Centre for Cognitive Science

Computational cognitive neuroscience: 3. Networks

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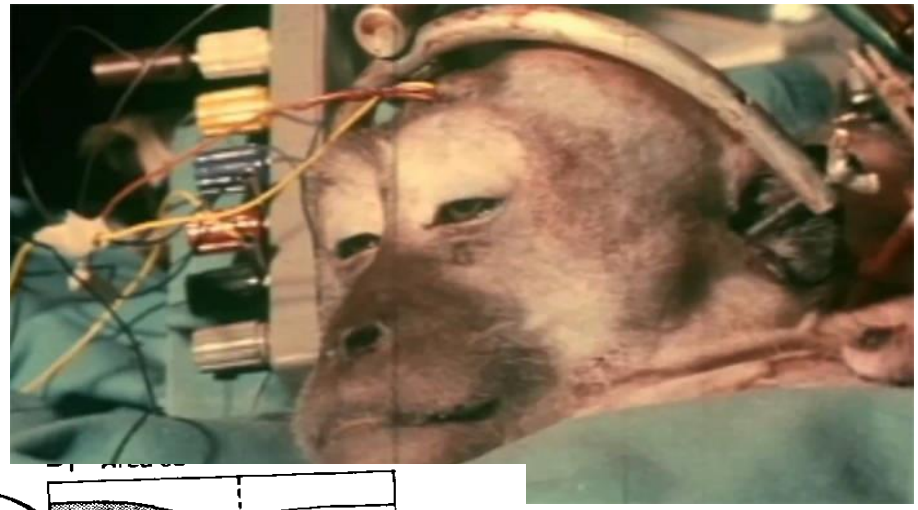
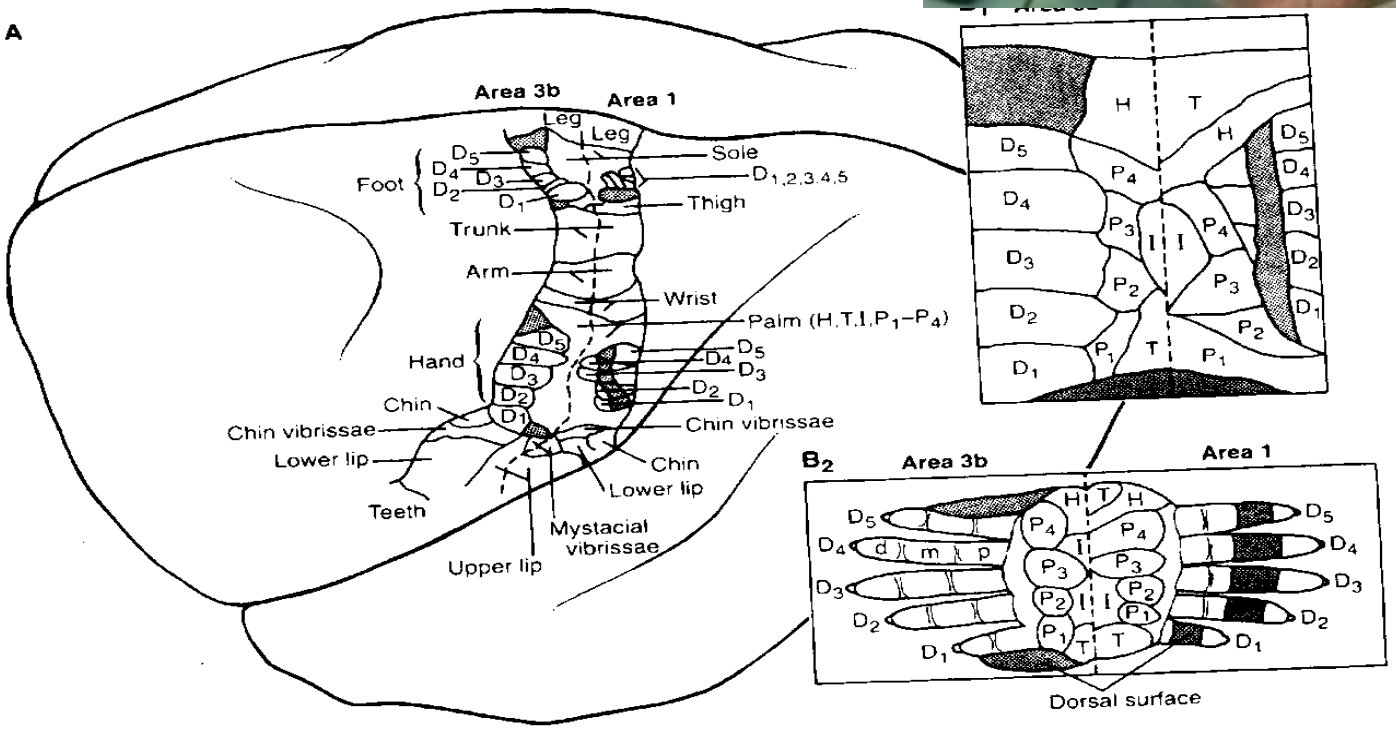
Why do we care about the brain when dealing with cognition?

Mapping the sensory experience to the brain

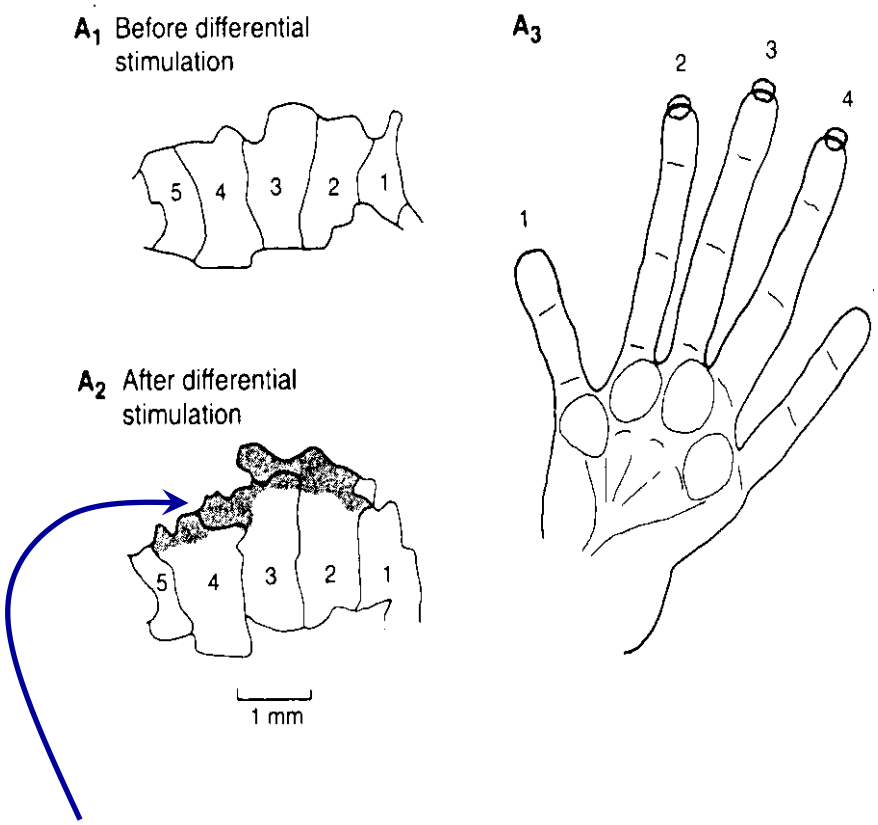
Neurons in the concrete area of the cortex fire spikes (i.e. respond) only when that particular concrete area of the body is touched





Topographic representation of the body in the somatosensory cortex

Cortex plasticity caused by new experience

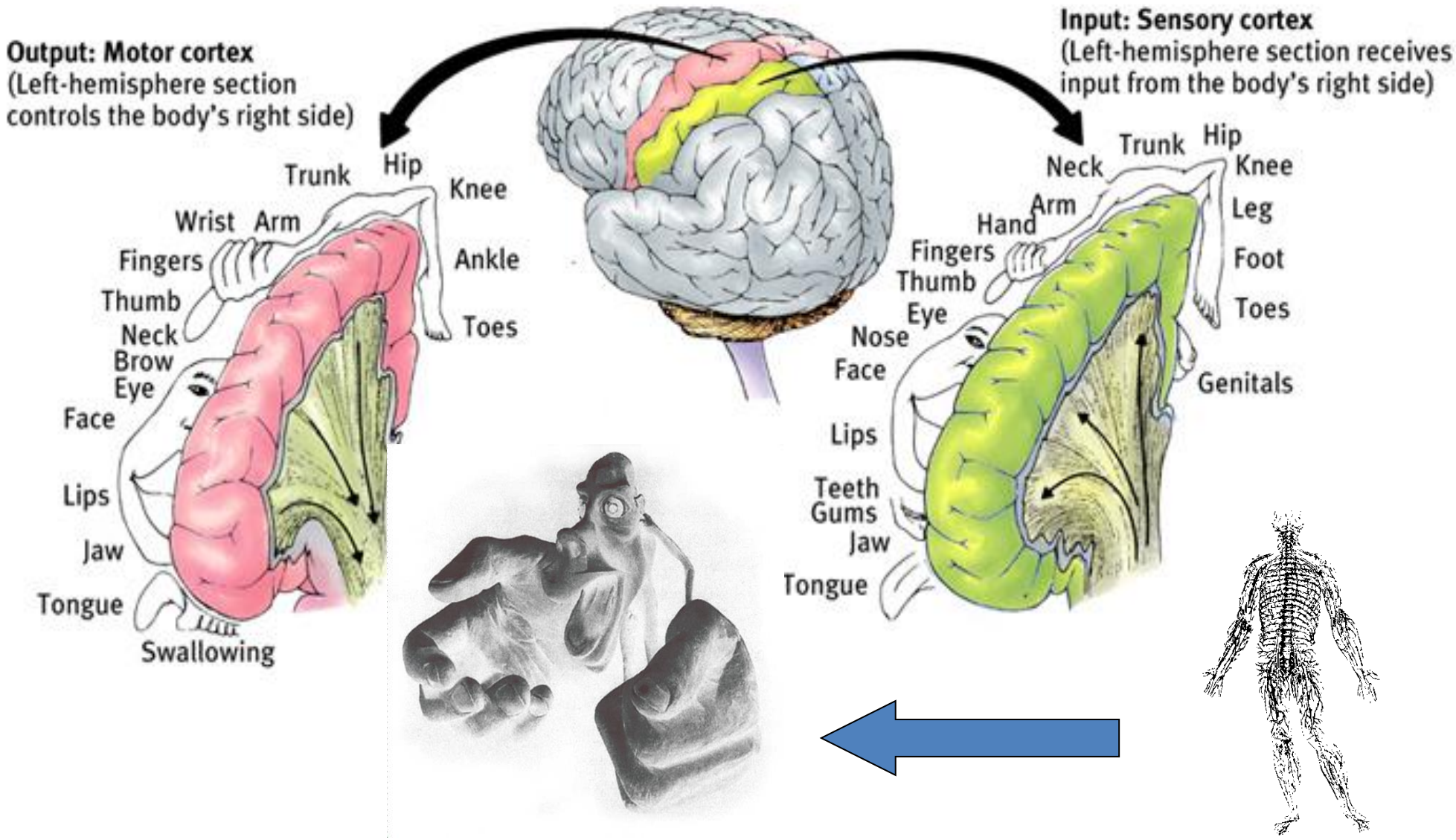


Use-dependent expansion of representation of more used fingertips

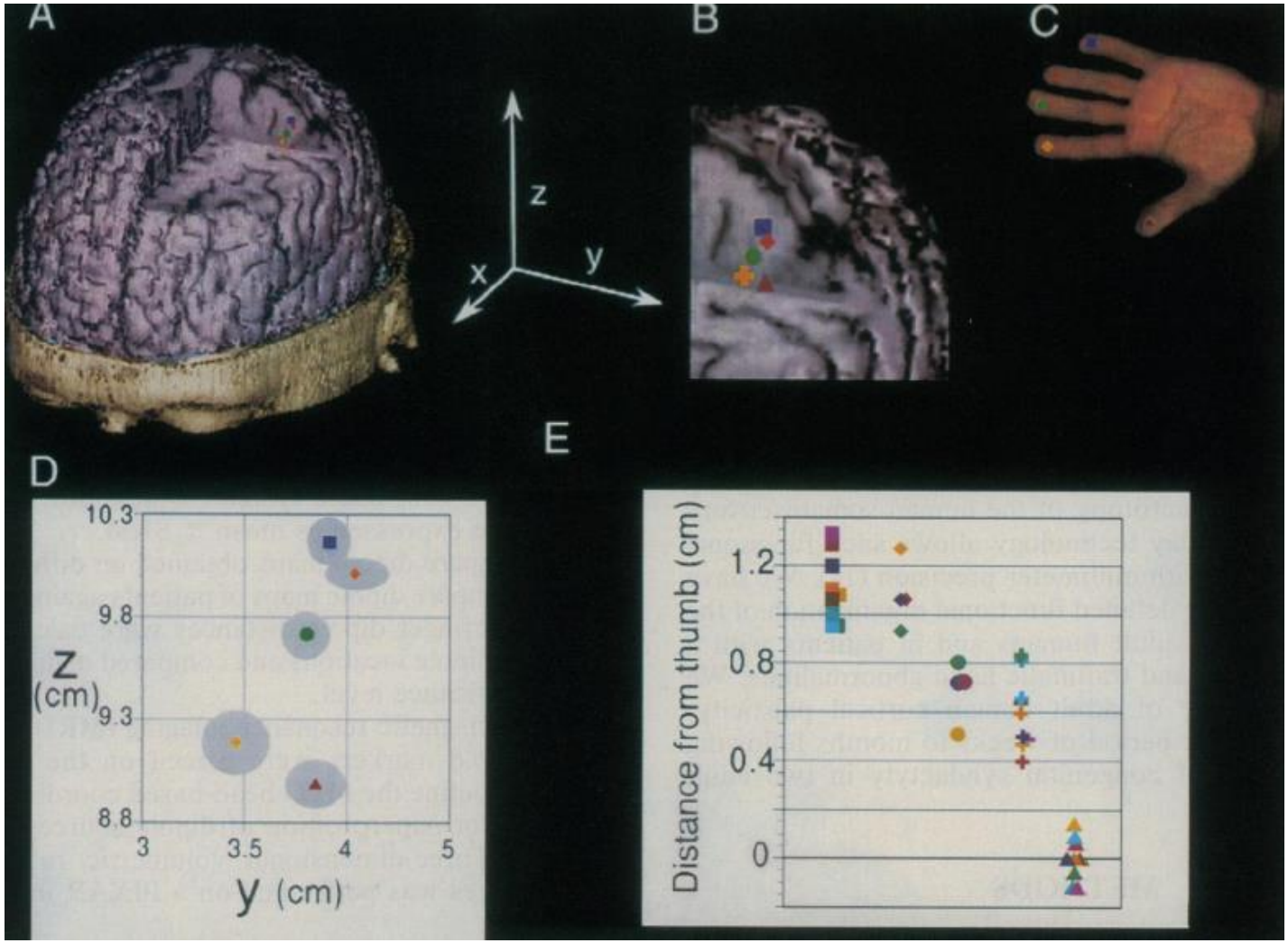
- Monkeys had to touch a rotating disk with a rough (but not painful) surface for 2 hours each day for 2-3 weeks, with fingers No. 2, 3 and 4.
- After few weeks, the areas of cortex, which previously responded to stimulated fingers 2,3,4 **expanded** in each of the monkeys, which underwent the training
- i.e. more neighbouring neurons were **recruited** to process the stimuli from these fingers

