Neuroengineering 2020/21

COMPUTATIONAL NEUROSCIENCE 1 - Motor control, high level models and neural basis of motor control

Neuroengineering 2020/21

COMPUTATIONAL NEUROSCIENCE 1 –
Part 1- Introduction to Motor Control and Learning

Intro

“General brain objective is to generate the movement”

Why movement is a complex task?

Why movement is a complex task?

- DELAYS:
  fast movements (300ms)
  visuomotor feedback (200ms)

- NOISE (intrinsic neural noise)
  Noise on the sensory data (resolution limit)

  Noise on the motor command imit)

  The SD of noise is about 10% and 25% of the mean activity of a motor neuron [Harris and Wolpert, Nature 1998]

PREDICTION and a PLANNING are NECESSARY -> feedforward controller

Why movement is a complex task?

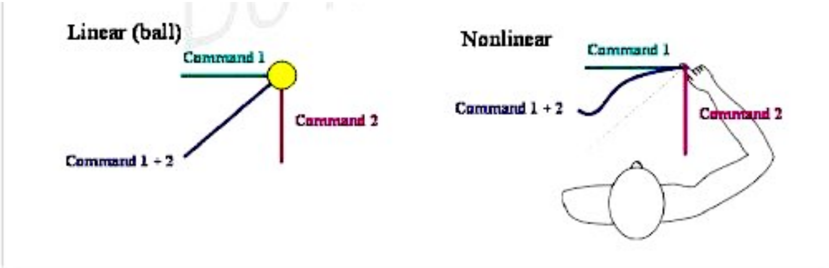
- NOT STATIONARY
  Long term scale: growth

Short term scale: different objects

LEARNING IS NECESSARY

Why movement is a complex task?

- NON LINEARITY
  Linearity=>effects overlapping
  But…Sum of two sequences of motor commands
  ≠ sum of the two movements!

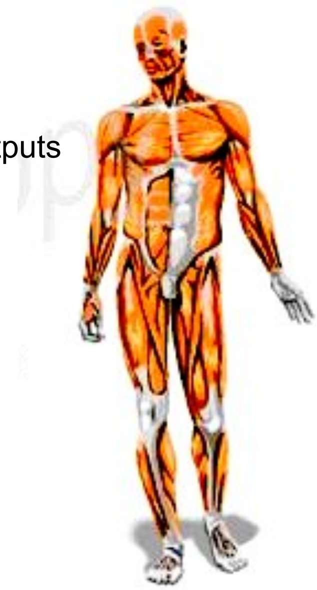


Why movement is a complex task?

-MULTIDIMENSIONAL

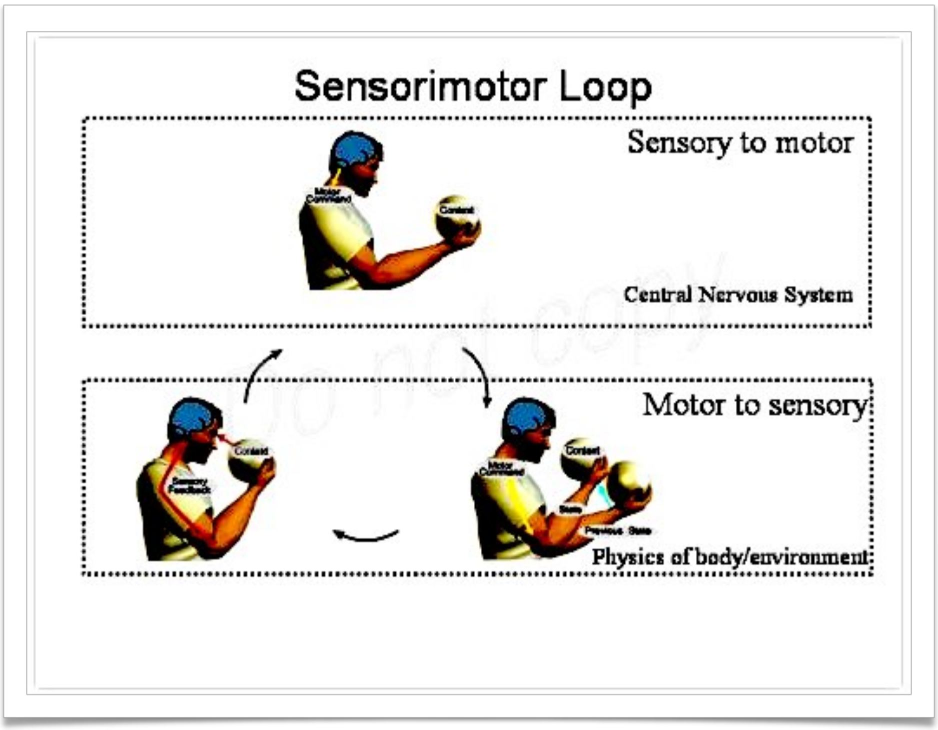
-Million of inputs

- Million of outputs



SYNERGIES AND MOTOR PROGRAMS ARE NECESSARY

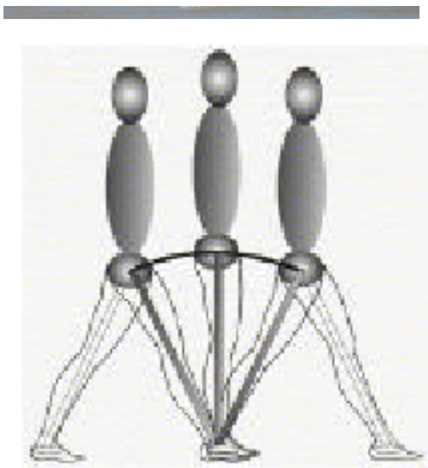
Sensorimotor integration



Motor learning

To adequate the behavior of the action according to the interaction with the environment

OBJECTIVE: improve the performance

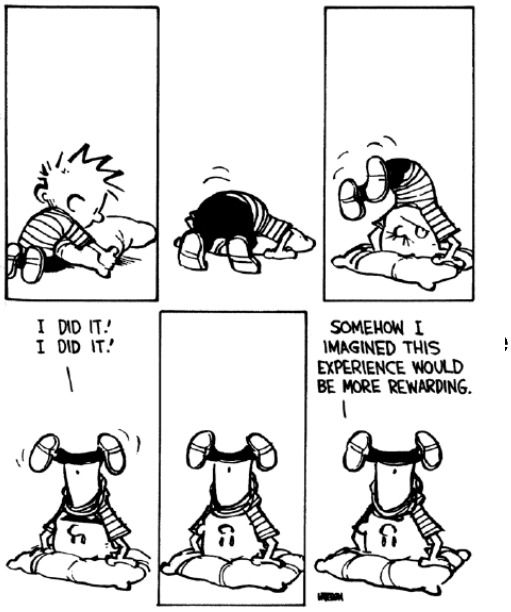


Motor learning

COMPROMISE

Innate capacities
- hard-wired
- robust
- fast

Learned capacities
- adaptable
- slow
- flexible



Motor learning

Simple species don't have any motor learning.

The necessity of motor learning appear in the species in which
- The environment,
- The anatomic characteristics
- The objectives

can change

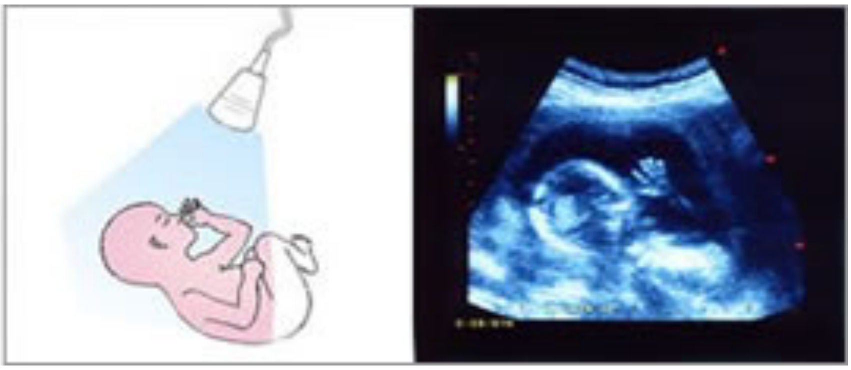
FLEXIBILITY of the control system

Motor learning

Does the man start from a tabula rasa?

There exist innate motor behaviors

Starting point for the future motor learning



Note: motor learning can require a decrease in the rigid synergies

(for instance neonatal reflexes)

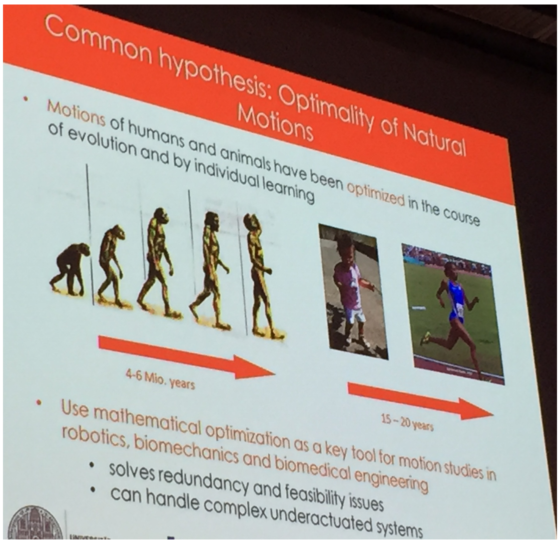
Motor learning

Anatomic structure

Co-adaptation of:

Neural machine

Human motor learning



The man is the unique species living everywhere all over the Earth

Human characteristics:

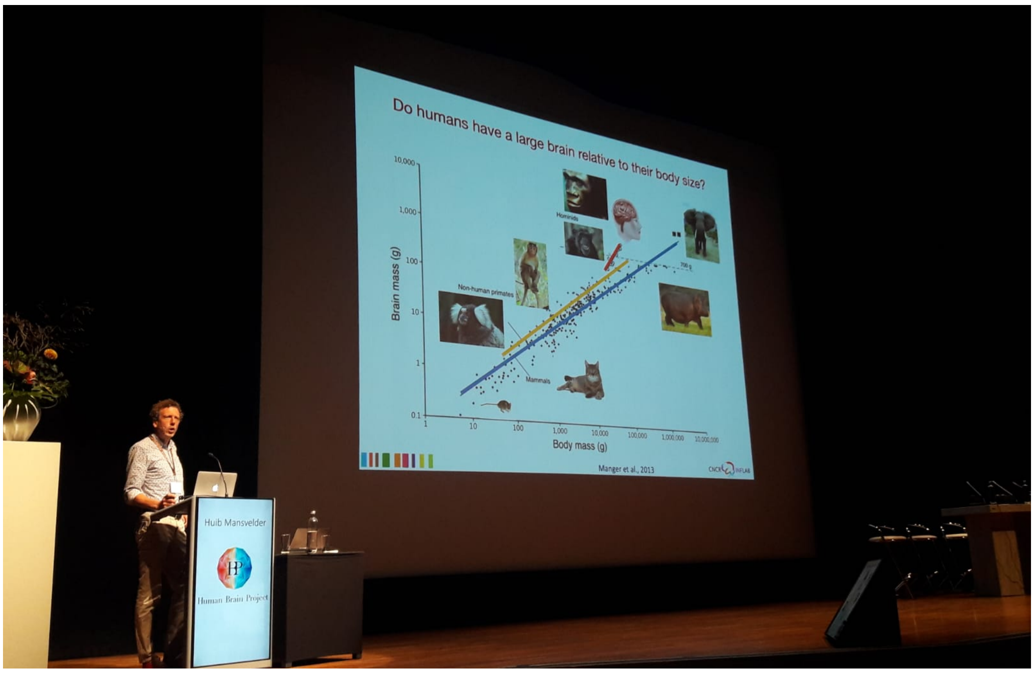
-Not specialized (it is able to adapt to changes and not to things)

