Mathematical Brain Modeling summary

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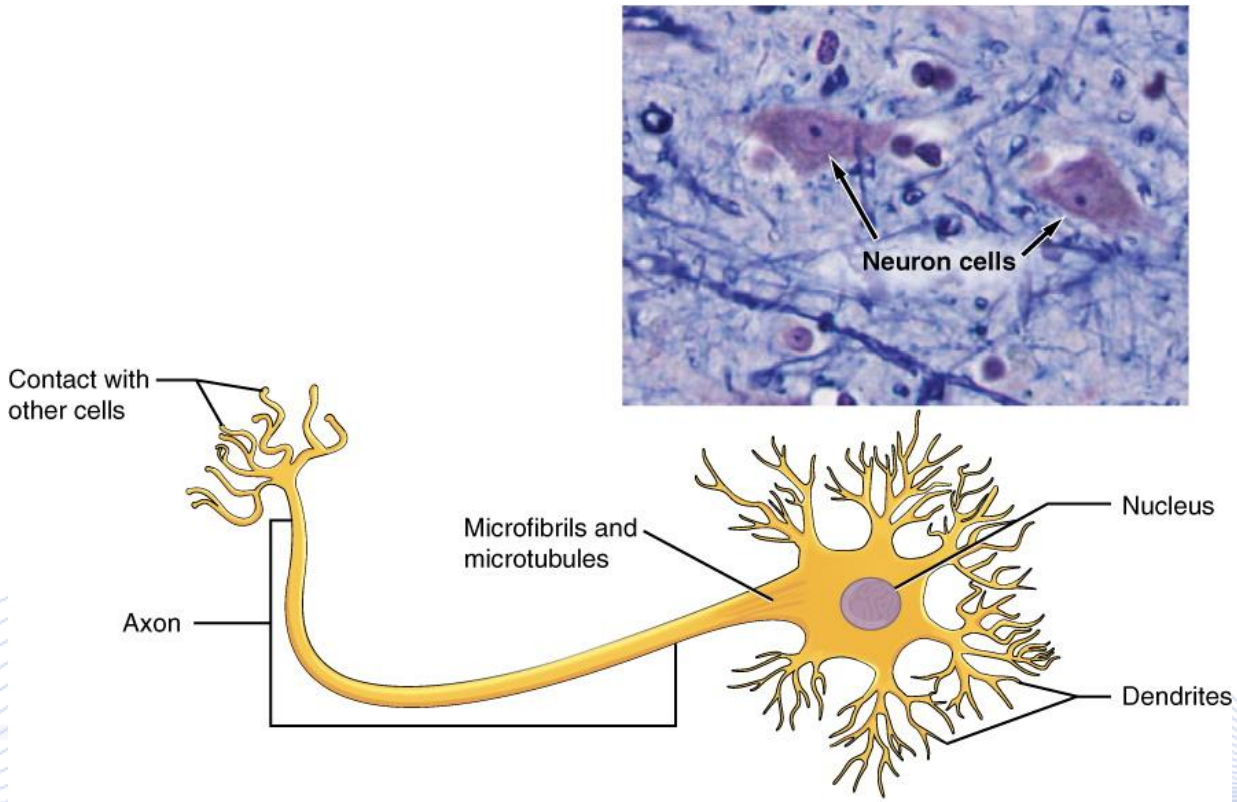
Artificial Intelligence & Information Analysis Lab

Mathematical Brain Modeling

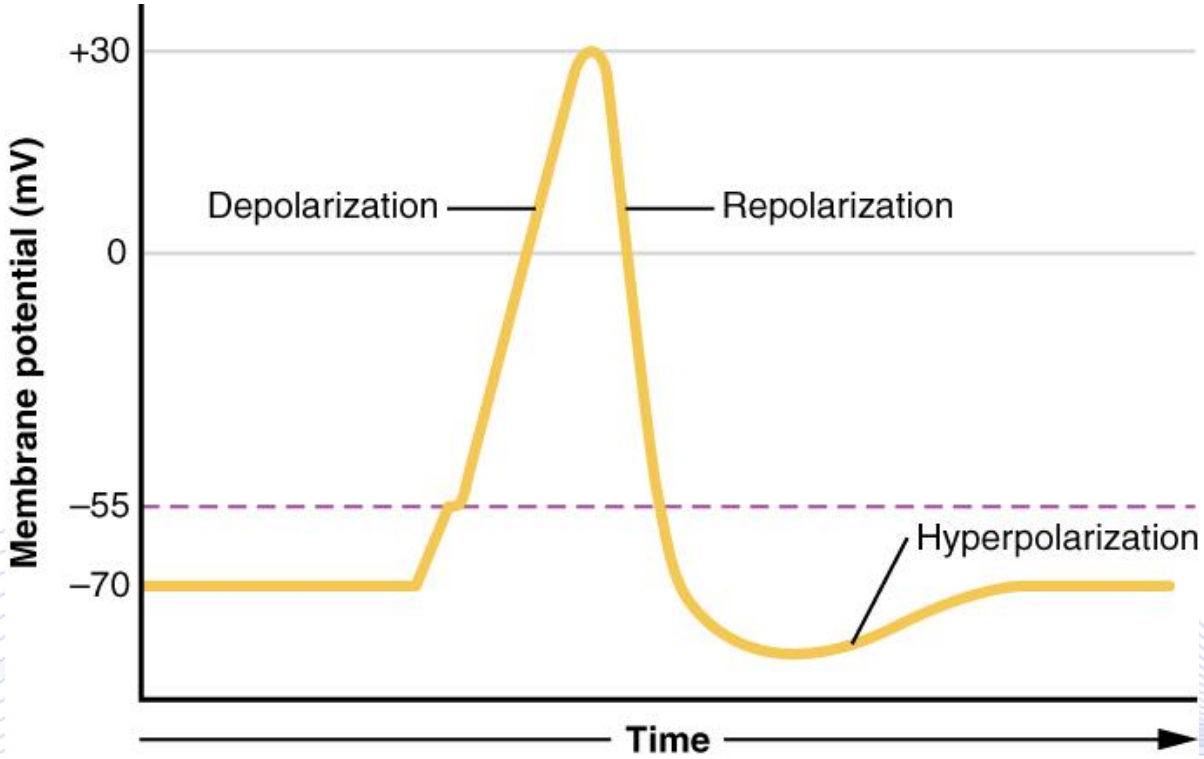
- ***Brain Cells***
- Anatomy of the Brain
- The Senses
- Neuroimaging
- Artificial Neural Networks
- Brain Graphs
- The Human Connectome

The Body of the Neurons



Neuron body [BIG2019].

