Introduction to Cognitive Neuroscience

Lecture 10: The Functional Organization of Perception and Movments

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Introduction

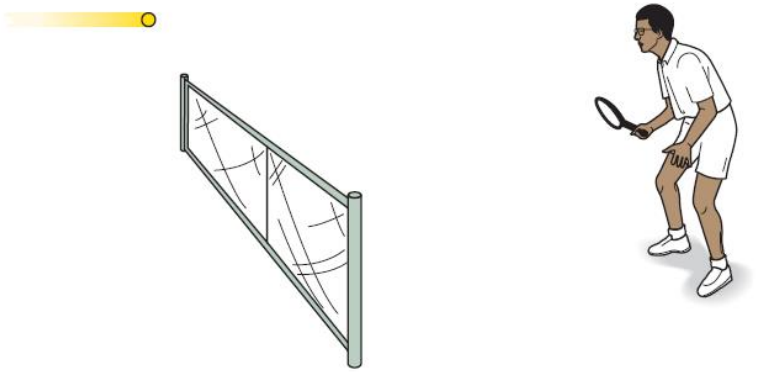
- The **Neural Basis of Cognition**:
  - We now begin to consider **larger**, **interconnected networks of neurons**, the **complex circuits** that give rise to **mental activity**: **perception, planned action, and thought.**
  - The field of **systems neuroscience** aims to understand **how these networks produce the cognitive functions** of the brain
- For understanding the major **functional systems of the brain** -the sensory, motor, motivational, memory, and attentional systems-, system neuroscience has benefited from a **reductionist approach** to mental function (the assumption that these functions will **emerge from the biological properties** of **nerve cells** and of their **pattern of interconnections**)
- **Mind** can be considered a **set of operations carried out by the brain**

A simple behavior is mediated by many parts of the brain

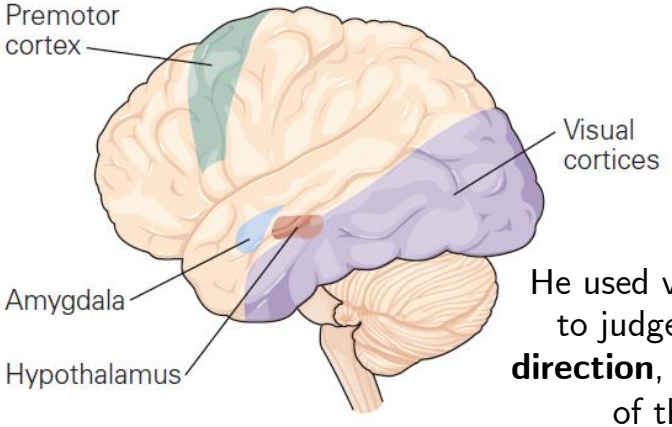
- The brain is organized into **functionally** specific areas
- Neurons in different parts of the nervous system are **quite similar**; however **number** and **types** of neurons in each brain area and **how they are interconnected** through development are **different**.
- The **specific patterns of interconnection** underlie the **individuation of behavior**.
- All **behavior**, from simple reflex responses to complex mental acts, is the **product of signaling between appropriately interconnected neurons**.

It is necessary to break down behavior into key components

Watching an approaching ball



Premotor cortex develops a **motor program** to return the ball.



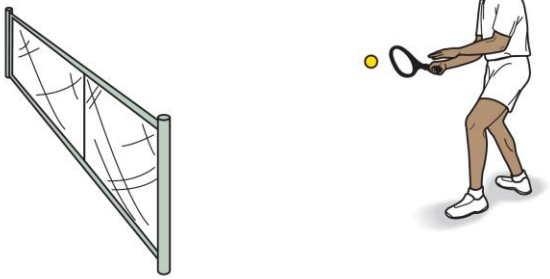
He used visual cortex to judge the **size**, **direction**, and **velocity** of the ball

The **amygdala** acts in conjunction with other brain regions to adjust the **heart rate**, **respiration**, and other **homeostatic** mechanisms and also activates the **hypothalamus** to **motivate** the player to hit well.

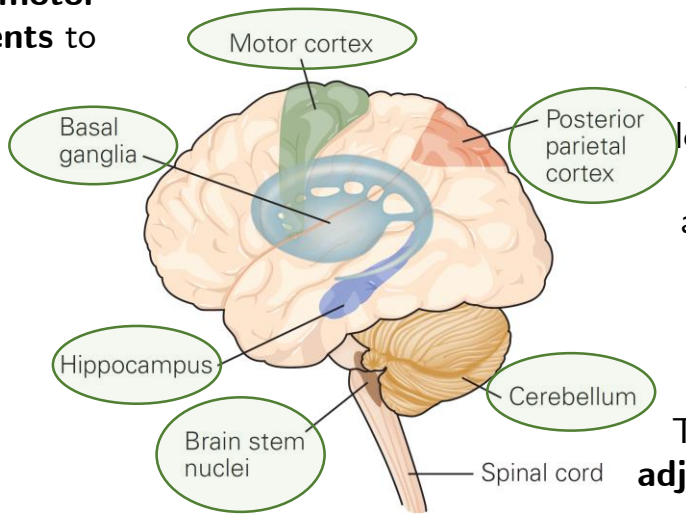
To execute the shot

The **motor cortex** sends **signals to the spinal** cord that activate and inhibit many **muscles** in the arms and legs.

The **basal ganglia** become involved **in initiating motor patterns** and perhaps **recalling learned movements** to hit the ball properly



The **hippocampus** is not involved in hitting the ball but is involved **in storing the memory** of the return so that the player can **brag about** it later



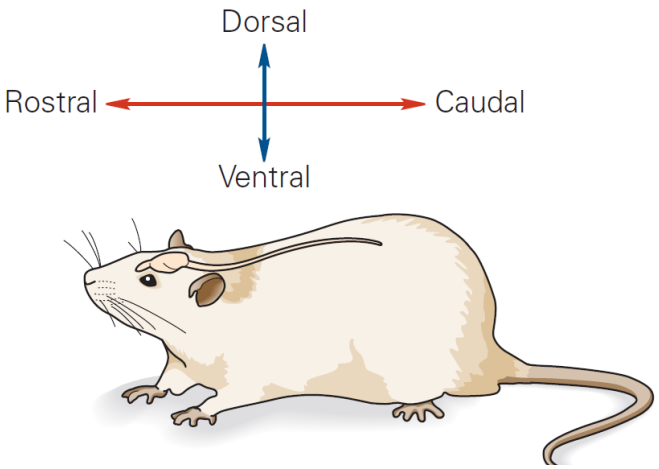
Throughout the movement, **brain stem neurons regulate** heart rate, respiration, and arousal

The **posterior parietal cortex** provides the player with a sense of **where his body is** located in space and where his racket arm is located **with respect to his body**

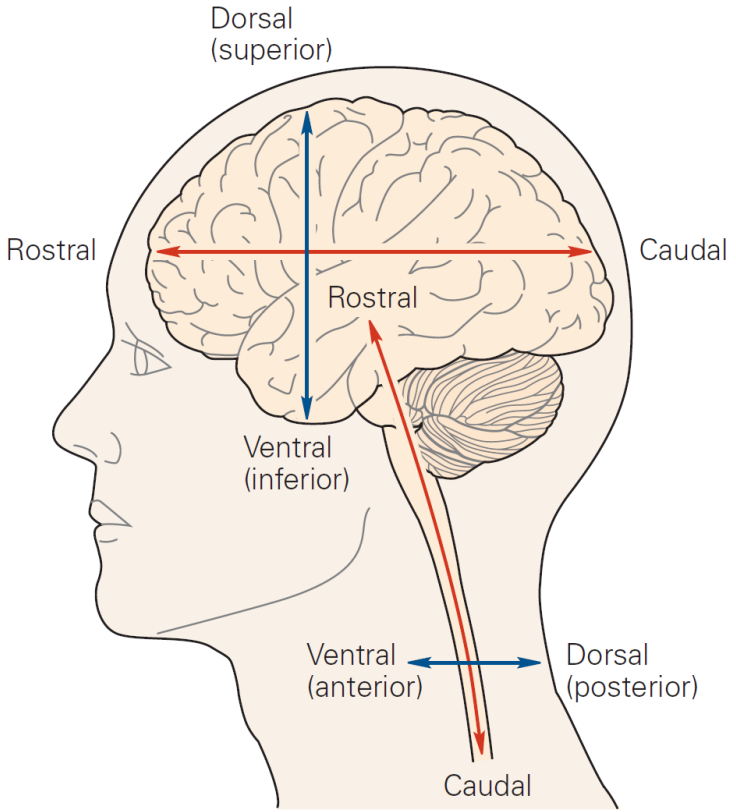
The **cerebellum adjusts movements** based on **proprioceptive** information from **peripheral** sensory receptors

Brain axes: rostral-caudal and dorsal-ventral

Rostral means toward the **nose** and **caudal** toward the **tail**.

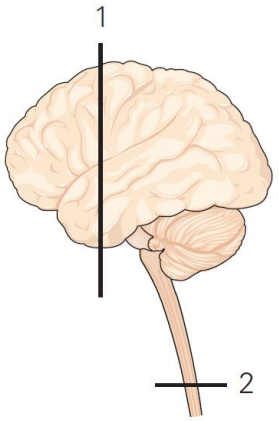


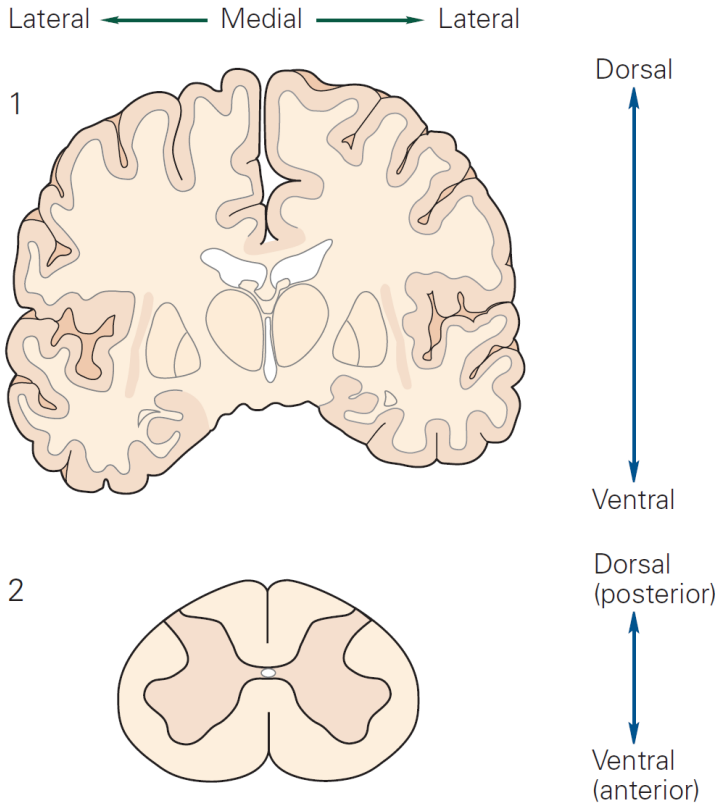
Dorsal means toward the **back** and **ventral** toward the **belly**



Brain axes: medial-lateral axis

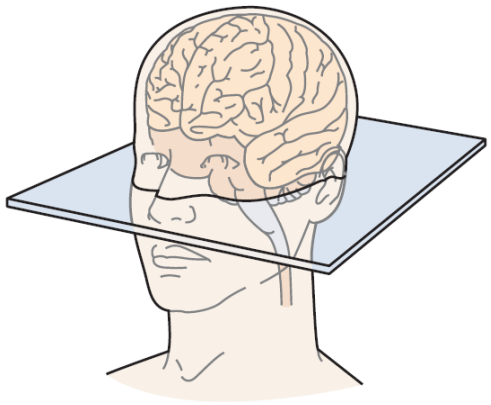
Medial means toward the **middle** of the brain and **lateral** toward the **side**.



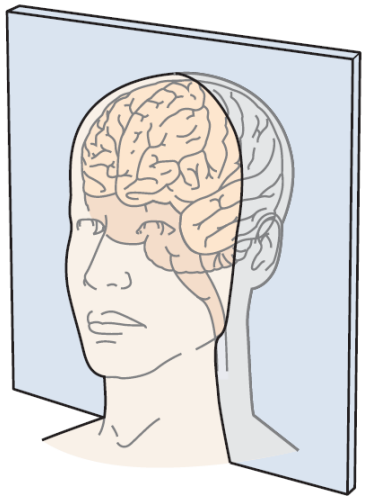


Section planes

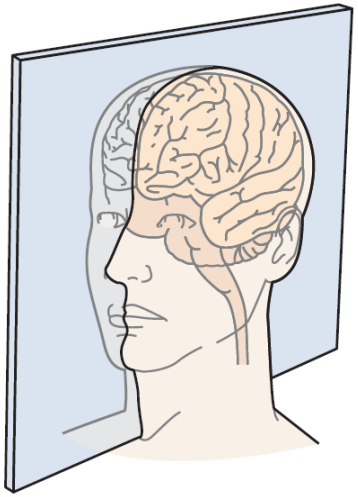
Horizontal plane



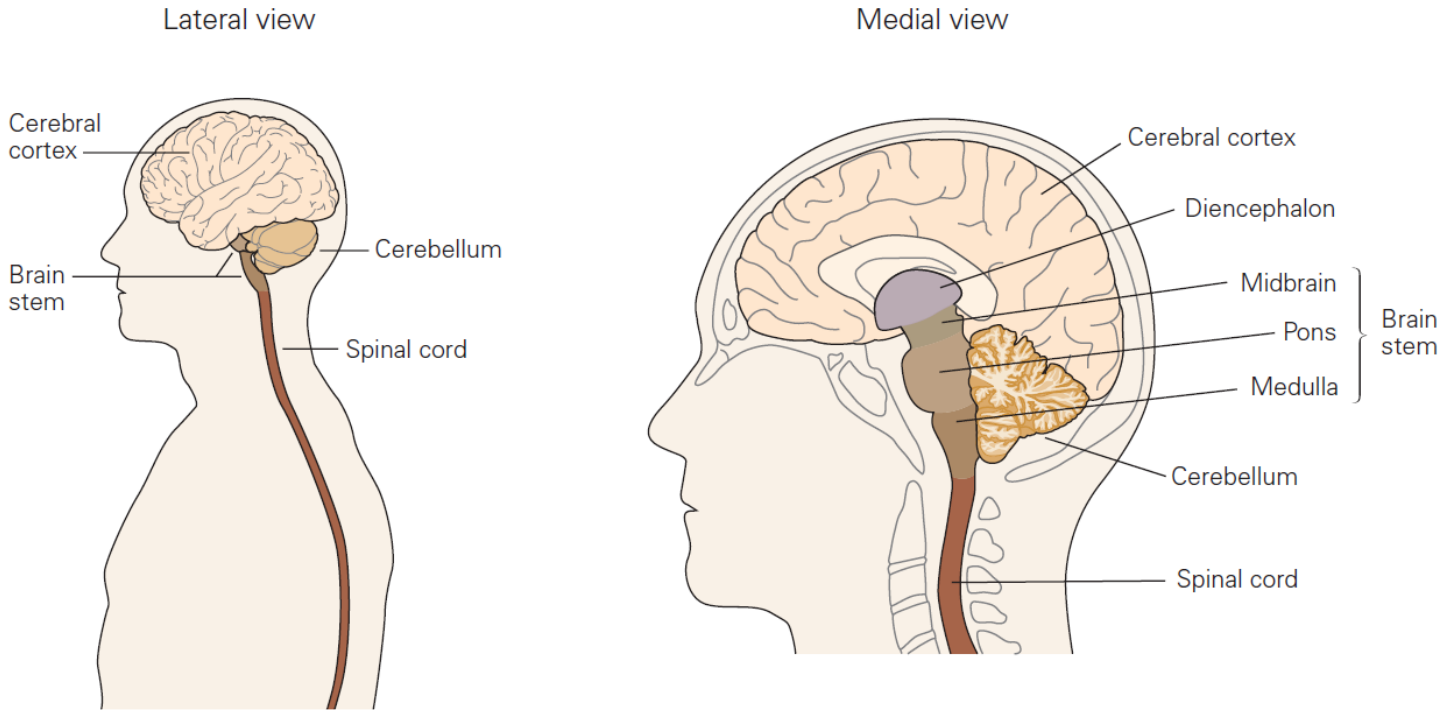
Coronal plane



Sagittal plane

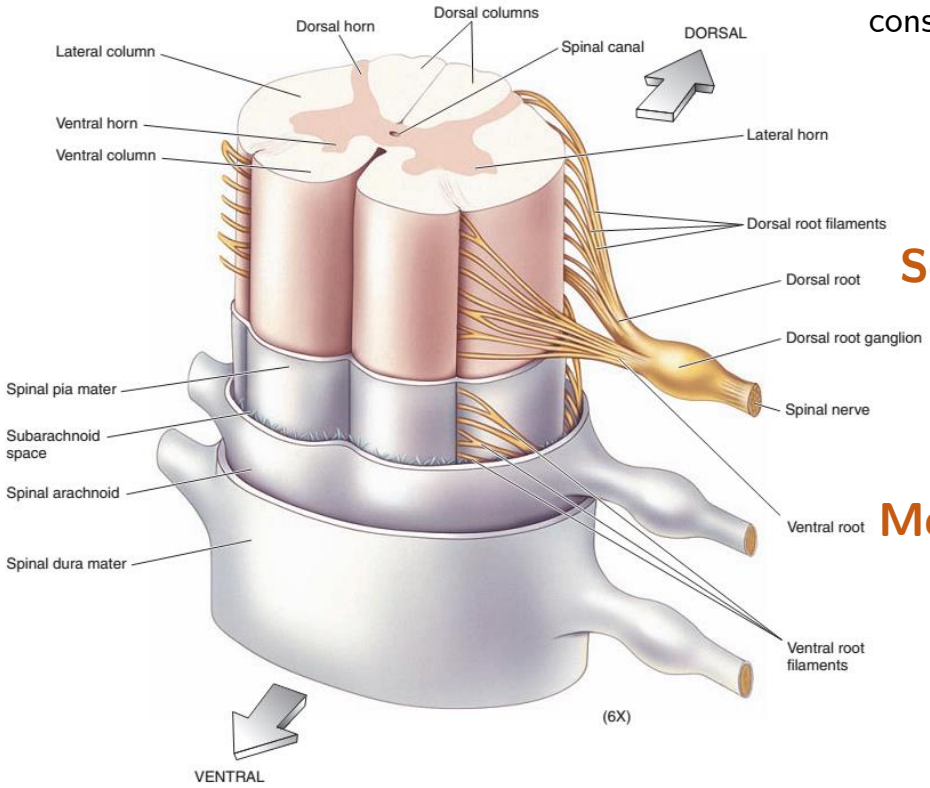


The major divisions of the central nervous system



The spinal cord

The **butterfly shaped** core of the spinal cord is **gray matter** consisting of **neuronal cell bodies**