Somatosensory and motor systems in humans

- Topological mapping from body to cortex in humans:

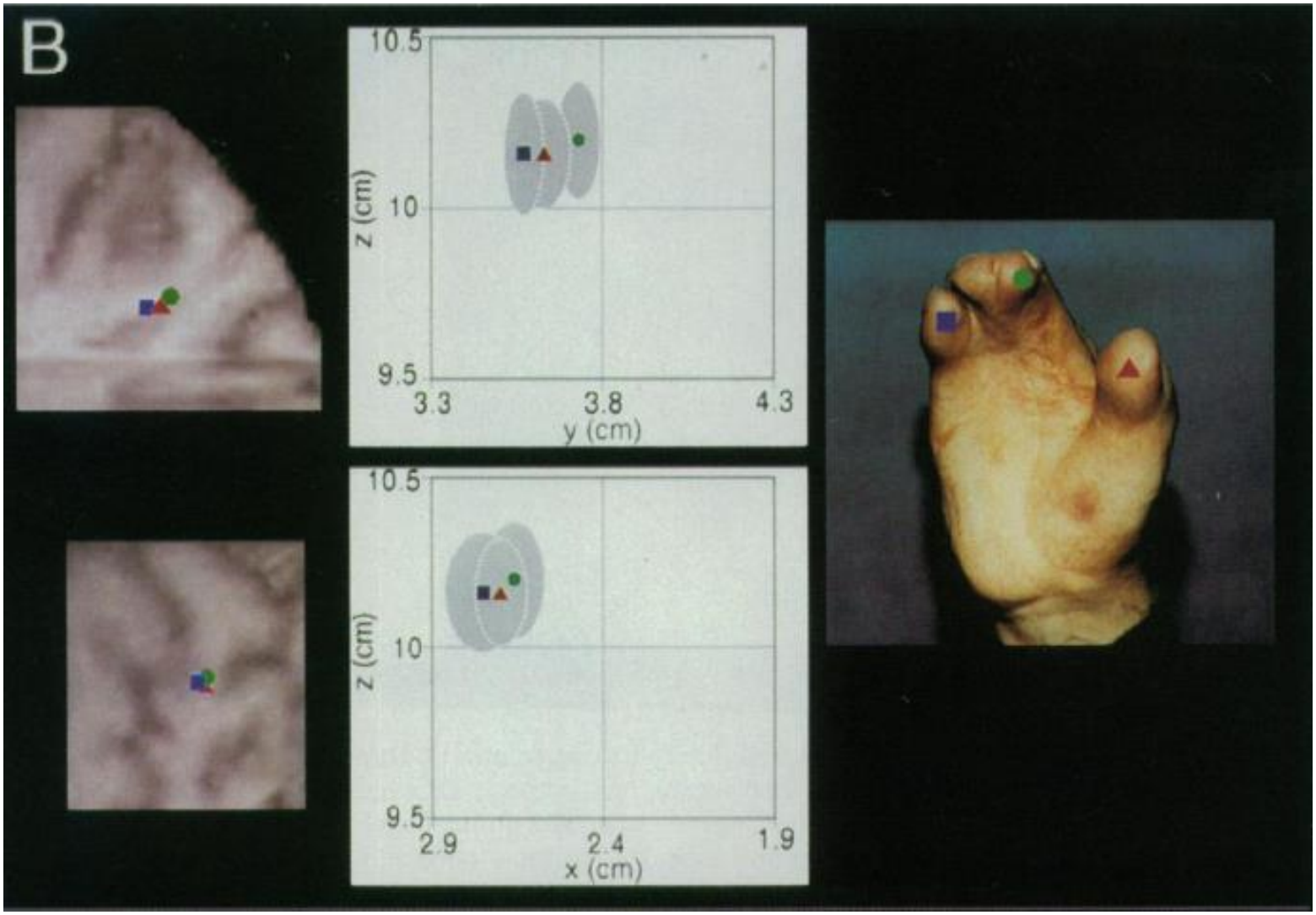


We feel each finger separately and each finger has a separate representation

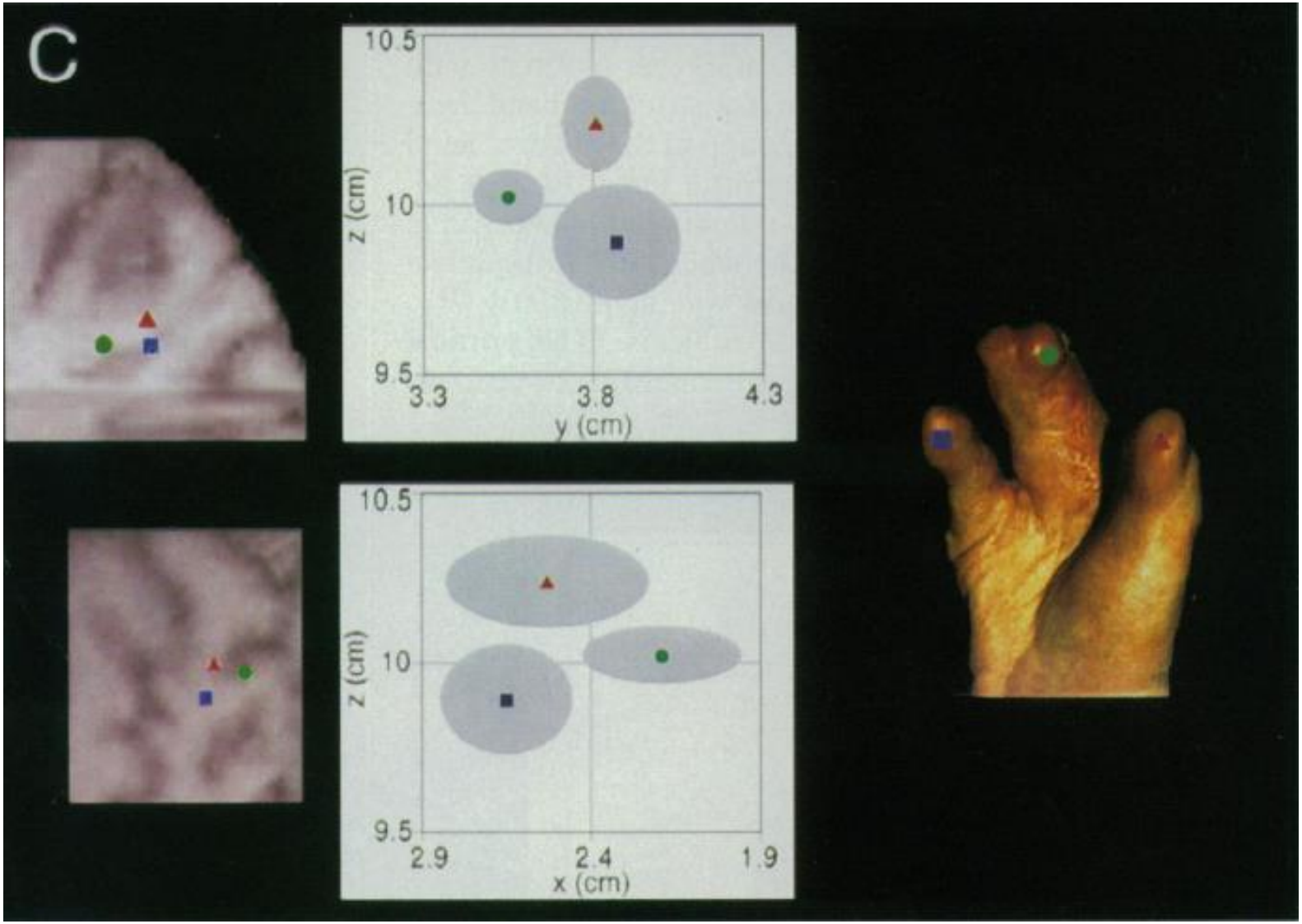


A Mogilner, et al. (1993) *Somatosensory Cortical Plasticity in Adult Humans Revealed by Magnetoencephalography*, PNAS 90: 3593-3597.

Syndactyly: joined fingers – joined representations and overlapping feeling

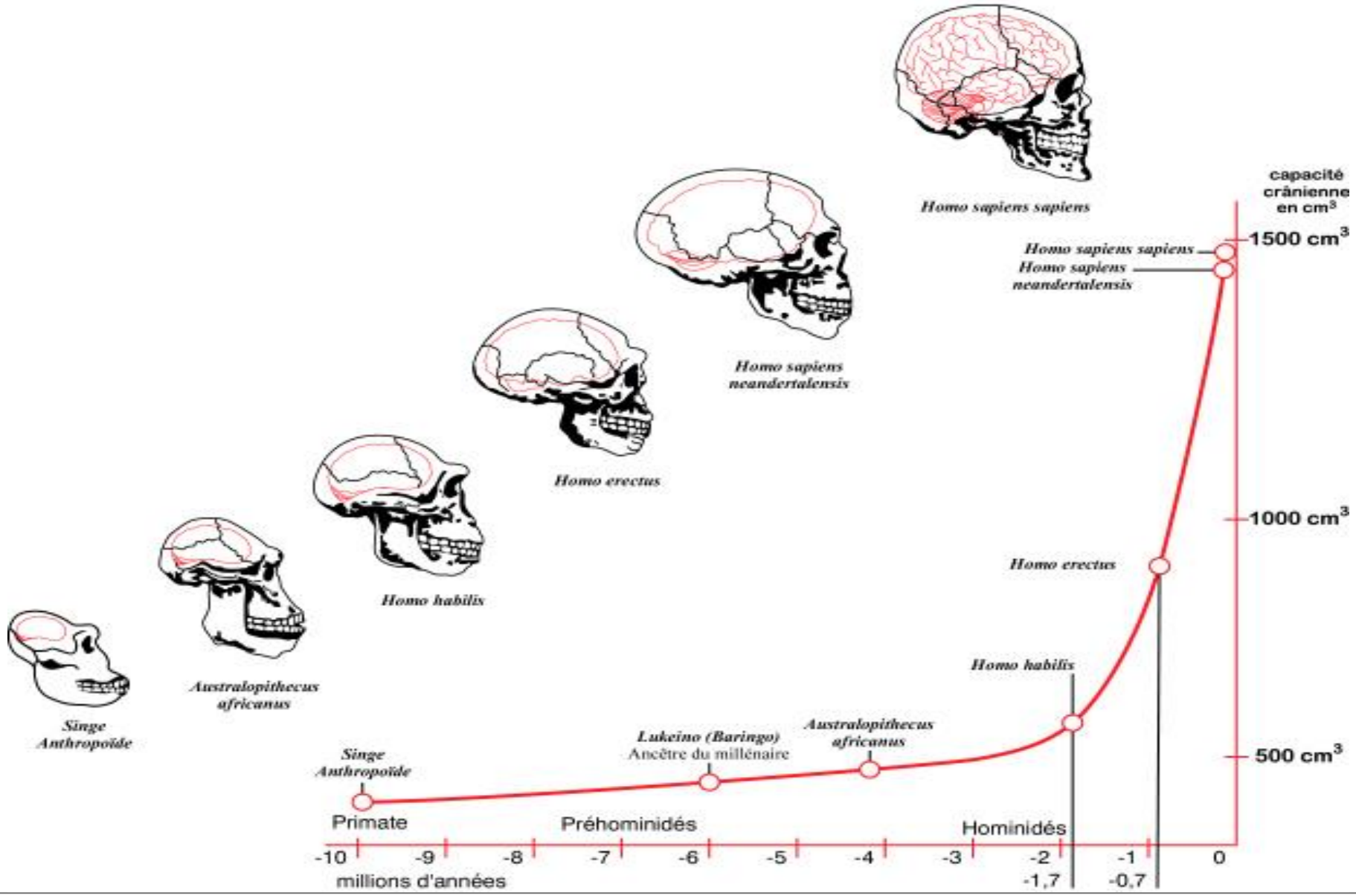


Surgery leads to cortical reorganization and **feeling** fingers as individual entities



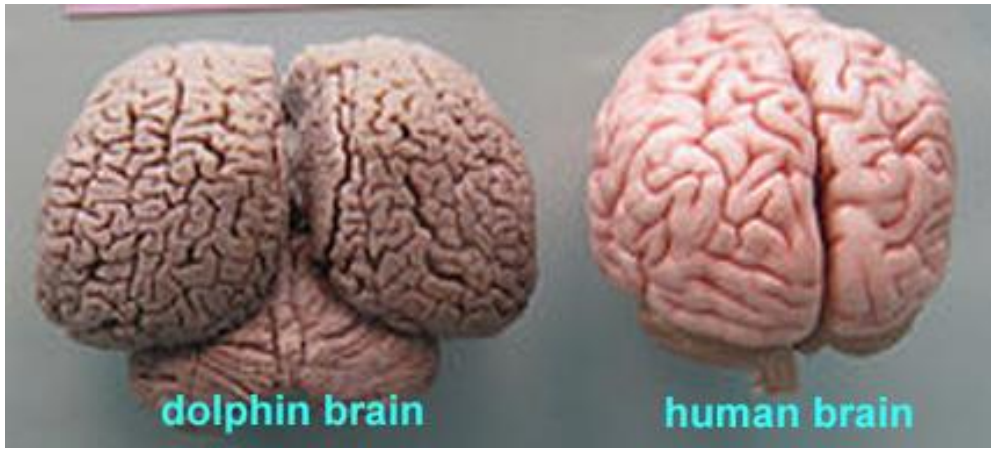
The neocortex

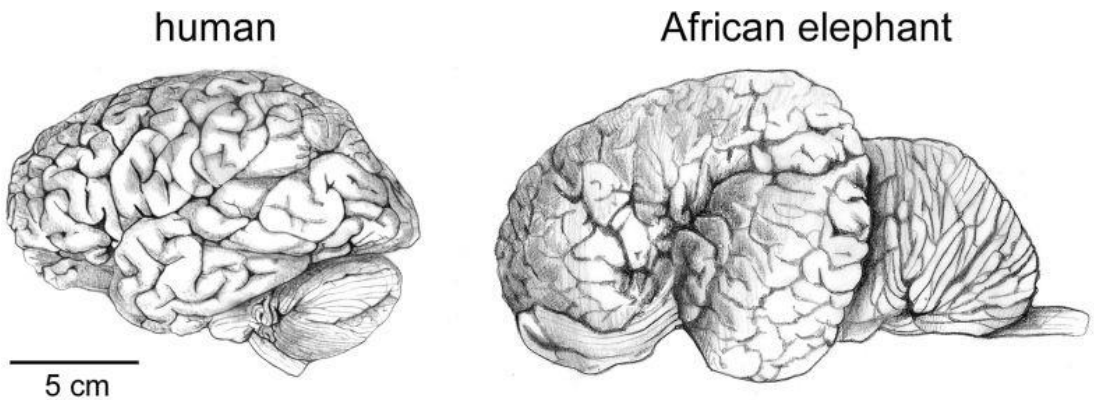
- At present we believe, based on vast scientific evidence, that cognition originates from the neocortex – the evolutionary most recent part of the brain.



