3 Basic Neuroscience

Based on: Lytton, *From Computer to Brain*, ch.3, L3 L3

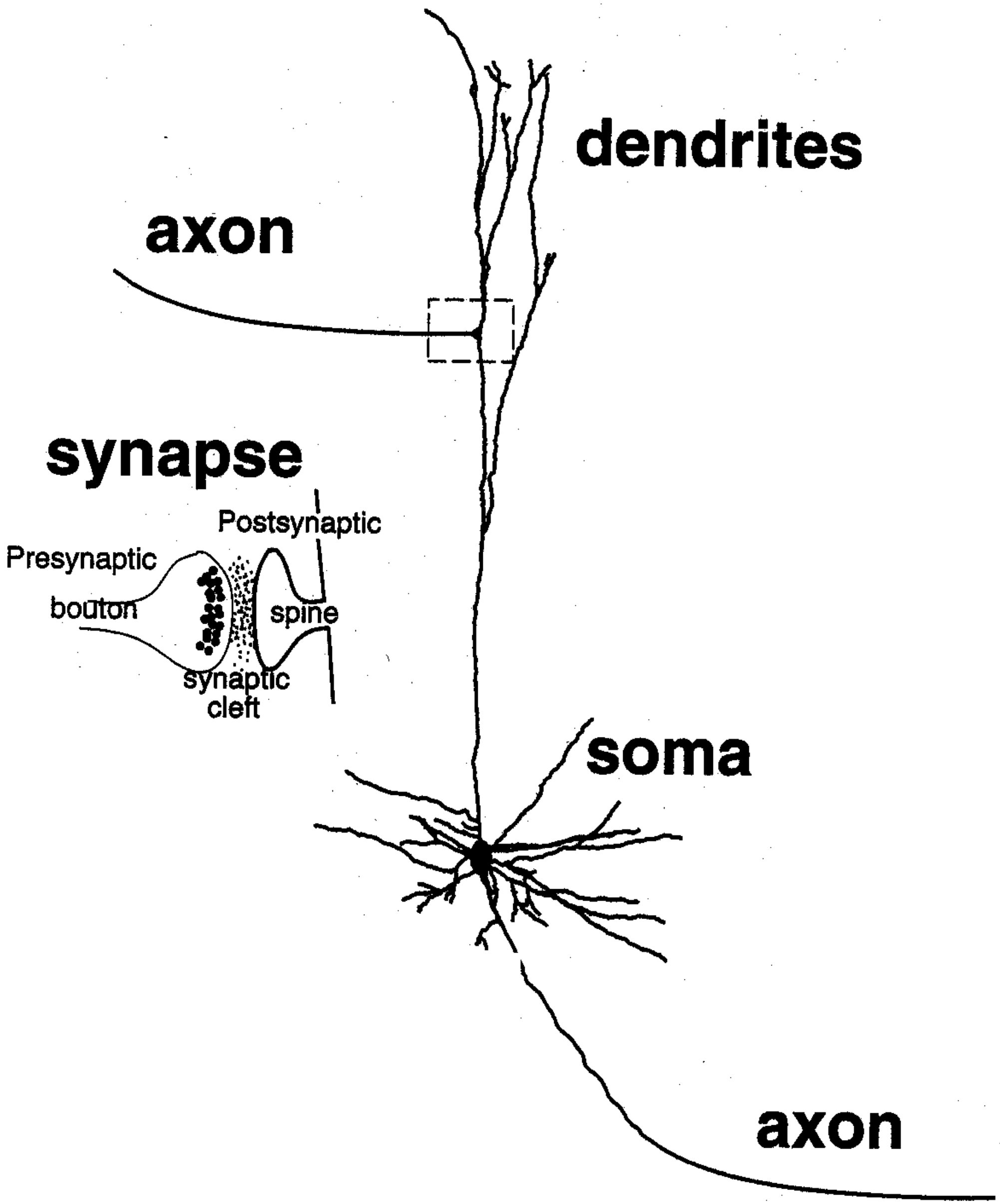
3.1 Microscopic view of the nervous system

- Living tissue is made up of cells. A **cell** has a fatty **membrane** and is filled with liquid and proteins known as cytoplasm as well as smaller functional parts called organelles.
- In the bodies of humans and other multicellular organisms, these cells are typically specialized and organized: Livers are made of liver cells and brains are made of brain cells.
- There are two major types of brain cells: neurons and glia.
- Neurons are usually identified by their ability to produce **action potentials**.
- It is believed that neurons are the principal elements involved in information processing in the brain.
- In the classical model, a neuron has **dendrites**, a **cell body**, and an **axon**.
- According to Cajal's "neuronal doctrine" information comes into the dendrites of the neuron.

  Signals then travel to the cell body, which in turn activates the axon, which can send a signal out of the neuron.

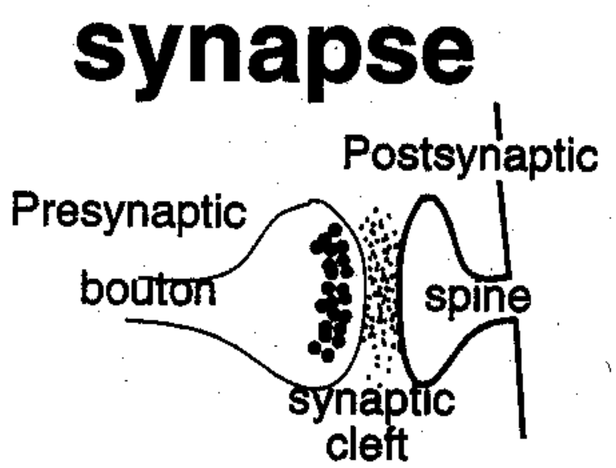
  Note that this is a classical view that may be true for many but certainly not all neurons.
- Santiago Ramón y Cajal shared the Nobel Prize in 1906 with Camillo Golgi for their studies on the nervous system. Their viewpoints were contradictory.
  http://nobelprize.org/medicine/laureates/1906/index.html

3.1.1 A typical pyramidal cell of the mammalian cortex:



- Pyramidal cells are considered principal cells because of their large size and long projections to other areas.
- The **cell body or soma** (small oval), which would be the bulk of the cell in other cell types, is dwarfed by the **dendrites**, which extend out in all directions.
- In this cell type, there are lots of small dendrites and then one major long dendrite with only a few branches.
- This major, **apical dendrite** can be a millimeter in length.
- The **axon** is typically much longer than the dendrites — several of them go from your lower back to your big toe, a distance of about a meter.
- Axons branch to connect with multiple targets.
- An axon branch from another cell is shown at the upper left forming a synapse on the cell (rectangle).