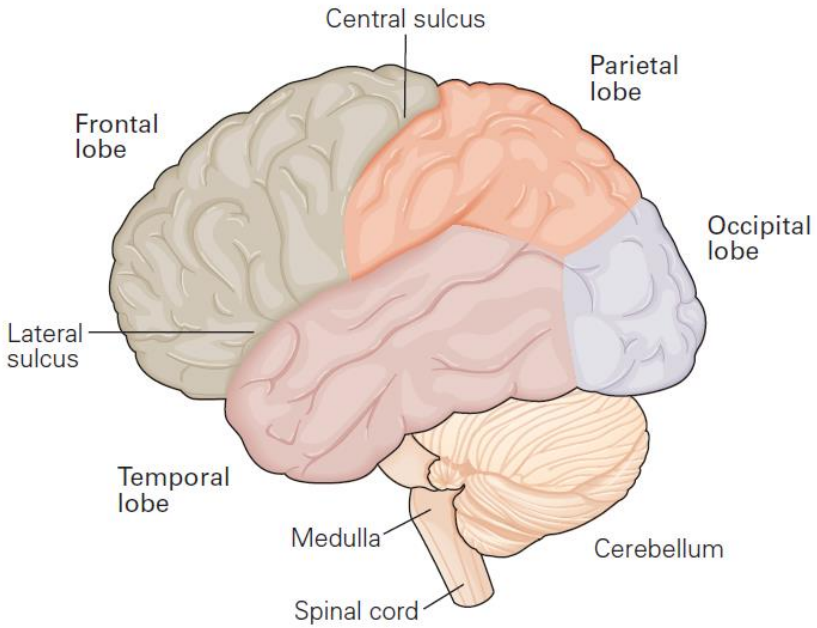


Sensory axons

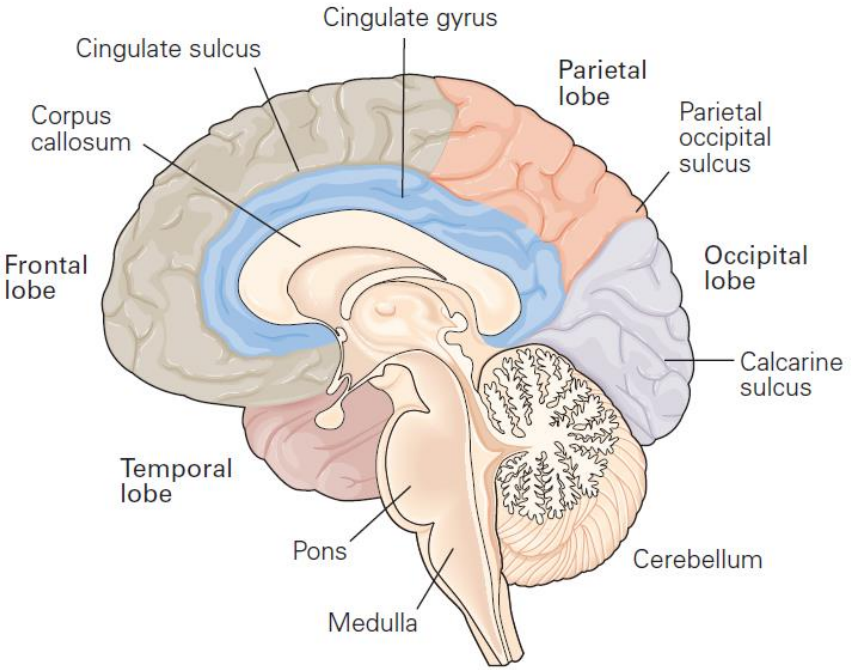
Motor axons

Organization of **gray** and **white** matter in the spinal cord **differs** from that in the forebrain

lateral view



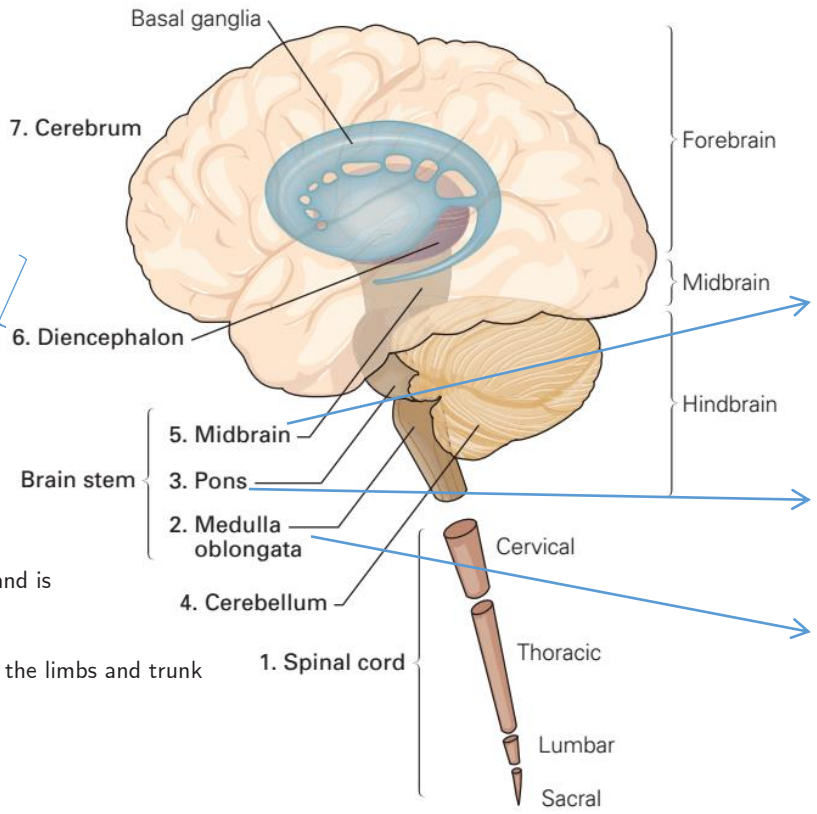
medial view



The central nervous system can be divided into seven main parts

thalamus processes most of the information reaching the cerebral cortex from the rest of the central nervous system

hypothalamus regulates autonomic, endocrine, and visceral functions



- Input/ output for spinal cord
- motor control for the head's musculature
- regulates levels of **arousal** and awareness through the reticular formation

modulates the force and range of movement and is involved in the learning of motor skills

Input/ output: skin, joints, and muscles of the limbs and trunk

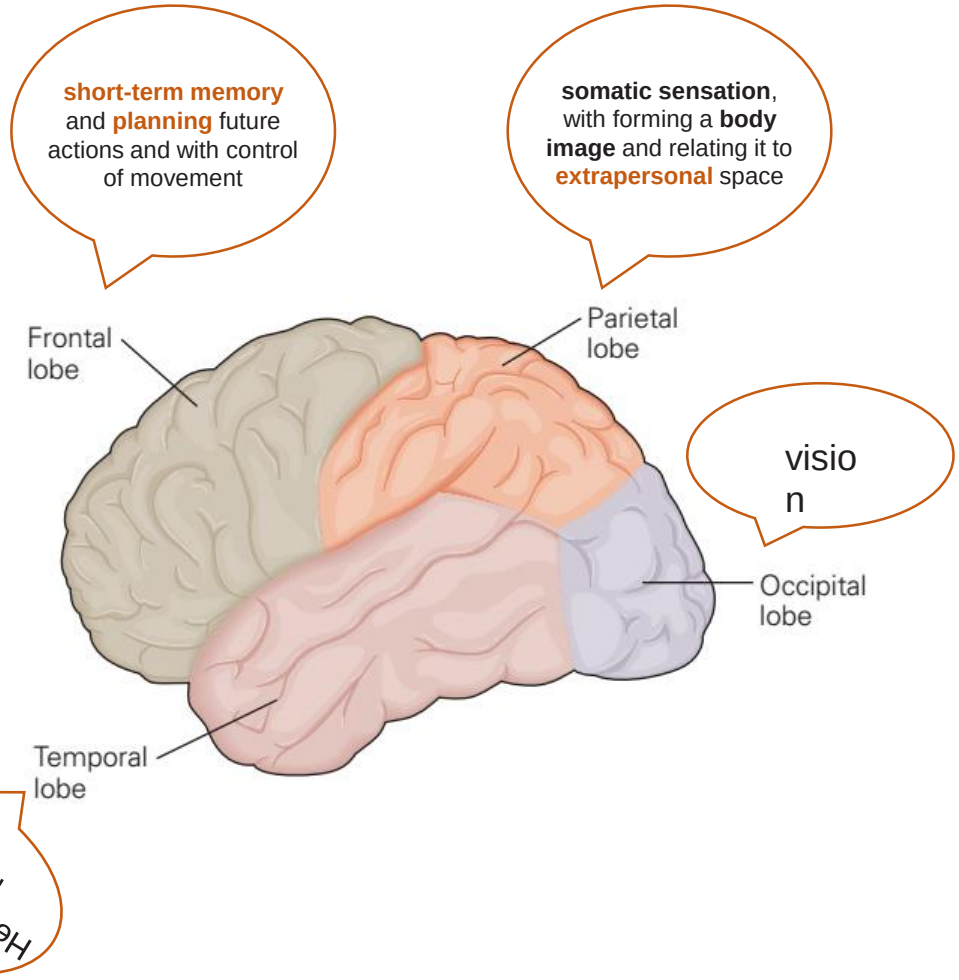
controls many sensory and motor functions, including **eye movement** and the coordination of visual and auditory reflexes

conveys information about movement from the cerebral hemispheres to the cerebellum

includes several centers responsible for vital autonomic functions, such as **digestion**, **breathing**, and the control of **heart rate**

Cerebrum

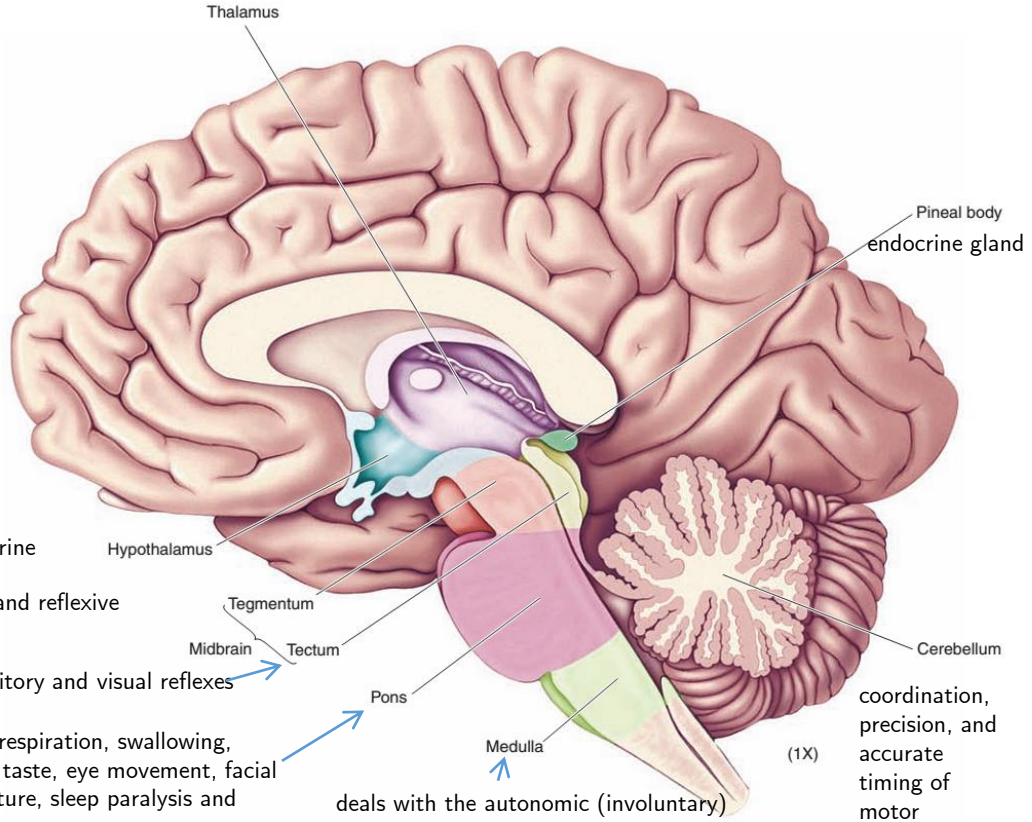
- Two cerebral hemispheres
- Four component:
  - **cerebral cortex**: heavily superficial wrinkled outer layer; consist of 4 lobes
  - Three **deep-lying** structures:
    - **Basal ganglia**: regulating motor performance
    - **Hippocampus**: aspects of memory storage
    - **Amygdaloid** nuclei: coordinate the autonomic and **endocrine** responses of emotional states



The Medial Surface of the Brain; Brain Stem Structures

midsagittal cut surface of the brain stem consisting of the:

- diencephalon (thalamus and hypothalamus); **encephalon: head**
- midbrain (tectum and tegmentum); **mesencephalon** (from the Greek **mesos**, *middle*, and **enkephalos**, *brain)*
- Pons, contain with matter and nuclei
- Medulla; marrow



link the nervous system to the endocrine system

many unconscious homeostatic and reflexive pathways

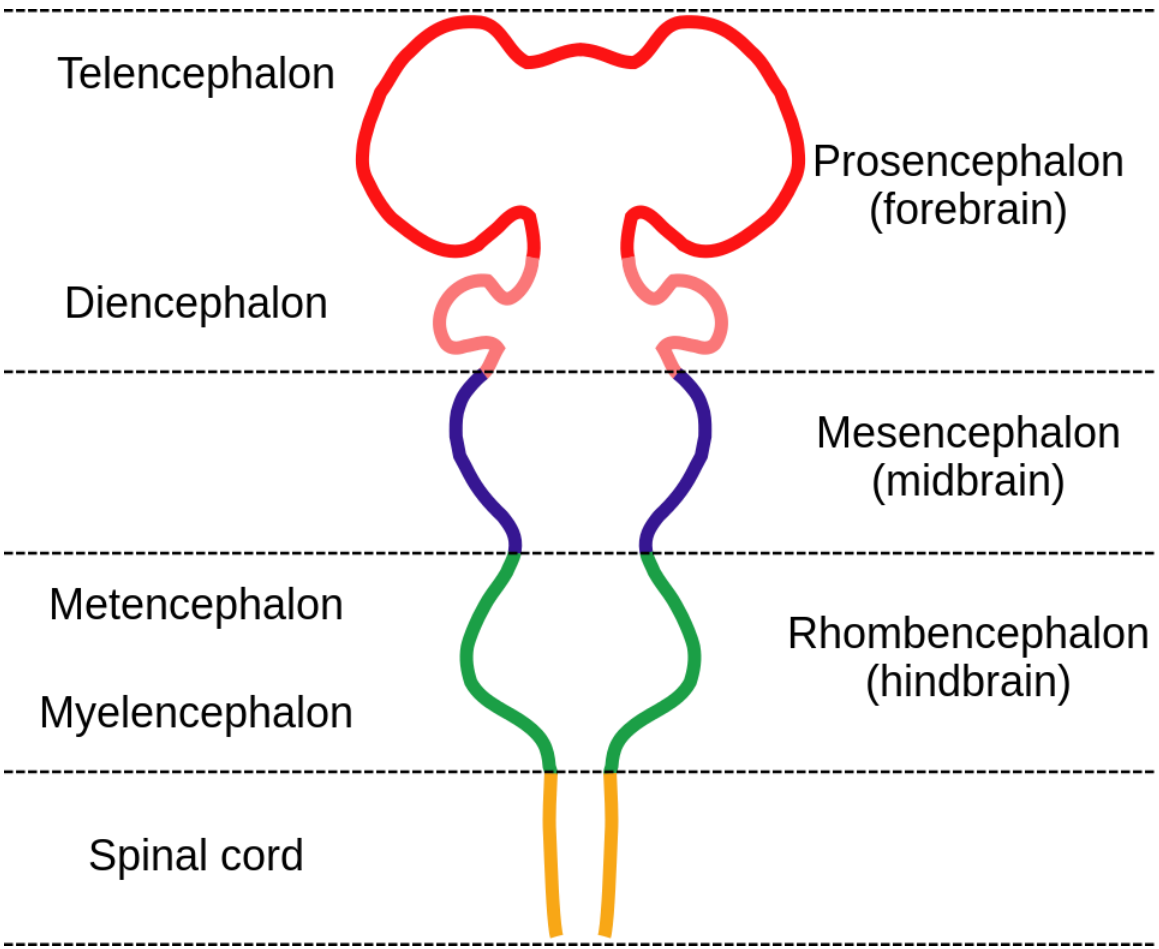
responsible for auditory and visual reflexes

nuclei that deal primarily with sleep, respiration, swallowing, bladder control, hearing, equilibrium, taste, eye movement, facial expressions, facial sensation, and posture, sleep paralysis and dream

deals with the autonomic (involuntary) functions of breathing, heart rate and blood pressure

coordination, precision, and accurate timing of motor

Embryonic vertebrate brain

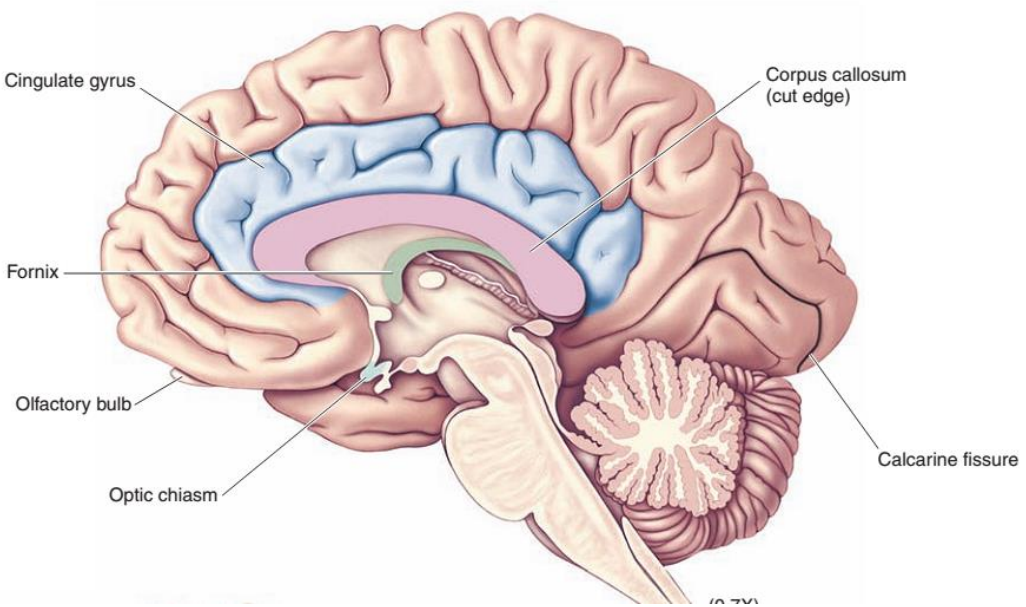


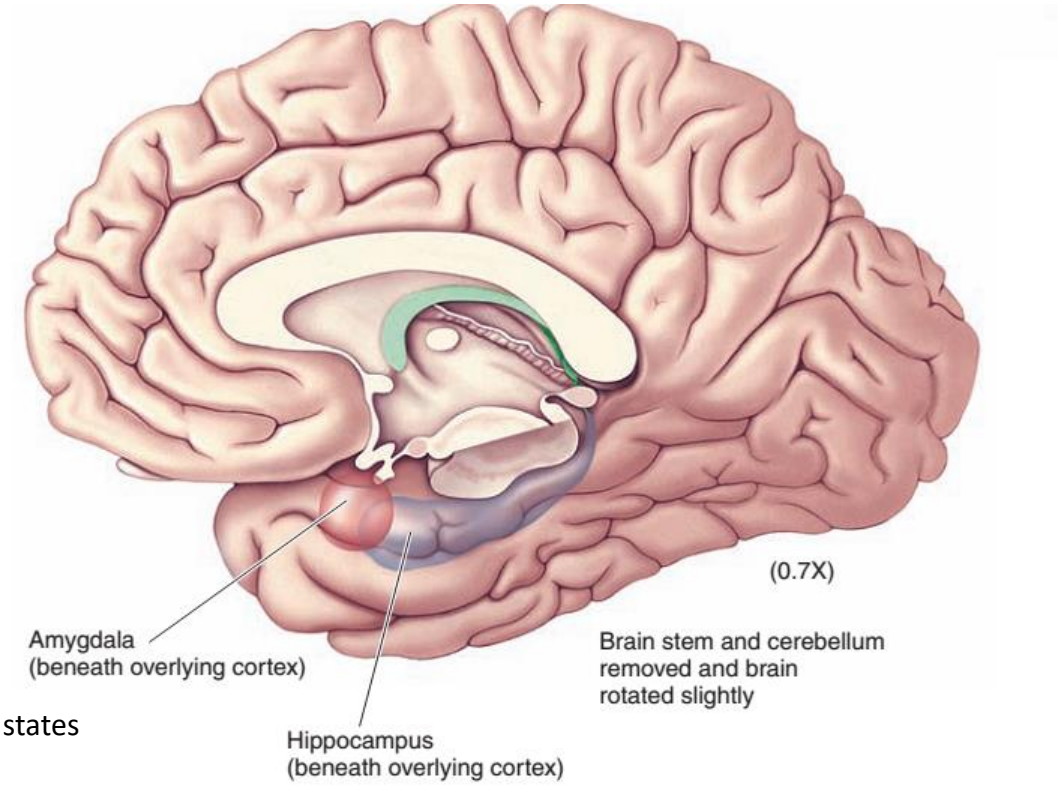
Forebrain Structures

Allocortex are mostly the **olfactory** system, and the **hippocampus**.
Neocortex vs. **allocortex**
Allocortex have **fewer cell layers**