Action Potential



Action Potential [BIG2019].

Glia

- The second type of cells found in the brain.
- They are the caretakers of the neurons.
- Unlike neurons, they cannot transmit information.
- Depending on their job they are separated into four categories.
- Their actual number is unknown. Estimations range from a $50:1$ to a $1:4.3$ glia to neurons ratio.

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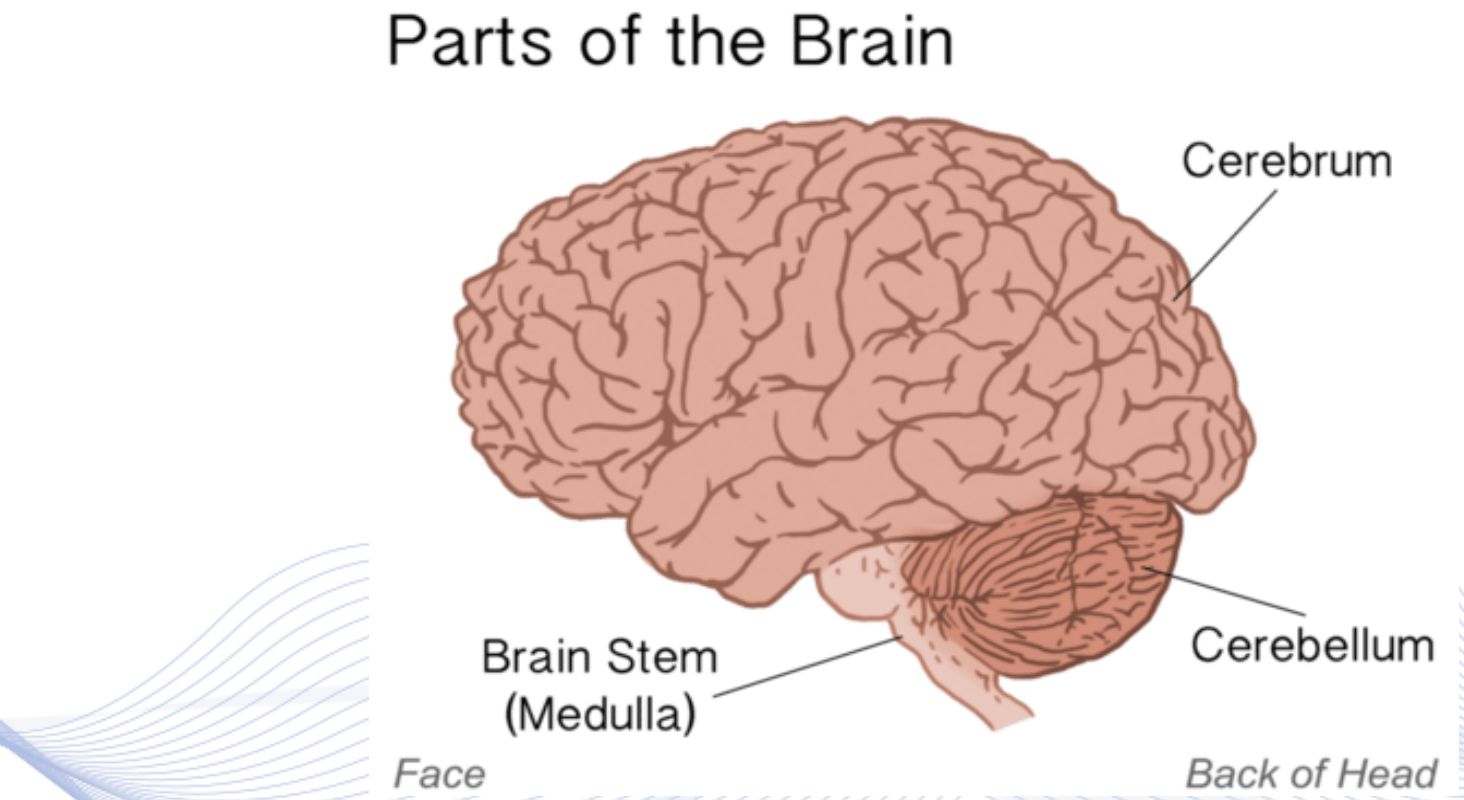
Anatomy of the Brain

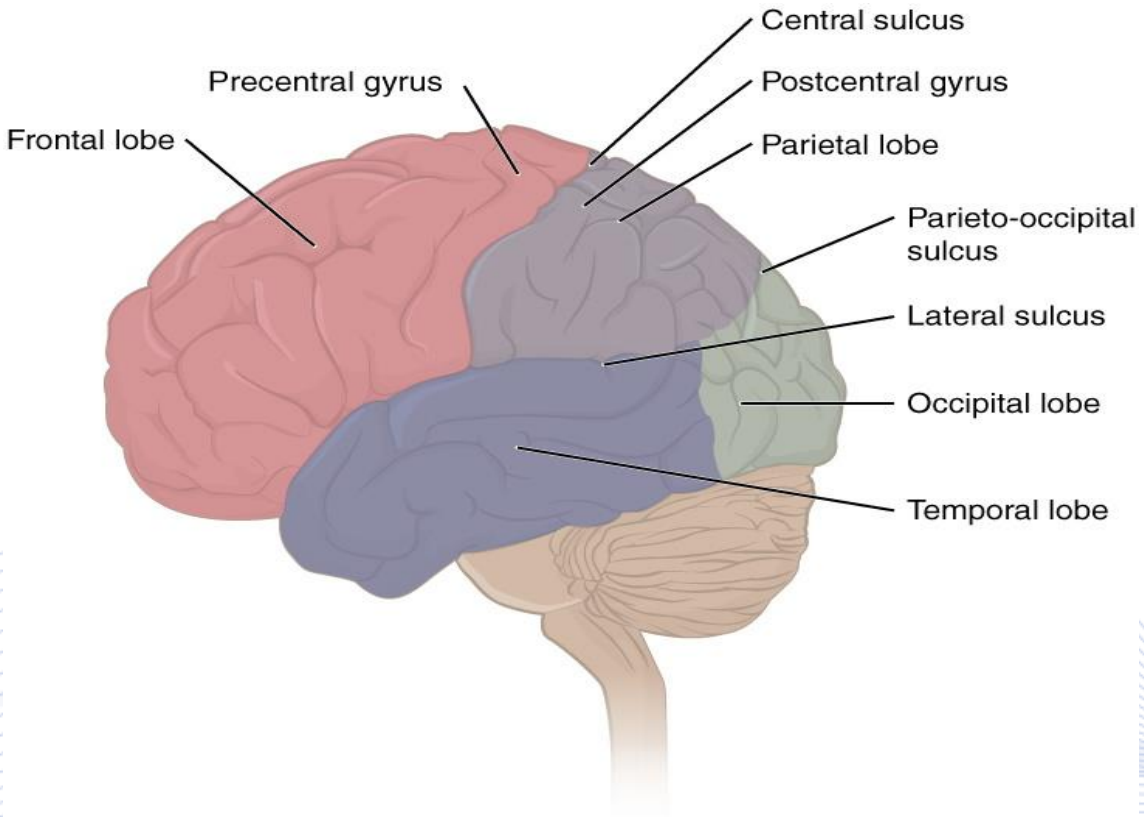
- The brain is separated into three major regions.
- The ***Cerebrum*** is the largest of the three and it is responsible for all the complicated processes of the brain.
- The ***Cerebellum*** controls the movement of the muscles and the balance.
- The ***Brain Stem*** is the intermediary between the spinal cord and the brain, and controls the subconscious functions of the body.

