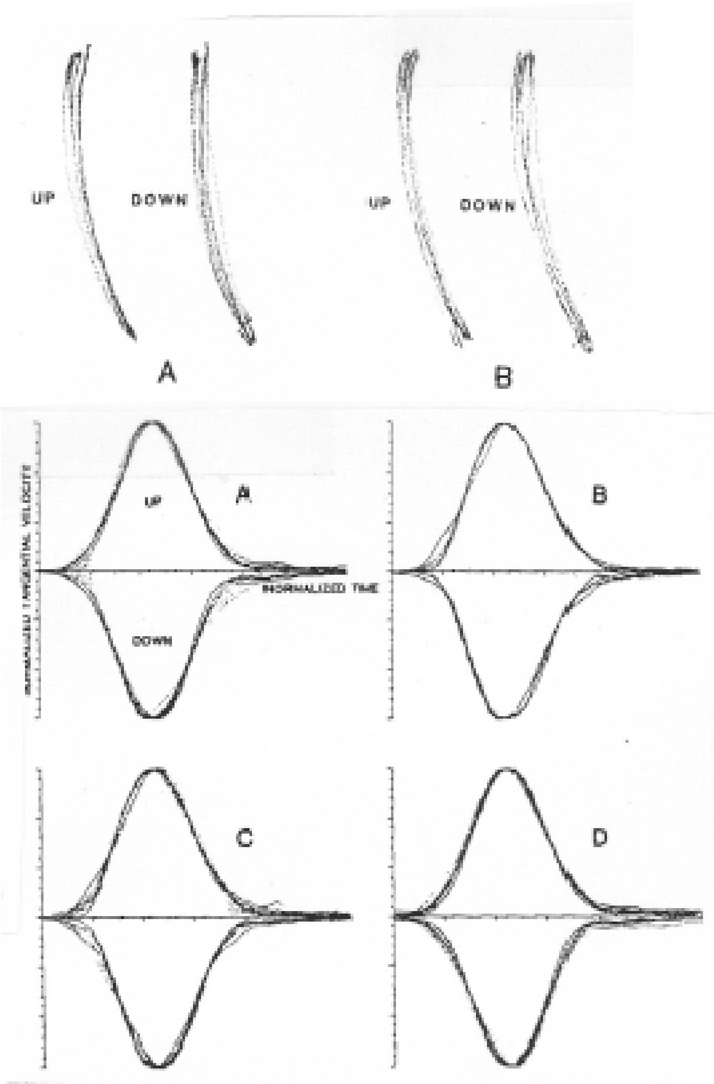
- Parametric relationships
  - Amplitude / duration, peak velocity
  - Direction / duration
  - …



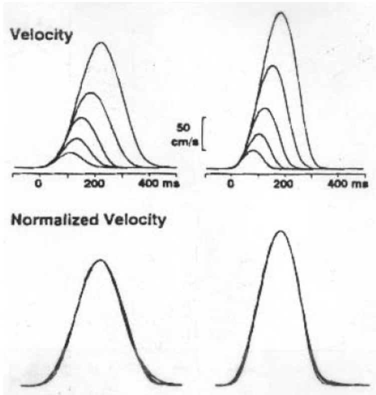
- EMG
  - Triphasic pattern

- Variability
  - Structure

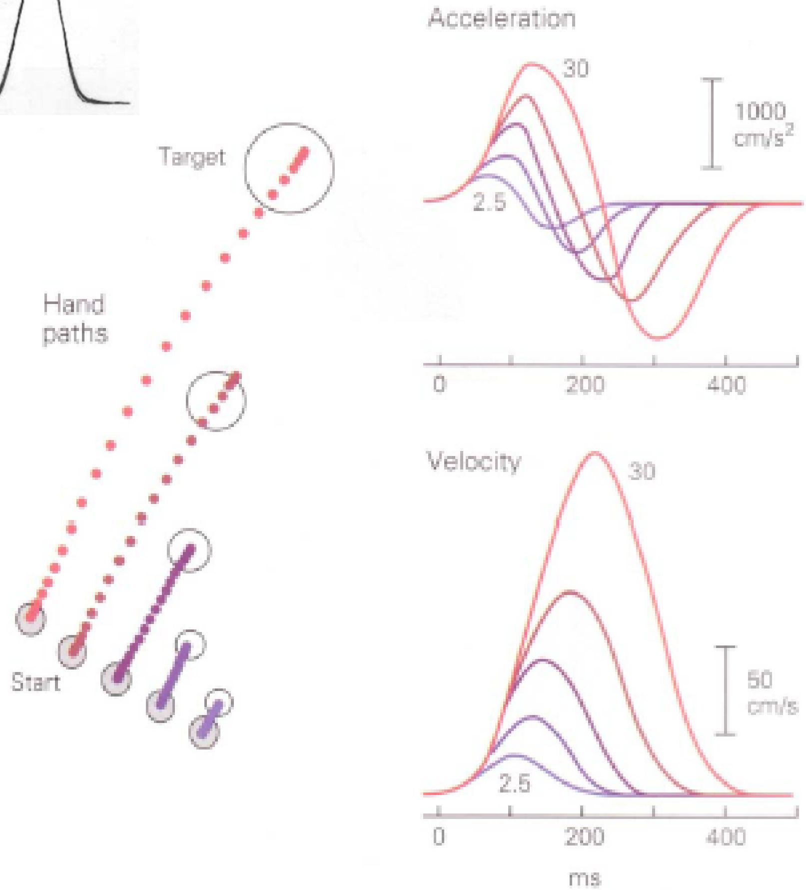
Invariants of movement (...)