- Polyvalent

Removability + multifunctionality+ cosmopolitism= exodarwinism

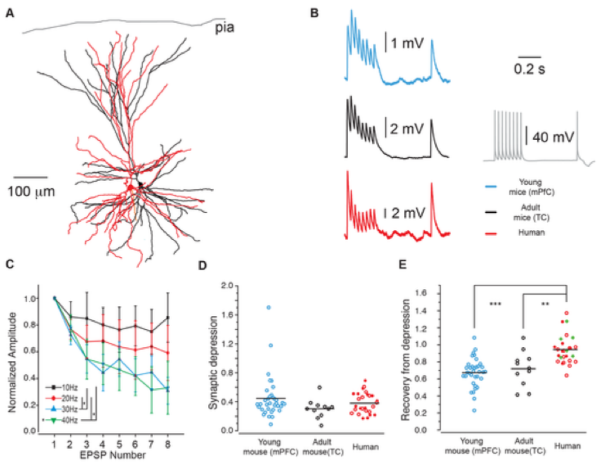
The time scale changes in the evolution

Brain and species - HBP Summit Oct 2018



Prof. Mansvelder Univ. Amsterdam

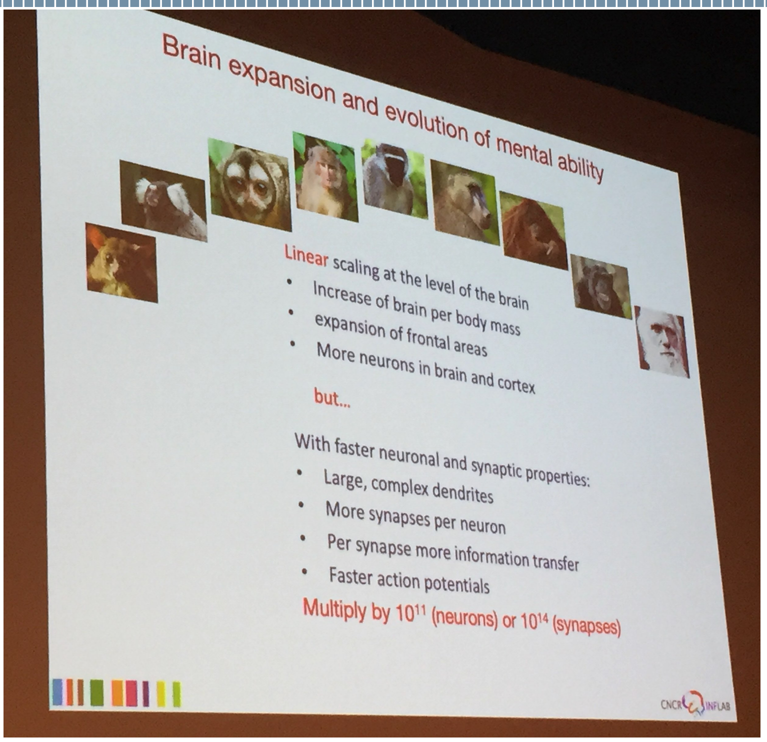
Figure 1. Synapses in the adult human neocortex rapidly recover from depression.



adult human neurons show a three to four times faster recovery from depression.

Testa-Silva G, Verhoog MB, Linaro D, de Kock CPJ, Baayen JC, et al. (2014) High Bandwidth Synaptic Communication and Frequency Tracking in Human Neocortex. PLOS Biology 12(11): e1002007. https://doi.org/10.1371/journal.pbio.1002007
https://journals.plos.org/plosbiology/article?id=10.1371/journal.pbio.1002007

PLOS BIOLOGY
FIFTEENTH ANNIVERSARY



Top down in perception

The learning and experience become guides to the acquisition of sensorial data and they both affect perception.

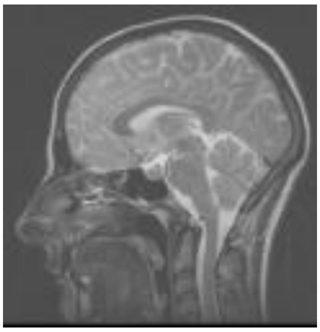
Top down and bottom-up in perception

Top down and bottom-up in perception

Sensory-motor integration

Sensorial signals

- internal
- external



Motor commands

Kinematic Transformation: conversion between the system coordinates

Dynamic Transformation: it translates the coordinates in motor command, force to apply in order to obtain the desired movement

Movements happen through a transformation cascade

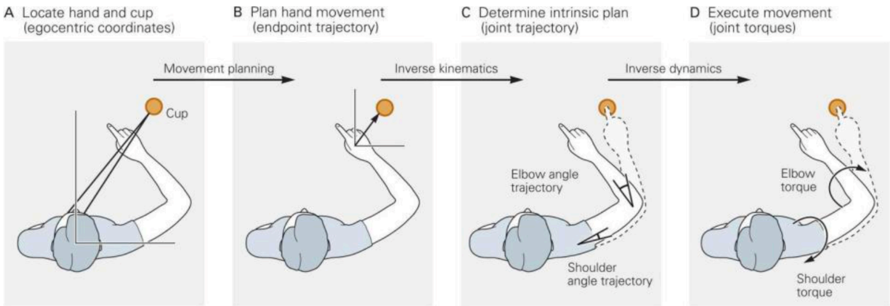


Figure 1.2: ***Sensorimotor transformations in a reaching movement***: *(A)* ***Spatial orientation***. *To reach for an object, the object and hand are first located visually in a coordinate system relative to the head (egocentric coordinates). (B)* ***Movement planning***. *The direction and the distance that hand must move to reach the object (the endpoint trajectory) are determined based on visual and proprioceptive information about the current locations of the arm and object. (C)* ***Inverse kinematic transformation***. *The joint trajectories that will achieve the hand path are determined. The transformation from a desired hand movement to the joint trajectory depends on the kinematic properties of the arm, such as the lengths of the arm's segments. (D)* ***Inverse dynamic transformation***. *The joint torques or muscle activities that are necessary to achieve the desired joint trajectories are determined. The joint torques required to achieve a desired change in joint angles depend on the dynamic properties of the arm such as the mass of the segments. (From [1])*

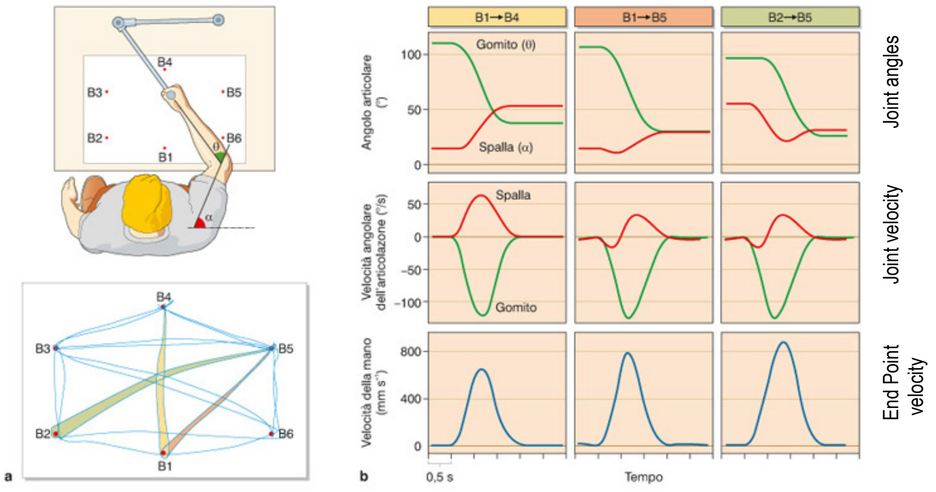
Reflexes vs voluntary movements

- Reflexes= simple transformation, hard wired, automatic.
  - Input causes the direct output
  - Tendon jerk reflex

- Voluntary movement:
  - Goal directed
  - Independence of the effector
  - Response time depends on the amount of information to process
  - Execution speed is inversely correlated to the accuracy
  - Learned by experience

We have to circumscribe our investigation: we will primarily cover voluntary motor control.

Voluntary movements



OOBA © 2006 edi.ermes milano

Green: Elbow joint
Red: Shoulder joint

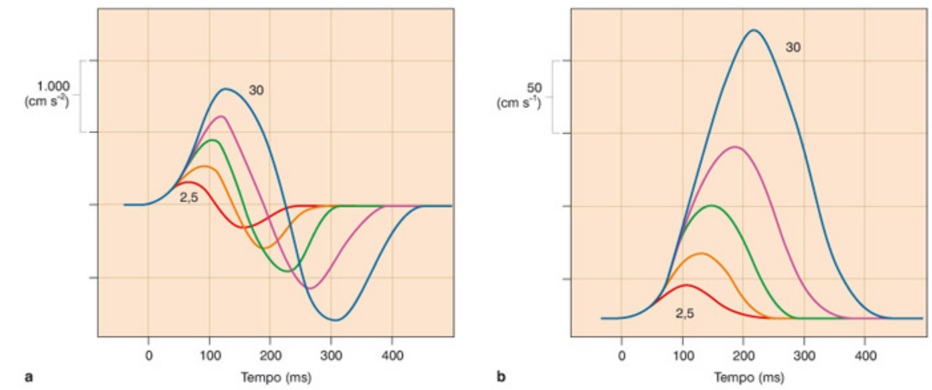
Panels a) The subject is required to make reaching tasks to multiple targets on the horizontal plane. Lower plot: The trajectories of the End Point are quite rectilinear.

Panels b) Different shoulder rotation (red traces) are used to get to the different targets, while very similar elbow joint traces (green) are shown (first raw). Also the joint velocity (second row) are modulated to achieve a very similar end-point velocity (third row).

Voluntary movements

The motor plan is the sequence of tasks to accomplish the target, including the amplitude , the kinematics and the dynamics of the movement.

