Introduction to Neuroscience

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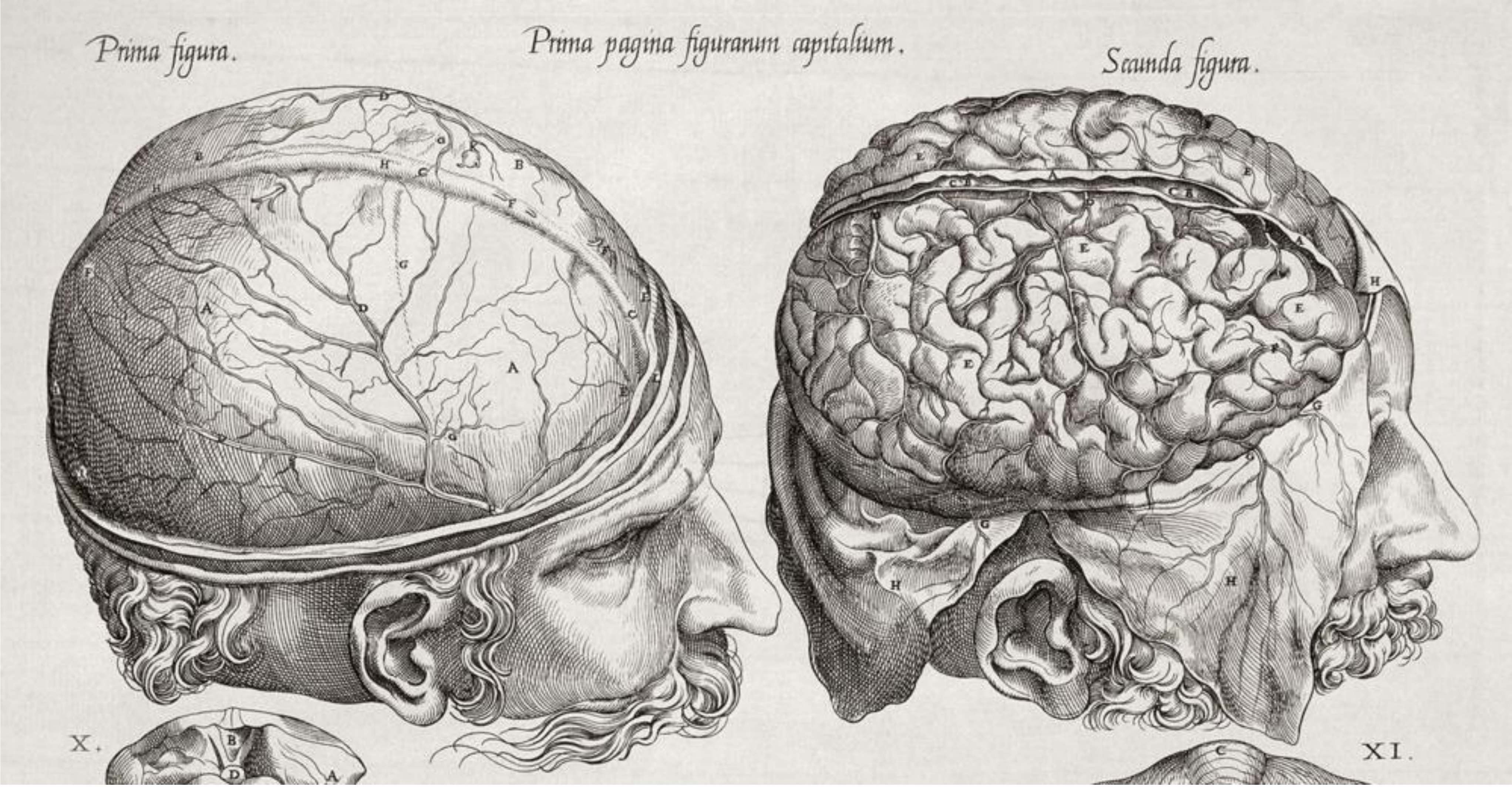
Computational Neuroscience (Lecture 2, 2023/2024)

The Brain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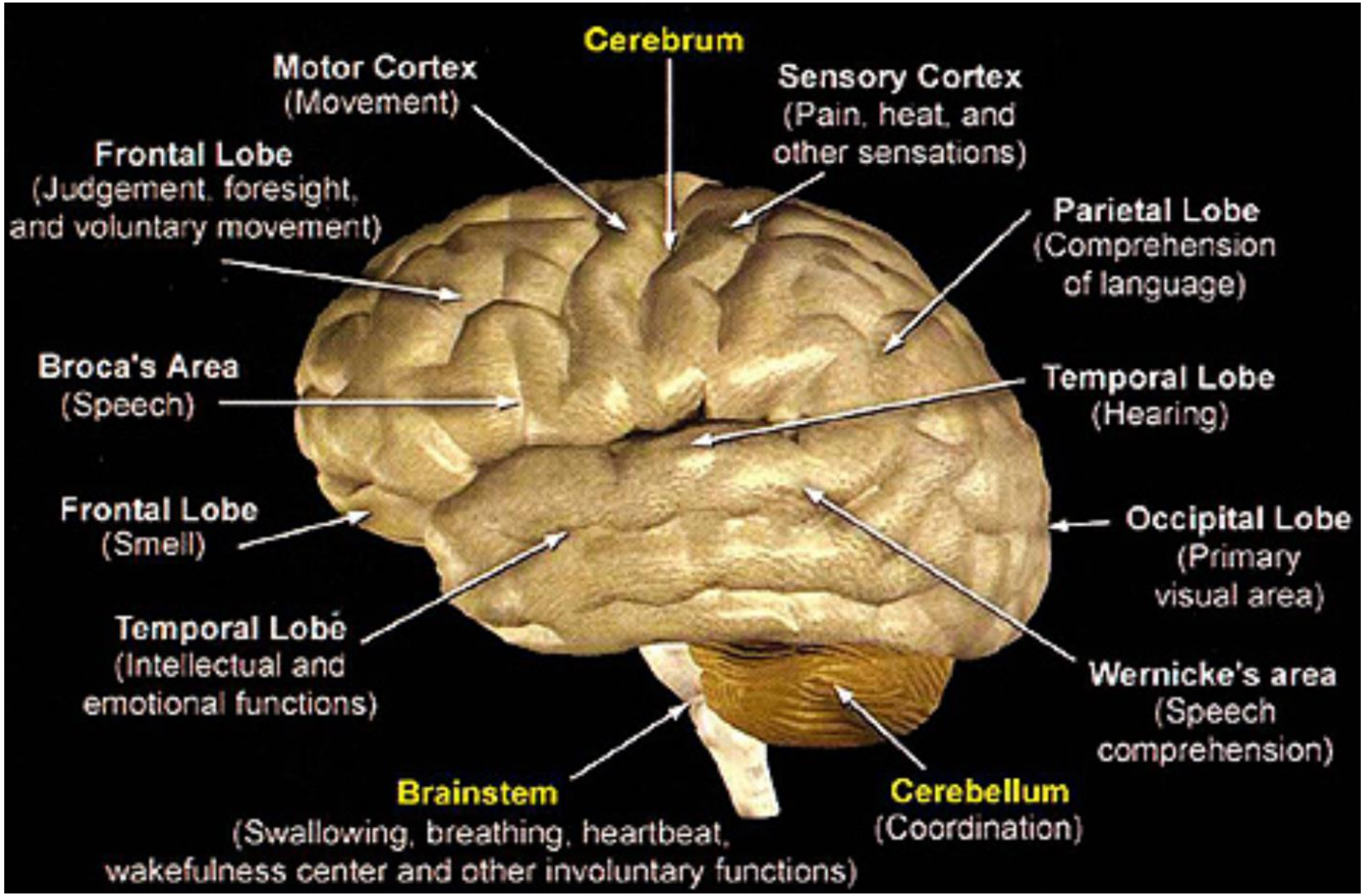
The Brain – Gross Anatomy



Localisation of function: based on e.g. lesion studies, more recently fMRI etc.

Localisation of Function

Damage to prefrontal cortex (executive brain region)

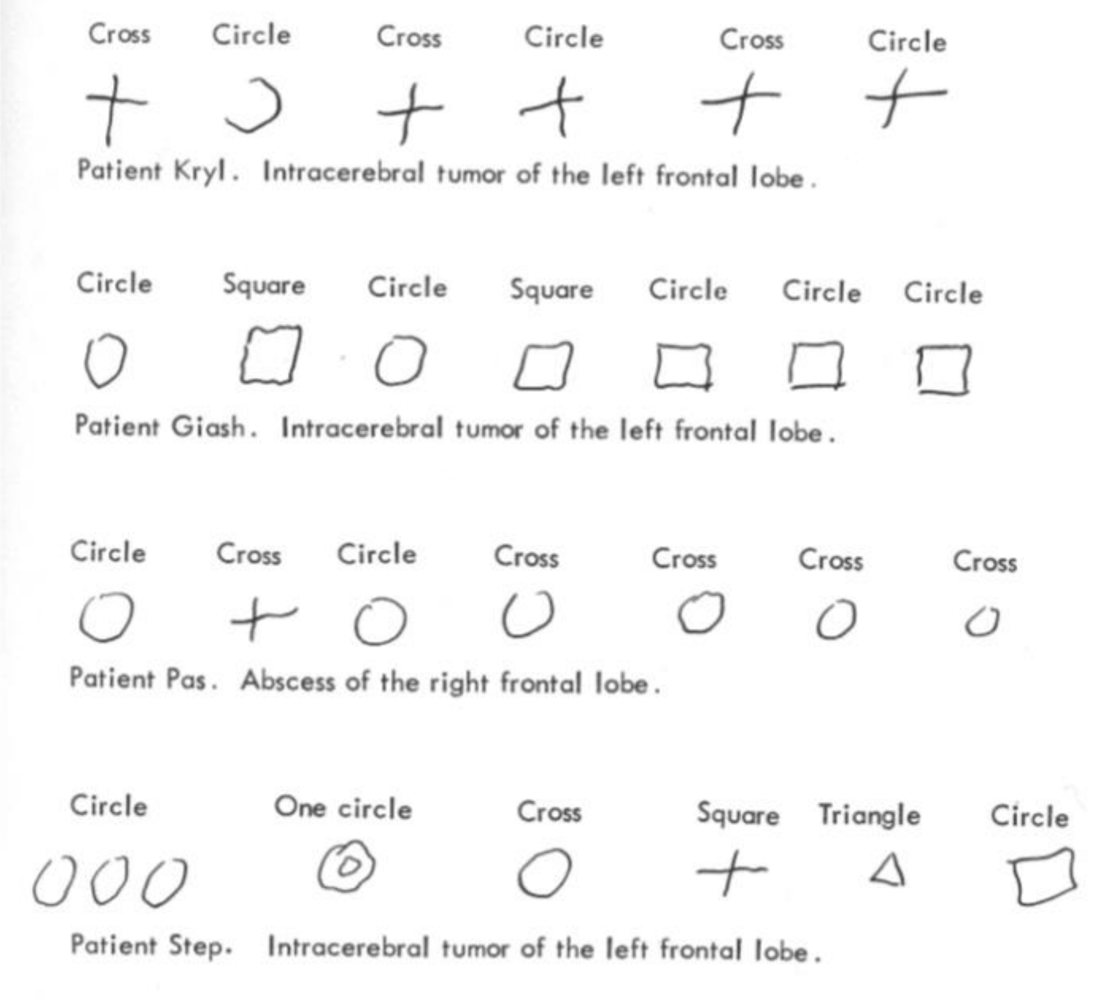


FIGURE 66 Disturbance of the performance of single tasks as a result of pathological inertia of action in patients with extensive lesions of the frontal lobes.