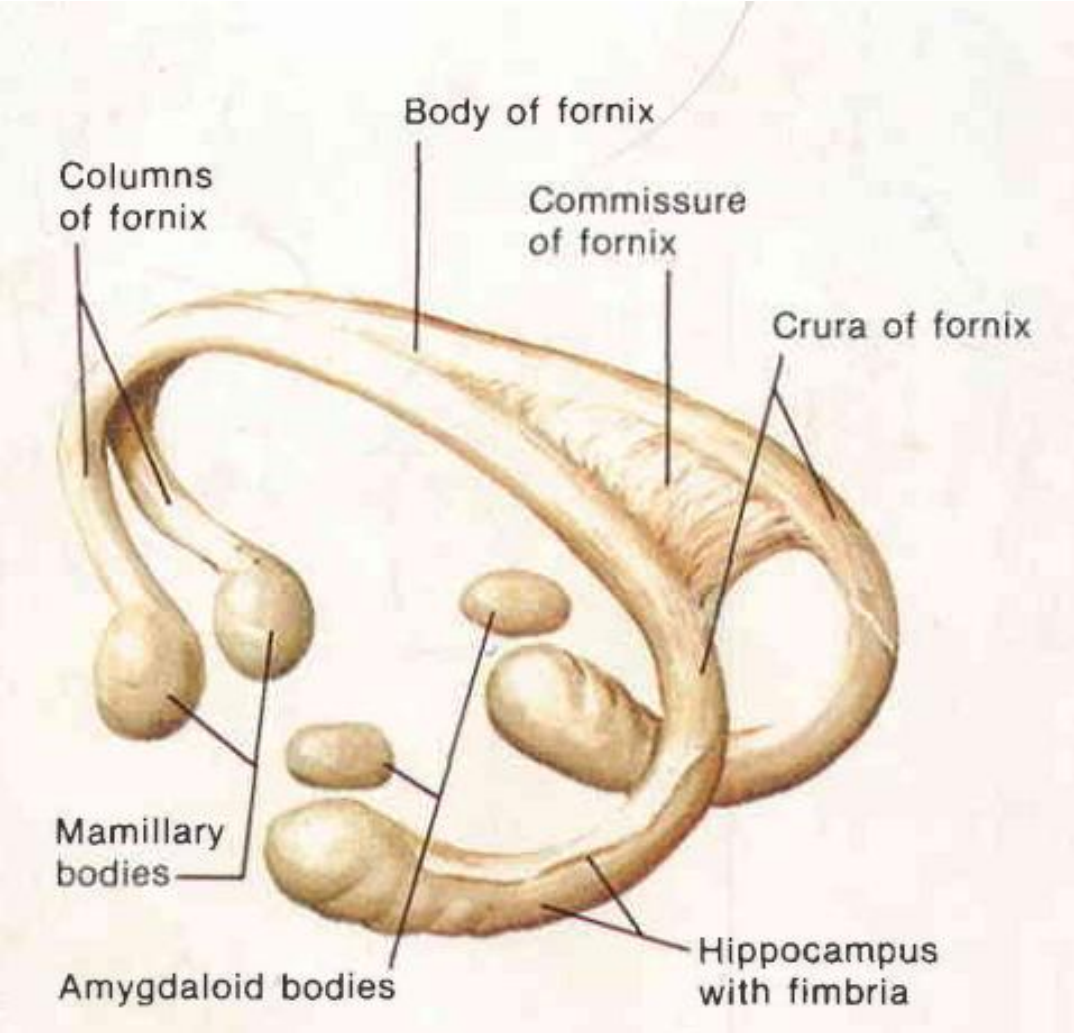
Receives inputs from the **thalamus and the neocortex**, and projects to the **entorhinal cortex**

Fornix is Latin for "**arch**." carries signals from the **hippocampus to the hypothalamus**



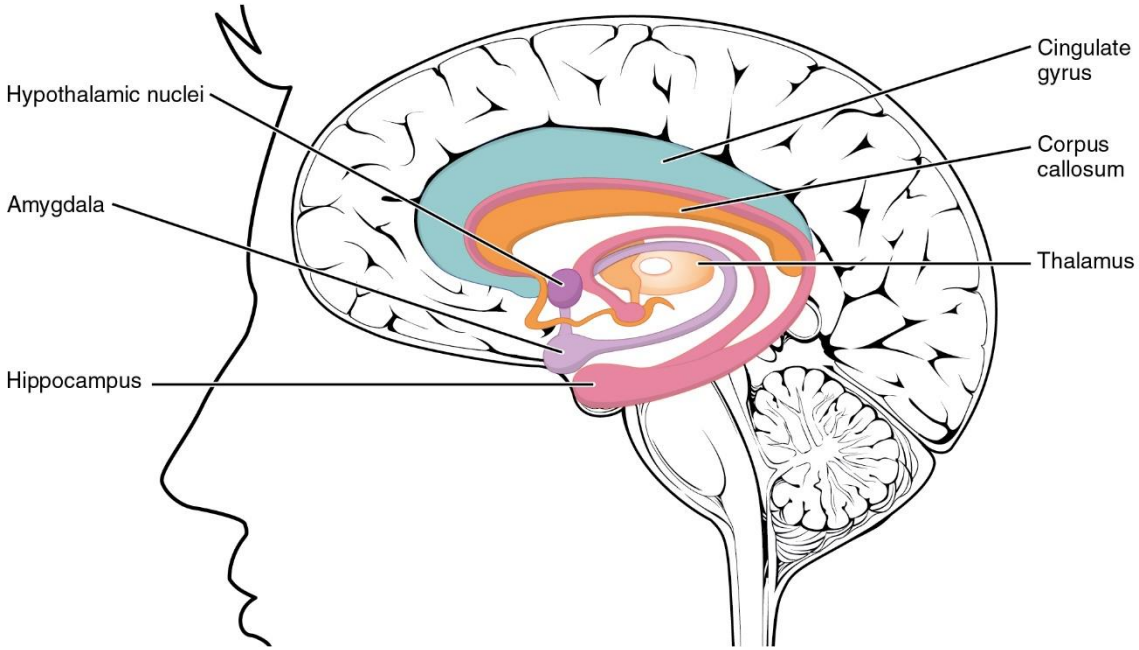


Latin for “**almond**”;
regulating **emotional** states


Body of fornix
Columns of fornix
Commissure of fornix
Crura of fornix
Mamillary bodies
Amygdaloid bodies
Hippocampus with fimbria

Limbic system

- The limbic system, also known as the paleomammalian cortex, is a set of brain structures located on both sides of the thalamus, immediately beneath the medial temporal lobe of the cerebrum primarily in the forebrain.
- Its various components support a variety of functions including emotion, behavior, long-term memory, and olfaction

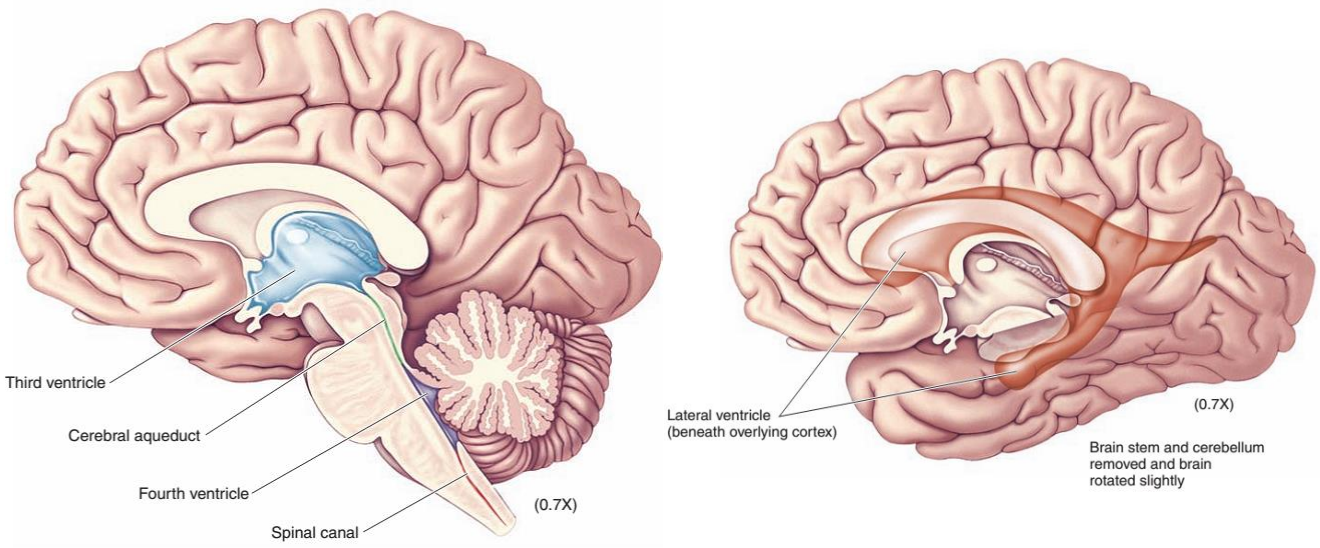


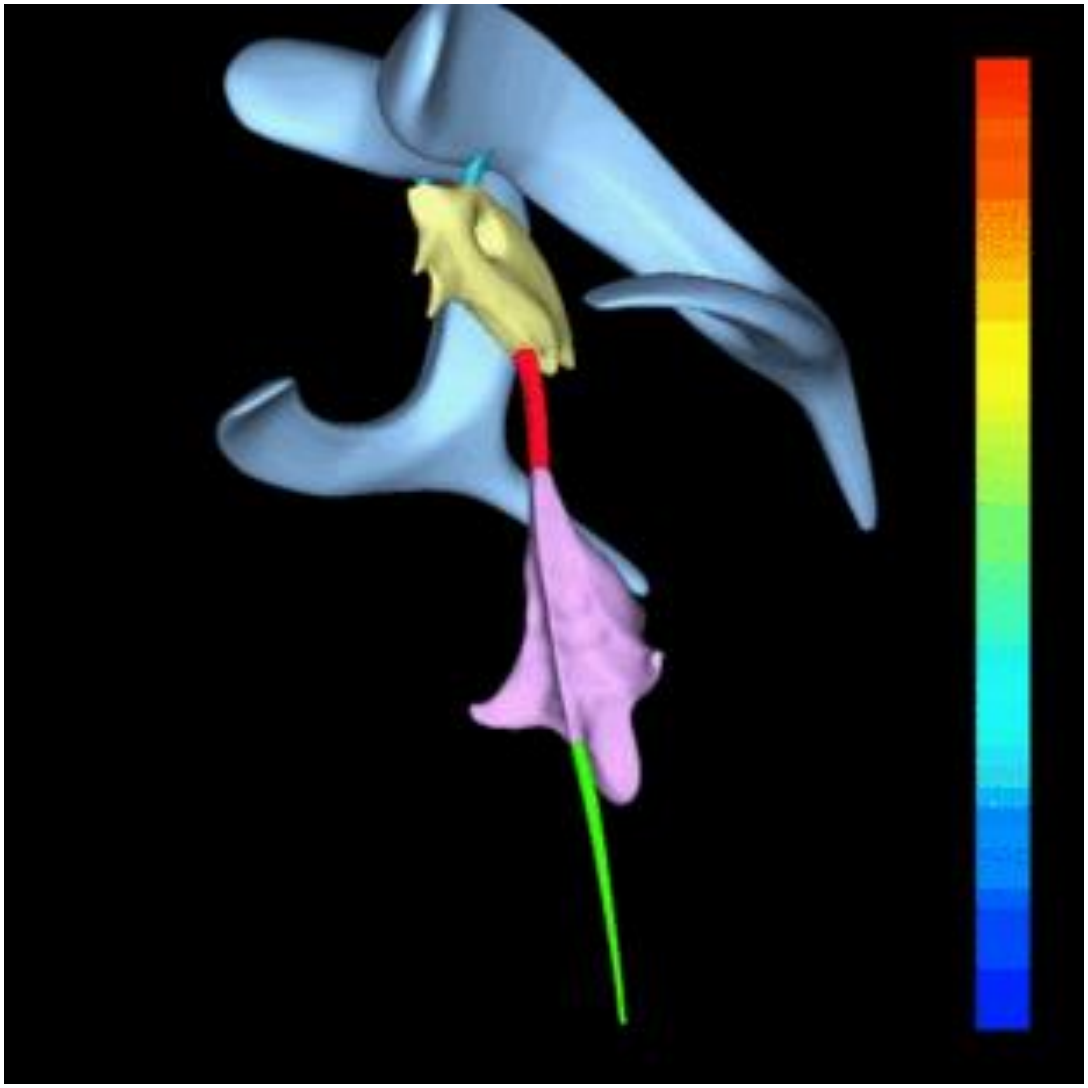
Limbic system

- The set of anatomical structures considered part of the limbic system is controversial. The following structures are, or have been considered, part of the limbic system
- Cortical areas:
  - Limbic lobe
  - Orbitofrontal cortex: a region in the frontal lobe involved in the process of decision-making
  - Piriform cortex: part of the olfactory system
  - Entorhinal cortex: related to memory and associative components
  - Fornix:
- Subcortical areas:
  - Septal nuclei: a set of structures that lie in front of the lamina terminalis, considered a pleasure zone
  - Hippocampus and associated structures: play a central role in the consolidation of new memories
  - Amygdala: located deep within the temporal lobes and related with a number of emotional processes
  - Nucleus accumbens: involved in reward, pleasure, and addiction
- Diencephalic structures:
  - Hypothalamus
  - Mammillary bodies
  - Anterior nuclei of thalamus

Ventricles

Where the **cerebrospinal fluid** (CSF) is produced.



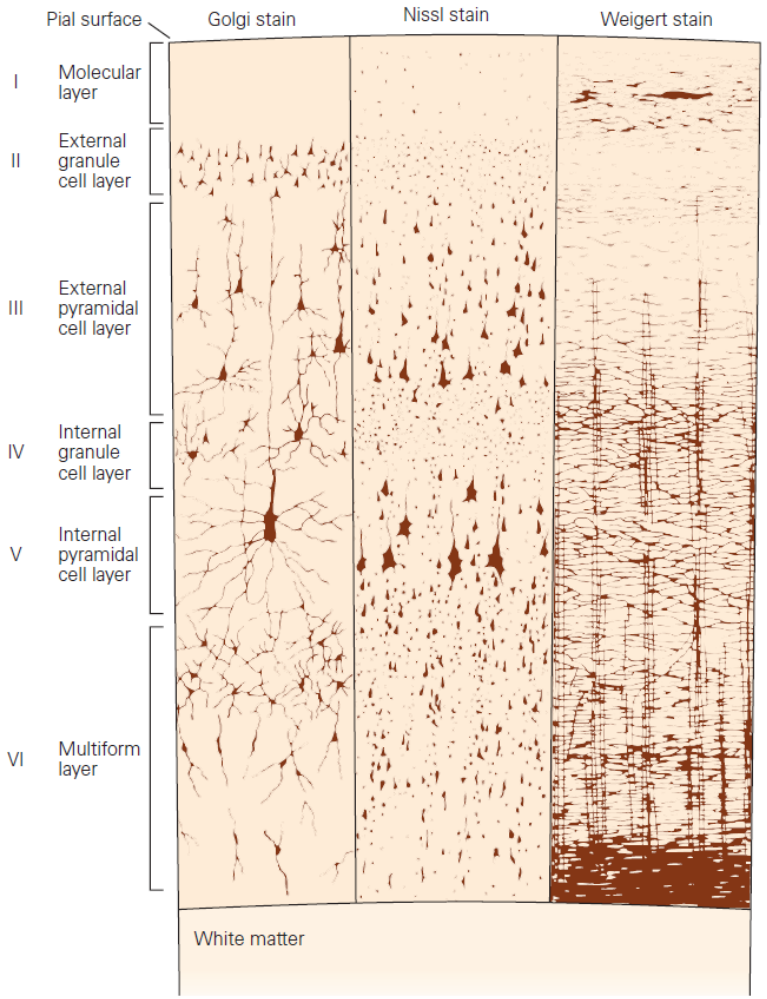


Information processing in sensory and motor systems

- Information is transformed at each **synaptic relay**
- Neurons at each synaptic relay are organized into a **neural map** of the body
  - Arranged **topographically throughout successive stages of processing**
  - **Neighboring** groups of cells in the retina, for example, project to neighboring groups of cells in nuclei of the **thalamus**, which, in turn, project to neighboring regions of the visual cortex
  - **Neural map** reflects the **density of innervation** of that part
- Each functional system is **hierarchically organized**
  - **Primary sensory** areas of cortex are the initial site of cortical processing of sensory information,
  - Each **higher-order sensory area** sends its outputs to one or another of three major **multimodal association areas** that integrate information from two or more sensory modalities and coordinate this information with **plans for action**
- **Decussations**: functional systems on one side of the brain control the other side of the body (**pain** at early stage, fine **touch** in medulla)

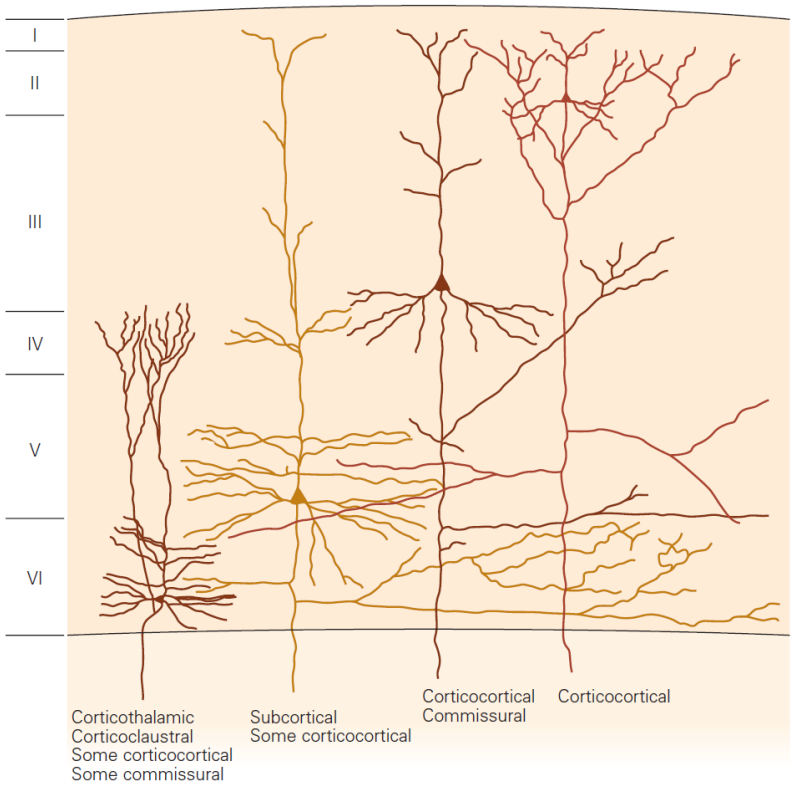
Neurons in the cerebral cortex are organized in layers and columns

- The cerebral cortex is **concerned with cognition**
- The **Golgi** stain:
  - Reveals a subset of neuronal **cell bodies**, **axons**, and **dendritic** trees.
- The **Nissl** method:
  - Shows **cell bodies** and proximal dendrites.
- The **Weigert** stain:
  - Reveals the pattern of **myelinated fibers**



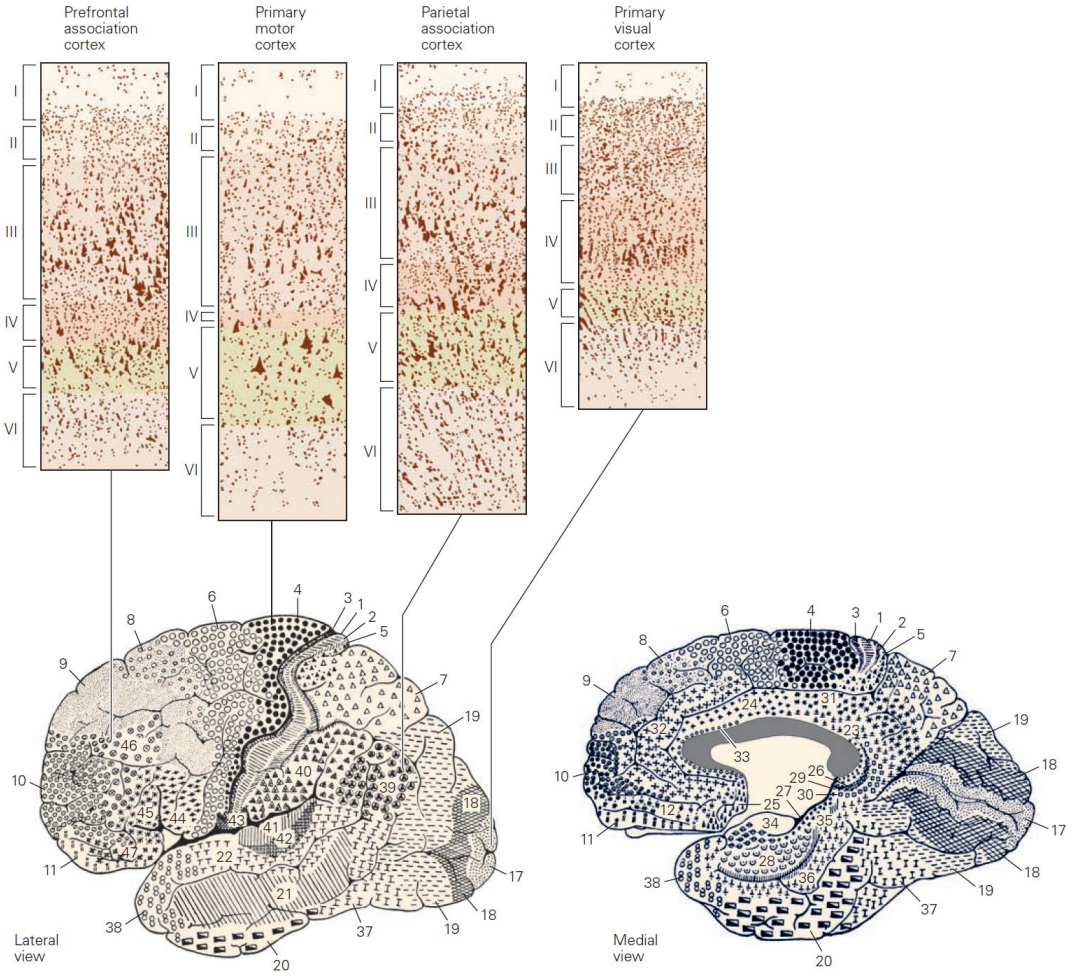
Neurons in different layers of neocortex project to different parts of the brain.

