Neurorobotics

Module 1: Background and Foundations

Lecture 2: Neuroscience. Neurons and synapses; systems neuroscience

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www.vernon.eu

Neurons and Synapses

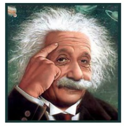
Brain are comprised of neurons and synapses

- Also comprised of support cells (glia) and a vascular system to provide oxygen and nutrients
- The type of neurons and synapses doesn't vary much
- But the number of brain regions, neurons, and synapses does vary

Species	Neurons	Synapses
Nematode	302	10^{3}
Fruit Fly	100,000	10^{7}
Honeybee	960,000	10^{9}
Mouse	75,000,000	10^{11}
Cat	1,000,000,000	10^{13}
Human	85,000,000,000	10^{15}



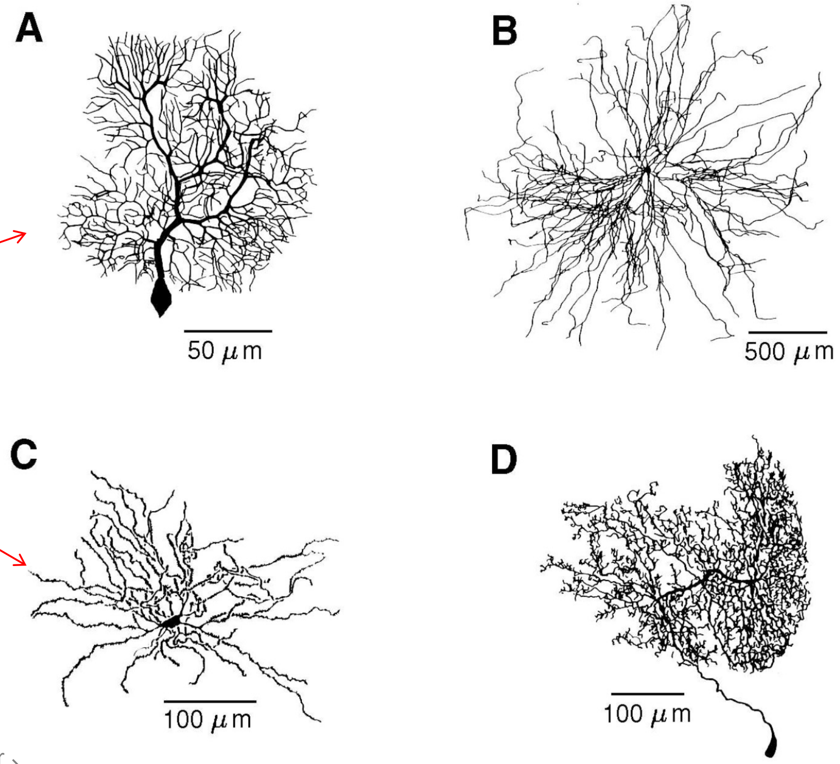


Neurons

Neurons are nerve cells

- Generate electrical signals in response to chemical and other inputs
- Wide variety of shapes and sizes



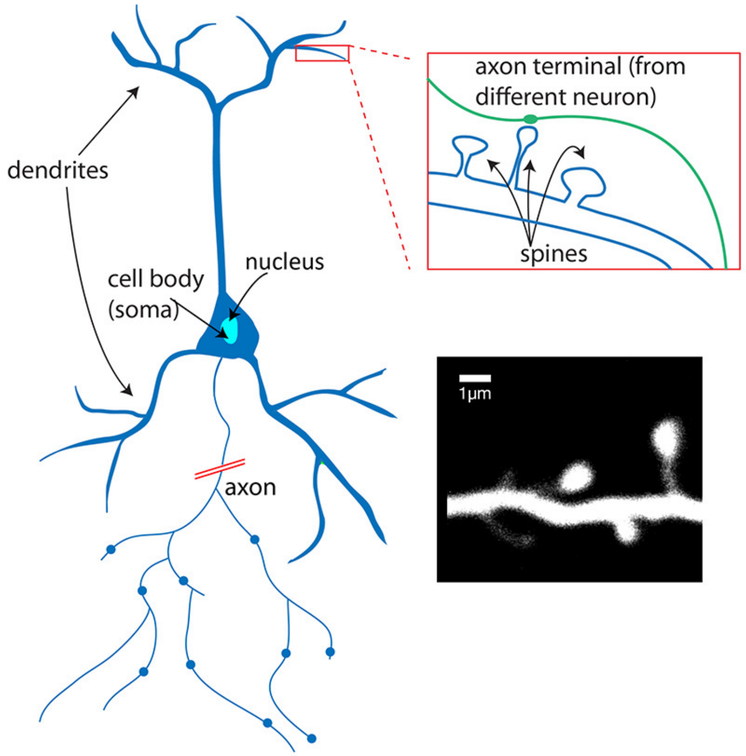
More on the cerebellum later

A. Cerebellar Purkinje cell. B. Motoneuron from the spinal cord.
C. Neostriatal spiny neuron from cortex. D. Axonless interneuron from locust.

Neurons

Structure of a neuron

- A soma, the cell body
- Dendrites that received inputs from other neurons
    - Dendritic tree allows a neuron on the receive inputs from many other neurons
- Axon, the output of the neuron
    - Emanates from the soma, and can traverse large distances to other parts of the brain or body
- Synapses, i.e., synaptic connections between axons of other neurons with dendrites



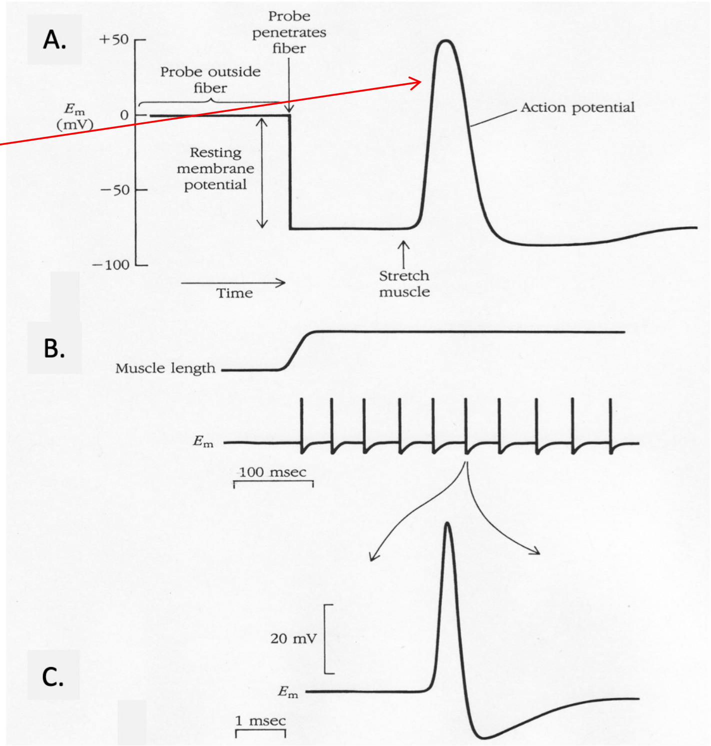
https://qbi.uq.edu.au/brain/brain-anatomy/what-neuronlocust.

