Human Motor Systems

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Autonomous Robotics: Action, Perception, and Cognition (ST 2025)
Prof. Dr. Gregor Schöner
Teaching unit: Human motor systems (10.07.2025)

Outlines

- **How muscles work?**

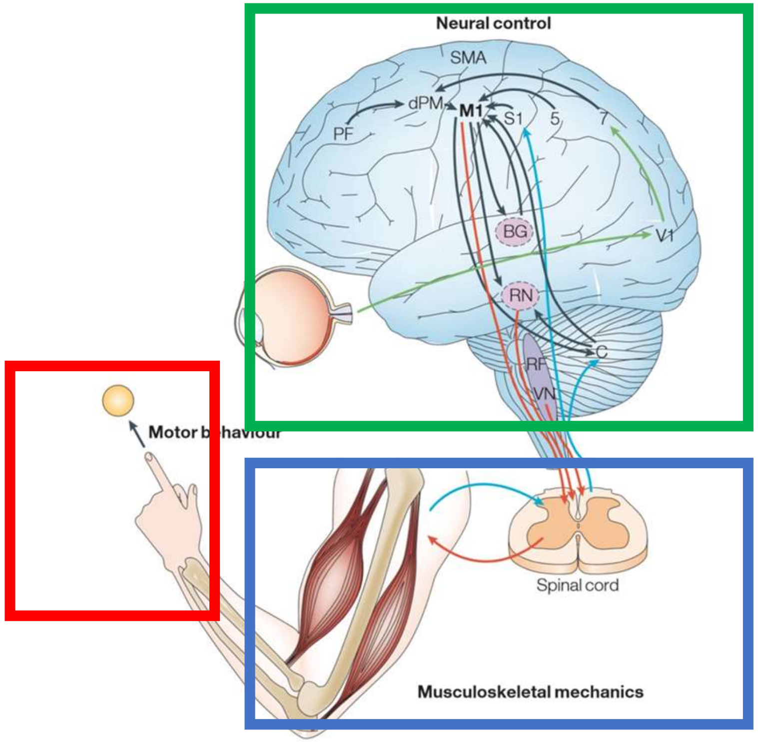
  - muscles, motoneurons, reflexes, spinal cord

- **How movements look like?**

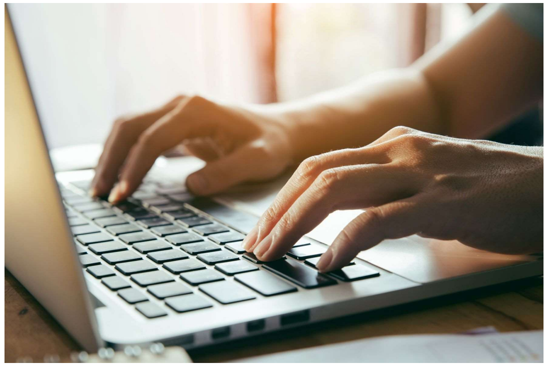
  - kinematic patterns

- **How the brain works in movement generation?**

  - neuroanatomy, function

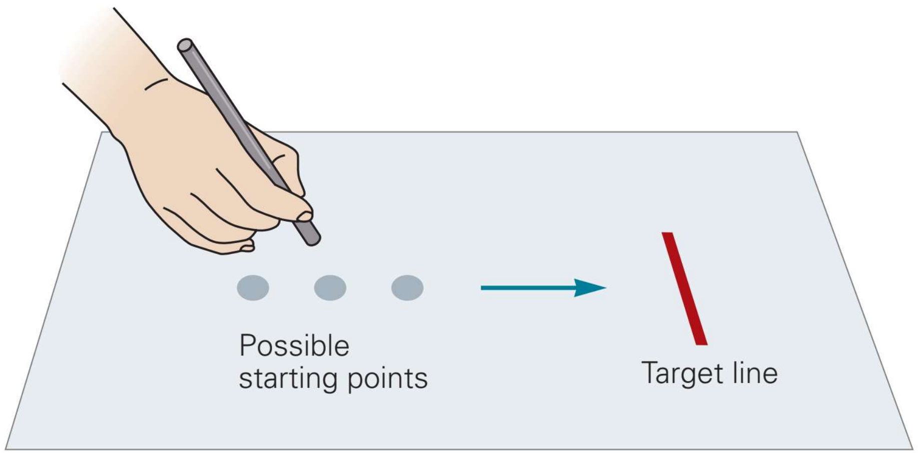


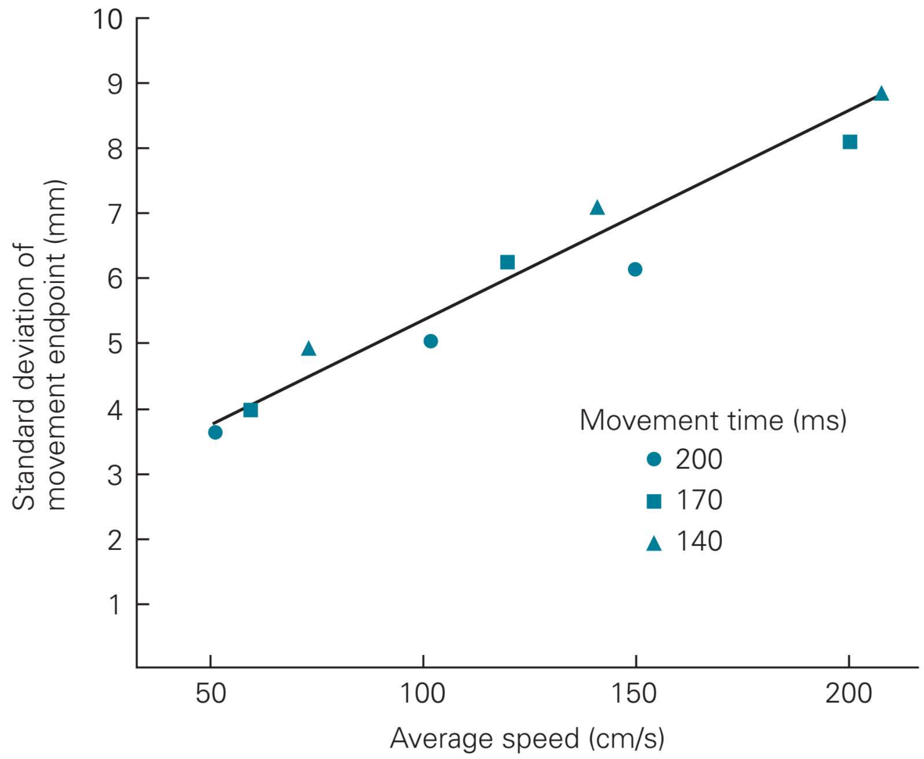
How movements look like



Kinematic regularity

- The speed-accuracy trade-off



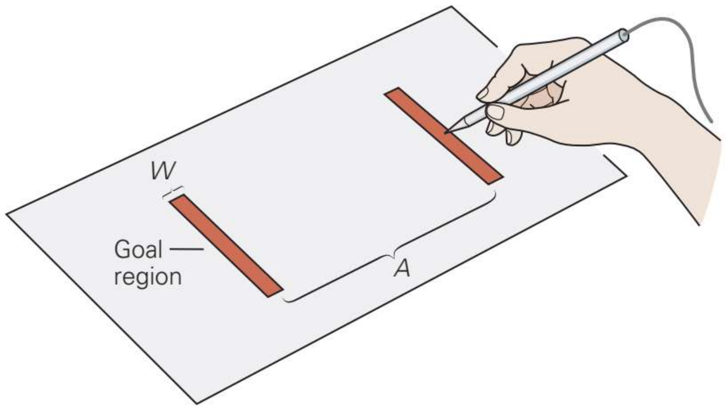


- Three initial positons
- Different movement times (140, 170, or 200ms)
- Variability in proportion to speed (force)

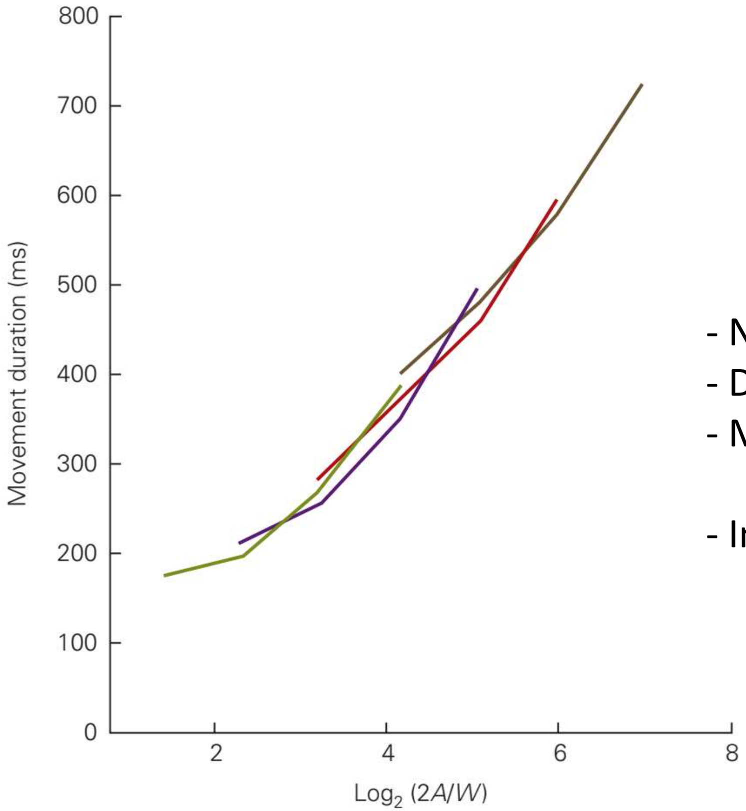
Kandel et al. Figure 33-4

Kinematic regularity

- Fitt's law describes the speed-accuracy trade-off



$$Movement\ duration = a + b * log_2(\frac{2A}{W})$$



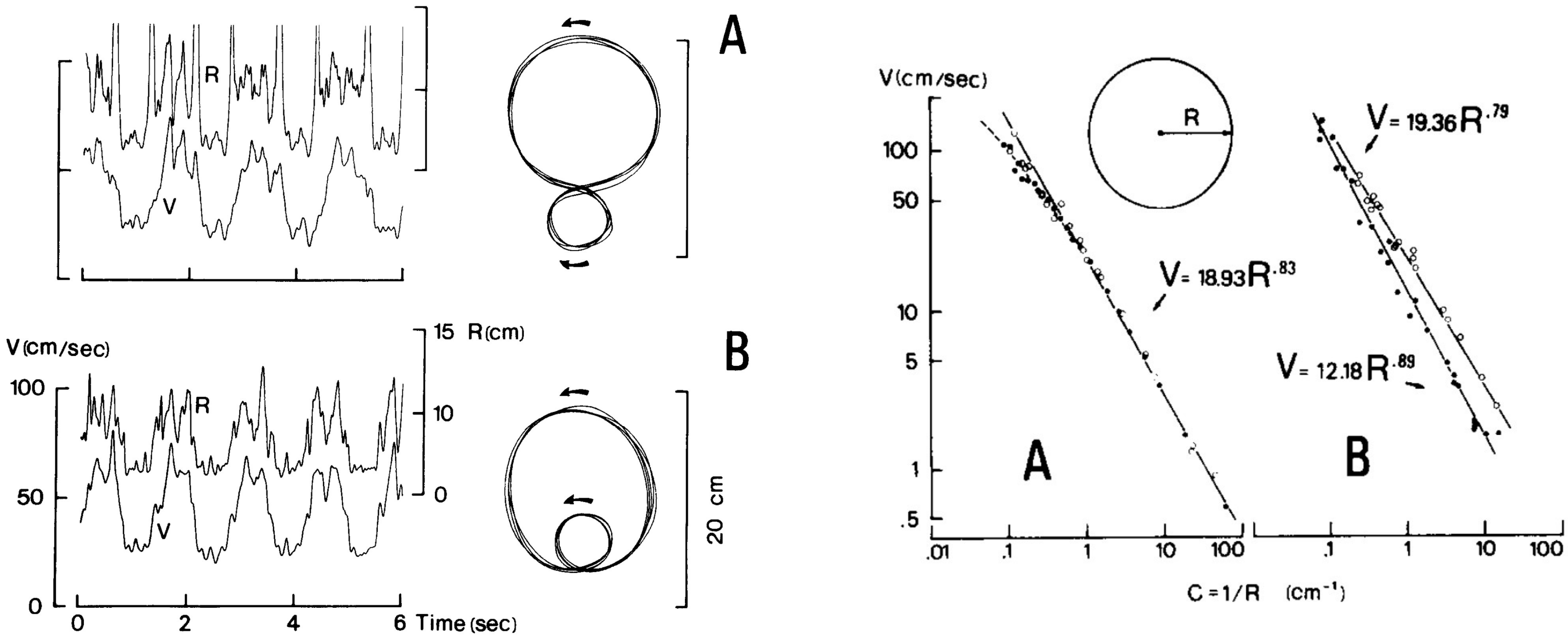
- Narrow and wide targets (W)
- Different distances (A)
- Move as fast as possible

- Index of difficulty: $log_2(\frac{2A}{W})$

Kandel et al. Figure 33-8

Kinematic regularity

- Velocity* (V) vs. curvature** (C) obeys "power-law"

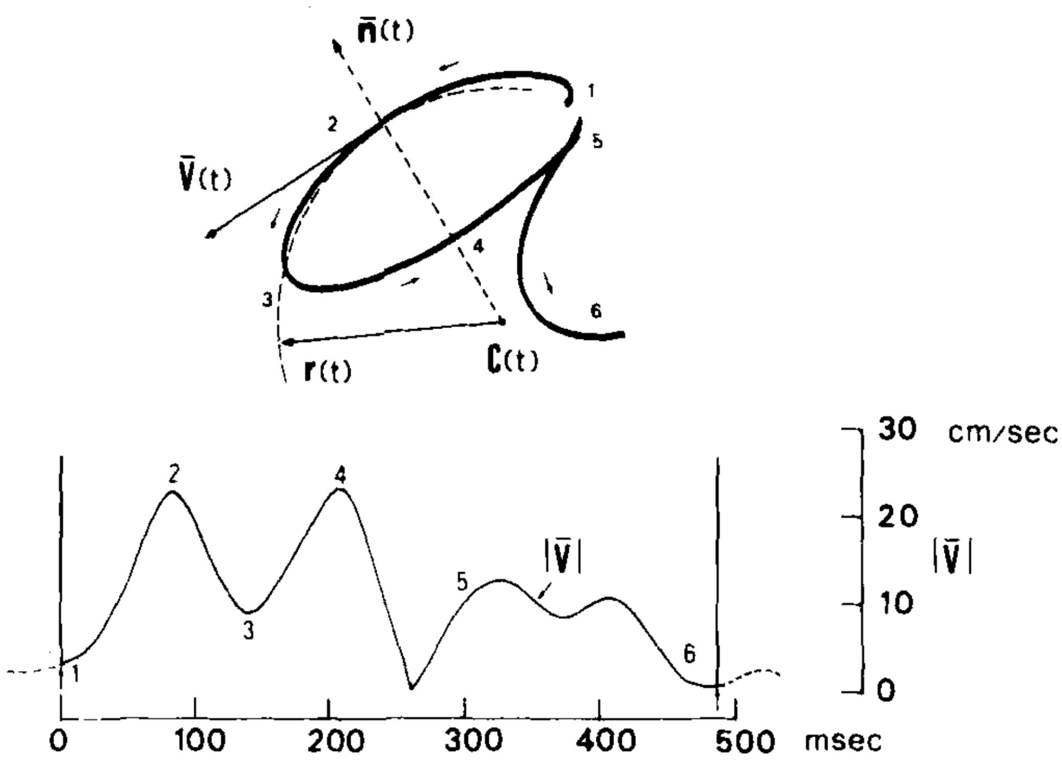


Viviani and McCollum 1983

*Tangential velocity ** C=1/R

Kinematic regularity

- Velocity (V) vs. curvature (C) obeys “power-law”