Velocity and acceleration change with the distance of the target.



a) Hand acceleration over time

b) Hand velocity over time

(Colours: Target distance from 2,5 to 30 cm)

Laws of voluntary movements

I law:

Voluntary movements show invariant features

- Motor Equivalence (Hebb, 1950)
- Independence from the effector
- Writing: Velocity varies as a continuous function of the curvature raised to the 2/3 power

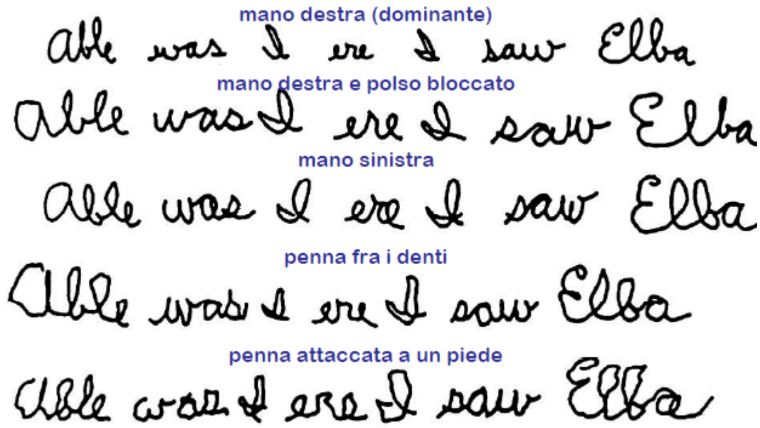
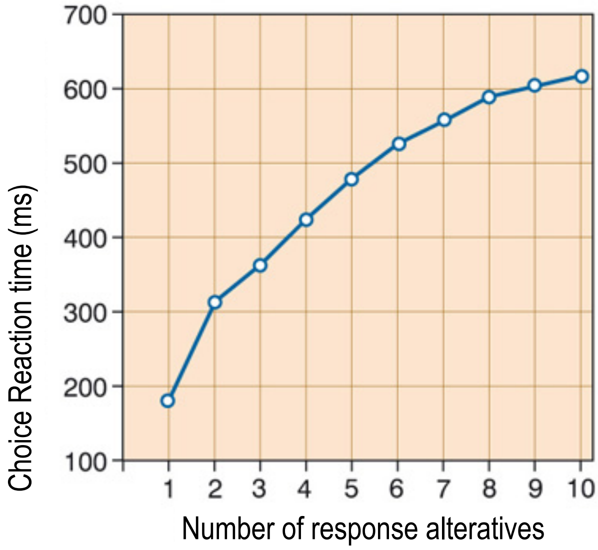


Figure: It is possible to write using different parts of the body. The examples shown in figure are written with the right hand (A), with the right hand but with the wrist fixed (B), with the left hand (C), with the pen between the teeth (D), and with the pen fixed to the foot (E). The capacity to perform the same motor behavior with different muscular groups is called motor equivalence

Laws of voluntary movements

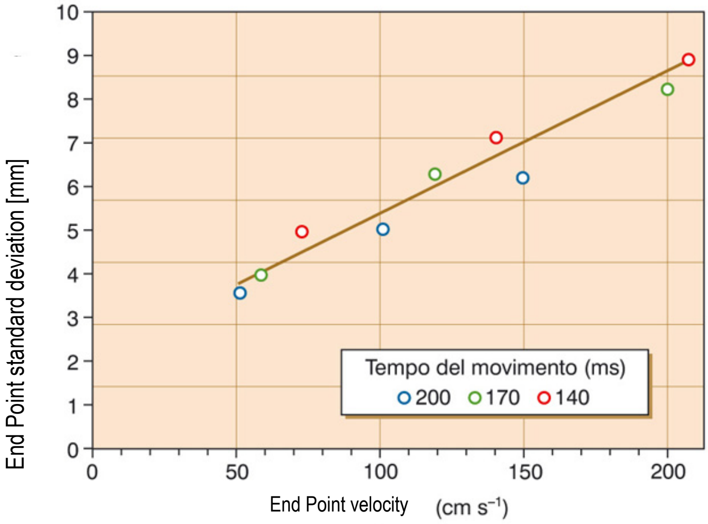
II law: reaction time increases with the information to be processed

Reaction time increases nonlinearly with the number of response alternatives available to the subject.



Laws of voluntary movements

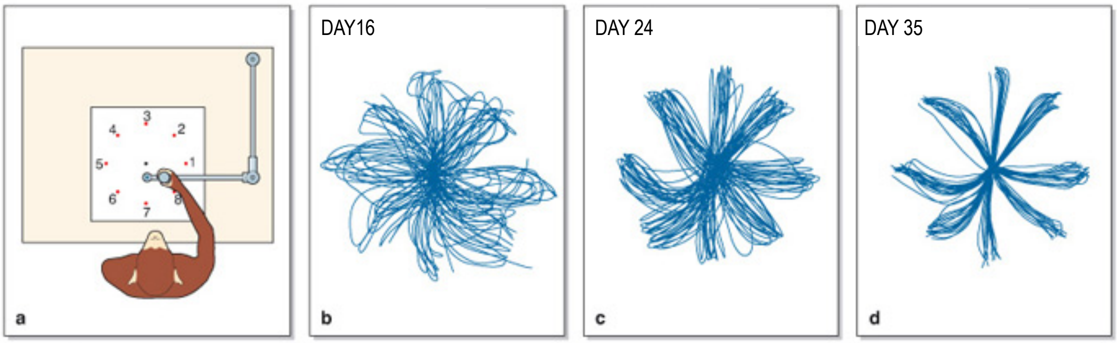
III Law: Speed-accuracy tradeoff – Fitt's law



Short time -> no feedback corrections

This tradeoff is linked to signal-dependent noise: higher speed → more recuited motor units(EMGs) → higher signal-dependent noise → lower accuracy

IV law: Movement efficacy grows with experience and learning



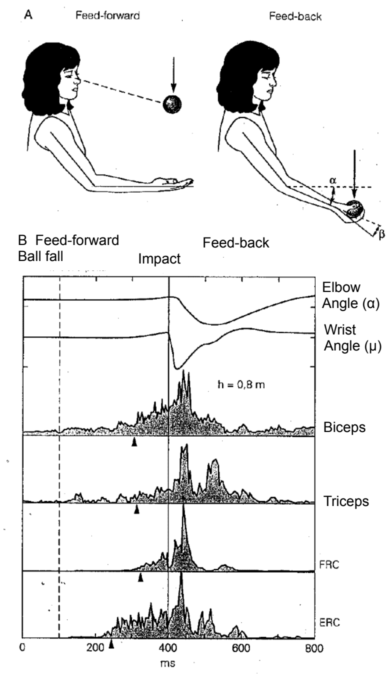
Learning induced by repetitive training

(motor memory results from trail and error)

Feedback control / feedforward control

Feedforward:
- Anticipatory control
- Sensorial information + previous experience

Feedback:
- Actual control
- Dependent on the actual sensory information
- Comparison with a reference signal
- Characterized by a gain

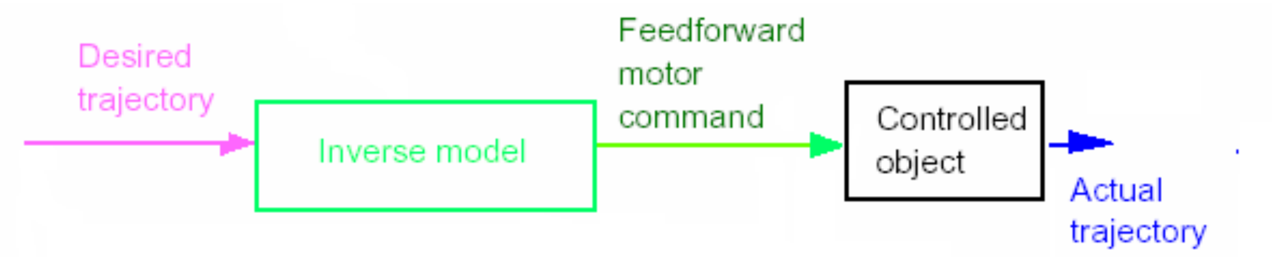


Modelling brain functions in motor control: Internal models

INTERNAL MODELS
Representations of the sensorimotor and motor sensory transformations that occur within our brain

They mimic, inside our brain, the functions of the system to be controlled

Feedforward control: INVERSE MODEL



Inverse model: estimates the motor commands required to achieve the desired sensory feedback (anticausal direction)

- It is fast, cancels delays
- It is not able to correct the movement on errors occuring because of its inaccuracy or because of unexpected disturbances

Ballistic movements

Inverse model+ Efference copy + Forward model

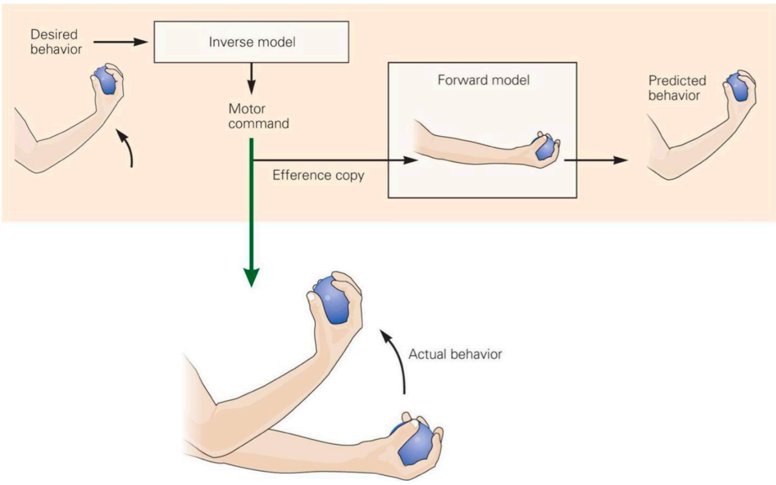


Figure 1.12: ***Inverse and Forward model:*** *Forward model maps motor commands in the sensory space; Inverse model estimates motor commands to obtain a desired sensory feedback. (From [1]).*

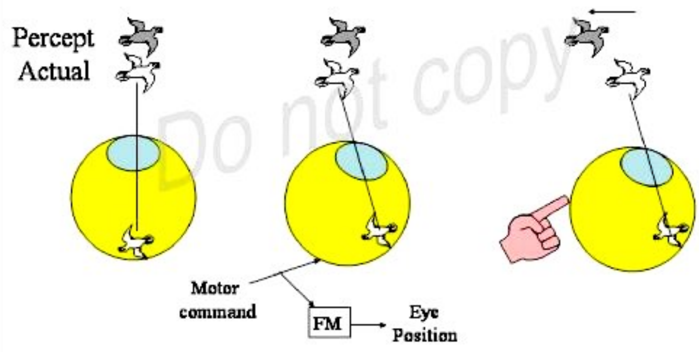
Forward model
Maps motor commands in the sensory space

Inverse model estimates motor commands to obtain a desired sensory feedback

FORWARD MODEL: state estimation

Efference copy + forward model allows us to distinguish between our own actions and external events

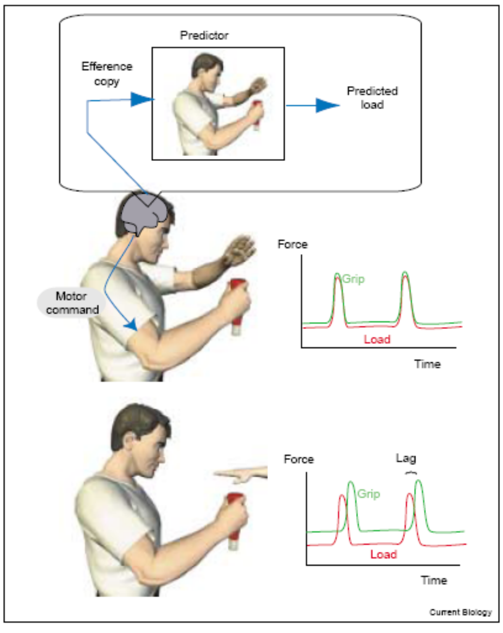
GOALS:
Detecting the consequences of our own actions
Perceptual stability
Modulate attention



Helmholtz

Efference copy + forward model

Figure 1



To prevent a ketchup bottle from slipping, sufficient grip force must be exerted to counteract the load. When the load is increased in a self-generated manner (left hand strikes the ketchup bottle, top), a predictor can use an efference copy of the motor command to anticipate the upcoming load force and thereby generate grip which parallels load force with no delay. However, when the load is externally generated (another person strikes the bottle, bottom), then it cannot be accurately predicted. As a consequence, the grip force lags behind the load force and the baseline grip force is increased to compensate and prevent slippage.