Damage to hippocampus (memory region)

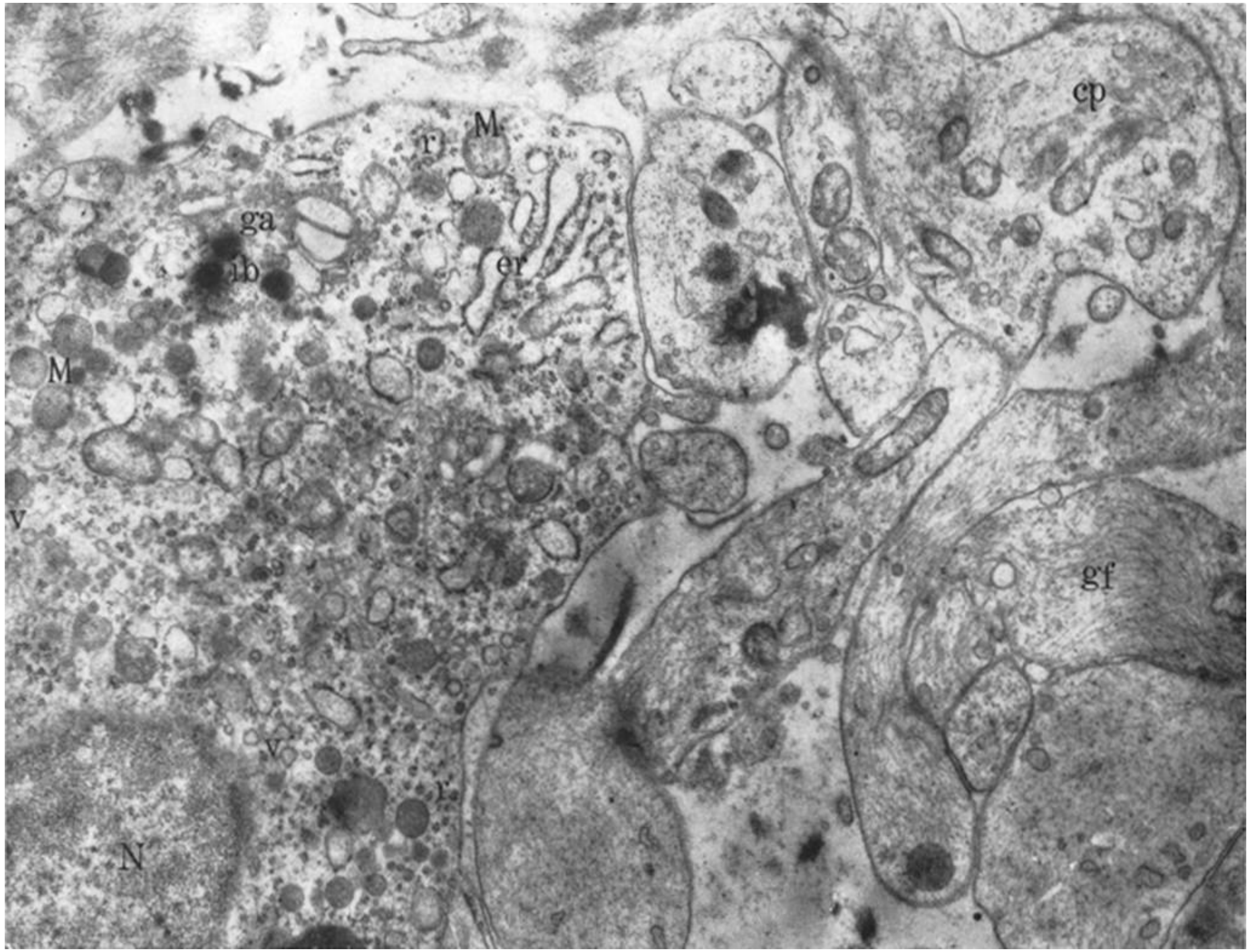
The Brain – In Numbers

10^11 neurons

10^3 connections per neuron

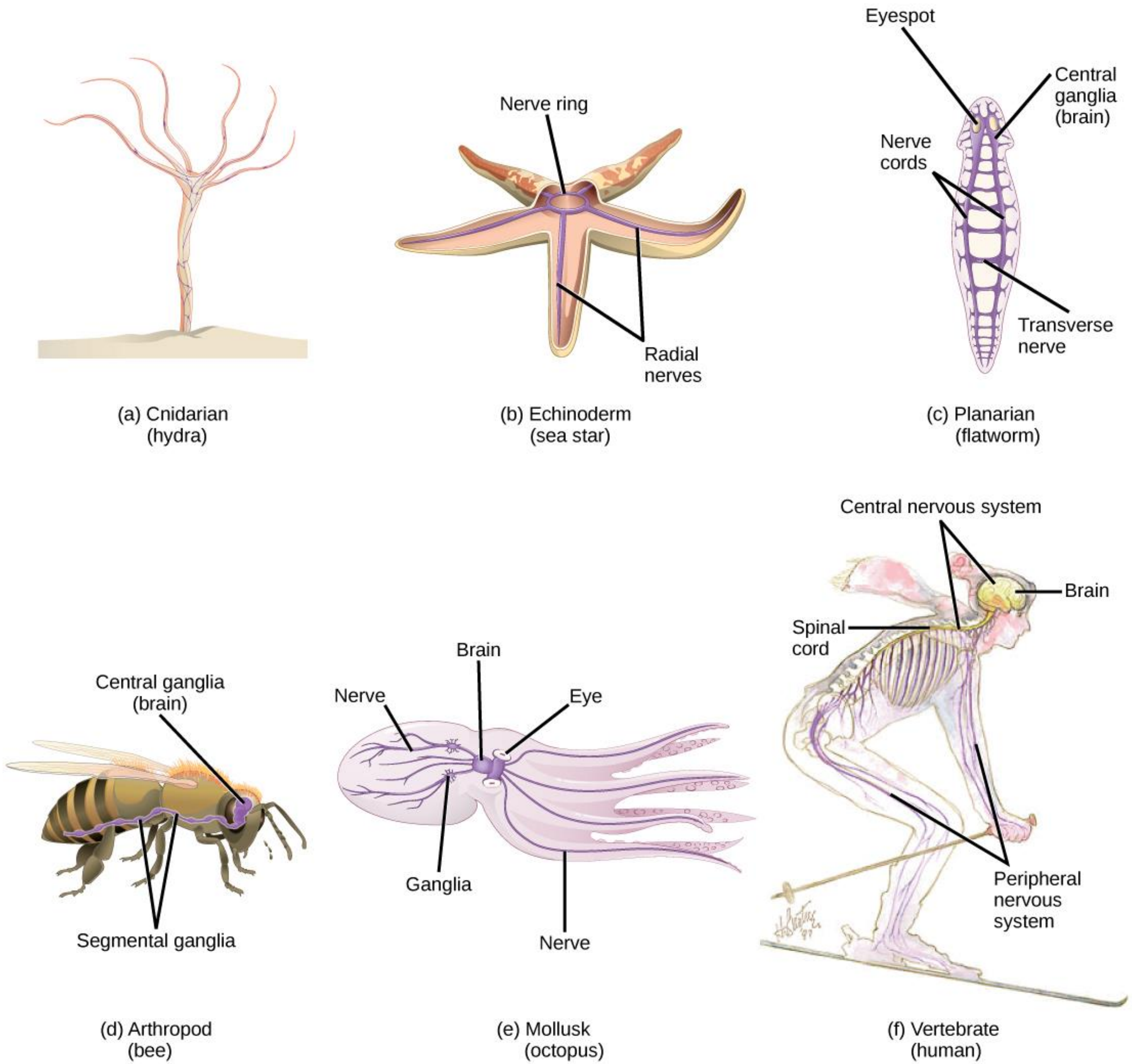
10^14 connections (synapses)

10^6 km of wiring (axons) – enough to go to the moon and back!