Anatomy of the Brain



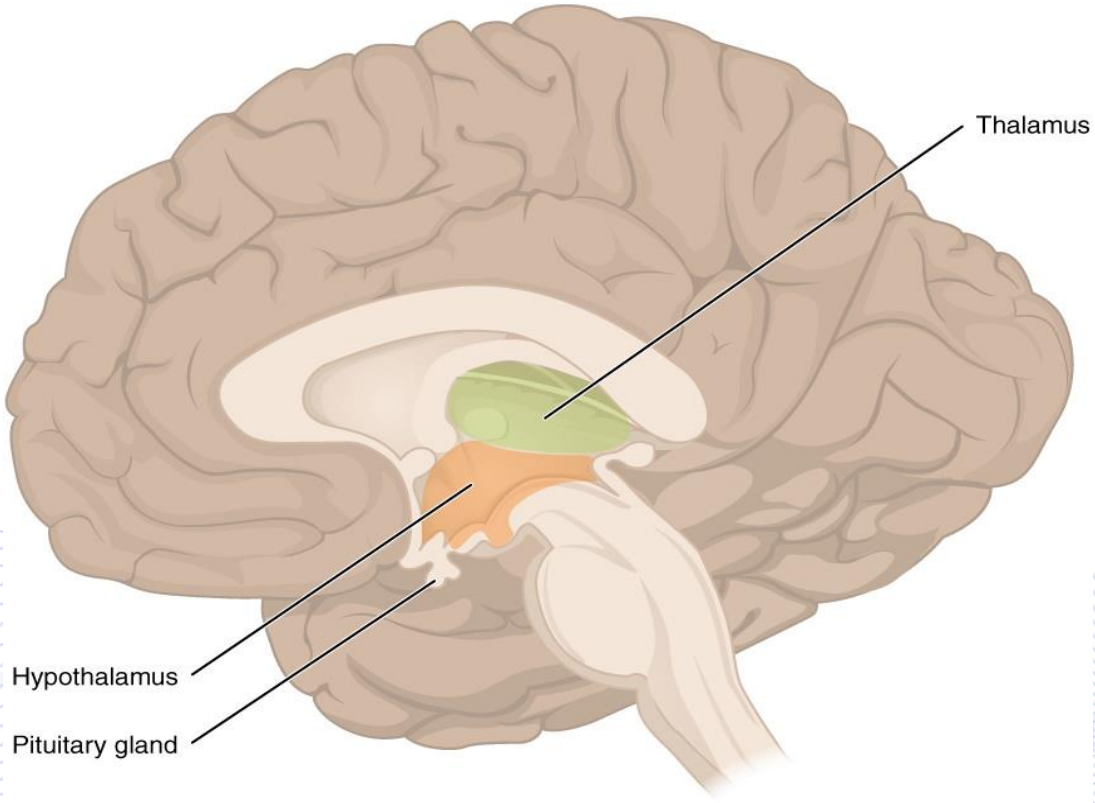
The three parts of the brain [WIL2012].

The Lobes of the Brain



The four lobes of the brain(from [BIG2019]).

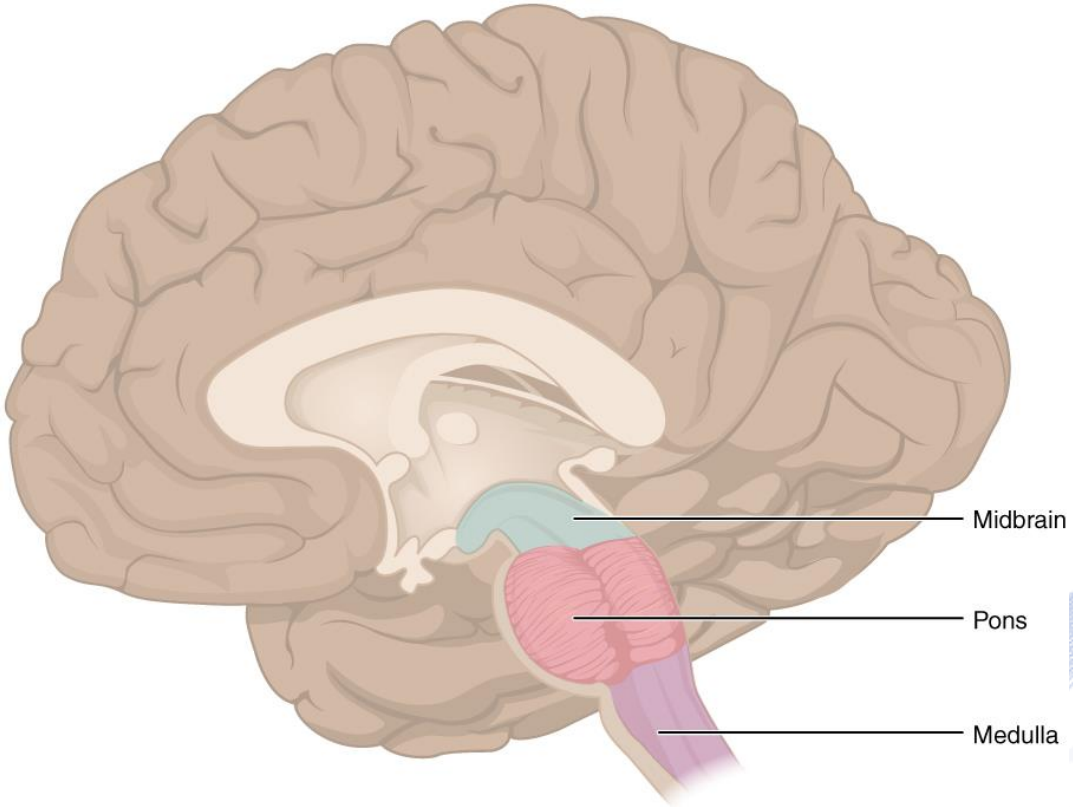
Deep Structures of the Brain



Diencephalon [BIG2019].