Neurons

Operation of a neuron

Neurons convey messages via an action potential

- A neuron fires (an action potential)
- A neuron spikes
- ~ 1 ms for a firing or spike
- Firing / spiking is an all or nothing "binary" event
- After firing, there is a refactory period, during which the neuron can't spike again
- Firing rates: 5 – 100 Hz (i.e. low frequency)
  - Overall firing rate is referred to as rate coding

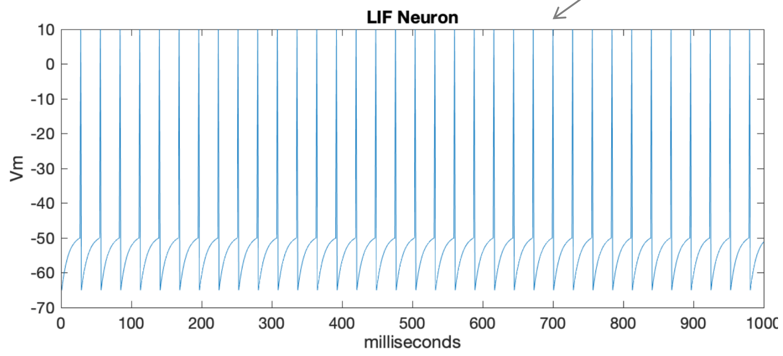


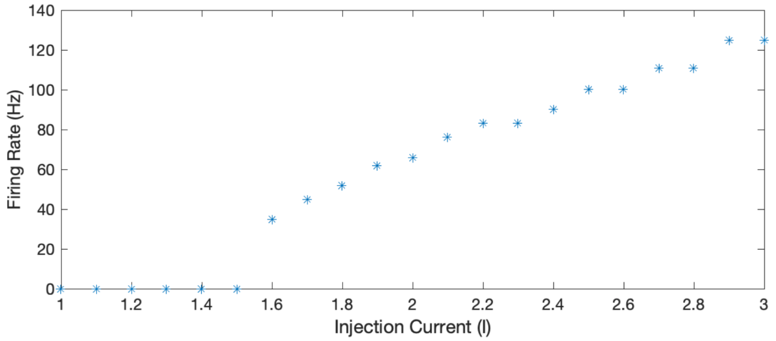
Neurons

Neuron models

- Model action potential with differential equations
- Referred to as spiking neurons
- Example model: Leaky Integrate and Fire (LIF) neuron
  - Integrates inputs
  - Sums these inputs
  - Generated a spike if the sum > some threshold
  - If no inputs, the summation decays: leaks

Response to an injection current





Firing rate as a function of injection current

Neurons

Neuron models

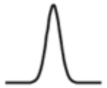
- Spiking neurons may be computationally intensive
  - Can't run on a robot in real-time on a conventional computer
  - Use custom neuromorphic integrated circuits instead

    (see second case study in NR01-03)

Neurons

Neuron models

- Alternatively, model with mean firing rate neuron
  - Average firing rate of a pool of neurons over tens of milliseconds
  - Several rate functions are used
    - Step, sigmoid, tanh, threshold-linear (ReLU), …
  - Same as activation functions

Type of function	Graphical represent.	Mathematical formula	MATLAB implementation
Linear		$g^{\text{lin}}(x) = x$	`x`
Step		$g^{\text{step}}(x) = \begin{cases} 1 & \text{if } x > 0 \\ 0 & \text{elsewhere} \end{cases}$	`floor(0.5*(1+sign(x)))`
Threshold-linear		$g^{\text{theta}}(x) = x\,\Theta(x)$	`x.*floor(0.5*(1+sign(x)))`
Sigmoid		$g^{\text{sig}}(x) = \frac{1}{1+\exp(-x)}$	`1./(1+exp(-x))`
Radial-basis		$g^{\text{gauss}}(x) = \exp(-x^2)$	`exp(-x.^2)`

Neurons

Neuron models

- Alternatively, model with mean firing rate neuron
  - Average firing rate of a pool of neurons over tens of milliseconds
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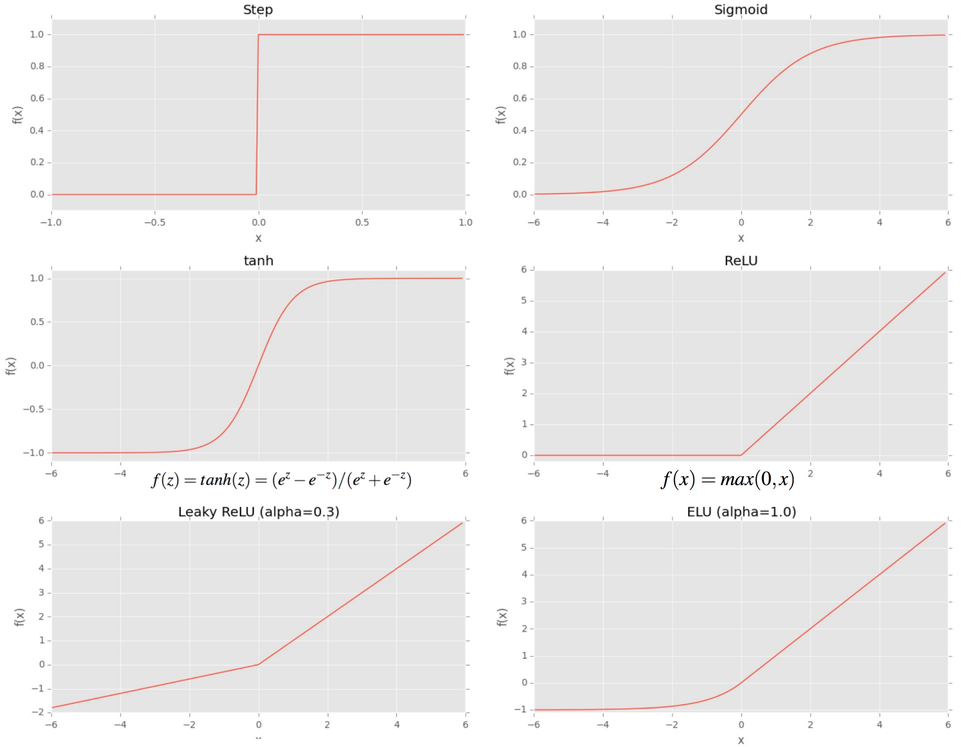


$$f(net) = \begin{cases} 1 & \text{if } net > 0 \\ 0 & \text{otherwise} \end{cases}$$

$$s(t) = 1/(1+e^{-t}) \qquad t = \sum_{i=1}^{n} w_i x_i$$

$$f(z) = tanh(z) = (e^z - e^{-z})/(e^z + e^{-z})$$

$$f(x) = max(0, x)$$

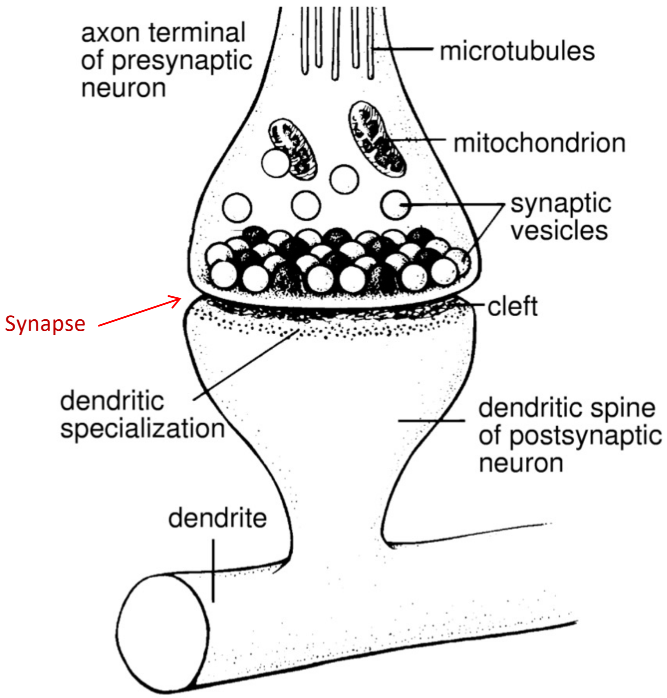
$$f(net) = \begin{cases} net & \text{if } net >= 0 \\ \alpha \times net & \text{otherwise} \end{cases}$$

$$f(net) = \begin{cases} net & \text{if } net >= 0 \\ \alpha \times (exp(net) - 1) & \text{otherwise} \end{cases}$$