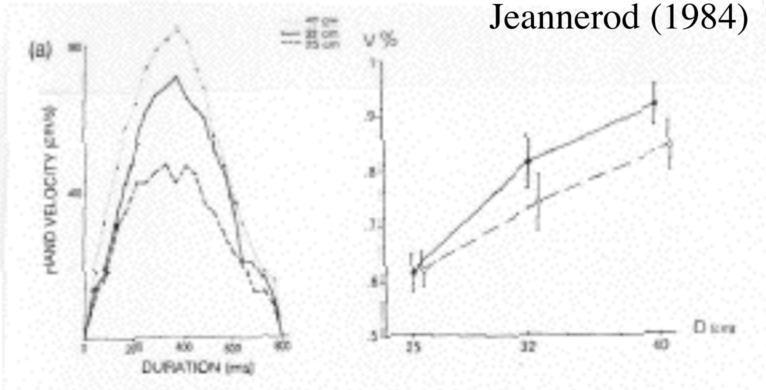
Atkeson & Hollerbach (1985)



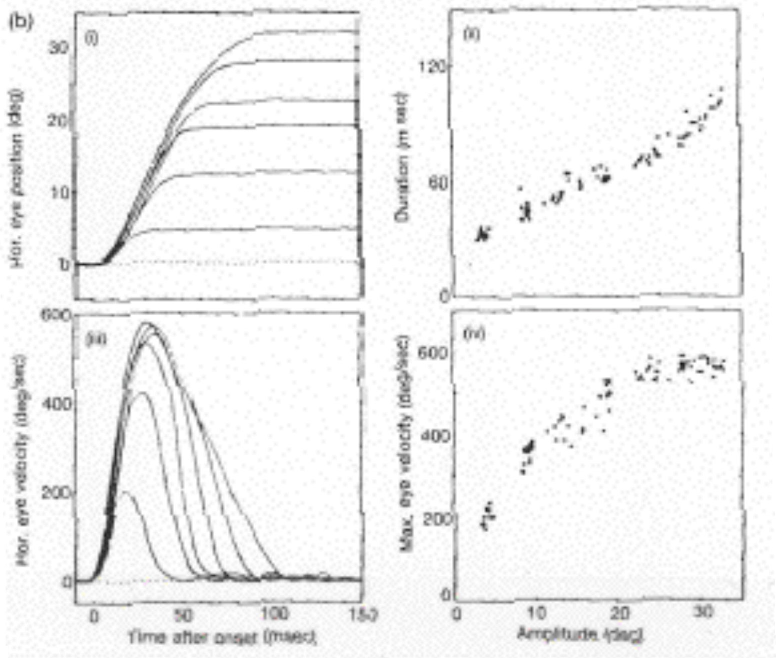
Gordon et al. (1994)



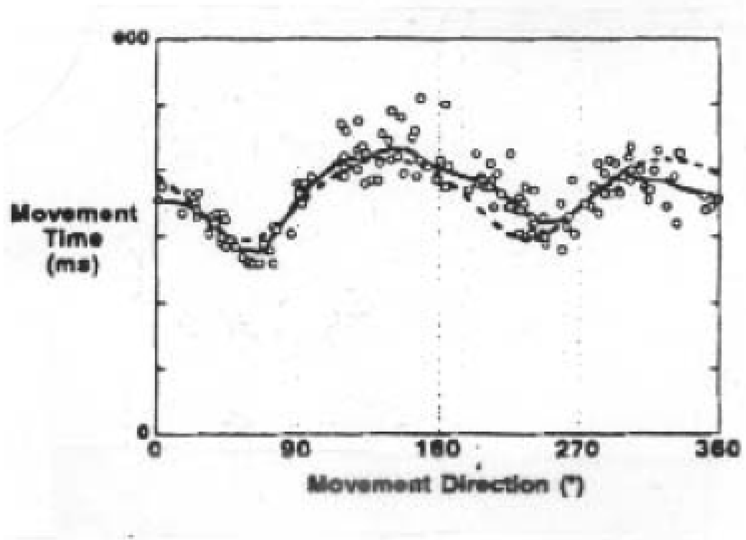
Invariants of movement (...)

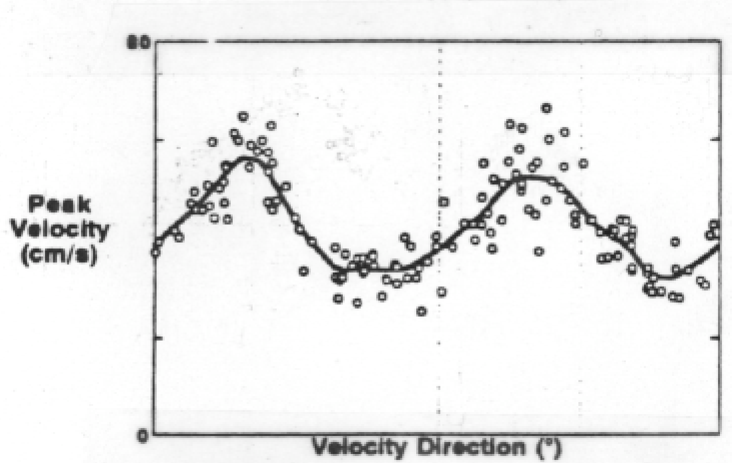


Jeannerod (1984)