Electron microscopy scan of human brain tissue

Evolution of the Nervous System



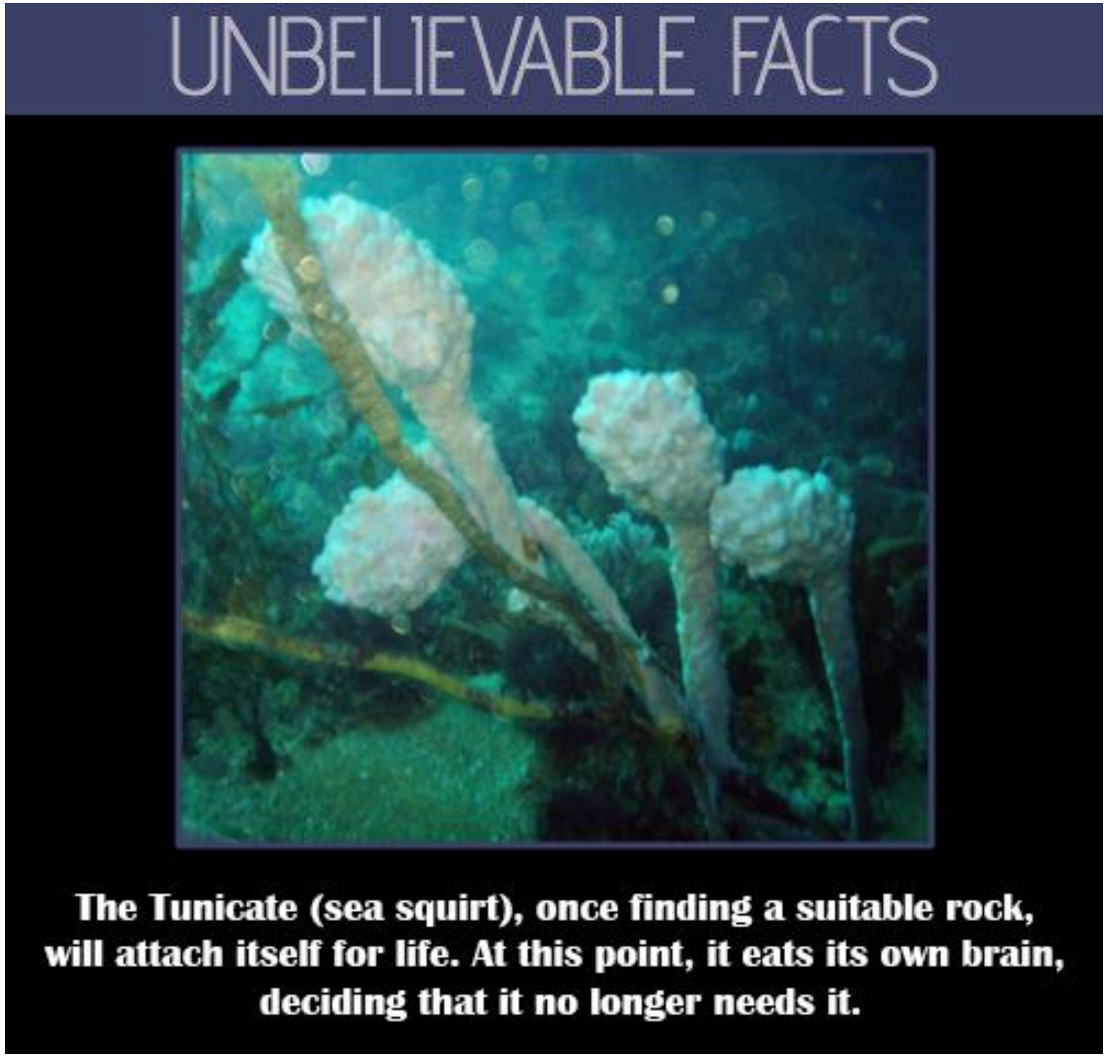
What are Brains for?

- Detect signals from environment (sensory)
- Control muscles/**motor behaviour**
- Regulate internal bodily physiology

- Everything else is just complex control loops to interpret sensory signals and execute motor output (including thoughts, emotions etc.)

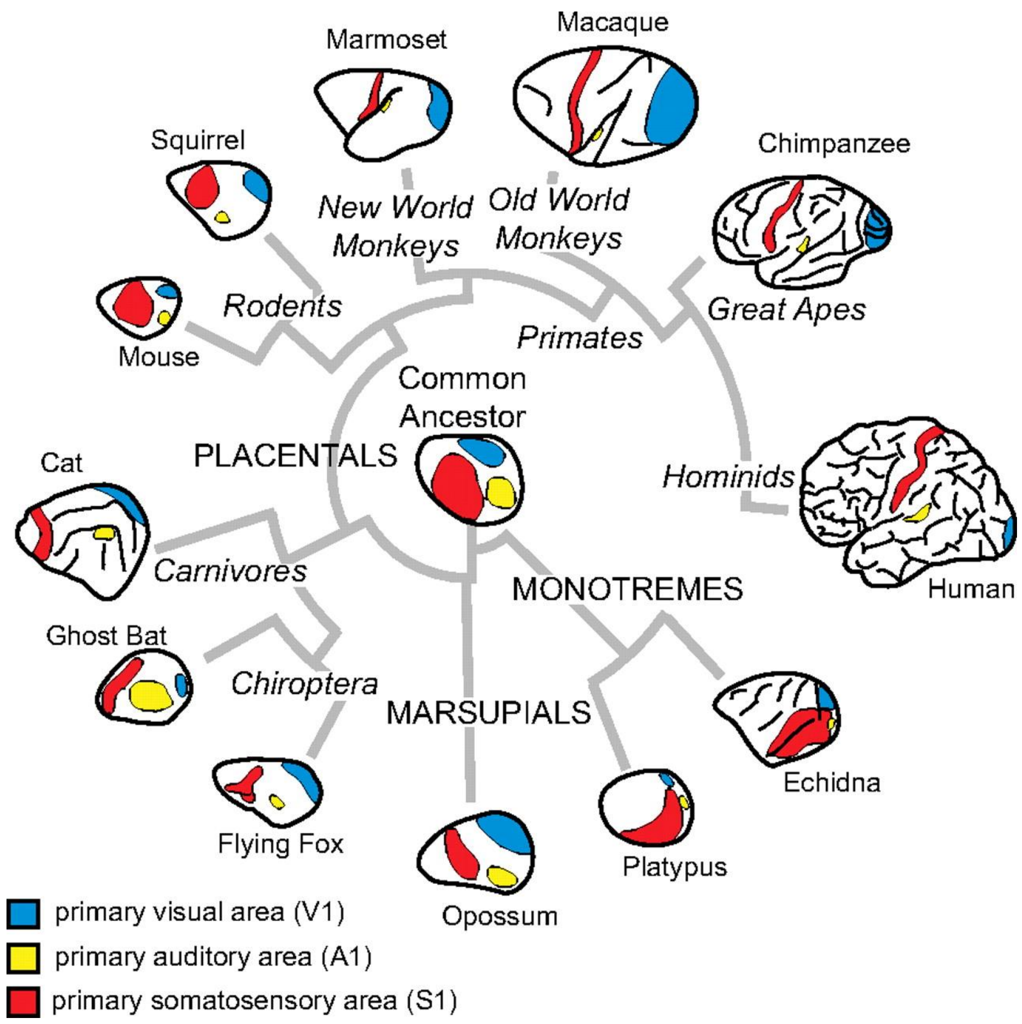
- What motor actions should the brain choose? Those which maximise "reward" (What is rewarding? Ask evolution. How do we get rewards? See e.g., Reinforcement Learning)

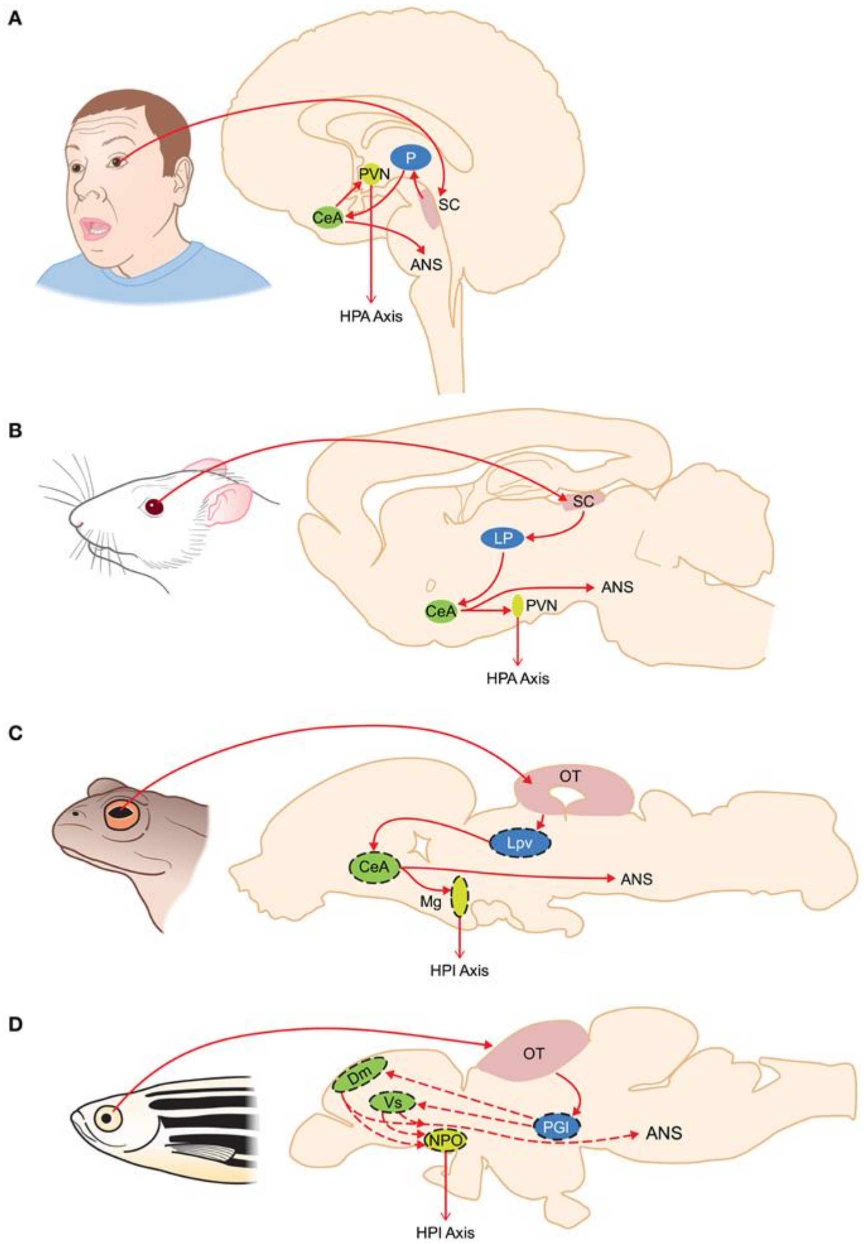
- Brains are energetically expensive! (roughly 20% of total bodily energy consumption). Evolution may not favour big/powerful brains…



Evolution of the Mammalian Cortex

Subcortex is evolutionarily ancient, controls reflexive/instinctive stimulus-response behaviours. Cortex evolved later for learning flexible/complex associations/behaviours: <u>cortex is a control system for subcortex</u>





What Challenges do Brains Face?