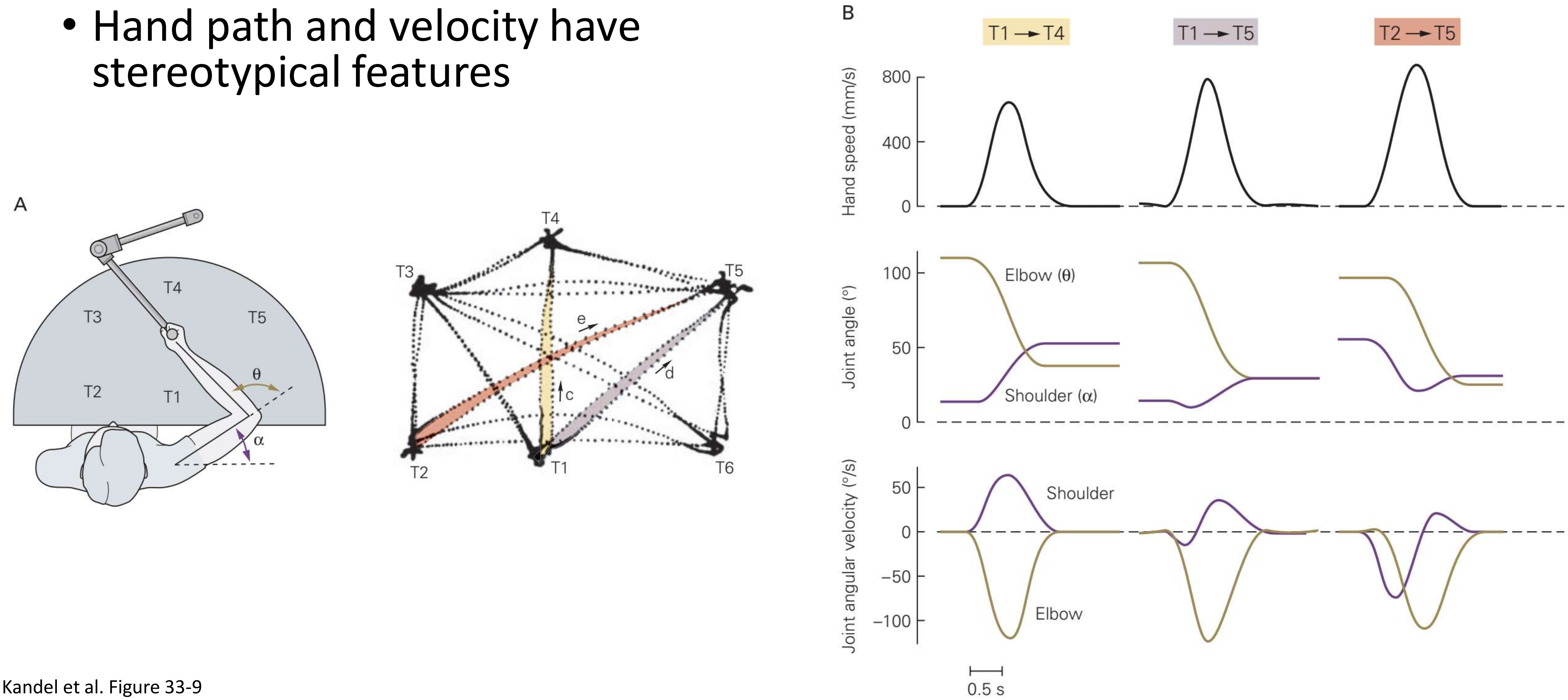


Viviani and Terzuolo 1980

- Smaller C (=1/R): larger V
- Points when movement direction is inverted: V goes to zero.

Kinematic regularity

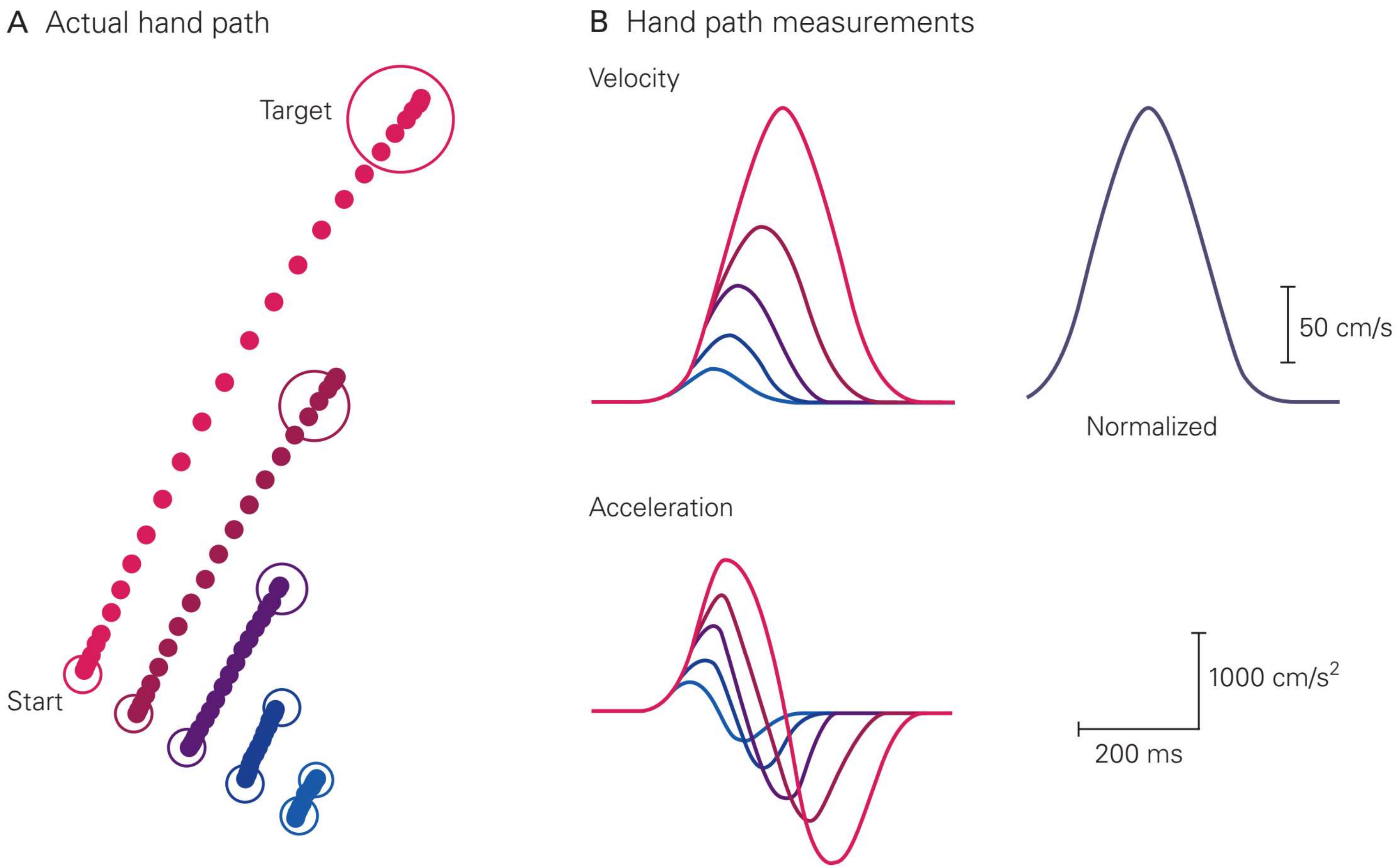
- Hand path and velocity have stereotypical features



Kandel et al. Figure 33-9

Kinematic regularity

- Velocity and acceleration as a function of distance



Kandel et al. Figure 33-12

Kinematic regularity

- Minimum jerk model

Smoothness can be quantified as a function of jerk, which is the time derivative of acceleration (Hogan 1984)

$$\text{jerk}\ \dddot{x}(t) = \frac{d^3x(t)}{dt^3}$$

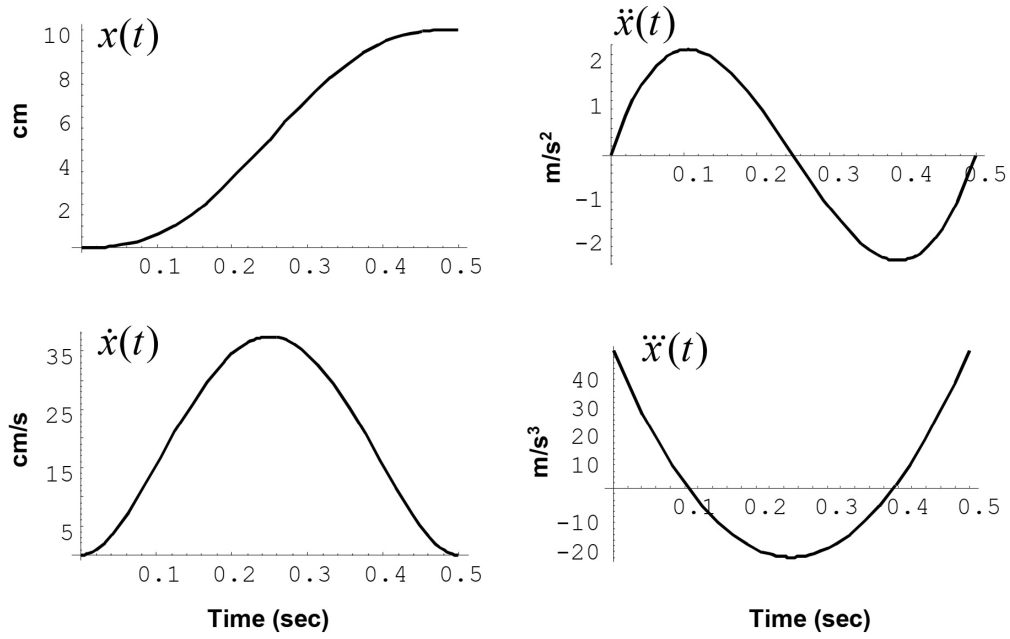
Minimum jerk cost

$$\int_{t=t_i}^{t_f} \dddot{x}_1(t)^2\,dt$$

Solution: Minimum jerk trajectory

$$x(t) = x_i + (x_f - x_i)\left(10(t/d)^3 - 15(t/d)^4 + 6(t/d)^5\right)$$

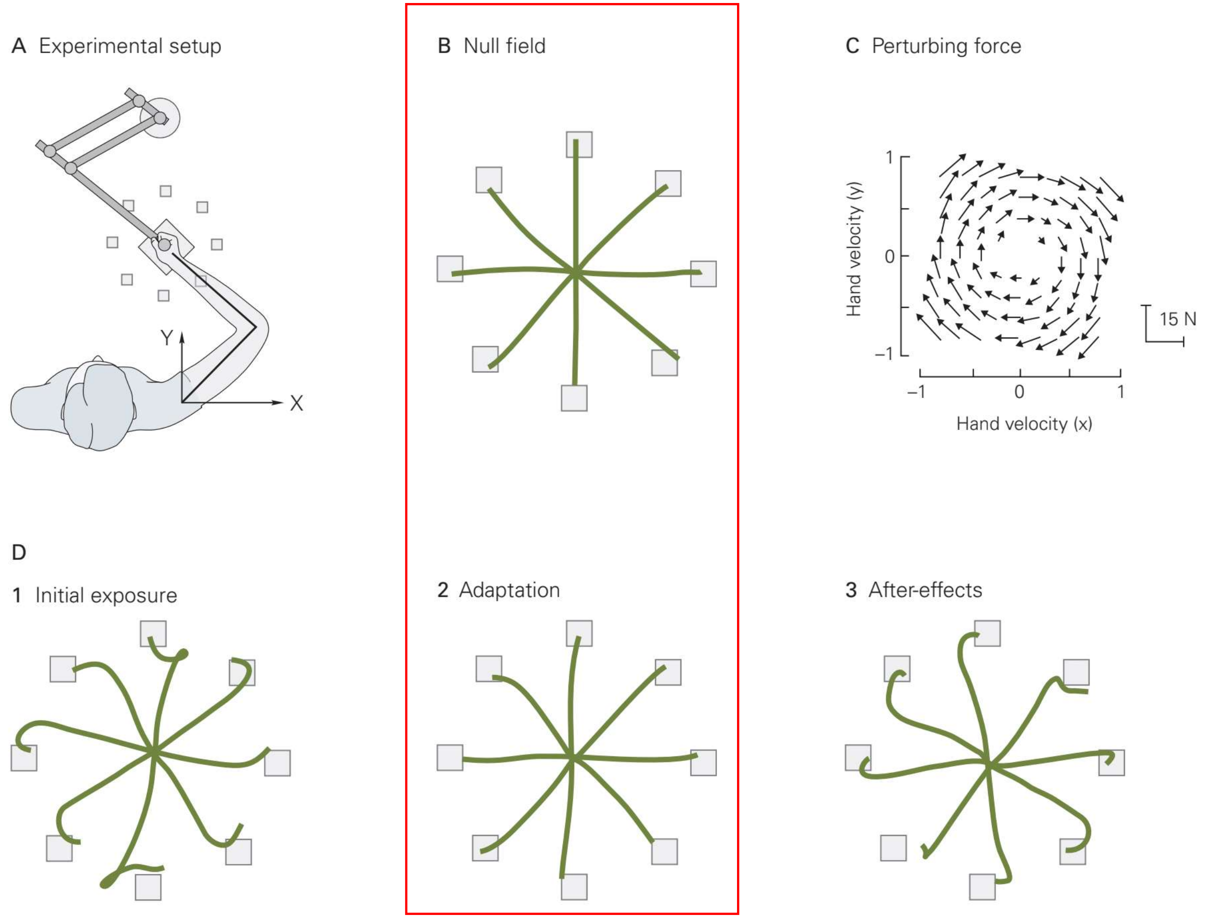
i: initial; f: final; d: movement duration



Complete derivation see: https://courses.shadmehrlab.org/Shortcourse/minimumjerk.pdf

Kinematic regularity

- Reaching movements are straight (no obstacles)