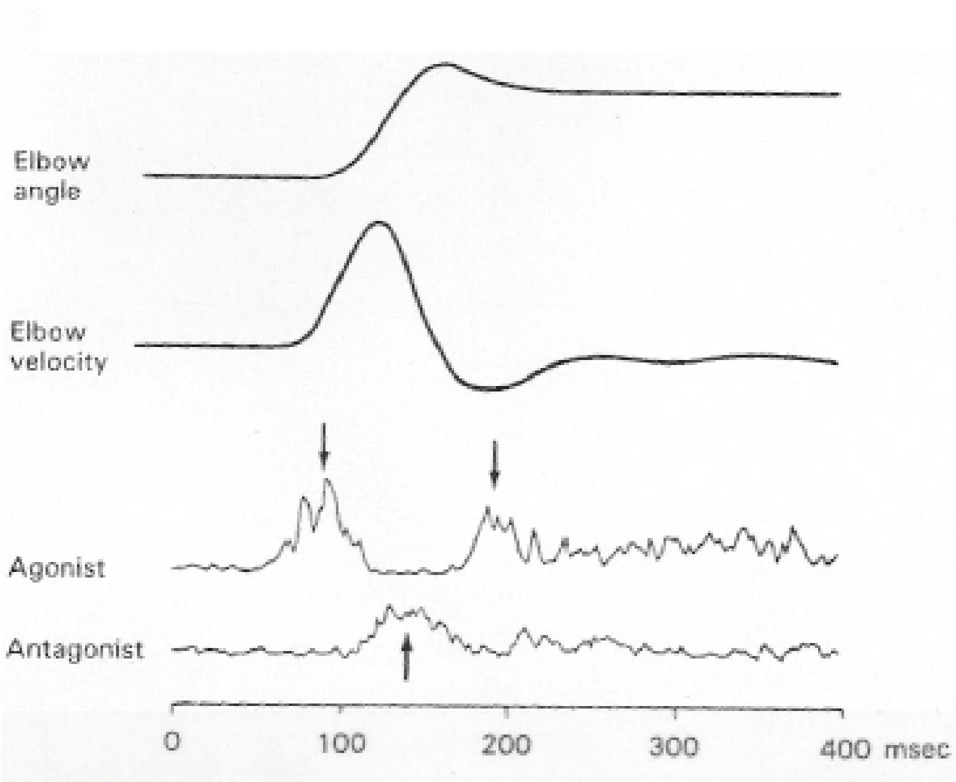
van Opstal et al. (1985)

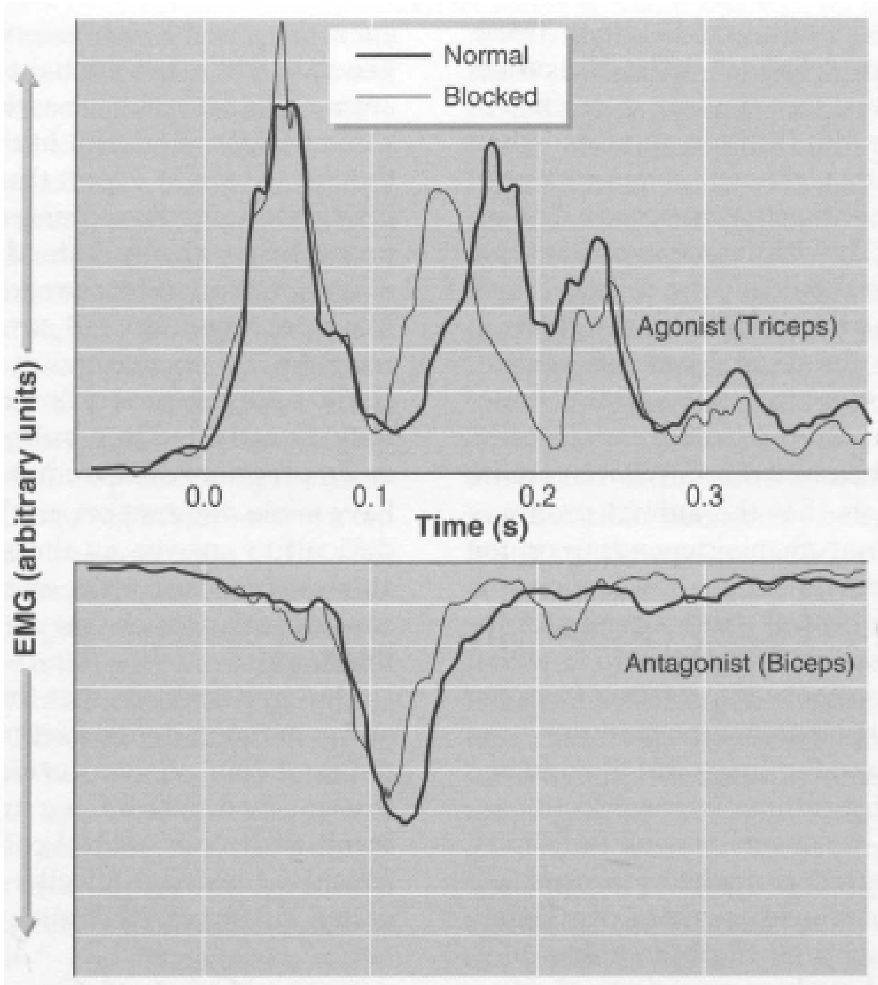




Gordon et al. (1994)

