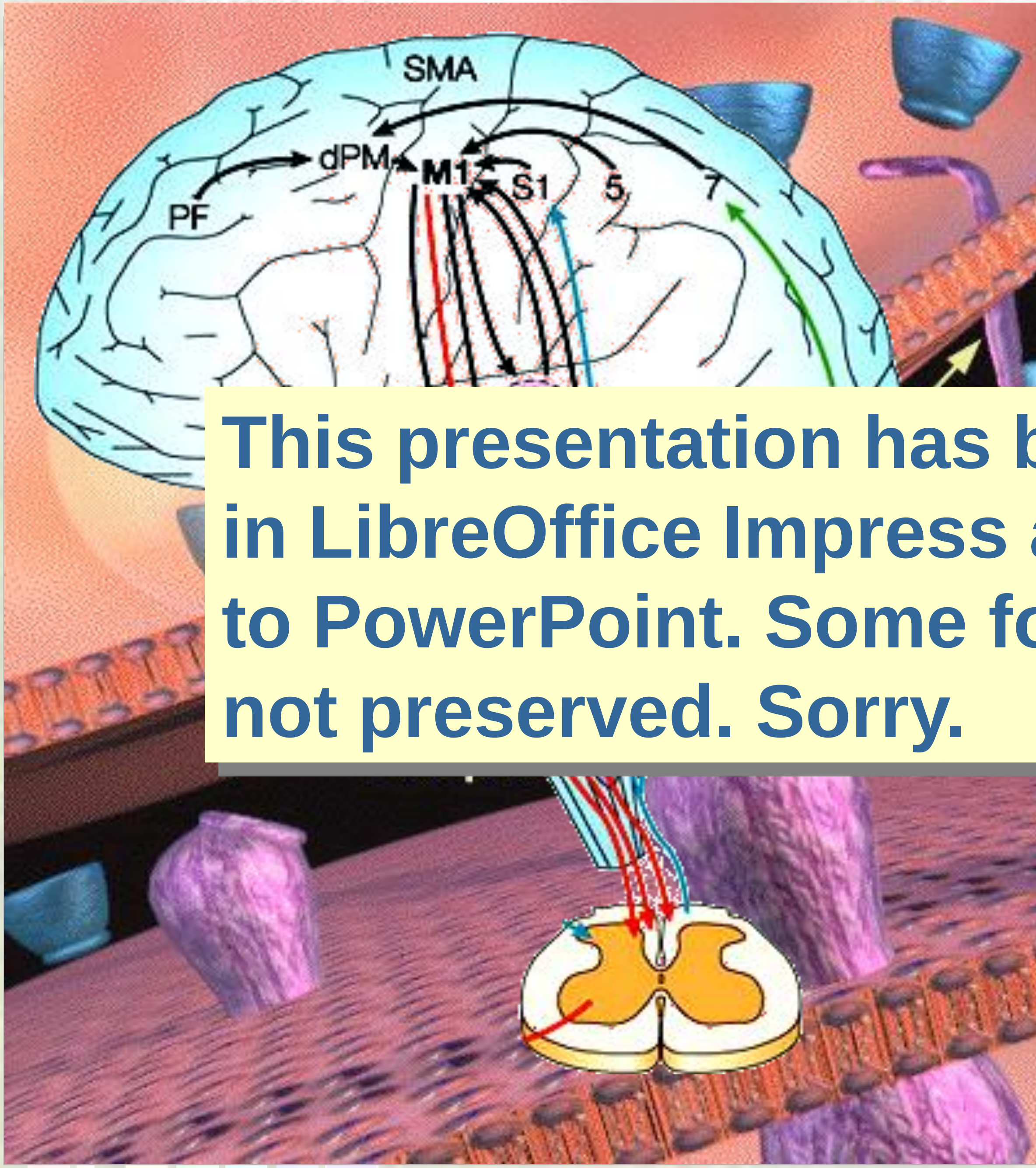
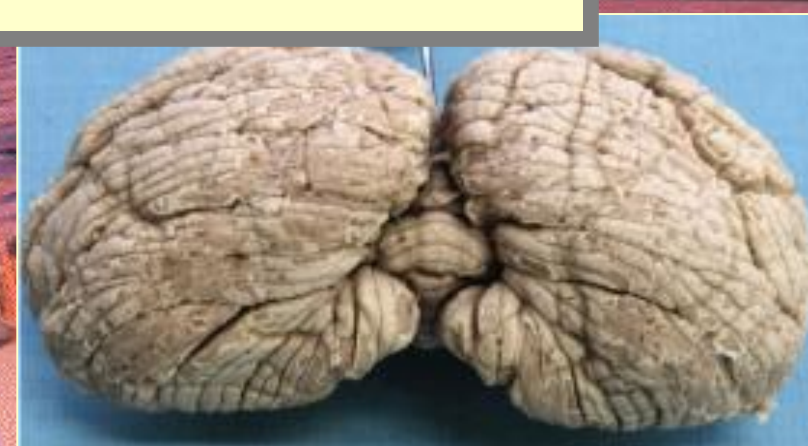
Motor control



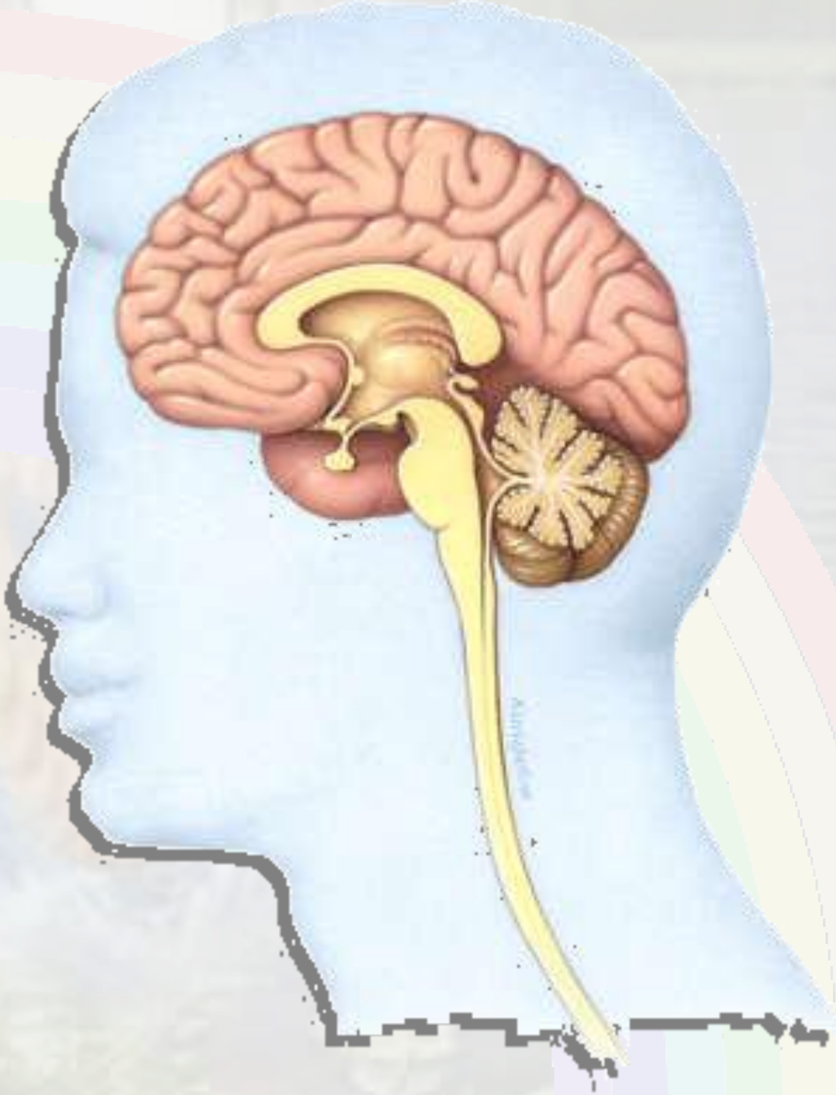


This presentation has been created in LibreOffice Impress and exported to PowerPoint. Some formatting was not preserved. Sorry.

Motor control

CNS parts that play role in motor control

- Cerebral cortex
- Basal ganglia
- Red nucleus
- Tectum
- Cerebellum
- Brainstem nuclei
- Descending tracts
- Spinal cord



Motor control by CNS

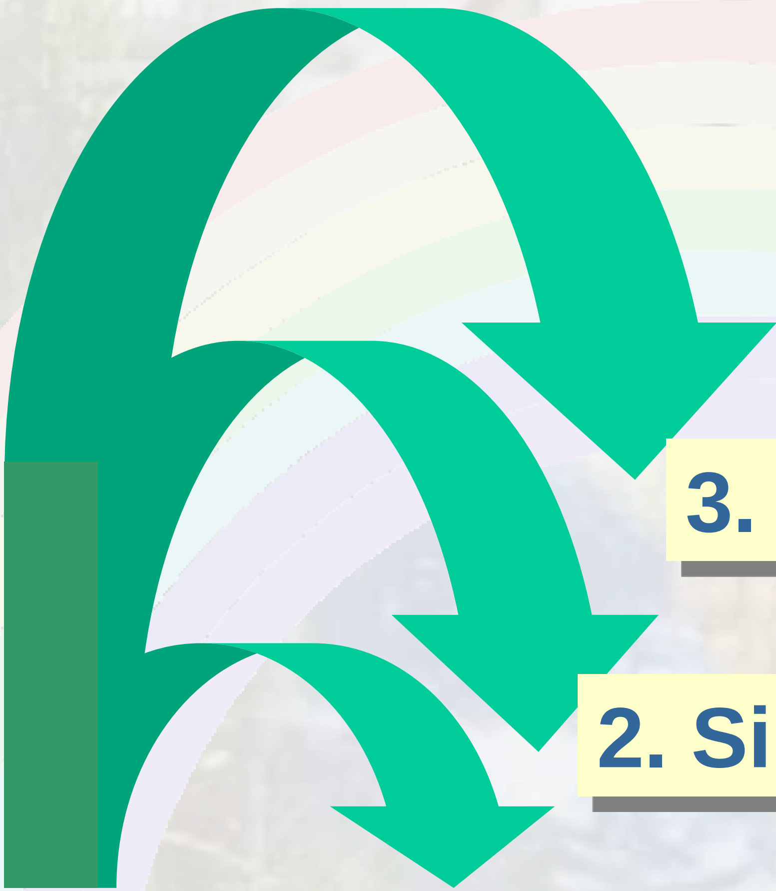
We will procede from:

- simple to complex
- fundamental to supplementary
- phylogenetically old to phylogenetically young

First 3 chapters – not fancy but true
Last 3 chapters – fascinating but speculative

Motor control

CNS design: stimululs - response



3. Cognition, behaviour

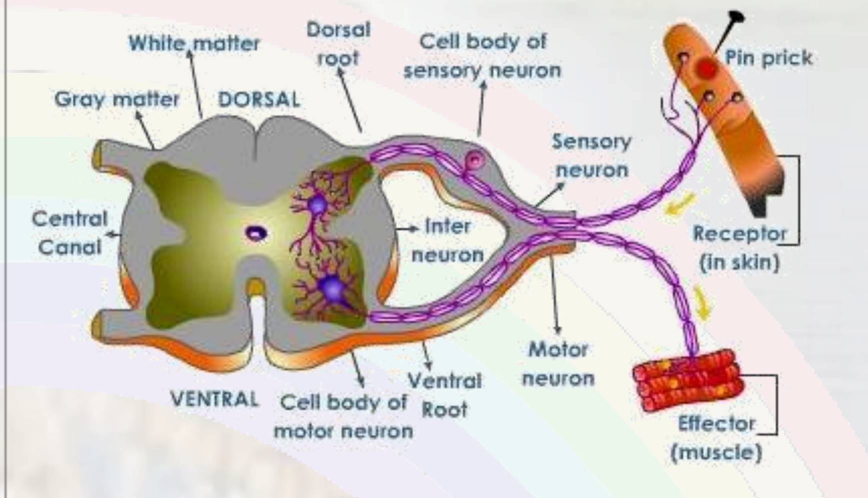
2. Simple movements

Stimulus

1. Simple reflexes

Motor control

1. Spinal reflexes



The Pathway for a Reflex Action - the Reflex Arc

Characteristics:

- automatic
- stereotyped
- always triggered by the same stimulus
- non-repetitive

1. Spinal reflexes

Summary - schematic

nothing is missing from here :-)

spinal cord

Simple reflexes **do not generate *behaviour*** that is typical for animals, such as locomotion and alimentary and copulatory acts.

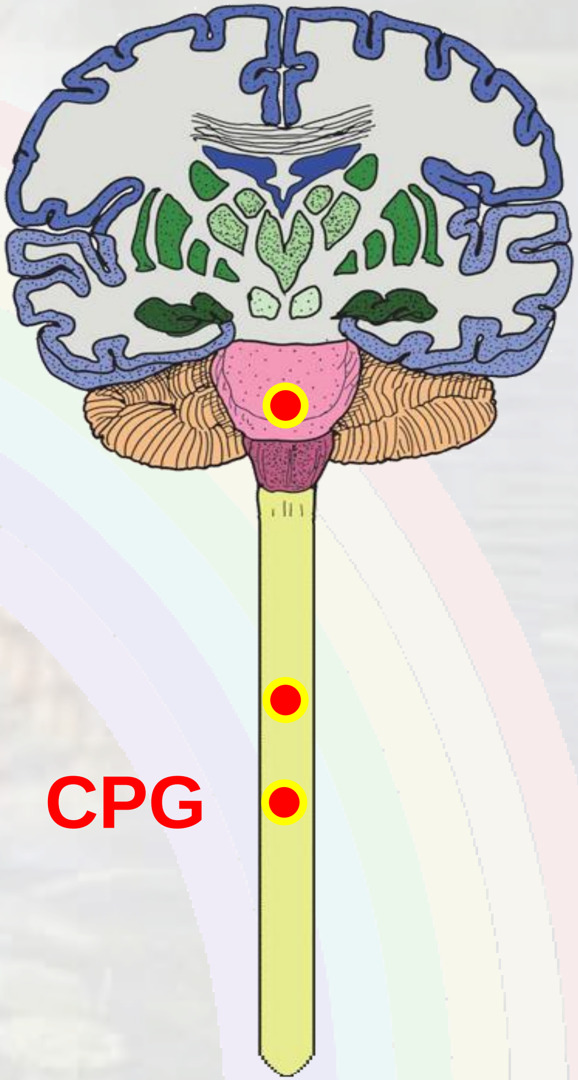
More complex neuronal networks are needed in which the activity that is correlated with movement is generated and lasts even in the absence of a stimulus.

2. Central pattern generators (CPG)

Examples: walking, running, swimming, scratching, breathing, chewing

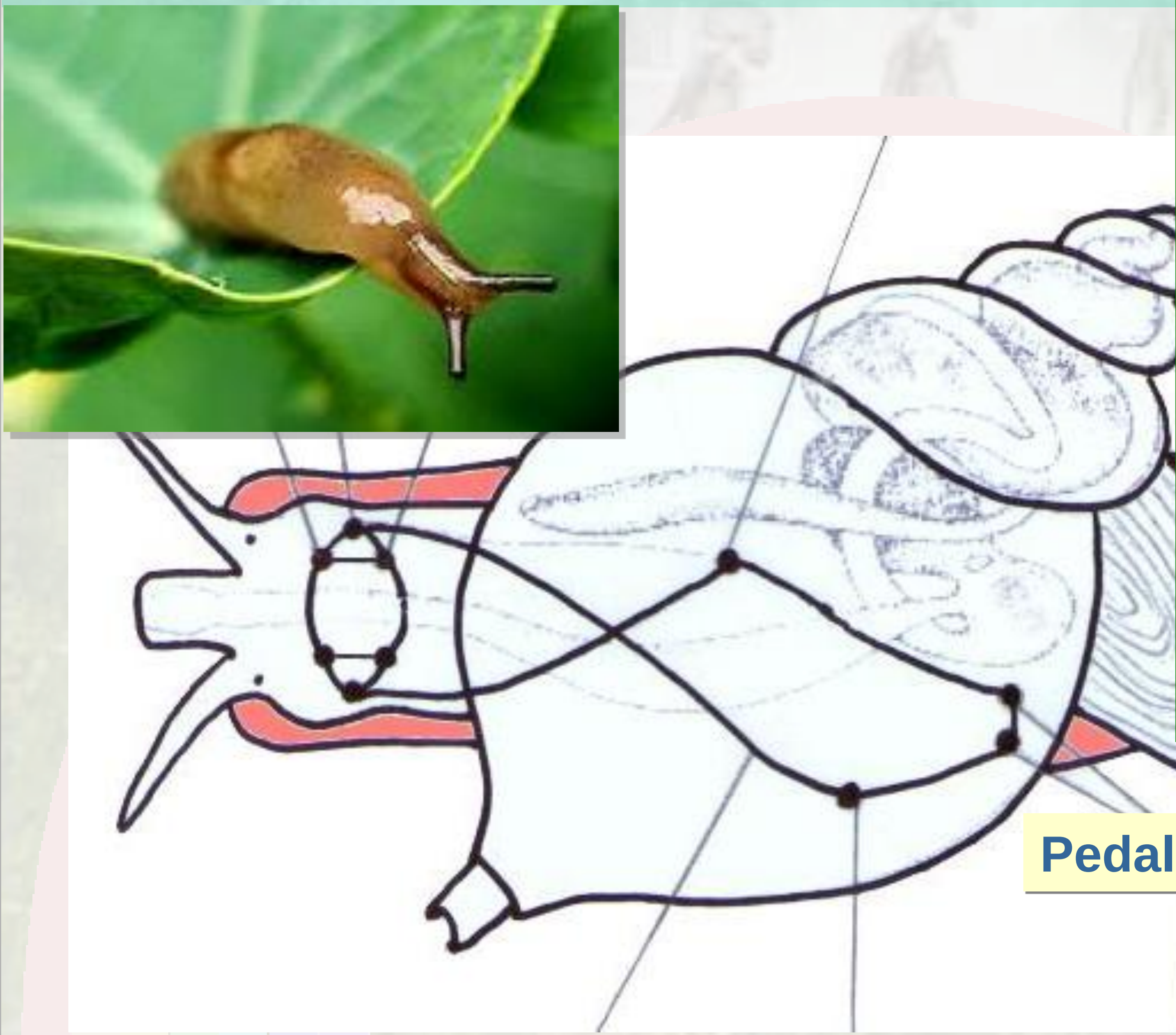
CPGs are:

- automatic
- stereotyped
- repetitive
- generated by individual neurones or by a network of neurones

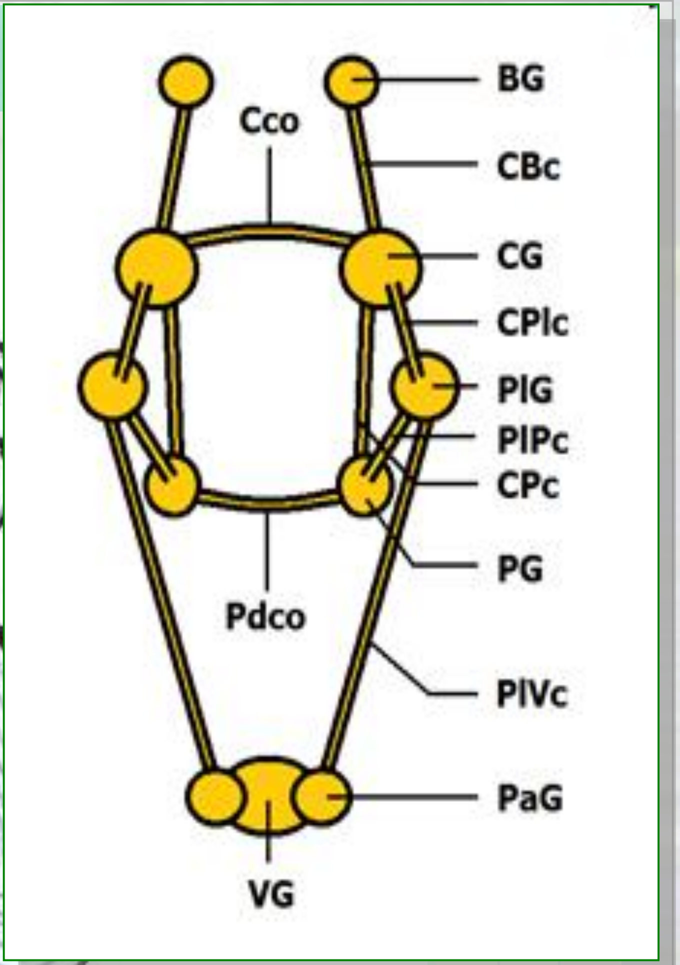


Motor control

Mollusks - no brain: Ganglia contain CPGs



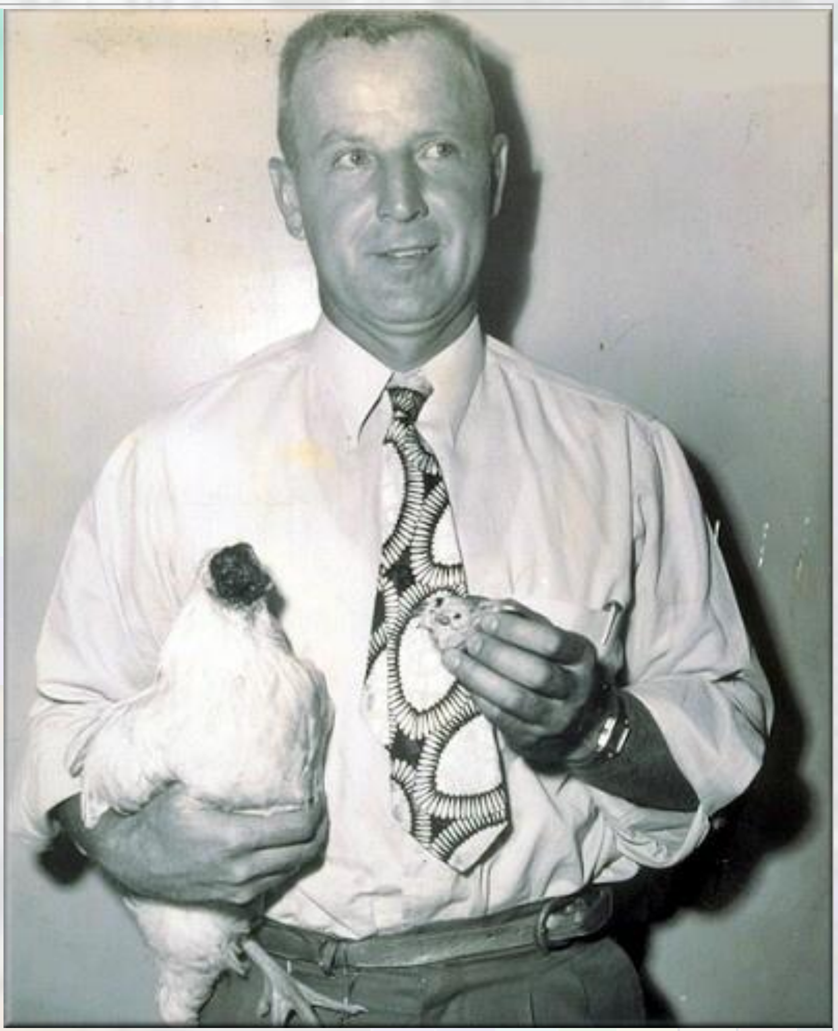
Pedal ganglion



Motor control

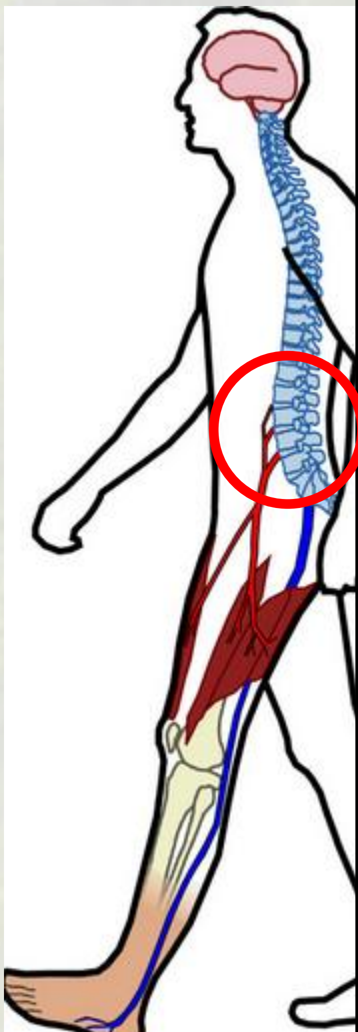
CPGs in decerebrated animals

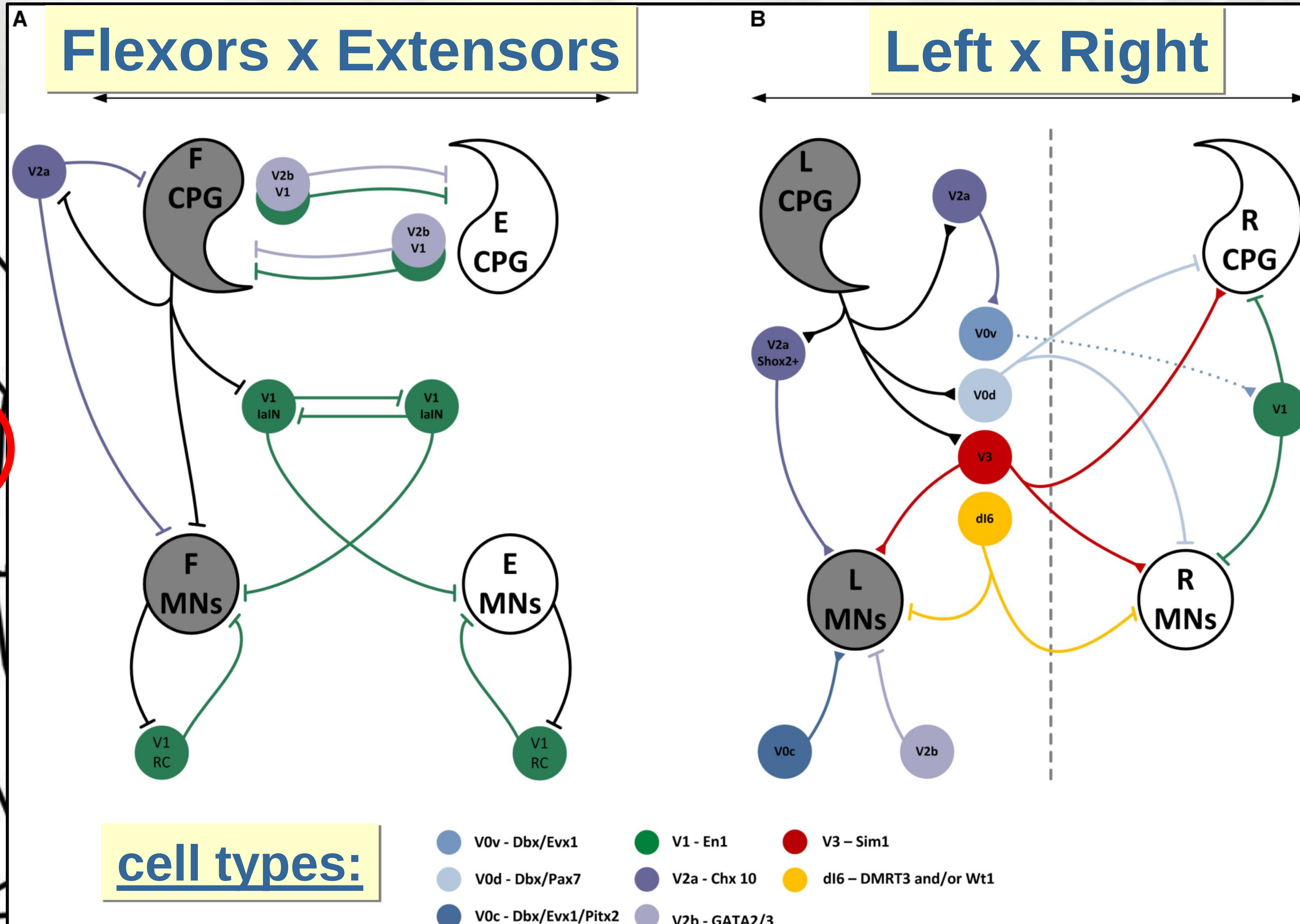
Reflexive movements and movements produced by CPGs are driven by local neural circuits and do not require control from higher centres. They are present even after the transection of neuraxis above their central pattern generators.



When an important part of the brainstem is spared, an animal can live without the head. Mike the rooster lived for 18 months.

CPGs in human locomotion (rhythm, muscles, sides)





Motor control

2. Central pattern generators

Summary - schematic

spinal cord

The CPGs are local networks that control a limited range of skeletal muscles. Some of them are triggered by a stimulus and then maintain their activity for a limited period of time, some are active all the time (e.g., the respiratory centre).

Together with simple reflexes, the CPGs are sufficient to support vital functions of primitive organisms or simple decerebrate vertebrates.

3. Extrapyramidal system

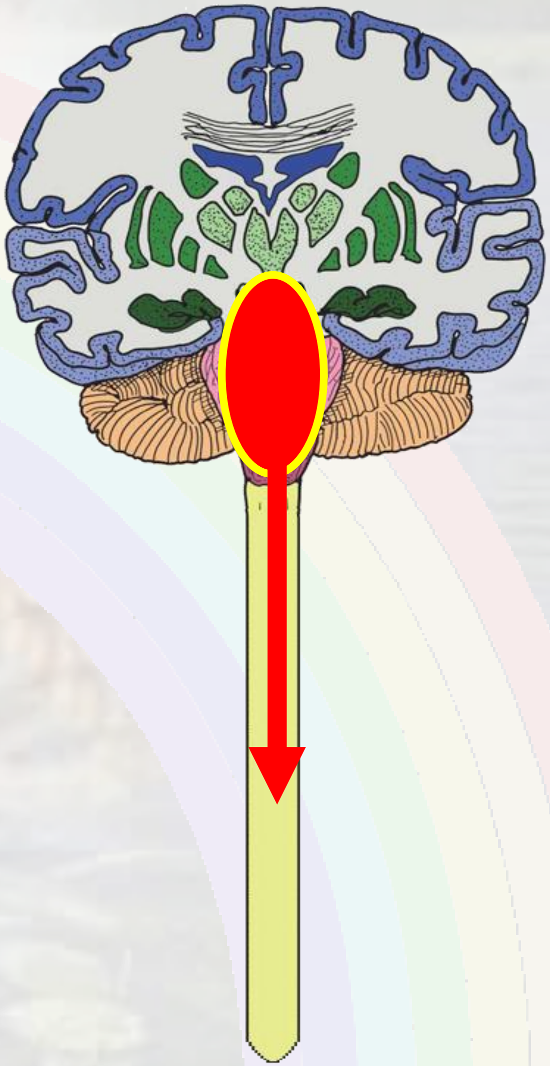
Rubrospinal tract
contralateral α and γ motoneurones

Tectospinal tract
contralateral α and γ motoneurones

Reticulospinal tract - pontine
ipsilateral γ motoneurones

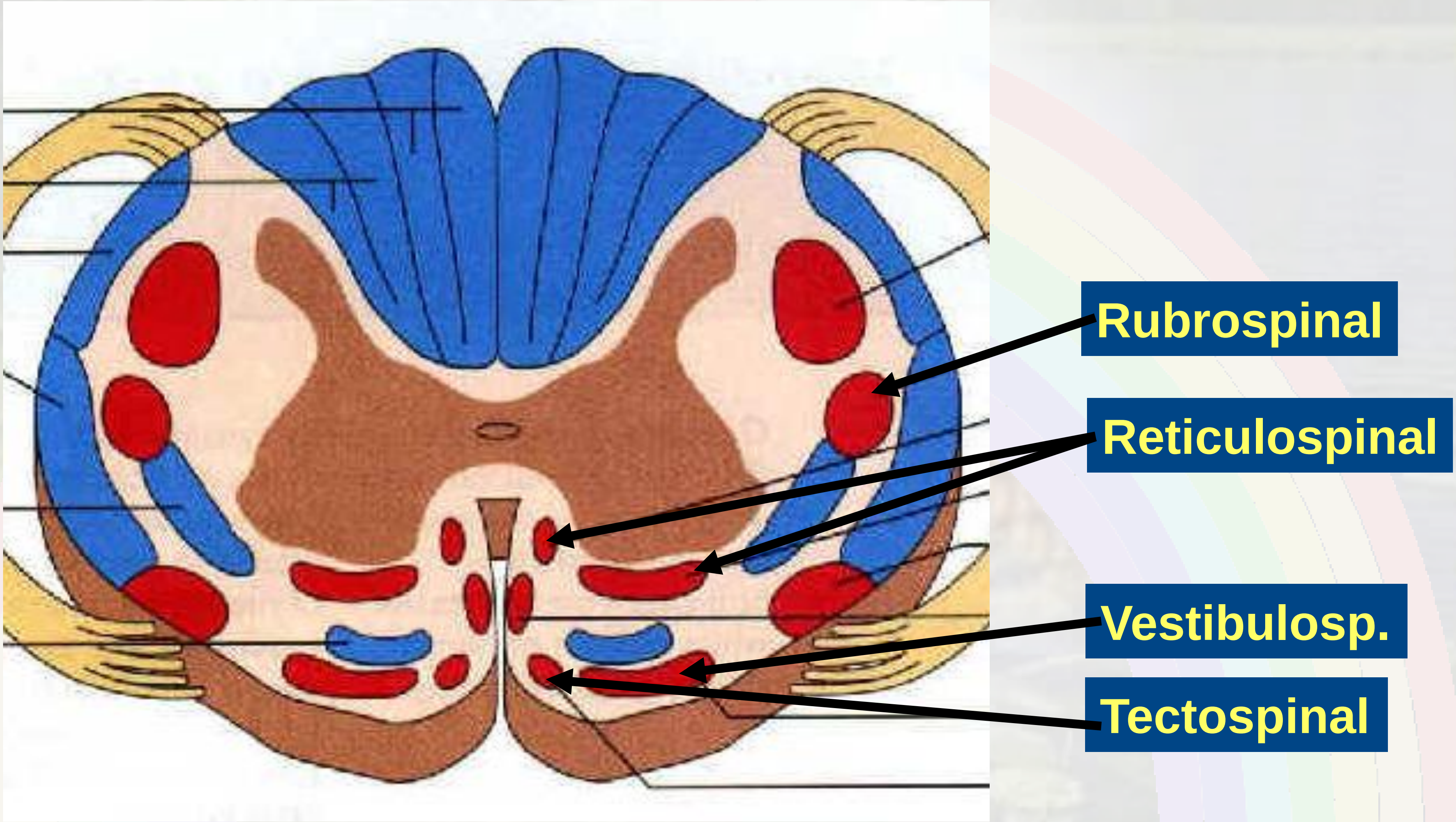
Reticulospinal tract - medullary
bilateral α and γ motoneurones