Motor prediction
Daniel M. Wolpert* and J. Randall Flanagan†
Current Biology Vol 11 No 18, 2001

Two eyes for an eye

(Shergill et al., vol 301 p 187 Science 2003)

Two Eyes for an Eye: The Neuroscience of Force Escalation
Shergill, Bays, Frith, Wolpert
Science 11 Jul 2003:
Vol. 301, Issue 5630, pp. 187
DOI: 10.1126/science.1085327

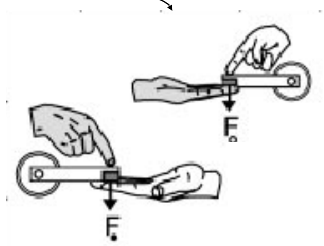
Tit for tat experiment:

Physical conflicts tend to escalate

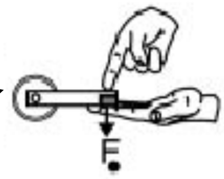
Two eyes for an eye

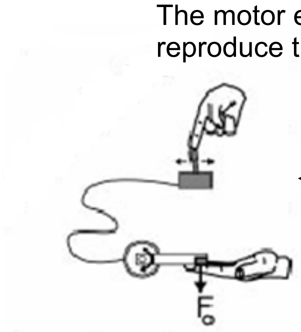
EXPERIMENTAL PROTOCOL

Cond. 1:
Each person in the couple is required to exert the same level of force he/she receives



Cond. 2:
The motor exerts a force and the subject has to reproduce the same force with the other finger





Cond. 3:
The motor exerts a force on the left finger and the right finger controls the motor with a joystick to reproduce the same force

Two eyes for an eye

RESULTS: escalation of force

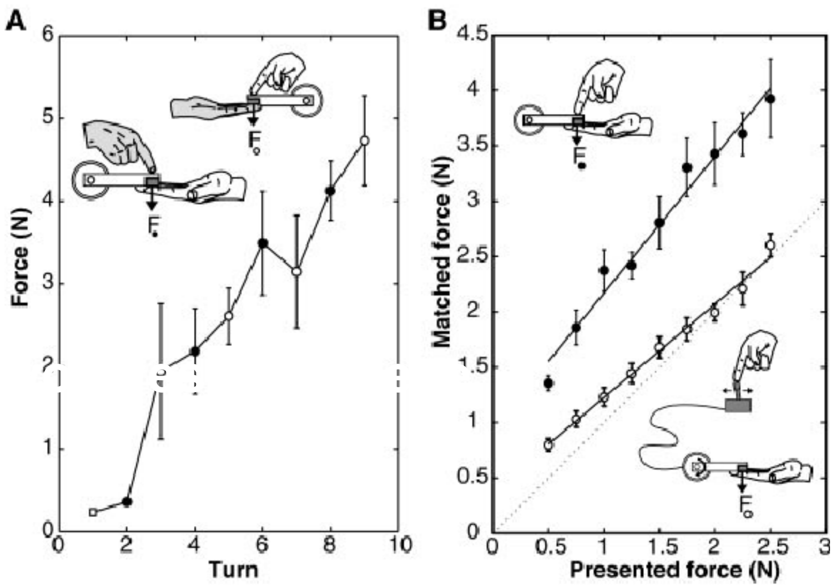


Fig. 1. (**A**) Force escalation in a typical pair (participant 1, solid circles; participant 2, empty circles; mean ± SE across four trials). The initial force (white square) was generated on participant 1 by the torque motor.

(**B**) Matching force generated using the right finger (solid circles) and joystick (white circles) as a function of the externally generated force (mean ± SE across participants). Dotted line, perfect performance. On each trial, the torque motor generated a force between 0.5 and 2.75 N for 3 s (40 pseudo-randomized trials). Each participant experienced both conditions in a counterbalanced order (participant 1, gray hands and solid circles; participant 2, white hands and open circles; mean ± SE across four trials).

Why can't you tickle yourself?

(Blakemore et al., Neuroreport 2000)

Use of the efference copy to reduce the sensory feedback due to our own actions

Goal: augment attention on external unexpected perturbations

Experimental evidence:
The consequences of our own actions are perceived differently from the same input due to external actions (Why can't you tickle yourself?)

Why can't you tickle yourself?

Cond .1: robot generates movement (external tickling)

Cond. 2: robot is moved by the left hand of the subject (=self tickling)

Cond. 3: robot is moved by the left hand but with a delay (100, 200, 300 ms)

Cond. 4: robot is moved by the left hand but the robot motion is rotated with respect to the hand motion

Why can't you tickle yourself?

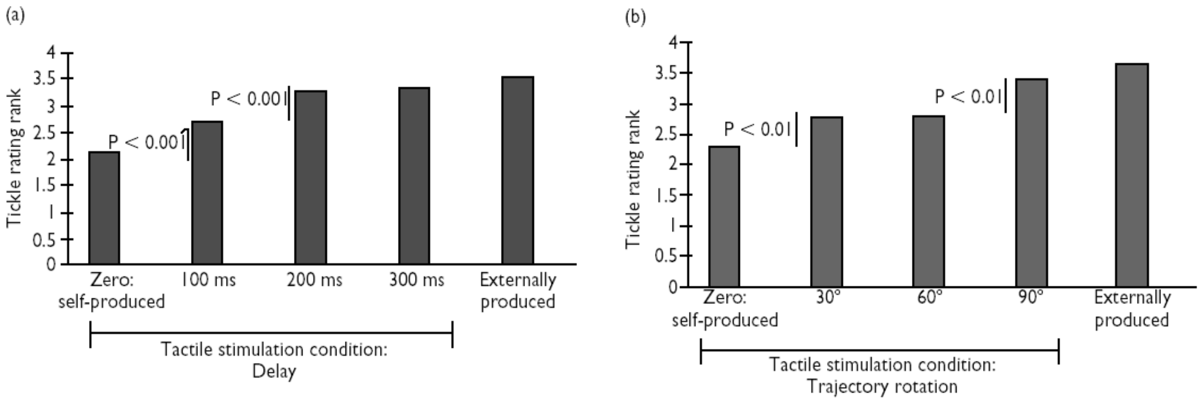
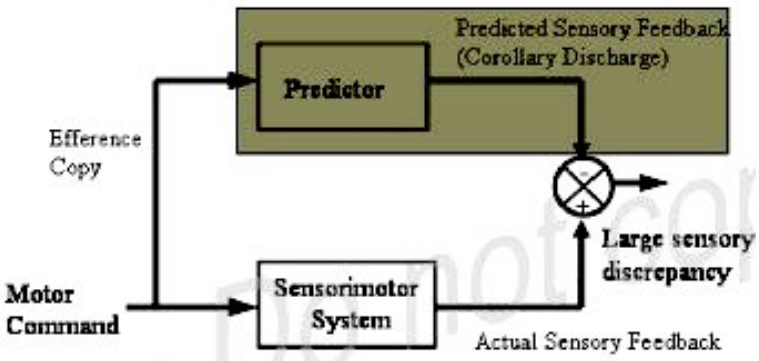


Fig. 2. Graph to show that the tickliness of a tactile stimulus increases with increasing delay (**a**) and trajectory rotation (**b**) between the movement of the left hand and the tactile stimulus on the right palm. These results suggest that the perceptual attenuation of self-produced tactile stimulation is based on specific sensory predictions made by a forward model.

Further proof: pathological behaviour

Schizophrenia:
auditory hallucinations /passivity of experiences: first rank features of schizophrenia



Further proof: pathological behaviour

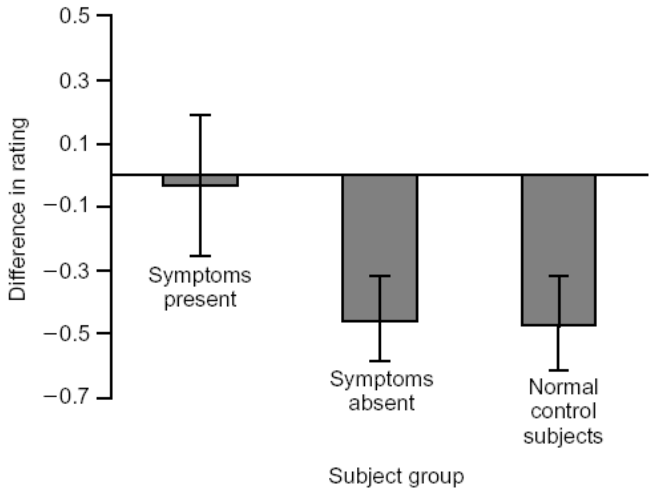


Fig. 6. Graph showing the mean (tickly, pleasant and intense combined) perceptual rating difference between self-produced and externally produced tactile stimulation conditions for the three subject groups: patients with auditory hallucinations and/or passivity, patients without these symptoms and normal control subjects. There was no significant difference between the perceptual ratings in the two conditions for patients with auditory hallucinations and/or passivity, hence the mean rating difference was close to zero. In contrast, there was a significant difference between the perceptual ratings in the two conditions for patients without these symptoms and in normal control subjects: both groups rated self-produced stimulation as less tickly, intense and pleasant than externally produced stimulation.

Blackmore et al. Nature Neuroscience 1998

Summary

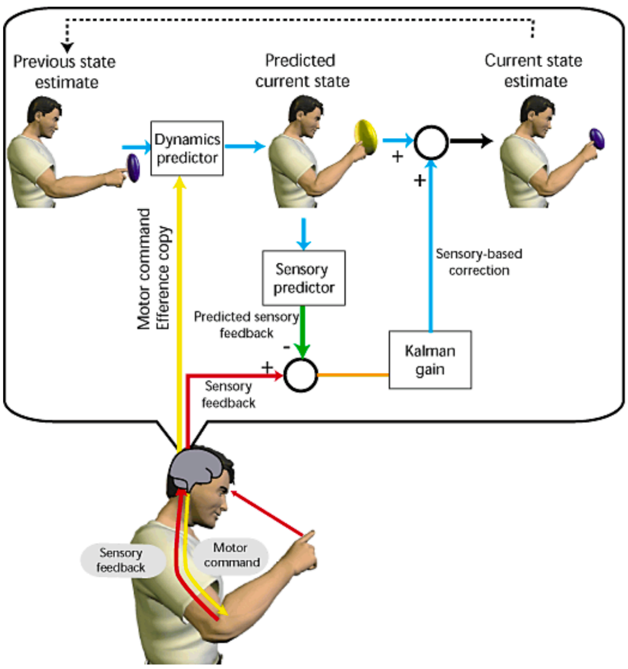
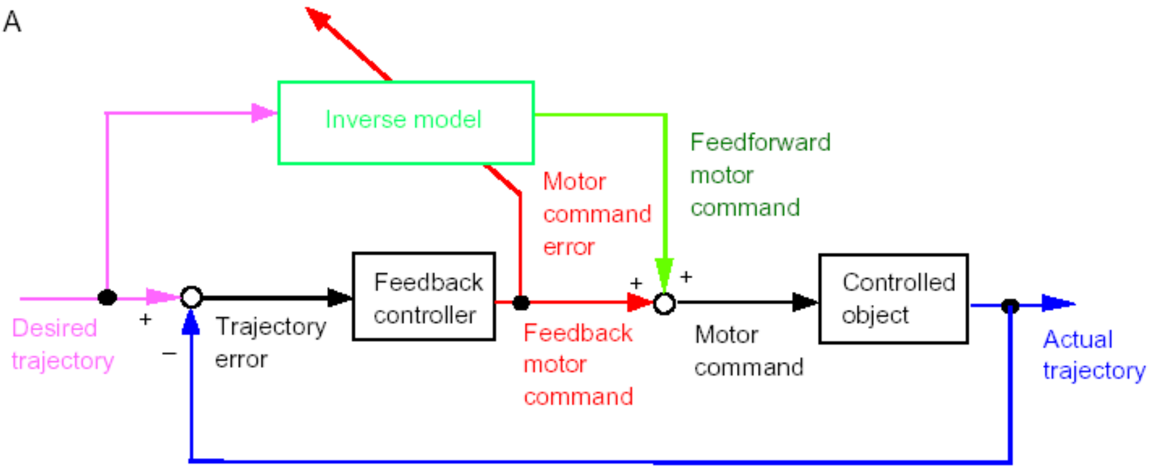


Figure 1.22: ***Re-afference and Kalman Filter*** (From [16].)