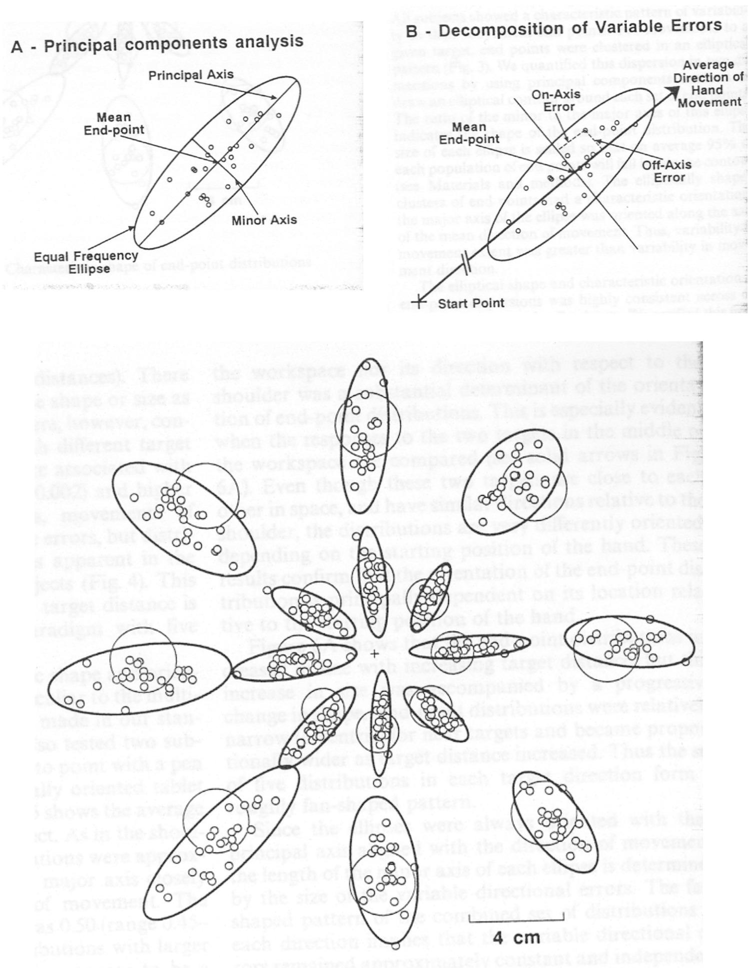
Invariants of movement (...)



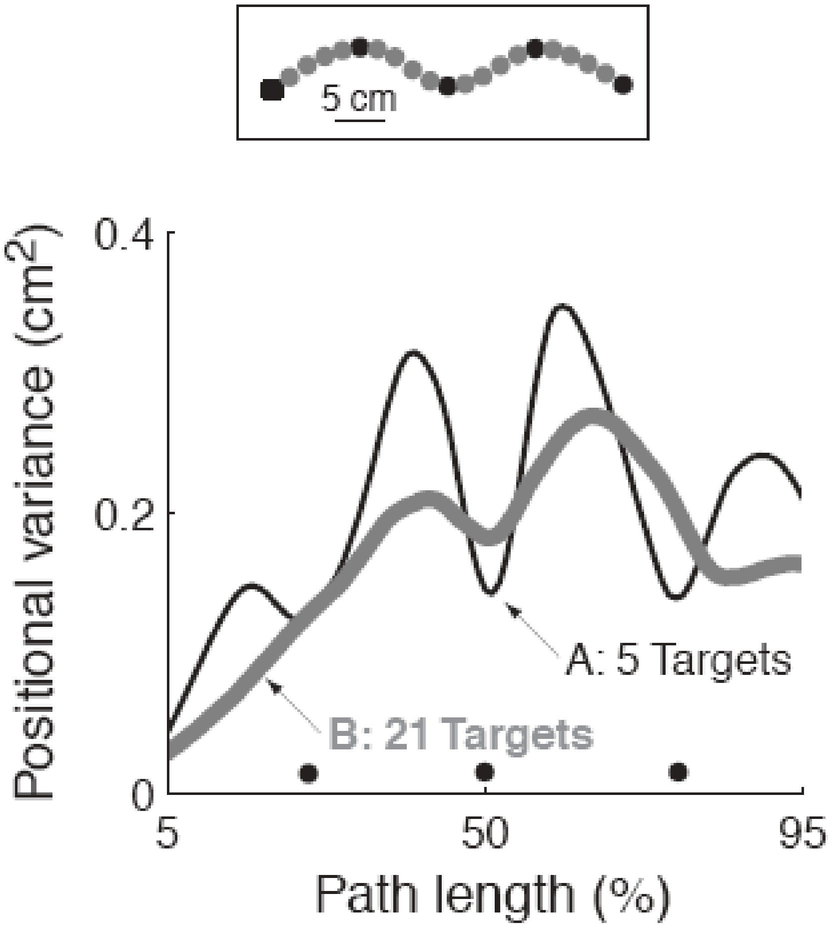


Wadman et al. (1979)

Invariants of movement (end)



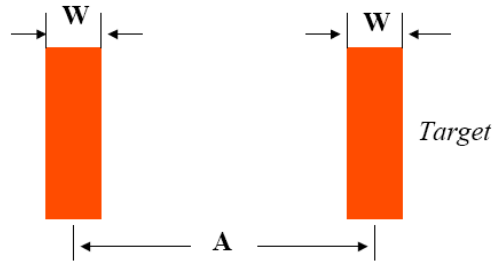
Gordon et al. (1994)