The neocortex

- Most evolved in humans but also in dolphins (and other cetaceans) + elephants





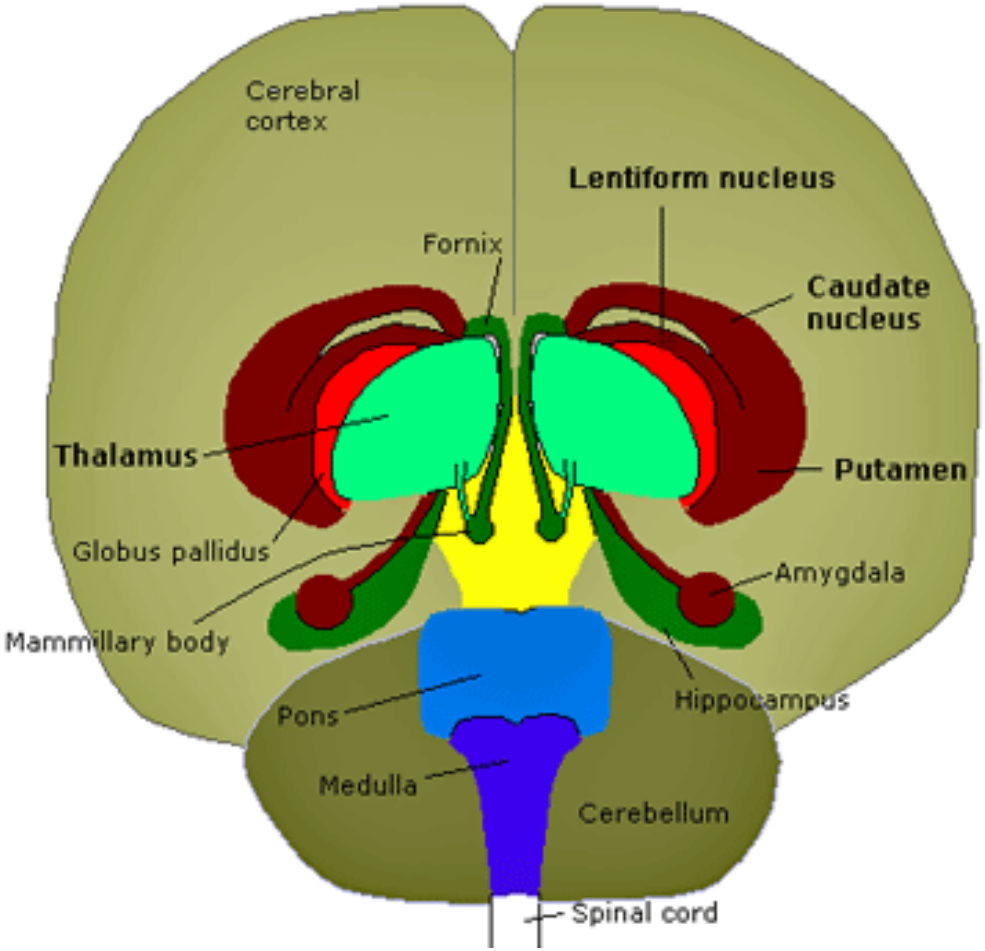
- There is **something**, which connects the cortex and cognition…
- Therefore we are learning about particular processes in the brain.

Cortex works together with subcortical areas

- Cerebral cortex receives signals from the subcortical areas that are related to perception of the world and perception of the body.

- After processing, the cortex sends the signals back to the subcortical parts to instruct them what action should be performed.

- The main subcortical structure mediating the output is the BG = basal ganglia comprised of Caudate nucleus, putamen, globus pallidus and lentiform nucleus.

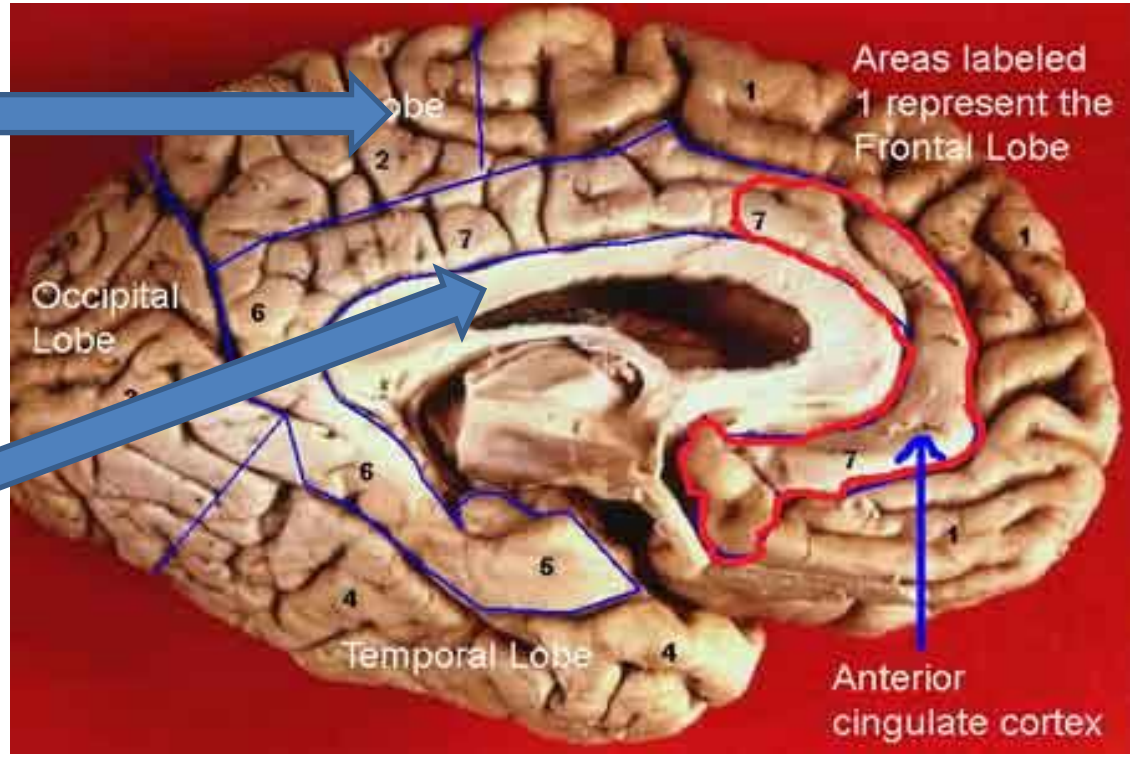


The human brain

- Humans have a large neocortex as a percentage of the total brain matter when compared with other mammals. For example, there is only a 30:1 ratio of neocortical gray matter to the size of the subcortical matter of chimpanzees, while the ratio is **60:1 in humans**.

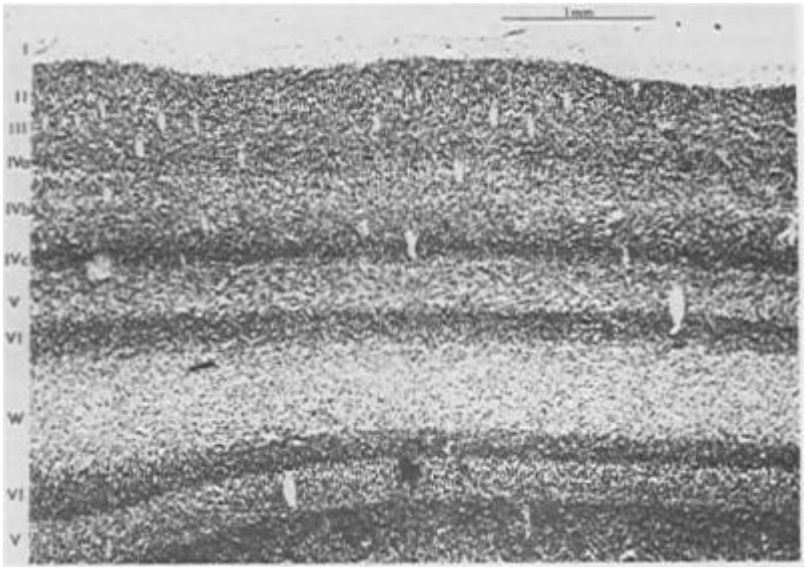
Cortex = gray matter (neuron bodies and dendrites)

White matter (axons) connecting the neurons and hemispheres

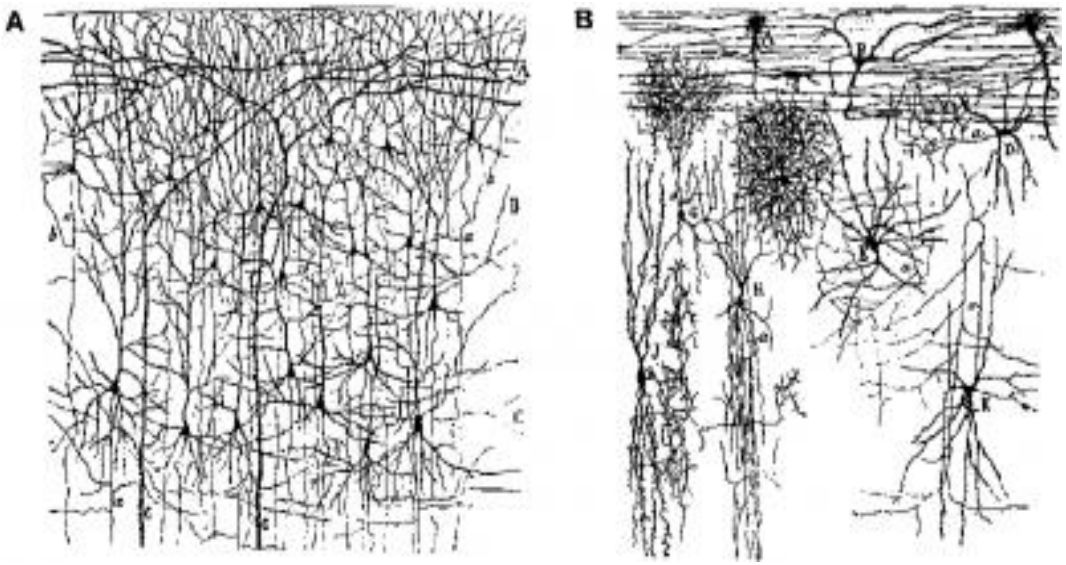


Structure of the neocortex (cortex) in mammals

- The structure of cortex is strikingly similar through **ALL** the mammal classes, i.e. it is the same for monkeys, cats, rats, etc.
- The cortex has 6 layers, the layer I from the top of the skull, then layer II, III, IV, and the layer V (or VI) towards the bottom of the skull.