Synapses

Synapses are connections between neurons

- Presynaptic side of the synapse: the axon terminal
  - Sends the signal
- Postsynaptic side of the synapse: the dendrite
  - Receives the signal



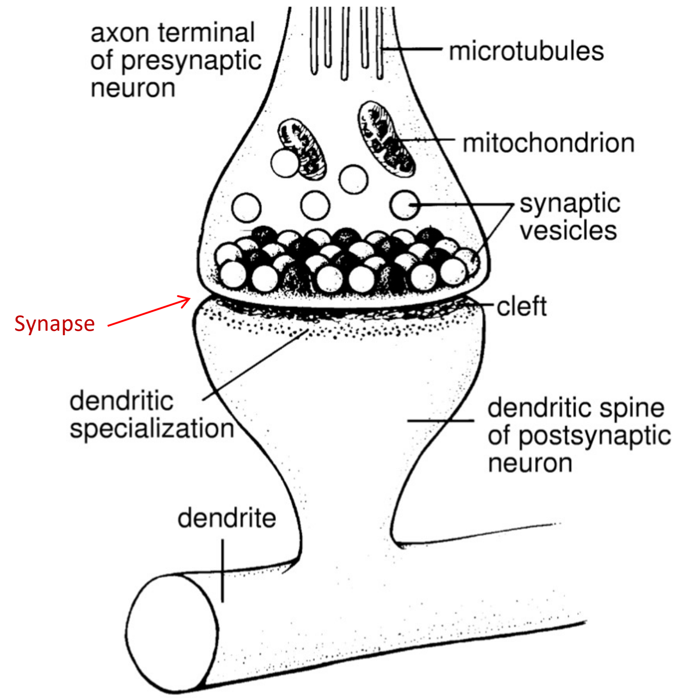
Synapses

Properties of synapses

- Some are electrical (called gap junctions)
    - Current from the presynaptic junction is received directly by the postsynaptic neuron
- Most are chemical
    - Neurotransmitters (packets of chemicals) are emitted by the presynaptic side (i.e. the axon terminal)
    - The receipt of a neurotransmitter causes the postsynaptic membrane potential to increase or decrease

Excitatory synapse

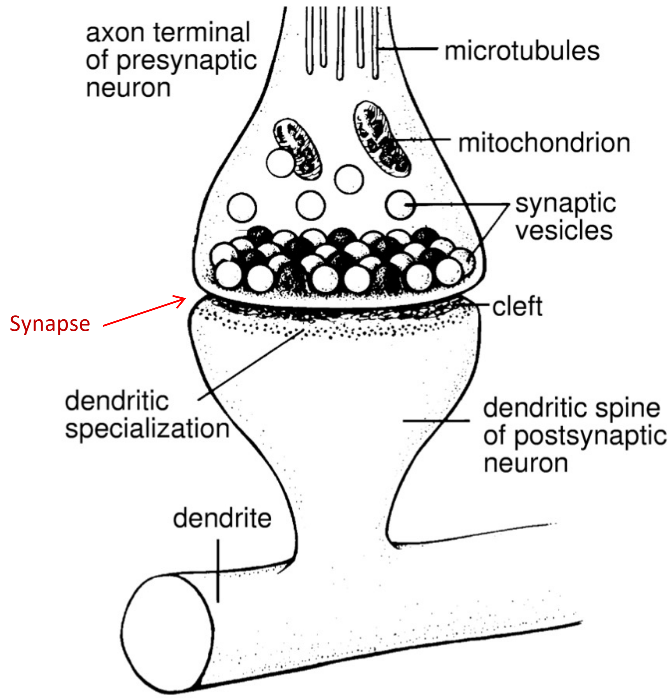
Inhibitory synapse



Synapses

Properties of synapses

- Signals from excitatory synapses are integrated at the soma
- If the membrane potential exceeds a threshold, the postsynaptic neuron will fire an action potential
    - It may require several excitatory synapses to cause the postsynaptic neuron to fire
    - Factors that determine whether the neuron will fire or not
        - Timing of the synaptic events
        - Distance of the synapse from the soma
        - Synaptic strength
        - ...

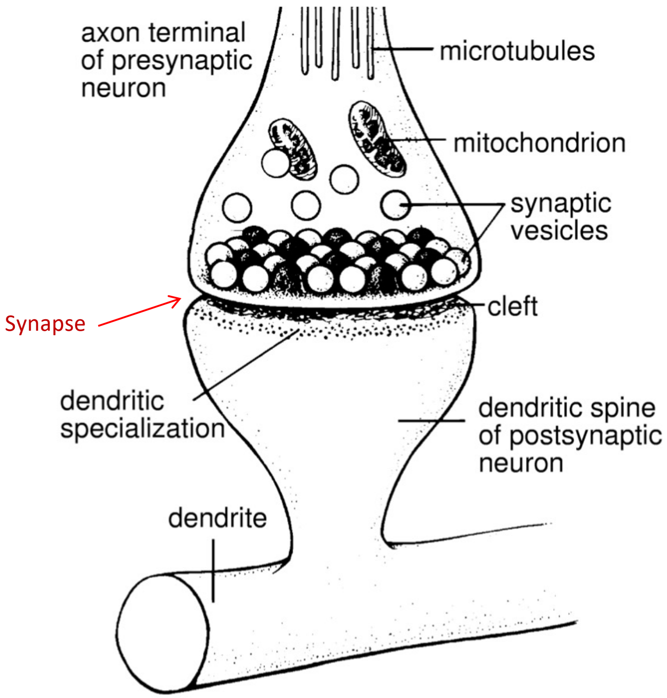


Synapses

Synaptic plasticity

- The ability to learn is mainly due to changes in synaptic strength
  - If the presynaptic neuron and the postsynaptic neuron fire at approximately the same time, the strength of the synapse increases
  - "Neurons that fire together, wire together"
    - Hebb Rule
    - Hebbian learning

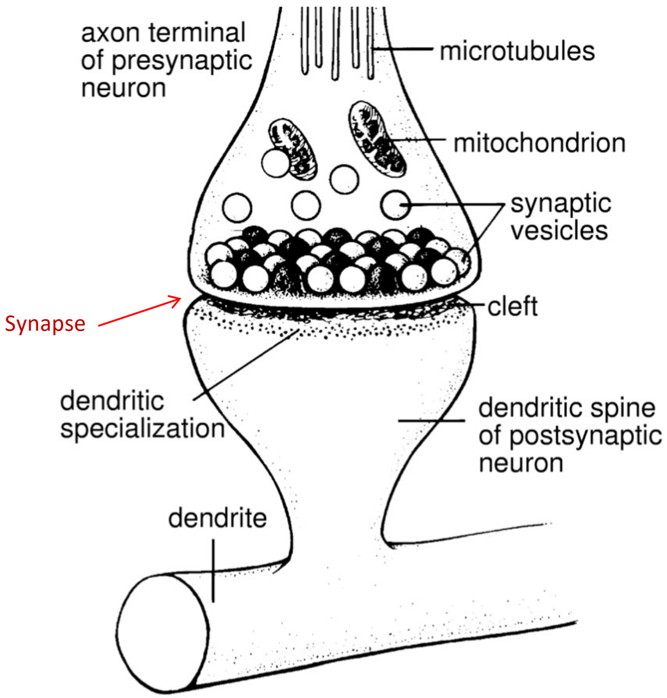
    Donald Hebb, 1949
  - Hebbian learning is realized by strong high frequency pulse
- Increase in synaptic strength (efficacy) is called long-term potentiation (LTP)



Synapses

Synaptic plasticity

- The ability to forget is also due to changes in synaptic strength
  - The opposite learning is realized by low frequency pulse
- Decrease in synaptic strength is called long-term depression (LTP)