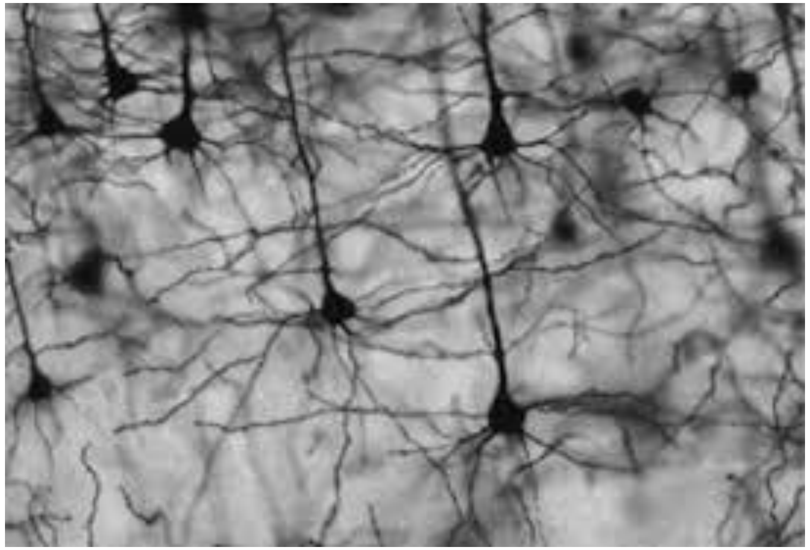
What challenges do brains face?

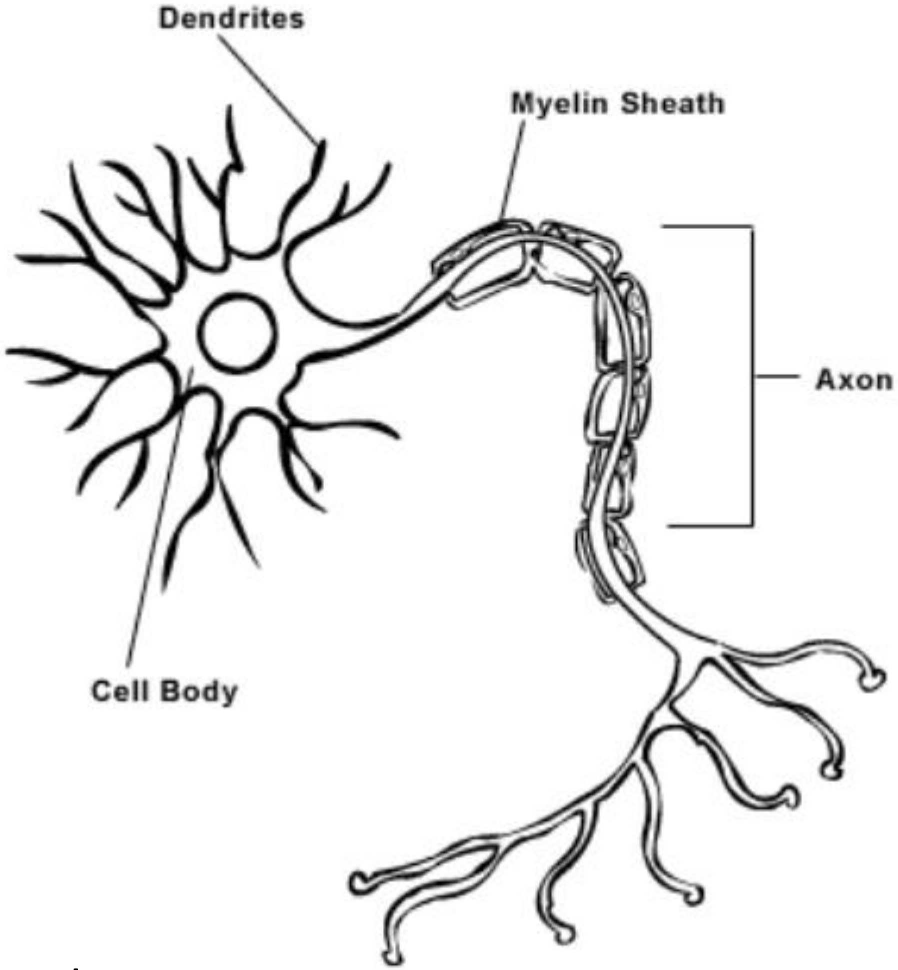
- Perception: Interpret sensory signals
- Decision making/planning/action selection: choose a course of action
- Motor control: execute action effectively
- Learning: learn to do all of the above

Why are these challenges difficult?

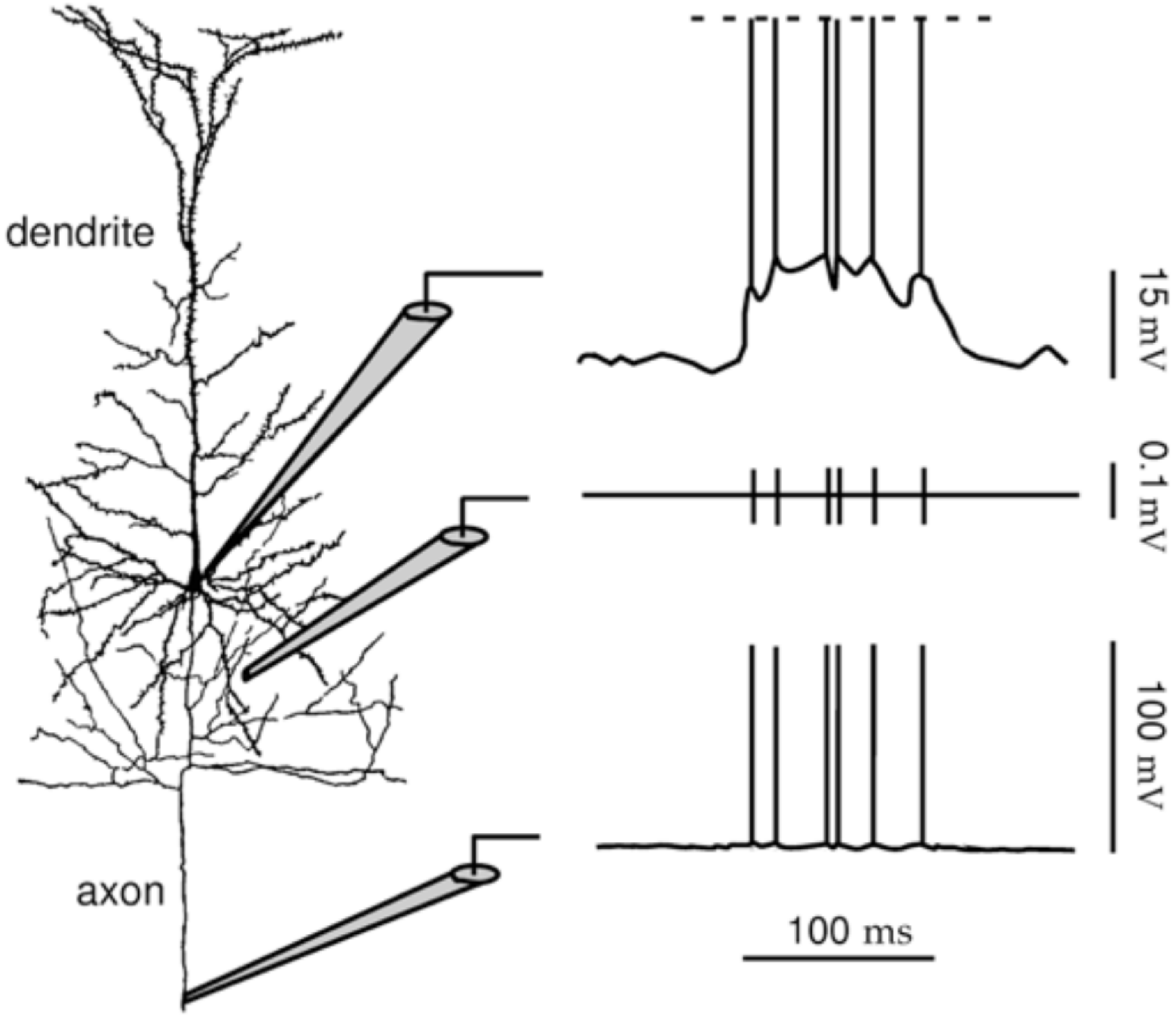
- Sense data are 1) unlabelled 2) noisy and incomplete 3) complex and multimodal
- The things we care about are “latent” (hidden) in those sense data (e.g., objects)
- Sparse reward signals (rarely get feedback on actions)
- Have to solve all this using a brain – noisy, messy, distributed, local, energy constraints, etc.
- Have to learn “online” during lifetime, and not die (not enough genes to specify all connections)