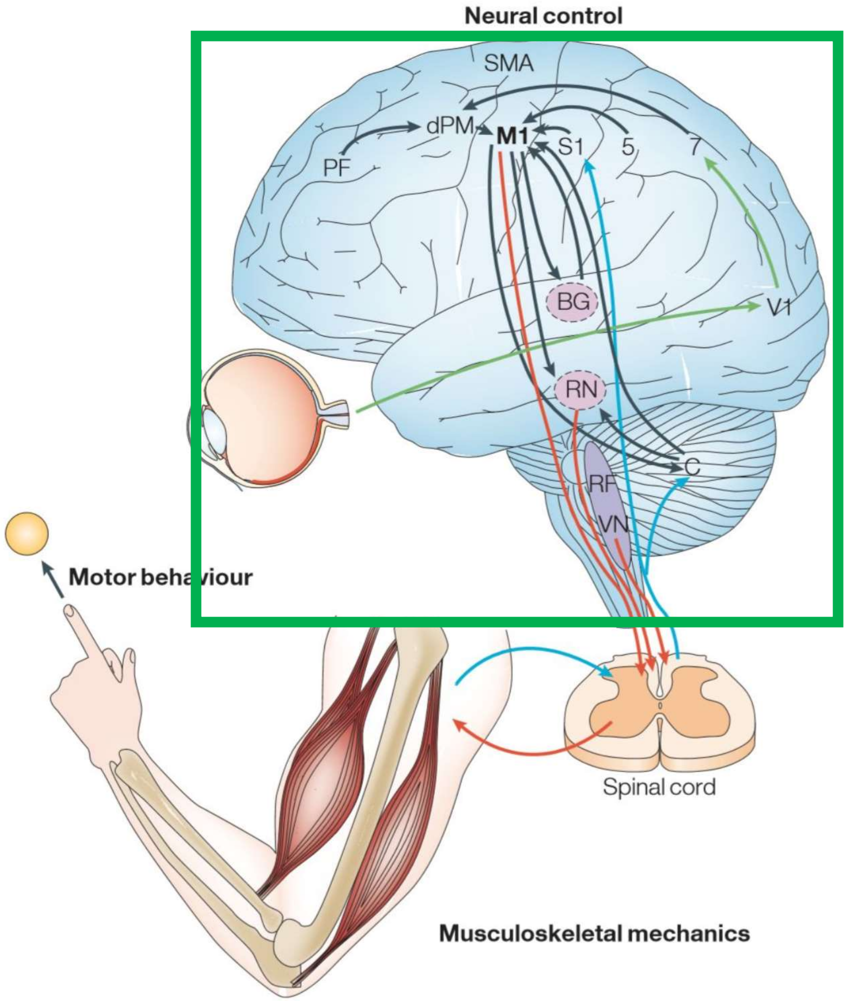
Kandel et al. Figure 33-9

Summary: How movements look like?

Human movements have certain kinematic patterns:

- Speed-accuracy trade-off – Fitt’s law
- Velocity vs. curvature - power law
- Bell-shaped hand velocity – minimum jerk model
- Force field adaptation (straight reaching movements)

Overview of human motor system

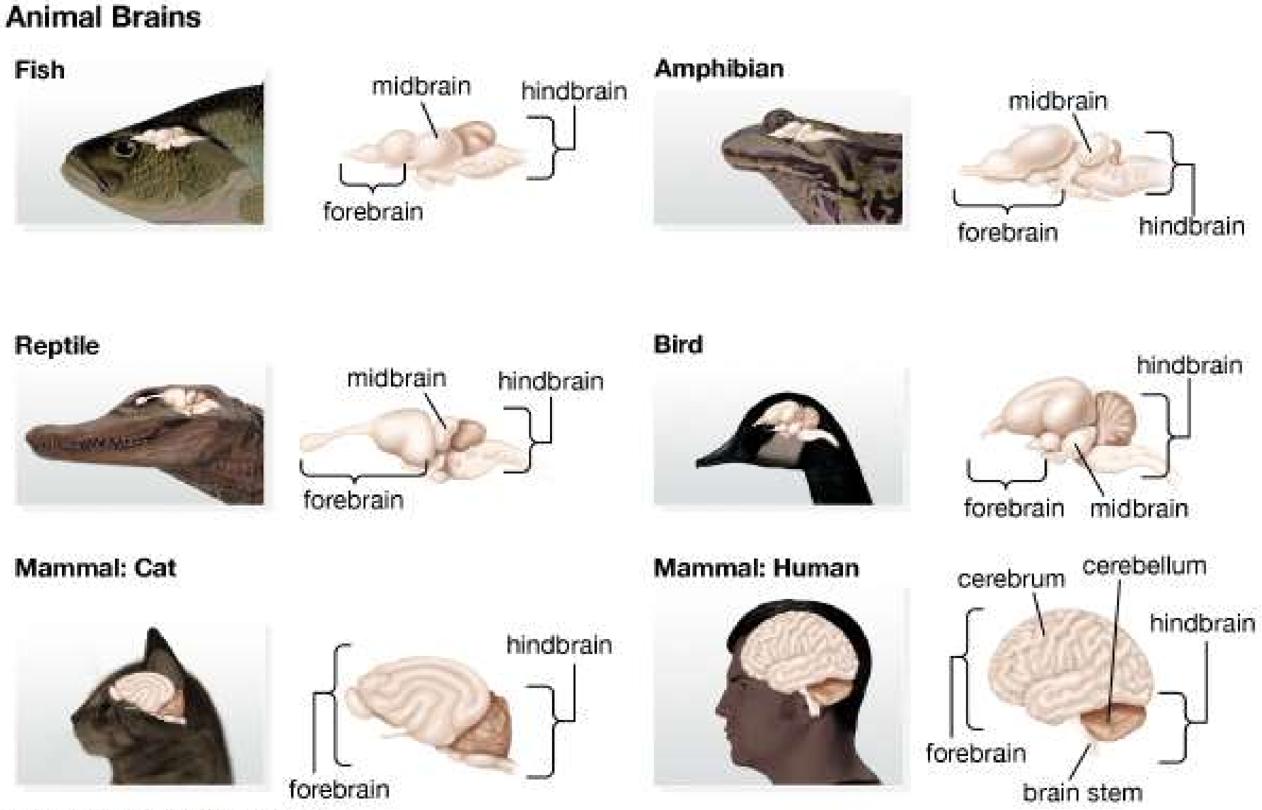


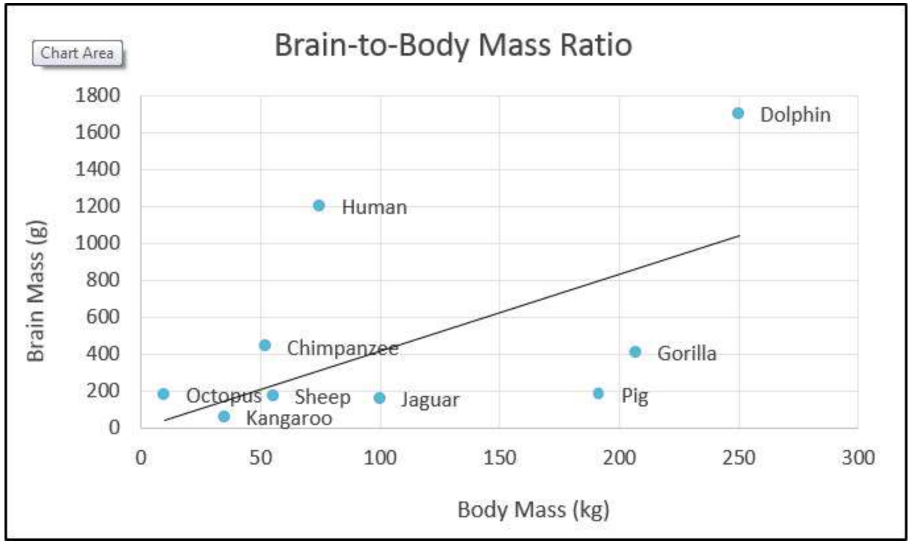
Scott. Nature Reviews Neuroscience 2004

- Central nervous system (CNS)
  - Brain
  - Spinal cord

- Muscles

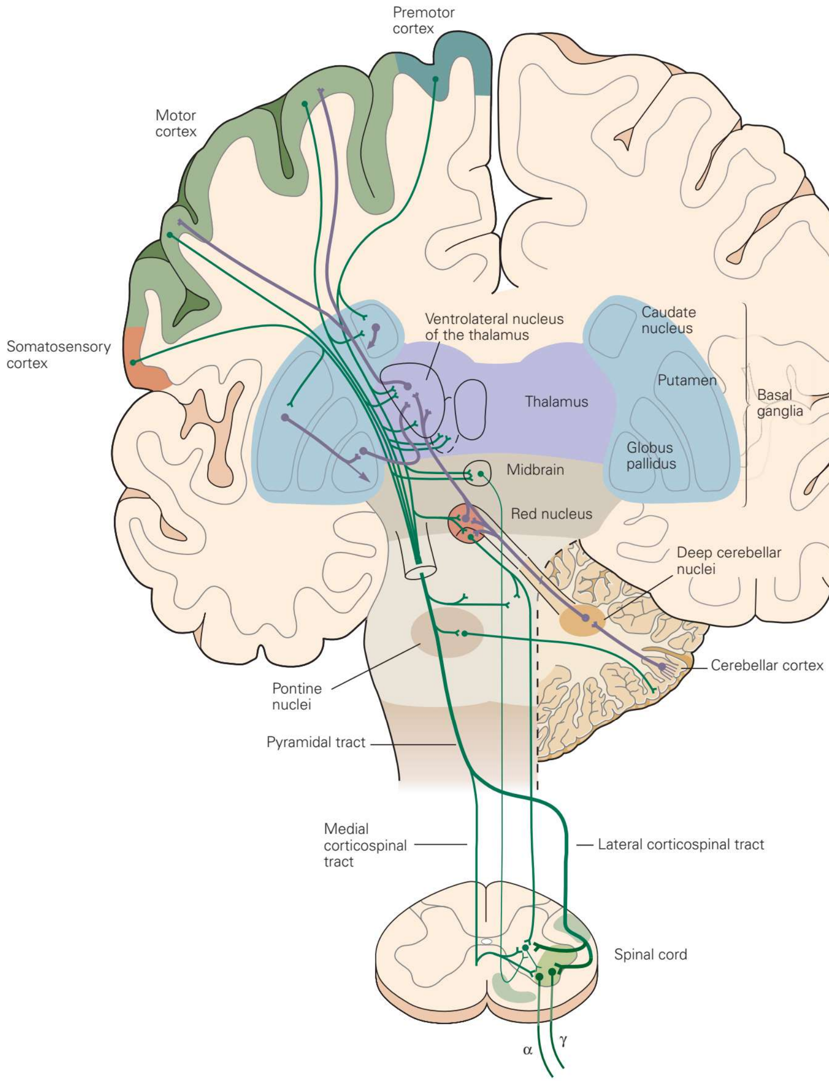
Comparison with animal brains

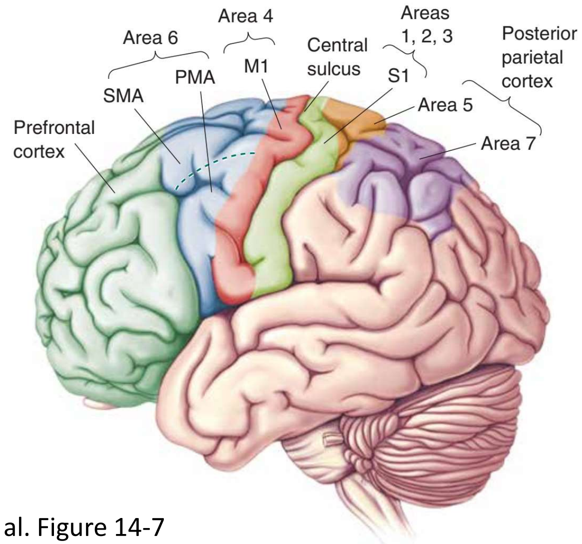




Human brain circuits for movement generation

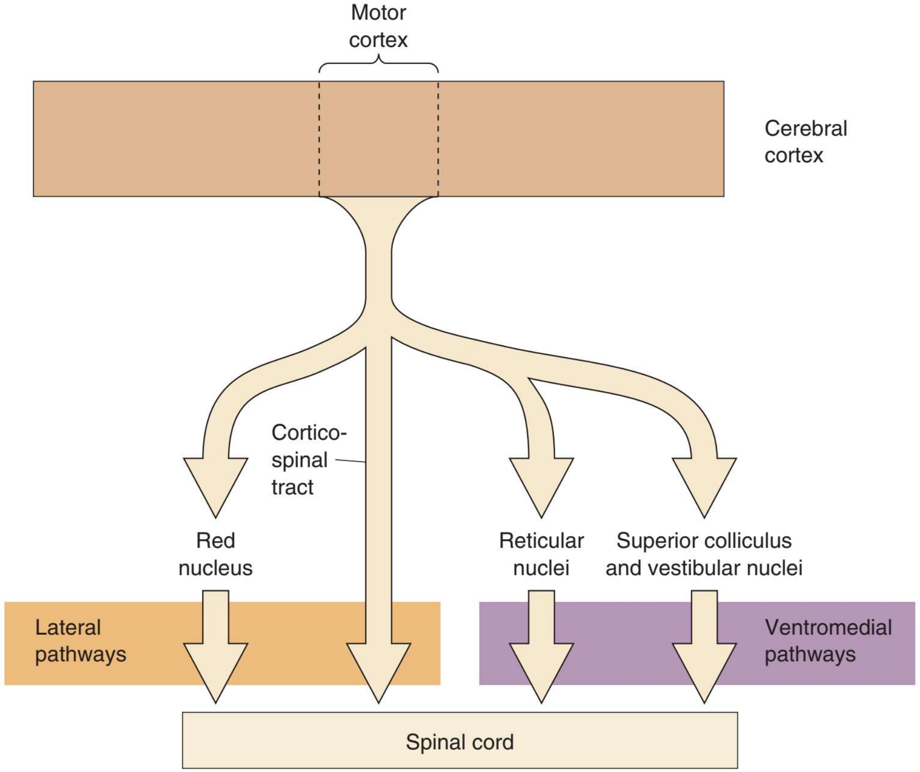
- Motor cortex
- Cerebellum
- Basal ganglia