Vestibulospinal tract
ipsilateral α and γ motoneurones

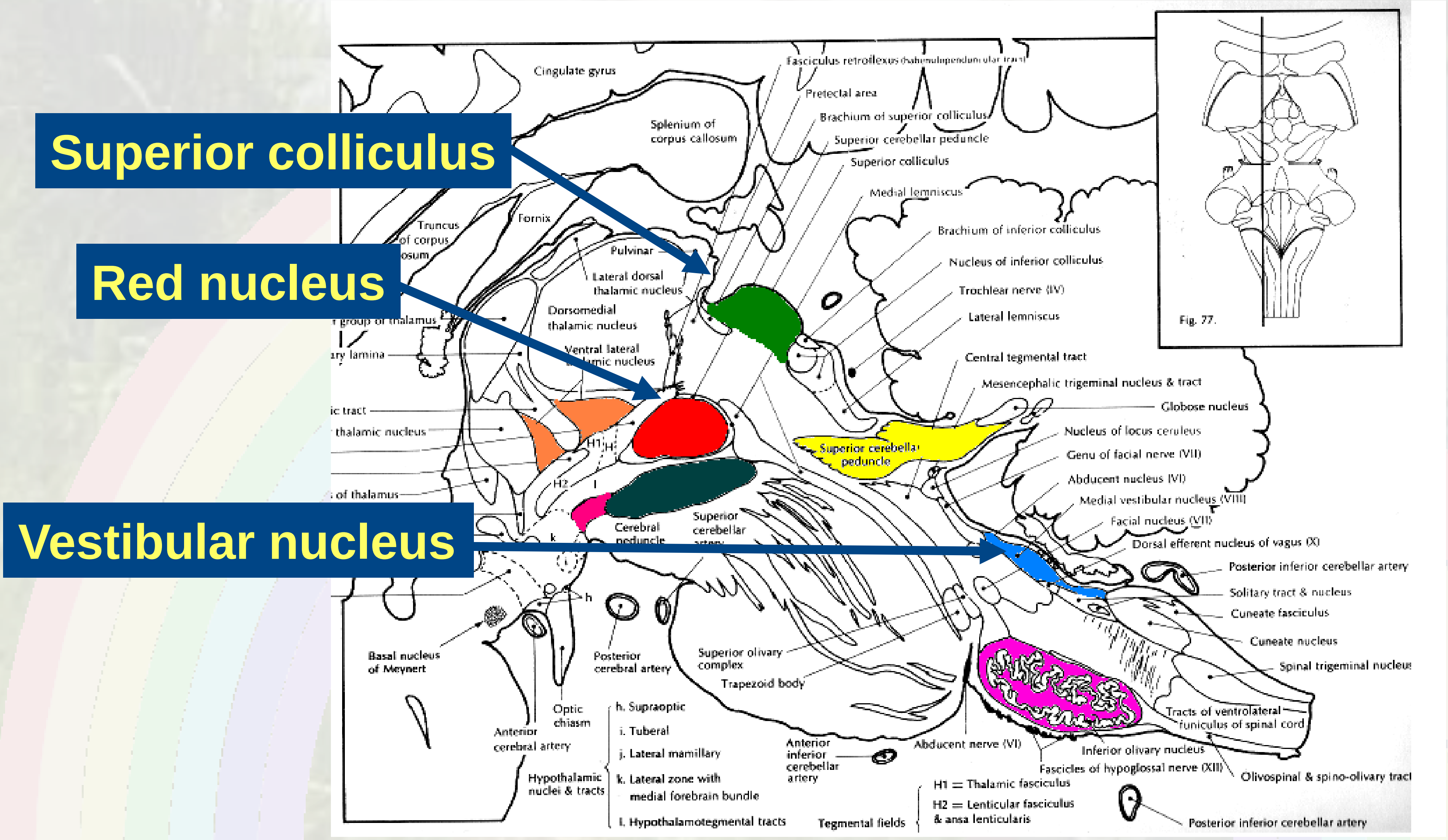


Motor control

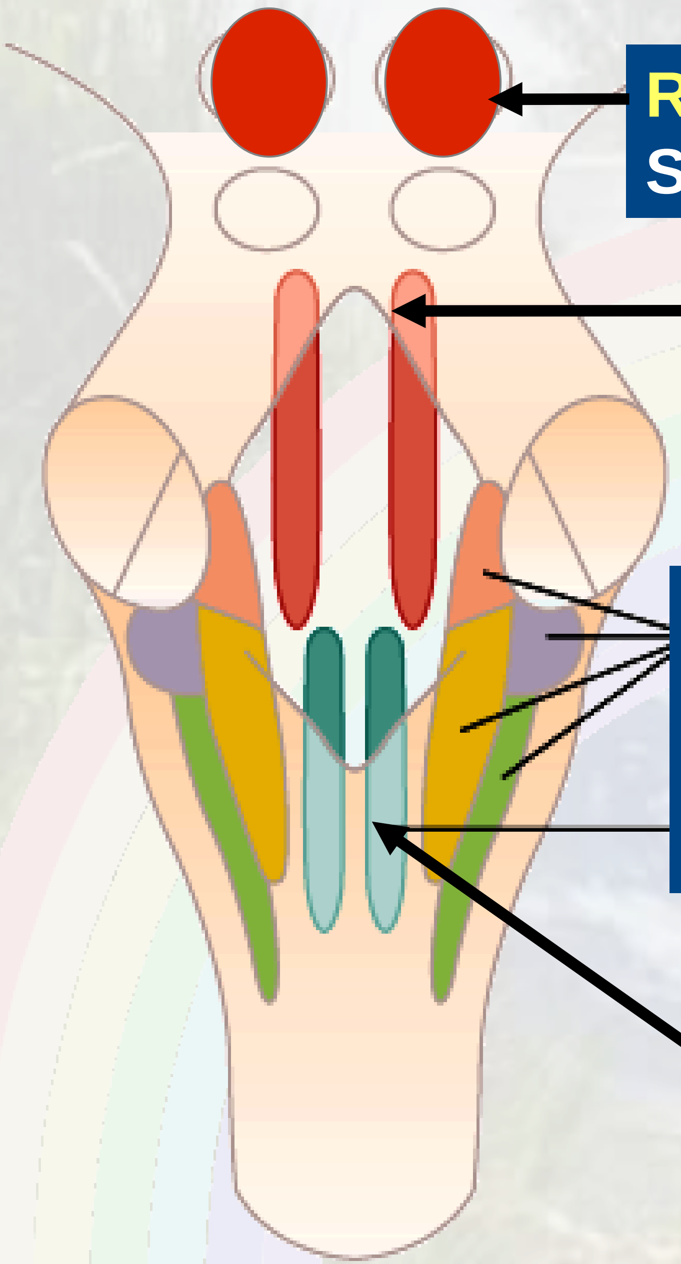
3. Extrapyramidal system - Tracts



3. Extrapyramidal system - origin



Motor control



Red nucleus – Rubrospinal tract
Stimulates upper limb flexors

Pontine reticular nucleus
- medial reticulospinal tract
Stimulates antigravity muscles

Vestibular nuclei – vestibulospinal tr.
Coordinate eye and head movements, gait, and balance.
Stimulate antigravity muscles

Medullary reticular nucleus
- lateral reticulospinal tract
Inhibits antigravity muscles

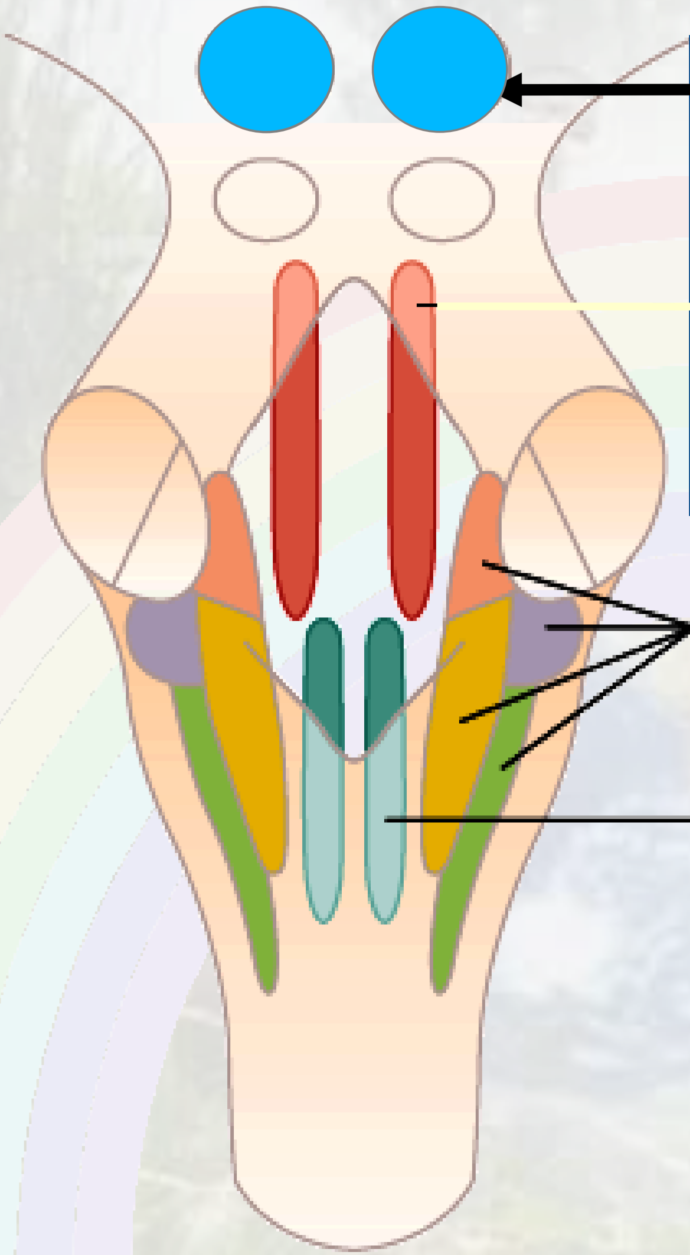
Motor control

Rubrospinal tract

The rubrospinal tract, which is phylogenetically younger than other extrapyramidal pathways, plays a greater role in animals than humans.

In humans, the motor control via the rubrospinal tract is present in newborns. As the motor cortex matures (= reduction of layer IV), the emphasis shifts from the red nucleus to the motor cortex.

Motor control

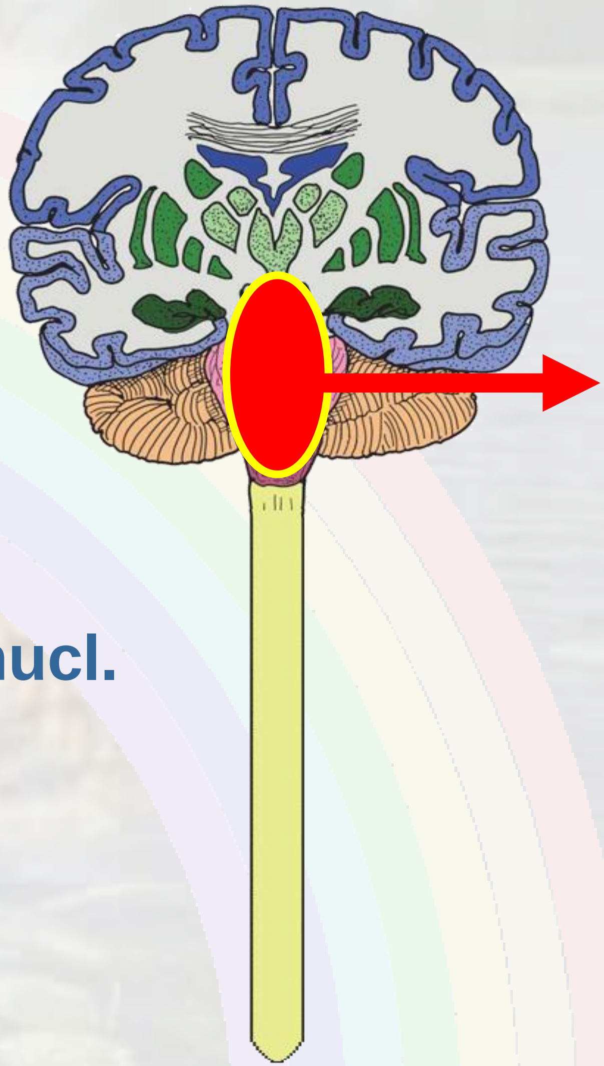


Superior colliculus
- tectospinal tract

Reflex movements of the head and eyes as part of an orienting response

3a. Cranial nerves – motor part

III Oculomotor – oculomotor nucleus
M. levator palpebrae,
M. recturs superior, medialis & inferior



IV Trochlear – contralat. trochlear nucleus
M. obliquus bulbi superior

V Trigeminal (mandib.) - motor trigeminal nucl.
Mastication muscles

VI Abducens – nucleus abducens
M. rectus bulbi lateralis

Motor control

3b. Cranial nerves – motor part

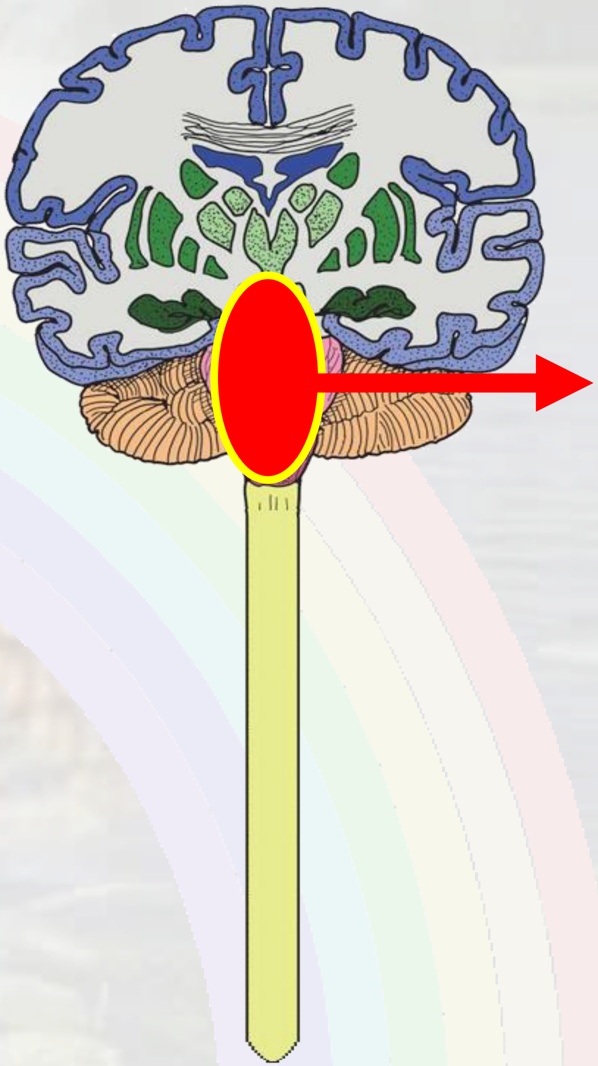
VII Facial – facial nerve nucleus
Muscles of the face

IX Glossopharyngeal – nucleus ambiguus
Stylopharyngeus muscle

X Vagus – nucleus ambiguus
Muscles of the larynx and pharynx

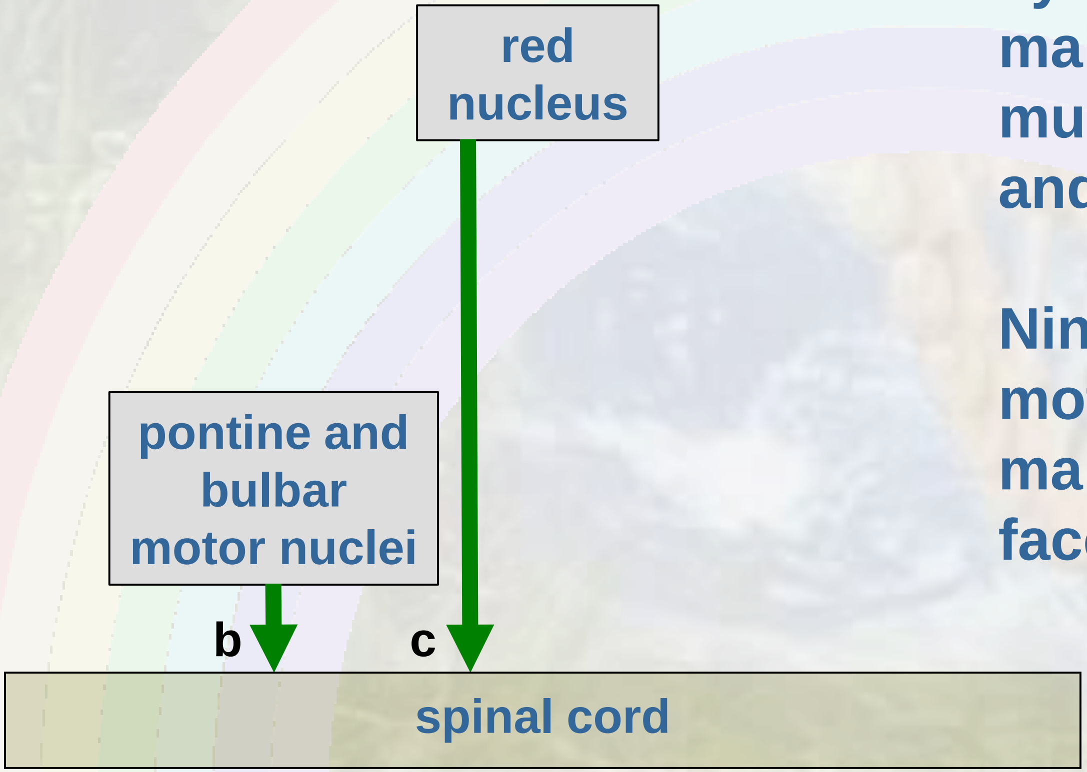
XI Abducens – spinal accessory nucleus
Sternocleidomastoid and trapezius muscle

XII Hypoglossal – hypoglossal nucleus
Muscles of the tongue



3. Extrapyramidal system

Summary - schematic



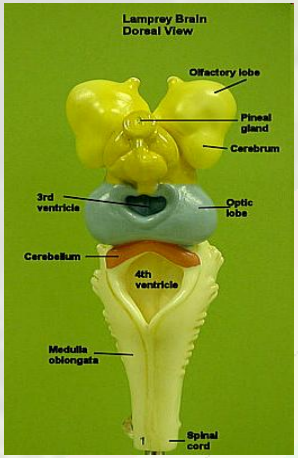
Spinal motor tracts belonging to the so-called extrapyramidal system control most muscles, mainly to maintain optimum muscle tone, posture, balance, and orienting towards stimuli.

Nine cranial nerves have a motor component that controls mainly the muscles of the eyes, face, and mouth.