Neurons

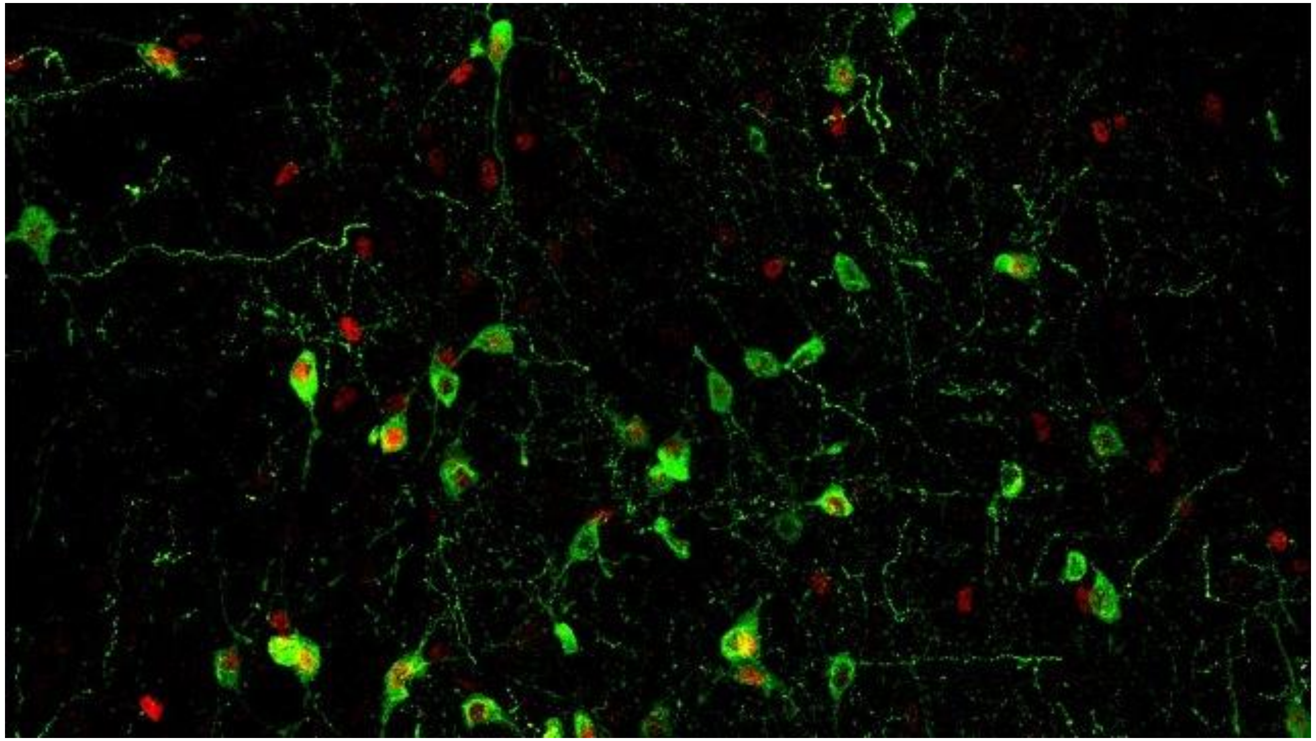




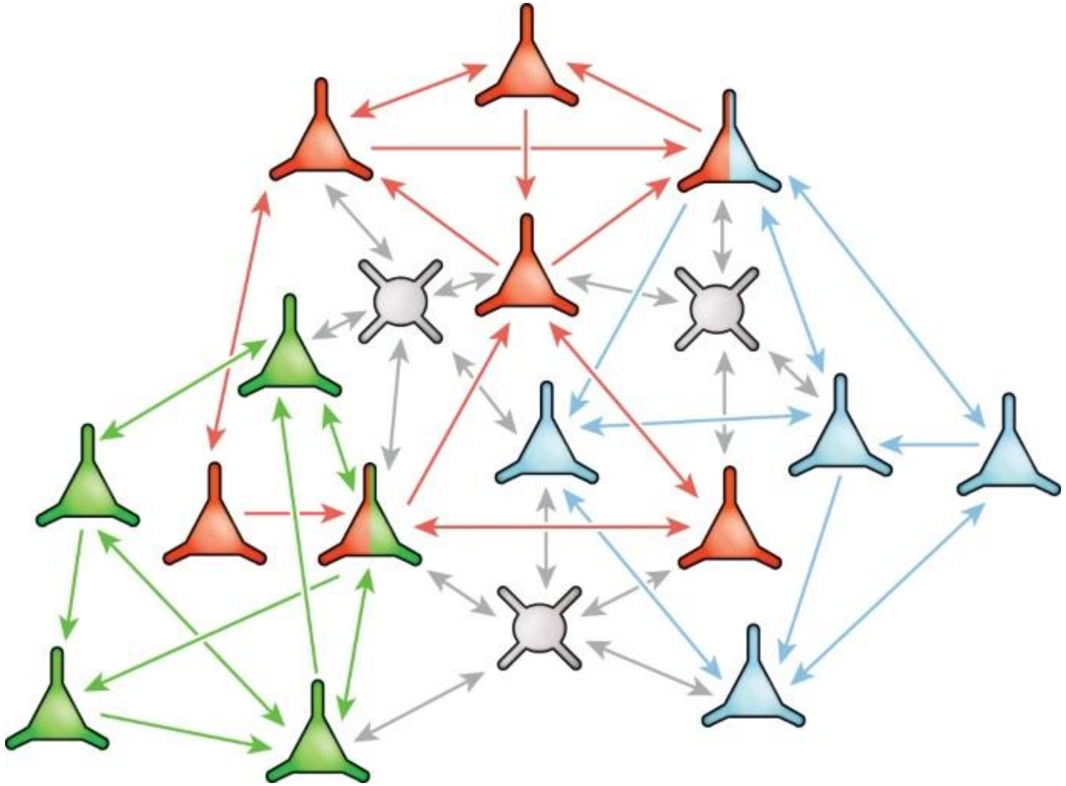
Brain is made of neurons (and glial cells!)
Dendrites: receive inputs from other neurons
Soma (cell body): Collects signals from dendrites
Axon: sends signals to other neurons
Synapse: Connection from axon to dendrite (usually)
Action potential (spike): Pulse signal sent down axon to another neuron (unit of communication)
Excitatory vs Inhibitory neurons: activate vs inactivate other neurons


dendrite
axon
15 mV
0.1 mV
100 mV
100 ms

Networks/Circuits of Neurons



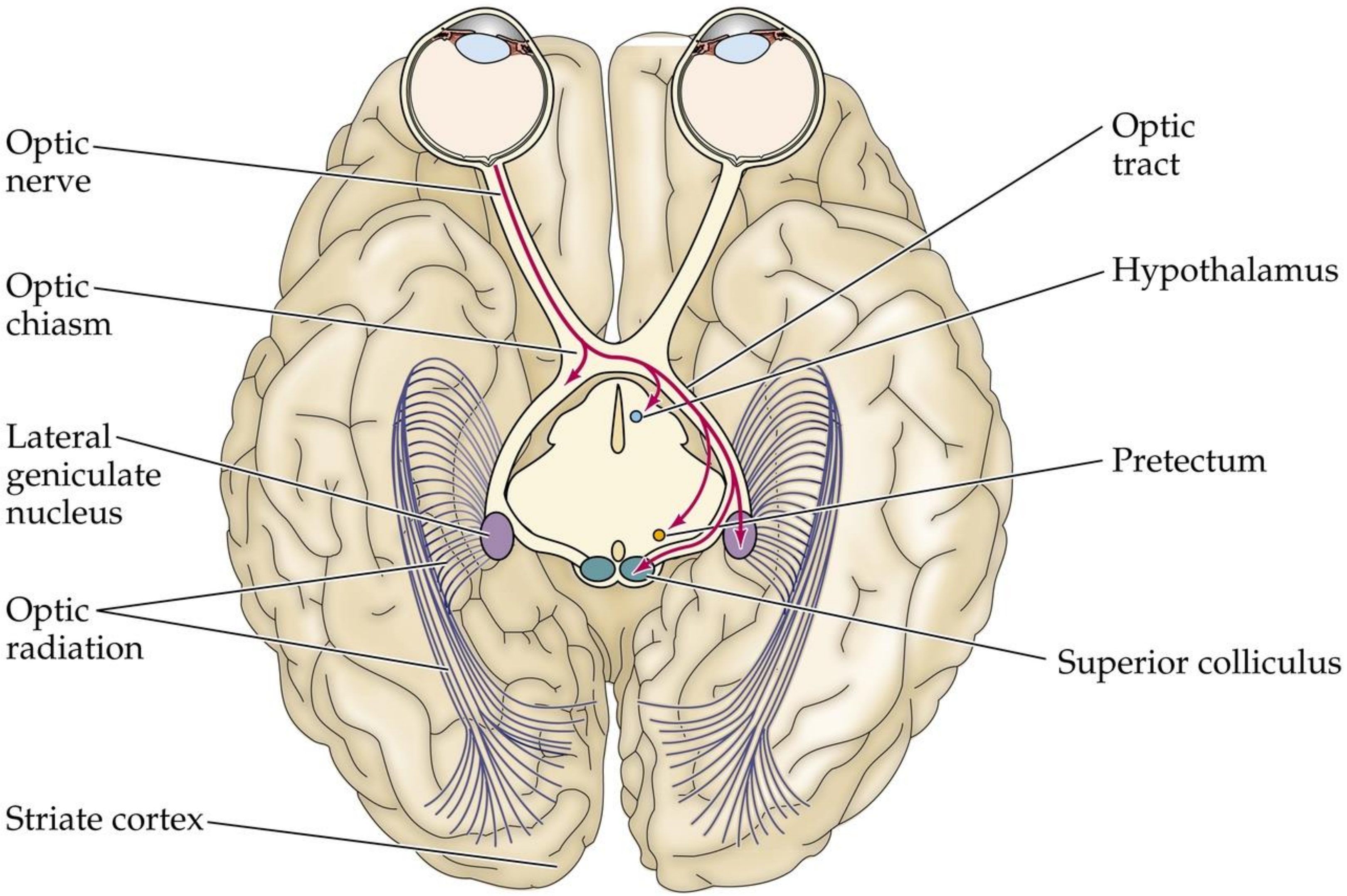
Staining of neuron cell bodies and axons/dendrites



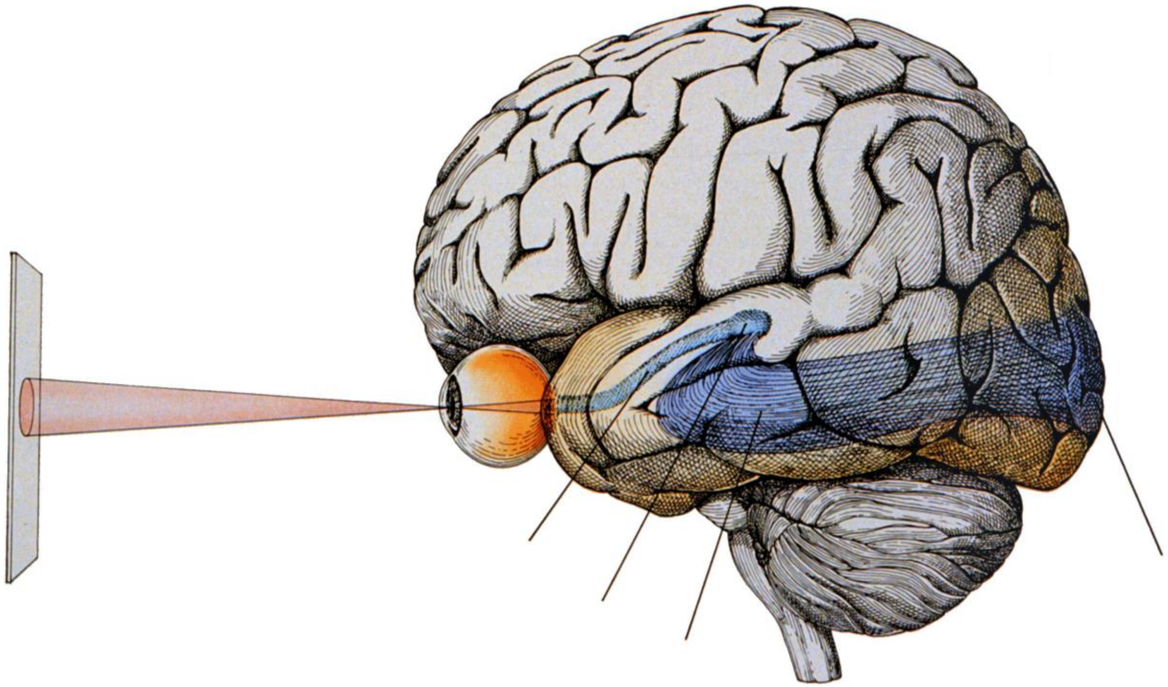
Schematic of different neuron types wired together to form a network/circuit