- **Corticocortical** or **associational** connections:
  - Projections to other parts of the neocortex
  - Neurons in **layers II and III**.
- Projections to **subcortical** regions arise mainly from **layers V and VI**

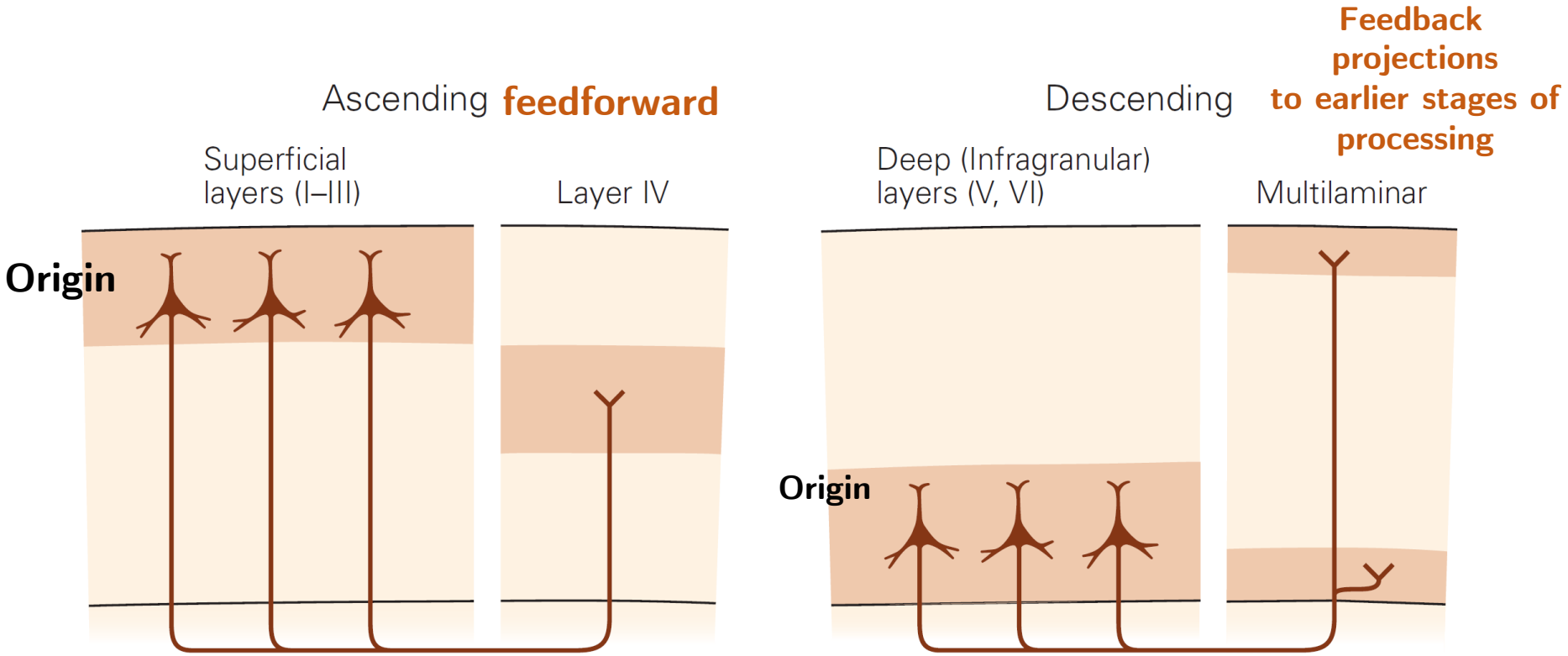


The extent of each cell layer of the neocortex varies throughout the cortex

- **Sensory areas:**
  - prominent **internal granular cell** layer (**layer IV**), the sit of **input**.
- **Motor areas** of cortex:
  - prominent **output layers**, such as **layer V**.
- These differences led **Brodmann** at the turn of the 20th century to **divide the cortex**



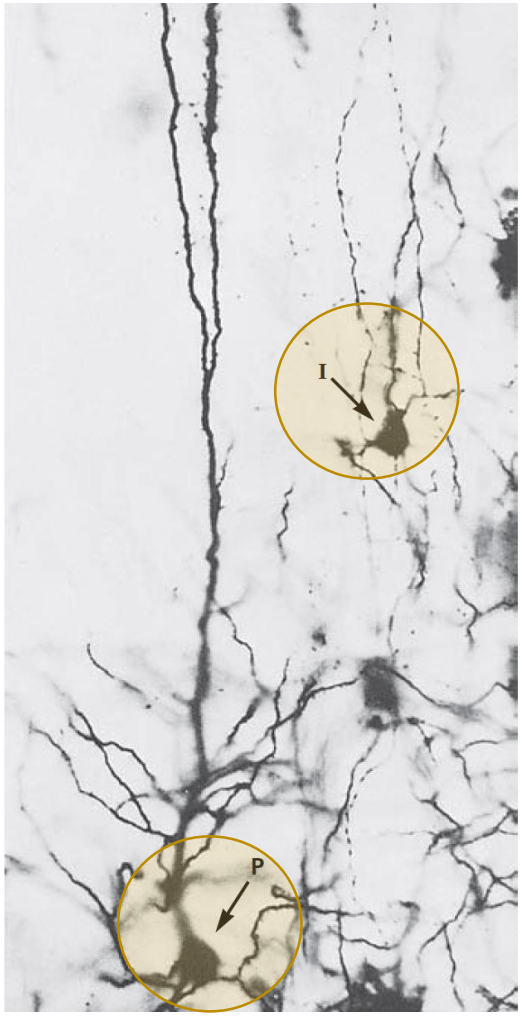
Feedforward and feedback connections in the cortex



Adapted, with permission, from **Felleman and Van Essen 1991**

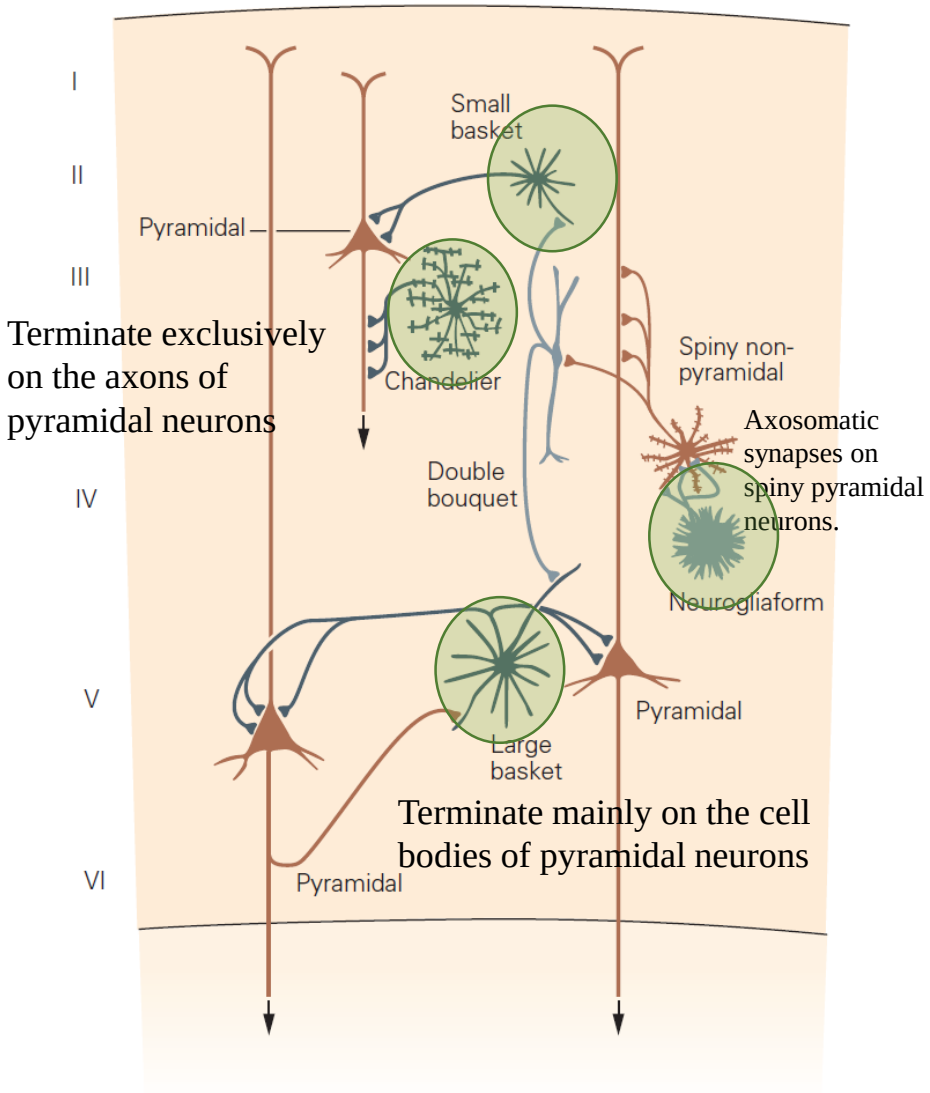
The cerebral cortex has a large variety of neurons

- Principal (**projection**) neurons:
  - Typically have **pyramidshaped** cell bodies.
  - They are located mainly in layers **III, V, and VI**
  - They use the amino acid **glutamate** as their primary transmitter at excitatory synapses.
  - The axons convey information to the **next synaptic relay** in the system.
- **Local** interneurons:
  - **Remain within the same area**
  - **GABA** at inhibitory synapses.
  - Constitute **20% to 25%** of the neurons



The cerebral cortex has several types of GABAergic interneurons

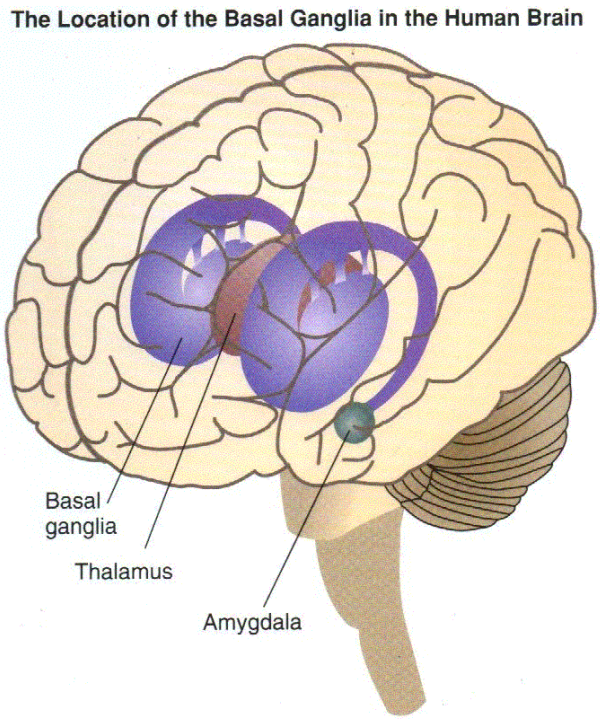
- Different connections with **projection neurons** in the neocortex
- The neocortex also has a population of **excitatory interneurons**:
  - Located primarily in **layer IV.**
  - These cells have **star-shaped** dendritic trees
  - Use **glutamate** as a transmitter.
  - These are the primary **recipients of sensory information** from the thalamus.

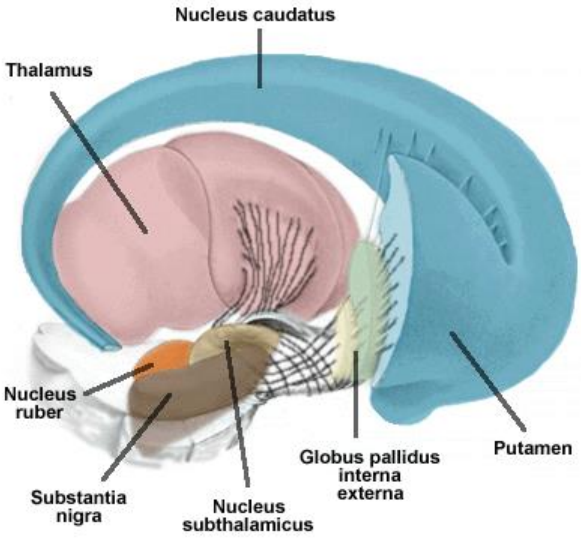


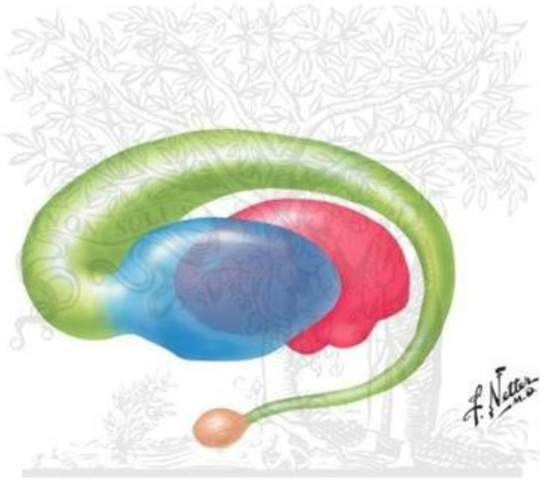
Subcortical regions of the brain are functionally organized into nuclei

- Three major structures lie **deep within the cerebral** hemispheres:
  - The **basal ganglia**:
    - Regulate **movement**, **input** from all cortex, **send** to prefrontal via thalamus
    - The **caudate** nucleus, **putamen**, **globus pallidus**, **subthalamic** nucleus, and **substantia nigra**
  - The **hippocampal formation**:
    - **Formation of long-term memories** about our daily experiences, so-called **episodic memories**
    - But are not the **permanent storage site** of these memories
  - The **amygdala:**
    - Analyzing the **emotional** or **motivational** significance of sensory stimuli.
- **Regulate** cortical activity

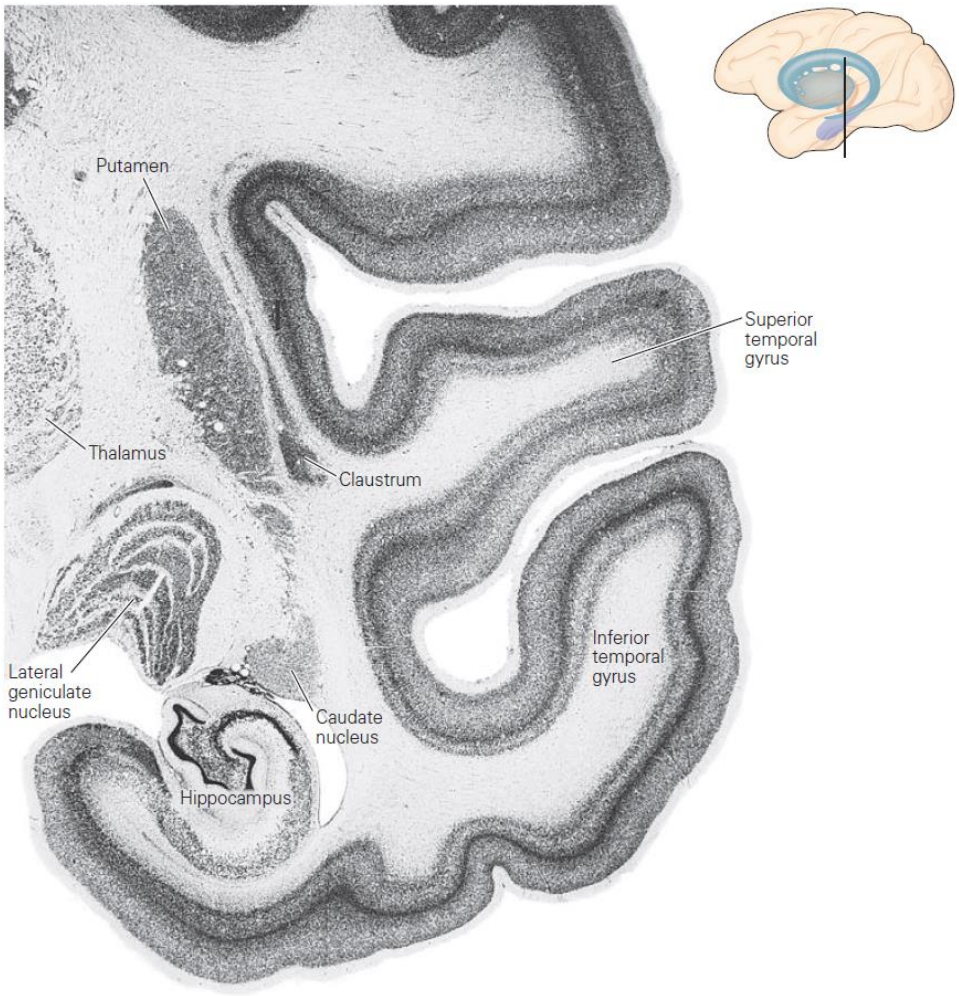
Basal ganglia





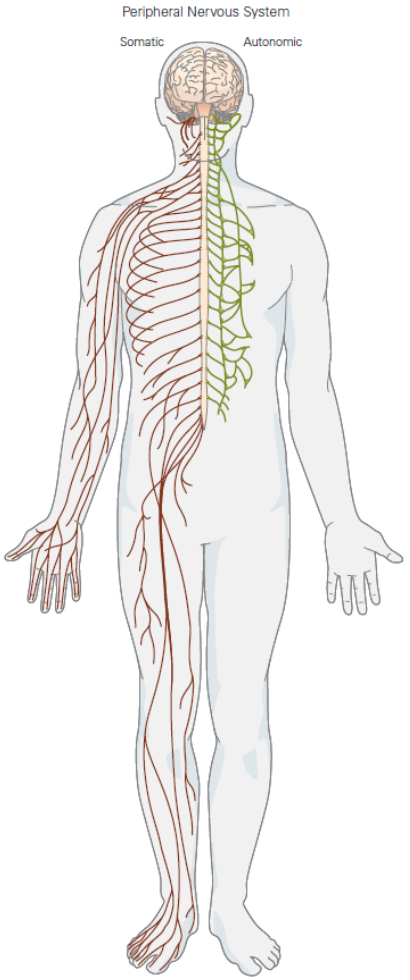


Nissl-stained

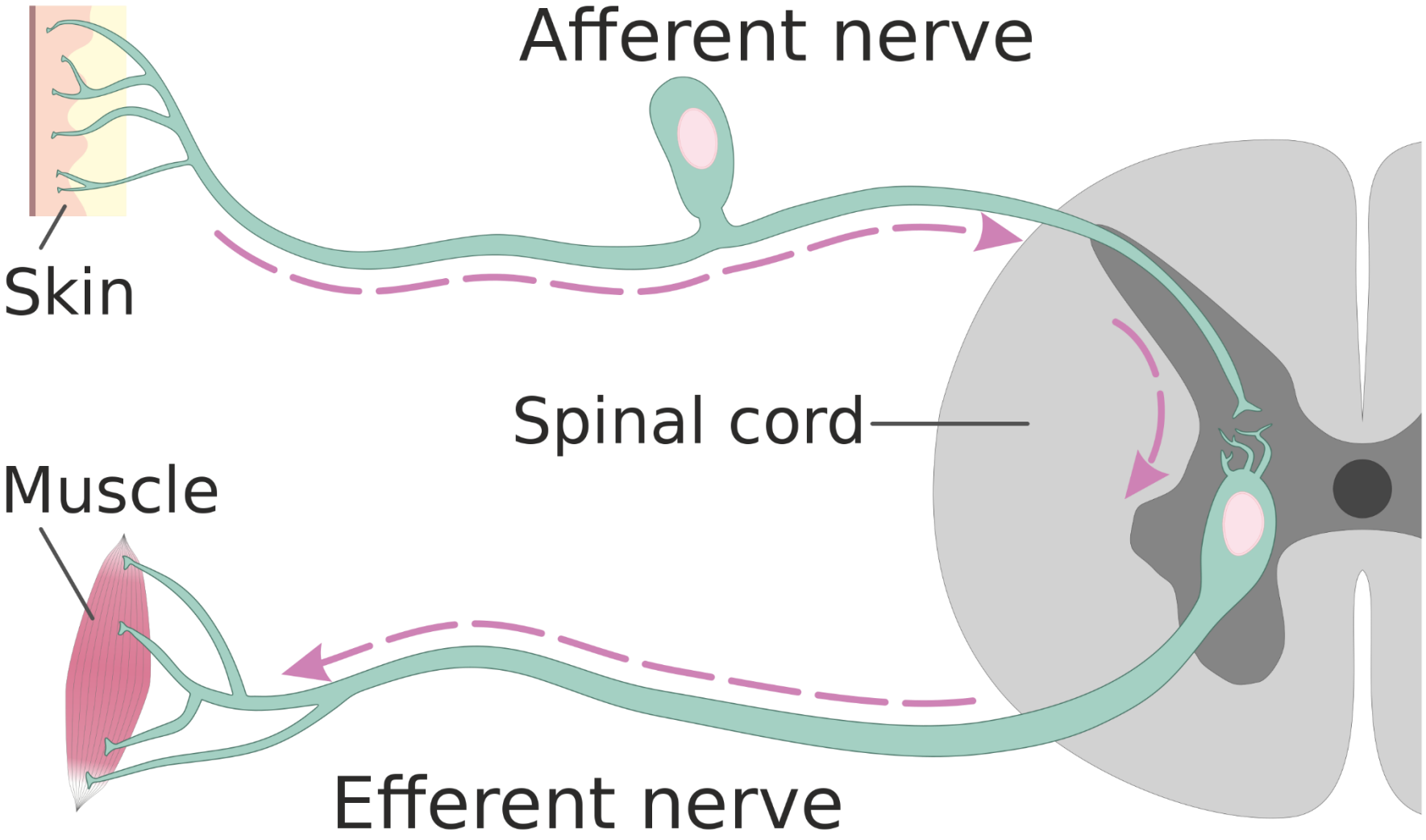


The peripheral nervous system is anatomically distinct from the central nervous system