Re-afference and Kalman filter

Claim that initial movemnt is feedforward and the final part is feedback
Optimal state is a mixture of :
- Predictive estimation(FF)
Sensory feedback (FB)

How to train the inverse model?

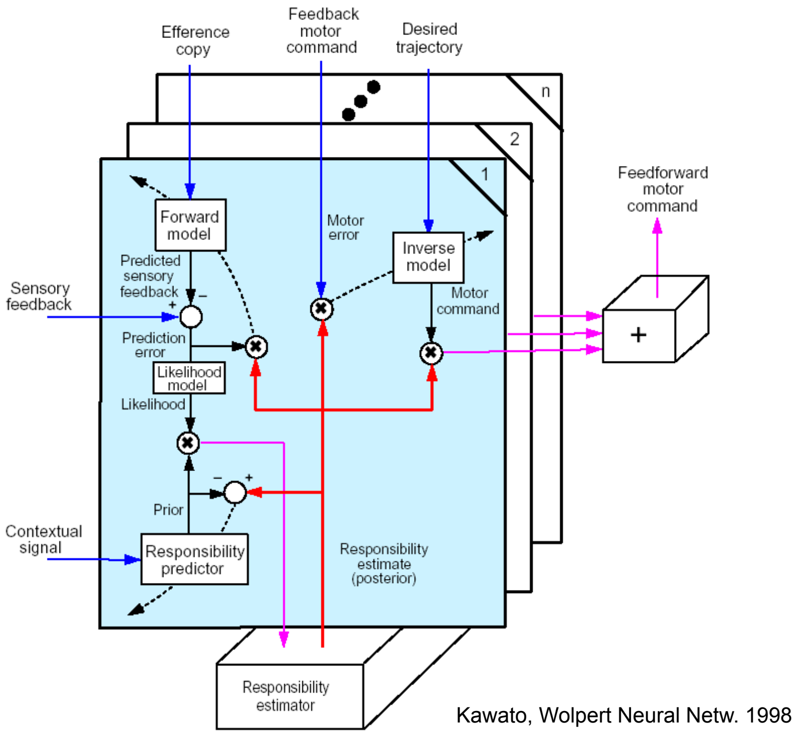


Da Wolpert et al. Trends in cognitive sciences 1998

TRAIN INVERSE MODEL = IDENTIFY FEEDFORWARD CONTROLLER

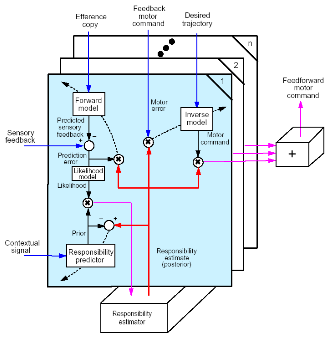
Multiple paired forward-inverse model

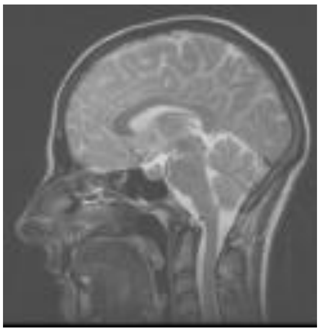
Forward models include the correspondence of a certain module to the current context and, accordingly, the corresponding inverse model contributes to the formation of the overall feedforward motor command



Kawato, Wolpert Neural Netw. 1998

Do these models actually exist?

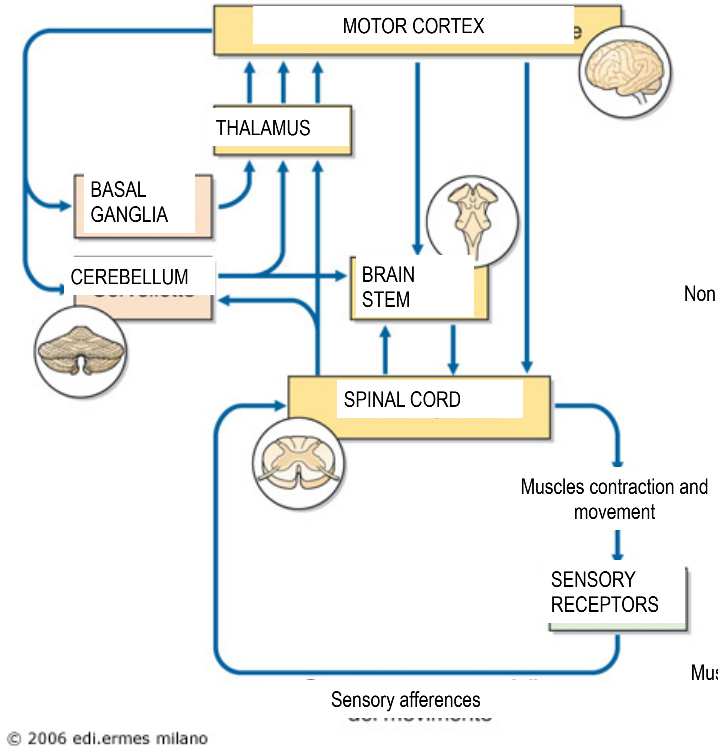


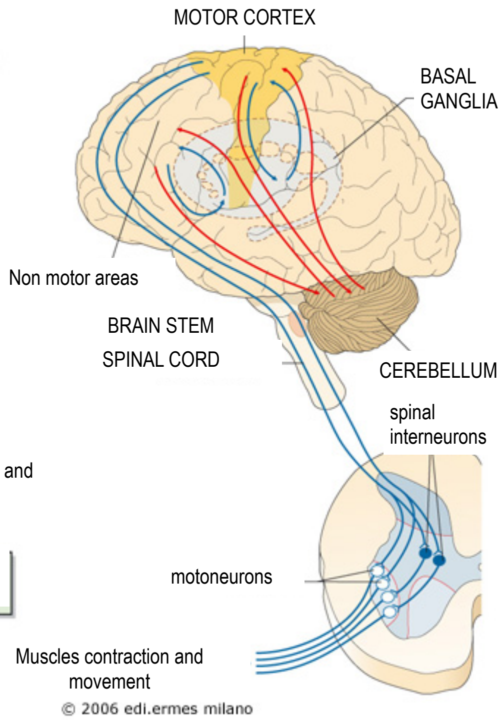


Neuroengineering 2019/20

COMPUTATIONAL NEUROSCIENCE 1 –
Part 2- Neural bases of Motor Control

Brain areas involved in motor control



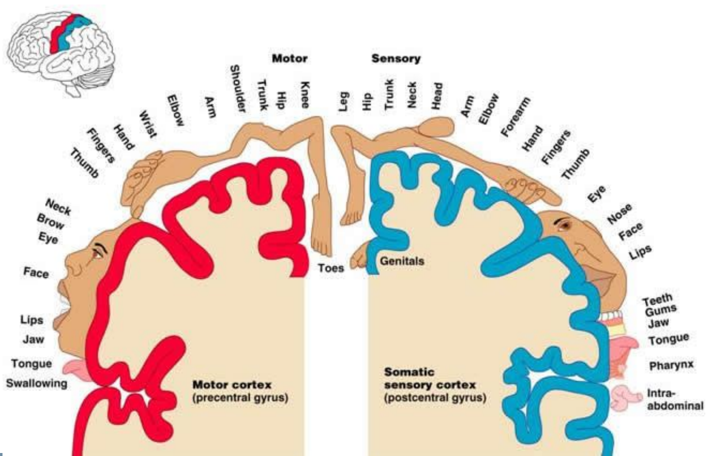


Primary Motor Cortex

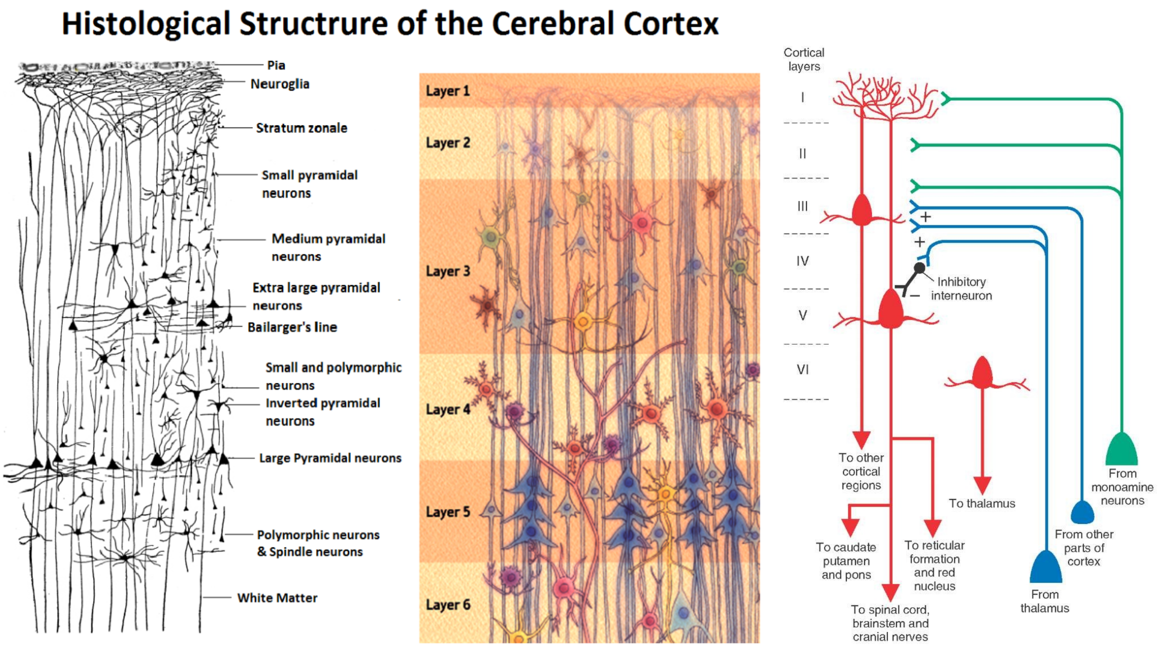
Primary motor cortex: area from which it is possible to evoke movements with the minimum stimulation intensity

- Low intensity stimuli can activate a single muscle (natural activation of a single muscle is rare)
- One muscle can be activated by the stimulation of different cortical sites
- Most of the stimuli activate different muscles
- Primary Somatosensitive cortex afference + area 5 posterior parietal cortex (sensorial integration)
- Afference from basal nuclei and cerebellum