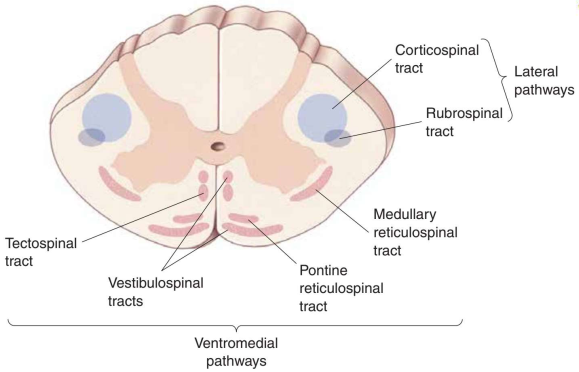


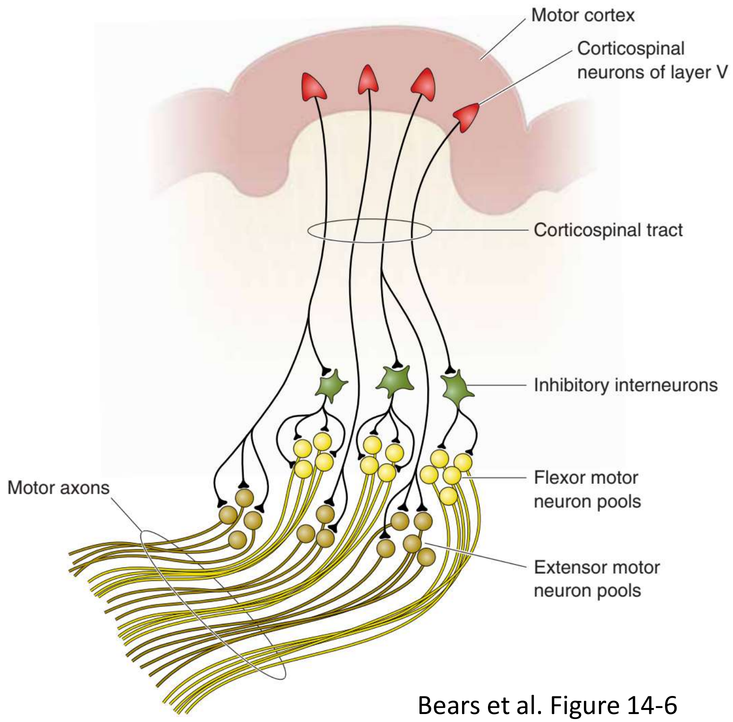
Kandel et al. Figure 14-7

Motor Cortex – descending control of spinal cord



Bears et al. Figure 14-6

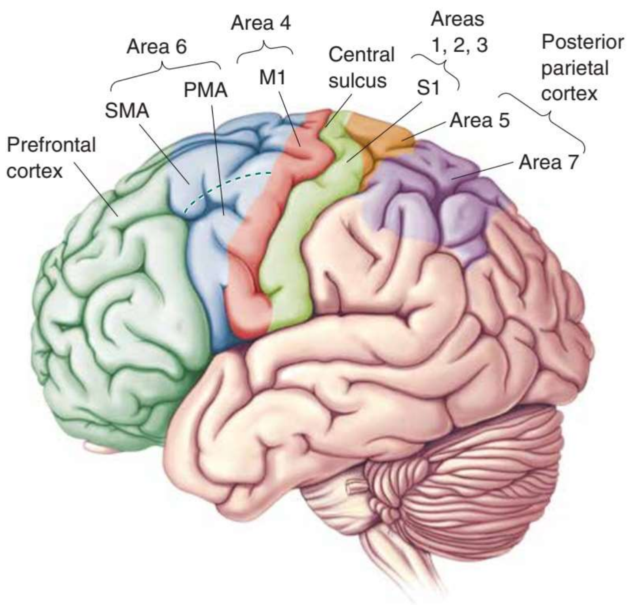




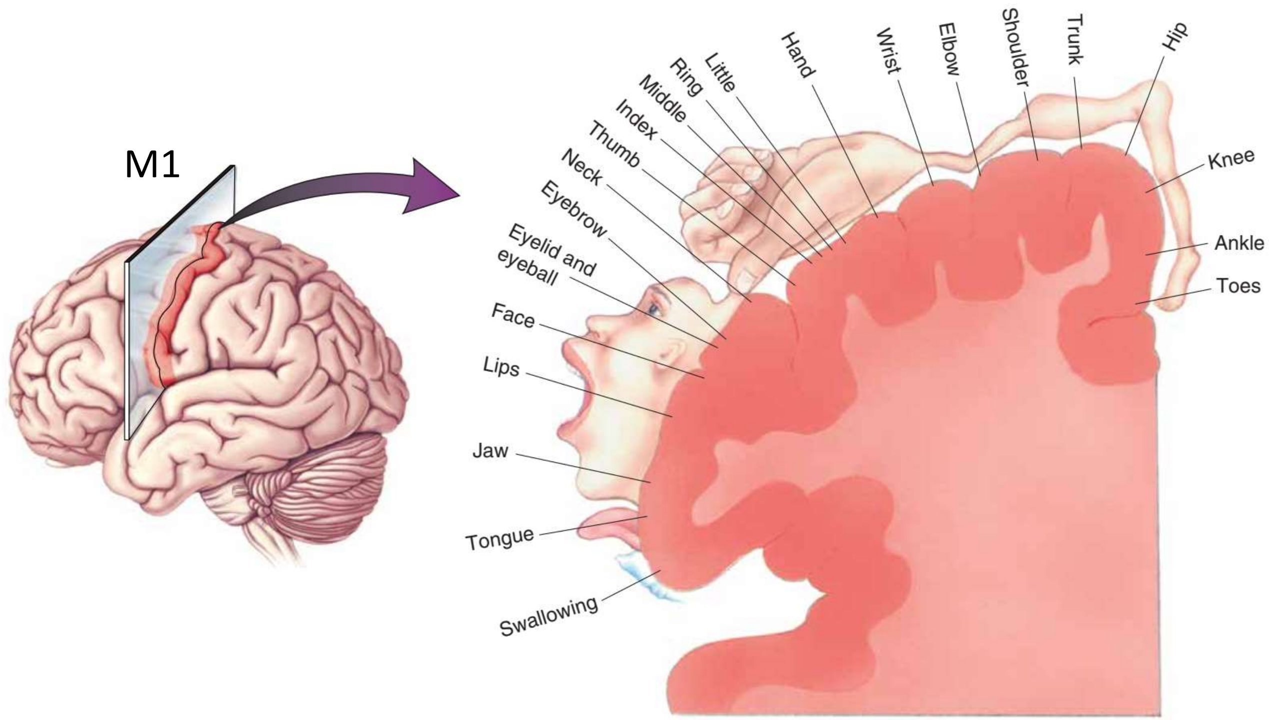
Bears et al. Figure 14-6

Motor Cortex:

Primary cortex (M1)
Premotor area (PMA)
Supplementary motor area(SMA)

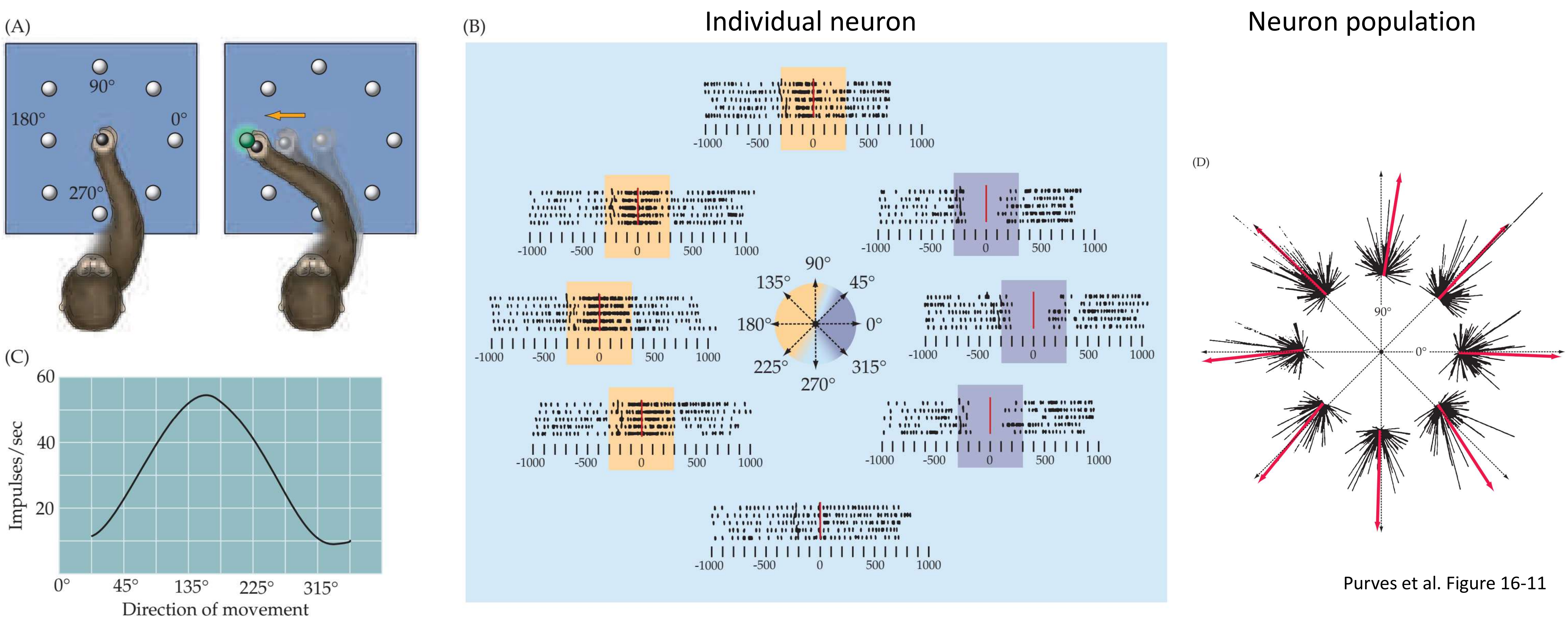


Bears et al. Figure 14-7



Bears et al. Figure 14-8

Primary cortex (M1) – population coding of movement direction

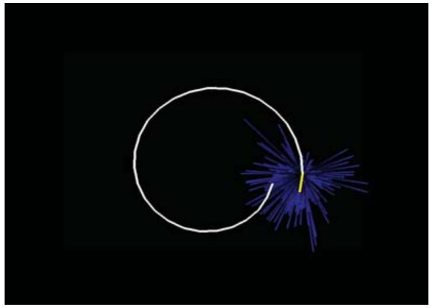


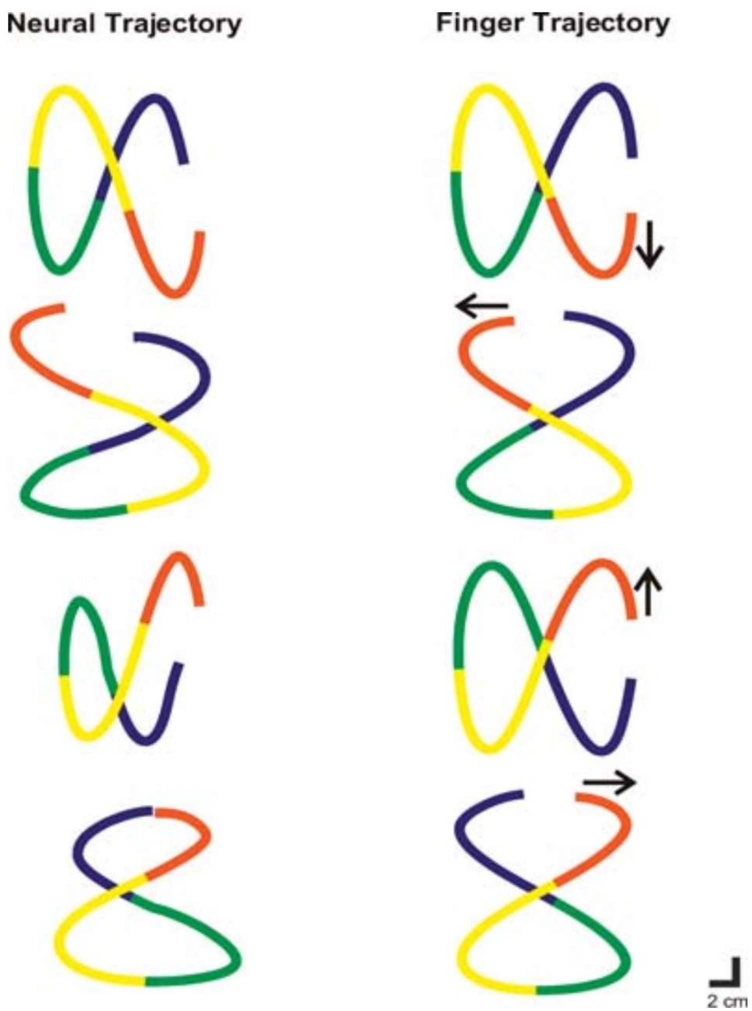
Purves et al. Figure 16-11

Individual M1 neuronal discharges cannot specify movement direction, because they are tuned too broadly;
Rather, each arm movement must be encoded by the concurrent discharges of a population of such neurons

Neural trajectory of M1 predicts motion

Neural trajectory is calculated from population vectors in time course



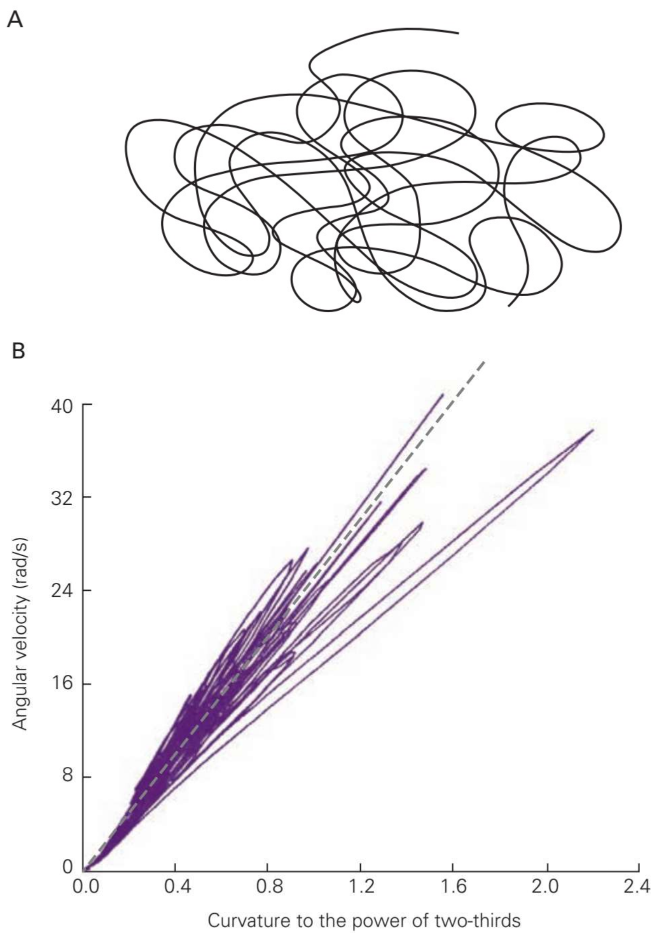


Segmentation during drawing

Schwartz J Physiol. 2007

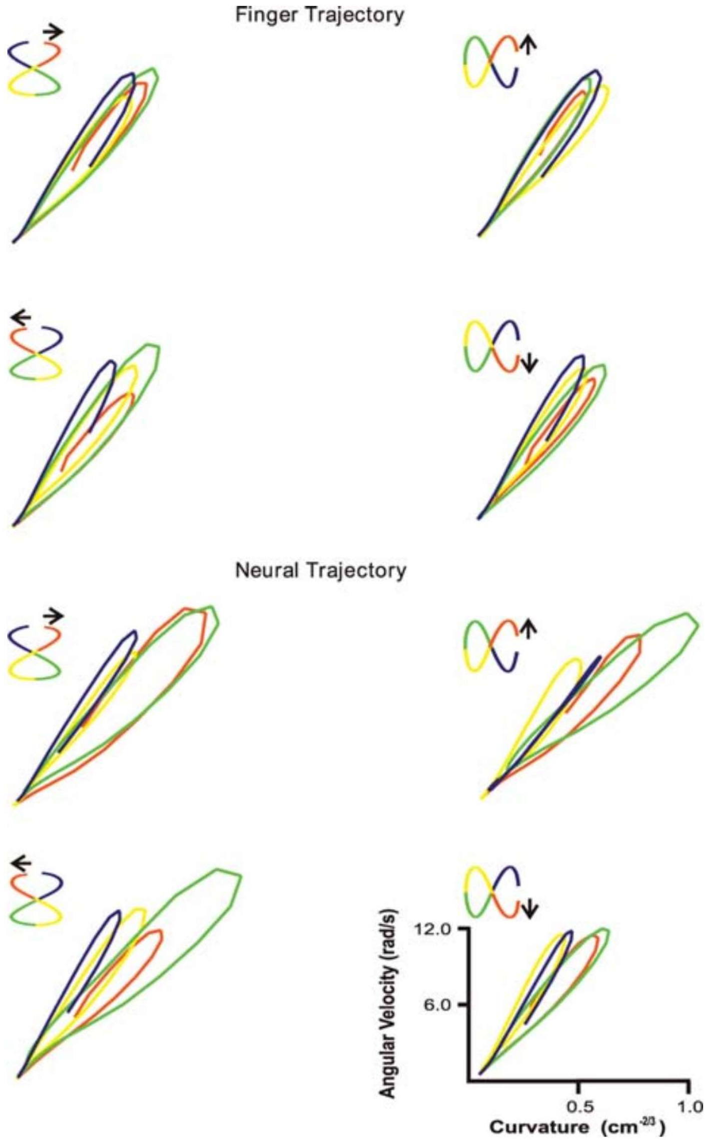
Kinematic regularity – movement planning in M1?