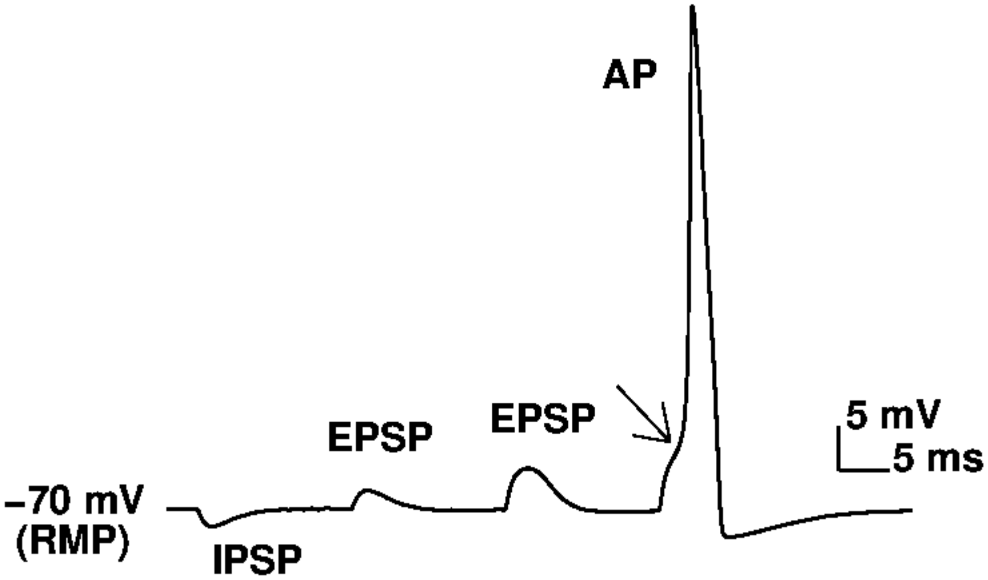
3.1.2 The synapse



- The **synapse** is a neuron input device and connects the axon of one neuron with the dendrite of the other.
- Note the **presynaptic**(axon) terminal at the end of the axon and a spine on the dendrite.
- The terminology of presynaptic and postsynaptic defines the direction of signal flow.
- **Transmitter** is released presynaptically, floats across the **synaptic cleft**, and activates receptors postsynaptically.
- The two neurons are not directly connected but communicate via this cleft.

3.1.3 The action potential

- The information in the neuron is in the form of electrical potentials (voltages) across the membrane.
- Information is conveyed via the synapse through arrival of neurotransmitter on receptors.



- Potentials can be **excitatory postsynaptic potentials** (EPSPs) or **inhibitory postsynaptic potentials** (IPSPs).
- The trace starts at a **resting membrane potential** (RMP) of about -70 mV.
- A pair of EPSPs of increasing size move the potential in a positive direction, toward firing threshold.
- Finally a larger EPSP reaches the firing threshold and the cell fires a spike (**action potential, AP**, indicated be an arrow).
- An IPSP pushes the membrane potential down to more negative values and away from its firing potential.
- The action potential is the signal that can be sent down the axon to create a PSP in another neuron.