- The **somatic division**:
  - **Carries information** from the skin to the brain (afferent nerve fibers) and from the brain (efferent nerve fibers) to muscles.
  - Associated with the **voluntary control** of body movements via skeletal muscles
- The **autonomic** division:
  - Regulates **involuntary** functions, including: activity of the **heart and smooth muscles** in the gut and Glands

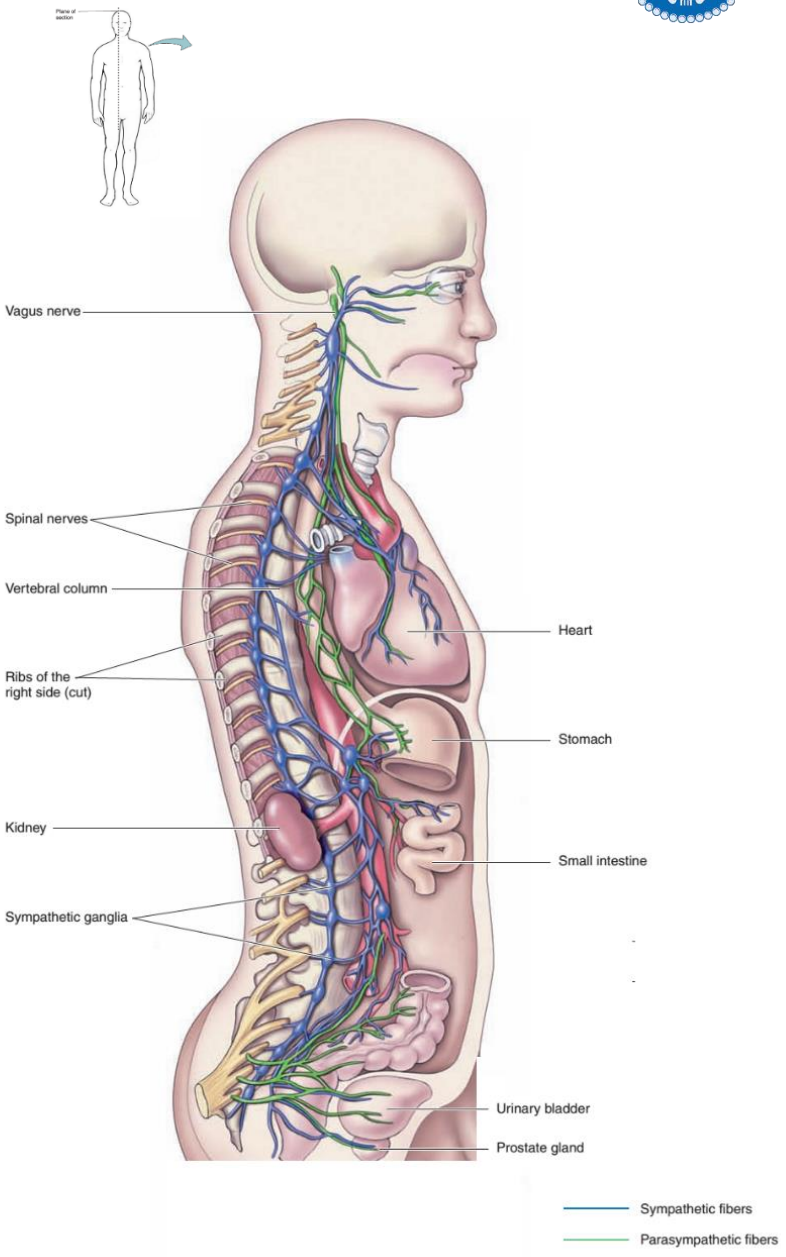


PNS: **somatic division**



Autonomic division

- **Visceral PNS**, devoted to the **regulation** of the internal organs, glands, and vasculature
- **Sympathetic** and **parasympathetic** divisions:
  - **Sympathetic** consists of a chain of ganglia that runs along the **side of the vertebral column**.
  - Much of the **parasympathetic** innervation arises from the **vagus** nerve, one of the cranial nerves emerging from the medulla. Other source is **sacral spinal** nerves.
- Opposite effects on body physiology:
  - The **sympathetic** system participates in the body's **response to stress**, whereas the **parasympathetic** system acts **to conserve body resources and restore homeostasis**.
  - e.g. The **sympathetic** nervous system speeds heart rate, while the **parasympathetic** nervous system slows it down



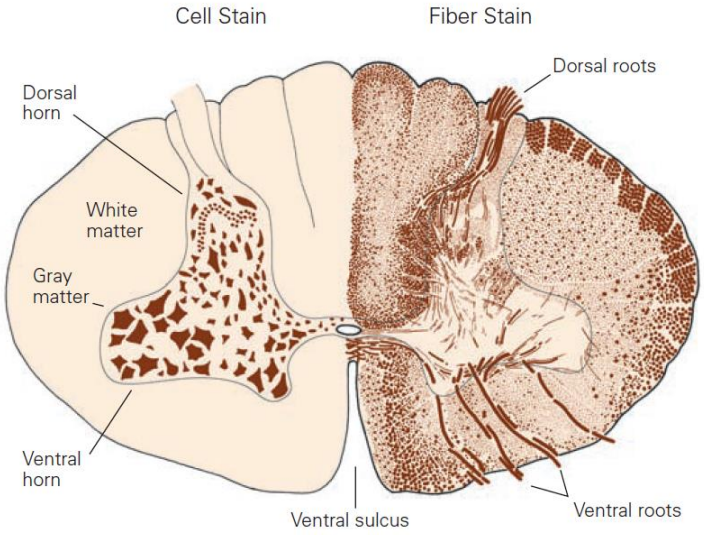
Functional organization of the brain is simplified by three anatomical considerations

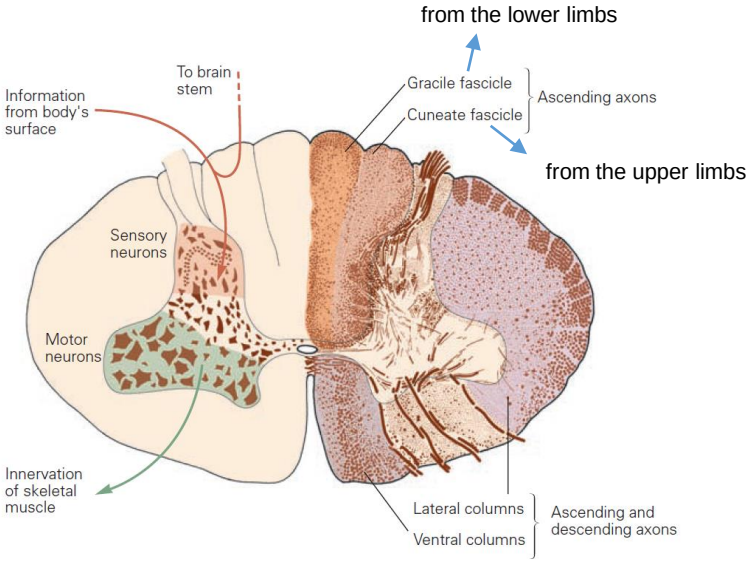
- First, there are relatively **few types of neurons**.
  - Cells has a similar structure and serves a similar function.
- Second, neurons are **clustered** in discrete **functional groups** called **nuclei**, which are connected to form functional systems.
  - The neurons in one **nucleus** usually have roughly **similar connections and functions**
  - A nucleus is one of the **two most common forms** of nerve cell organization, the other being **layered structures**
  - Nucleus shows up as a region of **gray matter**, often **bordered** by white matter
- Third, specific regions of the cerebral cortex are **specialized** for **sensory**, **motor**, or, **associational** functions

General rules in processing of complex behaviors

- Complex behaviors require the **integrated action** of several nuclei and cortical regions.
- Information is processed in the brain in a **hierarchical** fashion.
  - Information about a stimulus is conveyed through a **succession of subcortical and then cortical regions**
- At each level of processing the information becomes **increasingly complex**.
- **Different types of information**, even within a single sensory modality, are processed in **several** anatomically **discrete pathways**.

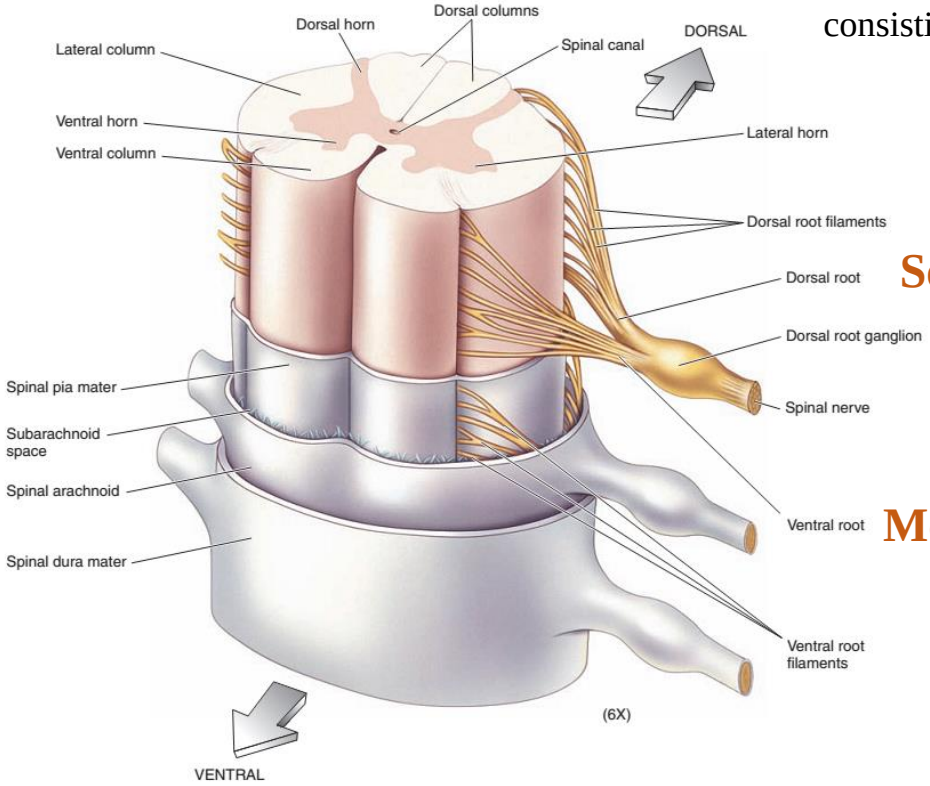
Somatosensory information from the trunk and limbs is conveyed to the spinal cord





Recall; the spinal cord

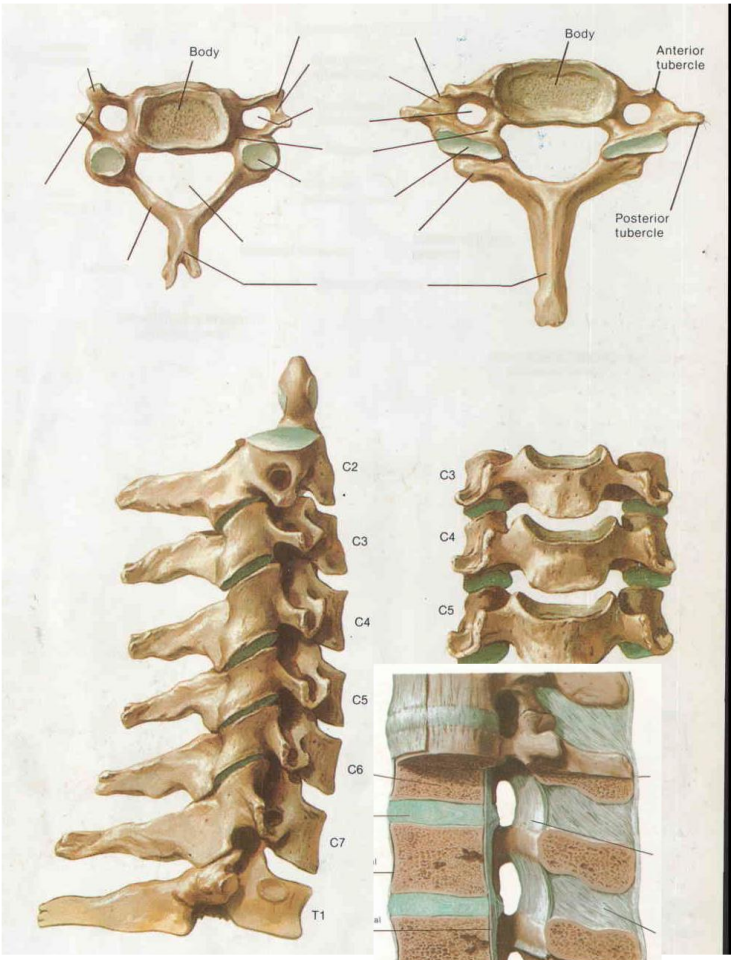
The **butterfly shaped** core of the spinal cord is **gray matter** consisting of **neuronal cell bodies**

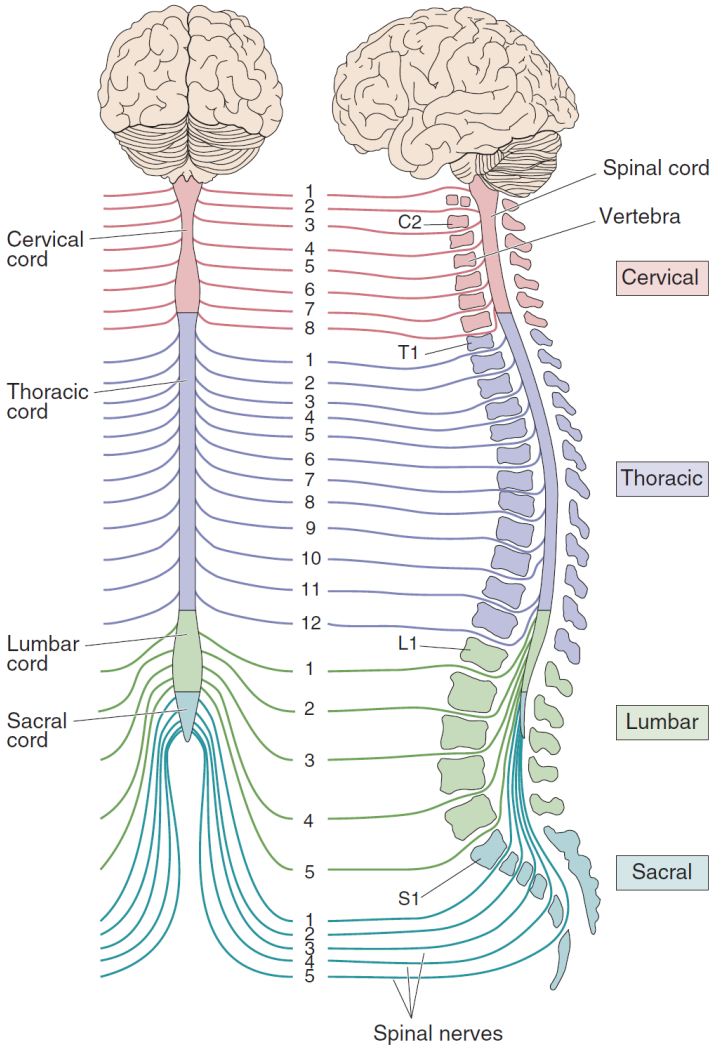


Sensory axons

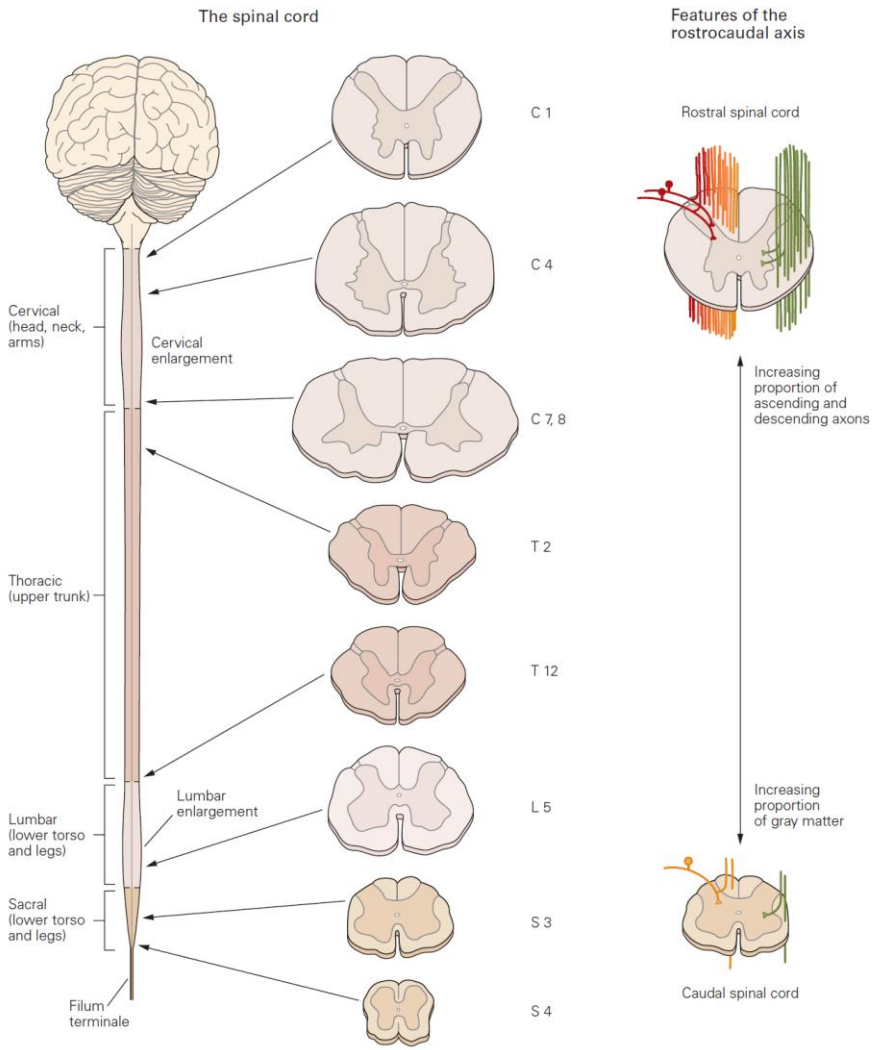
Motor axons

Organization of **gray** and **white** matter in the spinal cord **differs** from that in the forebrain