- Velocity* vs. curvature obeys "power-law"



*Angular velocity

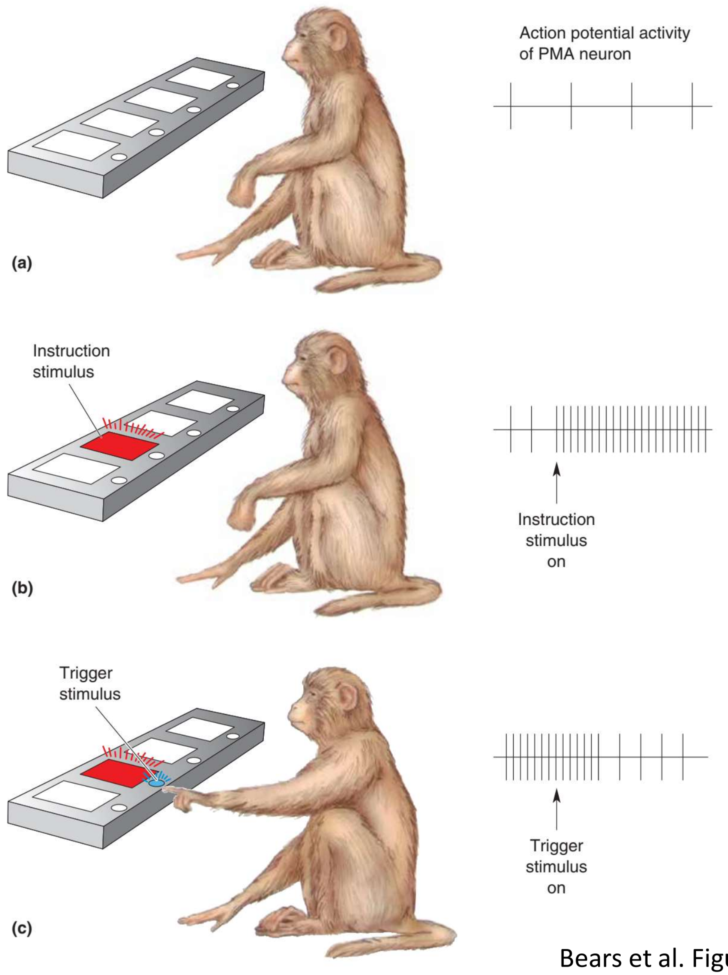
Kandel et al. Figure 33-8



Schwartz J Physiol. 2007

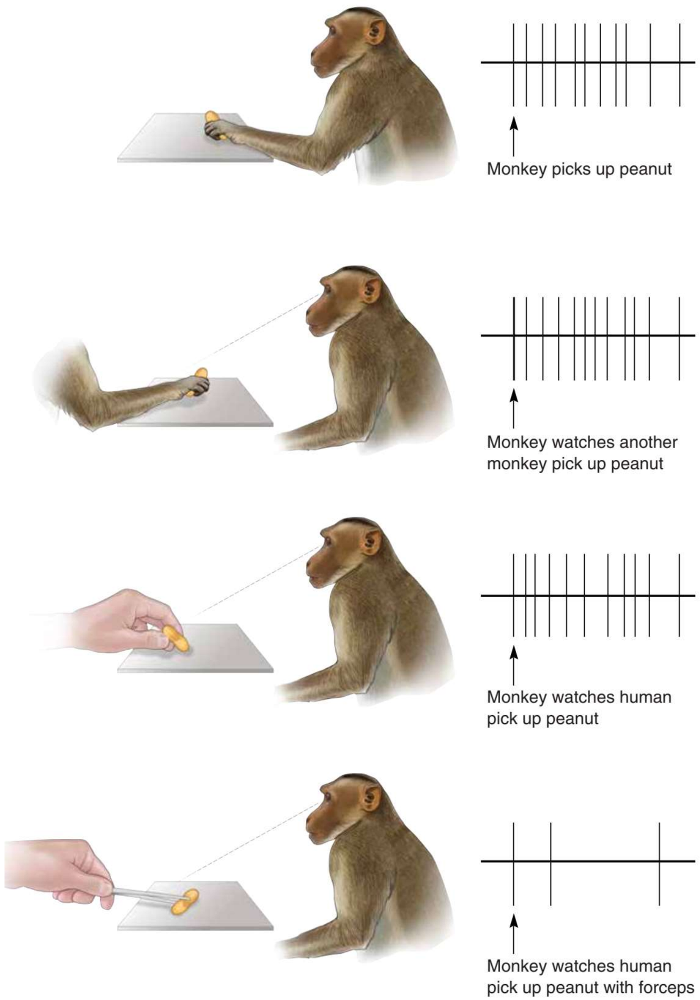
Premotor area (PMA)