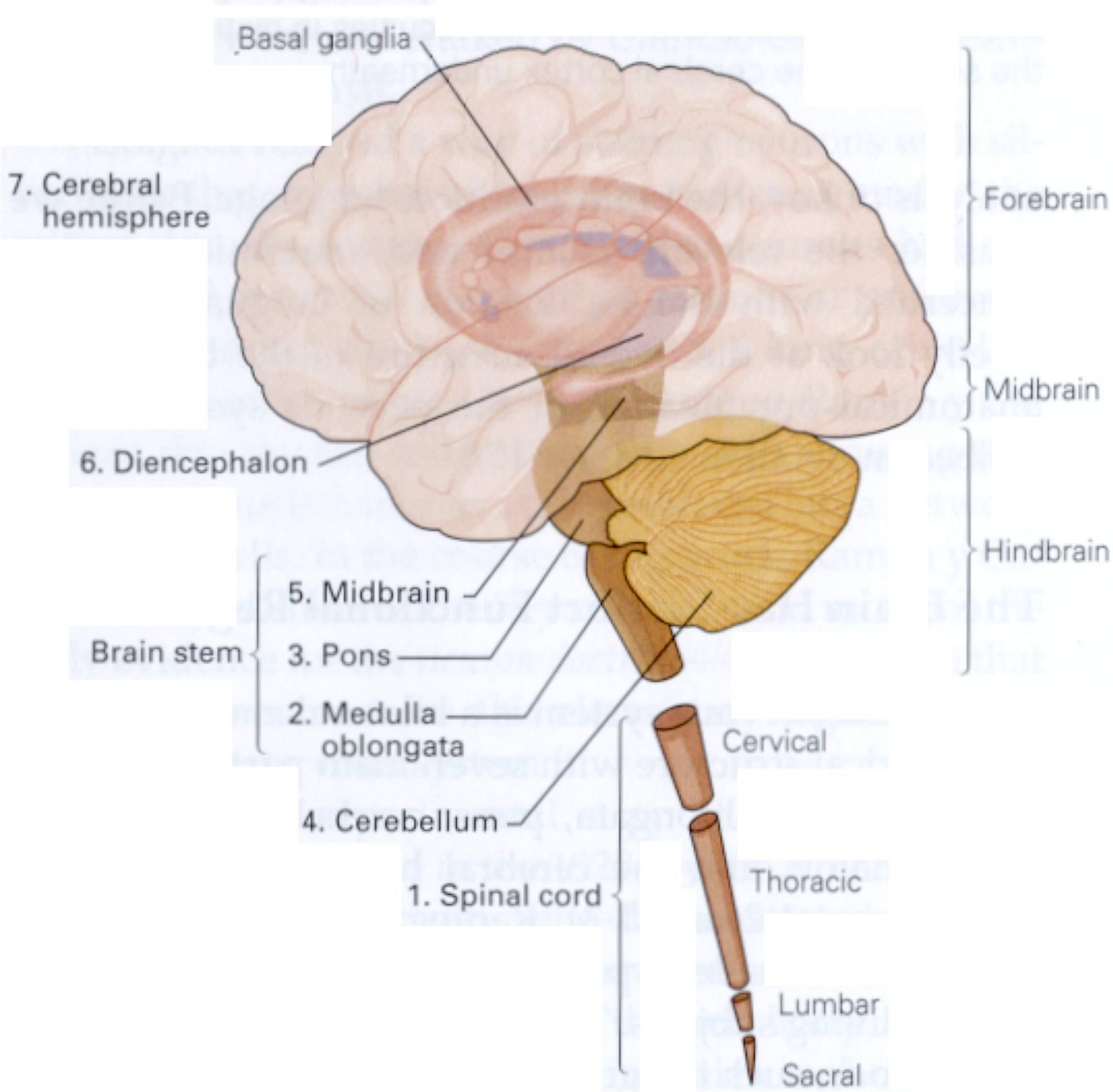
3.1.4 Synaptic mechanisms

- Most **synapses are chemical**: neurotransmitters are released from one neuron and picked up by receptors on another neuron, generating an electrical signal in the latter neuron.
- The classical synapse is **axodendritic**: it connects an axon to a dendrite.
- There also exist **dendrodendritic** synapses, which connect dendrites to dendrites.
- In addition to chemical synapses, there are **electrical synapses** with specialized channels (gap junctions) that allow current to flow directly from one neuron to another.
- Complementing these synaptic mechanisms are various **nonsynaptic interneuronal signals**.
- These signals includes volume transmission, where transmitters are broadcast through extracellular space to a lot of neurons.

  (Read about glia)

3.2 Macroscopic view of the nervous system

from Kandel, Schwartz and Jessel, *Principles of Neural Science*



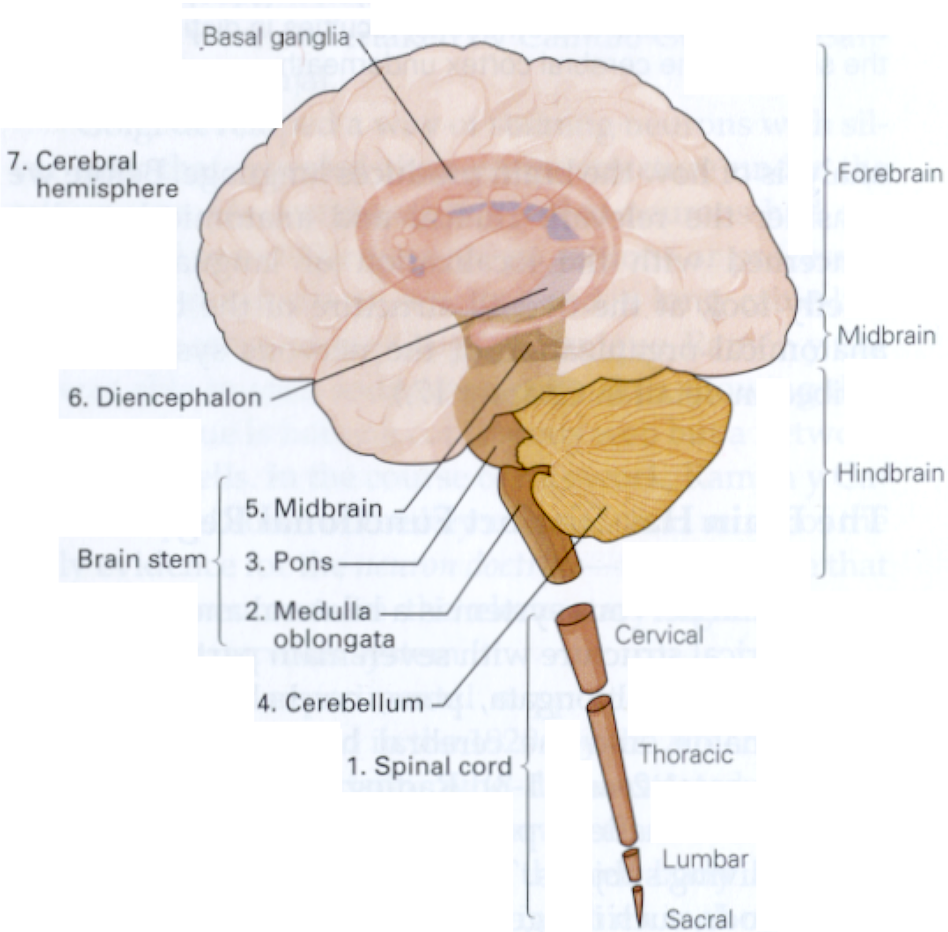
3.2.1 Seven main parts of the Central Nervous System (CNS):

The **cerebral hemispheres** consisting of a heavily wrinkled outer layer:

- the **cerebral cortex** responsible for cognitive functions,

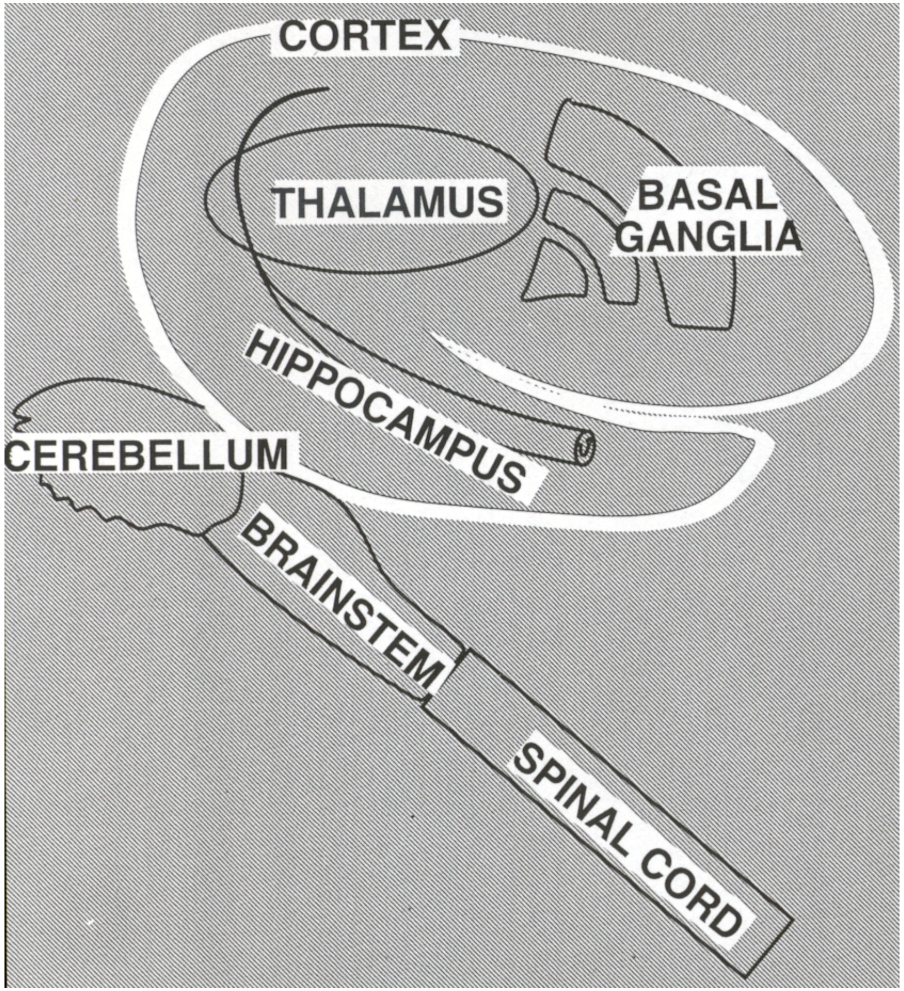
and three deep lying structures:

- the **basal ganglia**, which participate in regulating motor performance,
- the **hippocampus**, which is involved with aspects of memory storage,
- the **amygdaloid nuclei**, which coordinates the autonomic and endocrine responses of emotional states.



- The **diencephalon** (6) has two structures:
  - the **thalamus** processes most of the information reaching the cerebral cortex from the rest of the central nervous system.
  - the **hypothalamus** regulates autonomic, endocrine and visceral functions.
- The **midbrain** (5) controls many sensory and motor function, including eye movement and the coordination of visual and auditory reflexes.
- The **cerebellum** (4) modulates the force and range of movement and is involved in the learning of motor skills.
- The **pons** (3) conveys information about movement from the cerebral hemisphere to the cerebellum.
- The **medulla oblongata** (2) is responsible for vital autonomic functions such as digestion, breathing and control of heart rate.
- **The spinal cord** (1).

Labeled schematic of the brain in sagittal section (vertical plane "between the eyes".