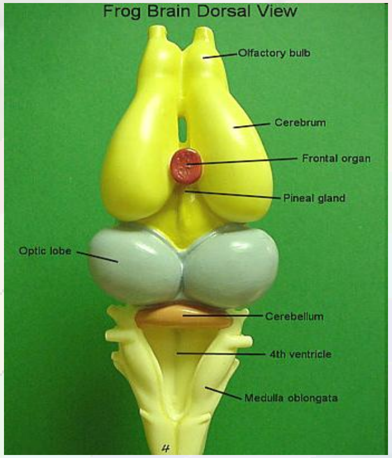
Motor control

4. Cerebellum (brown in the models)

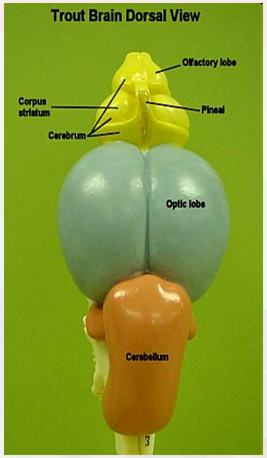
Lamprey



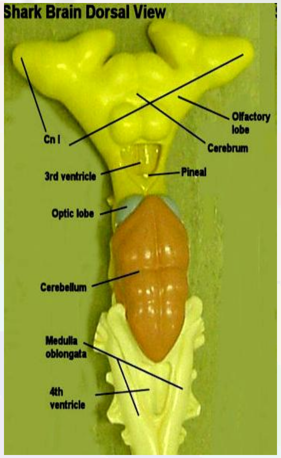
Frog



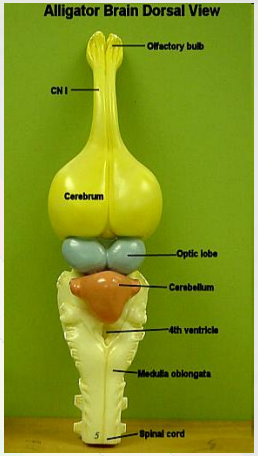
Trout



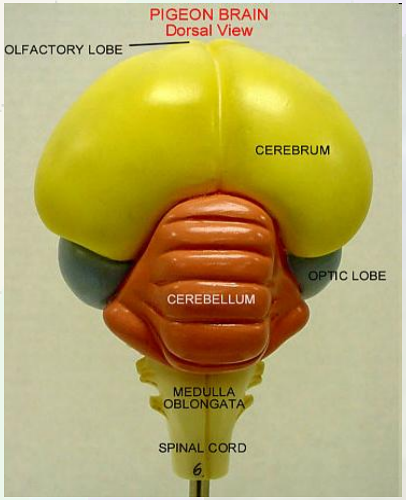
Shark



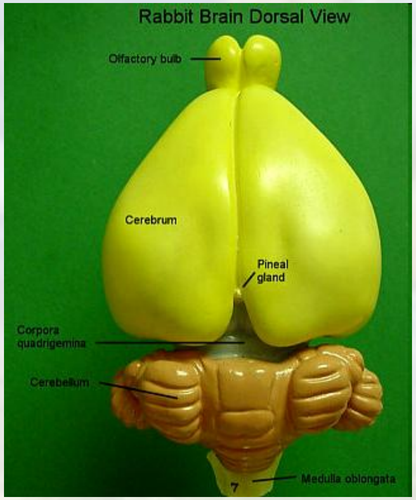
Crocodile



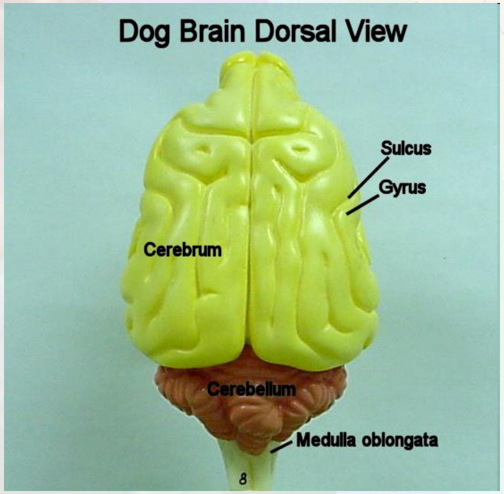
Pigeon



Rabbit

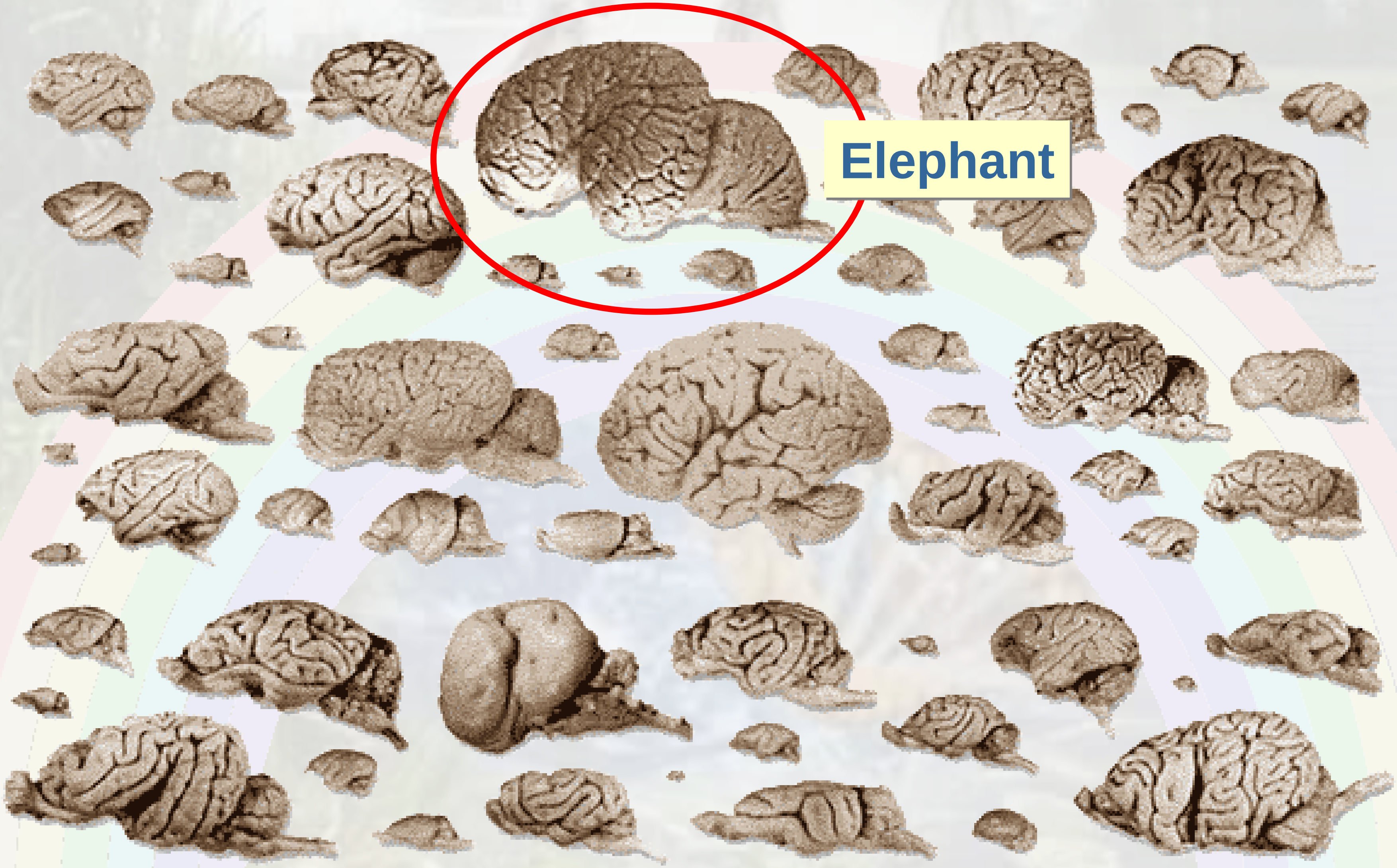


Dog



Motor control

4. Cerebellum (~ movement complexity)



Motor control

See why elephants have a large trunk. Oops, cerebellum!

video link

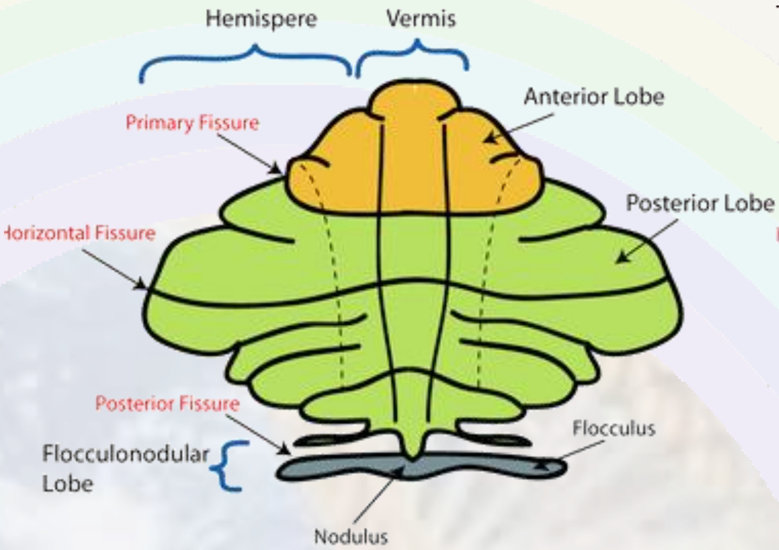
https://www.youtube.com/watch?v=owSZs7H24UY

4. Cerebellum – the structure of 'three'

ped. cerebellaris medius
ped. cerebellaris inferior
ped. cerebellaris superior

Cerebrocerebellum
Spinocerebellum
Vestibulocerebellum

Neocerebellum
Paleocerebellum
Archicerebellum



Vermis
Floculus
Nodulus

stratum moleculare
stratum gangliosum
stratum granulosum

nc. dentatus
nc. emboliformis
nc. fastigii

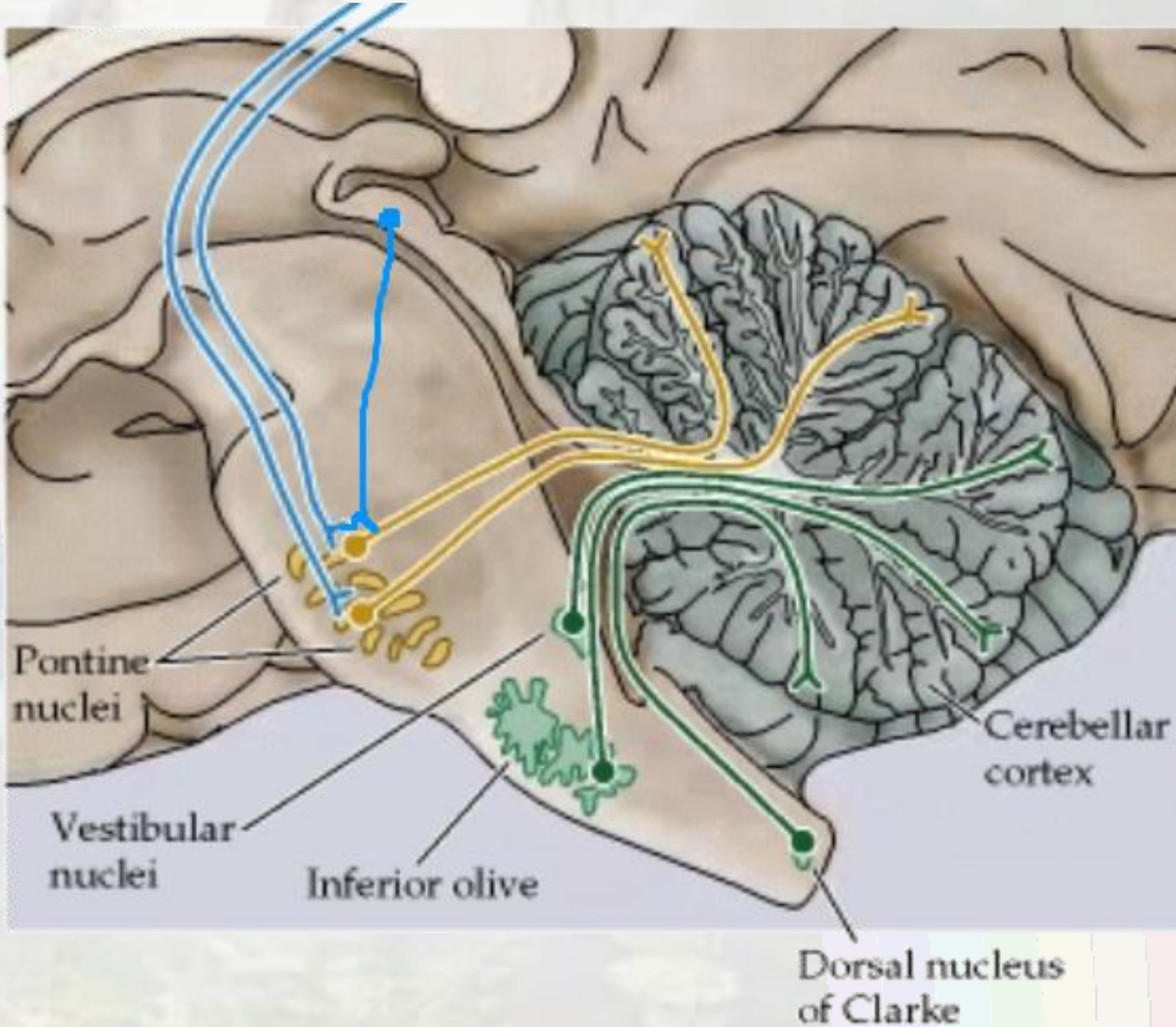
coordination
muscle tone
balance

Motor control

4. Cerebellum – afferents

Input via the medial cerebellar peduncle:
pontine nuclei (have *neocortical* and *tectal* afferents). Send 2 x 20 million axons!

Inputs via the inferior cerebellar peduncle from:
nc. olivaris inferior
tr. spinocerebellaris
ncc. vestibulares



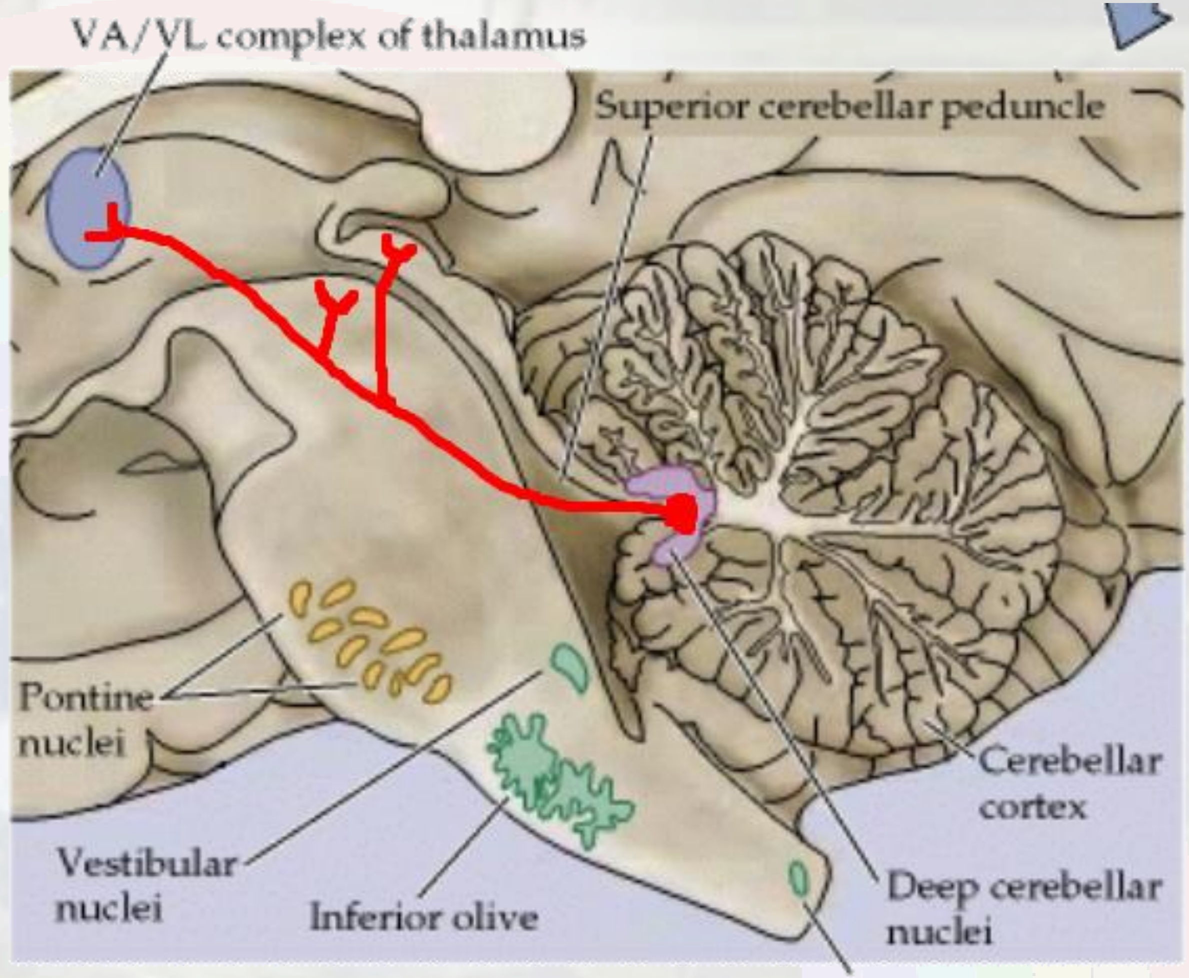
4. Cerebellum – efferents

Output via the superior cerebellar peduncle:

red nucleus
superior colliculus
ventral thalamus

Ventral thalamus to:

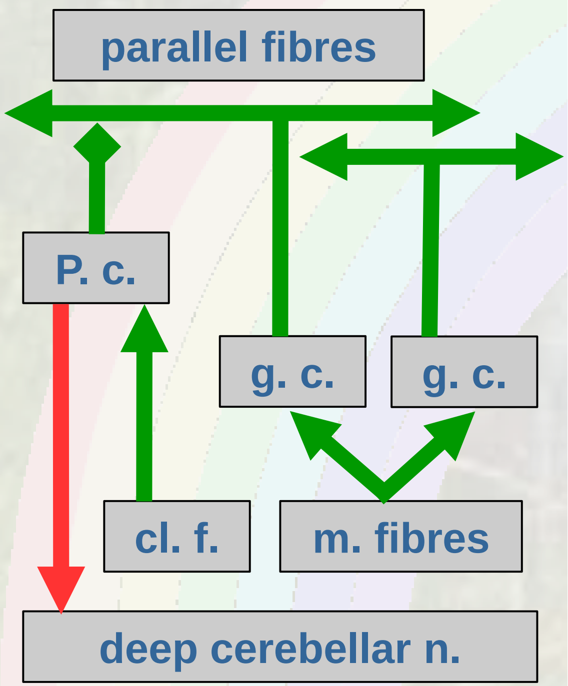
primary motor cortex
premotor cortex
supplementary m. area

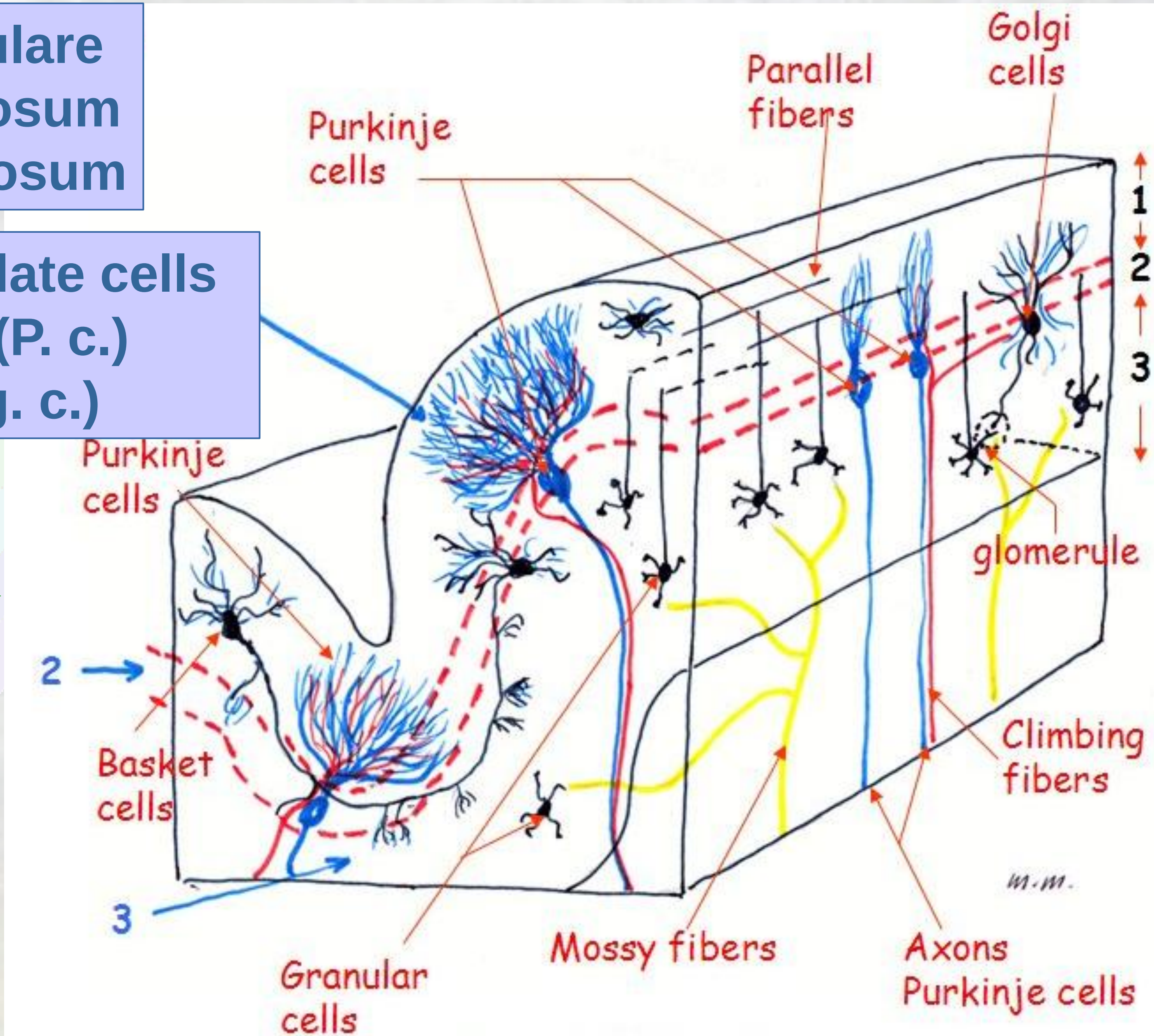


Motor control

1. stratum moleculare
2. stratum gangliosum
3. stratum granulosum

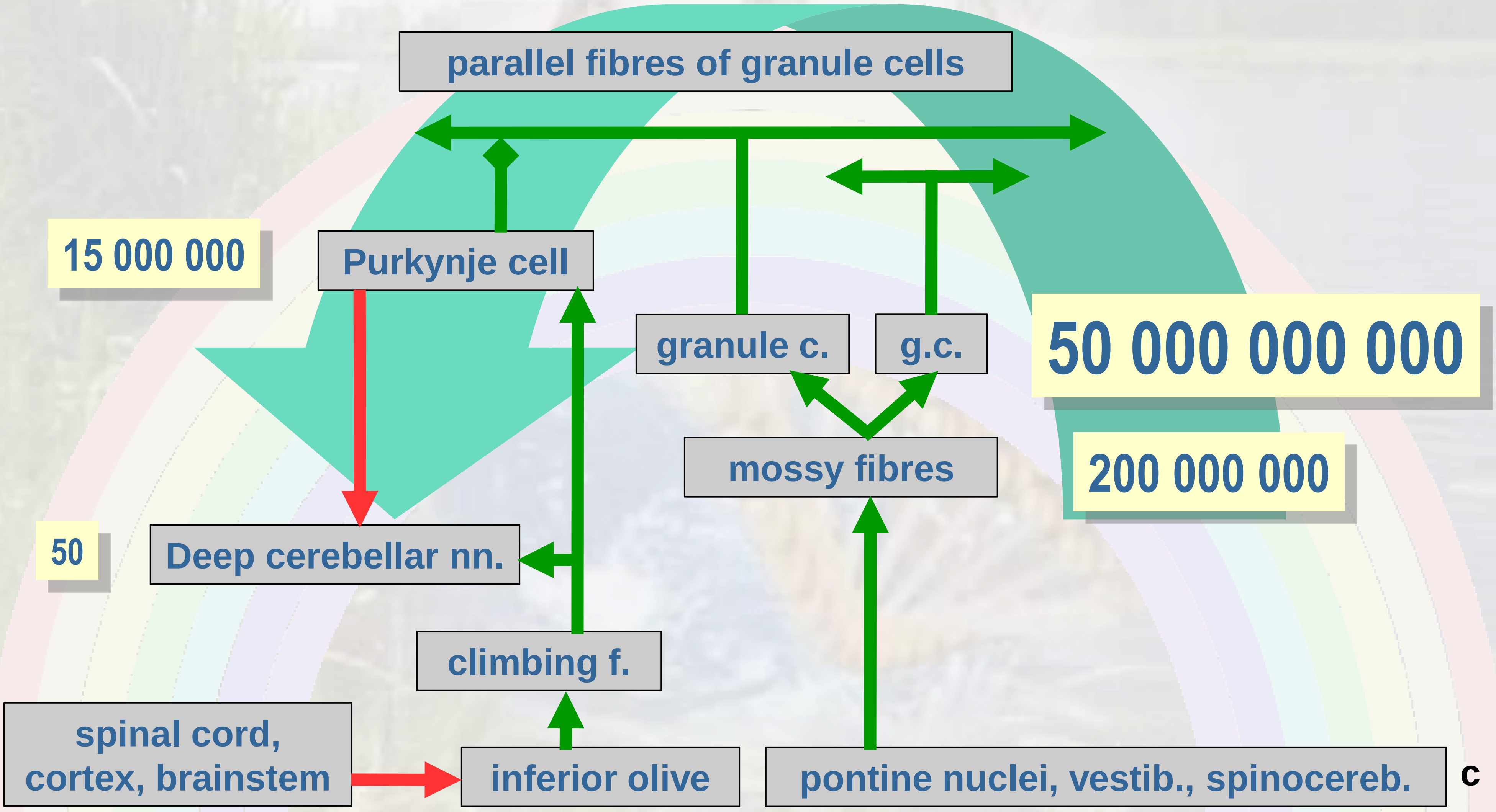
1. basket and stellate cells
2. Purkynje cells (P. c.)
3. granule cells (g. c.)





Motor control

4. Cerebellum – divergence and convergence



4. Cerebellum

Facts:

- Electrical stimulation does not cause muscle contraction
- Monkeys with the cerebellum removed can move well
- People born without the cerebellum do not need support

In humans:

- floccular destruction affects balance and eye movements
- destruction of the vermis leads to gait ataxia (drunken sailor)
- destruction of the hemispheres leads to upper limb ataxia

In general, the cerebellar dysfunction *affects* balance, posture, eye movements, and movements controlled from cortex by will

4. Cerebellum – Ataxia (YouTube videos)

Neurological examination

Link:
https://www.youtube.com/watch?v=owSZs7H24UY

Patient with Friedrich ataxia speaking

Link:
https://www.youtube.com/watch?v=VT8b-kKQC7E&feature=youtu.be&t=412

4. Cerebellum

Summary

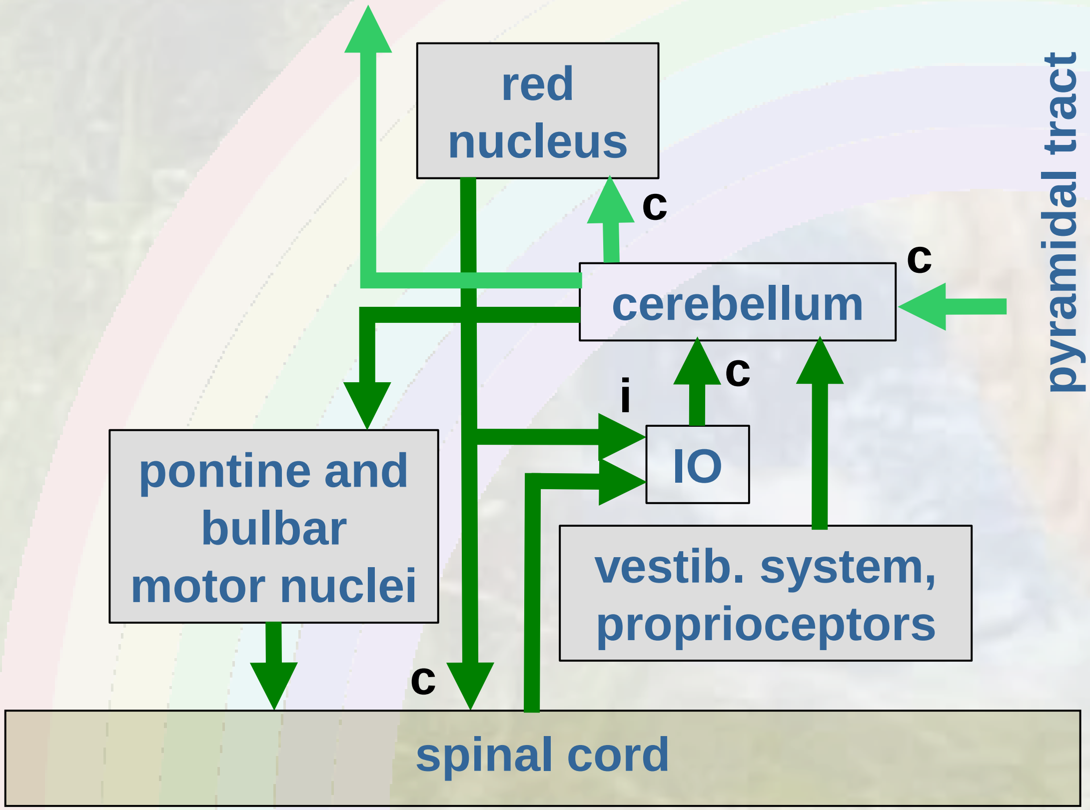
The cerebellum functions as a processing unit placed between the vestibular and somatosensory inputs and motor output paths.

Its task is to use available sensory information to produce fine modulations of efferent motor signals. This helps maintaining proper posture, balance, muscle tone, and timing of muscle contractions.

Motor control

4. Cerebellum

Summary - schematic



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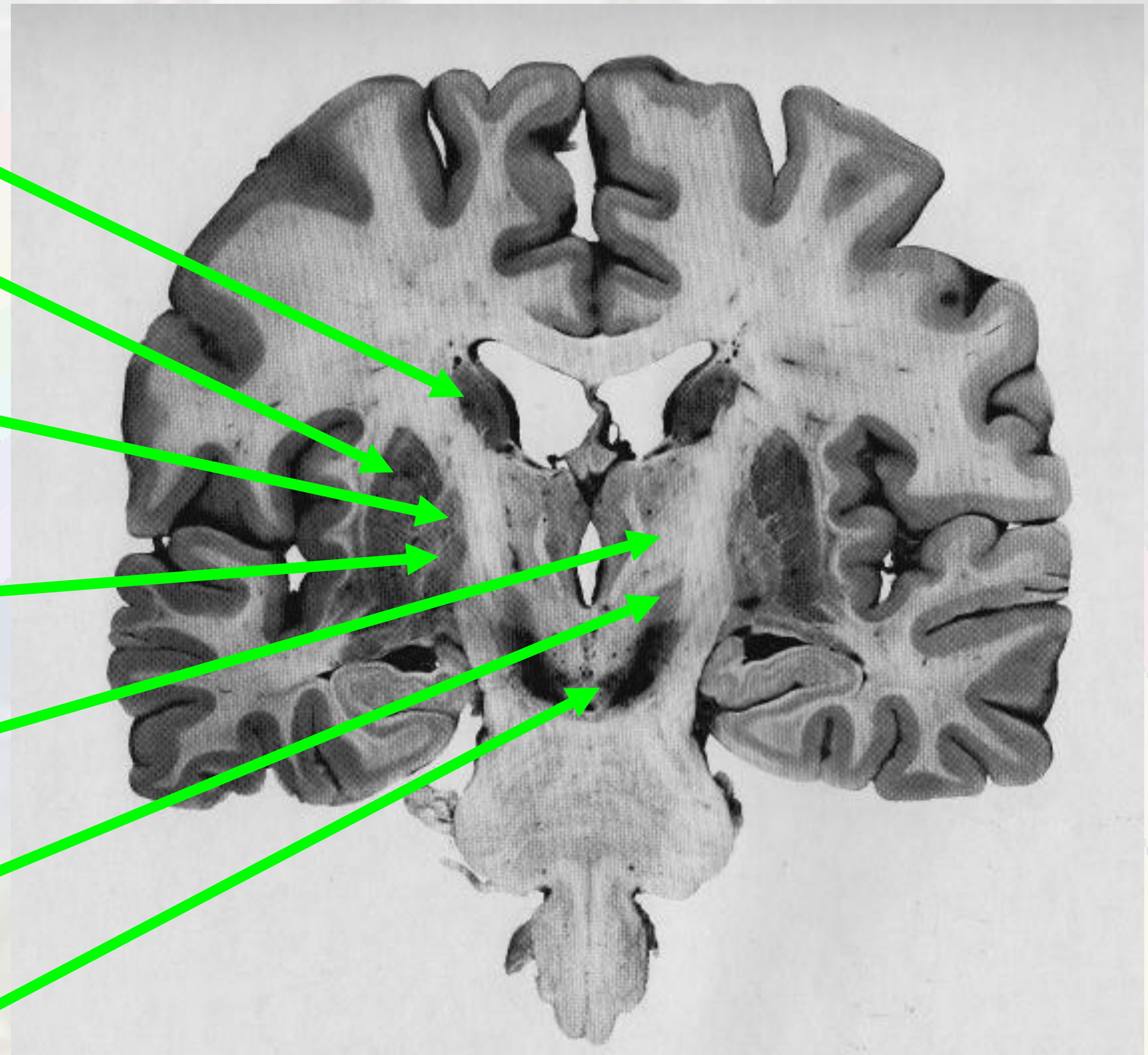
Motor control