Discharge of PMA neuron before a movement



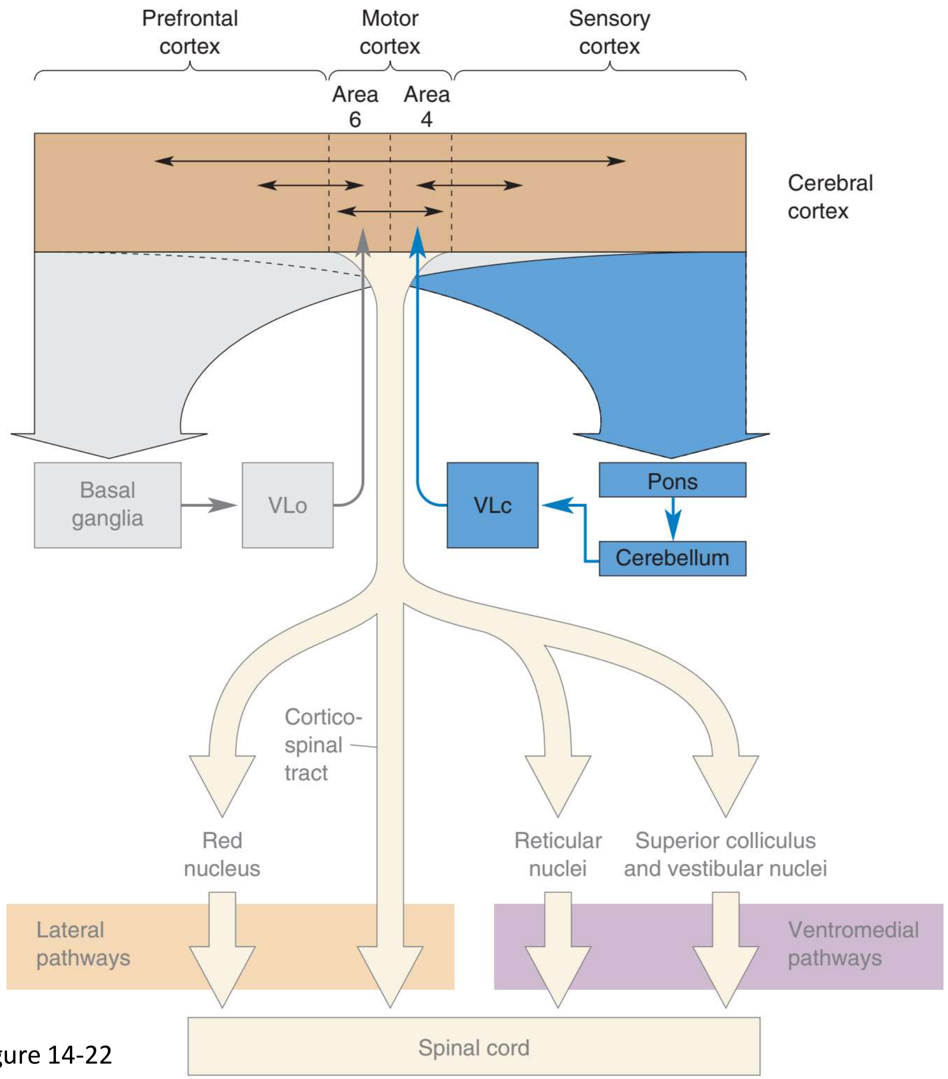
Bears et al. Figure 14-9

Discharge of a mirror neuron in PMA

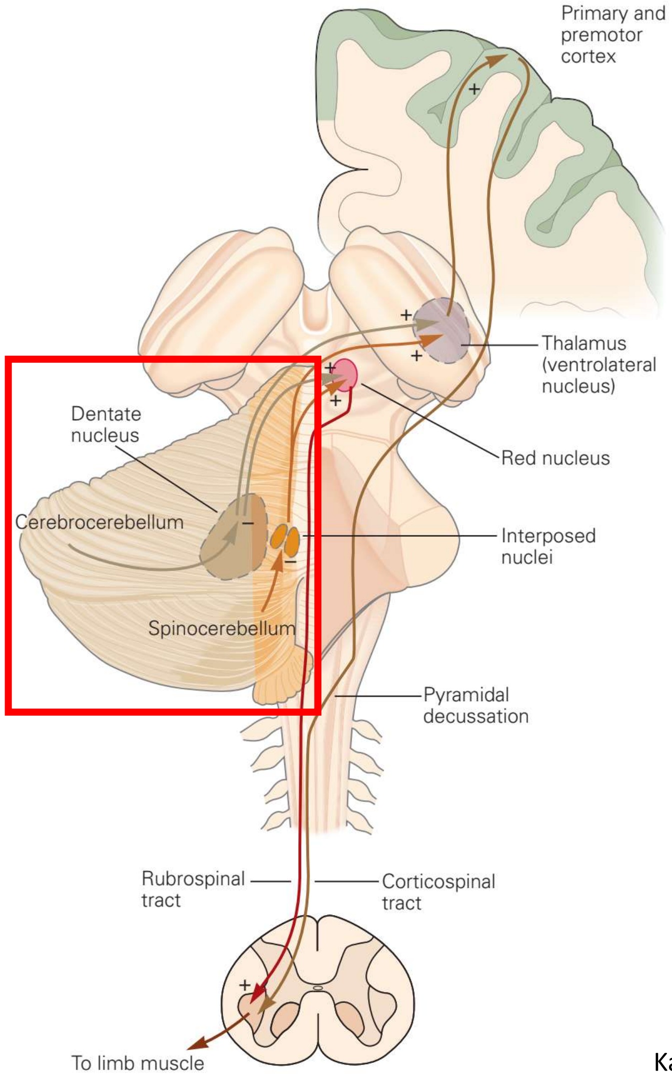


Bears et al. Figure 14-10

Cerebellum: coordination of movement

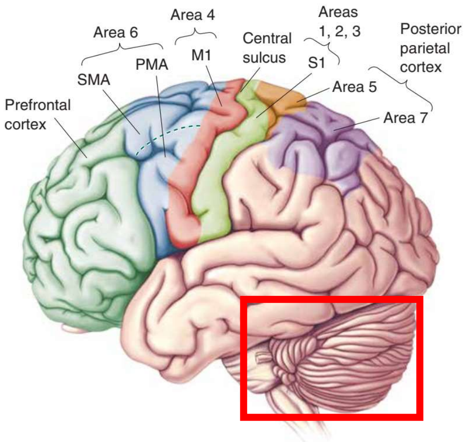


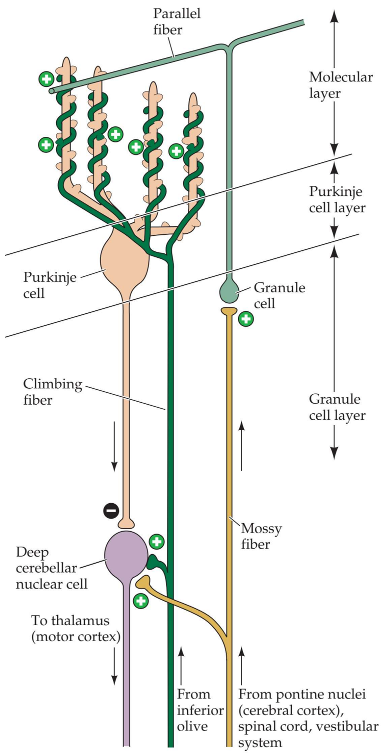
Bears et al. Figure 14-22



Kandel et al. Figure 42-7

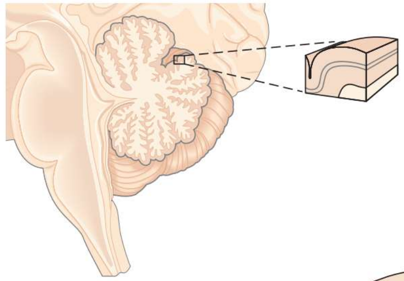
Cerebellum: anatomy

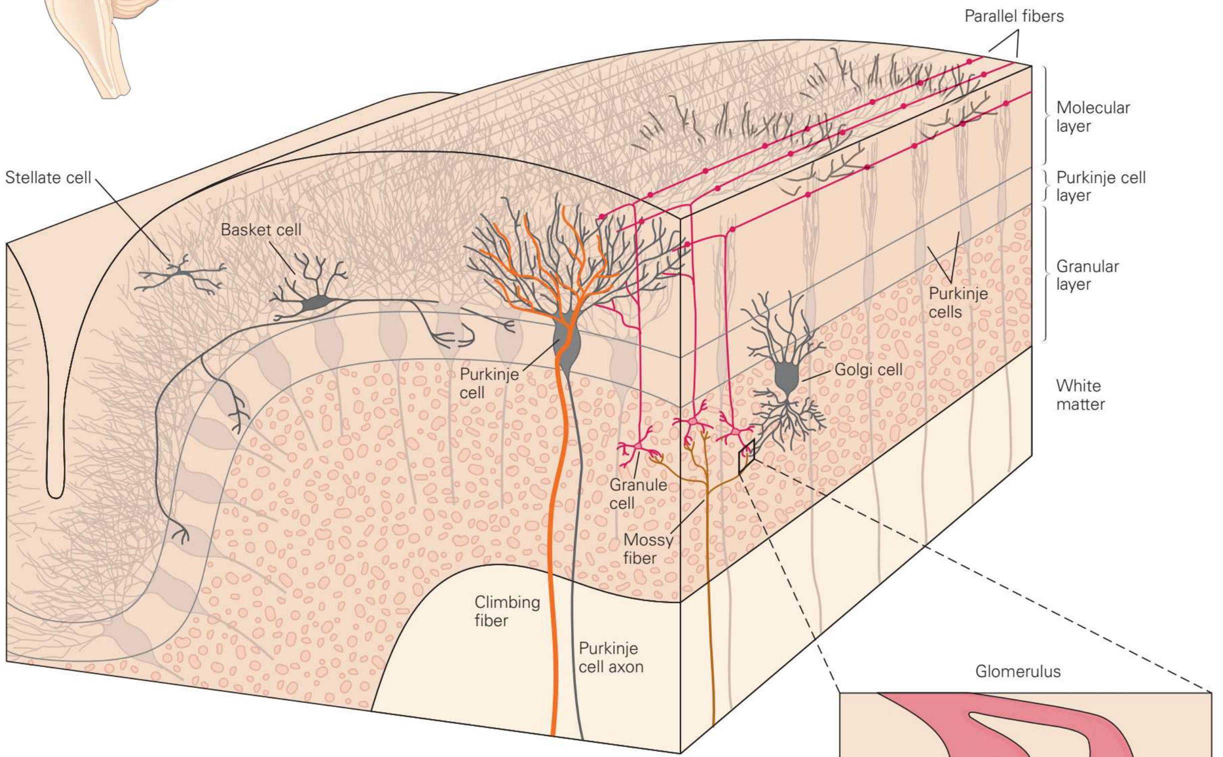


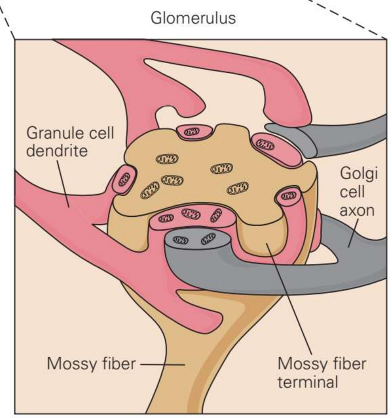


Bears et al. Figure 14-7

Kandel et al. Figure 42-4



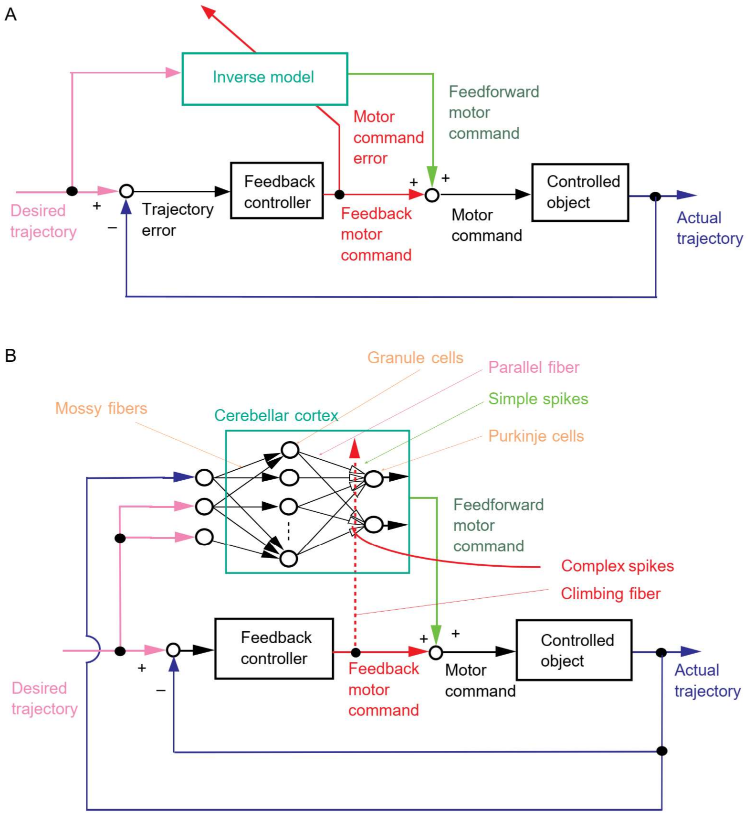




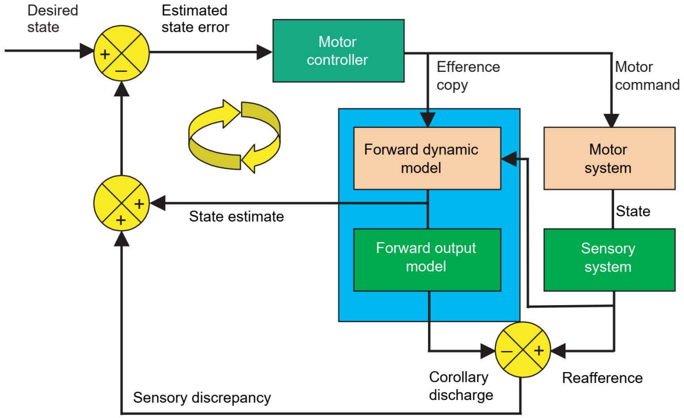
- Climbing fiber
- Purkinjie cell
- Mossy fiber
- Granule cell

Cerebellum - control model

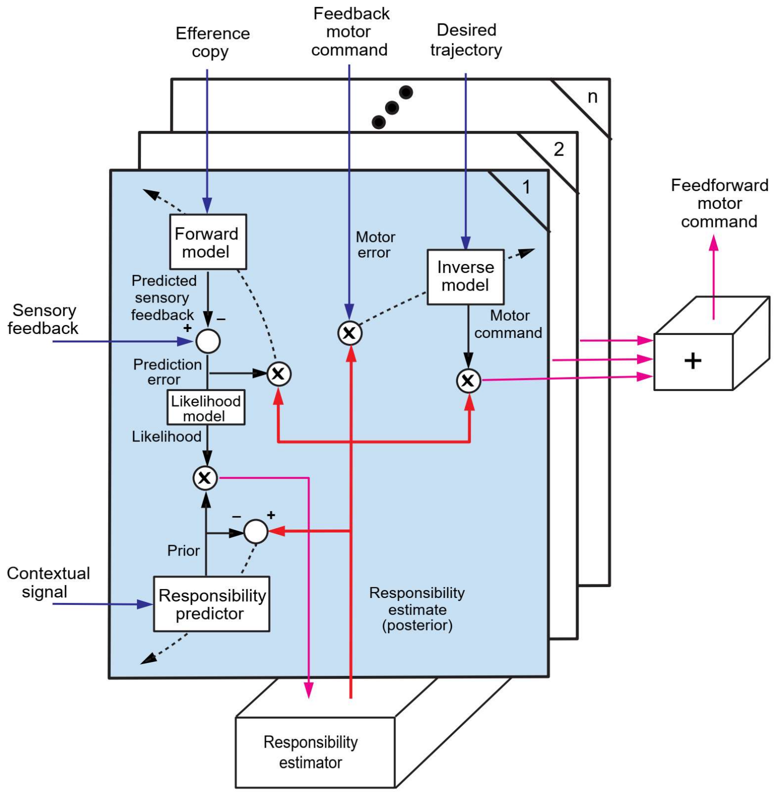
Inverse model (Feedback error-learning)



Forward model (Smith-predictor)