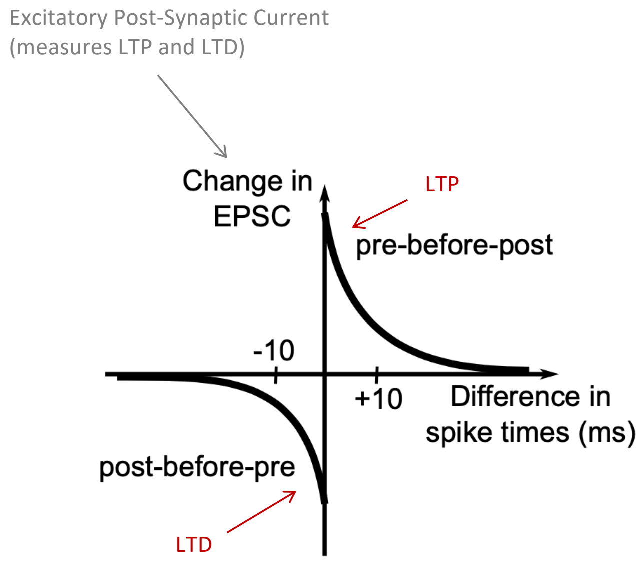


Synapses

Synaptic plasticity

- If the timing of the firing of the presynaptic neuron and the postsynaptic neuron varies, Hebb-like learning is still possible

- Spike-timing dependent plasticity (STDP)
  - Long-term potentiation (LTP) occurs if the presynaptic spike precedes the postsynaptic spike
    - Synapse is strengthened
  - Long-term depression (LTD) occurs if the presynaptic spike occurs after the postsynaptic spike
    - Synapse is weakened



Systems Neuroscience

The brain is a nervous system

- System of interconnecting regions
  - Each with different functions and specialities
- Sensory streams for
  - Hearing
  - Touch
  - Vision
- Motor streams for
  - Eyes
  - Head
  - Arms
  - Legs

Systems Neuroscience

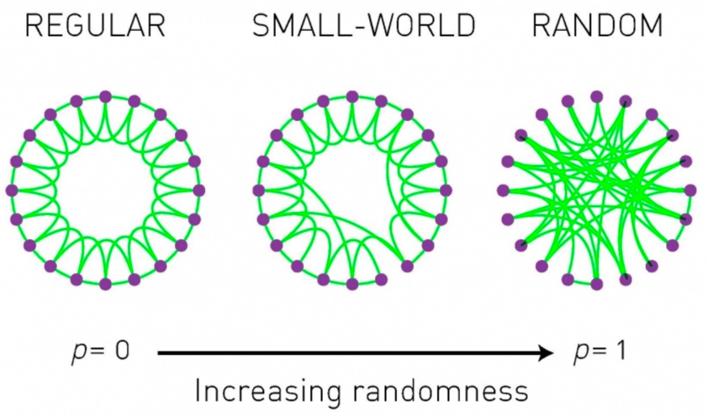
The brain is a nervous system

- Declarative memory
  - Places, events ← Episodic memory
  - Facts ← Semantic memory
- Procedural memory
  - Skills
- Short-term memory
  - Working memory
  - Seconds to minutes
- Long-term memory
  - Minutes to years

Systems Neuroscience

The brain is a small-world network

- Each region is connected to the others
- By just a small number of synaptic connections
- Watts-Strogatz Model (1998)

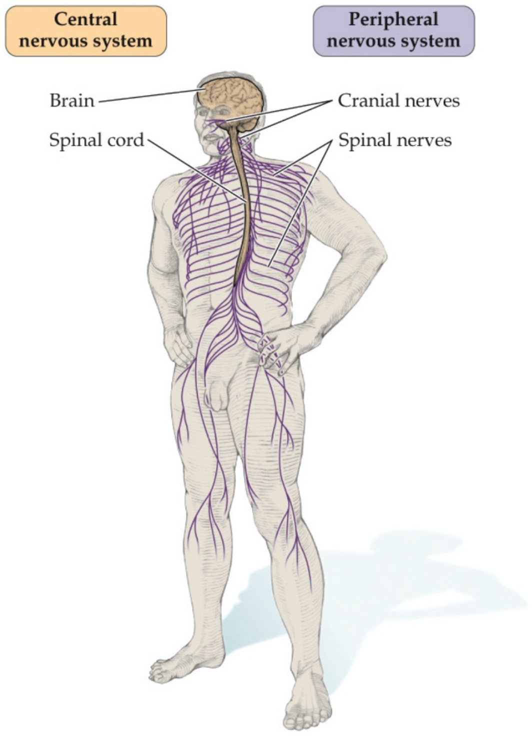


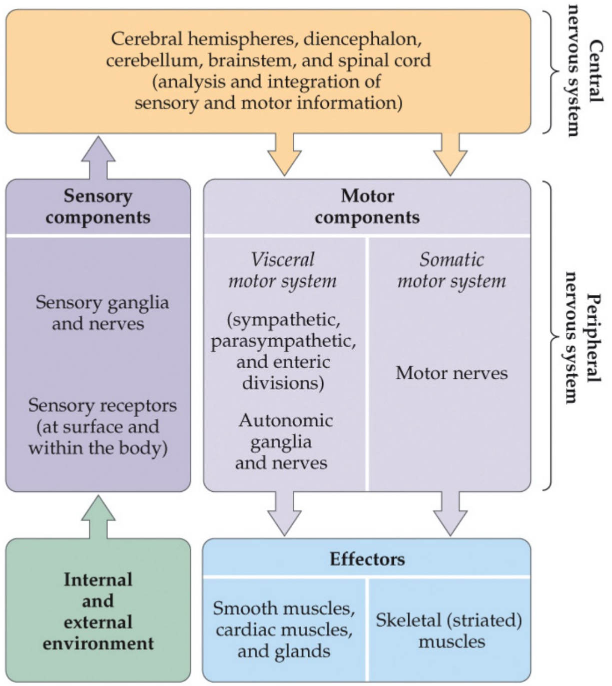
A.-L. Barabási, *Network Science,* 2014
http://barabasi.com/book/network-science

Systems Neuroscience

The nervous system has two parts

- Central nervous system (CNS)
  - Brain
    - Neocortex
    - Brainstem
    - Cerebellum
    - ...
  - Spinal cord
    - Connection to PNS
- Peripheral nervous system (PNS)
  - Sensory information
    - Internal to body ← Interoceptive
    - External to body ← Exteroceptive
  - Motor system
    - Somatic motor system ← Neurons to move parts of the body
    - Visceral motor system ← Neurons to control heart rate, breathing, digestion, ...

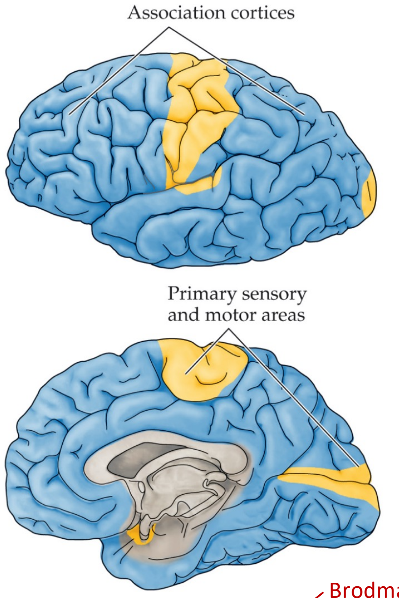




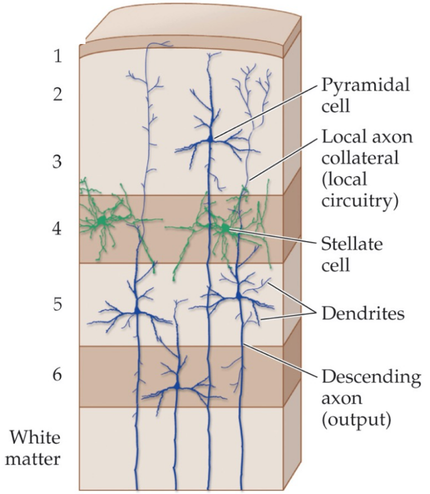
Systems Neuroscience

Cortical structures

- Neocortex
  - Folded structure in mammals
  - Columnar repeating structure
- Primary sensory cortex
  - Extracts features in stimuli
  - Primary visual cortex
  - Primary auditory cortex
- Primary motor cortex
  - Innervates muscles to cause movement