Neurons form networks/circuits via synaptic connections
The collective behaviour of a network of neurons may be complex
It is thought that these circuits carry out particular computations

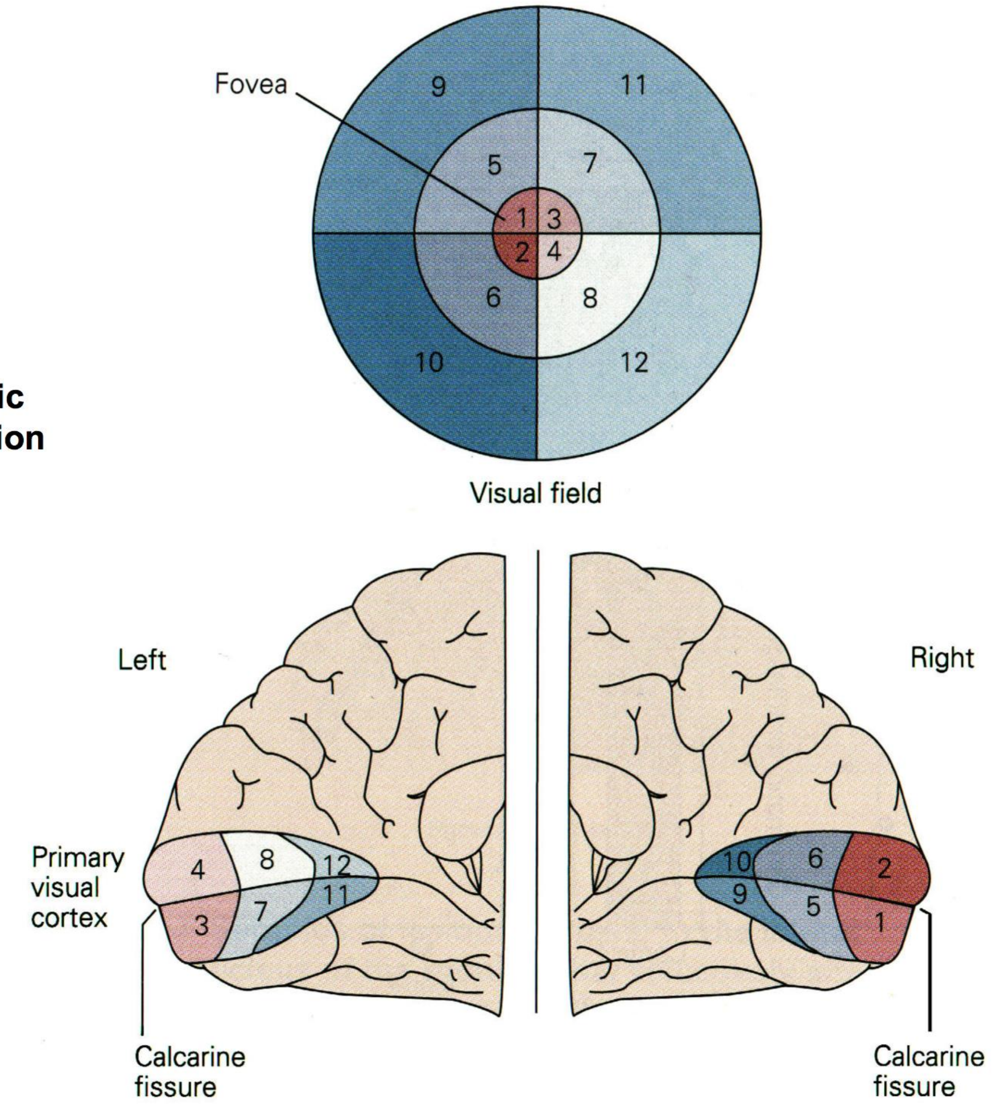
The Early Visual System



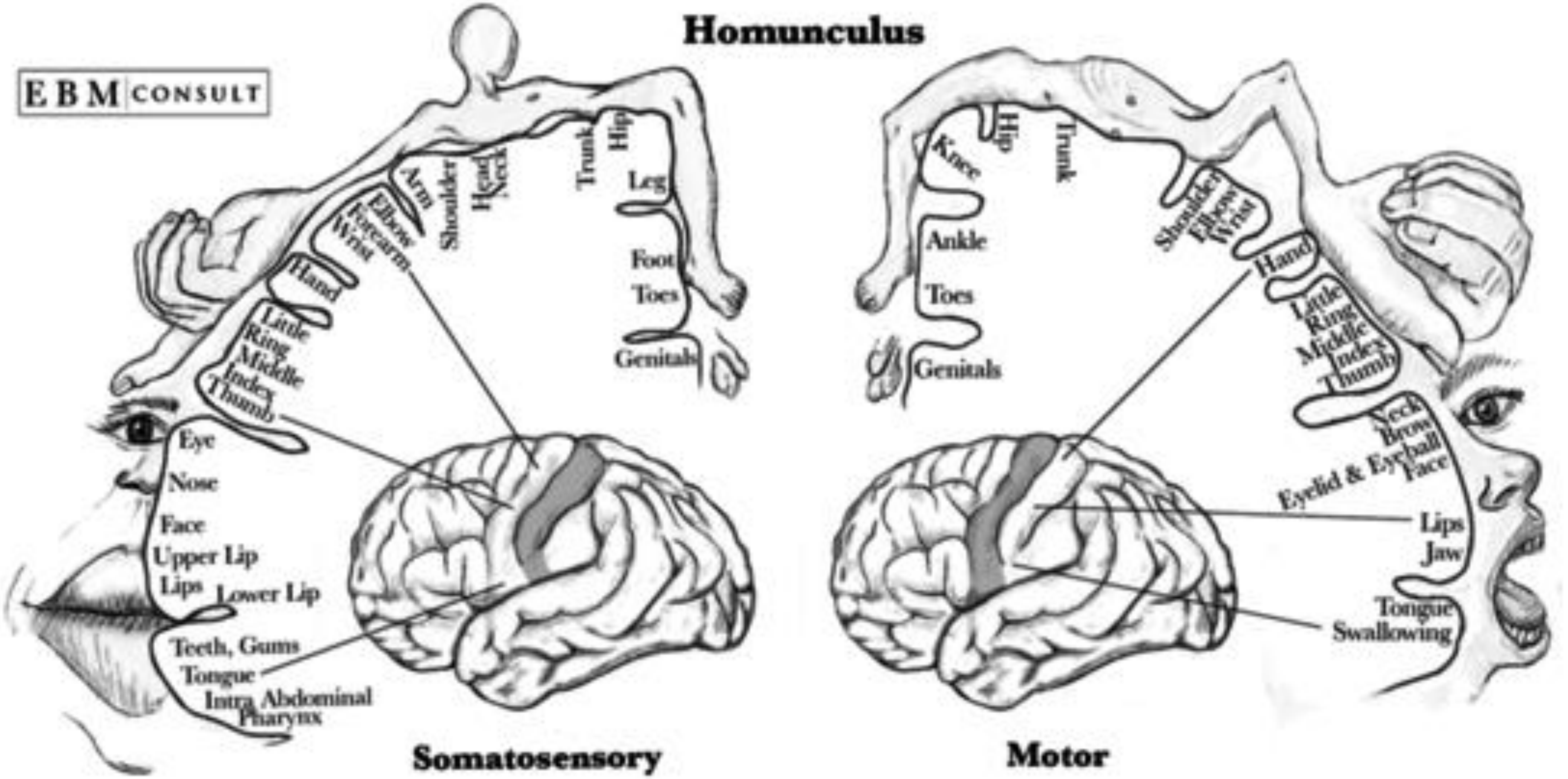
Representation of Visual Space



Retinotopic Organization

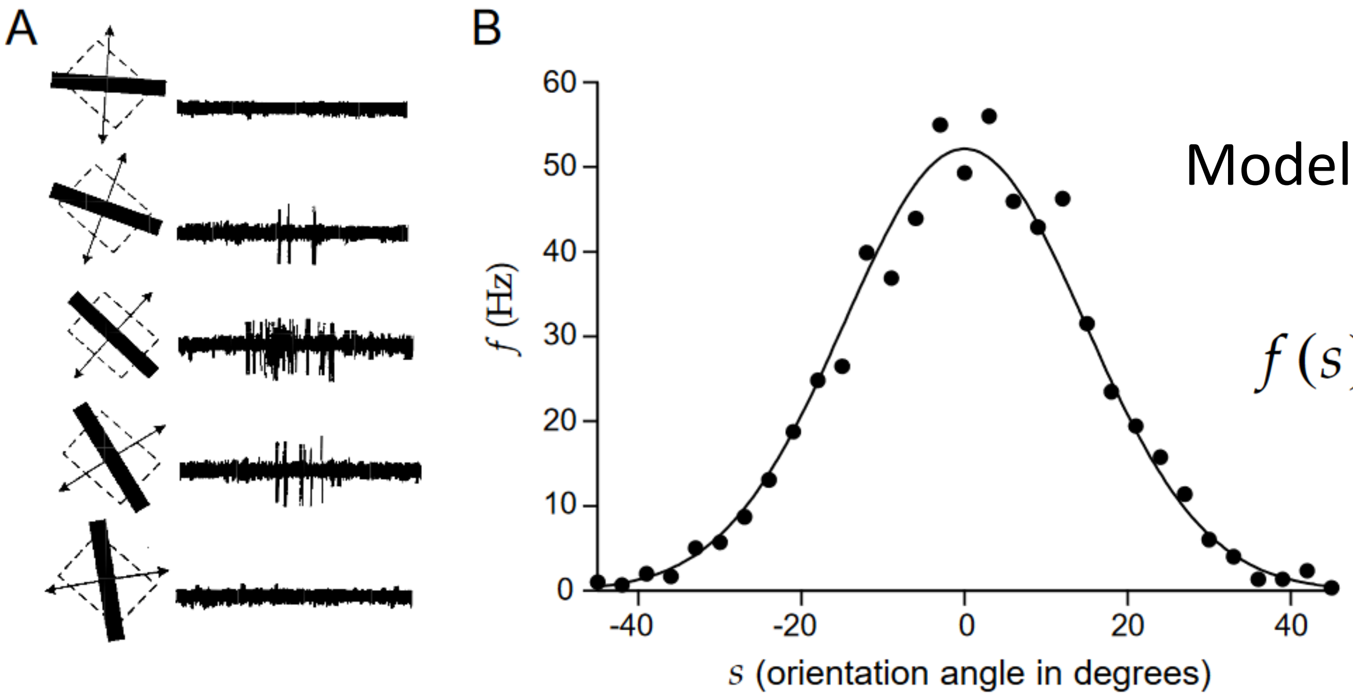


Representations of Bodily Space



Representations in Single Neurons – Tuning Curves

Tuning Curves: Vary stimulus and plot mean response of neuron

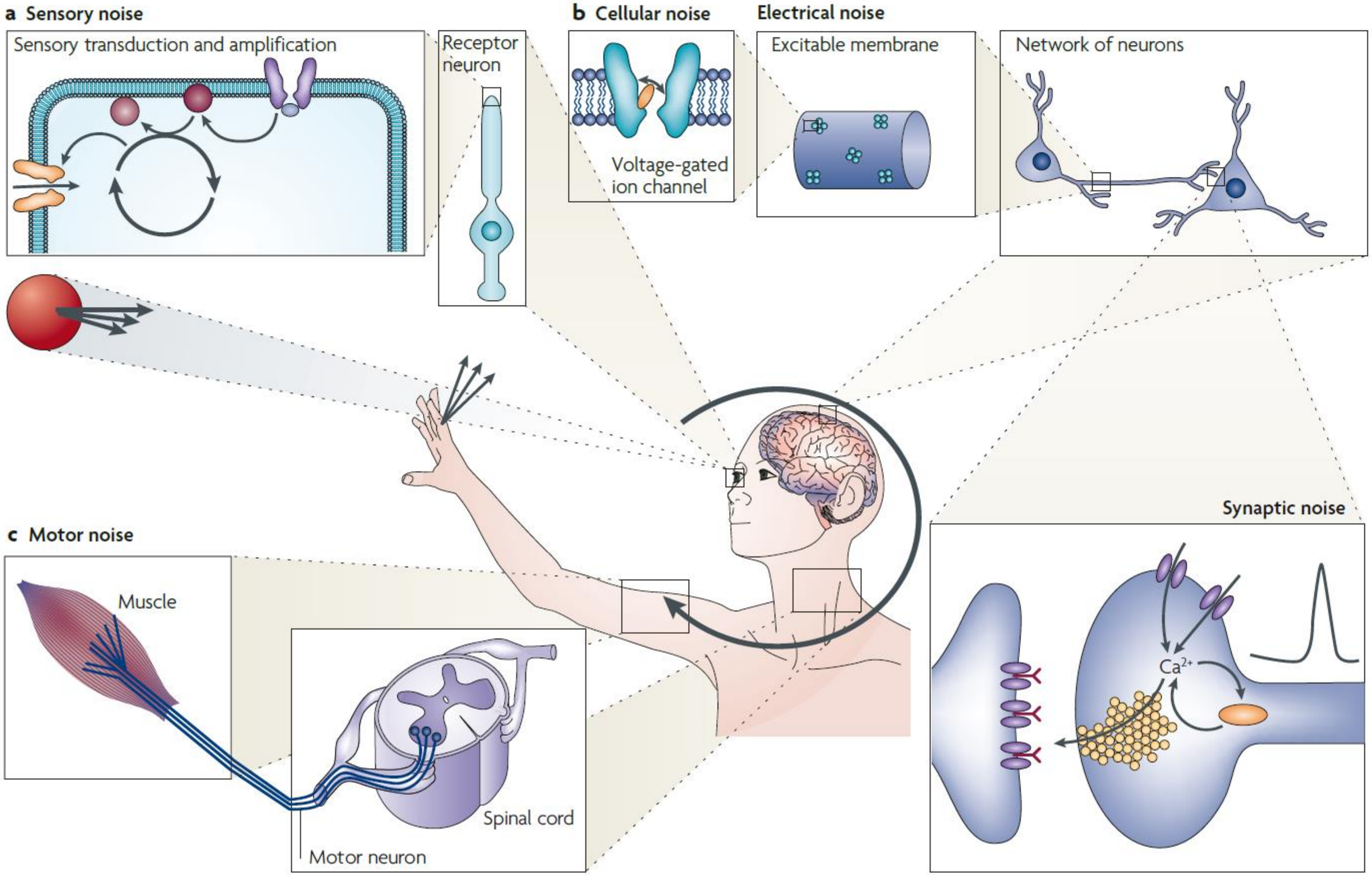