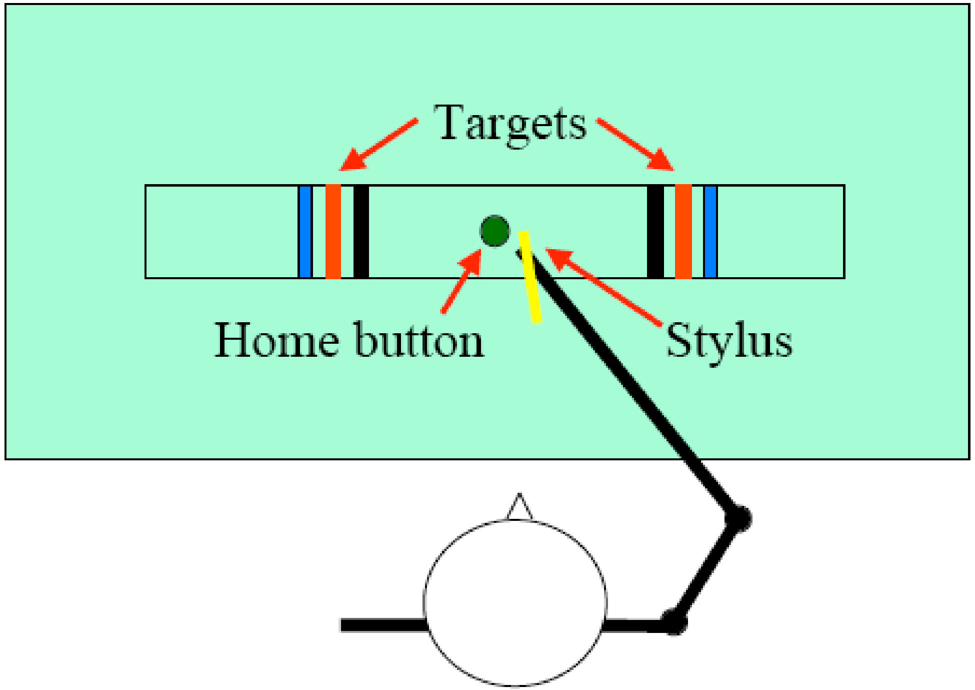
Todorov & Jordan (2002)

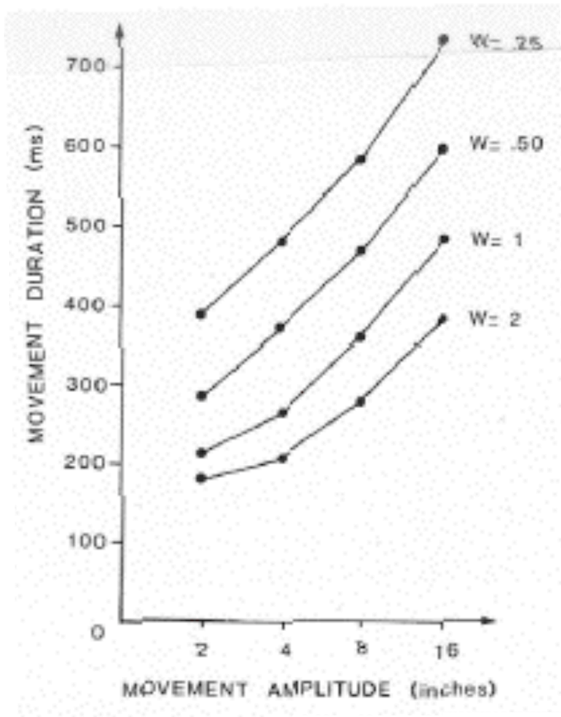
Laws of movement

- Fitts law
  - Speed/accuracy trade-off



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

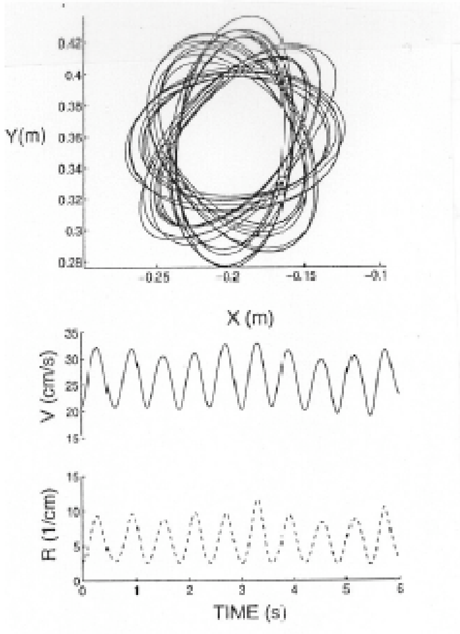


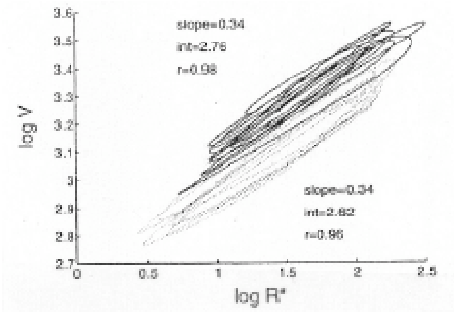


Fitts (1954)

Laws of movement (...)