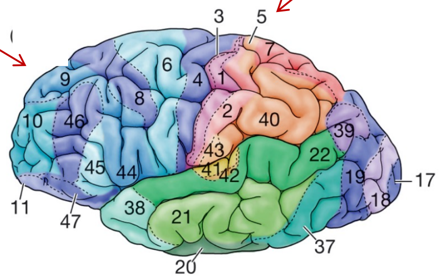


Cortical column

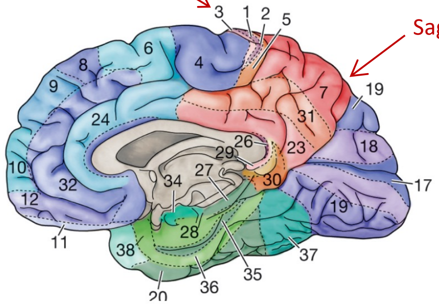


Brodmann area numbers

Lateral view



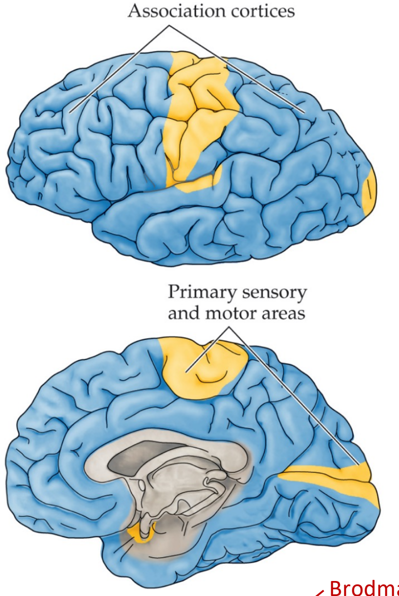
Saggital view

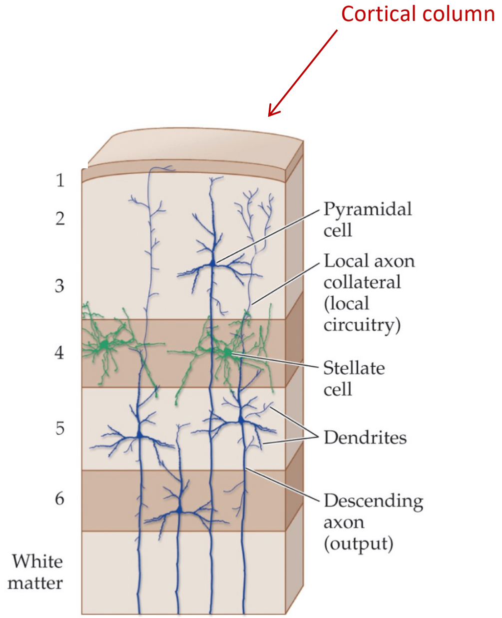


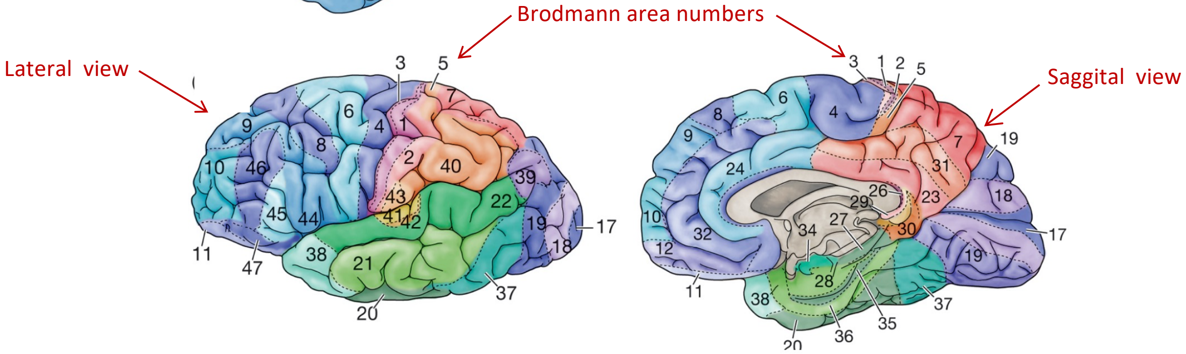
Systems Neuroscience

Cortical structures

- Association cortices
  - Multimodal
  - Integrate signals from primary & secondary sensory cortex
  - Generate activity in the motor cortex