Model tuning curves as a Gaussian function:

$$f(s) = r_{\max} \exp\left(-\frac{1}{2}\left(\frac{s - s_{\max}}{\sigma_f}\right)^2\right)$$

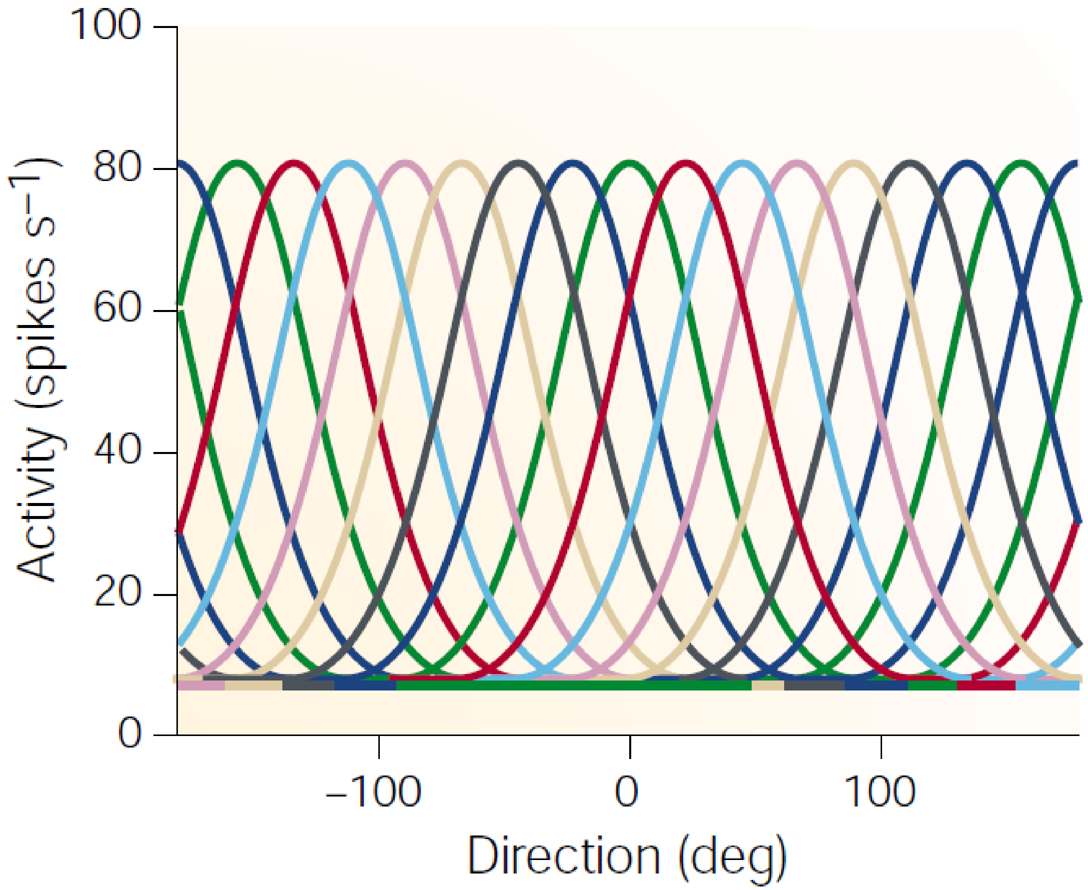
Figure 1.5 (A) Recordings from a neuron in the primary visual cortex of a monkey. A bar of light was moved across the receptive field of the cell at different angles. The diagrams to the left of each trace show the receptive field as a dashed square and the light source as a black bar. The bidirectional motion of the light bar is indicated by the arrows. The angle of the bar indicates the orientation of the light