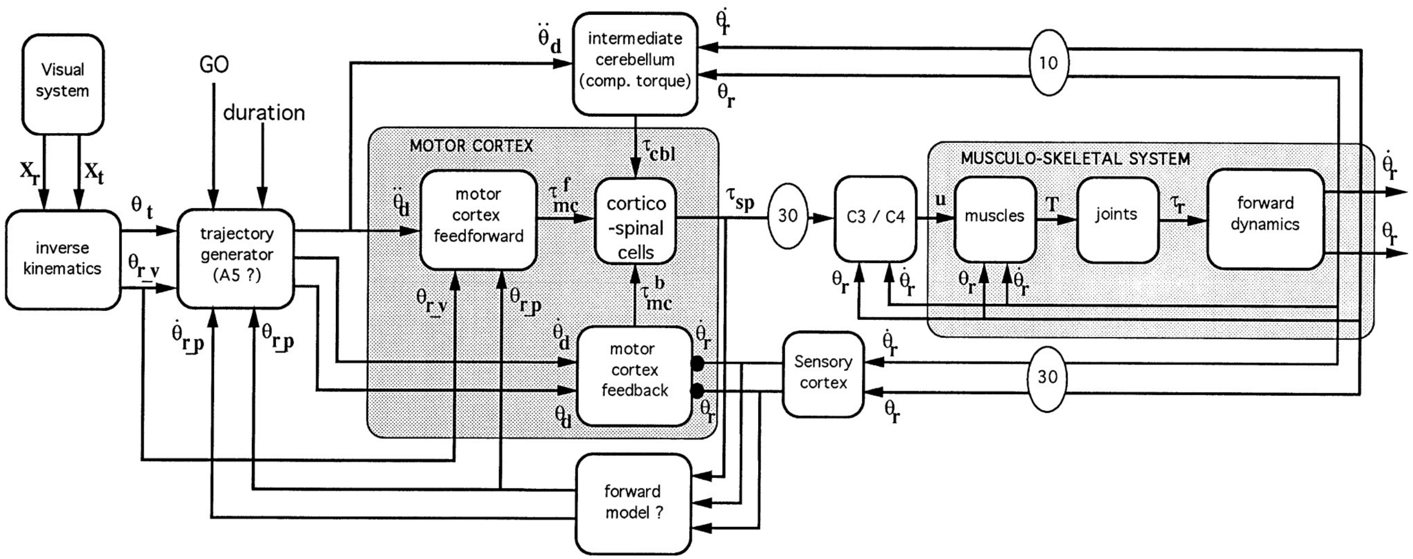


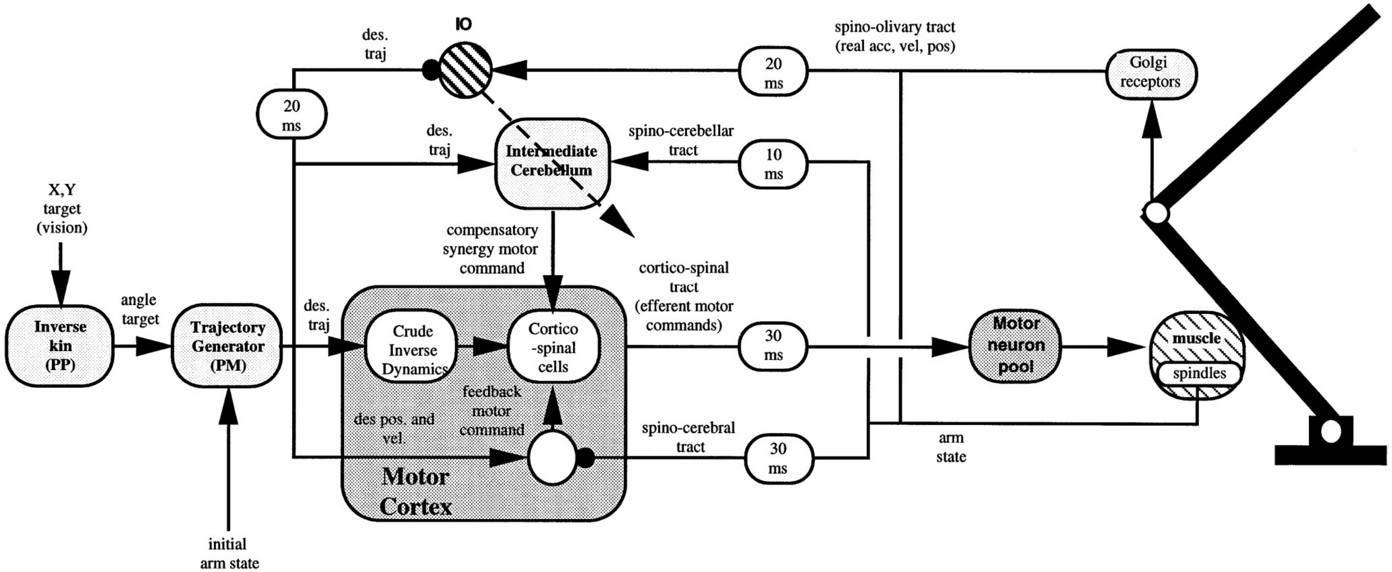
Multiple paired forward-inverse models



Wolpert et al. 1998

Cerebellar models for reaching movement

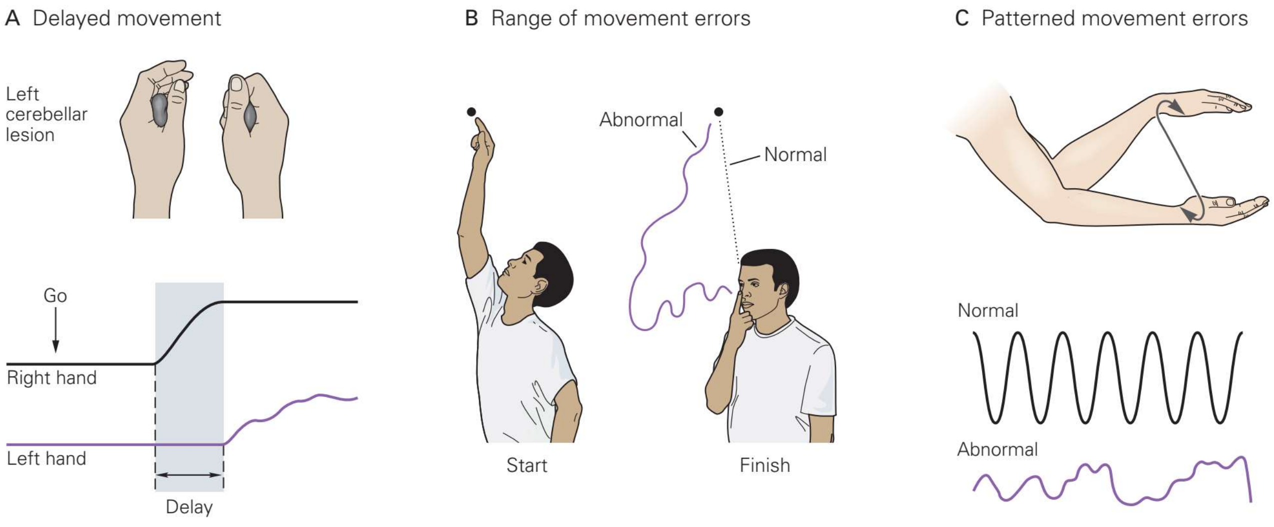


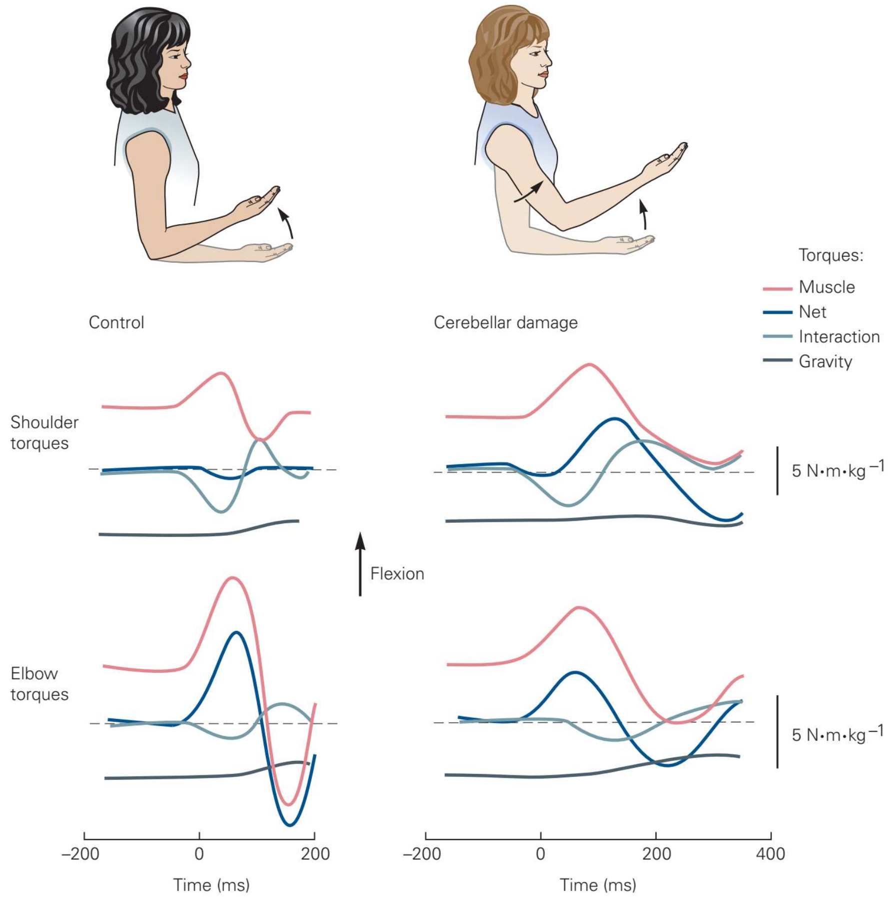


Schweighofer et al. 1998

Cerebellum: diseases

Deficits in coordination and timing

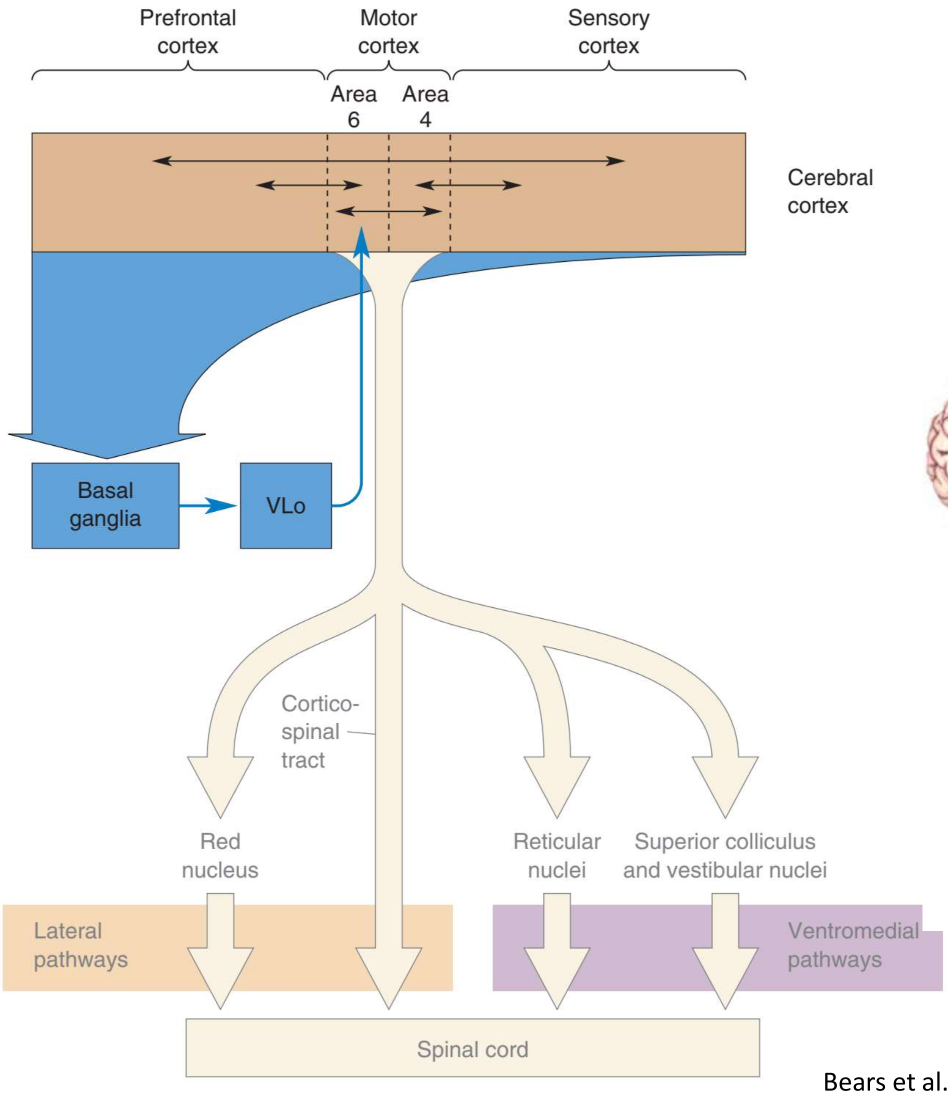




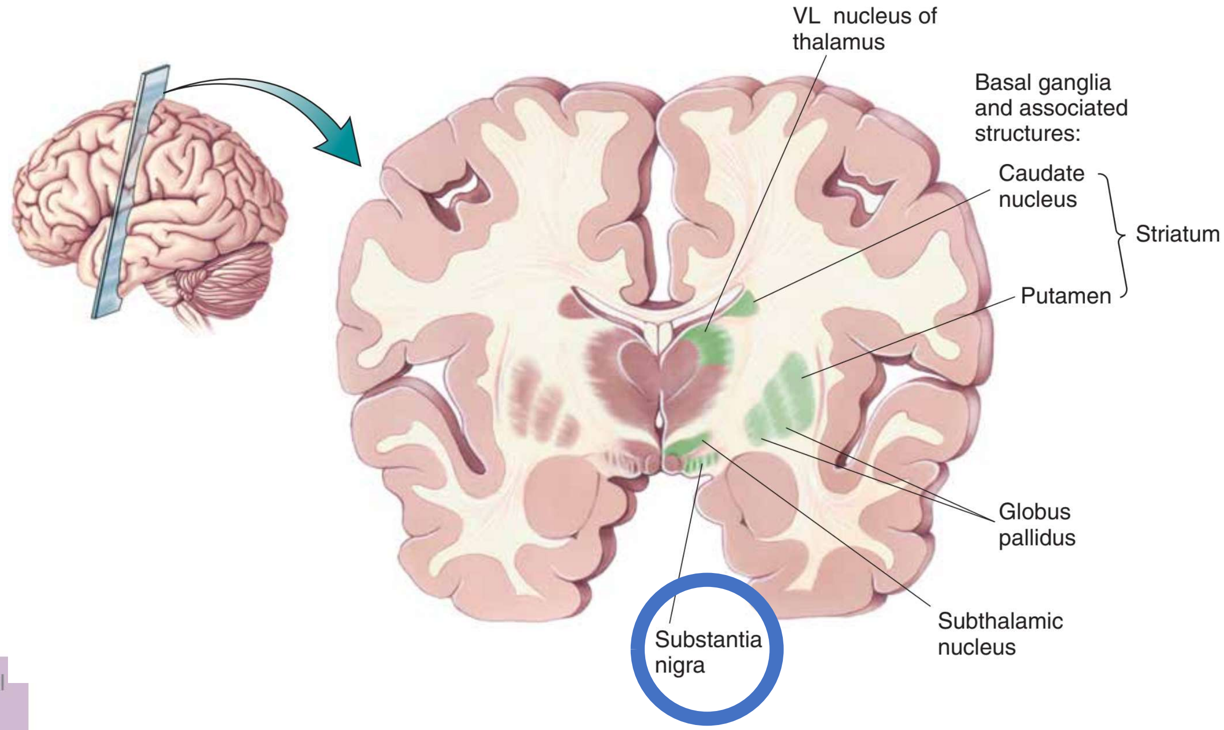
Kandel et al. Figure 42-1

Kandel et al. Figure 42-11

Basal ganglia: modulation of movement

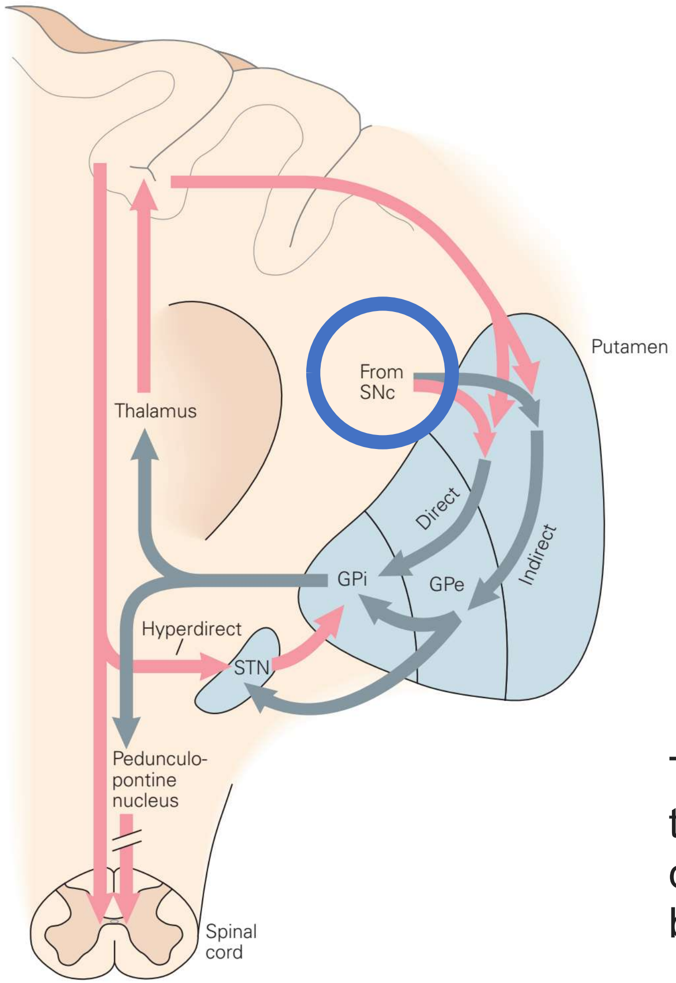


Bears et al. Figure 14-11



Bears et al. Figure 14-12

Basal ganglia: neural loop



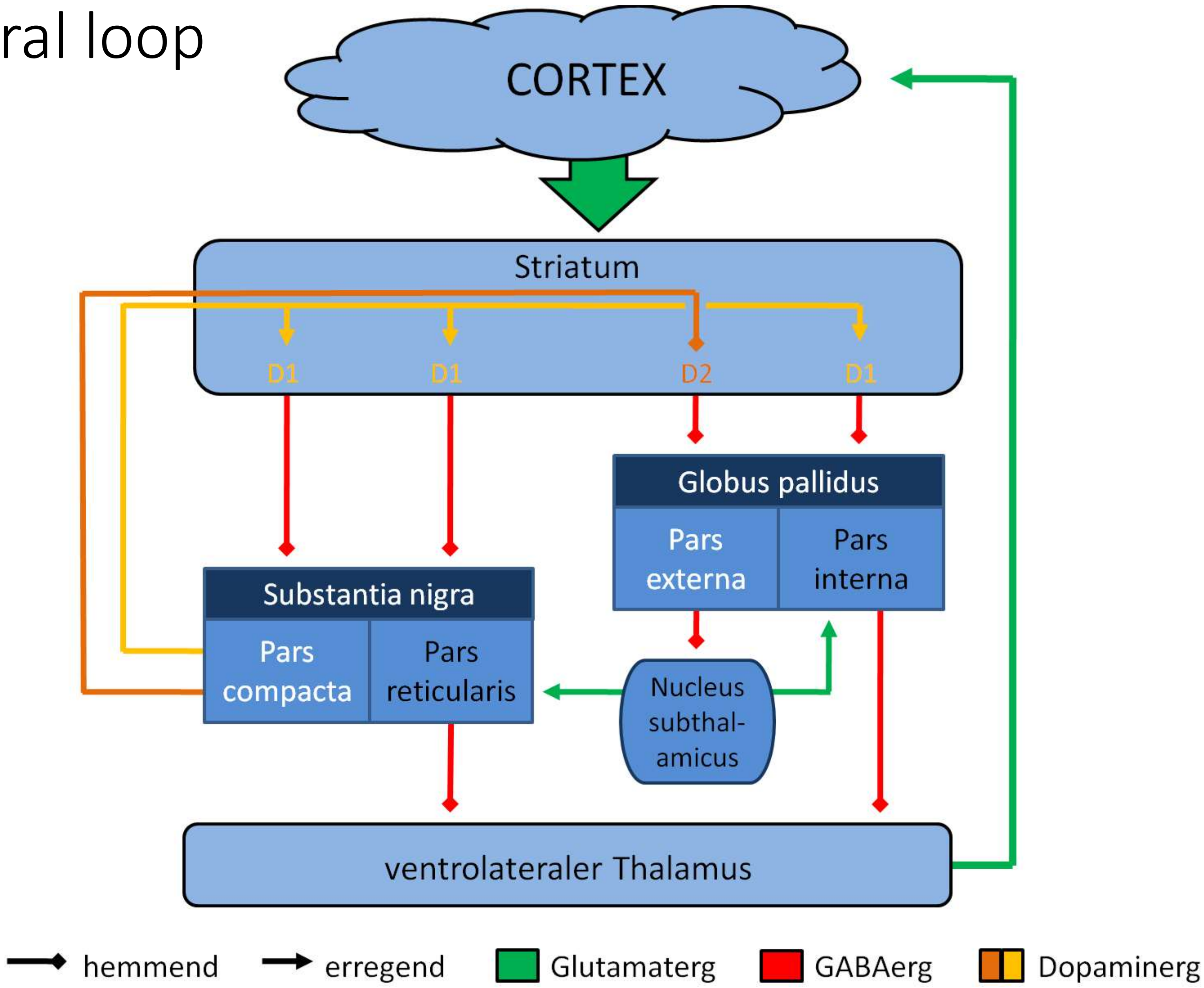
Kandel et al. Figure 43-2

The **substantia nigra** (SNc) is the source of the striatal input of the neurotransmitter dopamine, which plays an important role in basal ganglia function