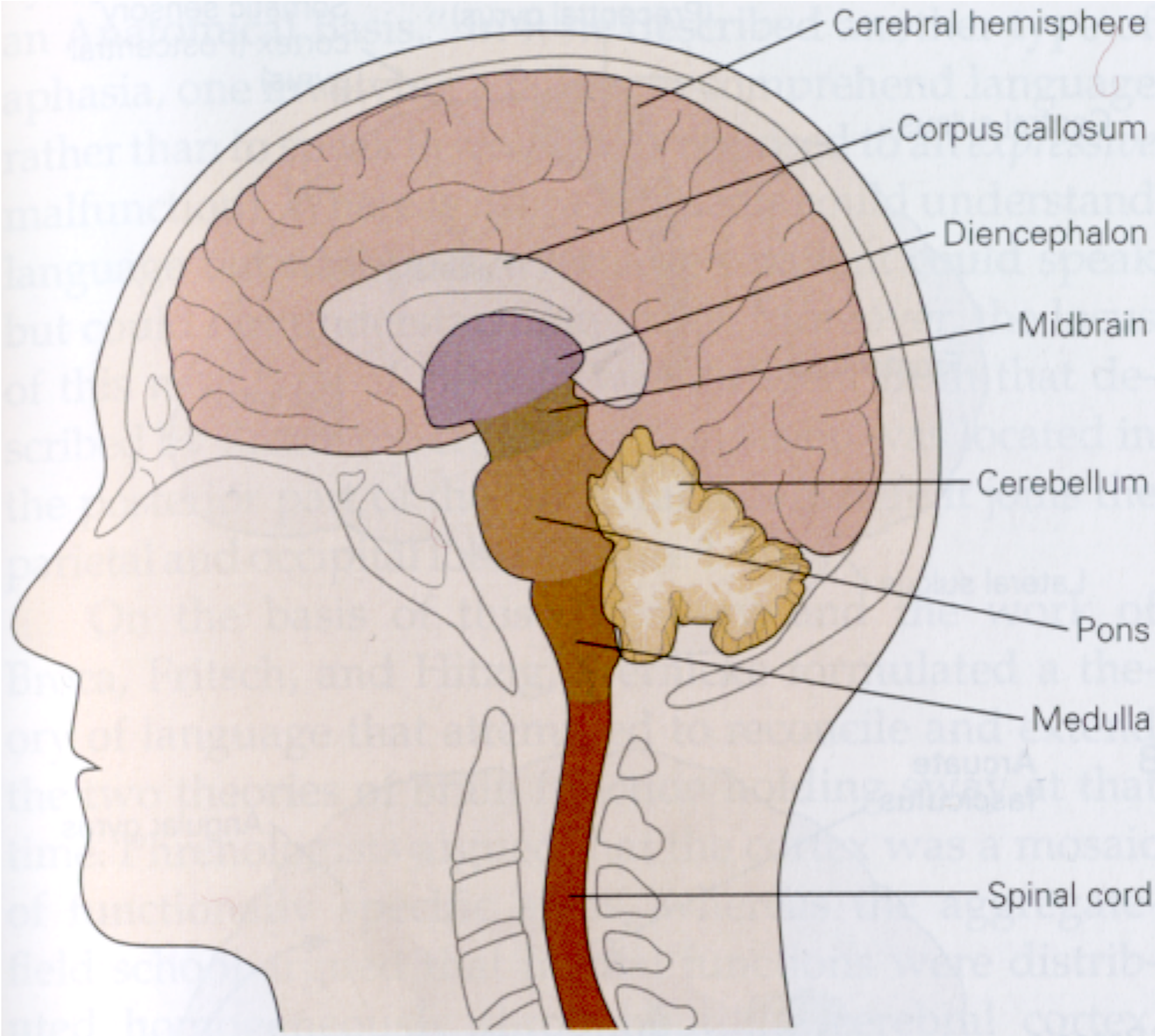


3.2.2 Simplified view at parts of the brain

- The brain is subdivided into an outer rind called the **cortex** and multiple internal nuclei.
- The **cerebellum** is an additional "mini-brain" stuck on behind; it has its own nuclei and cortex.
- Major deep nuclear complexes are the **thalamus** and the **basal ganglia**.
- Along with the wiring to and from the cortex, these fill up most of the brain.
- The nuclei and cortex are **gray matter**, made up primarily of **cell bodies and dendrites**, and
- the subcortical connections are **white matter**, made up of **axons**.

3.2.3 Another view at major brain divisions

from Kandel, Schwartz and Jessel, *Principles of Neural Science*

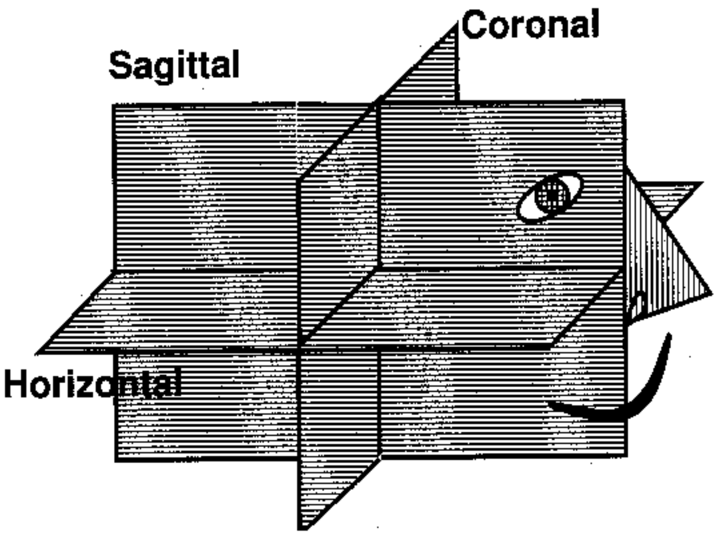


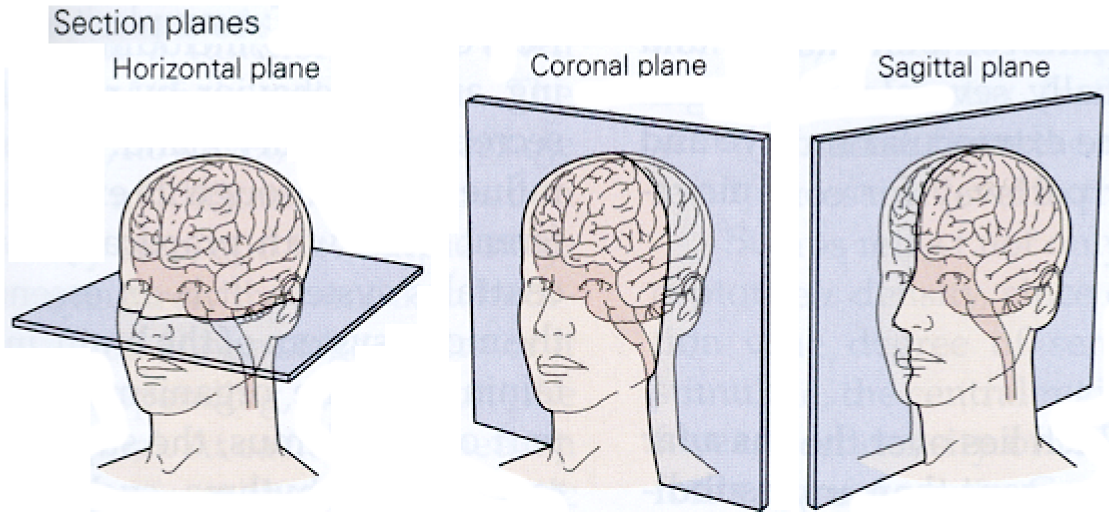
3.2.4 Coordinate systems

One of the coordinate system is based on the body axis and uses the terms:

- rostral (situated toward the oral or nasal region),
- caudal (situated in or directed toward the hind part of the body),
- ventral (of or relating to the belly),
- dorsal (relating to or situated near or on the back),
- lateral (of or relating to the side),
- medial (being or occurring in the middle).