- Two-third power law
  - Relationship between curvature and velocity





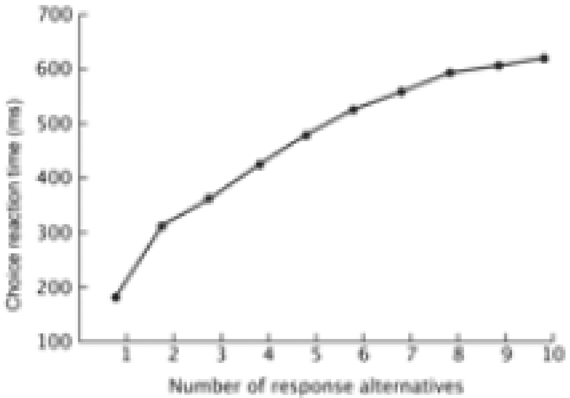
$$v(t) = kr(t)^{1/3}$$

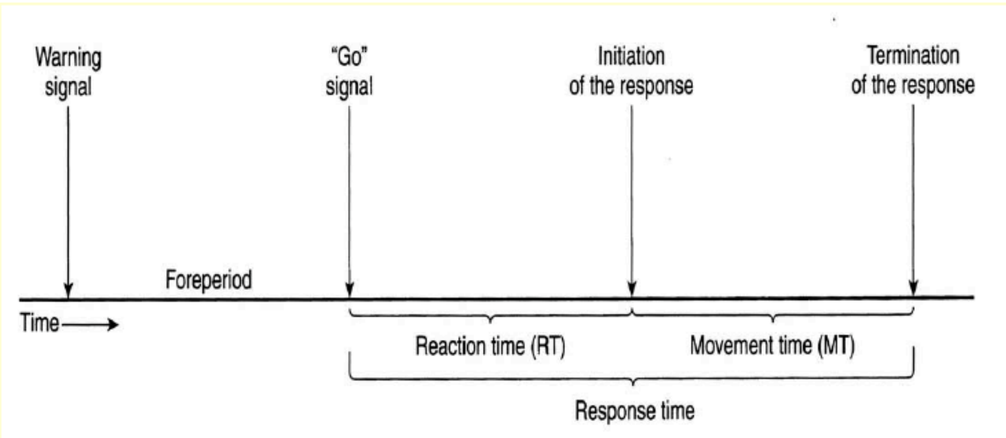
$$a(t) = kc(t)^{2/3}$$

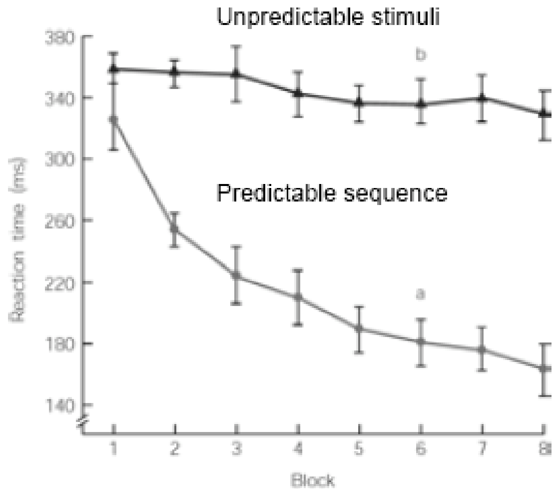
$\mathbf{x}(t) = [x(t), y(t)]^T$ trajectory
$a(t)$ angular velocity
$v(t) = ||\dot{\mathbf{x}}(t)||$ tangential velocity
$c(t)$ curvature
$r(t) = 1/c(t)$ radius of curvature

Internal processes

- Reaction time
  - Duration of the information processing phase that is necessary to the elaboration of movement
  - Depend on
    - Attention, motivation, modality (vision, …)
    - Intensity, complexity, predictability, …
  - Interpretation?

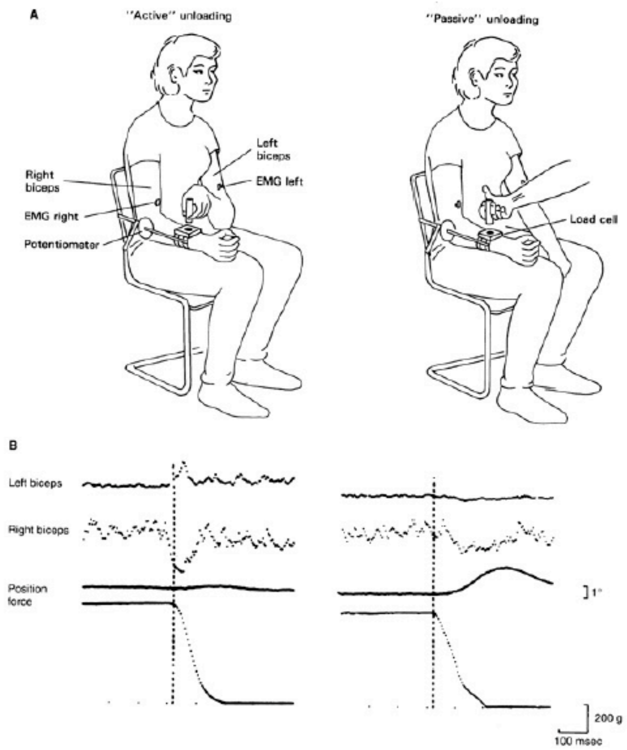


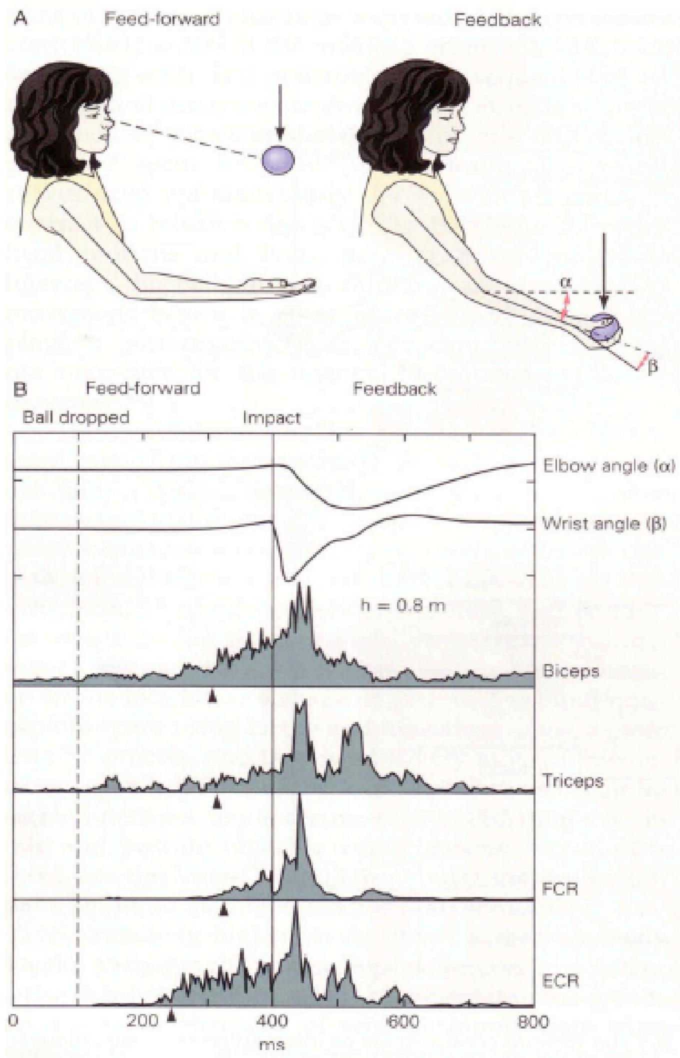




Internal processes (...)