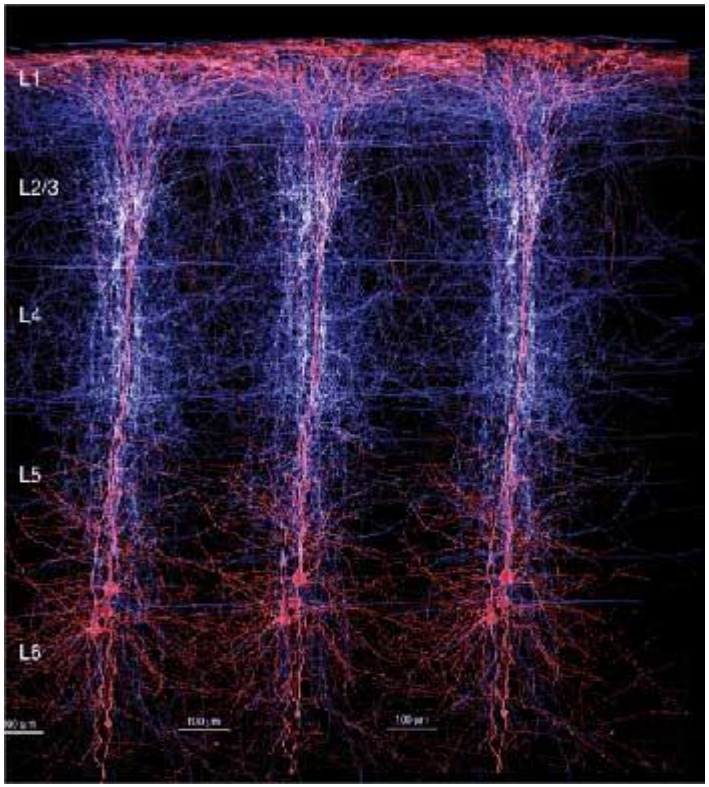
A real slice of the visual cortex of a cat
Showing the 6 major cortical layers

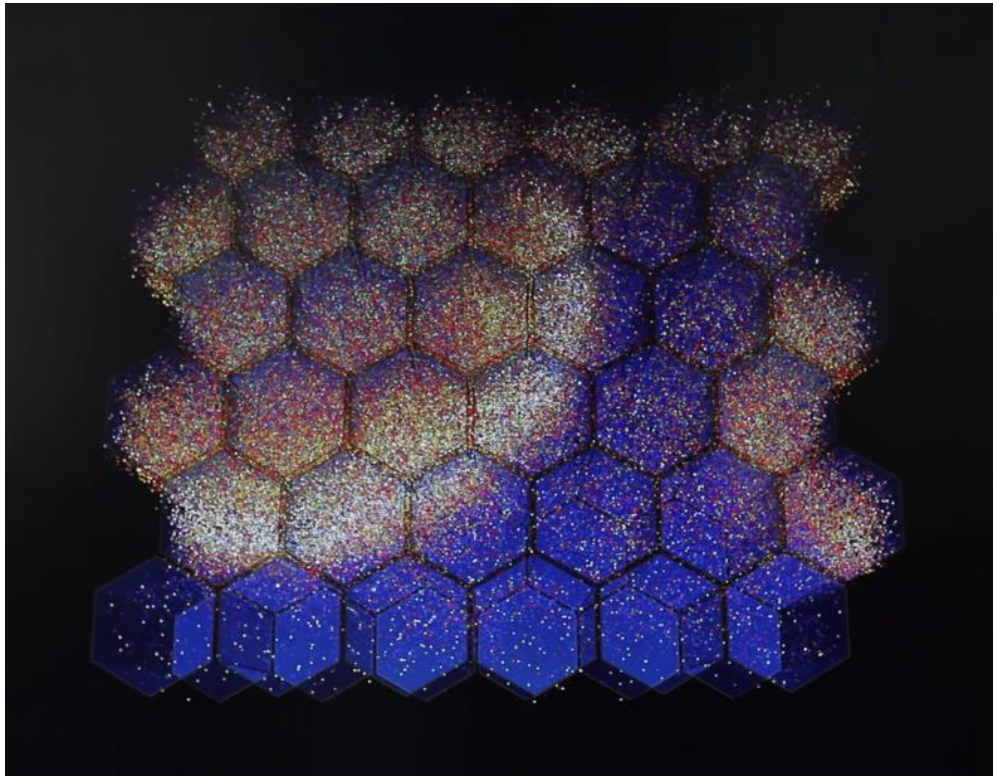


(A) Network of excitatory neurons across the 6 layers
(B) Network of inhibitory neurons across the 6 layers

Cortical column

- Cortical column is the basic processing unit in the cortex, which repeats itself "endlessly" over the whole cortex.
- Left: 3 cortical columns; Right: a view on the cortex from above with an array of repeating cortical columns.





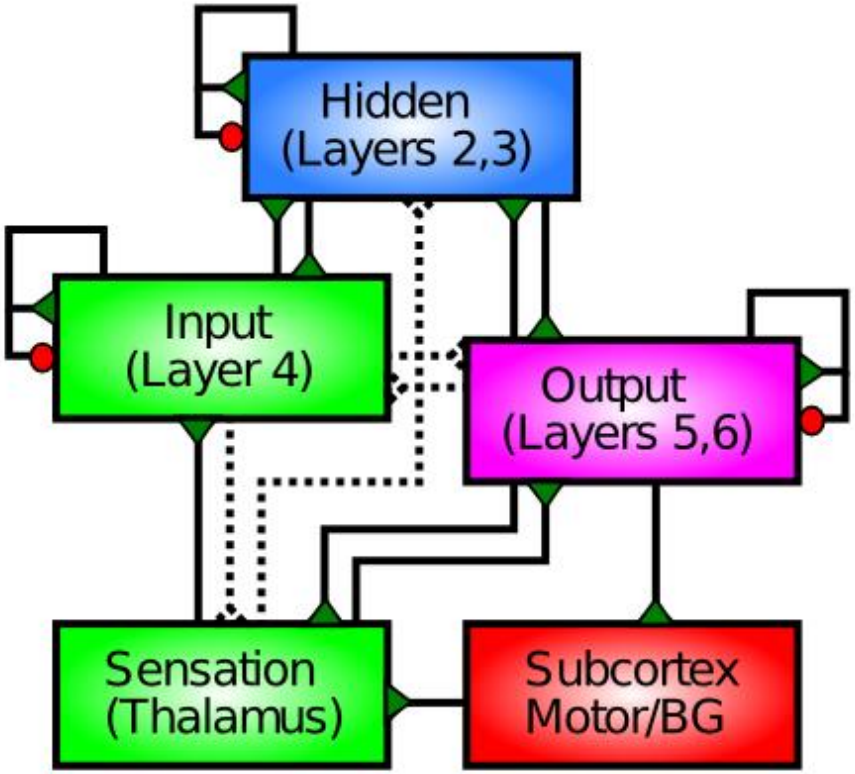
Specific function of cortical layers within a column

- **Green colour in the scheme denotes the input structures**, **blue colour denotes the hidden (internal) processing** and **red colour denotes the output structures of the network.**

- **Layer 4 receives** and processes input information, from thalamus which receives direct sensory inputs from eyes, ears, skin, etc.

- Then the signals are sent to the **superficial layers 2/3**, which provide extracting of behaviorally-relevant categories.

- Signals from layers 2/3 then drive deep **layers 5/6 to output** a motor response back to subcortical areas.



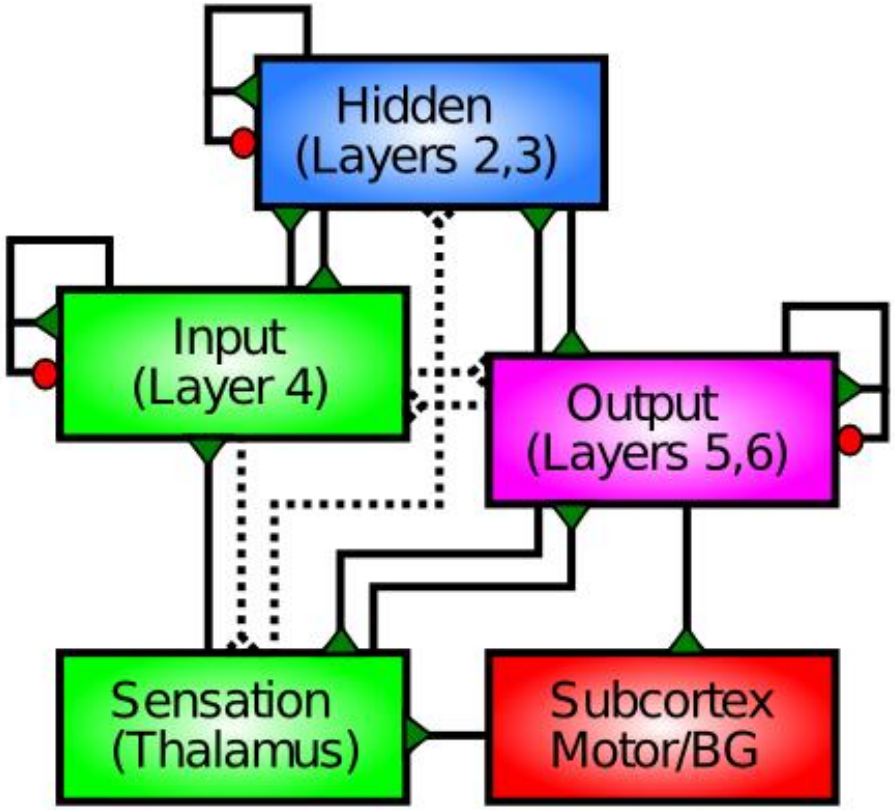
(Dotted lines denote sparse connections between layers.)

Feedforward and feedback connectivity within a column

- In addition to the **feedforward scheme**, i.e. from thalamus to layer 4 then 2/3, then 5/6, there are always **feedback connections** between all these areas, sending the signal backwards.

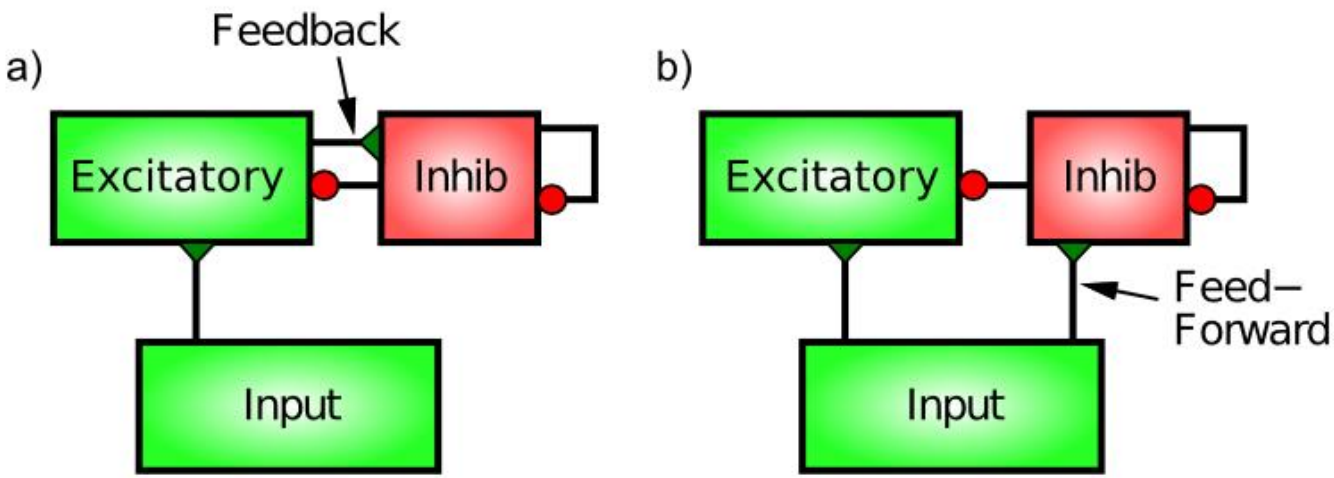
- Synapses relaying the feedforward messaging as well as feedback messaging are excitatory (triangles)

- However, the synapses within individual layers are of two kinds, excitatory and inhibitory (red circles).



BG = basal ganglia which is a crucial structure for driving motor outputs, communicates with the thalamus, the input gate for sensory inputs.

Feedforward and feedback inhibition



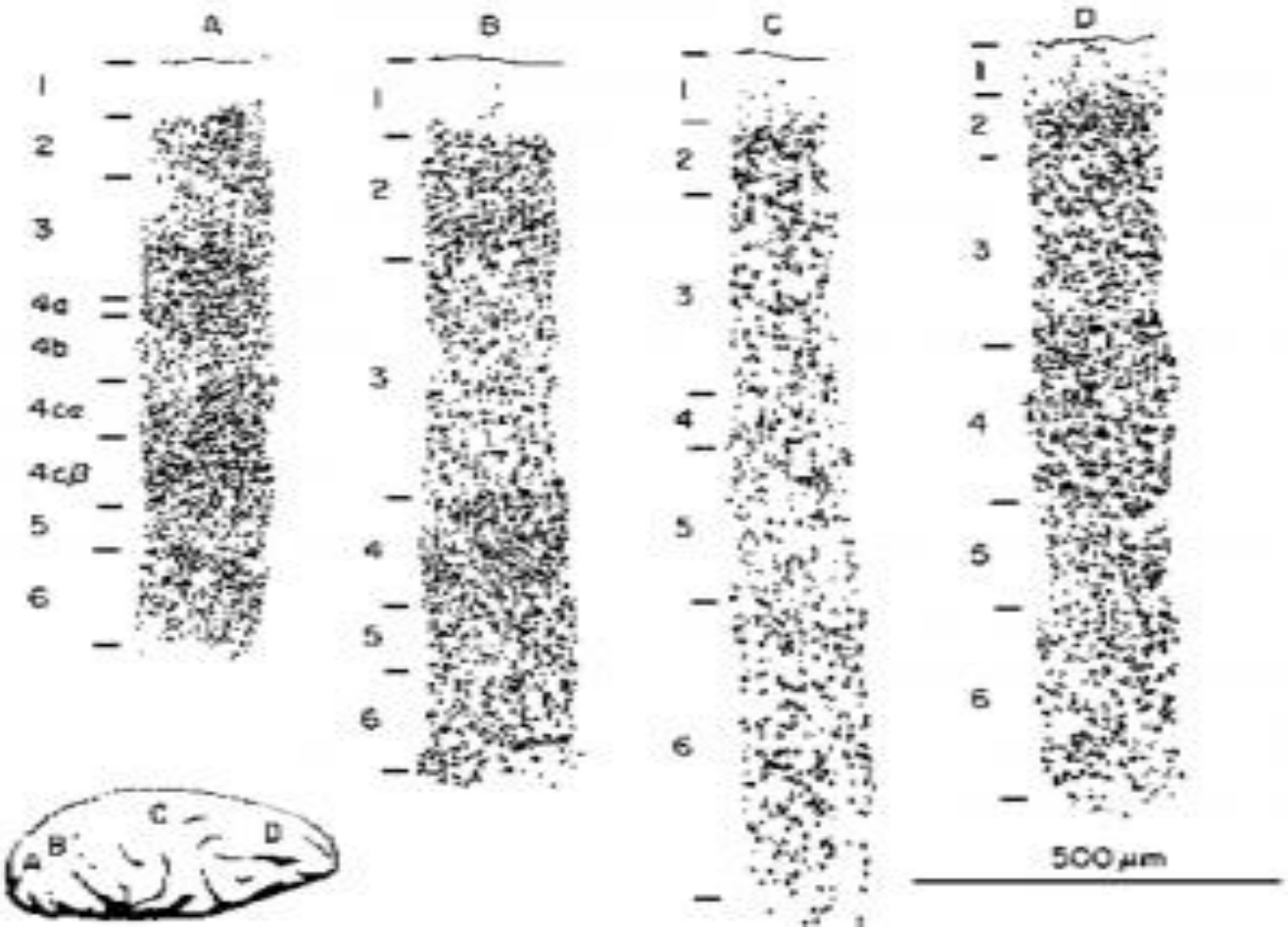
- (a) **Feedback inhibition** reacts to the actual level of activity in the excitatory neurons, by directly responding to this activity (much like an air conditioner reacts to excess heat).