3.2.5 The three planes of body sectioning:



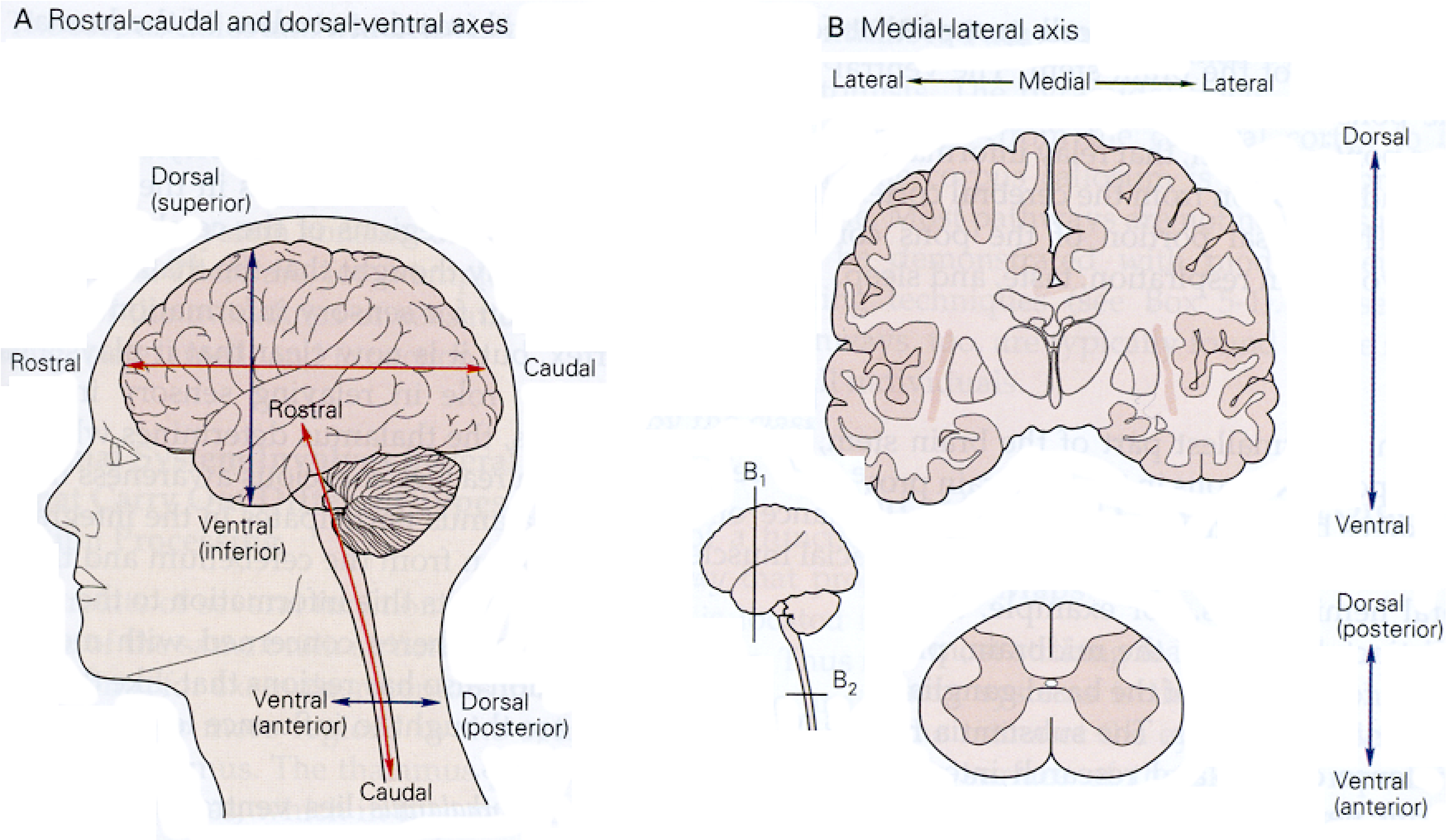


- We can conceptually (or actually) slice the body in three orthogonal planes:
  horizontally (a plane horizontal to the ground),
  sagittally (a vertical plane passing from belly to back), and
  coronally (a vertical plane running from ear to ear).
- In the horizontal plane, directions are anterior vs. posterior (toward or away from the nose), left vs. right, and medial vs. lateral (toward the middle or toward the edge).
- For the coronal plane, left vs. right and medial vs. lateral also pertain.
- For the brain coronal, up is dorsal and down is ventral.
- In the sagittal plane, we have anterior to posterior and dorsal to ventral.

- Sagittal planes can be mid-sagittal or parasagittal (off to the side).
- Coronal planes can be more anterior or more posterior.
- Horizontal planes are more dorsal or more ventral in the brain but are more caudal or more rostral in the spinal cord.

3.2.6 Another view at neuronal axes

from Kandel, Schwartz and Jessel, *Principles of Neural Science*



L4 — prac1, L5:

3.3 Organization and functions of main brain areas

- **Organization and functions** of many areas of the brain are still a mystery.
- Many brain areas are in the midst of a great system of other brain areas of equally unknown function.

  We take one of these areas out to study, shock one end, and look at the mysterious hissing coming out the other end.
- For this reason, many of the best-studied parts of the brain are those that interact directly with the environment.
- The **retina** is such a part. We know that it developed to perceive light, and we can control the amount of light that hits it.
- By contrast, although we know that the **hippocampus** has something to do with memory, we don't really know what it does.

  It is connected to structures on either side whose function is even more mysterious.
- Therefore, as we study the basic anatomy and physiology of the hippocampus, we need to hypothesize global as well as local functions.

3.3.1 The cortex

- The **cortex** is one of the most popular brain bits for humans since it is a major part that makes us different from other creatures.
- The major parts of the cortex, called **neocortex** (new cortex), form the outer layer of the brain. The cortex is heavily folded, giving it greater surface area.
- Human cortices are considerably more folded than those of most monkeys.
- Cortex can also be subdivided into different areas that are responsible for different aspects of sensory processing, motor control, and cognition.