The Brain Stem

- It is made up of three regions:
  - The Midbrain
  - The Pons
  - The Medulla



Brain Stem [BIG2019].

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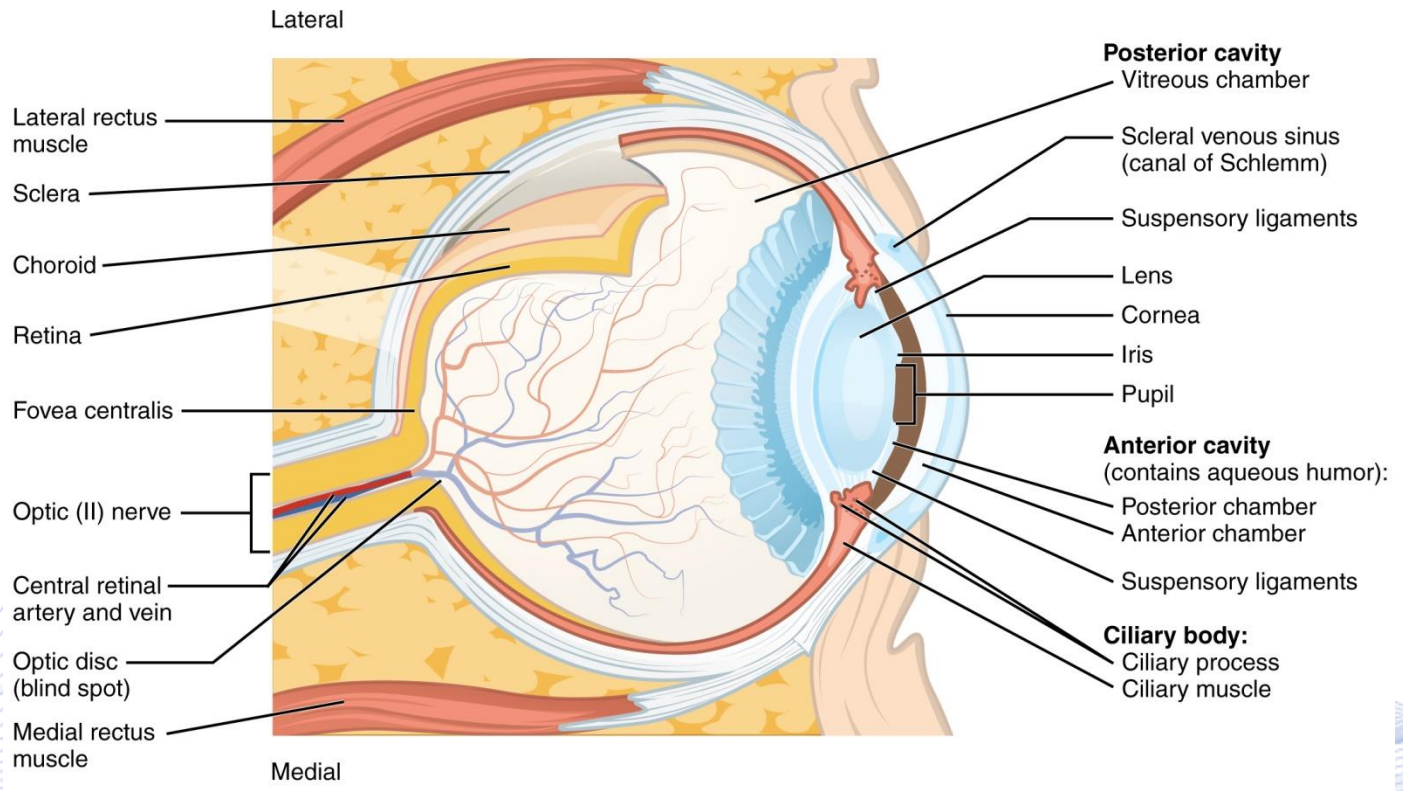
Vision

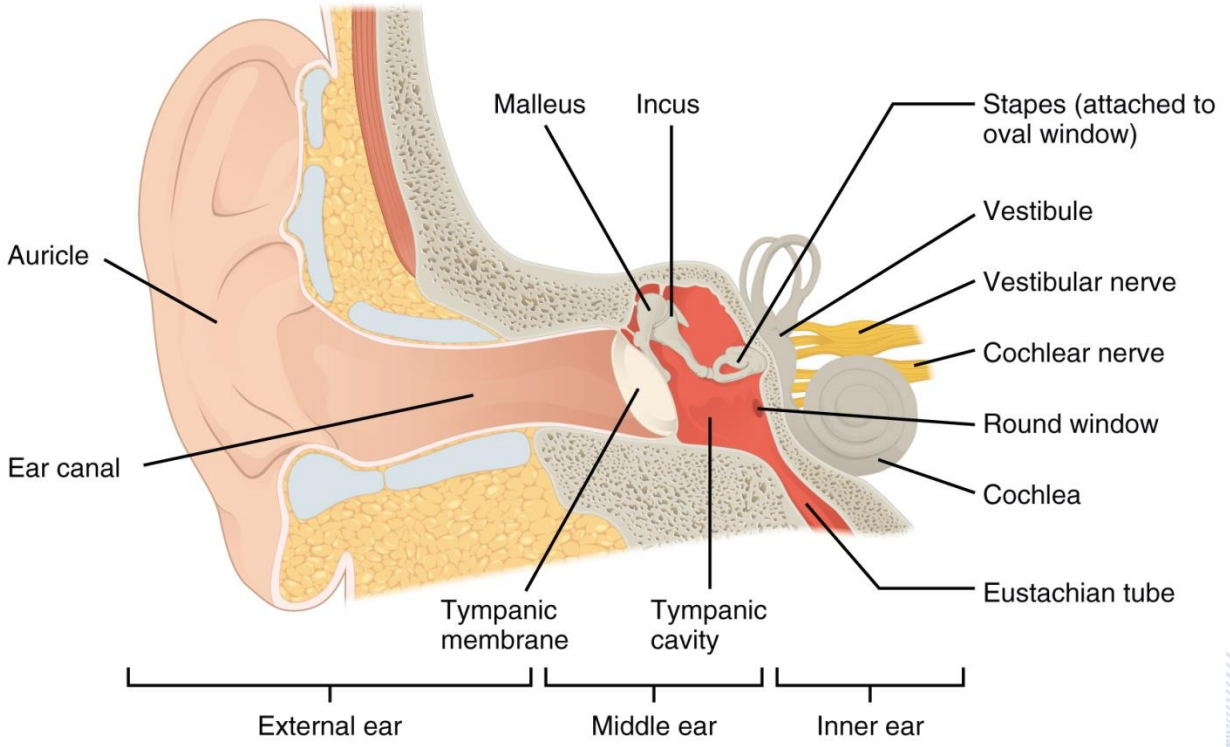
- The human eye is made up of three layers.
- The outermost is the ***fibrous tunic*.**
  - It contains the ***sclera***, the white of the eye, and the ***cornea***, which covers the front of the eye
- The ***vascular tunic*** is the middle layer.
  - It is composed of the ***choroid***, the blood supplier of the eye, the ***ciliary body***, responsible for bending the lens, and the ***iris***, the colored part of the eye.