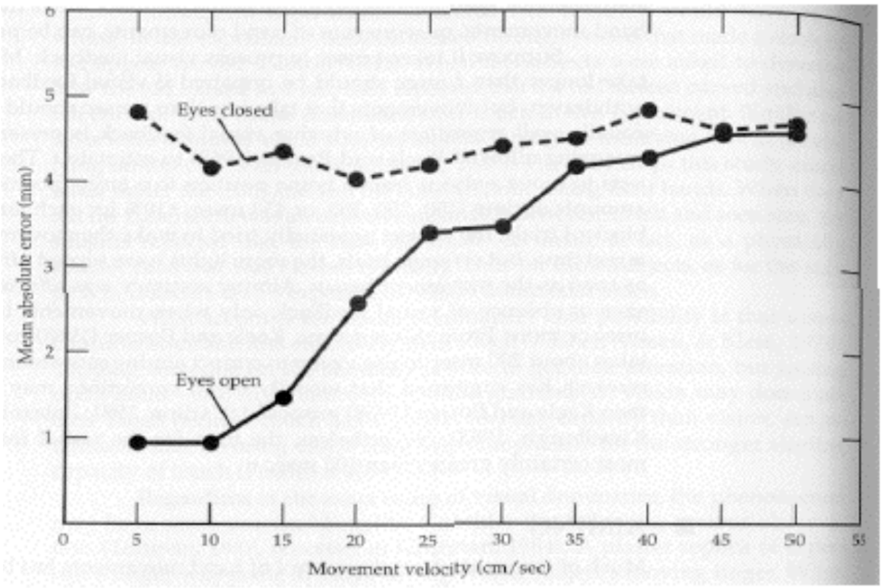
- Mode of control
  - Feedforward vs feedback



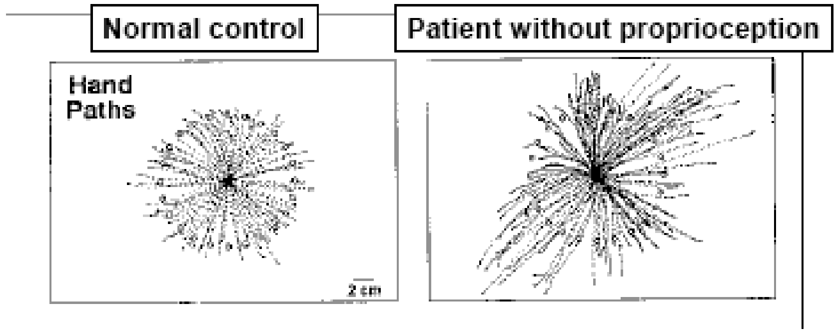


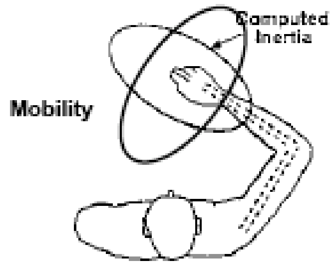
Internal processes (...)

- Role of sensory information

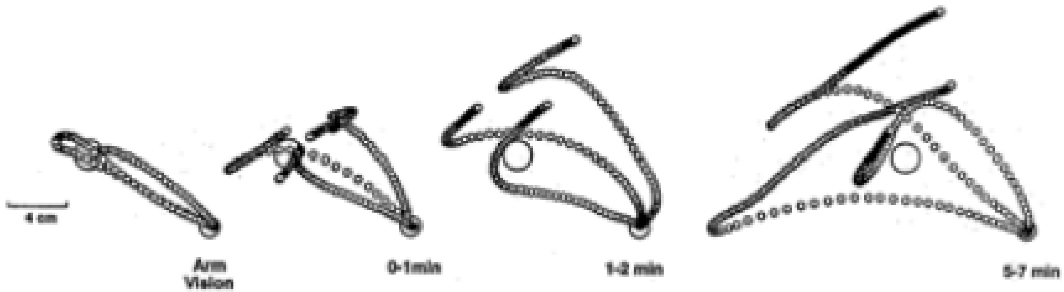


Woodworth (1899)



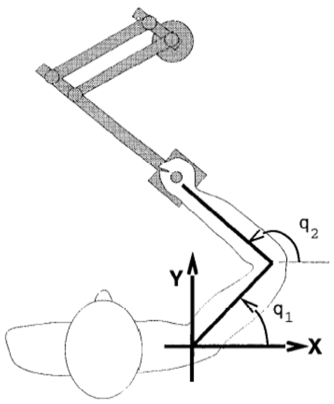


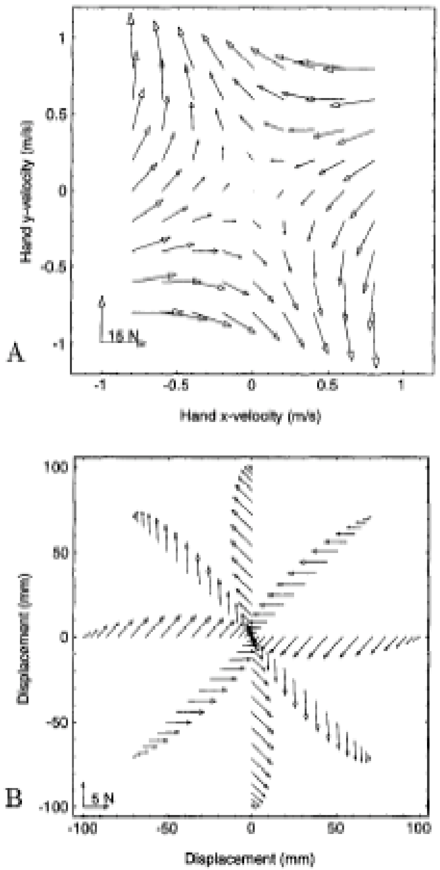
Ghez et al. (1990)