from Kandel, Schwartz and Jessel, *Principles of Neural Science*

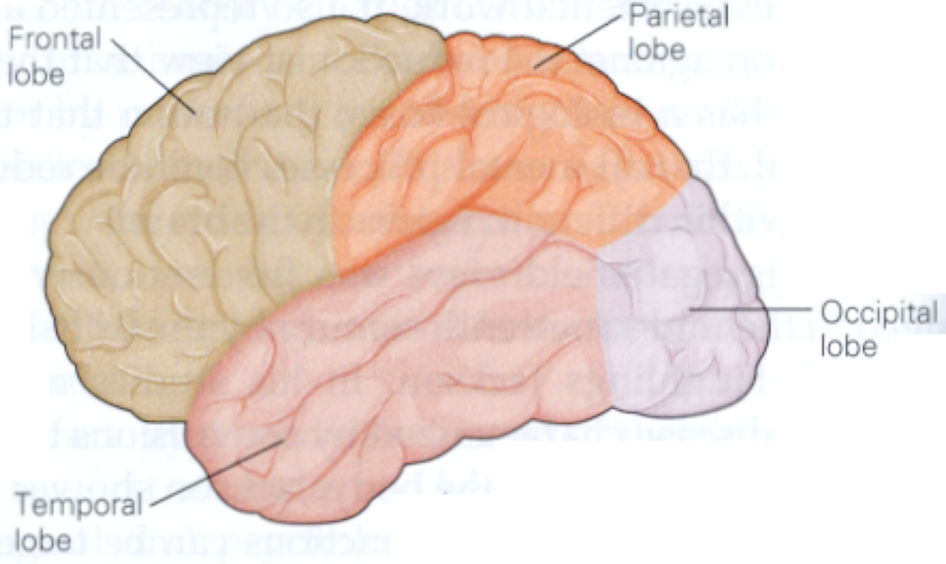
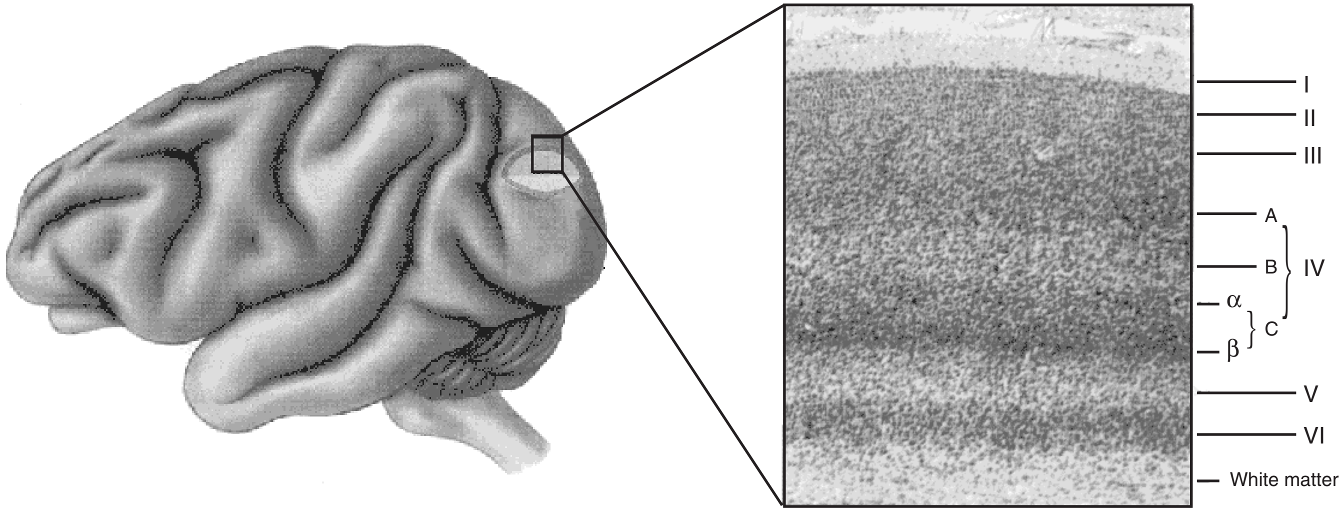


Figure 1-2B The four lobes of the cerebral cortex.

- **Occipital cortex**, in the back, does vision.
- **Frontal cortex**, in the front, does socializing and judgment.
- **Left temporal cortex** (lateral and ventral) does speech recognition.
- **Right parietal cortex** (more dorsal) does spatial orientation.
- The left brain is literate and numerate and the right brain is good at pictures.
- Areas of the brain may increase in size depending on their usage so that highly musical people will have a larger auditory area.

- Cortical areas are generally represented as forming a **hierarchy**
  from the **simple perceptions** of primary sensory areas,
  through **perceptual integration**, up to
  the **multimodal representations** of association areas.
- Cortical areas typically feature strong **recurrent loops** between connected areas, and there is much evidence to suggest that even lower areas participate in high-level perception.
- Moving down into neocortex, **six layers of interconnected axons, dendrites**, and **cell bodies** can be identified.



- The cortical layers are only a few millimeters thick and contain about 30 billion neurons.

3.3.2 The columnar organization of the neocortex

The cortex seems to be **functionally organized into columns** laid out in a two-dimensional array.