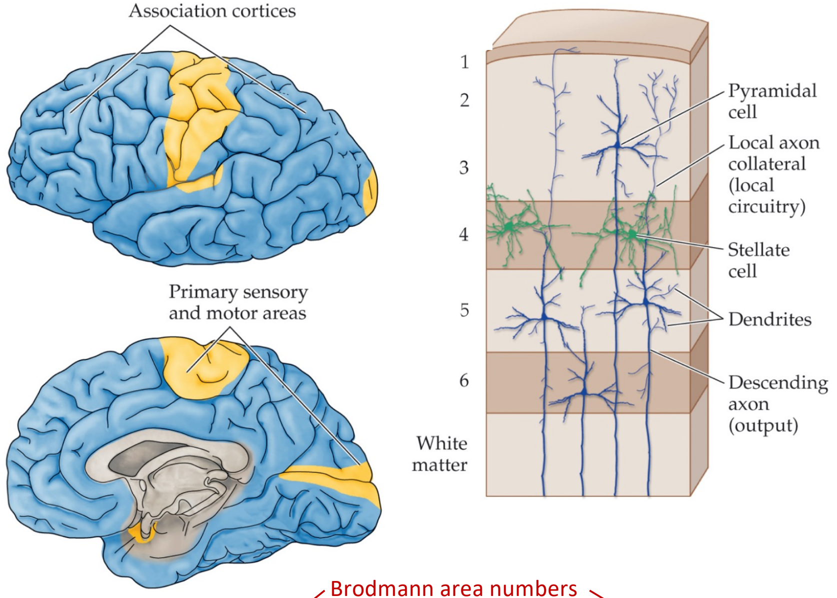
Systems Neuroscience

Cortical structures

The cortex is a series of repeating columnar structures

- Differences are the inputs to and outputs from these columns

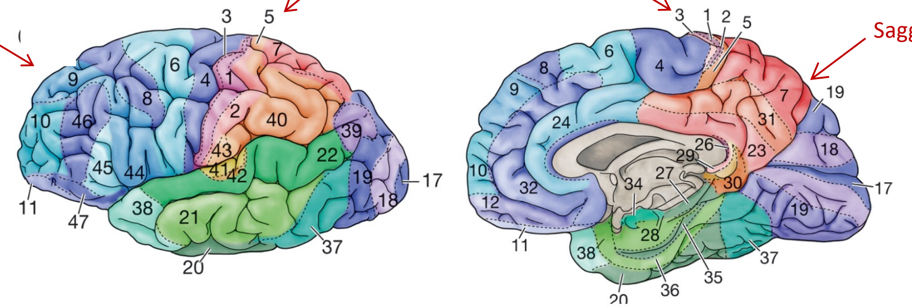
Cortical column



Brodmann area numbers

Lateral view

Saggital view



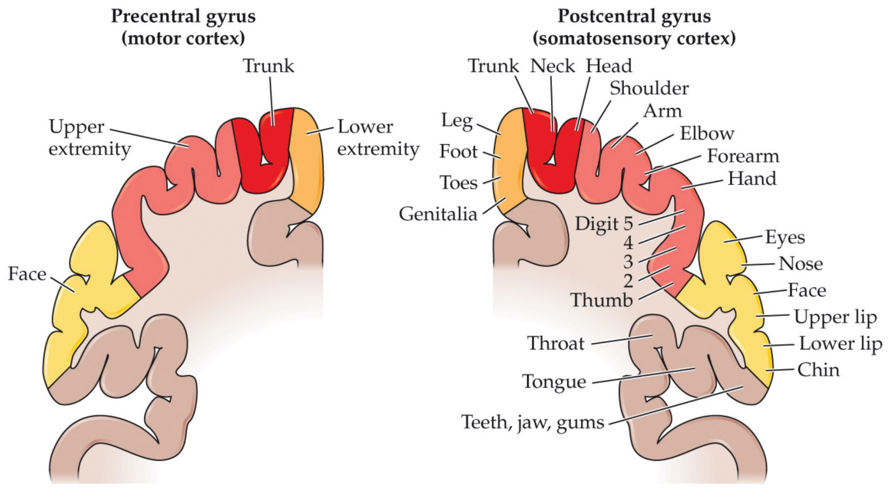
Systems Neuroscience

Cortical structures

The cortex is a series of repeating columnar structures

- Differences are the inputs to and outputs from these columns
- Motor cortex
  - Stimulating different areas will cause different parts of the body to move
  - Due to descending projections to the spinal cord, PNS, and muscles
- Somatosensory cortex
  - Touching different parts of the body
  - Will cause activity in specific areas
  - Different body parts have different amounts of cortical area
    - » e.g. large area for hand and face

Recall: soma means body

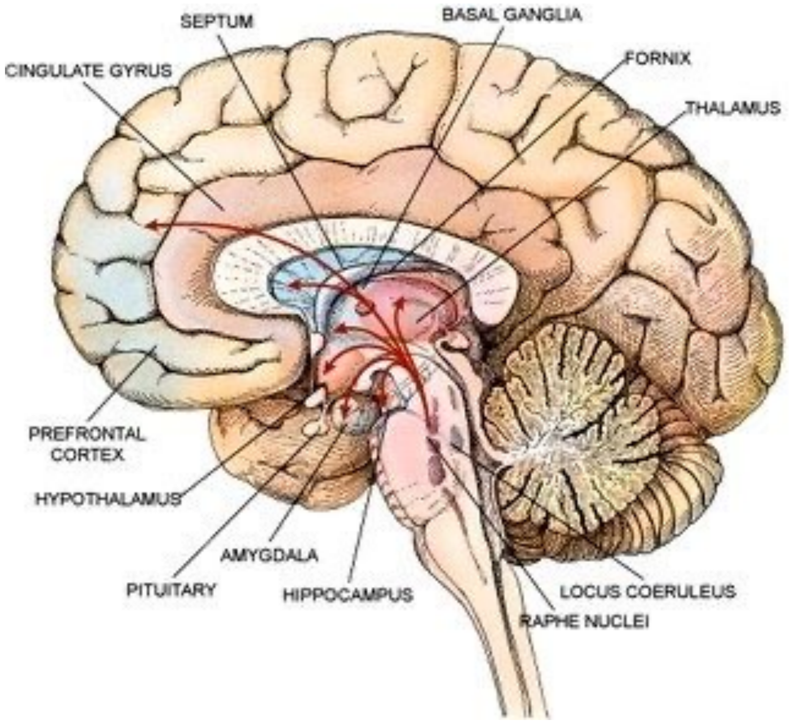


Cortical structure of a primate

Systems Neuroscience

Sensory systems

- There are pathways from the sensory receptors to the cortex in the CNS for each of our senses
  - Vision
  - Hearing ← Audition
  - Taste
  - Smell ← Olfaction
  - Touch
- The pathway starts at the periphery and reaches the thalamus after a few synapses and goes from there to the cortex
  - except the olfactory stimuli



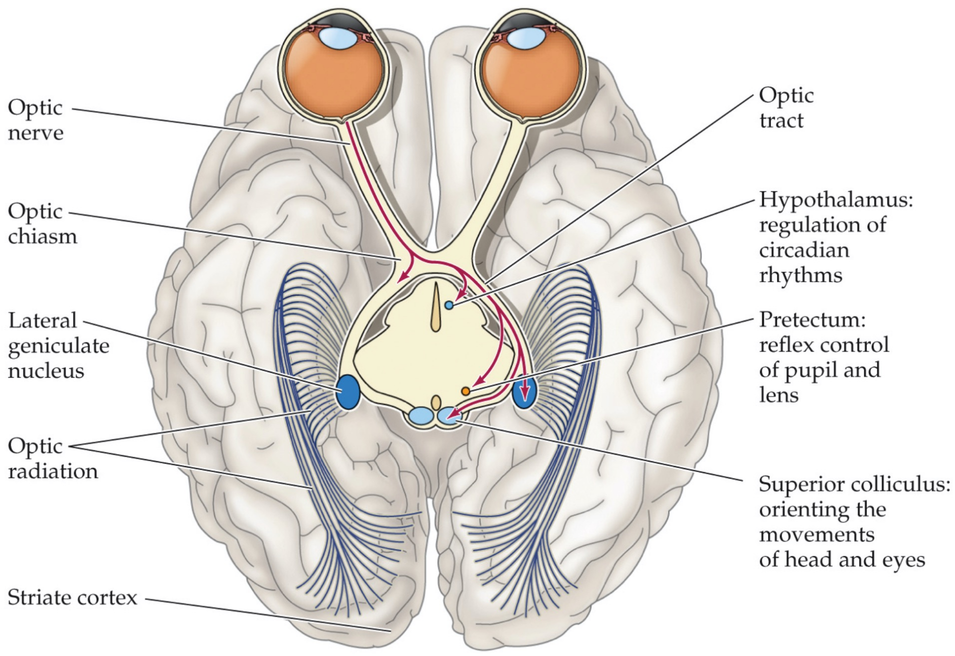
https://www.pinterest.com/pin/156570524517790126/

Systems Neuroscience

Visual stream

Rods and cones

- Eye to visual primary visual cortex
- Light incident on the retina activates photoreceptors
- Photoreceptor signals are subject to extensive preprocessing before reaching the lateral geniculate nucleus (LGN) in the thalamus
- Most paths are contralateral; some are ipsilateral
- LGN responds to
  - regions of light surrounded by darkness: on center, off surround
  - regions of darkness surrounded by light: off center, on surround



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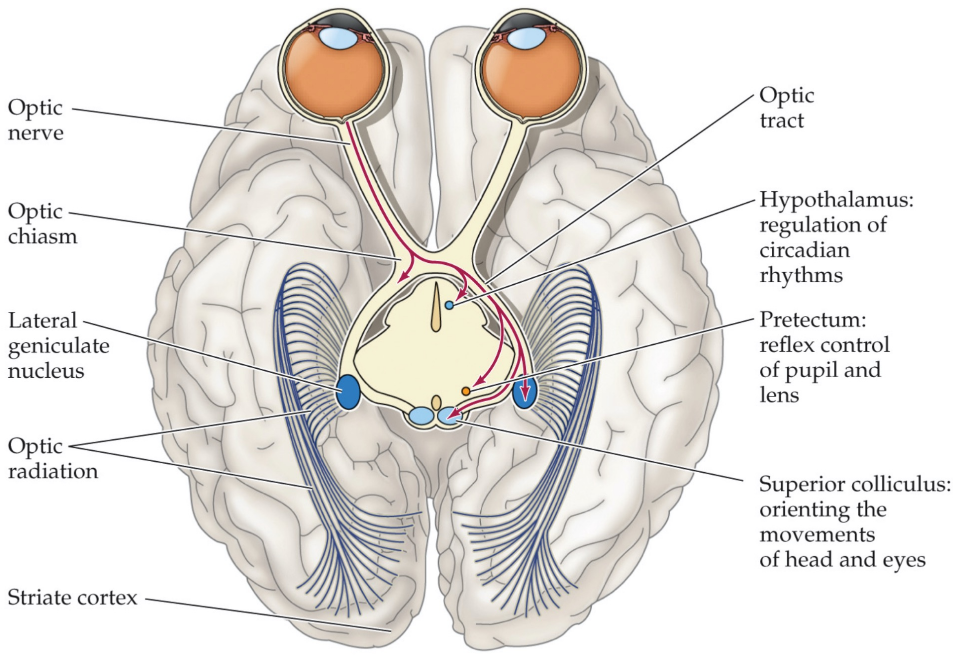
Visual stream