5. Basal ganglia

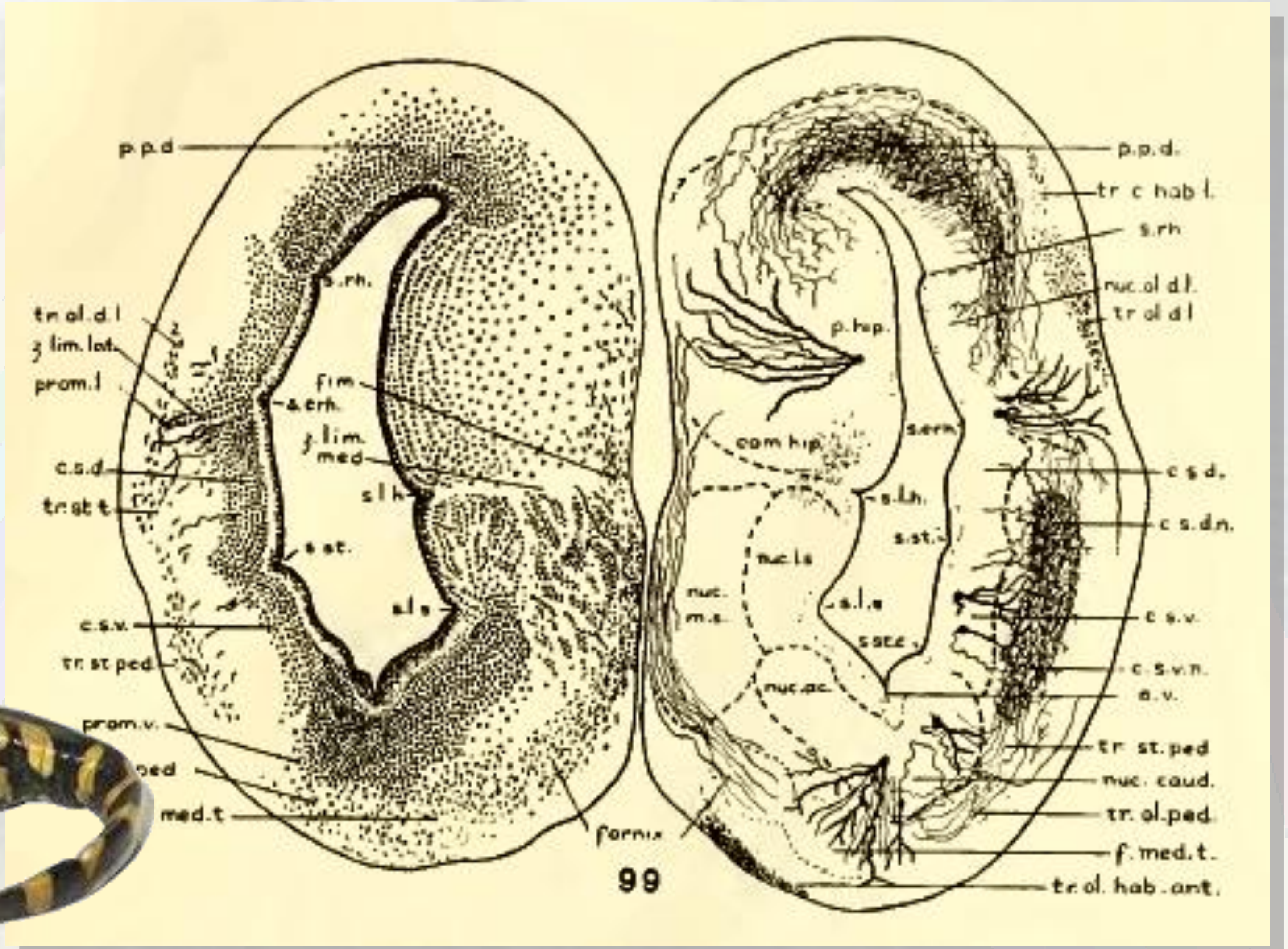


Motor control

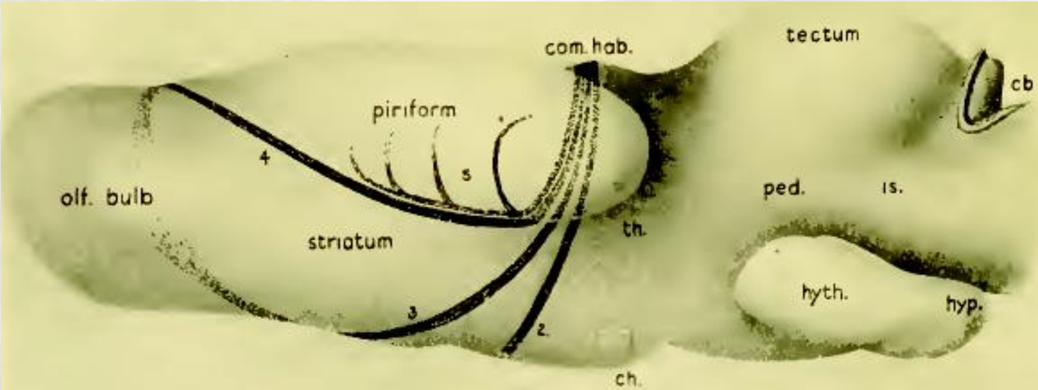
Vertebrate brain

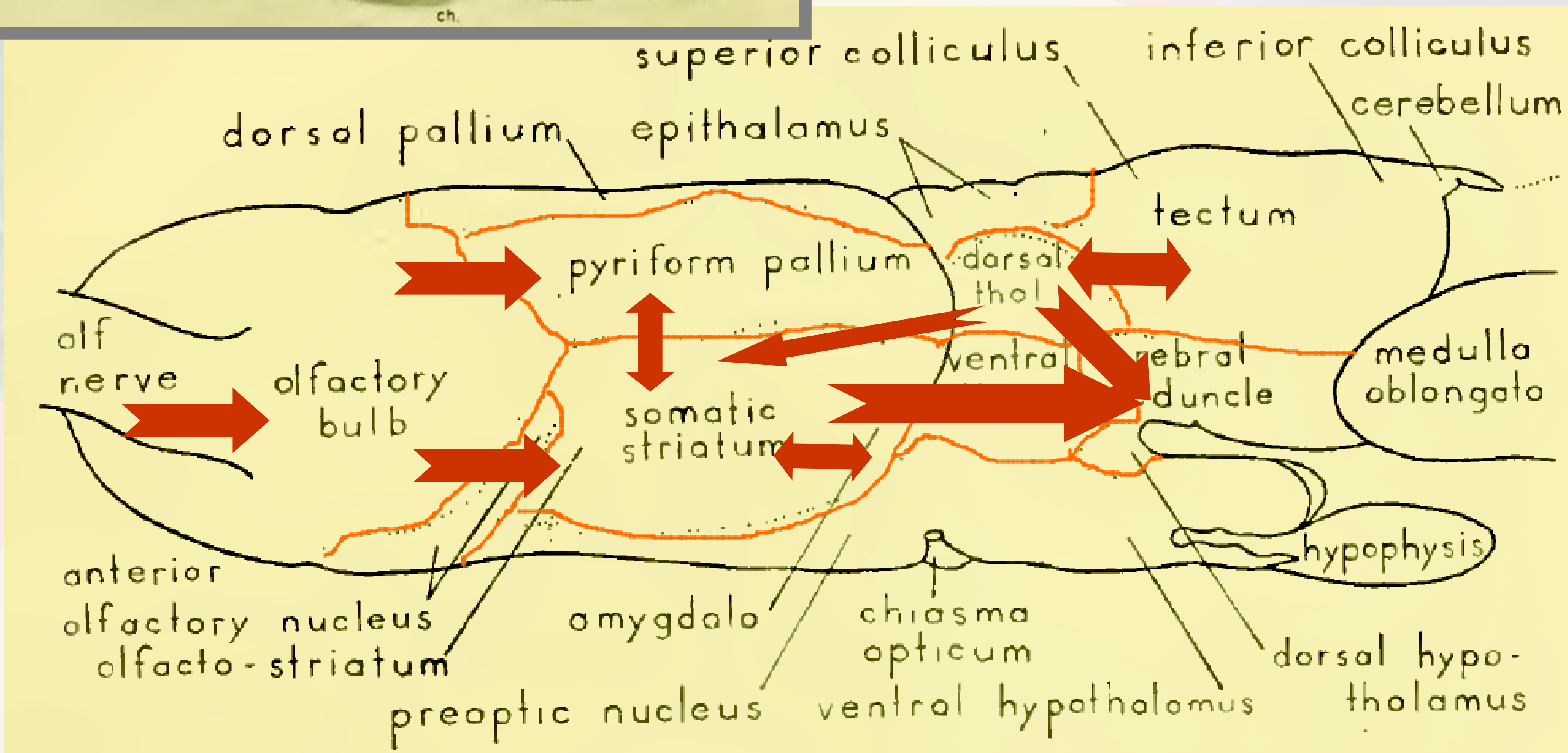
- Brain of the tiger salamander

C. J. Herrick
(1868-1960)



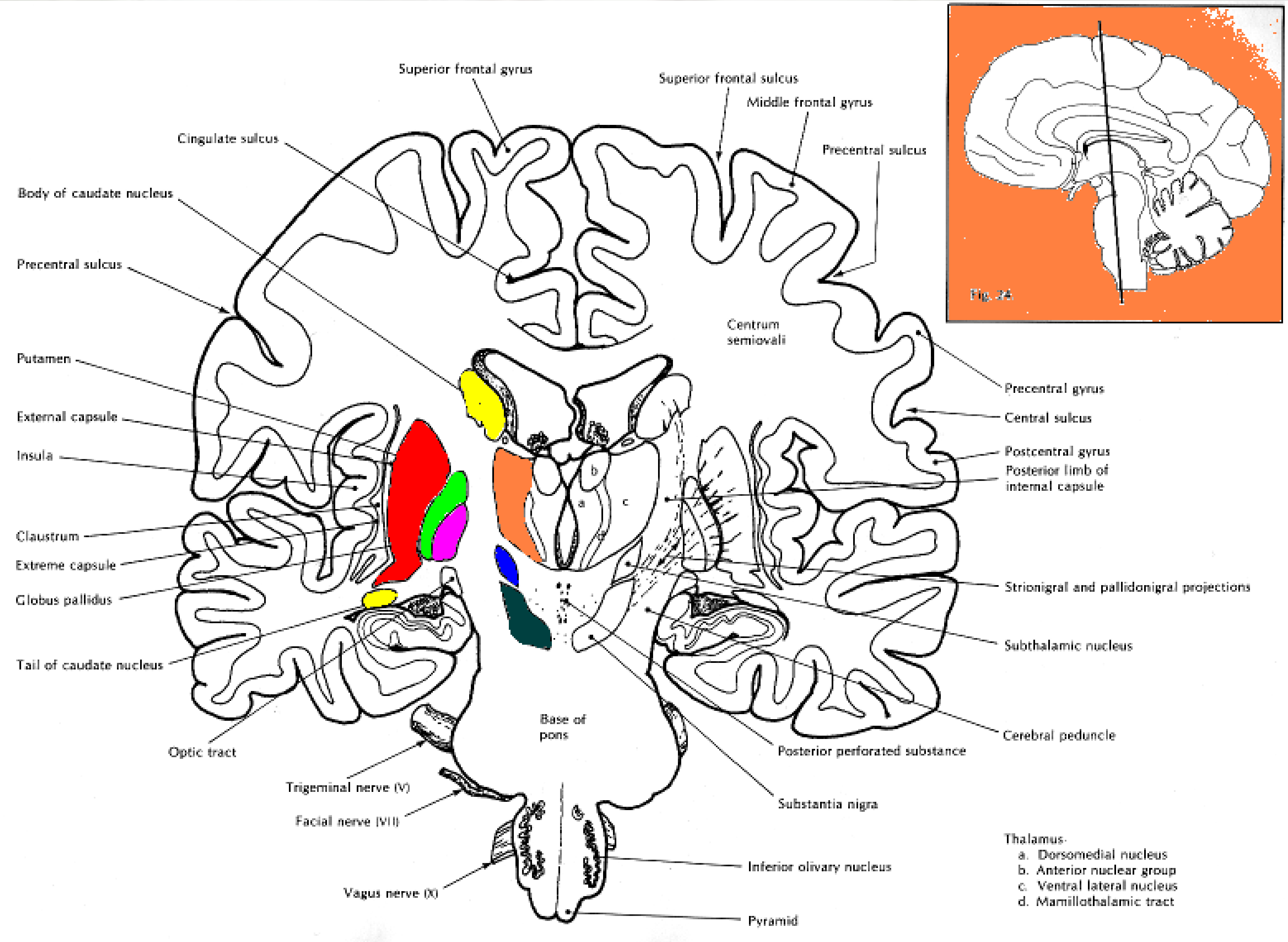
Motor control





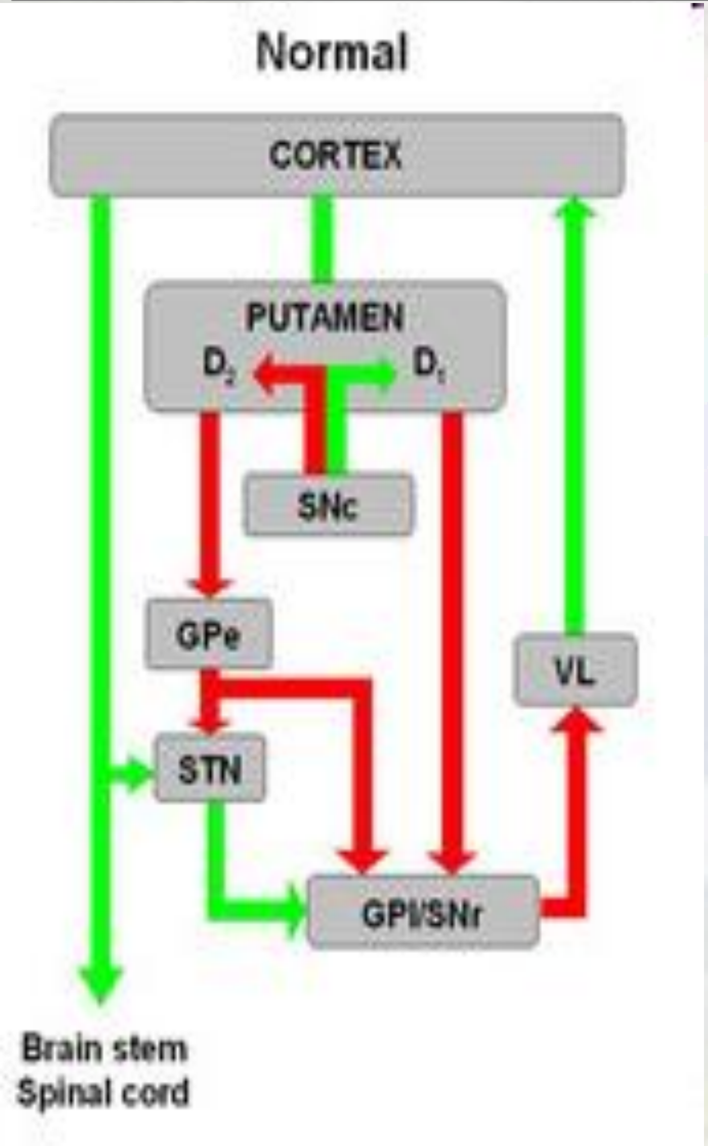
Motor control

5. Basal ganglia



Motor control

5. Basal ganglia



D1, D2 … dopamine receptors

GPe ... globus pallidus
- external segment
GPi ... - internal segment

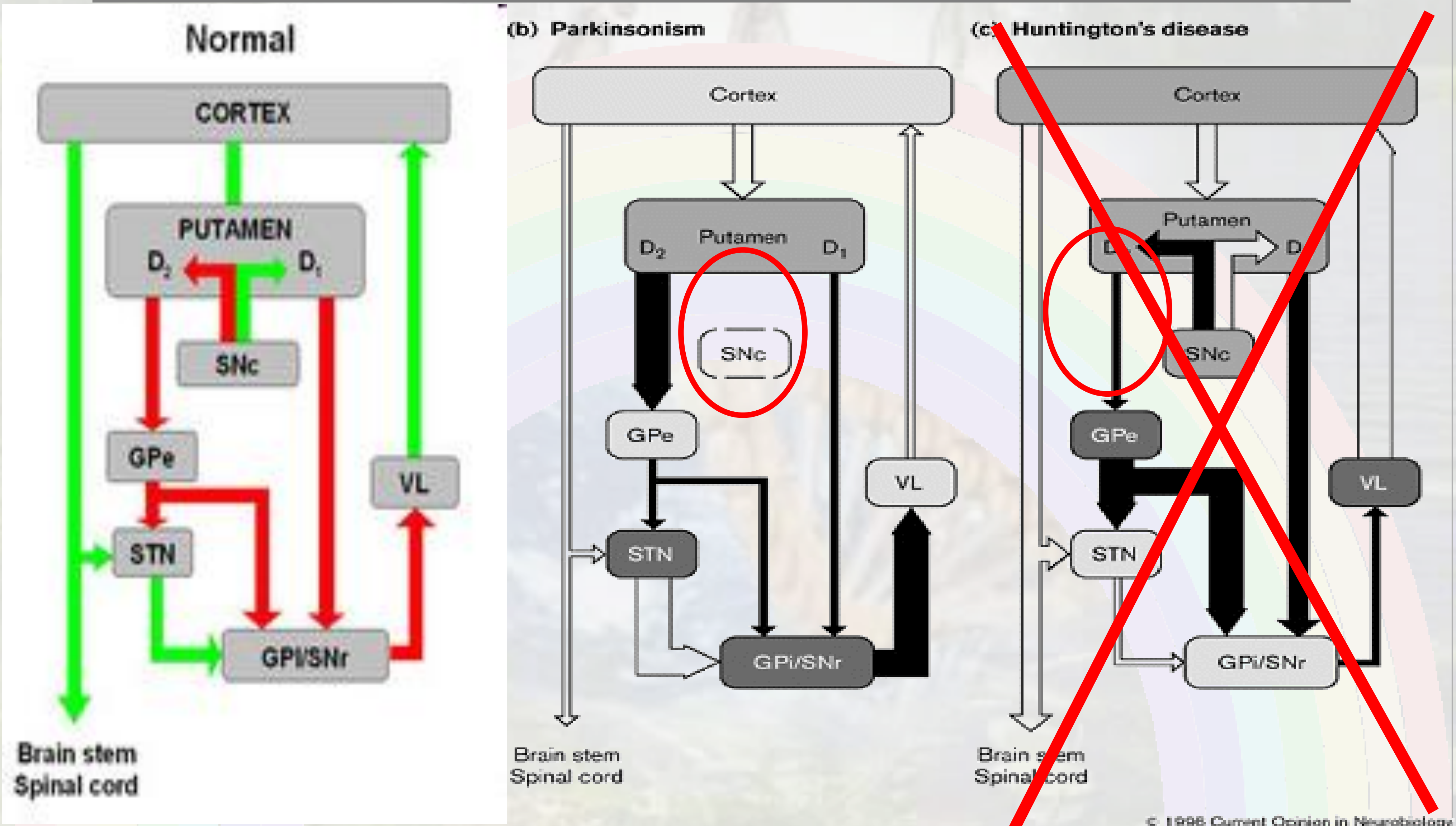
VL ... ventrolateral nucl. of thalamus

STN ... subthalamic nucleus

SNc ... substancia nigra
- pars compacta
SNr ... - pars reticulata

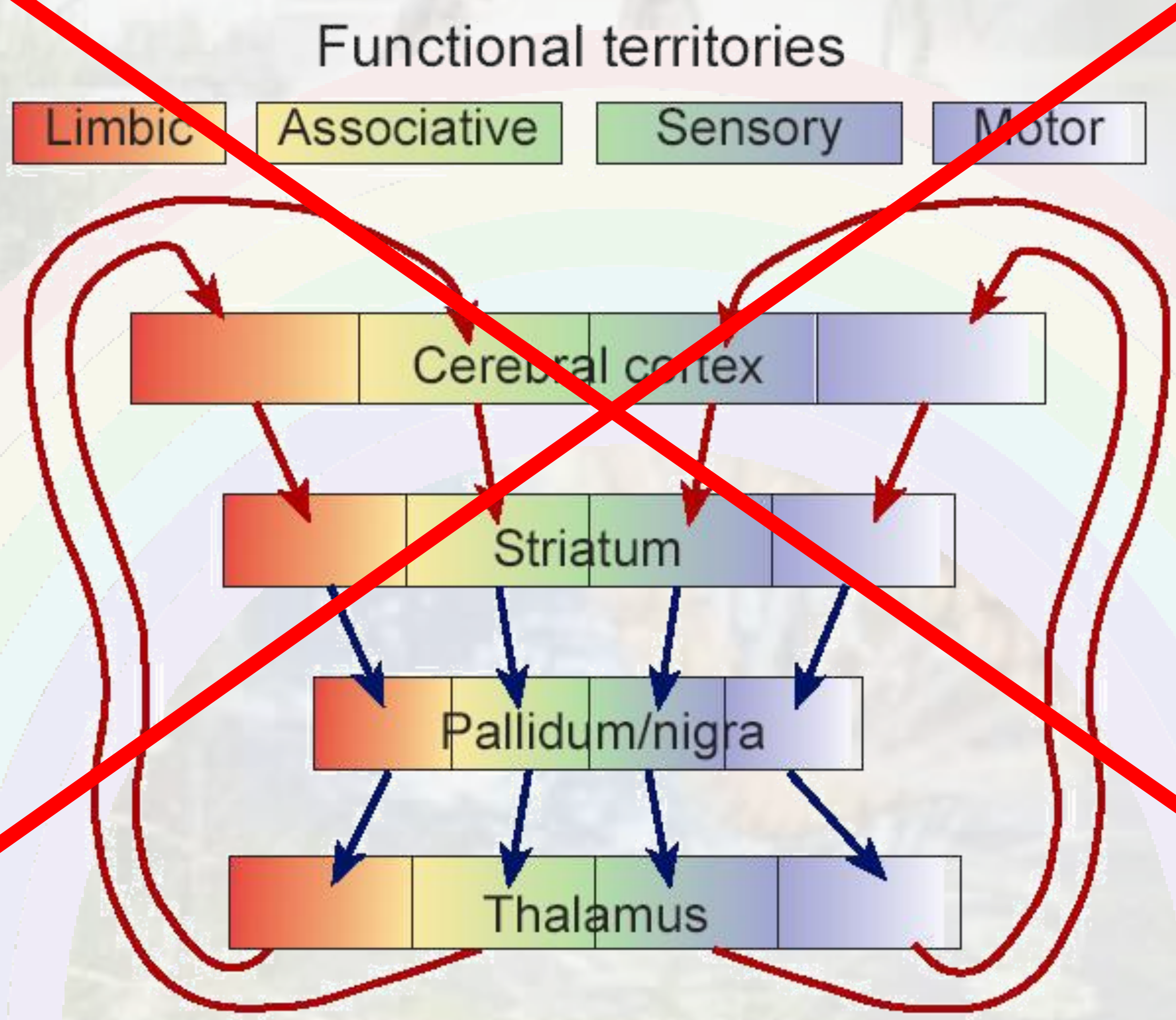
Motor control

5. Basal ganglia - pathology



Motor control

5. Basal ganglia – parallel cicruits



5. Corpus striatum

Facts:

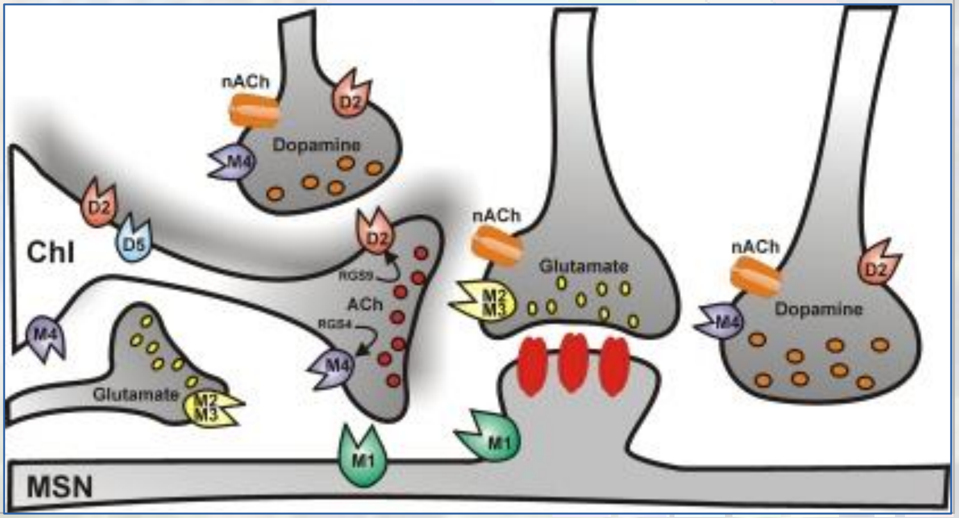
- Principal cells in the striatum are GABA-ergic medium spiny neurones. Within a short temporal window act on GABA-a receptors by excitation, otherwise by inhibition.
- Other neurones are GABA-ergic & *cholinergic* interneurones.
- Diffuse dopaminergic projection from subst. nigra p.c. and from ventral tegmental area target principal striatal cells. Most of those cells contain D1 and D2 receptors, but often other three dopamine receptors as well.
- Only the stimulation of D1 receptors leads to reinfocement of cortico-striatal connections by LTP.

Striatal neurones

1. Medium spiny neurones (MSN; 95%) have
- GABA-ergic projections
- **D1** receptors (30%; direct path through globus pallidus; enhance MSN response to glutamatergic stimulation)
- **D2** receptors (30%; indirect path through globus pallidus; reduce MSN response to glutamatergic stimulation)
- D1 and D2 receptors (40%)

2. GABA-ergic interneurones (4%; 3 types)

3. Cholinergic interneurones (1%; can release glutamate)



Pathways through the globus pallidus

1. Direct pathway (putamen D1 receptors of MSN -> GPi)
   - afferents mainly from sensory cortical areas
   - „excitatory“ - reduces thalamic inhibition due to stimulation of MSN from cortex and D1 from SNc.
   - defective in Parkinson‘s and Huntington’s disease

2. Indirect pathway (putamen D2 receptors -> GPe -> SNr)
   - afferents mainly from motor cortices
   - “inhibitory” - enhances inhibition of thalamus due to stimulation of MSN from cortex
   - “excitatory” - reduces inhibition of thalamus due to stimulation of D2 receptors from SNc