- (b) **Feedforward inhibition** anticipates the level of excitation of the excitatory neurons by measuring the level of excitatory input they are getting from the Input area.

- A balance of both types works best and is present in all circuits.

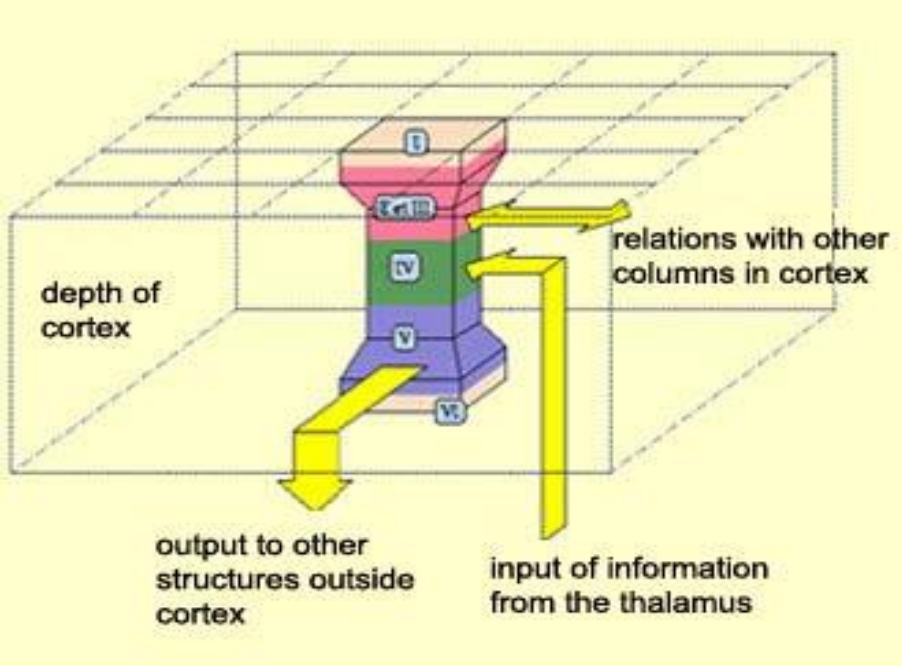
Thickness of the cortex (columns) varies between areas

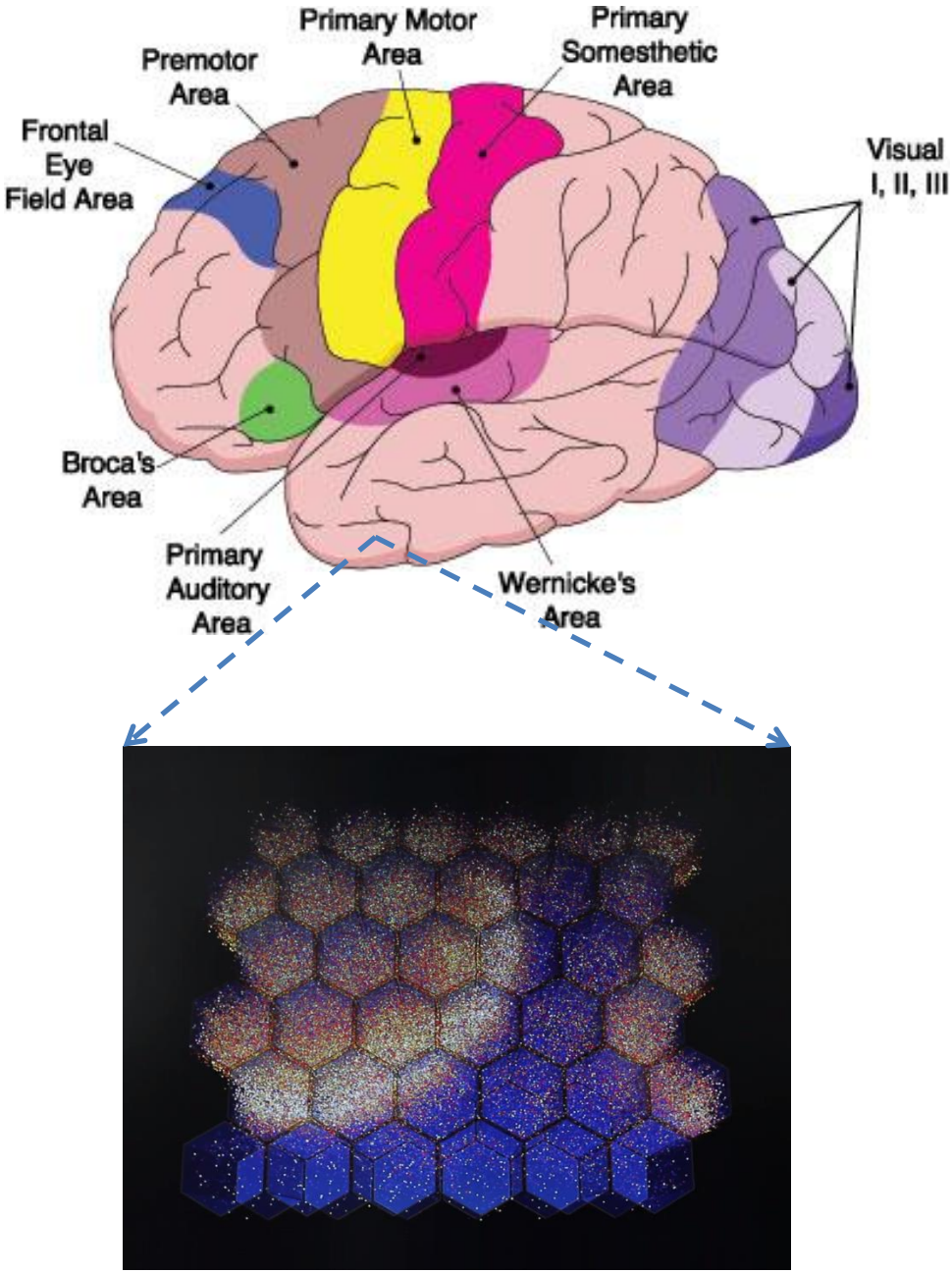
- **A**) shows **primary** visual cortex which emphasizes input layer 4. **B**) shows **extrastriate** cortex which processes visual information, and emphasizes superficial layers 2/3. **C**) shows **primary motor** cortex, which emphasizes deep layers 5/6. **D**) shows **prefrontal** cortex ("executive function") which has an even blend of all layers. Reproduced from Shepherd (1990).



Connectivity within and between cortical areas

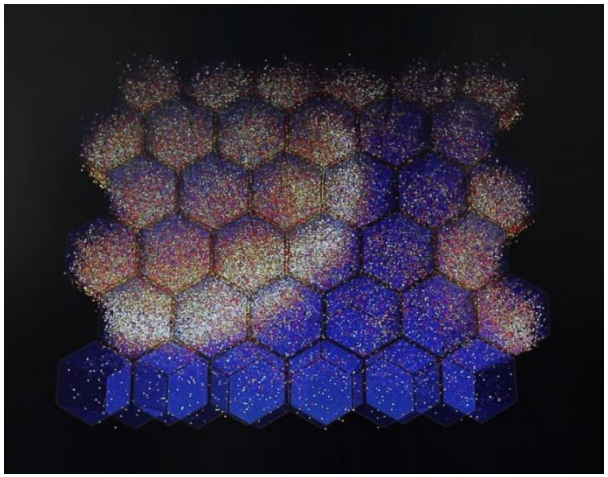
- Cortical columns communicate within the brain areas and between the brain areas.

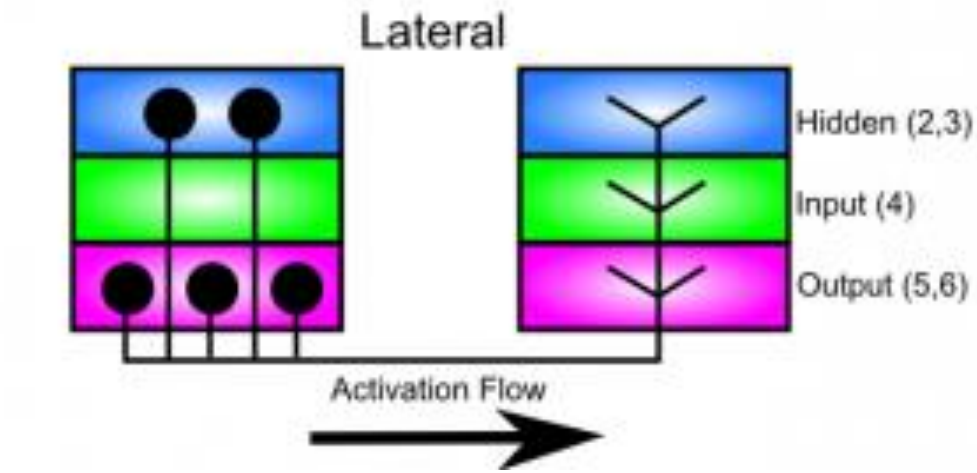




Communication within the same area (the same level)

- **Green colour in the scheme denotes the input cortical layers**, **blue colour denotes the hidden (internal) processing layers** and **red colour denotes the output layers of the cortical column**.

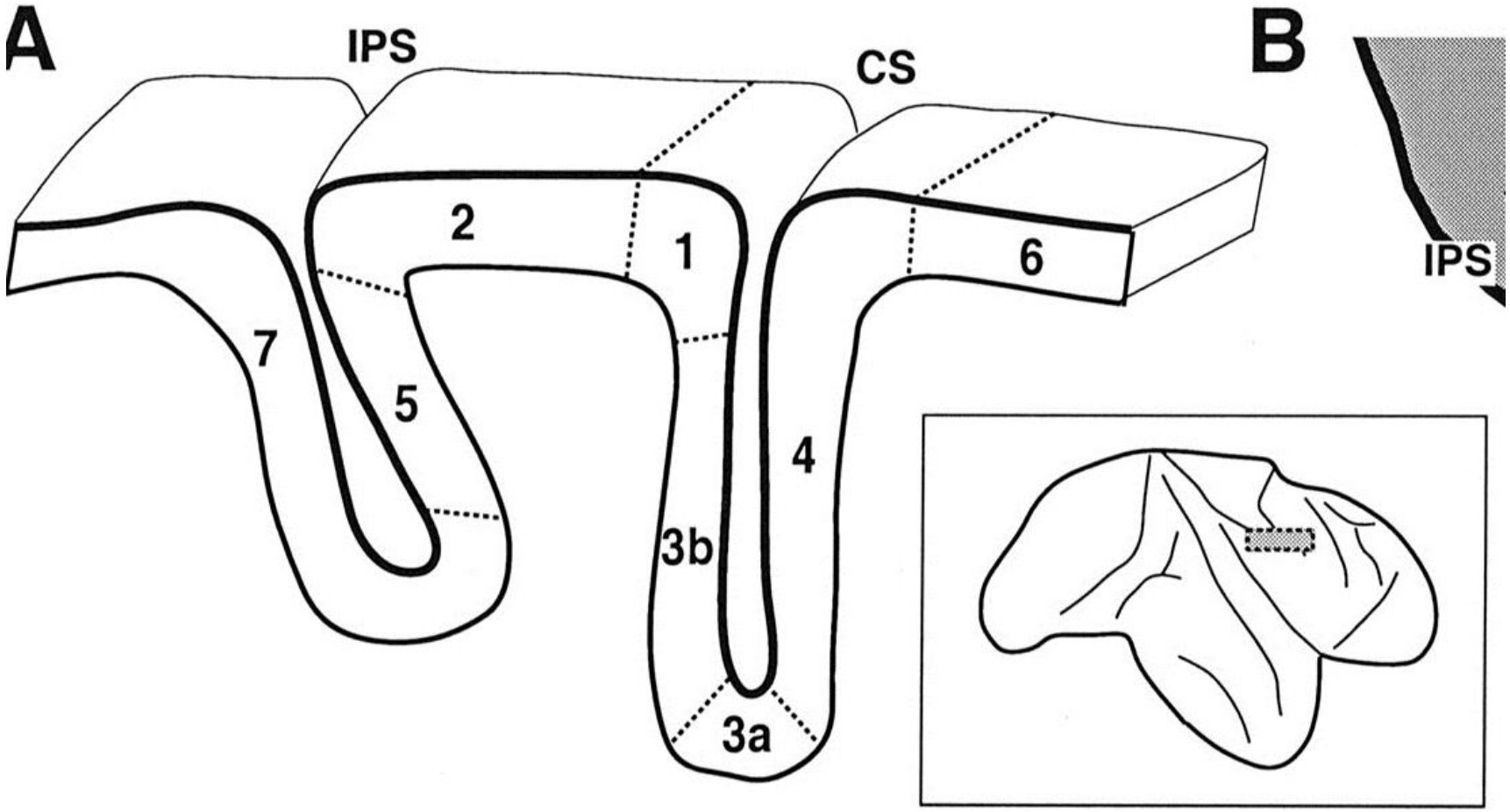




- **Lateral connectivity**: Information flows from layers 5/6 to all of the layers of the neighbouring columns. This is the scheme within one area ***at a particular level of processing.***

Brain areas are organised hierarchically

- Brain areas devoted to the same function, i.e. vision, audition, etc. are not uniform, they are organized hierarchically, i.e. information from one part of the cortex is sent **to a hierarchically higher part** of the cortex; i.e., from 1 to 2 to 3 a to 3b to 4 to 5 > to > 7, in case of the somatosensory cortex.