from Mountcastle *The columnar organization of the neocortex*, Brain 1997

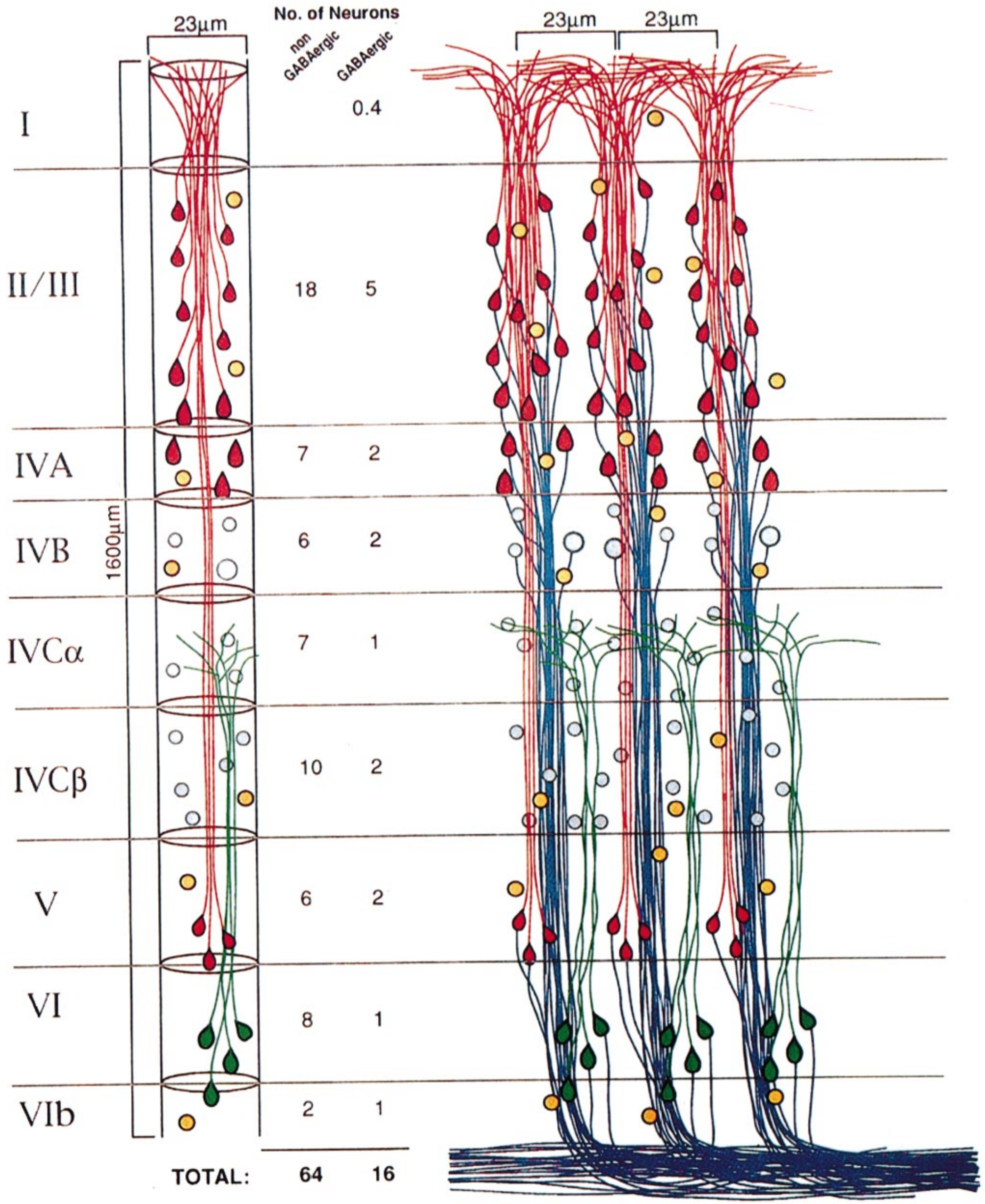


Fig. 16 Diagram of the arrangement of neurons, dendrites and axons in vertical modules of the striate cortex of the macaque monkey.

Left. A drawing to show the arrangement of the apical dendrites of pyramidal cells; for clarity, only one-half of the neurons present are shown.
The pyramidal cells in layers II/III, IVA and V are shown in red, those in layer VI in green.
Neurons of IVB and IVC are shown without dendrites, in grey; GABAergic neurons in azure. Total numbers of GABAergic and non-GABAergic cells are given to the right of the drawing.

`Rigt.` A drawing to represent the pyramidal cell modules (columns) showing die arrangement of dendrites and axons. Colour scheme the same as for the left, pyramidal cell axons are shown in blue.

(From Peters and Sethares, 1996, with permission from Wiley-Liss.)

3.3.3 Olfactory cortex and hippocampus

- In addition to neocortex, there are other cortical areas (10%) that are regarded as more primitive because they are found in lesser creatures and because they appear to be more simply organized.
- Two of these areas are favorites for modeling: the **olfactory cortex** and the **hippocampus**.
- **Olfactory cortex** is responsible for smell. Olfactory cortex is the only sensory cortex that receives its input directly from the end organ rather than receiving sensory information via the thalamus (described below).
- In addition to its simplicity, the closeness of olfaction to the periphery makes piriform cortex particularly popular for studying structure-function relations.
- The **hippocampus** is one of the most heavily studied and modeled areas of brain.

  It is the area responsible for episodic memory.
- **Episodic memory** means memory for specific incidents and can be contrasted with

  procedural memory (memory of how to do things like ride bikes and play simple games) and

  semantic memory (how many states in the U.S.).
- The hippocampus is characterized by largely feedforward excitatory connections and the presence of long-term potentiation, a form of synaptic weight change suggestive of the types of changes used in artificial neural networks.
- Additionally, the hippocampus is involved in certain types of epilepsy, making it a favorite modeling locus for clinically oriented studies as well.

3.3.4 The thalamus

- The **thalamus**, another favorite area for modeling, is thought of as the gateway to the cortex.
- All sensory information except smell comes into the brain through individual nuclei of the thalamus, which are called relay nuclei.
- One of the best studied of the relay nuclei is the one for vision, the **lateral geniculate nucleus** (LGN).
- In addition to sensory nuclei, there are other divisions of the thalamus that are involved in memory and with movement.
- In general, the thalamus and neocortex are heavily interconnected with excitatory feedback loops.
- There are also a number of inhibitory feedback loops within the thalamus.
- Overall, the thalamus's relay function remains obscure.
- One hypothesis is that the thalamus may be involved in directing attention to a particular stimulus.
- In addition to its role in sensation, the thalamus is also heavily involved in sleep.
- Again, its role here remains obscure, partially because the role of sleep remains obscure.

3.3.5 The basal ganglia and the cerebellum

- The **basal ganglia** is a central motor region in the brain.
- It appears to be involved in initiation and planning of movement.
- Diseases of the basal ganglia include Parkinson disease, which causes people to move too little, and Huntington and Tourette diseases, which cause people to move too much.
- Unusual features of basal ganglia organization include the facts that it is largely feedforward, that projections are largely inhibitory, and that there is massive convergence from cortex.
- The basal ganglia is part of a big loop involving

$$\text{motor cortex} \rightarrow \text{basal ganglia} \rightarrow \text{thalamus} \rightarrow \text{cortex.}$$

- The **cerebellum** is also generally regarded as a motor area, though it may better be thought of as being a site of sensorimotor organization.
- It gets a lot of limb and body position information and helps coordinate movement and posture.
- The cerebellum, like the basal ganglia, is notable for the dominant role of inhibition.
- Purkinje cells are massive inhibitory cells in the cerebellum.
- They are arrayed in long rows and look like power stanchions with 10,000 wires running by them making synapses. This very regular organization has made the area a favorite for modeling as well.

3.3.6 The autonomic and enteric nervous systems

- The **autonomic nervous system**, with both central and peripheral branches, is largely responsible for nonvoluntary activities such as heart function, blood flow regulation, and pupillary response to light.
- These systems generally maintain the level of some physiological variable such as blood pressure or light hitting the retina, just as a thermostat maintains temperature in a house.
- Such negative feedback systems are well explored in engineering, and these models have been applied to the autonomic nervous system.
- The **enteric nervous system** runs the gut. Although it has connections that allow it to communicate with the brain, it can function independently.
- An isolated gastrointestinal tube, disconnected from the body, will still eat and defecate quite happily.
- Fancifully, I think of the enteric nervous systems as a separate creature within (i.e., an alien), with the approximate sentient capabilities of a large worm.
- The brain is a complicated place. Areas I haven't mentioned include: cingulate cortex, claustrum, amygdala, Forel's field H3, red nucleus, substantia nigra (black stuff), locus ceruleus (blue place), nucleus solitarius, nucleus ambiguus.

  Some of these have an approximately known function, or at least known affiliations with areas of approximately known function.

  Others remain enmeshed in utter puzzlement and enigmatic mystery.