Vision



The Human Eye(from [BIG2019]).

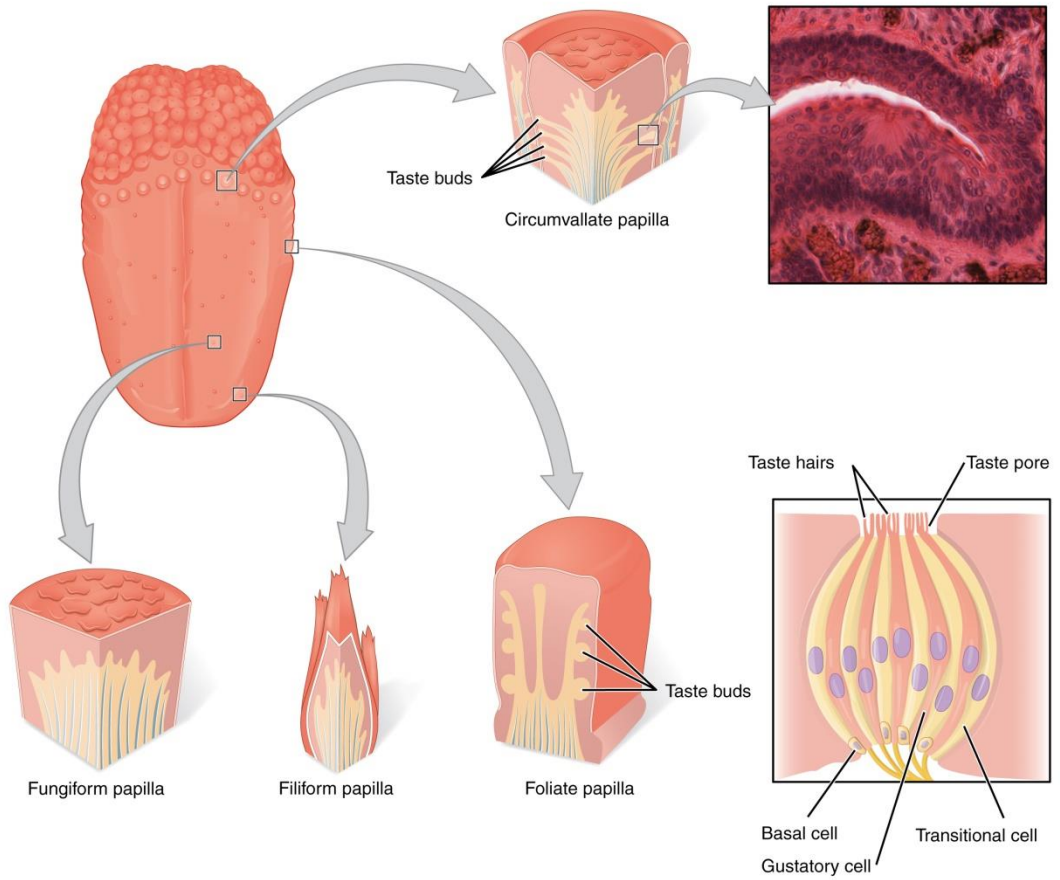
Hearing



Ear structure [BIG2019].

Taste

- There are four basic tastes: ***sweet***, ***salty***, ***sour***, and ***bitter***.
- Researchers suggest that there may additionally two others:
  - one for fats and one for deliciousness.
- Tastes are sensed by tongue ***papillae***.



Tongue papillae [BIG2019].

Smell

- It is perceived by ***olfactory receptor neurons*** in the upper part of the nose, known as the ***olfactory epithelium***.
  - The proteins that make up smells bind with mucus and are received by these neurons.
- Smell information is sent directly to the frontal lobe.
- From there it is dispersed to cerebrum, limbic system and hypothalamus.
- In the latter two ones, it can and will be associated with long-term memories.

Touch

- All ***skin layers*** have various receptors that are able to sense not only touch, but also temperature and pain.
- Fingers have the highest density of such receptors.
- This explains why they are the most sensitive part of the body to touch.
- Together with the rest of the tactile senses, touch signals are processed in the ***parietal lobe***.

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Neuroimaging

- Since communication in the brain is facilitated through electrical pulses, their detection allows us to see and map its activities.
- These pulses can be detected through various methods, that are generally separated into two categories:
  - ***Invasive Techniques*** require the removal of part of the skull in order to put sensors directly to the brain.
  - ***Noninvasive Techniques*** have their sensors put on the subject's scalp.