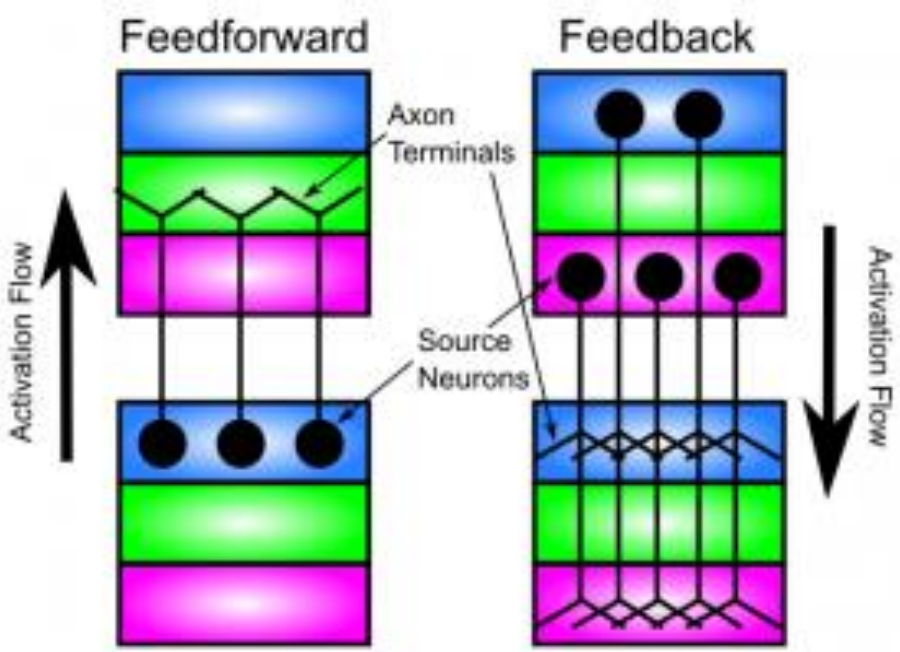


Communication between the areas

- **Green colour in the scheme denotes the input cortical layers**, **blue colour denotes the hidden (internal) processing layers** and **red colour denotes the output layers of the cortical column**.

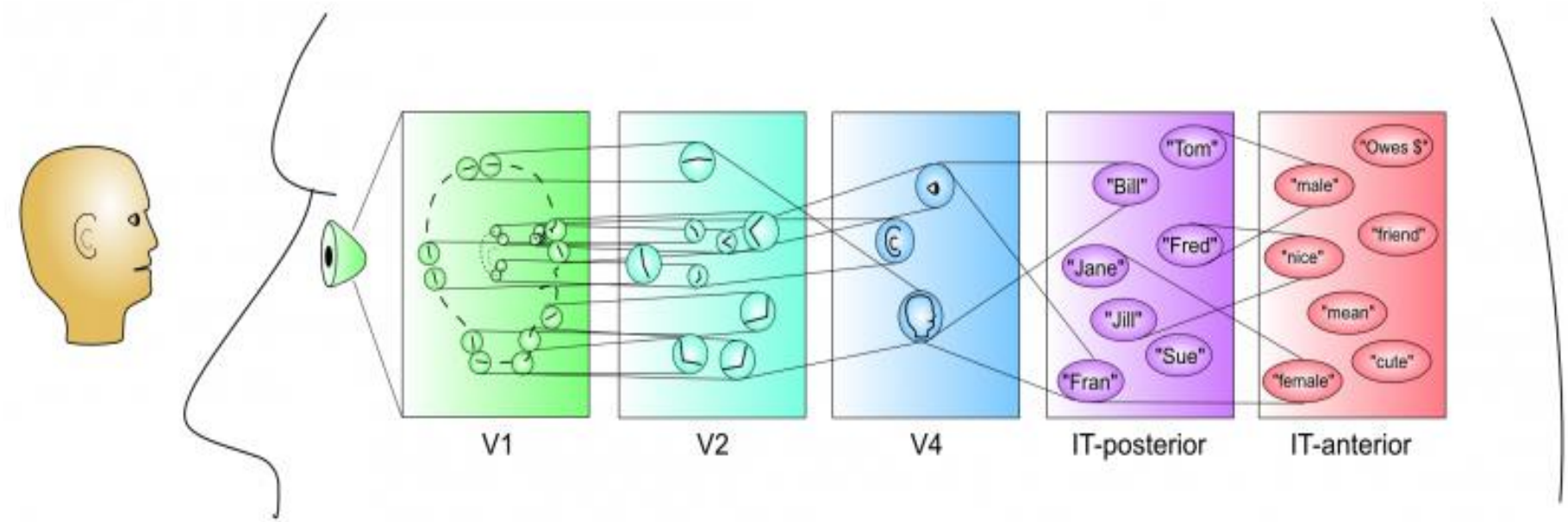
- Typical patterns of connectivity between cortical areas (Feedforward and Feedback).

- Information flows from the layers 2/3 of the first area in a feedforward direction into the input layers of the hierarchically higher area. From the hierarchically higher area, neurons in layers 2/3 and 5/6 axons back into the corresponding layers of the hierarchically lower area.



Feedforward visual processing

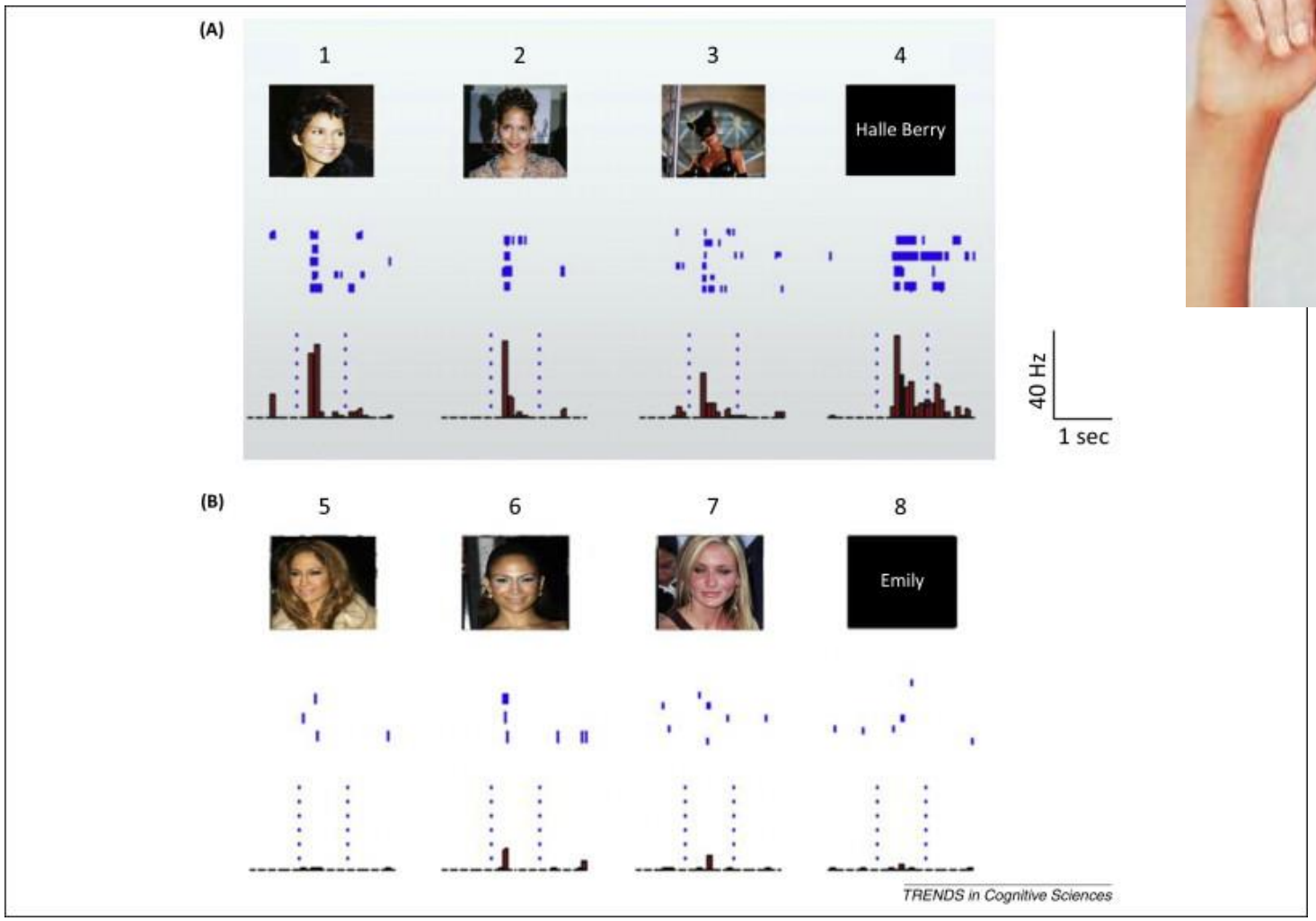
- V1 has elementary feature detectors (oriented edges). Next, these are combined into combinations of lines in V2, followed by more complex visual features in V4.



- Then individual faces are recognized in the IT-posterior.
- Finally, in the IT-anterior, there are important functional "semantic" categories which correspond to associations linked to those faces.

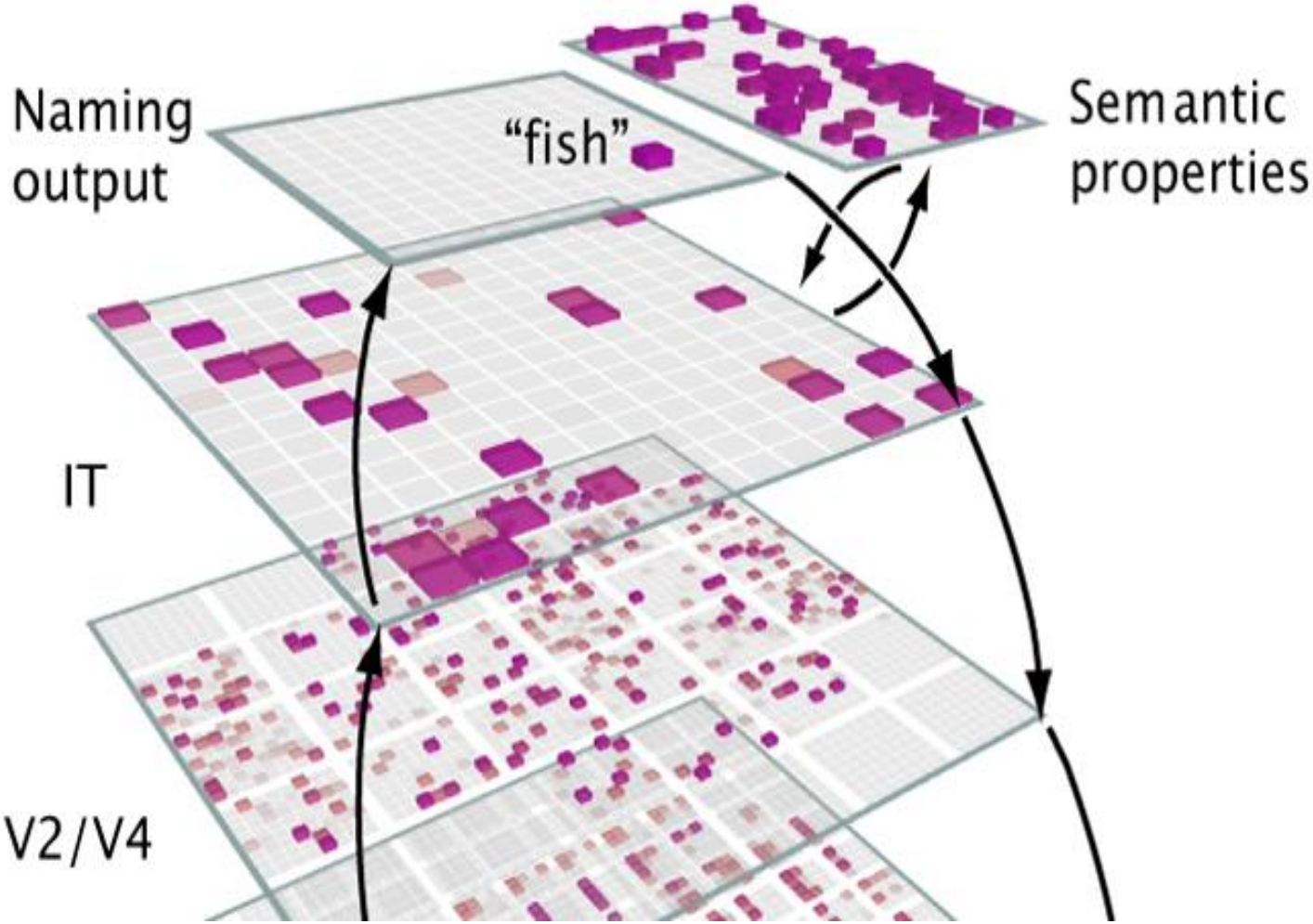
“Grand mother” or “Halle Berry” neurons

- It seems, based on the data, at the highest hierarchical level (IT-posterior) there is a single neuron or rather a small group neurons responding only to the face of a concrete person.

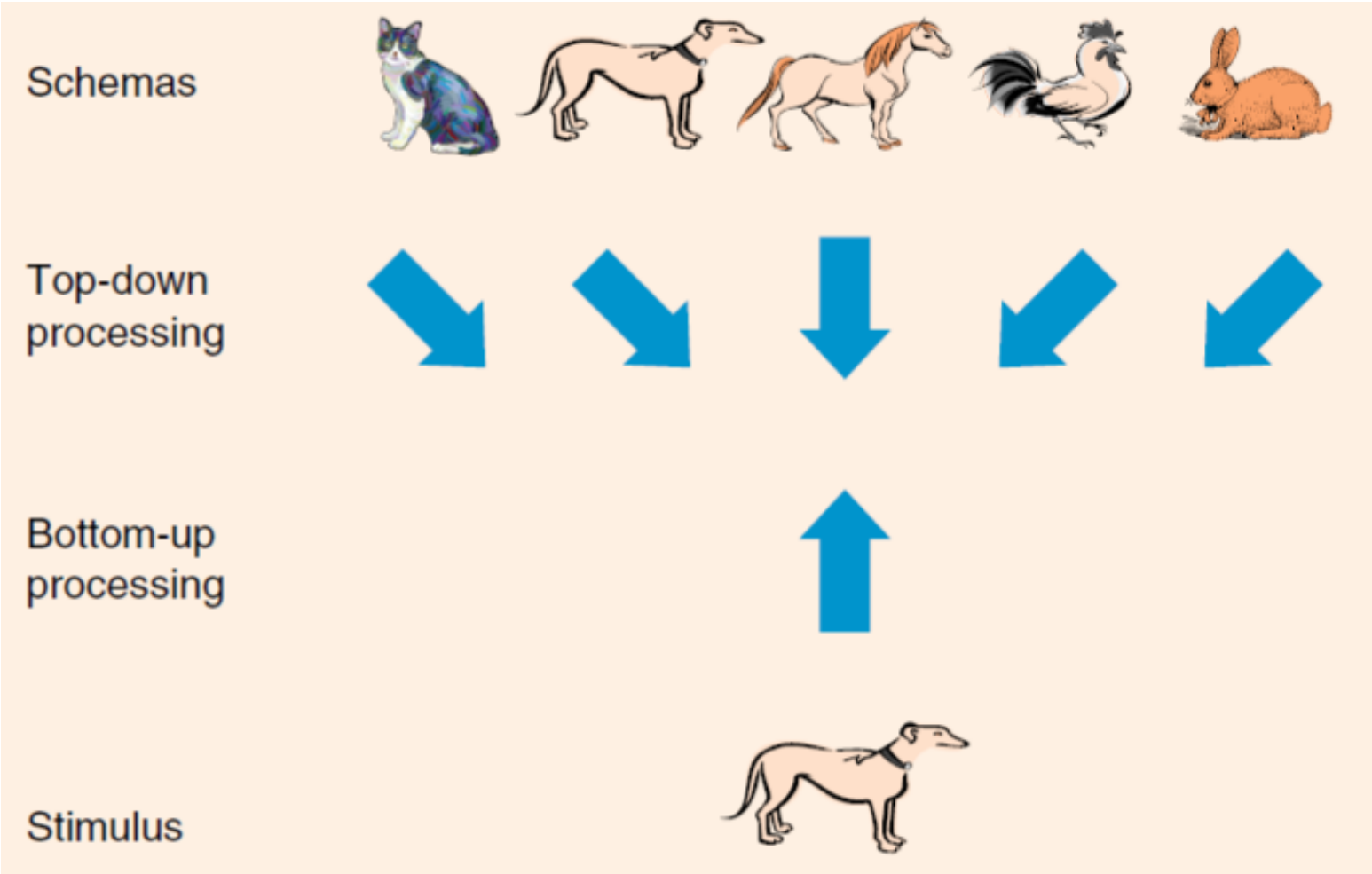


Neural representations

- At each hierarchical level, the features of the input are represented in a **coarse and distributed manner**, i.e. there is a particular distribution of active and silent neurons in **patterns** that are specific for a specific input .