- LGN projects to the primary visual cortex
  - Striate cortex or V1
  - V1 responds to short, oriented, contrasting segments … elements of shape
- The retina also projects to the superior colliculus
  - Controls rapid (ballistic) eye movements: saccades
  - These movements are important for directing (spatial) attention



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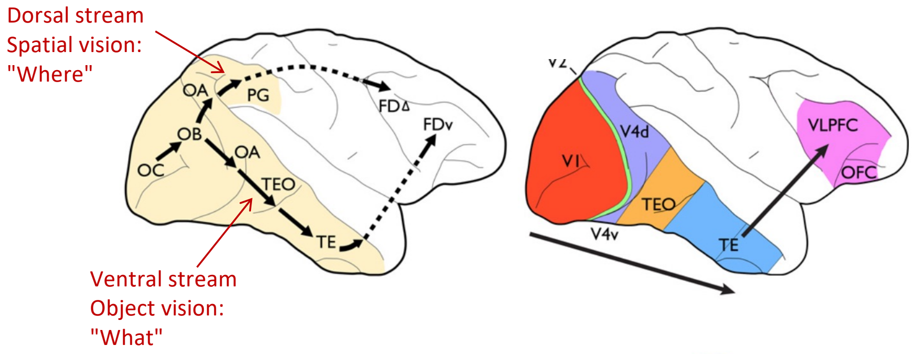
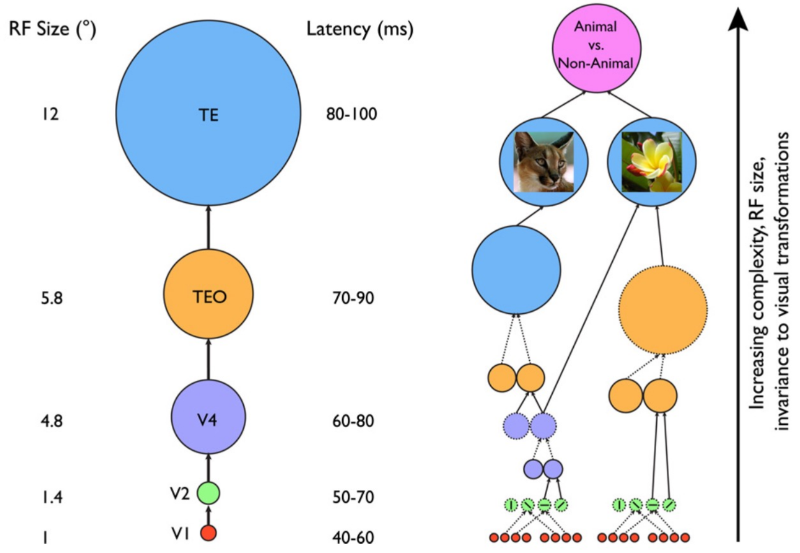
Visual stream

V1 projects to several cortical areas

- As the signals progress, the features they encode become more complex by combining earlier features
- The receptive field (RF) also gets larger
- A neuron in the inferior temporal cortex (TE) might respond to an animal, irrespective of its position, orientation, and size
(translation, rotation, and scale invariance)





Systems Neuroscience

Motor Systems

- The main goal of the brain is to promote action
- There are extensive areas in the brain dedicated to movement

Video

Daniel Wolpert: The real reason for brains

https://www.youtube.com/watch?v=7s0CpRfyYp8

Systems Neuroscience

Motor Systems

- Reflexive or involuntary movement in response to some stimuli
- For example, if your left foot steps on a sharp stone, it automatically lifts up and the right foot comes down to prevent a fall
    - This reflex circuit occurs between the legs and the spinal cord: it does not involve the brain
    - The brain would be too slow to respond
- For example, if something large moves in your peripheral vision, your eyes will move reflexively to centre the visual field on this potentially dangerous object
    - This reflex circuit is from the eye to the superior colliculus and then to the brainstem to control the eye muscles

The iCub humanoid robot – A platform for research in cognitive robotics

Systems Neuroscience

Motor Systems

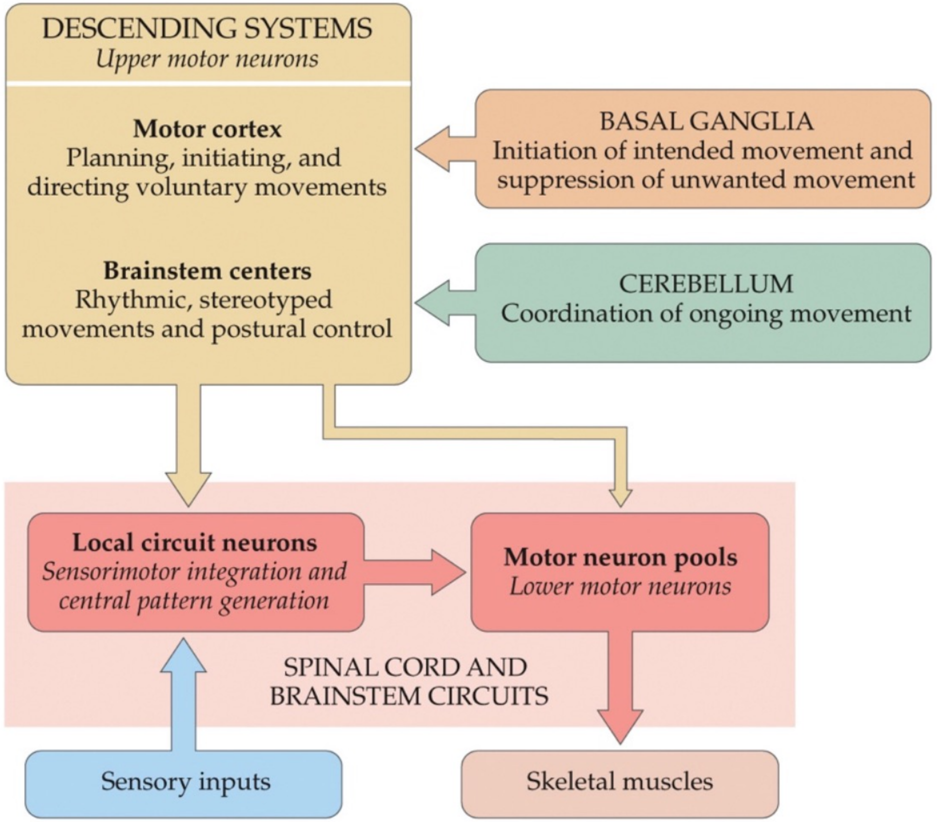
- Planned or voluntary movement
- We simulate several movements before choosing what seems to be the best one
- When the choice is made, this causes a preparatory signal in the premotor cortex
- This then drives specific areas, e.g. for the arm or hand, in the motor cortex
- These signals go through the spinal cord and eventually reach the muscles and activate them
- Again, prior to the movement, many brain areas, including the frontal and parietal cortex may have been involved in visualizing the movements and assessing different options