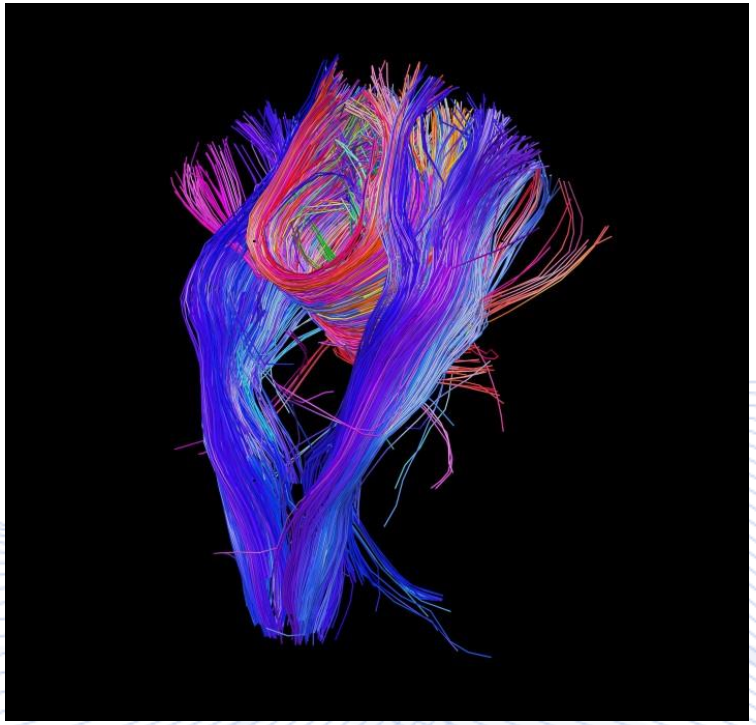
Noninvasive Techniques

- ***Electroencephalography*** (EEG).
  - Uses a cap of electrodes in the scalp that capture the brain's electrical signals
  - Good temporal but bad spatial resolution.

Noninvasive Techniques

- ***Positron Emission Tomography*** (PET).
  - Measures the emissions from radioactive chemicals that were injected to the subjects bloodstream
  - Good spatial resolution, bad temporal.
- ***Functional magnetic resonance imaging*** (fMRI).
  - Measures the changes in the blood flow of the brain in order to detect what areas show high activity.
  - Very good spatial resolution, bad temporal.
  - The subject needs to lie down with the head inside a scanner.

Noninvasive Techniques



Diffusion Tensor Imaging of White matter fiber architecture [HUM].

Brain Stimulation

- A subject growing in interest, especially in the field of brain-computer interfaces.
- It involves artificially stimulating the brain to:
  - Perform actions without thinking or wanting them.
  - Sense things it is not actually sensing.
- Invasive stimulation techniques use electrodes to shock the neurons and activate them.
- Noninvasive stimulation is performed through either magnetic fields or ultrasounds directed at the brain.

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Artificial Neurons

- They are attempts at mimicking the structure and function of the human brain.
- Originally created as single node networks, they have evolved into complicated multilayered neural networks.
- A fundamental part of machine learning, they can be used for supervised, unsupervised and reinforcement learning.

Perceptron

- The simplest neuron model is the ***perceptron*.**
- It is an evolution of the McCulloch-Pitt model as it includes a bias component.
- For a collection of inputs $x_i, i = 1, \ldots, N$, perceptron weights $w_i, i = 1, \ldots, N$ and a bias b, perceptron output is given by [KAW2000]:

$$y = f(\mathbf{w}^T\mathbf{x} + b) = f\left(\sum_{i=1}^{N} w_i x_i + b\right).$$

Perceptron

- Learning is achieved by adjusting perceptron weights, in order to match the input to the training target.
- The ***transfer*** or ***activation function*** f can take various forms:
  - Sigmoid function: $f(x) = \frac{1}{1+e^{-x}}$.
  - Rectifier function: $f(x) = \max(0, x)$.
  - Sign function: $f(x) = \begin{cases} -1, & if\ x < 0 \\ 0, & if\ x = 0. \\ 1, & if\ x = 1 \end{cases}$

Hopfield Network

Original Hopfield networks used binary neuron models instead of perceptrons.

- A vector $\mathbf{v}$ describes the state of the network in each step.
- A neuron i has activity v_i and bias b_i.
- The synapse from node j to i has a weight w_{ji}.
- The input of i is [HOP2007]:

$$x_i = \sum_j w_{ji} v_j + b_i$$

Hopfield Network

- If $x_i > 0$ then $v_i = 1$, otherwise $v_i = 0$.
- The network updates, by doing this for every node.
- For the weights we consider that:
  - Neurons do not connect with themselves $w_{ii} = 0$.
  - The network is symmetric, $w_{ij} = w_{ji}$.

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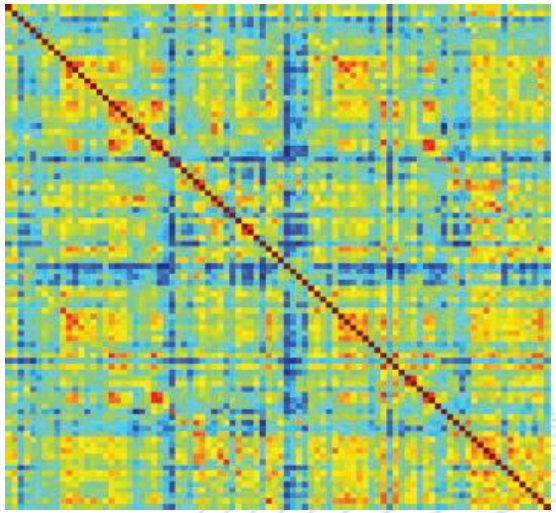
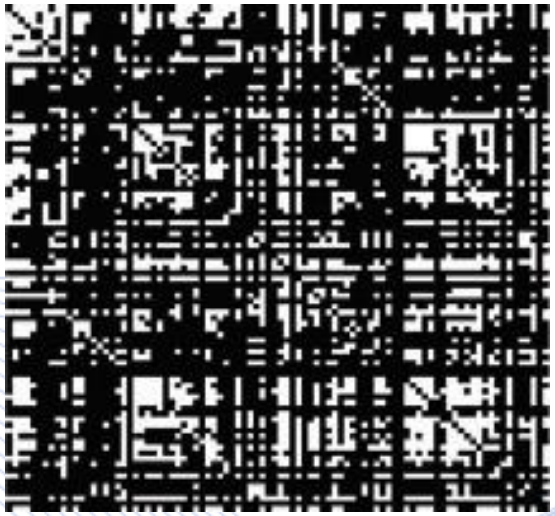
Brain Graphs

- They are a way of modeling the brain through the use of graphs and graph theory.
- They are useful because:
  - They allow us to see the brain's structural, functional and causal organization.
  - It is easier to compare the graphs of different brain mapping methods than the actual data.
  - They make possible the comparison of networks formed through large and small scale analytics.