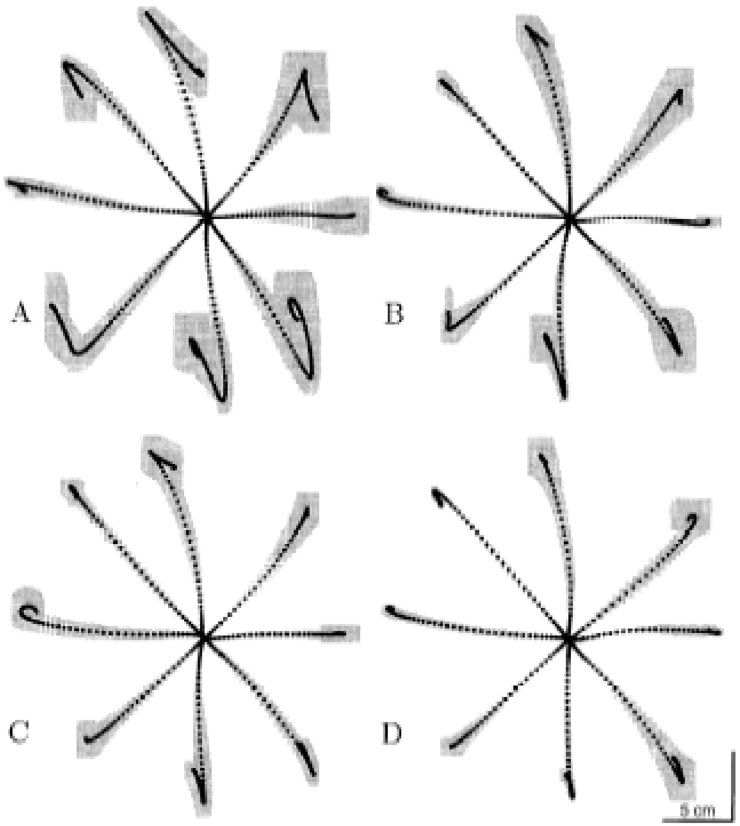


Internal processes (...)

- Adaptation



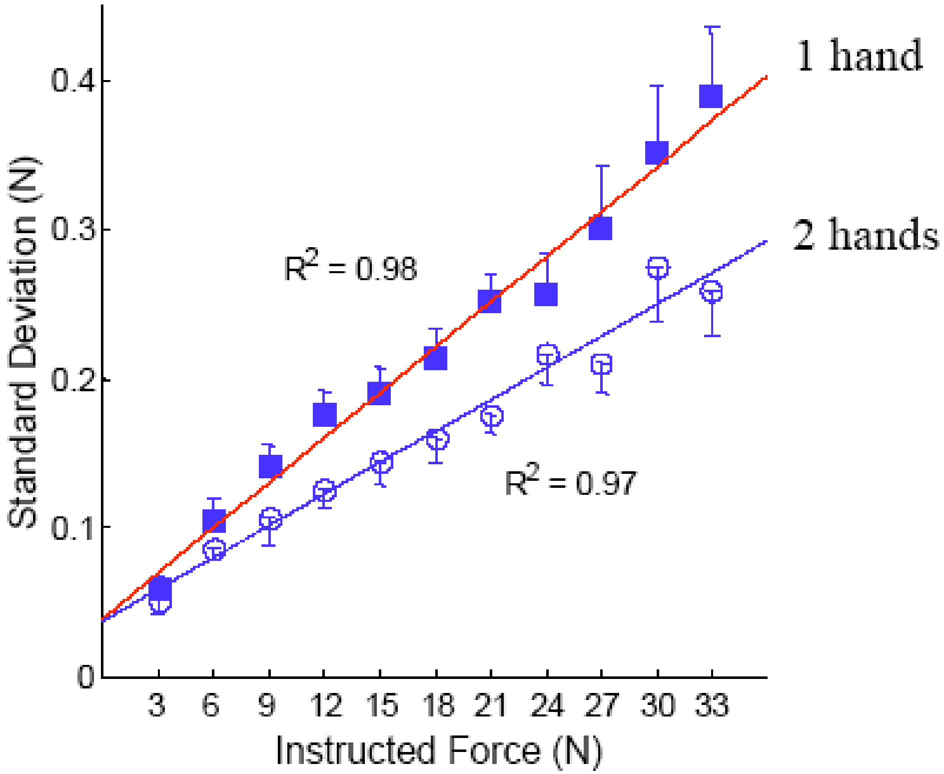




Shadmehr & Mussa-Ivaldi (1994)

Internal processes (end)

- Motor noise



Todorov (2002)

Key issues

- From symbols to muscles
  - Motor acts are in general specified at a symbolic level (e.g. *drink a glass of water*) whereas the CNS has to deal with low level muscle control
- Bernstein problem
  - Infinity of solutions
- Estimation and prediction
  - Noise, delays
    - e.g. visual estimation of the position of a moving objet can involve a 100 ms delay
- Neural representations
  - Neural networks for motor control