Body
Body
Anterior tubercle
Posterior tubercle
C2
C3
C4
C5
C6
C7
T1
C3
C4
C5


Cervical cord
Thoracic cord
Lumbar cord
Sacral cord
1 2 3 4 5 6 7 8
1 2 3 4 5 6 7 8 9 10 11 12
1 2 3 4 5
1 2 3 4 5
Spinal cord
Vertebra
C2
T1
L1
S1
Cervical
Thoracic
Lumbar
Sacral
Spinal nerves

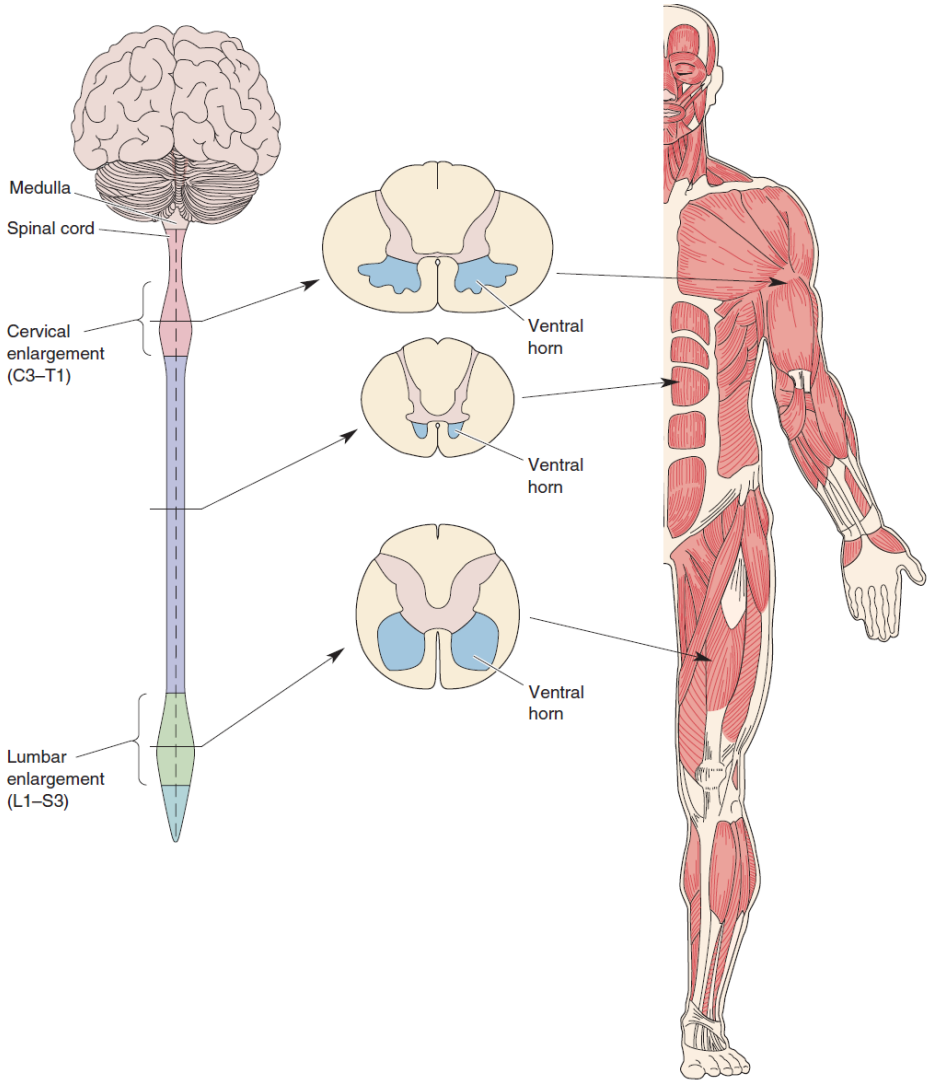
- There are **8 cervical** segments, **12 thoracic** segments, **5 lumbar** segments, and **5 sacral** segments.
- The proportion of gray matter (the H) to white matter:
  - **greater** at **sacral** levels than at **cervical** levels.
- Variation in the size of the ventral and dorsal horns.
  - The ventral horn is larger at the levels where the motor nerves that innervate the arms and legs exit the spinal cord



The distribution of motor neurons in the spinal cord

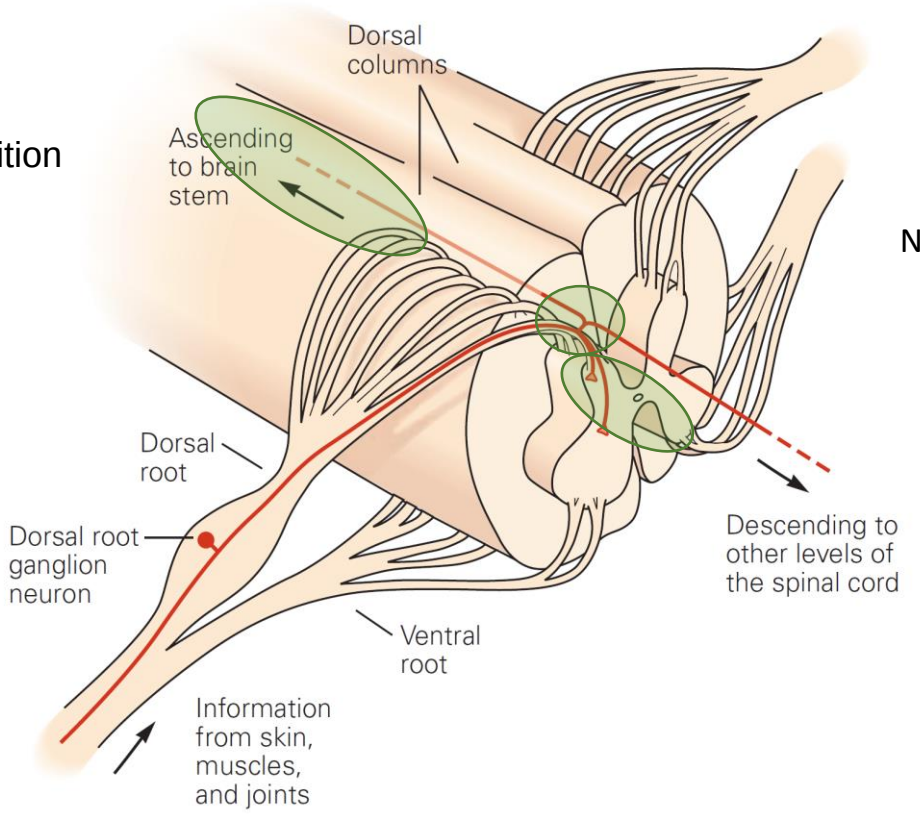
- The **cervical enlargement** of the spinal cord contains the motor neurons that **innervate** the arm muscles.

- The **lumbar enlargement** contains the neurons that innervate the **muscles of the leg**.



The primary sensory neurons of the trunk and limbs are clustered in the dorsal root ganglia

Raw material for the **perception** of touch, position sense, or pain

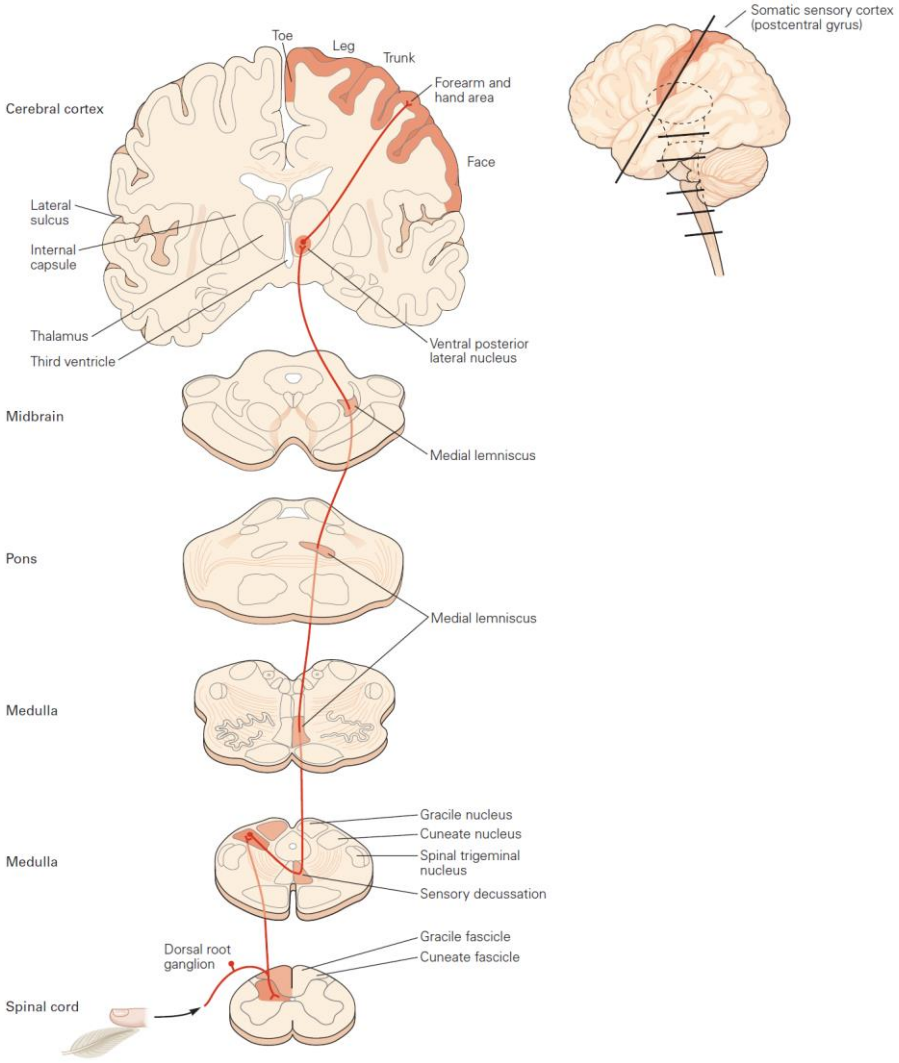


Neurons are **bifurcated** into peripheral and central branches.

local branches;
Activate **local reflex circuits**

Ascending dorsal column–medial lemniscal pathway to primary sensory cortex

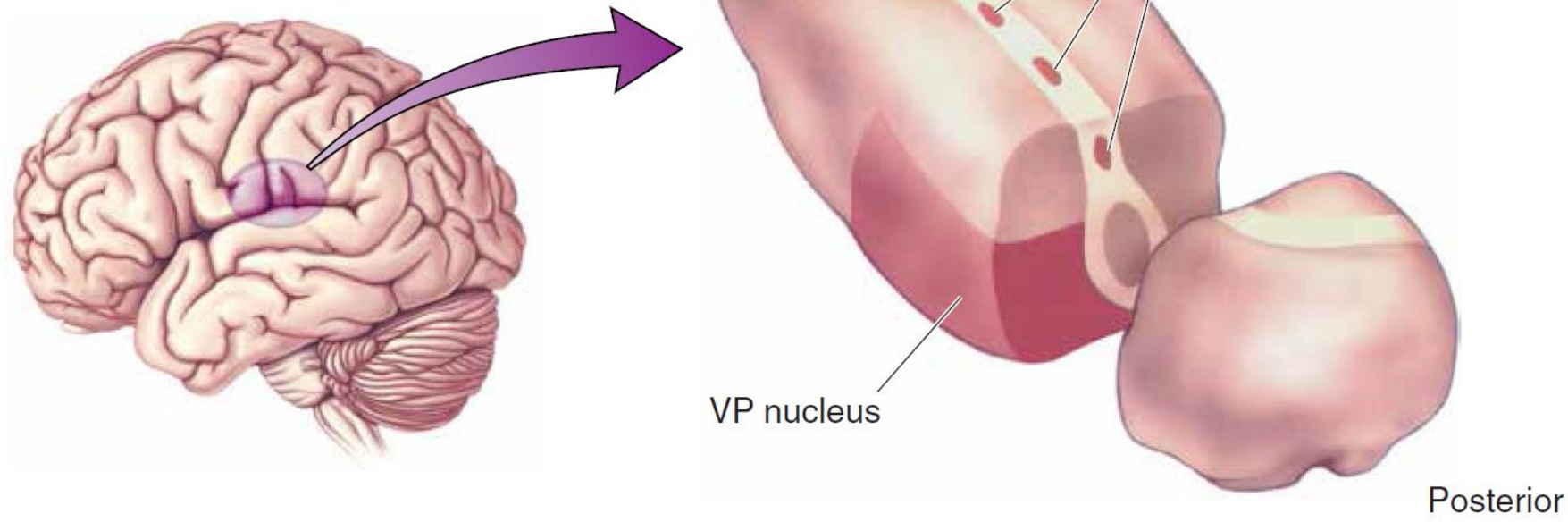
- Fibers that relay information from **different parts** of the body **maintain** an **orderly relationship** to each other and form a neural **map of the body** surface at each **synaptic relay**.
- Each somatic **submodality** is processed in a **distinct** subsystem from the periphery to the brain



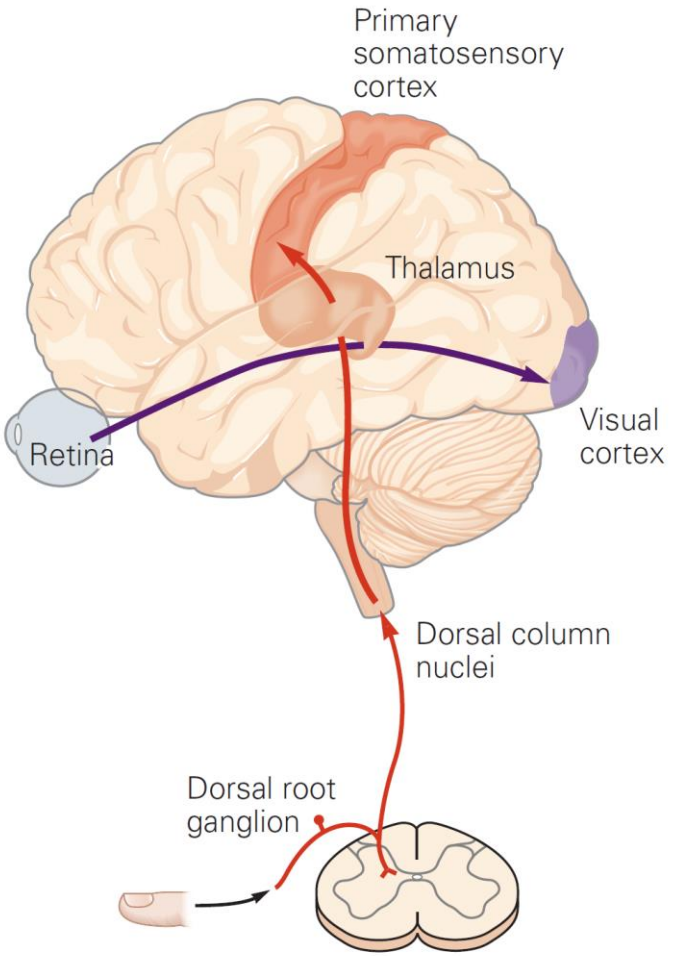
The thalamus as brain gate keeper

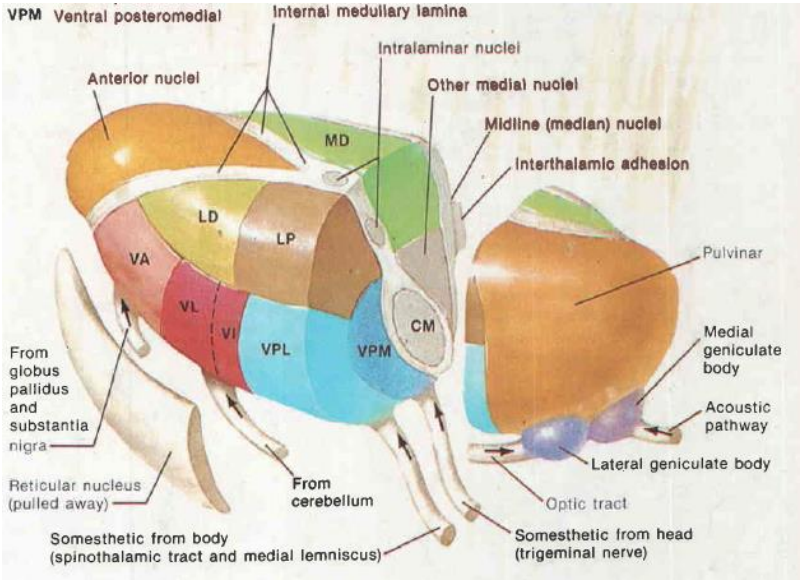
- The thalamus is an essential **link** between sensory **receptors** and the cerebral **cortex** for all modalities except olfaction
- More **than a relay**, a **gatekeeper** for information to the cerebral cortex, **preventing or enhancing the passage** of specific information **depending on the behavioral** state of the animal
- Made up of several well-defined **nuclei**. (As many as 50 thalamic nuclei)
  - Ventral posterior lateral nucleus (VPLE) for somatosensory
- Some portions of the thalamus participate in **motor** functions:
  - **Transmitting** information from the **cerebellum** and **basal ganglia** to the motor regions of the **frontal lobe**.
- **Internal capsule**:
  - A large **fiber bundle** that carries most of the axons running **to and from** the cerebral hemispheres
- The thalamus **not only projects** to the sensory areas of the neocortex but also receives extensive **return inputs back** from the neocortex

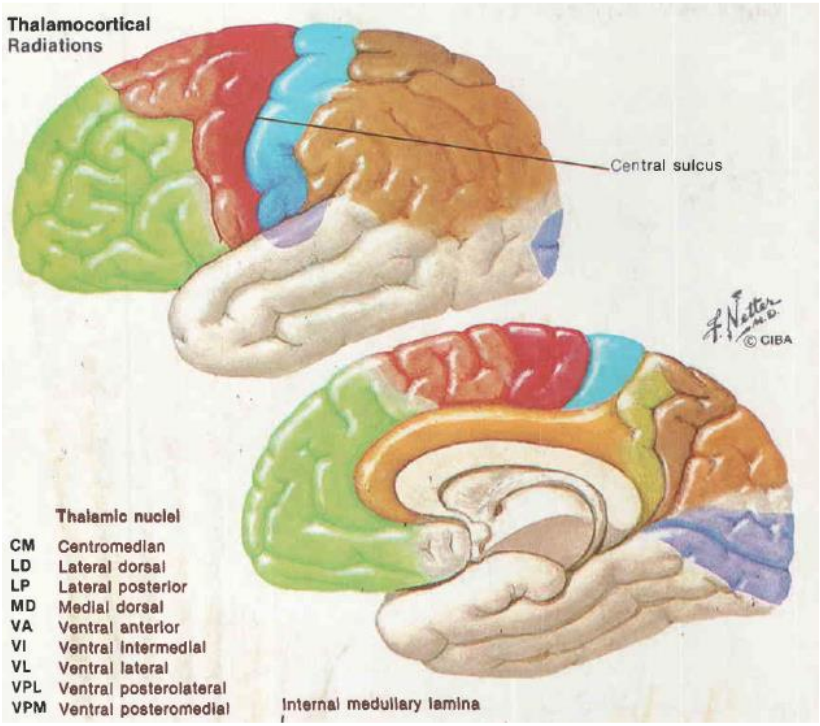
Somatic sensory nuclei of the thalamus. In addition to the **VP** nucleus, the **intralaminar nuclei** relay **nociceptive** information to a large expanse of the cerebral cortex.