Association and Adjacency Matrices





a)Association matrix, b) Adjacency matrix for $\kappa = 0.15$, c) Adjacency matrix for $\kappa = 0.30$ (from [BUL2011])

Brain Graphs

- Most studies agree that the most commonly found properties of the brain through the use of graphs are:
  - Small-worldness.
  - Modularity.
  - Network hub structure.

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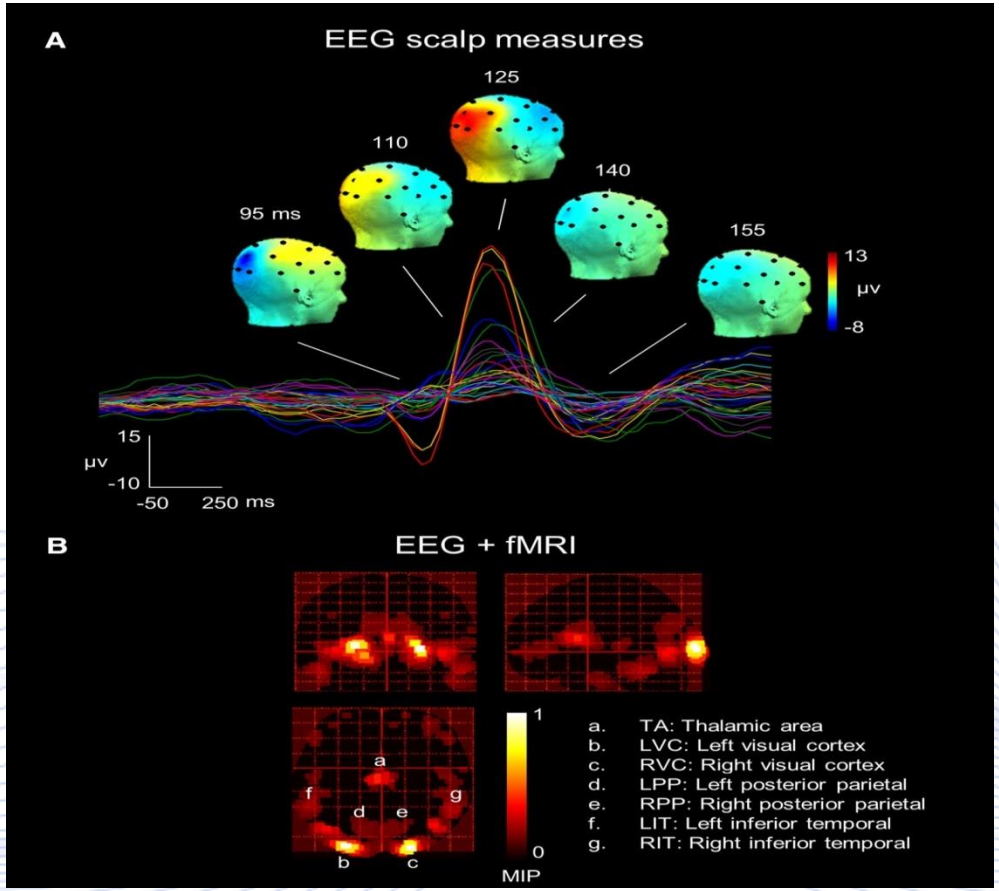
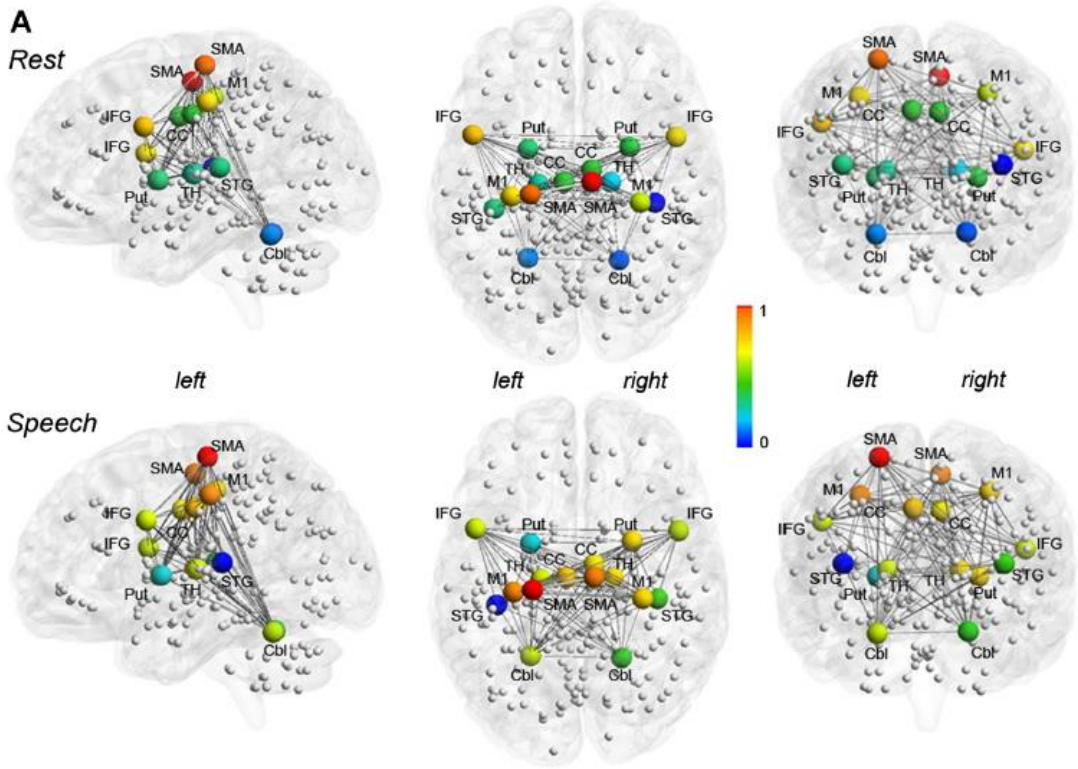
Visual Signals Propagation