Systems Neuroscience

Motor Systems

- Motor cortex and frontal cortex: planning and initiating voluntary movements
- Brainstem: voluntary and involuntary movements
  - Posture control
  - Rhythmic movements, e.g. walking
- Proprioceptive input from movement
  - Joint position
  - Torque
  - Load

are received by the spinal cord, causing adjustments



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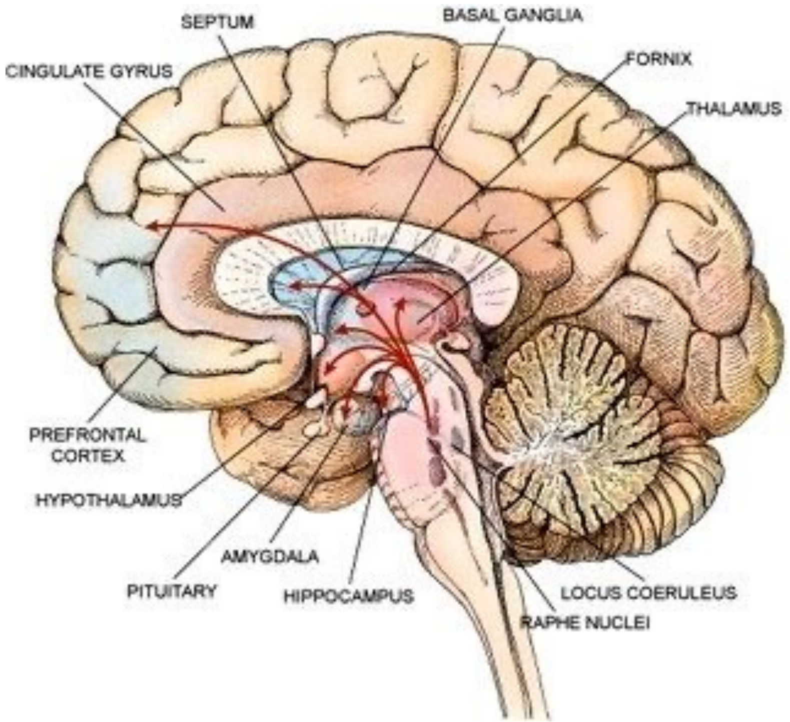

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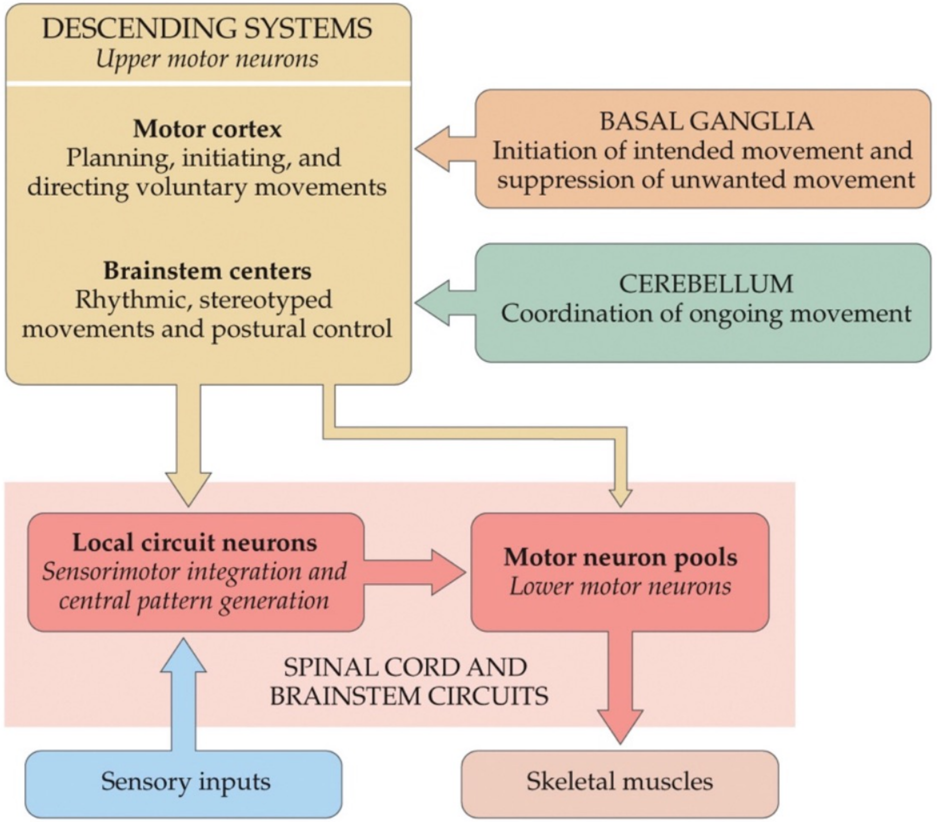
Systems Neuroscience

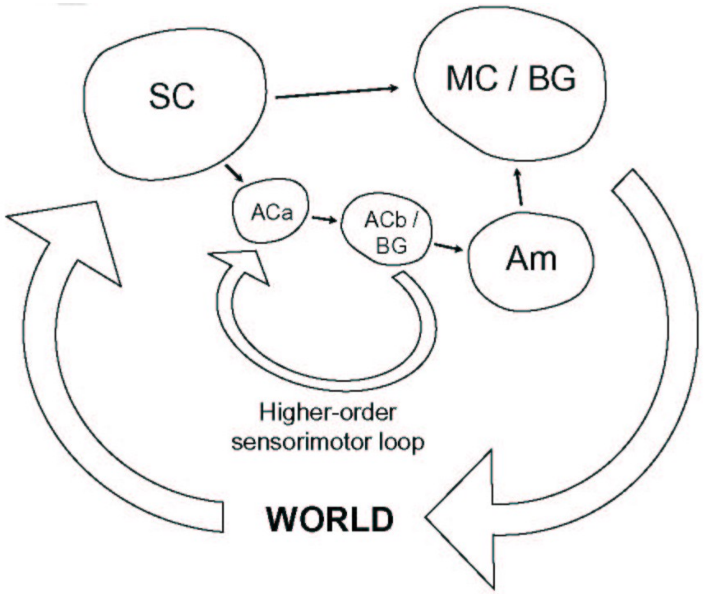
Motor Systems

- Basal ganglia
  - Perform action selection
  - Can initiate or suppress movement
  - Once selected, these action can recruit sequences of of movements: stereotypical motor program
- Cerebellum
  - Organizes movement
  - Provides fine motor control with precise timing, adapting movements when there are errors



Aside: Global Workspace Cognitive Architecture

- Modelled on the anatomy and operation of the brain
  - SC: Sensory Cortex
  - MC: Motor Cortex
  - BG: Basal Ganglia (action selection)
  - AC: Association Cortex
  - Am: Amygdala (affect)



- Implemented using G-RAMS (generalized random access memories)

M. P. Shanahan, 2006. A Cognitive Architecture that Combines Internal Simulation with a Global Workspace, Consciousness and Cognition, 15, pp. 433-449.

Systems Neuroscience

Closing message

- Although we teach different functions (e.g. perception, planning, motor control) separately, the brain is highly reticulated (i.e. there are links between different regions)
- Motor areas strongly and bidirectionally interact with sensory areas
- Attention is important for memory
- Memories dictate what we attend to and do
- Emotions dictate what we attend to and do
- The brain, as a whole, exists to serve the body's needs and its need to act in the environment
- Neurorobotics must address all three: brain, body, environment

“In the stream of cognitive processes one can conceptually isolate certain components, for instance

(i) the faculty to perceive,

(ii) the faculty to remember, and

(iii) the faculty to infer.

"But if one wishes to isolate these faculties functionally or locally, **one is doomed to fail.**

Consequently, if the mechanisms that are responsible for any of these faculties are to be discovered, then **the totality of cognitive processes must be considered**."

Heinz von Foerster

Understanding Understanding

Essays on Cybernetics and Cognition

2003

Reading

Hwu, T. and Krichmar, J. (2022). Neurorobotics: Connecting the Brain, Body and Environment, MIT Press.

Chapter 2 – Neuroscience: Background for Creating Neurorobots, pp. 16-34

Videos

Daniel Wolpert TED Talk on the real reason for brains

https://www.youtube.com/watch?v=7s0CpRfyYp8