Figure 2.4: Cortical Homunculus: somatotopic organization (From http://www.tulane.edu/ ~ h0Ward/ BrLg/ Cortex. html# id38)

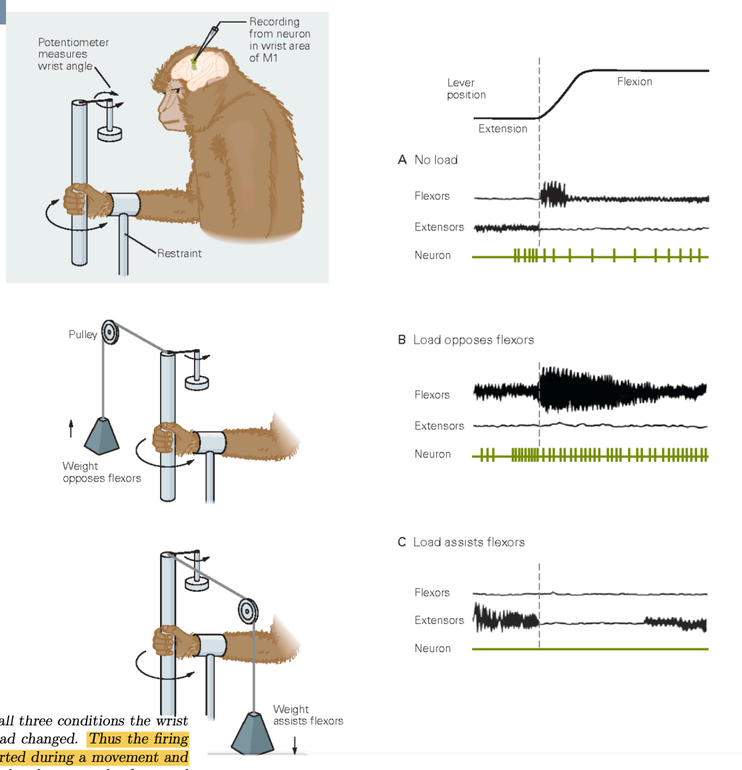


Cortex histological structure



Primary Motor cortex

Force coding
Evarts 1968



When a load-assisting flexion was applied, the neuron fell silent (C). In all three conditions the wrist displacement was the same but the neuronal activity changed as the load changed. Thus the firing of the corticospinal neuron in this experiment is related to the force exerted during a movement and not to the displacement of the wrist. (M1 single neurons activity is correlated to muscular force and it has been observed that there are some activities where the force firing frequency relationship is

Primary Motor cortex

The nature of the motor task changes the neurons activated also if the involved muscles are the same

Maier 1993

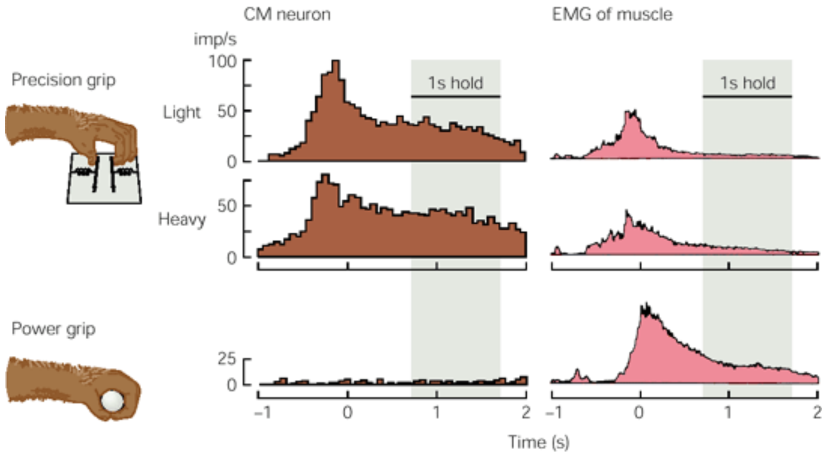
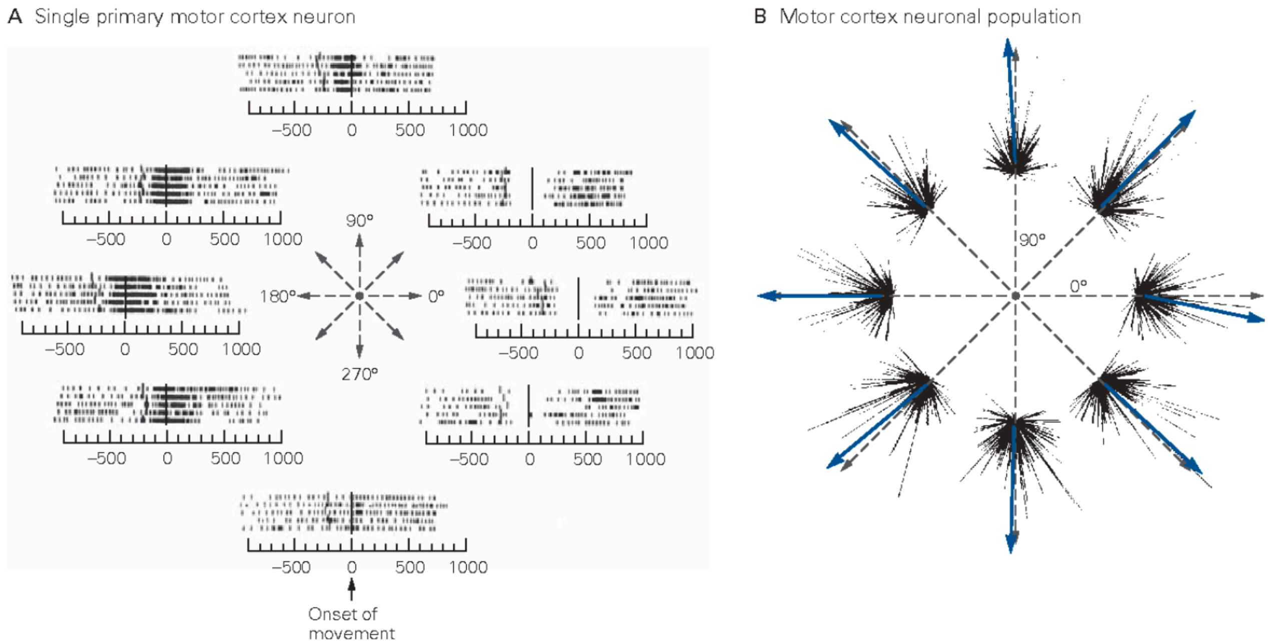


Figure 38-16 Whether an individual corticomotoneuronal (CM) cell is active depends on the motor task. The activity of a CM cell and the activity in its target muscle are not directly related. Cumulative histograms show the activity of a single neuron during a precision grip and a power grip. During the precision grip the neuron's activity is the same whether overall force is light or heavy and the level of electromyographic (EMG) activity in the target muscle is similar for both forces. During the power grip there is almost no activity in the neuron despite a greater amount of EMG activity in the muscle. Thus, even if a given motor neuron is monosynaptically connected to a given CM cell, their firing patterns do not have to parallel each other because the multiplicity of connections to motor neurons allows task flexibility. (imp/s = impulses per second.) (Maier et al 1993.)

Primary Motor cortex

Population vector

Georgopoulus et al.1982



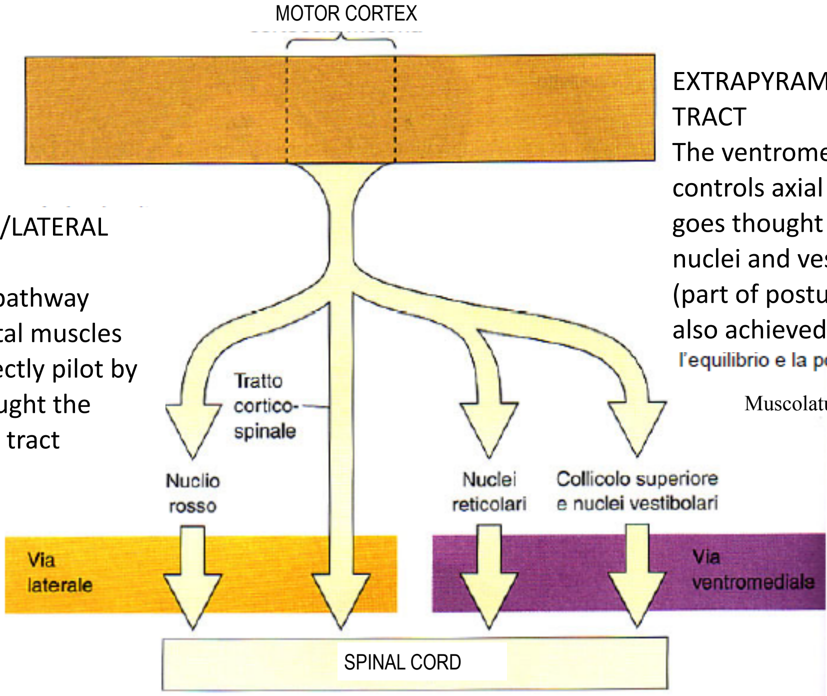
Summary: Primary Motor Cortex

Primary Motor Cortex has a doublefold control
- A low level control of single muscles (homunculus)
- A high level control of multiple muscles depending on High content motor parameters

Exercise and training modify both functions

Spinal cord

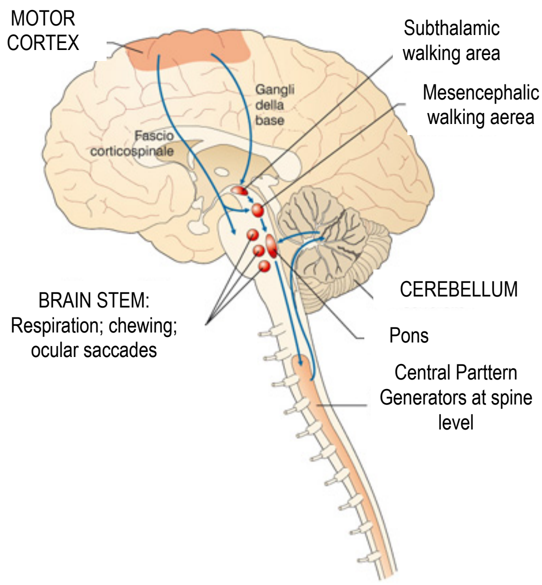
PYRAMIDAL/LATERAL TRACT
The lateral pathway controls distal muscles and it is directly pilot by PMC or thought the Rubrospinal tract



EXTRAPYRAMIDAL/MEDIAL TRACT
The ventromedial pathway controls axial muscles and goes thought reticular nuclei and vestibular nuclei (part of posture control is also achieved by reflexes).
l'equilibrio e la postura

Muscolatura assiale

Spinal cord

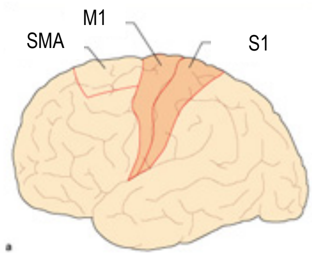


Control of cyclic motor tasks

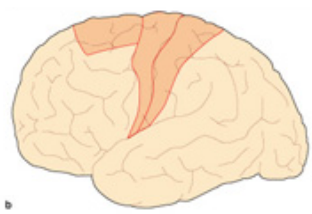
Rythmic tasks are a combination of voluntary tasks and reflexes. The trigger is, usually, volitional while the continuation is based on spinal reflexes.