Basal ganglia: neural loop

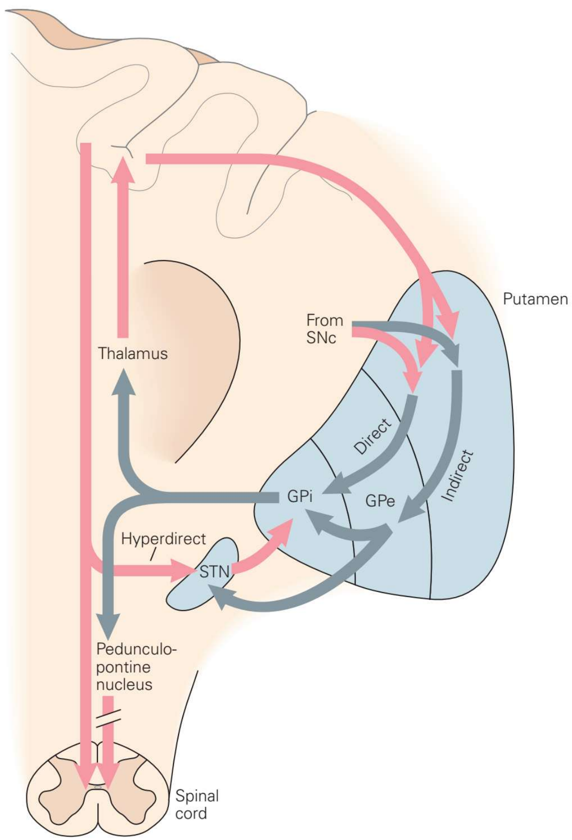
Neurotransmitters:
- Glutamate (+)
- GABA (-)
- Dopamine (+/-)

Dopamine receptor:
- D1 (+)
- D2 (-)

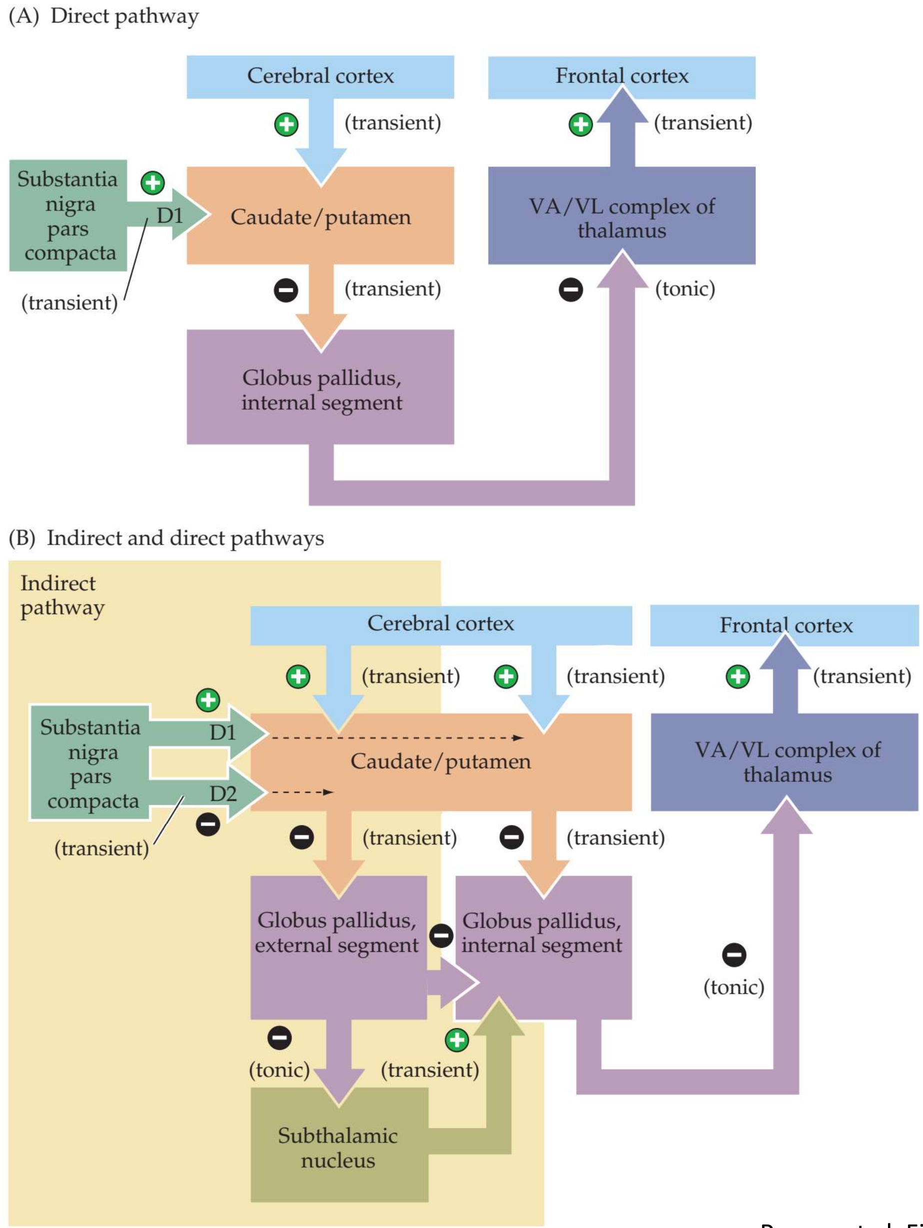


https://de.wikipedia.org/wiki/Basalganglien

Basal ganglia: neural loop



Kandel et al. Figure 43-2

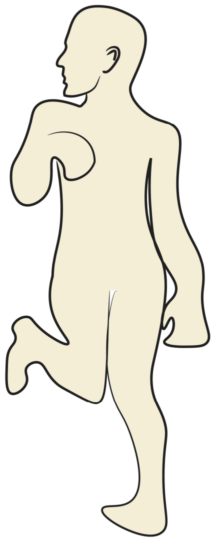


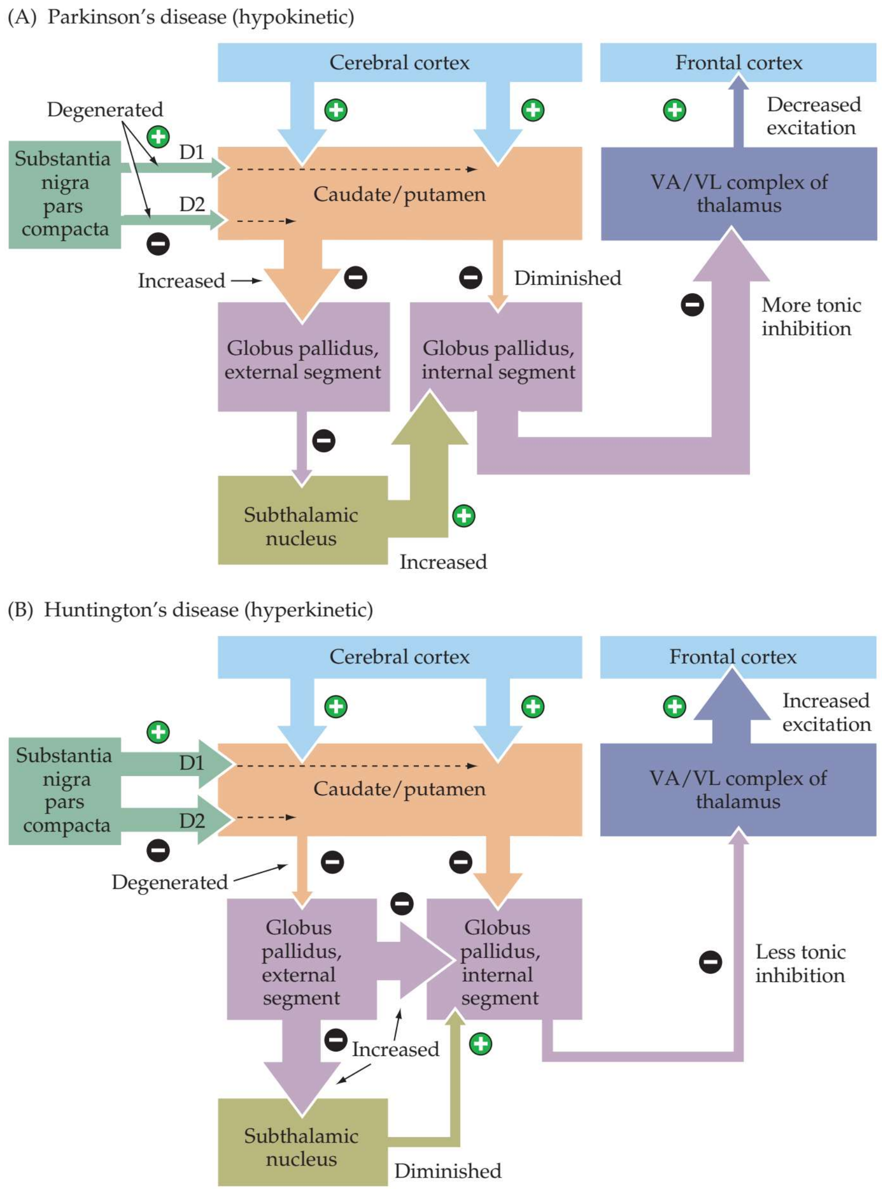
Purves et al. Figure 17-8

Basal ganglia: diseases

Parkinson‘s disease
- Resting tremor
- Rigidity/Freezing
- No tremor when moving
- Cause: loss of dopaminergic neurons
- Why such neurons die is unknown

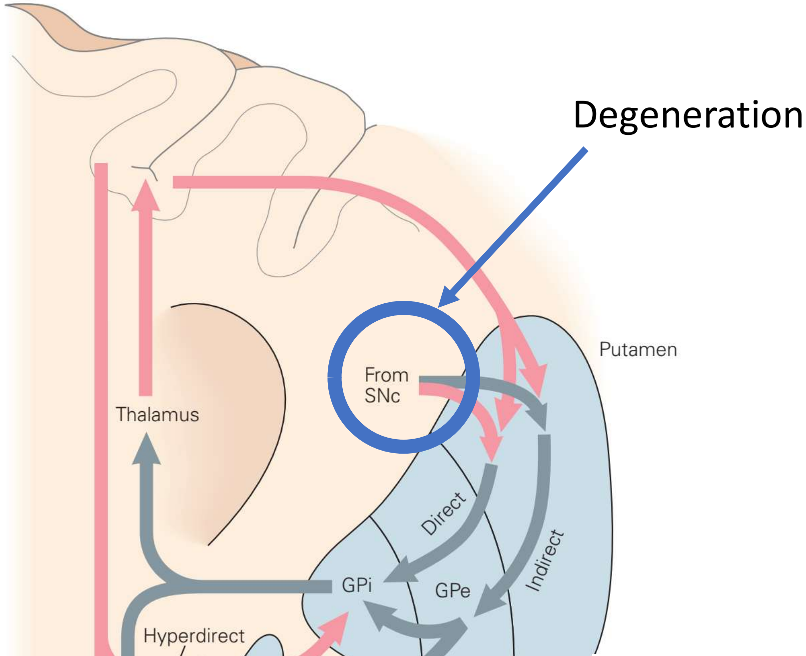
Huntington‘s disease
- Chorea (dance)
- Involuntary but coordinated
- Cause: gene mutation





Purves et al. Figure 17-10

Basal ganglia: Parkinson‘s disease



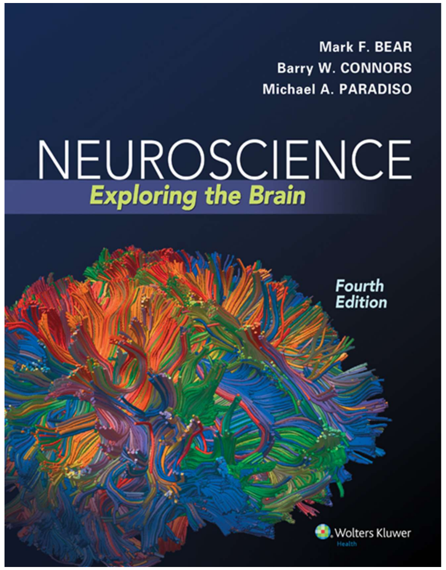
Video: Cycling for Freezing Gait in Parkinson's Disease. www.youtube.com

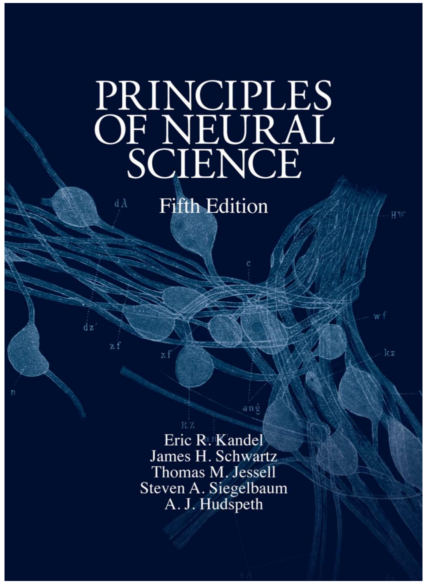
Summary: How the brain works in movement generation?

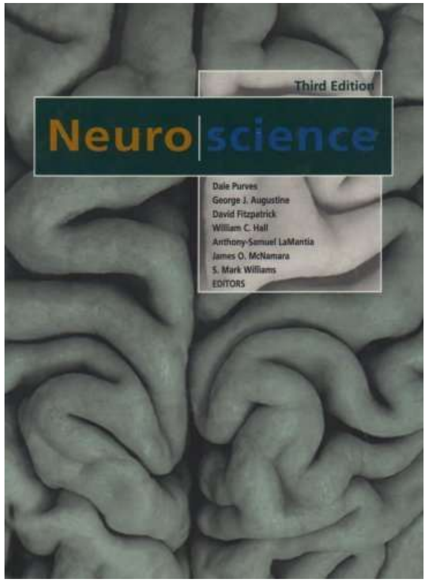
- **Motor cortex** involves in the planning, control, and execution of voluntary movements
- **Cerebellum** coordinates voluntary movements
- **Basal ganglia** strongly interconnects with several brain regions for movement production

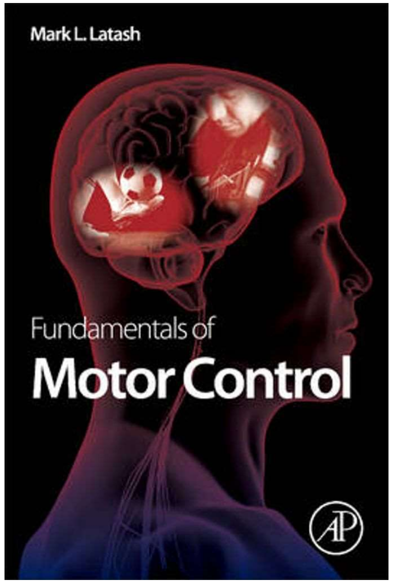
Conclusions (Take home message)

- Muscle forces are driven by descending activations and modulated by spinal reflex loops.
- Human movements have regular kinematic patterns.
- Several brain regions are directly involved in movement and interconnected. Deficits in those regions cause movement disorders.









Textbooks:

- [1] Bear et al. Neuroscience: Exploring the Brain, 4th Edition, 2016
- [2] Kandel et al. Principles of neural science, 5th Edition, 2013
- [3] Purves et al. Neuroscience. 3rd Edition, 2004
- [4] Latash. Fundamentals of motor control. 1st Edition, 2012