Bottom-up and top-down neural processing



- Relies on prior knowledge and experience.
- Relies on properties of the stimulus.

Neural processing is both top-down and bottom-up

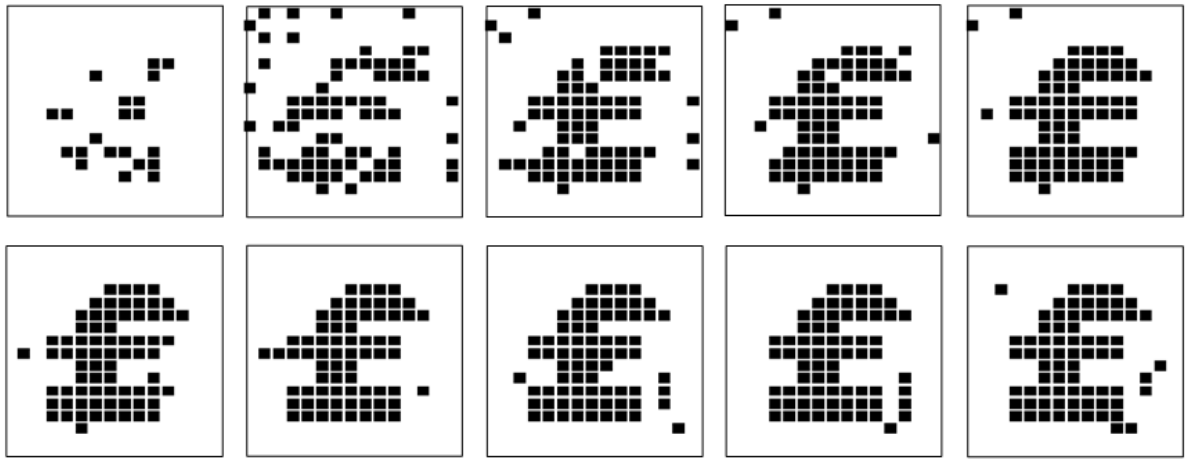
- In order to connect the dots/blobs in a meaningful way, you need a top-down information about what's in the image.

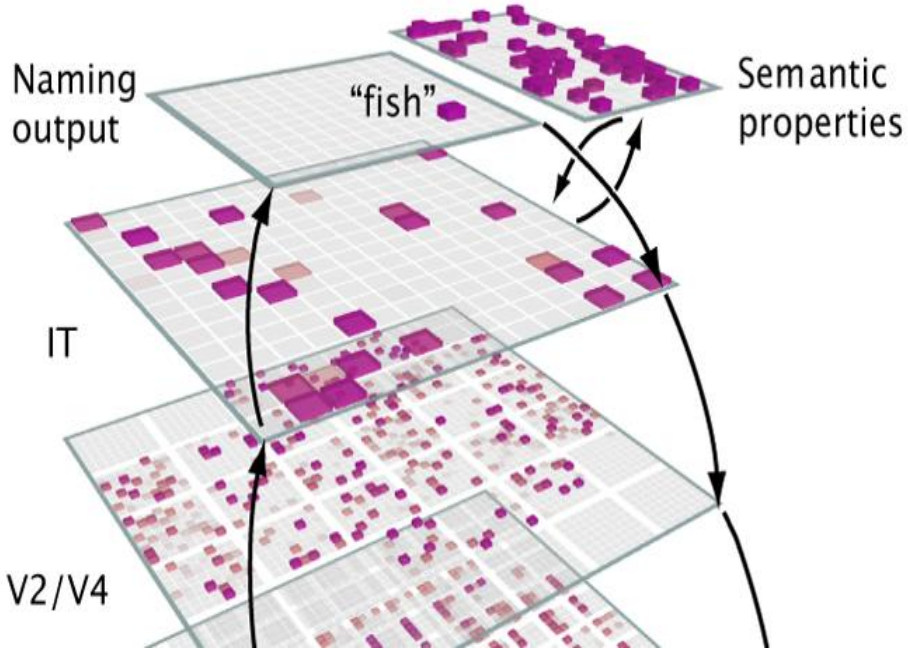
Neural processing is both top-down and bottom-up

- What is in **this** picture?

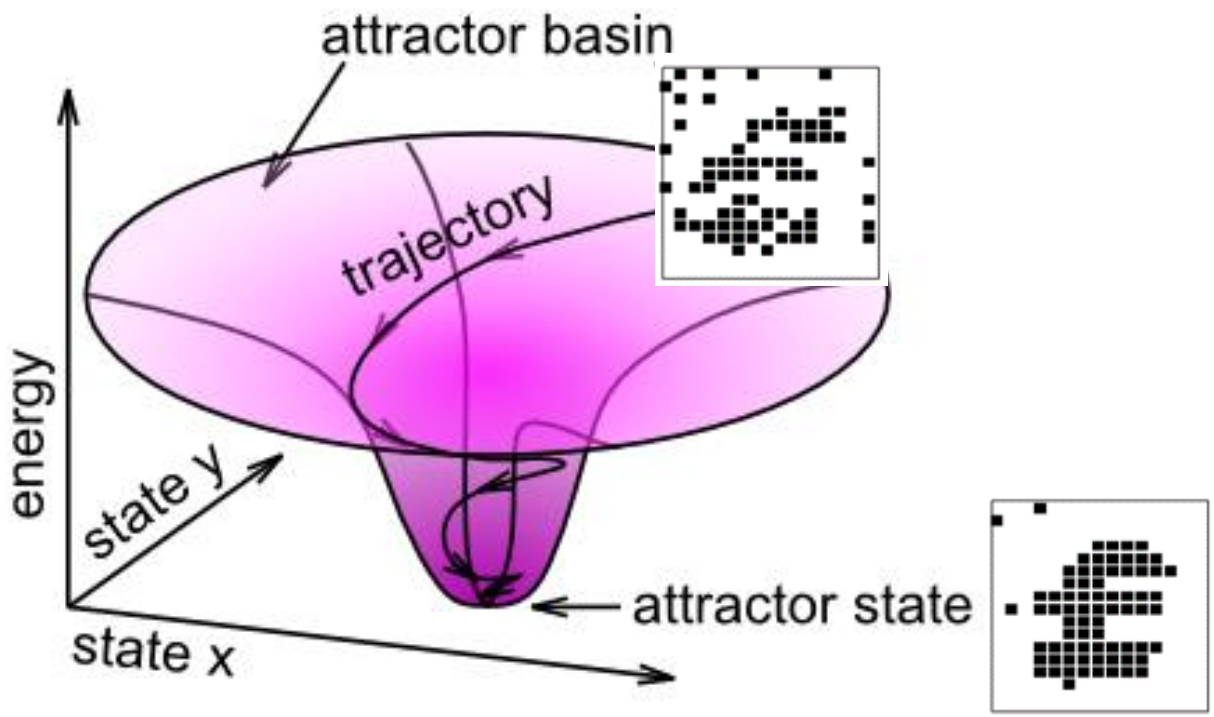
Filling-in and completion of an image

- Initial random activity distribution of neurons.
- Based on exchange of more spikes from "bottom" sensory input and "hypotheses" generated by the hierarchically higher areas, a meaningful pattern emerges.
- Suddenly a meaningful image emerges out of the blobs and the system stays in this state and does not return to the initial naïve state.



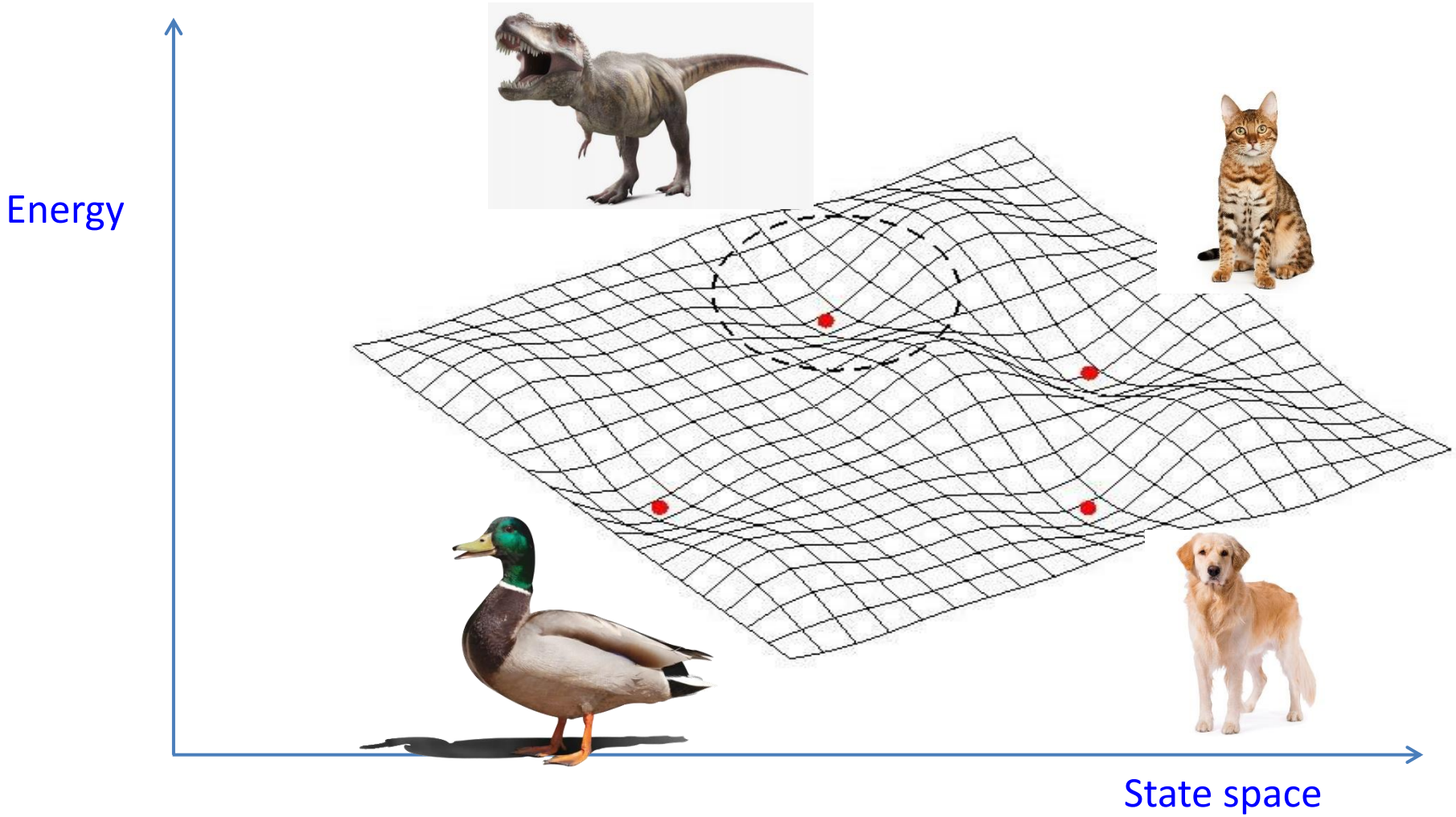


The final recognition state corresponds to an attractor



- In the theory of dynamic system, the so-called **point attractor** is a single state, which once the system converges to, it will never get out of it until a new stimulus forces the system to seek a new attractor.
  - **Trajectory** is a sequence of states on the way to an attractor.
  - **Attractor basin** is a set of states that end up in the same final attractor.