CENTRAL PATTERN GENERATORS:
oscillatory generators at high level

Supplementary Motor Areas

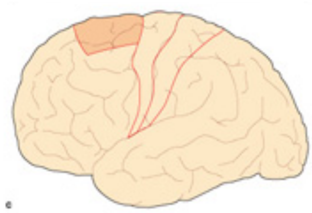


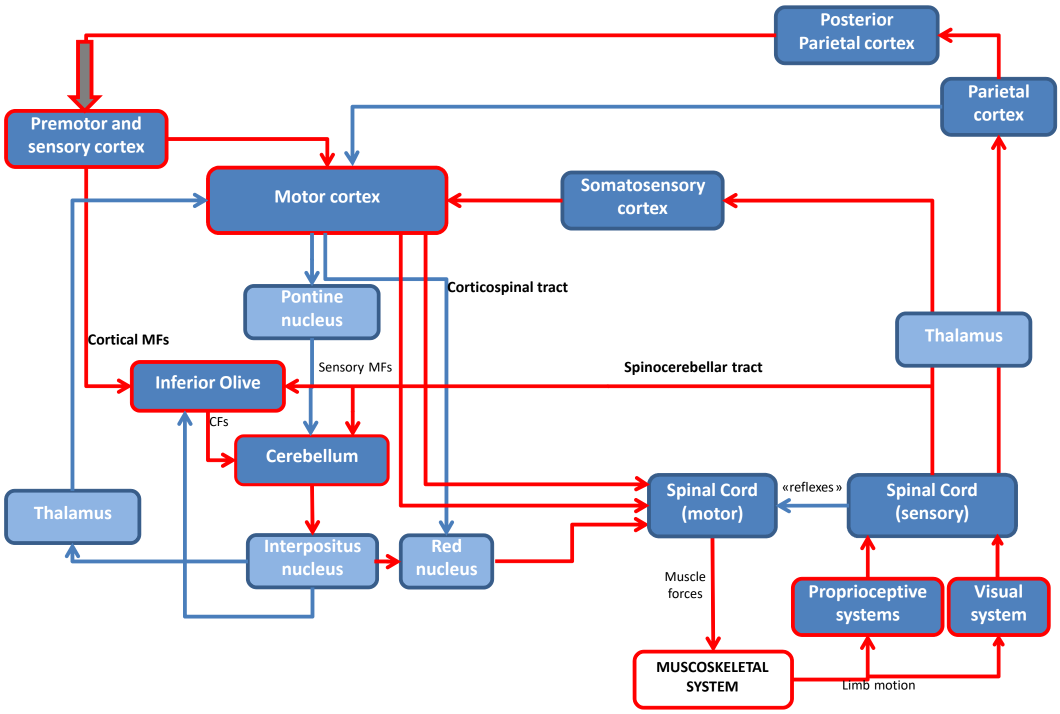
Simple finger flexion
•(M1)
•A (S1)



Sequential finger tapping
• (M1)
• (S1)
•PMC or SMA

Mental repetition of sequential finger tapping
•SMA PMC





Neuroengineering 2019/20

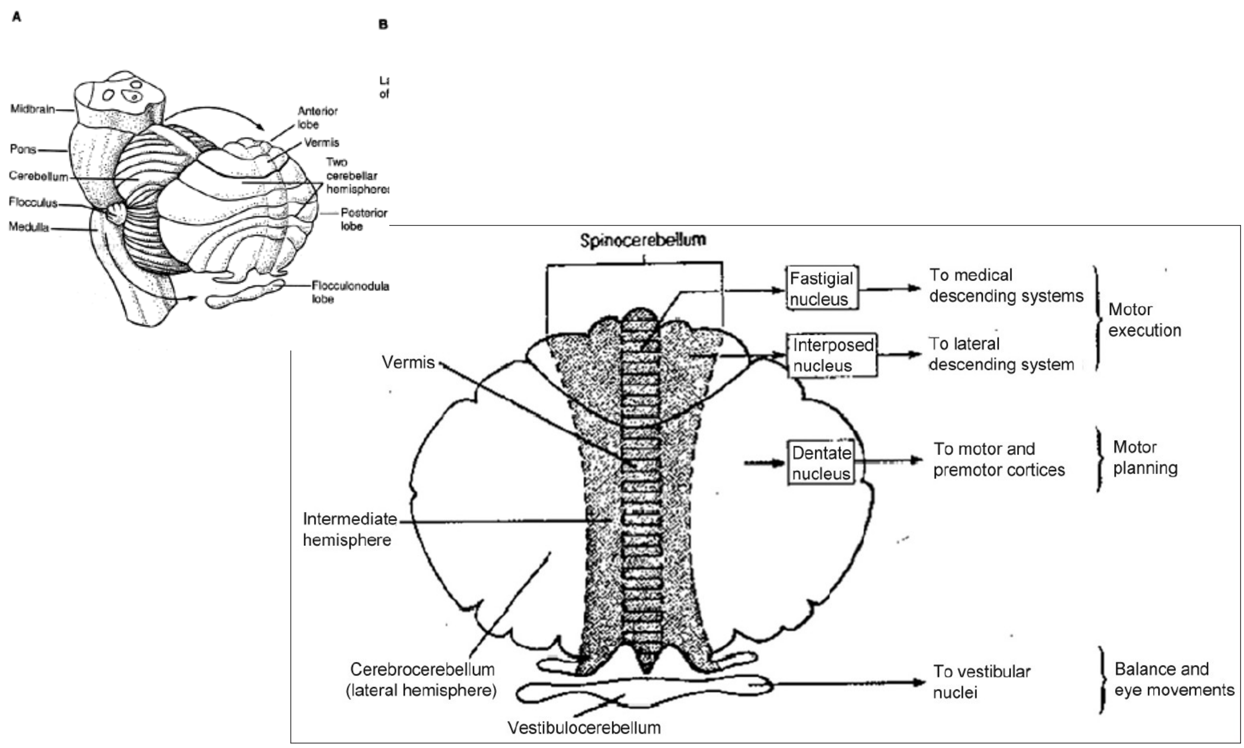
COMPUTATIONAL NEUROSCIENCE 1 –
Part 3- Neural bases of Motor Control – Focus on the Cerebellum

Cerebellum

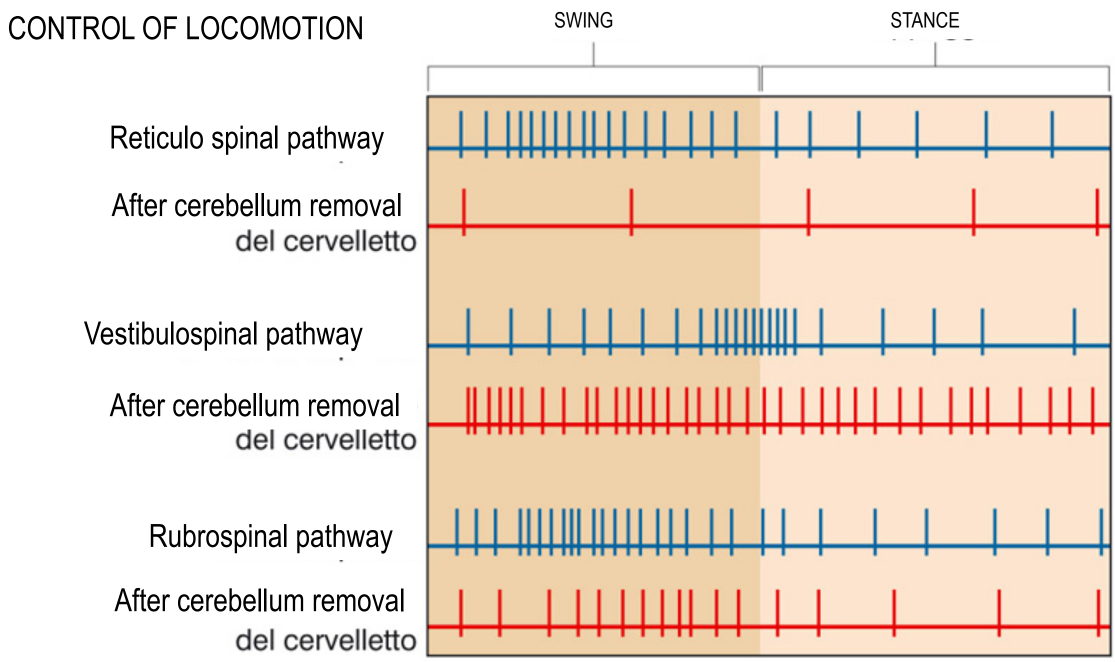
- What does it receive as input? (Inputs=40*outputs)
  - Info on the objective of motor actions
  - Info on the motor commands
  - Sensorial feedback signals associated to the planning and execution of movements

- What does it produce as output?
  - The output projections of the cerebellum are focused mainly on the premotor and motor systems of the cerebral cortex and brain stem, systems that control spinal interneurons, and motor neurons directly
- It has the property of modulation of the input/output connections (adaptation and motor learning: synaptic plasticity)

Anatomical structure



Effects of cerebellar removal

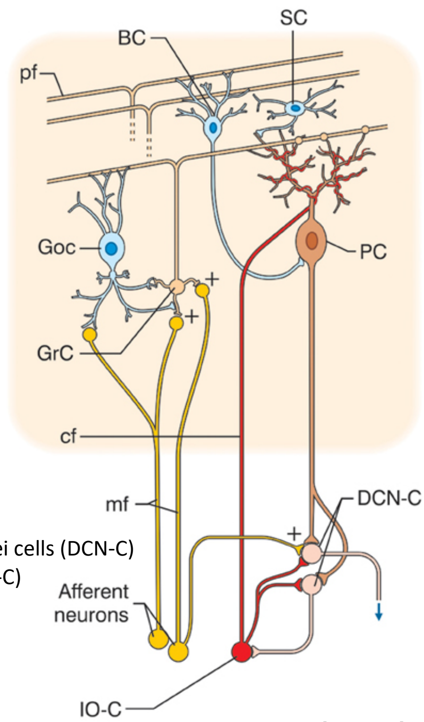


Cerebellar microcircuits

The two main inputs are represented by mossy fibers (mf) originating in various brain stem and spinal cord nuclei, and by climbing fibers (cf) originating from the IO.

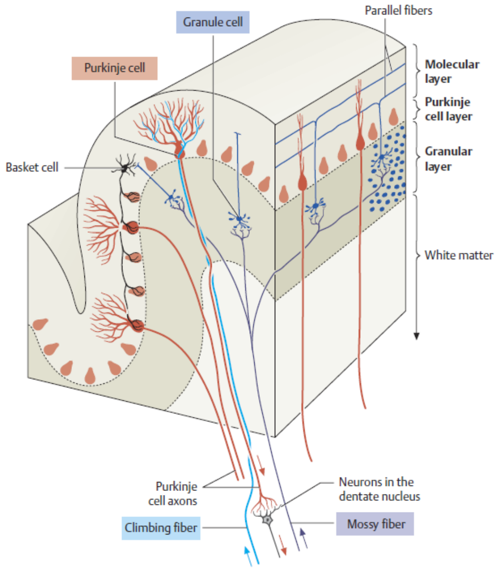
The structure of the cerebellum is formed by the granular layer (containing GrC bodies and GoC) and the molecular layer (containing PC, SC, and BC) and the parallel fibers (pf- axons of GrC).