- **Somatosensory** information:
  - it is conveyed from dorsal root ganglia to the **ventral posterior lateral** nucleus and from there to the primary somatosensory cortex
- **Visual** information
  - from the retina reaches the **lateral geniculate nucleus**, which conveys it to the primary visual cortex
- Each of the sensory systems, **except olfaction**, has a similar processing step within a distinct region of the thalamus




VPM Ventral posteromedial
Internal medullary lamina
Intralaminar nuclei
Anterior nuclei
Other medial nuclei
Midline (median) nuclei
Interthalamic adhesion
MD
LD
LP
VA
VL
VI
VPL
VPM
CM
Pulvinar
Medial geniculate body
Acoustic pathway
Lateral geniculate body
From globus pallidus and substantia nigra
Reticular nucleus (pulled away)
From cerebellum
Optic tract
Somesthetic from body (spinothalamic tract and medial lemniscus)
Somesthetic from head (trigeminal nerve)

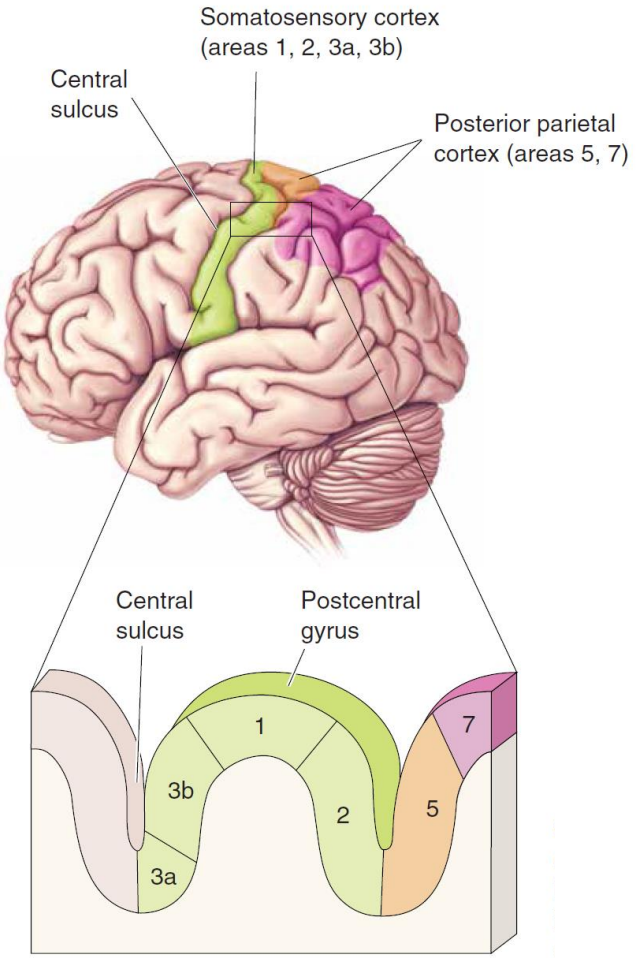

Thalamocortical Radiations
Central sulcus
F. Netter M.D.
© CIBA
Thalamic nuclei
CM Centromedian
LD Lateral dorsal
LP Lateral posterior
MD Medial dorsal
VA Ventral anterior
VI Ventral intermedial
VL Ventral lateral
VPL Ventral posterolateral
VPM Ventral posteromedial
Internal medullary lamina

Output of thalamus is subject to four types of processing

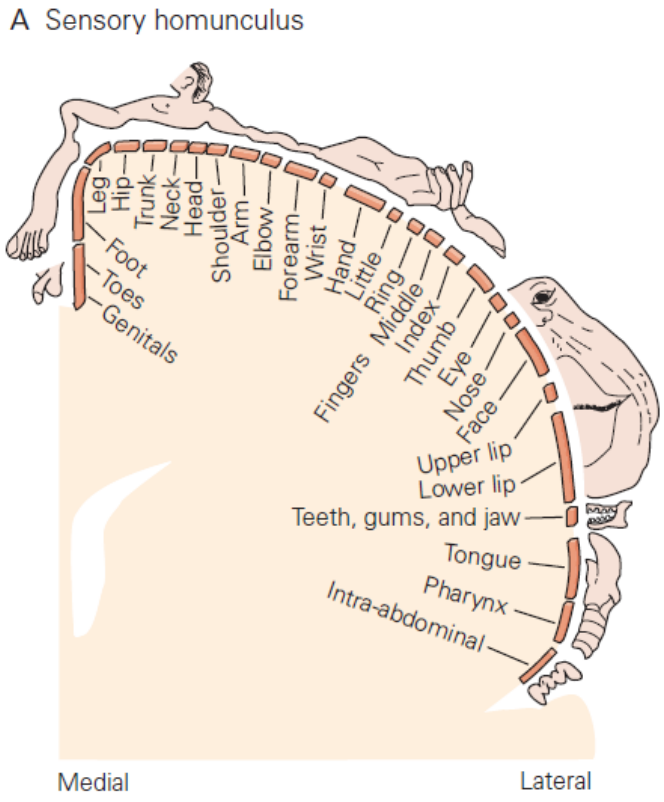
- (1) **local** processing **within** the nucleus;
- (2) **modulation** by **brain stem** inputs, such as the **noradrenergic and serotonergic** systems;
- (3) **inhibitory** feedback from the **reticular** nucleus; and
- (4) excitatory **feedback** from the **neocortex**.

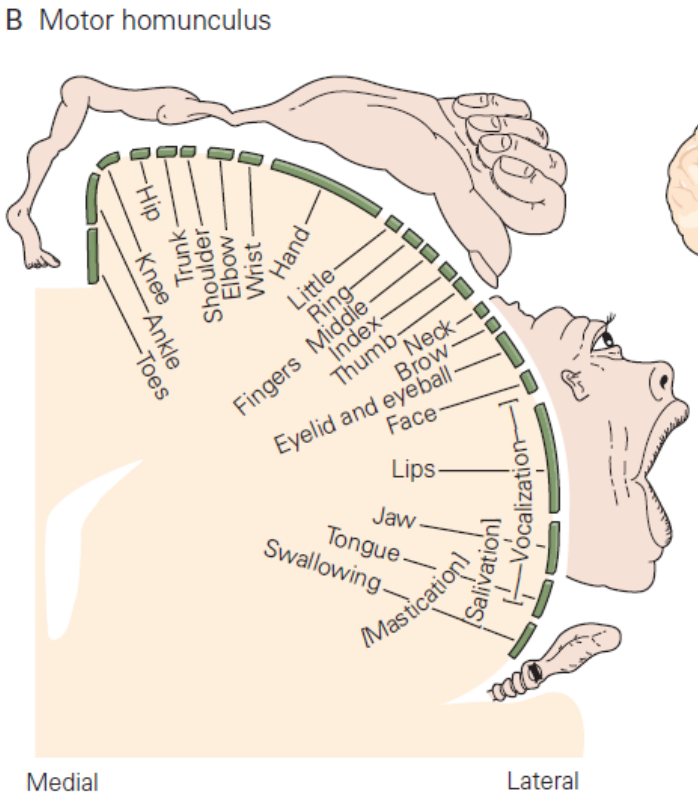
Sensory information processing culminates in the cerebral cortex

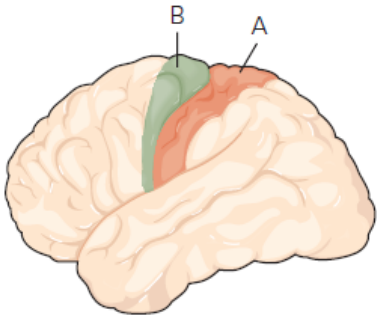
- It is **proportional to the density of innervation**, which translates to the **fineness** of discrimination in the body part
- The cells in **each column** comprise a **computational module** with a highly specialized function.
- The primary somatosensory cortex (anterior parietal cortex) has four **complete maps of the skin**, one each in areas **3a, 3b, 1**, and **2**
  - 3: **basic** processing of **tactile** information
  - 1: more **complex** or higher-order processing
  - In area 2 tactile information is **combined** with information concerning **limb position** to mediate the **tactile recognition of objects**.

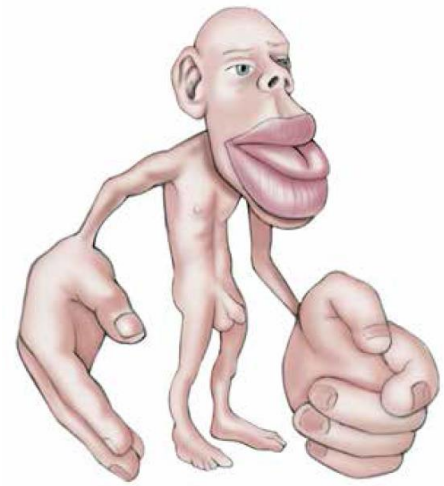


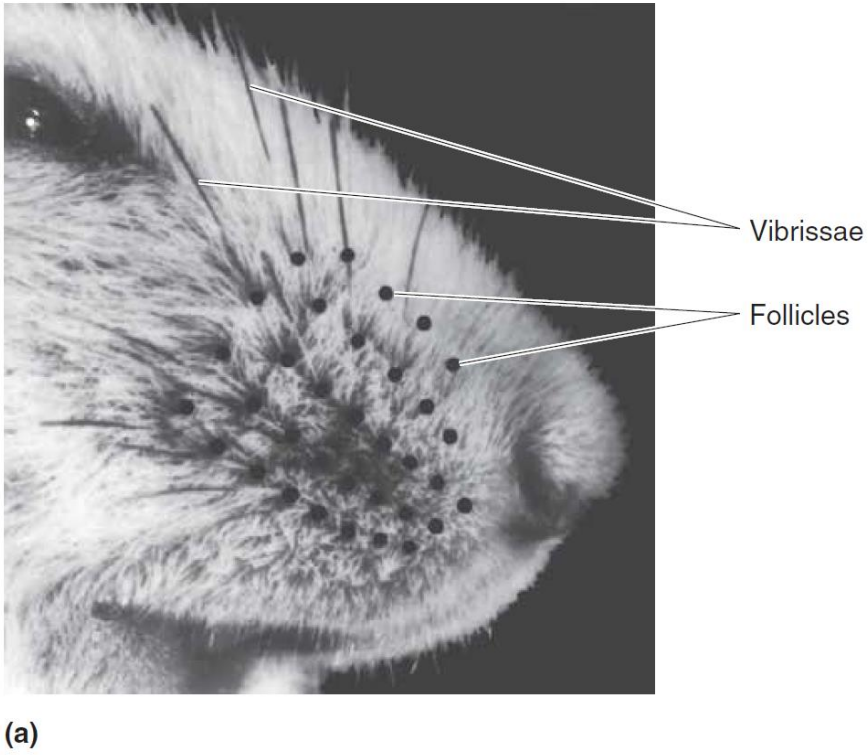
Homunculus illustrates the relative amounts of cortical area dedicated to individual parts of the body

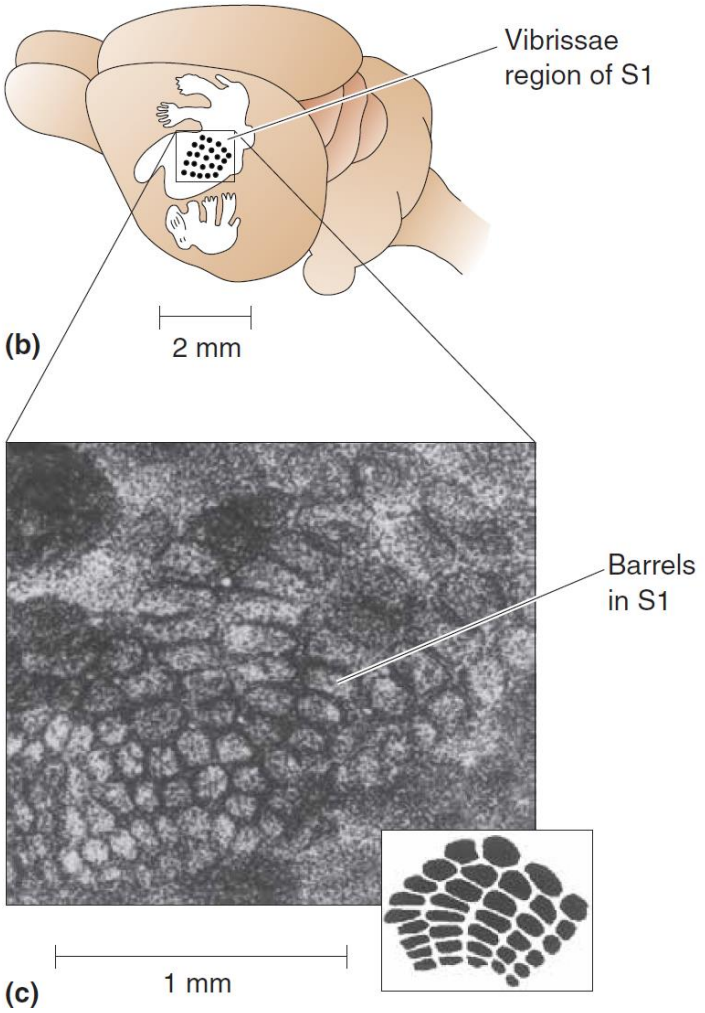










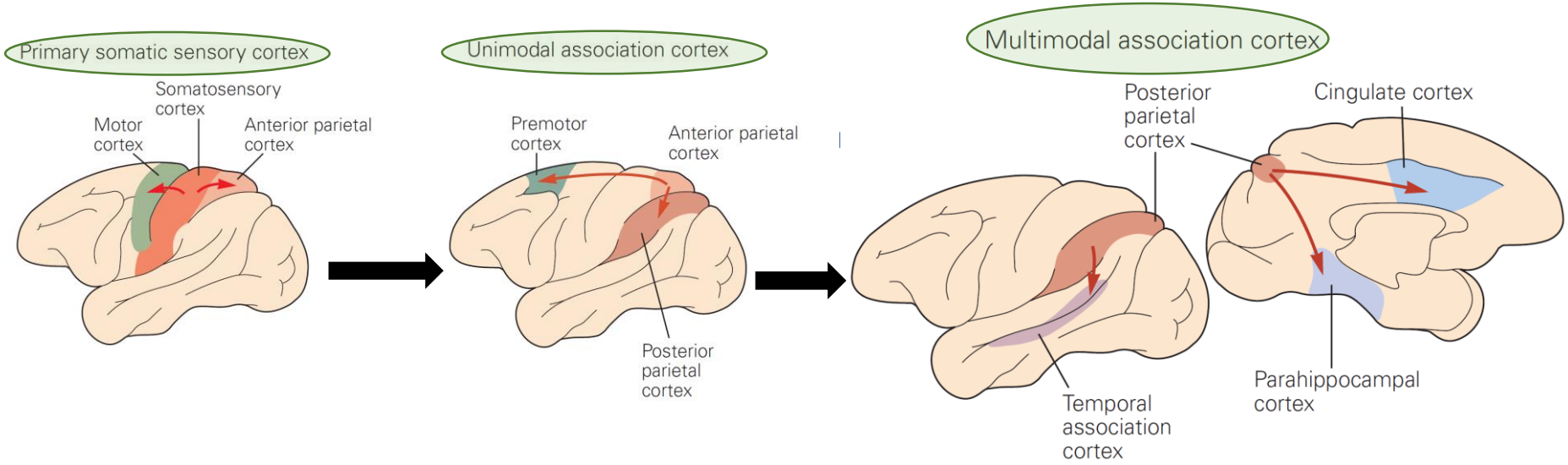


Somatotopic map of the facial vibrissae on mouse cerebral cortex

Information stream

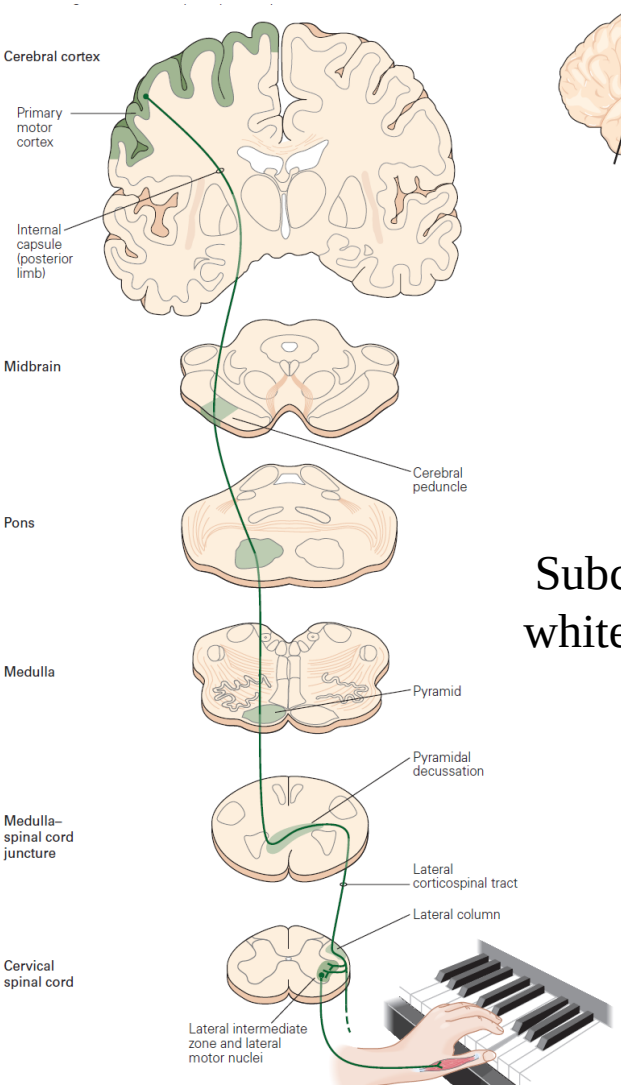
- Information is processed in **serial** and **parallel** pathways
- **e.g.** in somatosensory:
  - **From the dorsal root ganglia to the somatosensory cortex**, to **unimodal** association areas, and finally to **multimodal** association areas
- Multimodal associational areas, which are heavily interconnected with the **hippocampus** and **other part of brain**, appear to be particularly important for two tasks:
  - (1) the production of a **unified** percept
  - (2) the representation of the **percept in memory**

The processing of sensory information in the cerebral cortex begins with primary sensory areas, continues in unimodal association areas, and is completed in multimodal association areas



Direct connections between the cortex and spinal cord: descending lateral corticospinal pathway

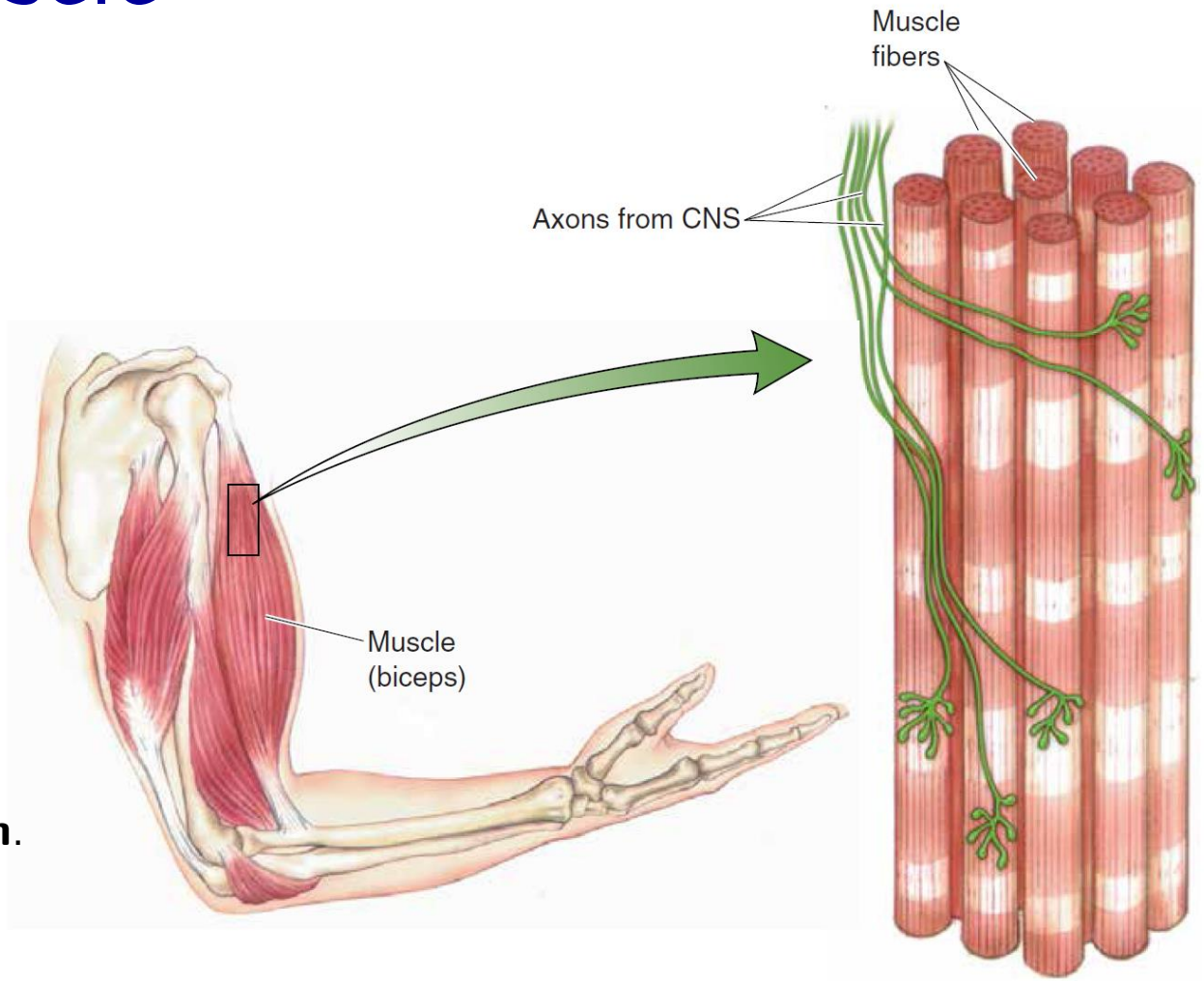
- In **voluntary movements**, fibers that **originate** in the primary motor cortex and terminate in the ventral horn of the spinal cord constitute a significant part (40% originate in the motor cortex) of the corticospinal tract.
- **10% of the fibers** do not cross until they reach the level of the spinal cord at which they will terminate (most of them in **pyramidal decussation**)
- Corticospinal fibers make **monosynaptic** connections with motor neurons
- They also form **synapses with interneurons** in the spinal cord
- The motor information carried in the corticospinal tract is significantly **modulated by sensory information**