   - defective in Huntington’s disease

5. Corpus striatum - mystery

Facts:

- MacLean: “More than 150 years of investigation has failed to reveal specific function of the striatal complex.”
- Large lesions in the striatal complex result in no obvious motor disability. Bilateral lesions of the caudate nucleus may produce behavioural persistence and hyperactivity.
- Electrical stimulation has no motor effects. It can cause blocking of voluntary behaviours. Laughing and crying has also been described.
- Jung and Hassler: “Bilateral destruction of the pallidum does not produce any motor symptoms.”

5. Basal ganglia – role of the thalamus

Facts:

- Cooper: "The role of the thalamus in motor activity likewise appears difficult to define at this time. One may interrupt pathways from the globus pallidus, red nucleus, and the cerebellum to the thalamus as well as the thalamo-cortical and cortico-thalamic circuits without causing either motor weakness or faulty coordination upon the patient."
- MacLean: "The evidence indicates that the striatal complex is not solely a part of the motor apparatus under the control of the motor cortex."

5. Basal ganglia – GP output

- Parent et al.: “The major axonal branches of the GPi are those that descend within the brainstem, whereas the GPi innervation of the thalamus is made up of fine collaterals that detached from these thick descending fibers. The GPi descending fibers arborise principally in the PPN [pedunculo-pontine nucleus].”
- GPi is activated after the activation of the primary motor cortex.
- The motor cortex –> corpus striatum –> thalamus circuit does not represent an array of mutually segregated loops through which motor programs reverberate unchanged, as previously thought.

Motor control

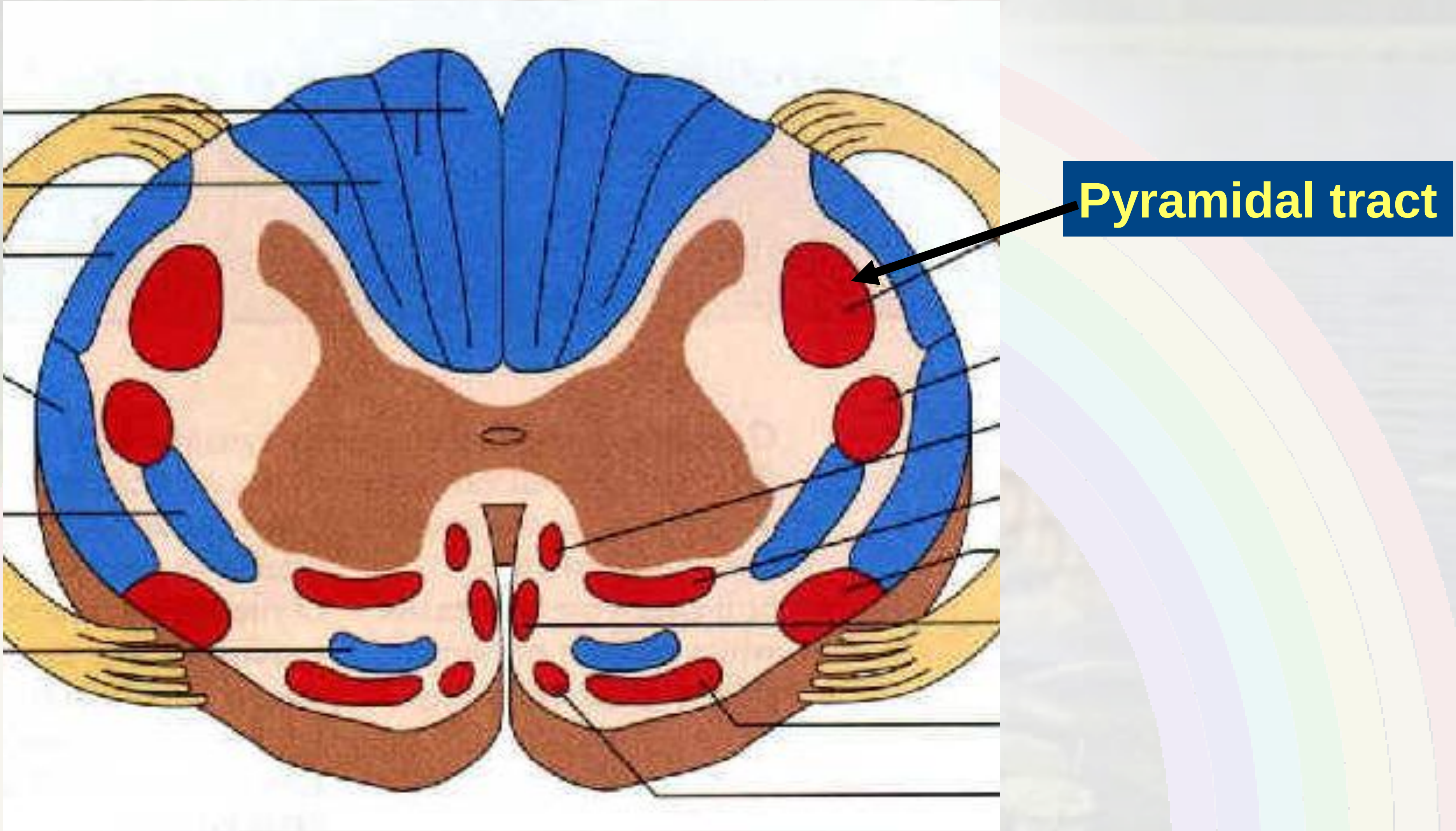
5. Basal ganglia

Strong hypotheses:

- **BG lesions specifically block the influence of task incentives on movement vigor.**
- **BG are important for learning new motor skills.
The limbic input provides for reinforcement signals that determine what is or what is not to be learnt.**
- **Long-term memories are stored in motor cortices.**

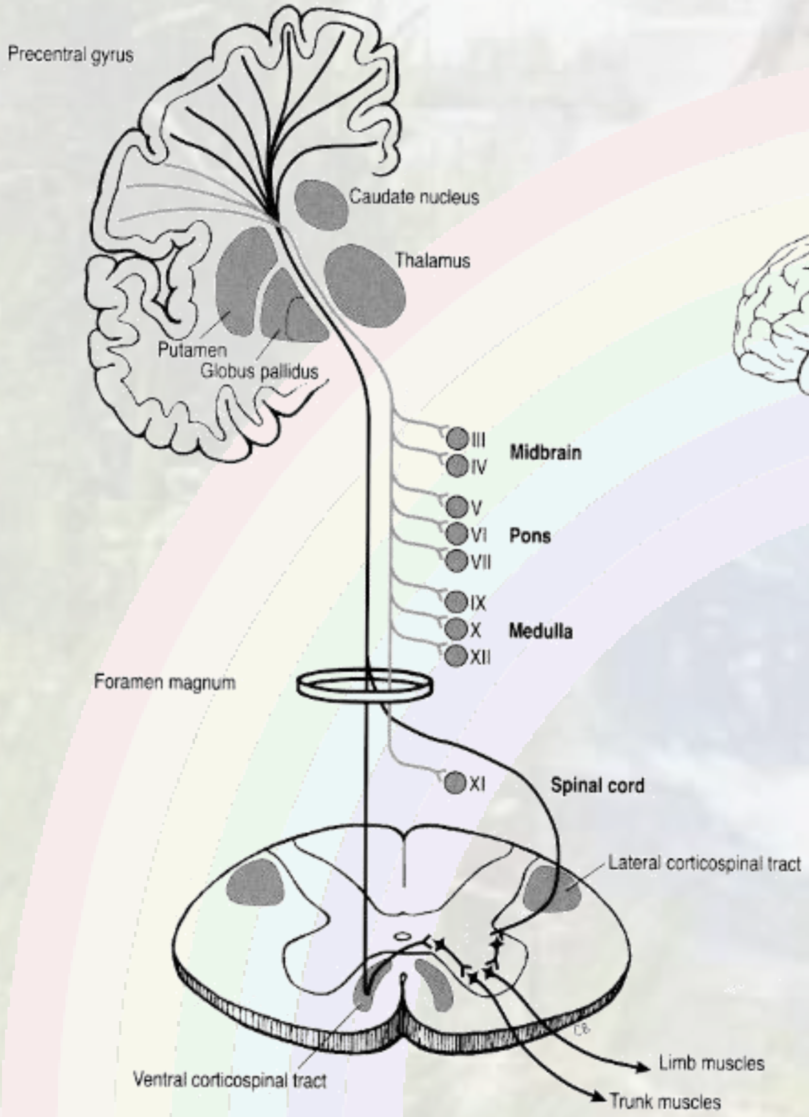
Motor control

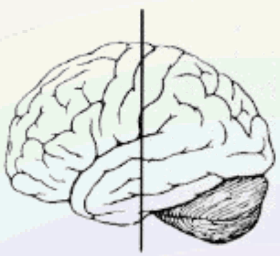
6. Pyramidal system



Motor control

6. Pyramidal tract





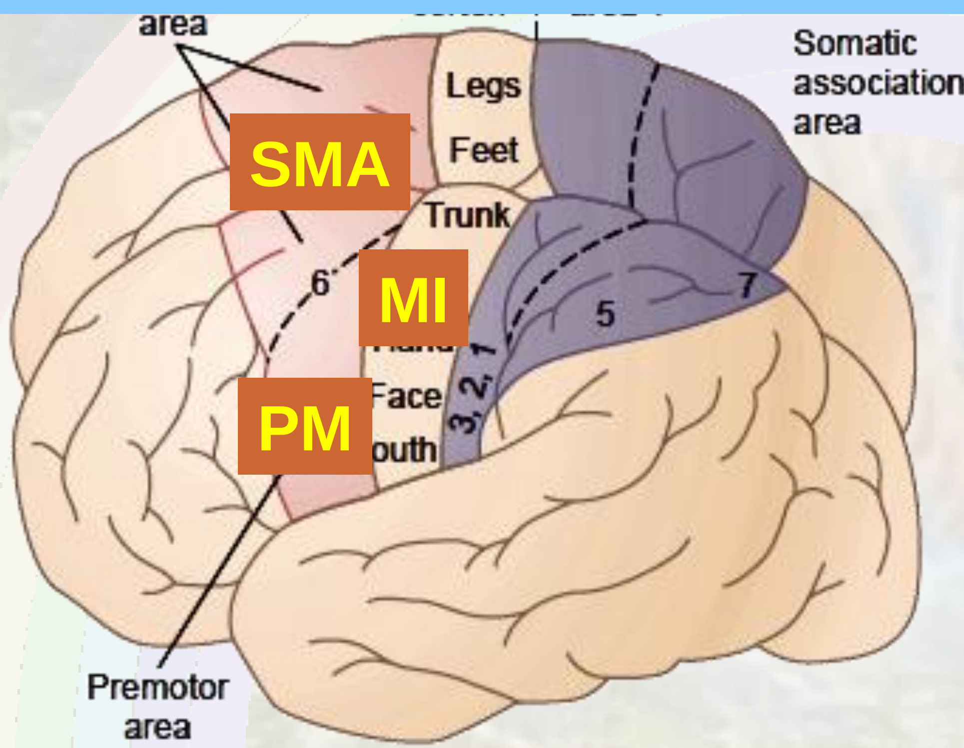
Pyramidal tract starts in layer V of MI, PM, and SMA areas of the motor cortex (see next slide for abbreviations).