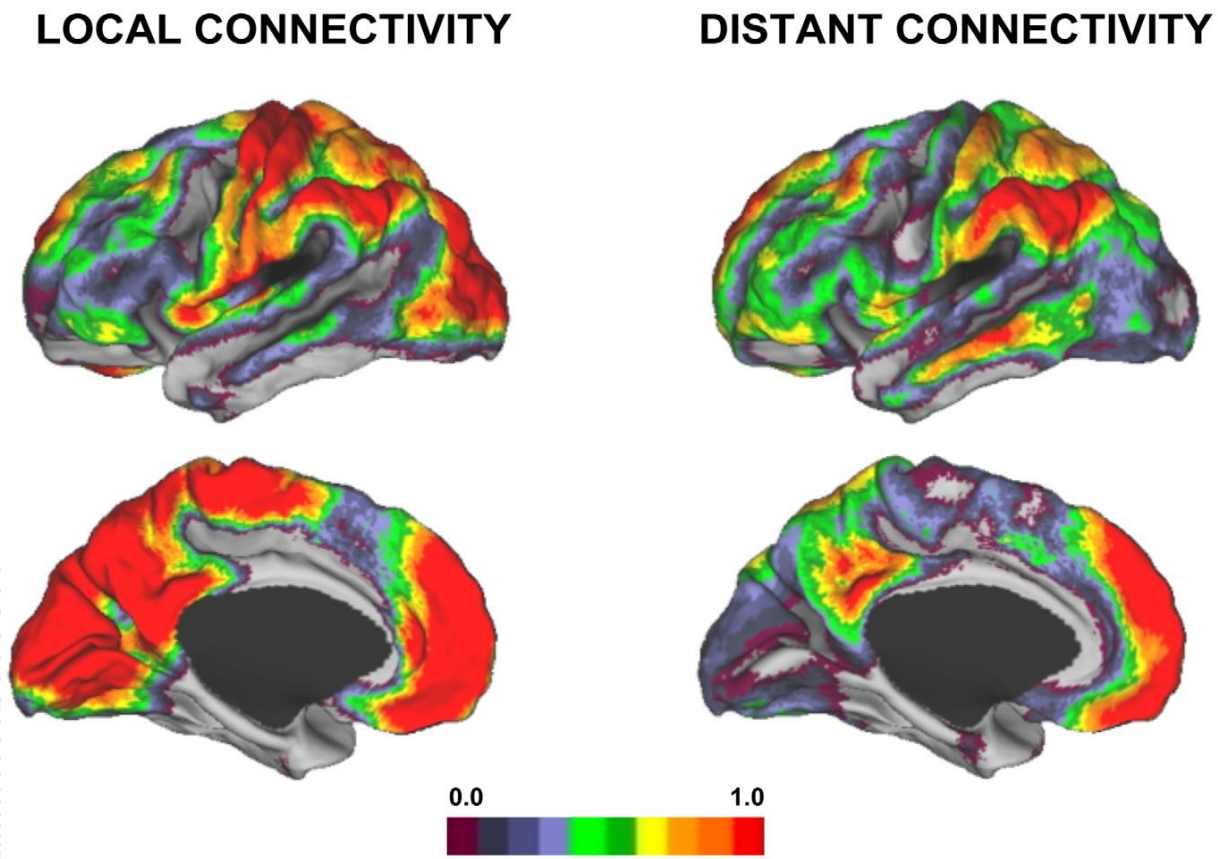
Brain activation during passive stimuli(from [YOU2014]).

Brain Speech Graphs



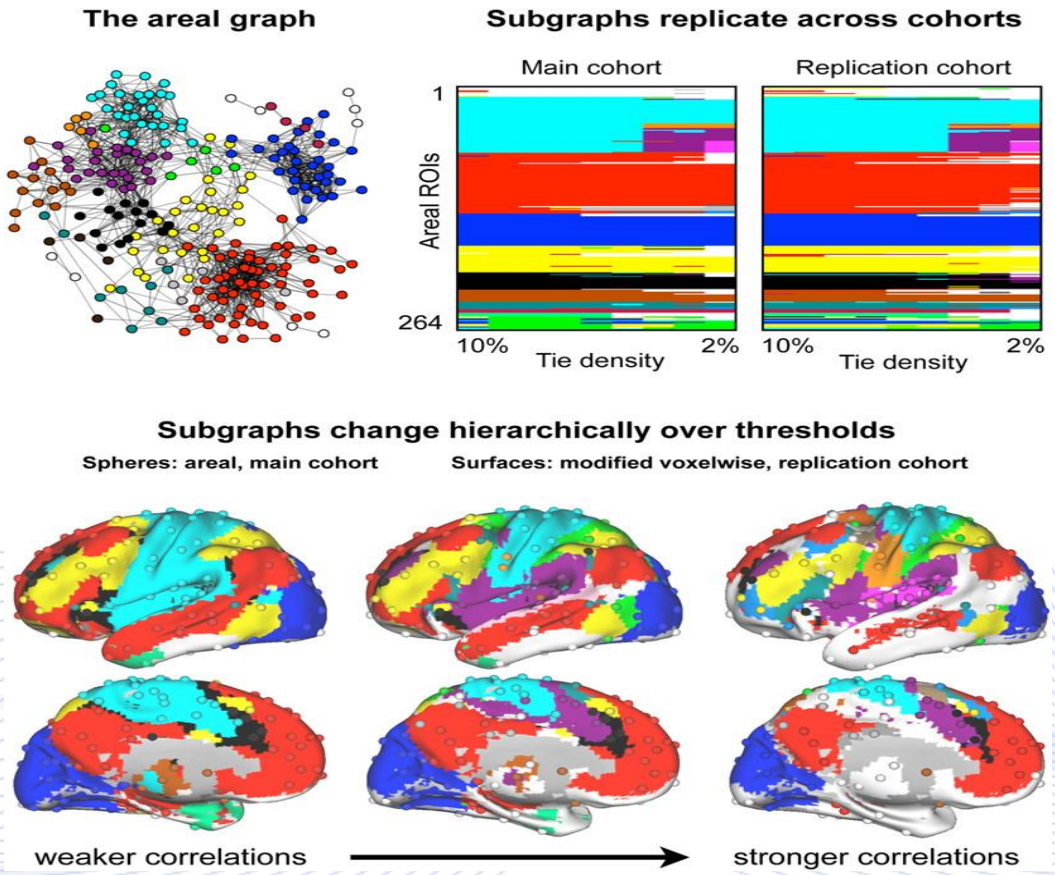
Brain speech graphs at rest and during speech production [SIM2015].

Connectivity Across the Brain



Connectivity patterns of the left brain hemisphere [SEP2010].

Brain Graphs and Subgraphs



The two graphs used[POW2011]).

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Q & A

Thank you very much for your attention!

More material in
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