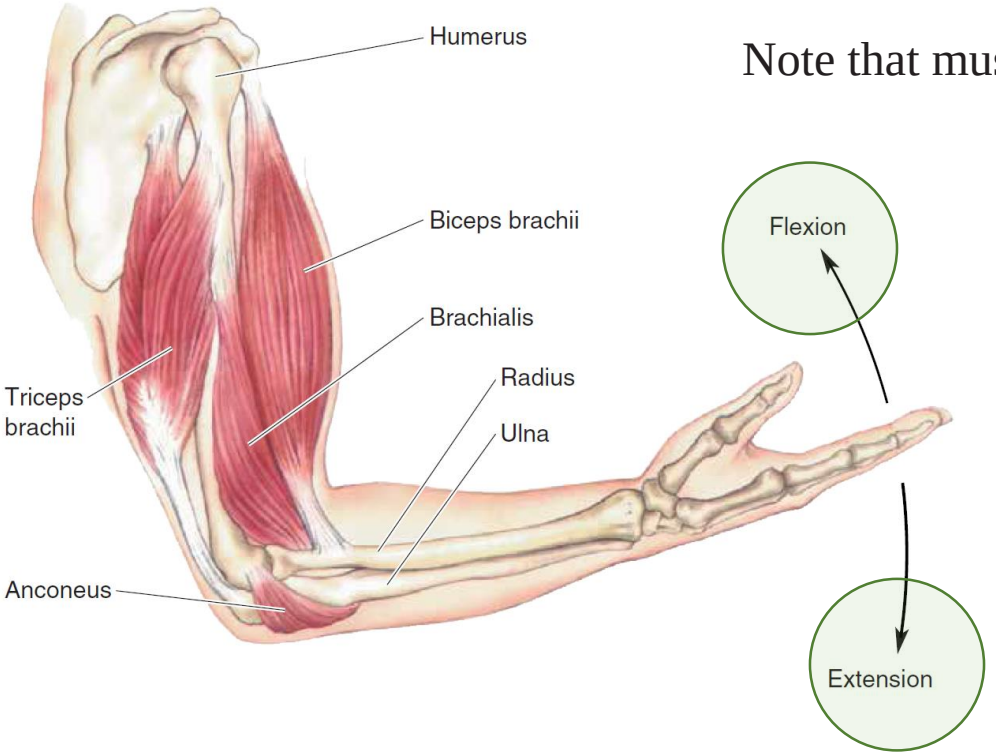
Subcortical white matter

The structure of skeletal muscle

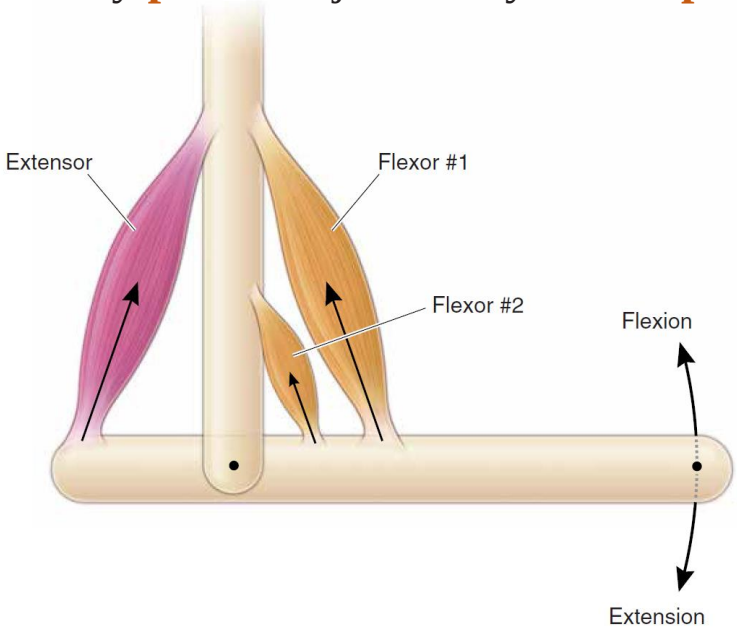
- Each muscle fiber is innervated by a **single axon**
- **Muscles** and the parts of the **nervous system** that control them are collectively called the **somatic motor system**.



How contracting muscles flex or extend a joint.

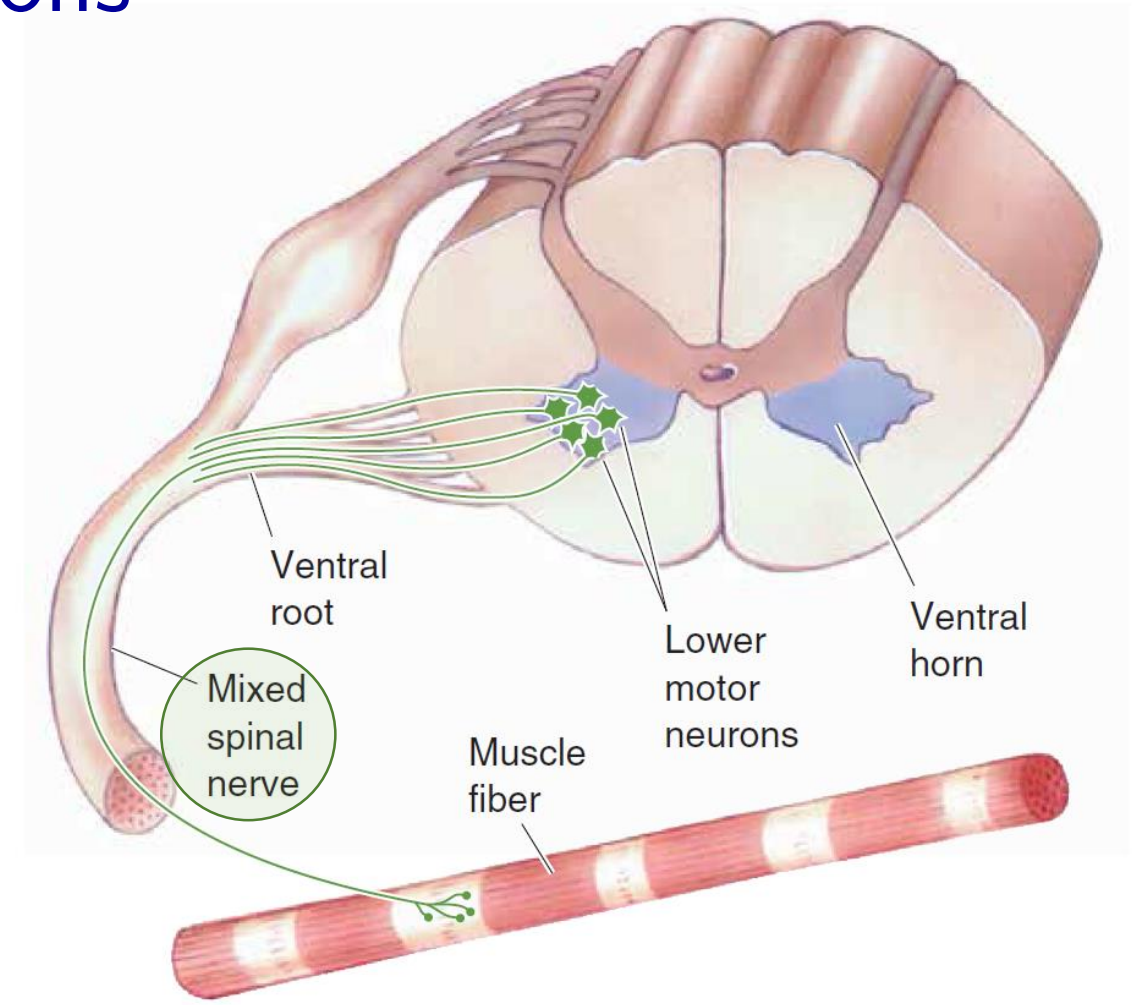


Note that muscles only **pull** on a joint; they cannot **push**

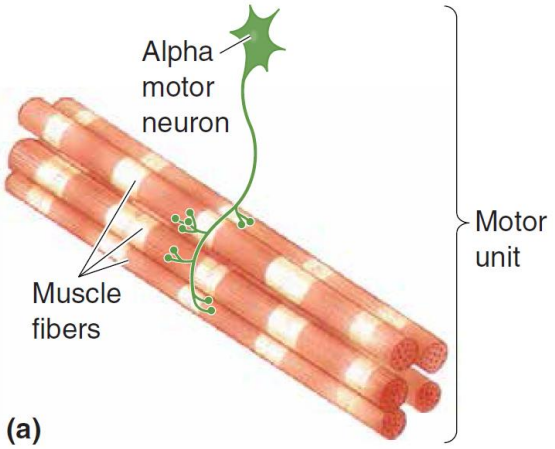


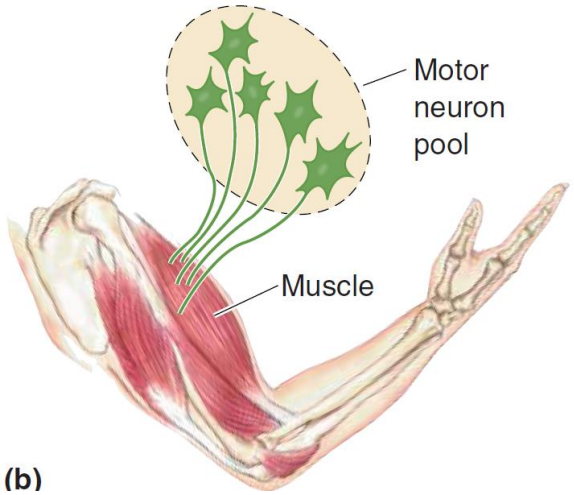
Muscle innervation by lower motor neurons

- **Upper motor neurons:**
  - Supply input to the spinal cord
- **Mixed spinal nerves**
  - It contain sensory and motor fibers,



A motor unit and motor neuron pool



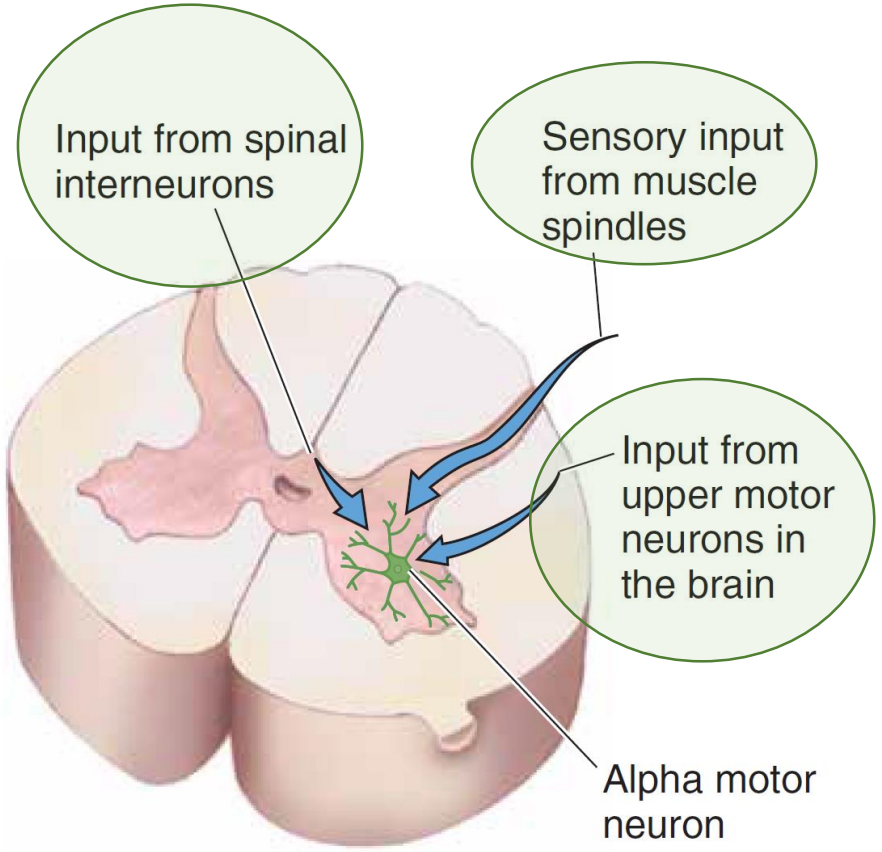


- **(a)** A motor unit is an alpha motor **neuron** and **all the muscle** fibers it innervates.

- **(b)** A motor **neuron pool** is all the alpha motor neurons that innervate **one muscle**.

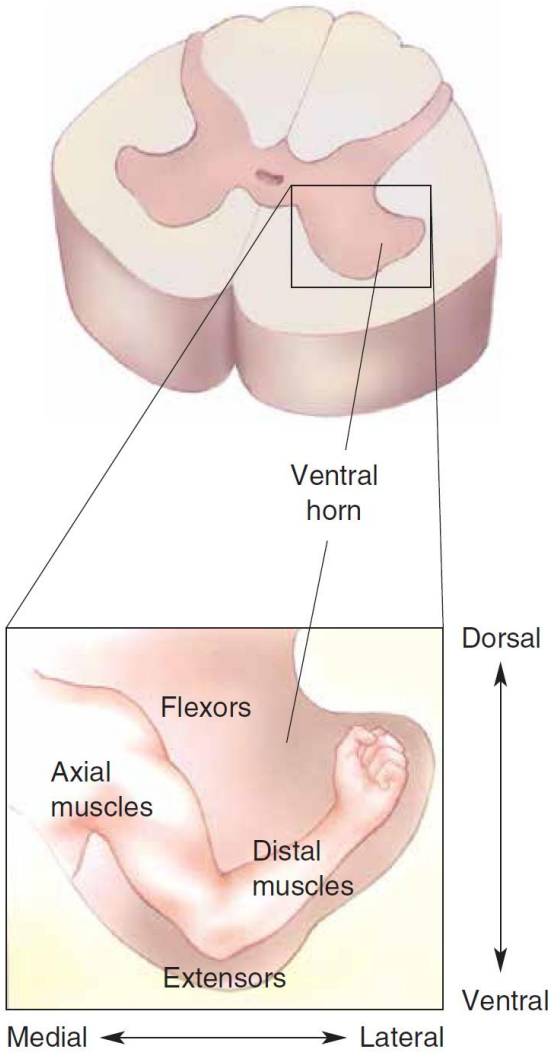
An alpha motor neuron and its three sources of input.

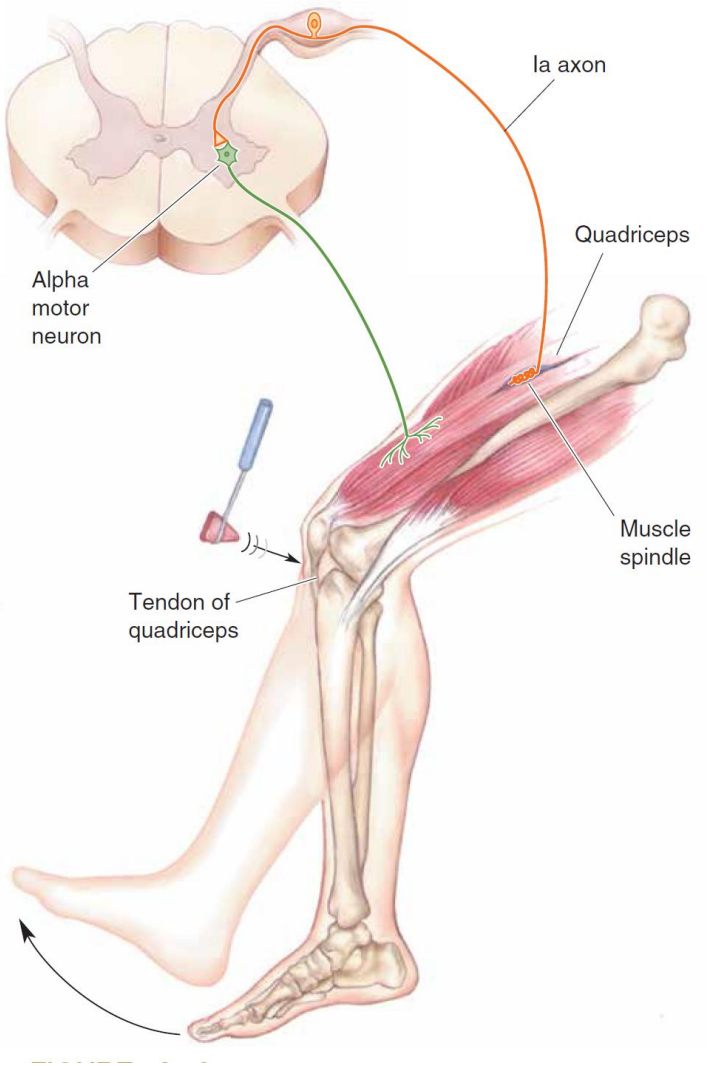
- First:
  - Dorsal root ganglion cells with axons that innervate a specialized sensory apparatus **embedded** within the muscle known as a **muscle spindle** .
  - This input provides **feedback** about muscle length
- Second:
  - **Upper motor neurons** in the motor cortex and brain stem
  - **Voluntary** movement
- Third
  - **Interneurons** in the spinal cord
  - **Circuitry** that generates the **spinal motor programs**



The distribution of lower motor neurons in the ventral horn

- Refer to the location of the joints muscles act on:
- **Axial muscles:**
  - The muscles that are responsible for movements of the **trunk**
  - Important for maintaining **posture**,
- **Proximal** (or **girdle**) **muscles** :
  - Those that move the shoulder, **elbow, pelvis, and knee**
  - Critical for **locomotion**
- **Distal muscles:**
  - Those that move the **hands, feet, and digits** (fingers and toes)
  - Specialized for the **manipulation of objects**





Stretch reflex

- The function of this **sensory input** to the spinal cord
- Stretch reflex:
  - When a **muscle is pulled** on, it tends to pull back (contract).
- It involves **sensory feedback** from the muscle
- The knee-jerk reflex

Cerebellum error-correcting mechanism

- Cerebellum receives **somatosensory** information:
  - Directly from primary afferents originating in the spinal cord
  - Corticospinal axons descending from the neocortex.
- The cerebellum can **compare** **movement commands** from the cortex with **somatic sensory information** about what actually happened.
- Cerebellum is thought to be important in "**predictive control**" of movements, in which commands for movements are adjusted based on information about the **effectiveness of prior movement**.

Adaptive cerebellum

- Cerebellum enables motor control systems to **adapt** motor commands to the **changing condition** of the musculature
  - As **muscles get stronger** with exercise and as our bodies grow, the neural signals for a particular movement must change, as they must if muscles are damaged.

- The major influence of the cerebellum on movement is through its connections in the **ventrolateral nuclei** of the **thalamus**, which connect directly to the motor and premotor cortex.

Voluntary movement requires coordination of all components of the motor system.

- The principal components are the motor cortex, basal ganglia, thalamus, midbrain, cerebellum, and spinal cord.
  - **Descending** projections: **green**;
  - **Feedback** projections and local connections: in **purple**.
- All of this processing is **incorporated** in the inputs to the motor neurons