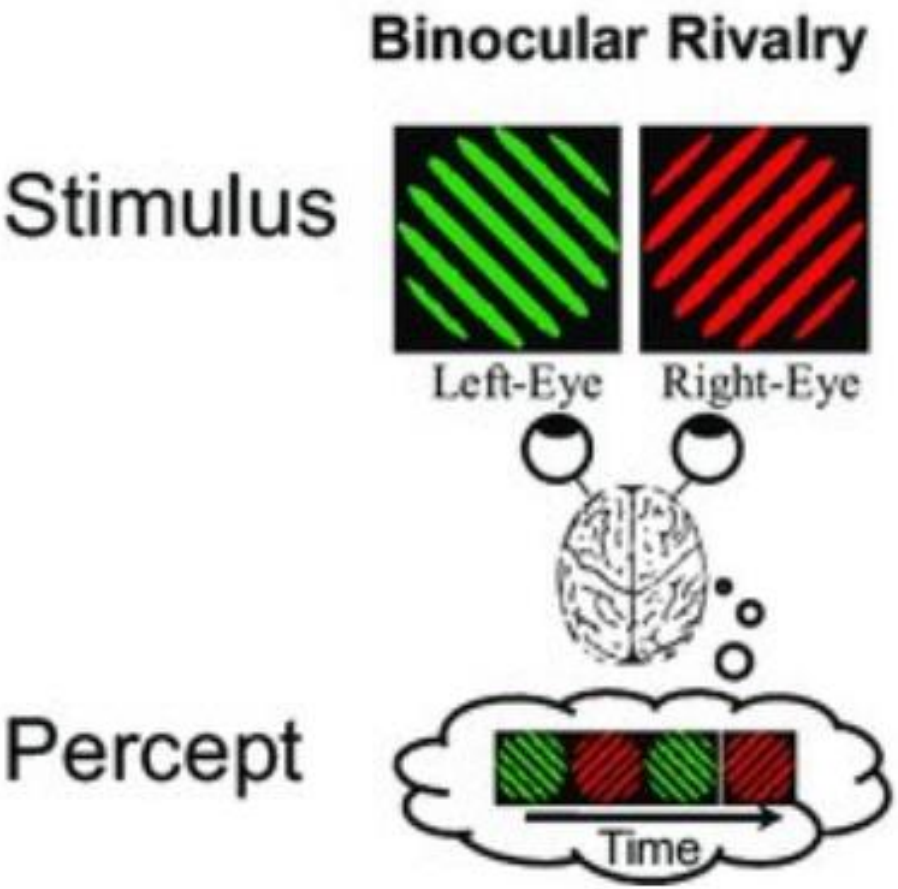
There are zillions of attractors in the brain state space

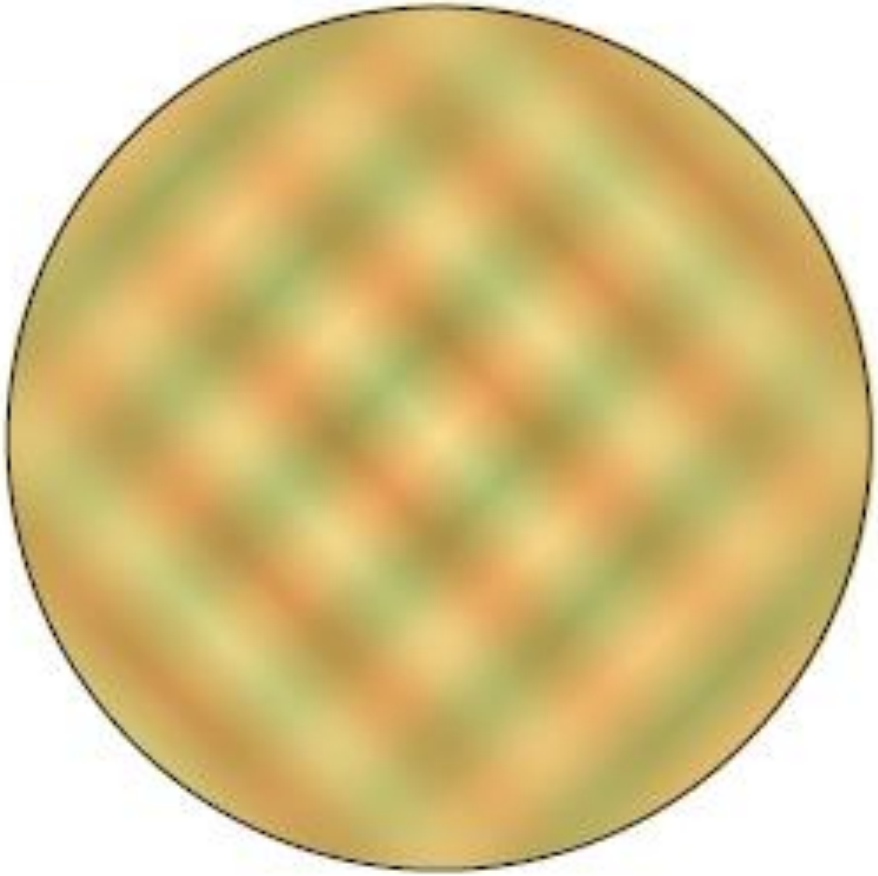


- Each **point attractor** corresponds to a single state (memory, concept, image, etc.) to which the system can converge.

Binocular rivalry and bistable perception

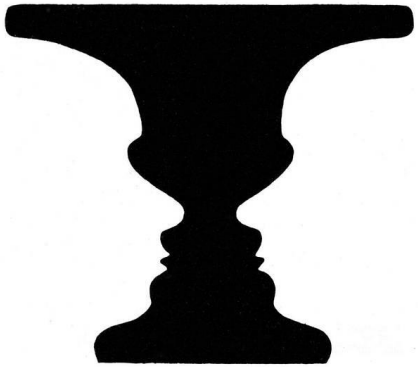
- Binocular rivalry: presentation of mutually incongruent images to the left and the right eye results in the perceptual alternation of the two percepts, instead of their perceptual fusion. Special case – monocular rivalry.

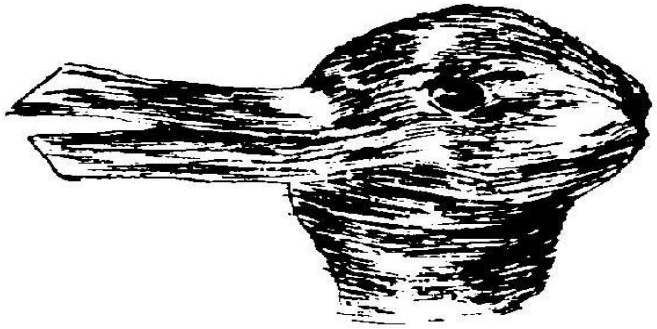




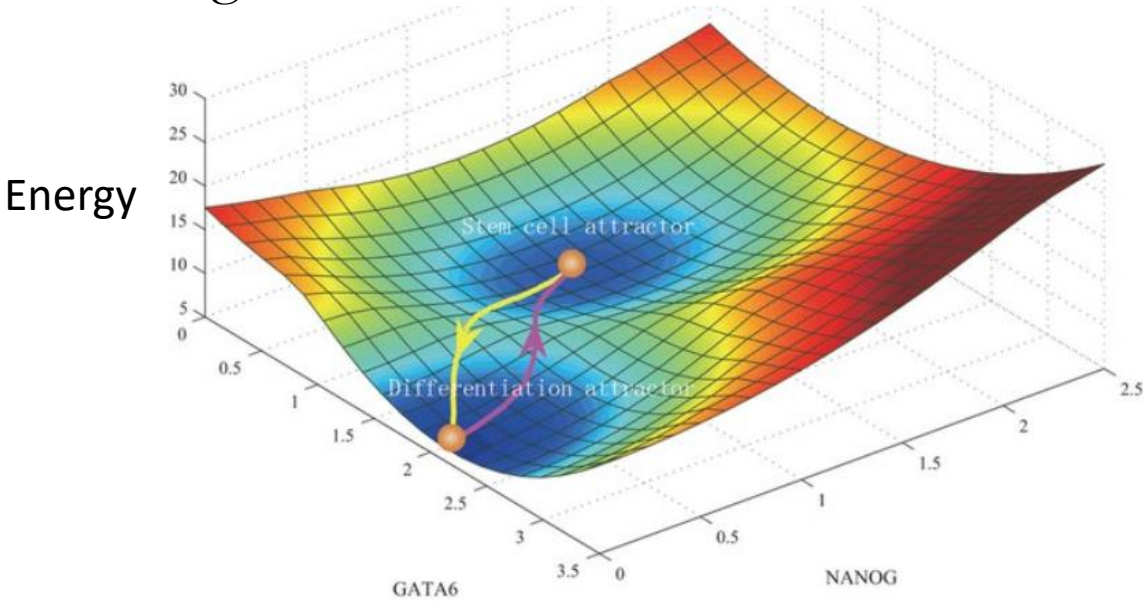
Bistable perception

- Physically invariant stimulation leads to fluctuations in perception.



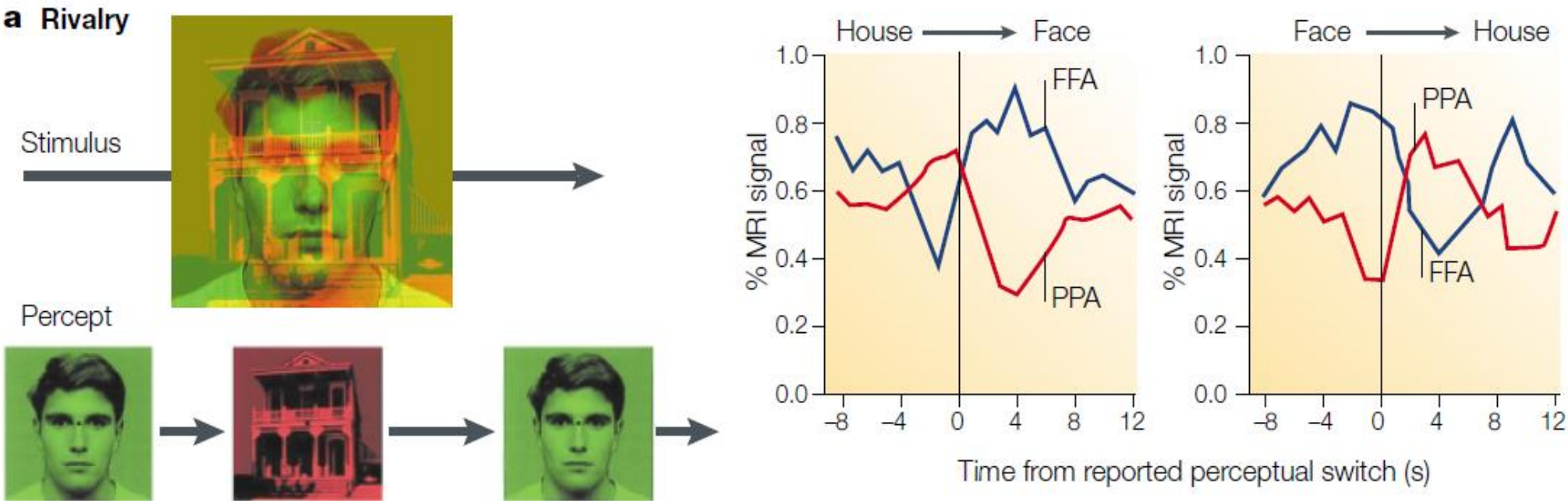


- In the state space of neural nets, periodic or bistable attractor means oscillation, switching between two attractors in an alternative manner.



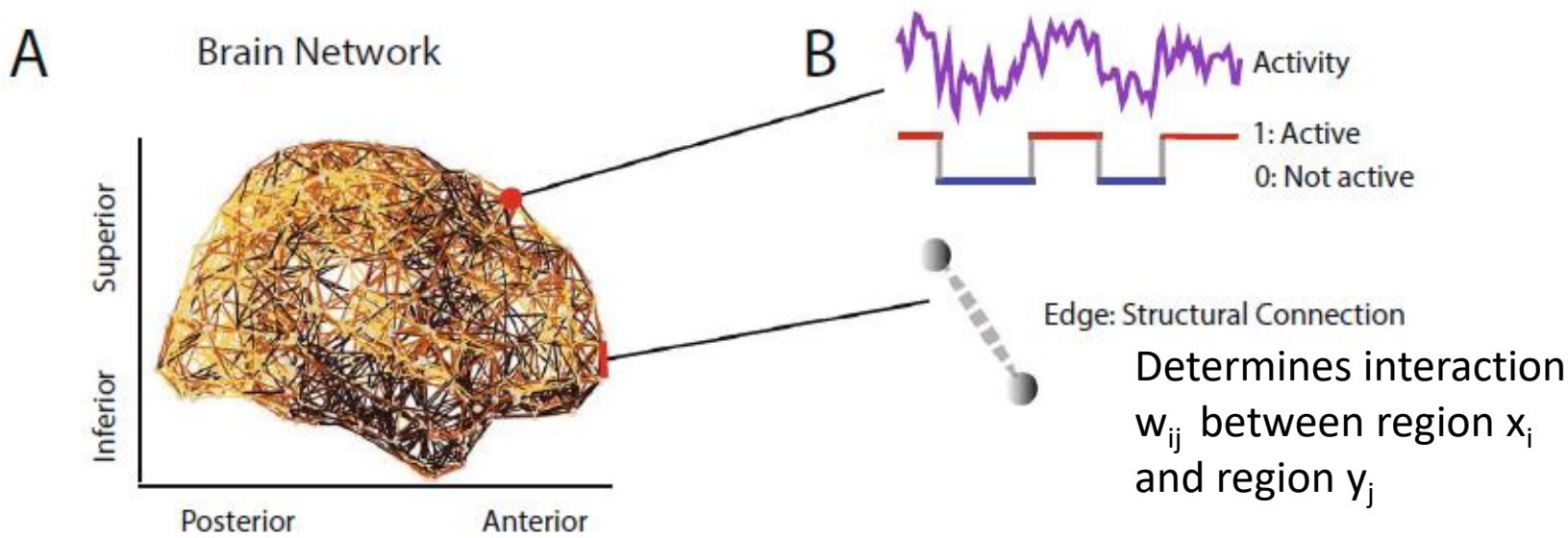
Bistable perception – fMRI

- FFA: a region along the fusiform gyrus known to be selectively responsive to faces (FFA), and PPA: a region in the parahippocampus known to be selectively responsive to spatial locations and buildings.
- The magnitude of the fMRI signals from these two brain areas fluctuates over time in phase with the observer's perceptual experience (Blake & Logothetis, Nature Rev. Nsci., 2002).



The energy landscape of brain activity

- How does large-scale brain circuitry constrain states of neuronal activity and transitions between those states? (Shi Gu et al., Sci. Rep., 2018)
- (A) A weighted structural brain network represents the number of white matter streamlines connecting brain regions.
- (B) While neurophysiological dynamics create rich time series of continuously-valued activity magnitudes, they study a simplified model in which each brain region is a binary object, being either active or inactive.



Dynamical trajectories of brain states

- Brain states correspond to energy minima. Dynamic trajectories are those that the brain takes through a set of states to move from an initial state to a target state. Dynamical trajectories may be initiated either by external or internal stimuli.

$$E = -\frac{1}{2}\sum_j \sum_i x_i w_{ij} y_j$$