It controls most muscles, mainly the distal ones.

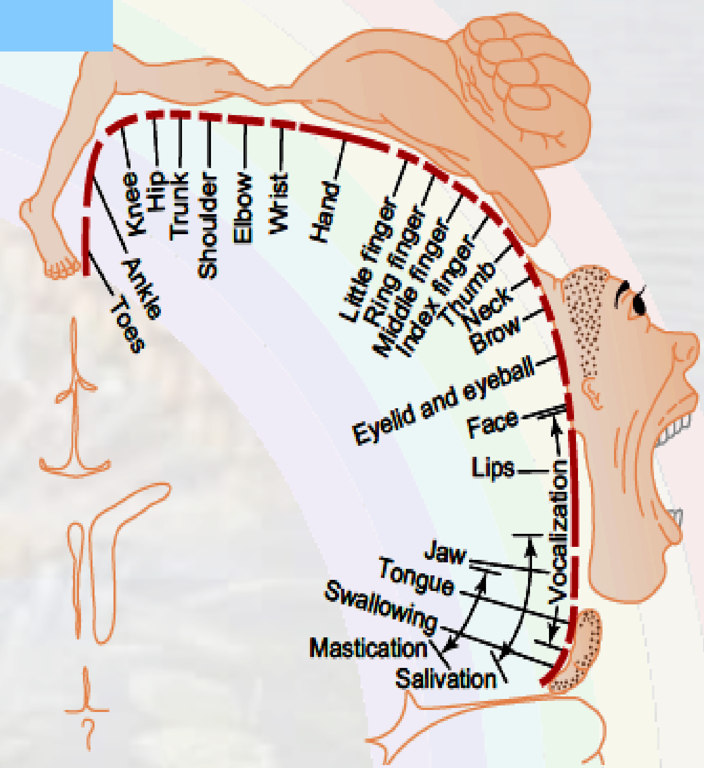
Motor control

6. Motor cortex

- Primary motor cortex (MI)
- Premotor cortex (PM)
- Supplementary motor area (SMA)



Motor "homunculus"



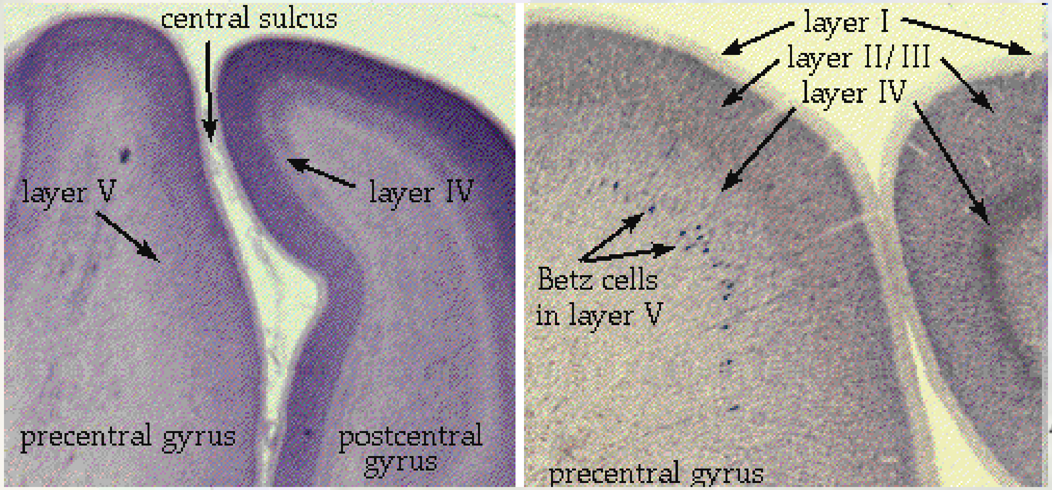
6. Supplementary vs. Premotor cortex

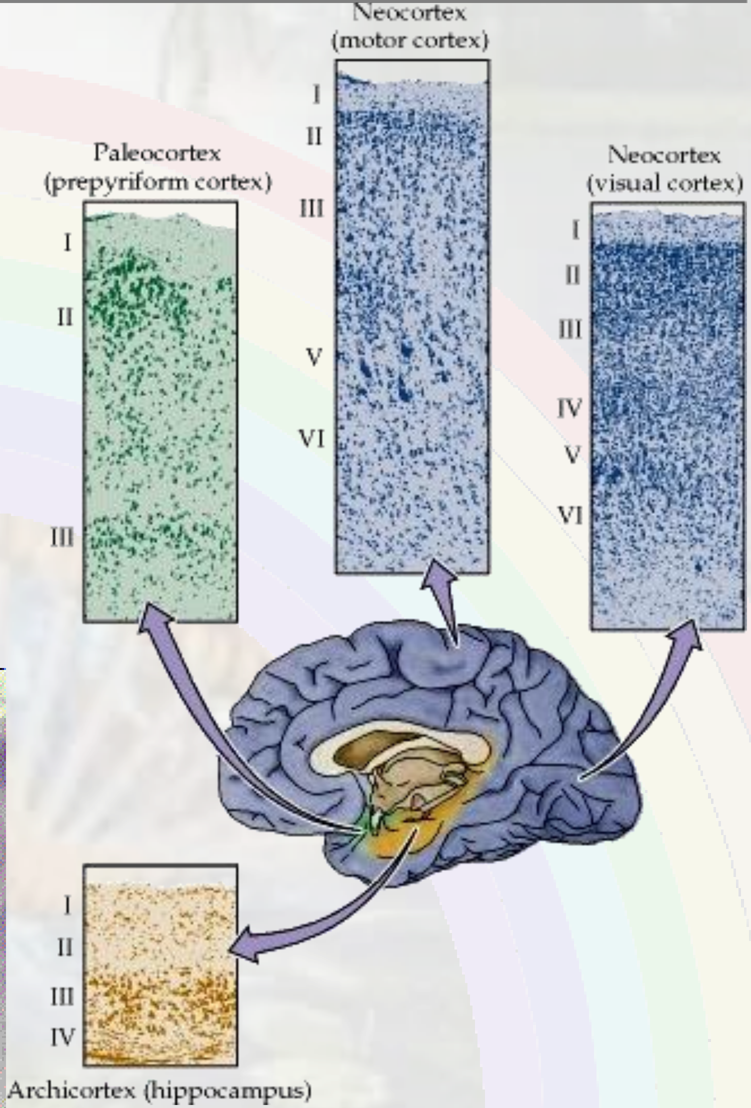
	SMA	PM
Phylogenetic origin	hippocampus	pyriform cortex
Mode of control	predictive	interactive
Subcortical affer.	basal ganglia	cerebellum
Interhem. communic.	big	small
Bimanual	simultaneous	alternating
Speech	spontaneous	repetitive
Motor skills	smooth	segmented

Motor control

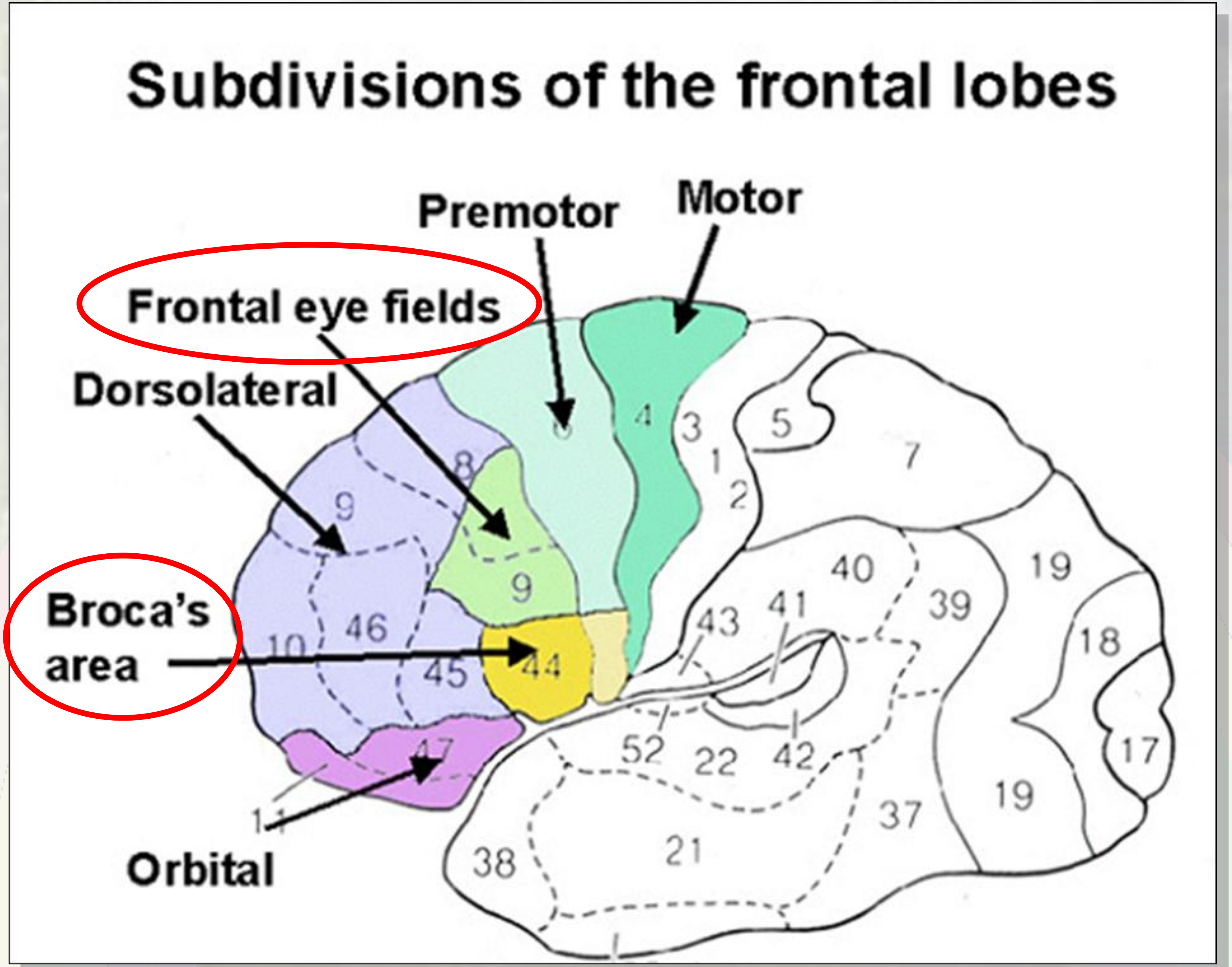
6. Motor cortex

- Primary - agranular
- Premotor - dysgranular
- Supplementary - dysgranular





Motor control



6. Motor cortex - connections

- **Somatosensory cortex** ⇨ nucl. ruber and RF and <u>partially tractus corticospinalis</u> (pyramidal tract)
- Cerebellum ⇨ VL thalamus ⇨ **primary motor cortex (MI)** ⇨ pyramidal tract
- Palidum ⇨ AV thalamus ⇨ **premotor cortex (PM)** ⇨ nucleus ruber and RF and partially pyramidal tract
- Palidum ⇨ AV thalamus ⇨ **supplem. motor area (SMA)** ⇨ nucl. ruber and RF and partially pyr. tract
- visual cortex ⇨ (**frontal eye field** ⇨) colliculus superior
- Wernike's area ⇨ **Broca's speech centrum**

6. Motor cortex (brain mapping)

6. Motor cortex

Facts:

MI – Is active during movement. It activates simple movements or even individual muscle groups.

PM – Is active before movement. The movement does not have to happen. It is important for the control of learnt automatic movements under the influence of sensory feedback. Speaking, eye control, and writing are a few examples.

SMA - Is active before movement. The movement does not have to happen. It is active during planning of movement.

6. Motor cortex

Conclusions

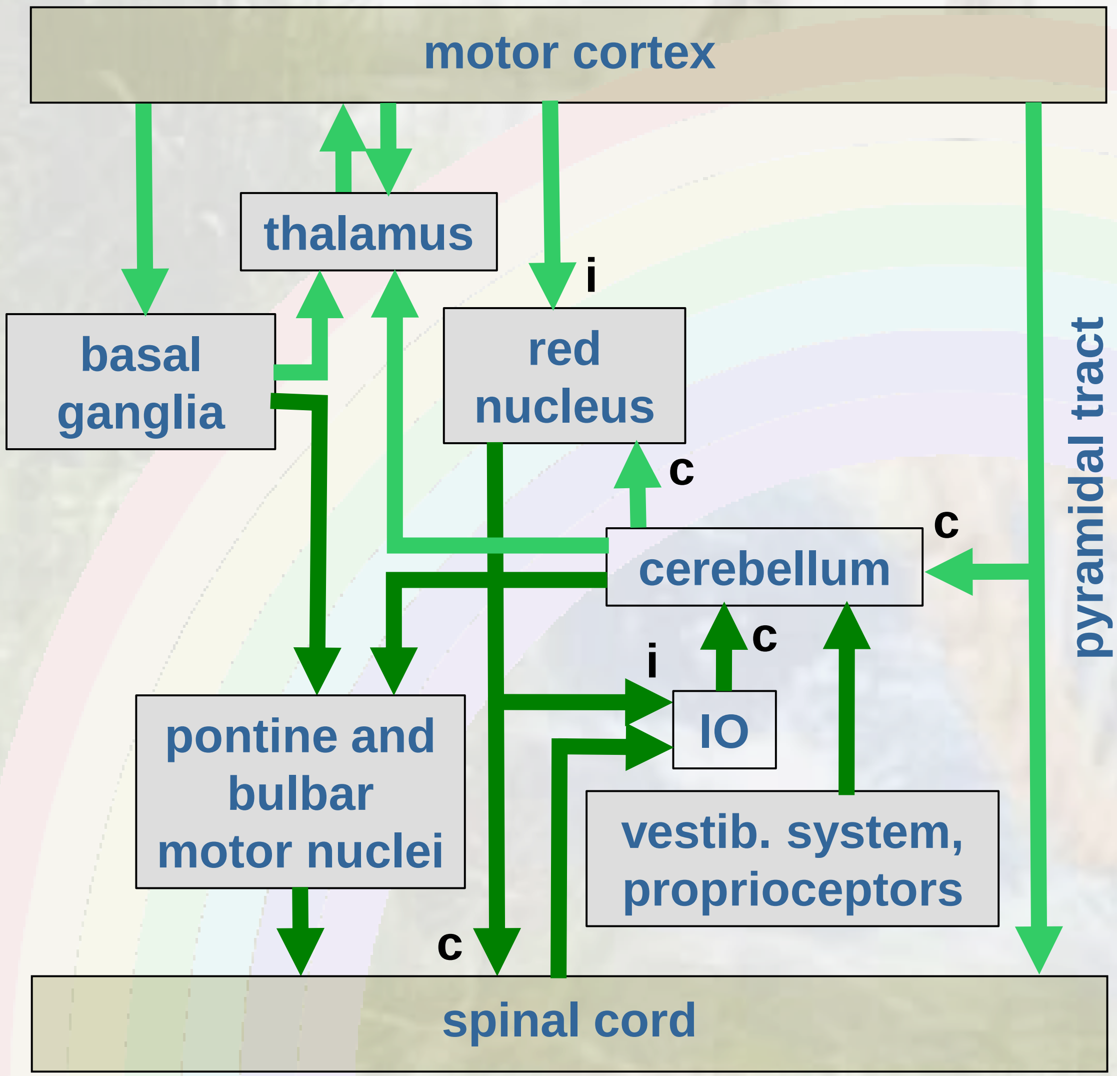
The primary motor cortex (MI) has evolved from the somatosensory cortex. It shares the same function with other (sensory) neocortical areas: It serves as a substrate for conscious awareness and as storage of long-term memory traces.

The MI stores "motor primitives" (that may correspond to individual muscle groups), PM and SMA helps store more complex patterns of movement and behaviour.

Motor control

Summary of connections (simplified)

- see full diagram at the end



Phylogenetically older connections are dark green.

Projections from the basal ganglia and cerebrellum into the thalamo-cortical system allow for conscious awareness of movement and its storage in declarative memory.

Basic design – ref. previous slide

1. Grasping movements, manipulation, locomotion.
   These are generated by red nucleus.
2. Vital and species-specific behaviours such as approach, escape, reproduction, maternal behaviour, and defense.
   These are generated by striatum.
3. Coordination and feedback control of otherwise coarse movements generated by the red nucleus or striatum, or even produced in a more reflexive way.
   Performed by cerebellum.
4. Conscious reflection of processes listed above, memory, and cognitive processing.
   Introduced by the thalamo-cortical system.

Overall summary

1. Even the simplest vertebrates cannot do with simple reflexes and central pattern generators, despite the fact that they can be surviving with them.
2. Even the simplest vertebrates are able to fine-tune movement coordination and move in the gravitational field (with the help of the cerebellum).
3. Even the simplest vertebrates must possess patterns of species-specific behaviours. A major role here is played by the corpus striatum.
4. In man and higher vertebrates, a system has evolved that consciously processes information from long-distance sensory modalities – vision and hearing. It has affected the system that controls behaviour - basal ganglia. The motor cortex then emerged along with its connections to the spinal cord and with the cerebellum and striatum..

Motor control

Legend for next page

- SMA – supplementary motor area
- PM – premotor cortex
- M I – primary motor cortex
- GP – globus pallidus (i – internal segment, e – external segment)
- STN – subthalamic nucleus
- SN – substantia nigra (c – pars compacta, r – pars reticularis)
- VTA – ventral tegmental area
- PPN – pedunculo-pontine nucleus
- RAS – reticular activating system
- vl – ventrolateral thalamic nucleus
- cm – centromedial thalamic nucleus
- av – anteroventral thalamic nucleus

→ (light green arrow)	Excitatory (glutamate)	→ (dark green arrow)	phylogen. old (glutamate)	→ (pink arrow)	serotonin	c	contralateral
→ (red arrow)	Inhibitory (GABA)			→ (blue arrow)	dopamine	i	ipsilateral

Motor control