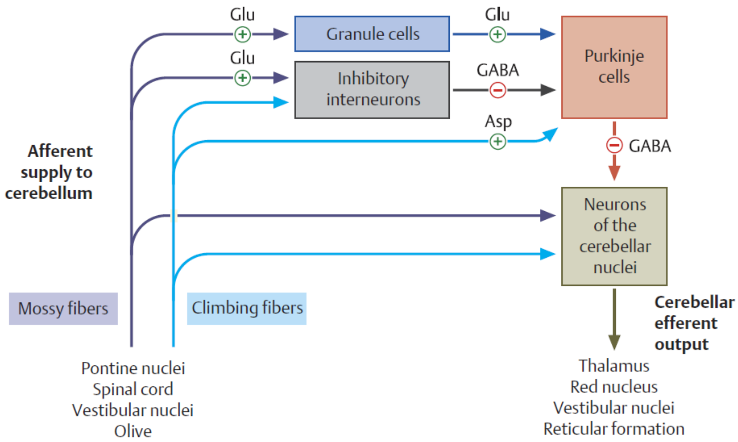
The cerebellar cortical circuit is organized as a feedforward excitatory chain assisted by inhibitory loops: mfs excite GrCs, which activate all the other cortical elements.
In the granular layer, inhibition is provided by GoC, in the molecular layer by SC and BC.
Finally, PCs inhibit DCN.
The IO, which is also activated by brain stem and spinal cord nuclei, controls PC activity though a single powerful synapse. Thus, the whole system can be seen as a complex mechanism controlling the DCN output.



Deep Cerebellar Nuclei cells (DCN-C)
Inferior Olive cells (IO-C)
Granule cells (GrC),
Golgi cells (GoC),
Purkinje cells (PC),
Stellate cells(SC)
Basket cells (BC).

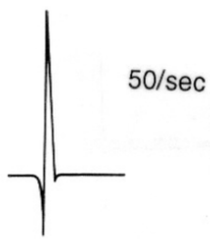
[Ito 2006]





Cerebellum - input

- **Mossy fibers**
  - They originate from:
    - nuclei in the spinal cord and brain stem carrying sensory information from the periphery
    - the cerebral cortex (cortical MFs) carrying motor commands (efference copy)
  - They have excitatory synapses on the dendrites of granule cells (state generator; not-recurrent; sparse coding: high divergence rate of connections)
- **Granule Cells**
  - Granules excite large numbers of Purkinje inducing a constant simple spike (SS)
  - The frequency of the SS could codify the intensity and the duration of the peripheral or the behaviors generated by the CNS
  - They have a center-surround coding



Cerebellum - input

Climbing fibers (IO)

- They have excitatory synapses on the Purkinje cells (generating complex spike, CS)
- each Purkinje neuron receives only one climbing fiber
- They generate low frequency CS;
- The CS could codify the temporal features of the peripheral events and/or act as starting signals for behavioral actions

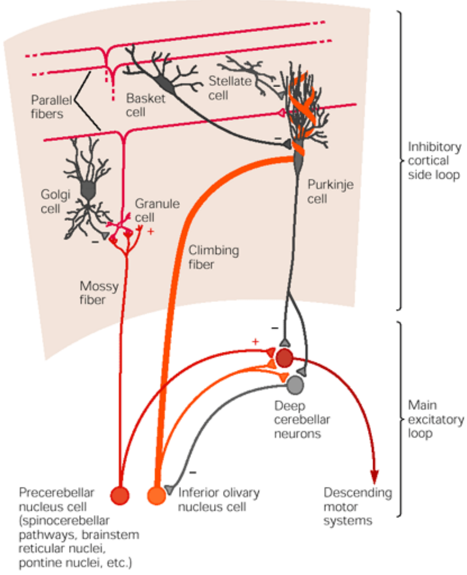
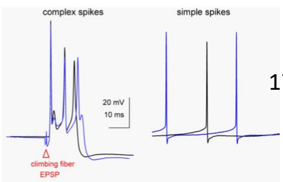


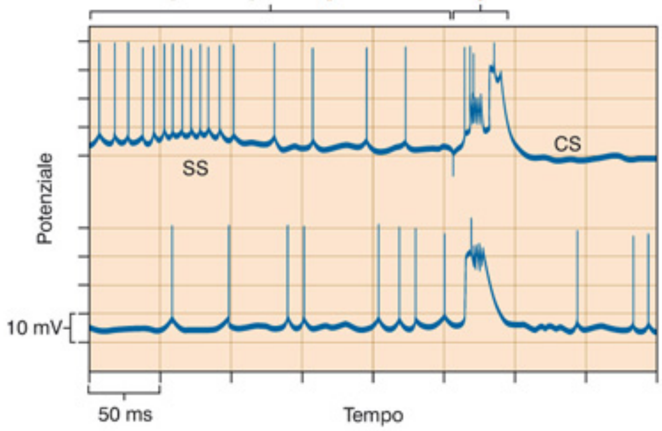
Figure 42-6 Synaptic organization of the basic cerebellar circuit module. Mossy and climbing fibers convey output from the cerebellum via a main excitatory loop through the deep nuclei. This loop is modulated by an inhibitory side-loop passing through the cerebellar cortex. This figure shows the excitatory (+) and inhibitory (-) connections among the cell types.

Cerebellum output

1-3 Hz



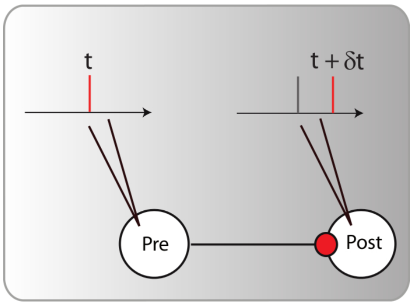
17 – 150 Hz



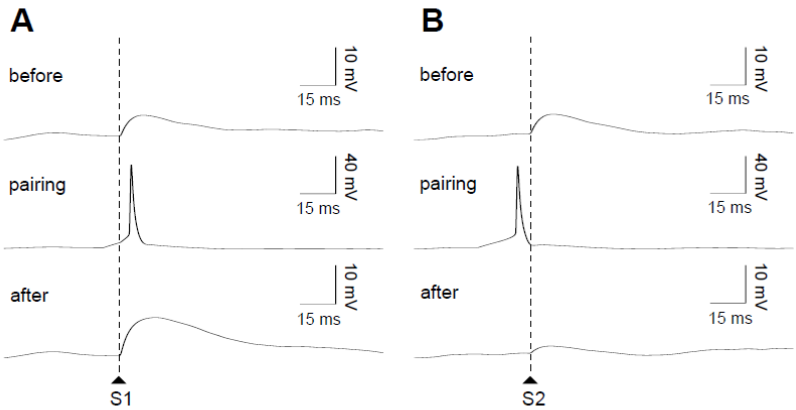
OOBA © 2006 edi.ermes milano

Hebbian plasticity: Spike Timing Dependent Plasticity (STDP)

Hebb hypothesis 1949
Experimental proofs:
Bi 1998, Markram 1997,
Gerstner 1996



Experimental protocol of Spike Timing Dependent Plasticity in vitro. Pre and Post synaptic neurons are patched and forced to fire with a time difference, while the modification of the synaptic strength is monitored



excitatory postsynaptic potentials EPSP

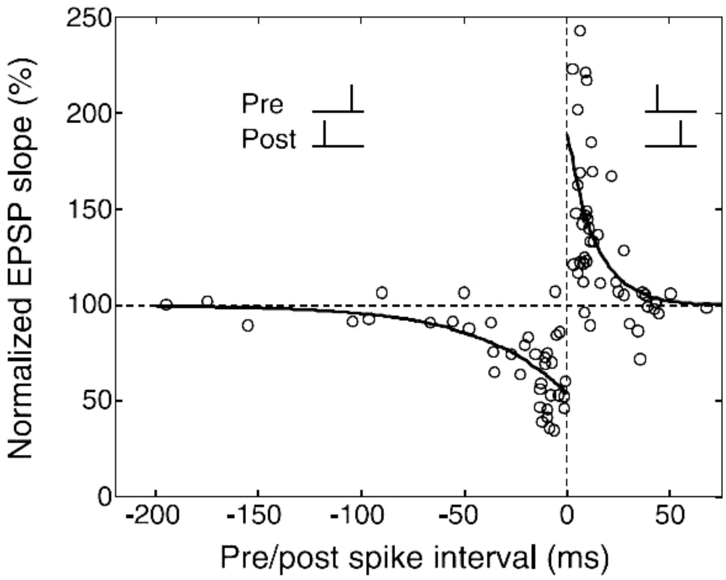
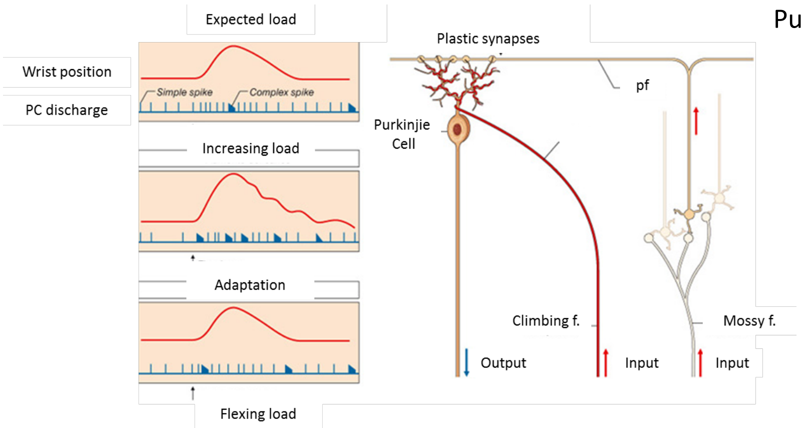
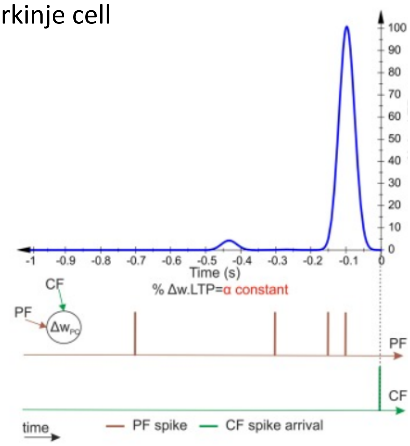


Illustration of spike timing dependent plasticity time windows, taken from (Bi et al, 1998). Depending on the precise time difference between a post- and a pre-synaptic spike, the synaptic weight can be either depressed or potentiated (excitatory postsynaptic potentials EPSP)

Cerebellum output



Synapic plasticity at parallel fiber–Purkinje cell



Changes in the strengths of parallel fiber–Purkinje cell synapses could store stimulus-response associations by linking inputs with appropriate motor outputs, following a **Hebbian learning** approach but with supervision of Cf discharge.

Summary

Structure and organization of the brain suggest computational analogies:

•INFORMATION STORAGE: Physical and chemical structure of neurons and synapses
•INFORMATION TRANSMISSION: electrical and chemical signaling
•PRIMARY COMPUTING ELEMENT: the neuron
•COMPUTATIONAL BASIS: still unknown!!!

Summary

- What is motor control and motor learning and high level models of motor control by the Human Brain
- The human brain areas involved in motor control
- Focus on Cerebellum
- The physiology of the cerebellum accounting for its functional features