Noise in the Nervous System

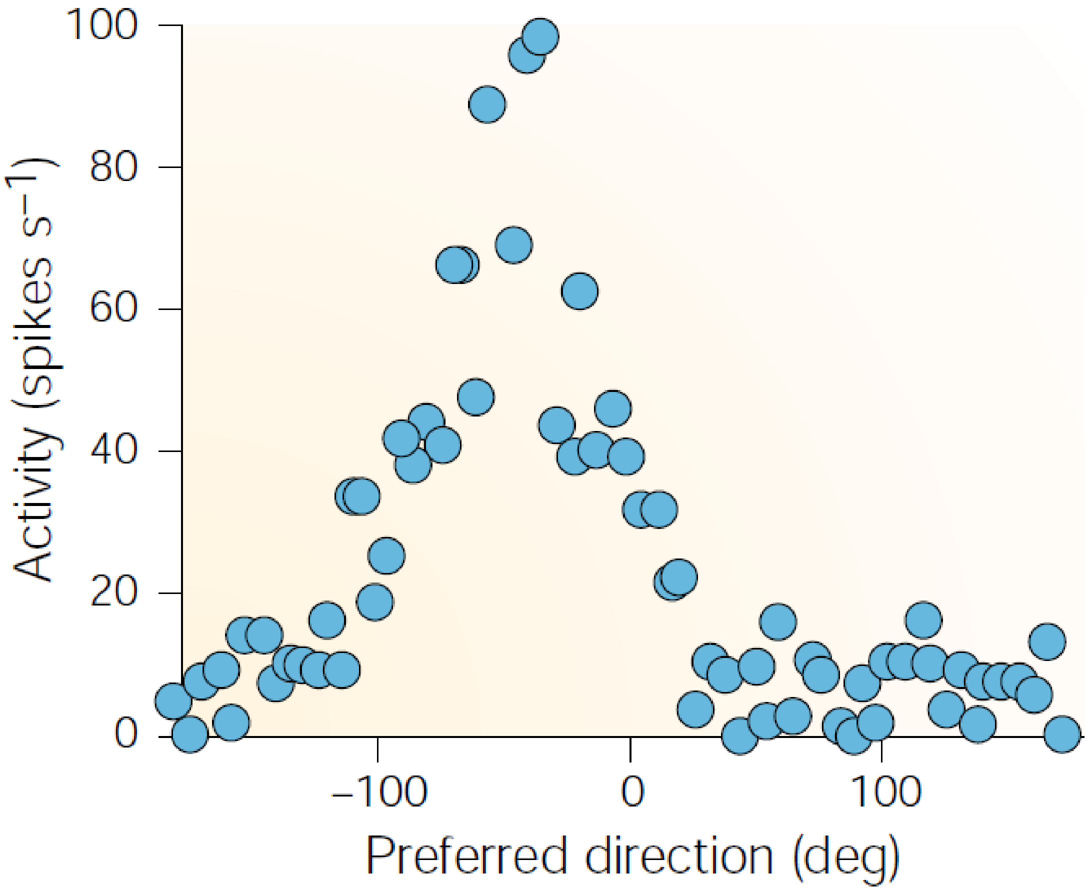


Representations in Populations of Neurons

Many neurons, each with a different preferred orientation



Noisy response of population to a single stimulus presentation



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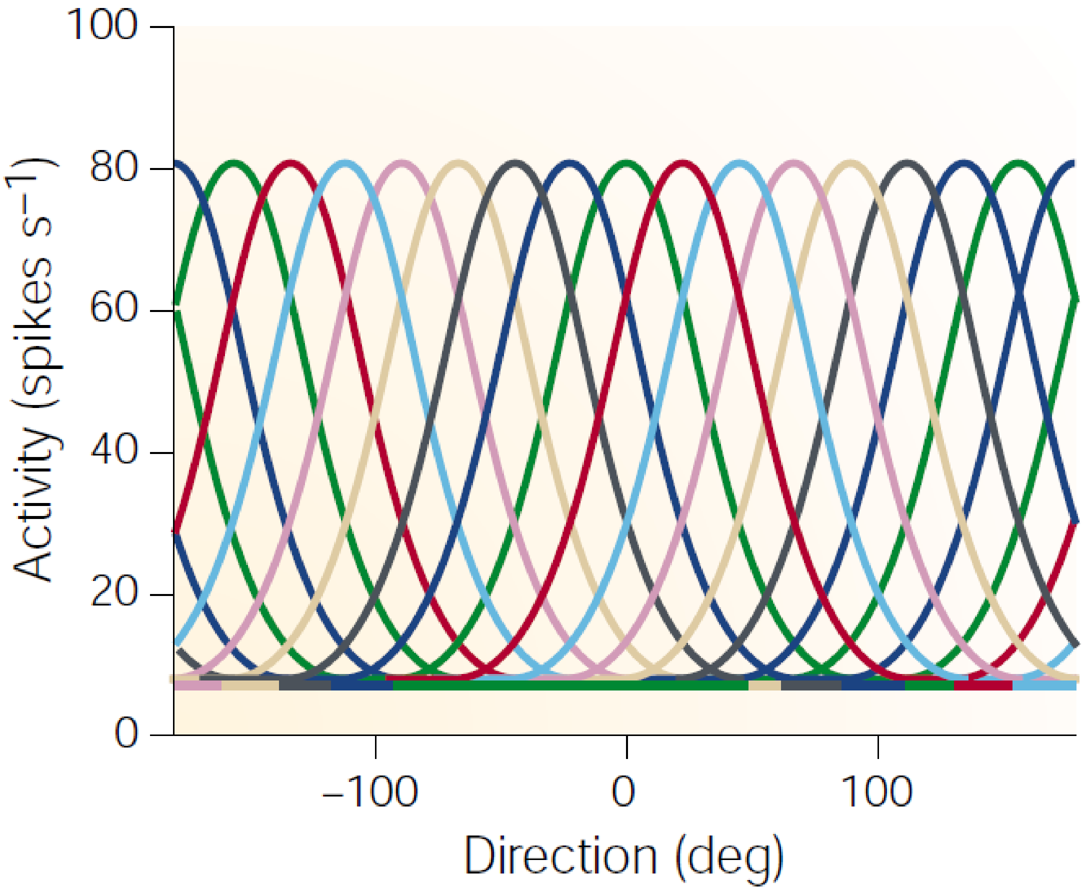

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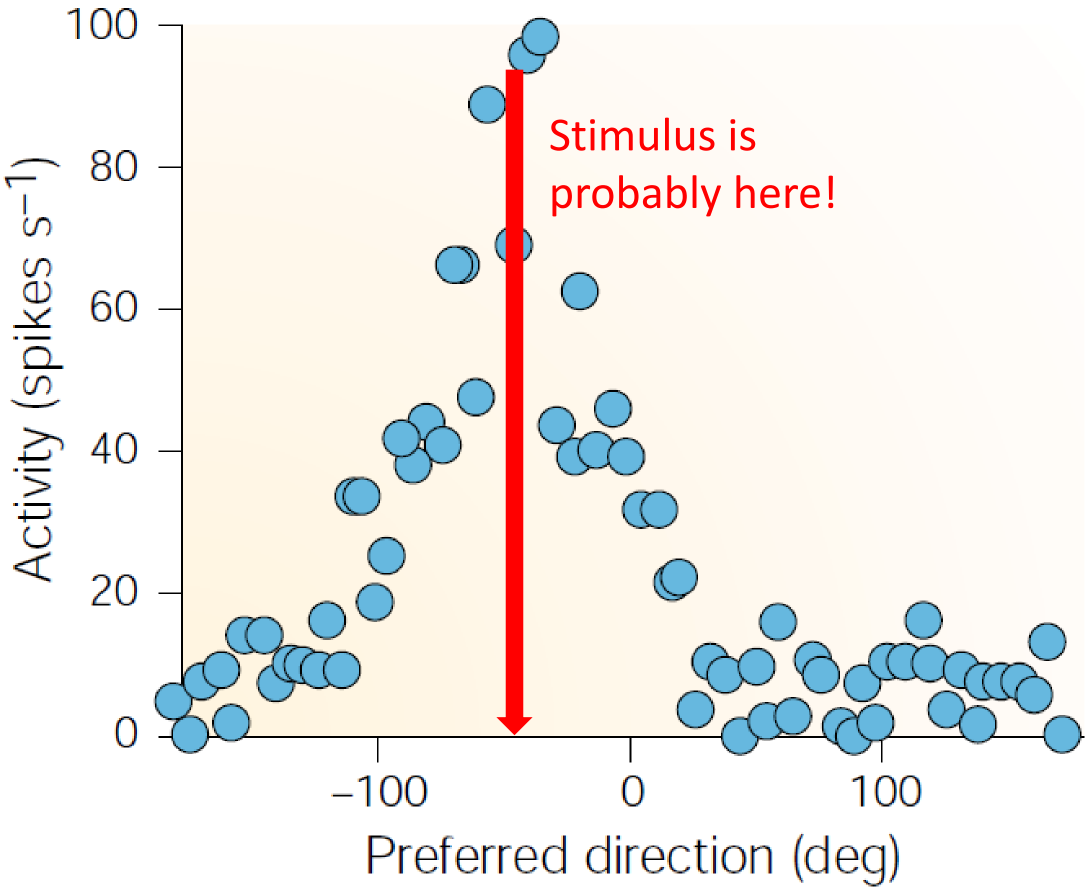
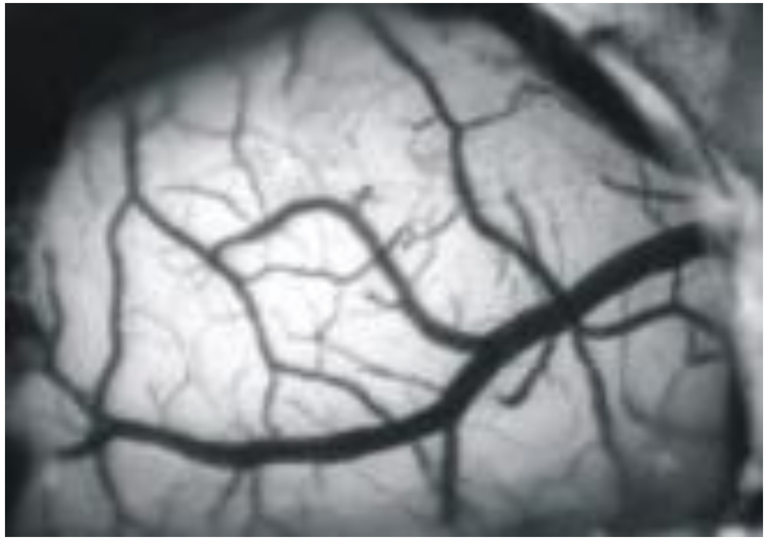
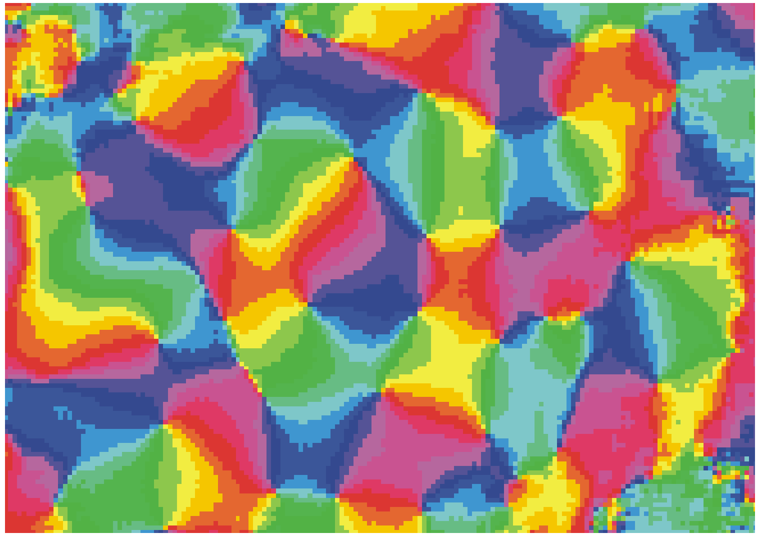


Representations in Populations of Neurons

Topographic Map: Vary stimulus and plot preference of each neuron on cortical surface (max of tuning curve)

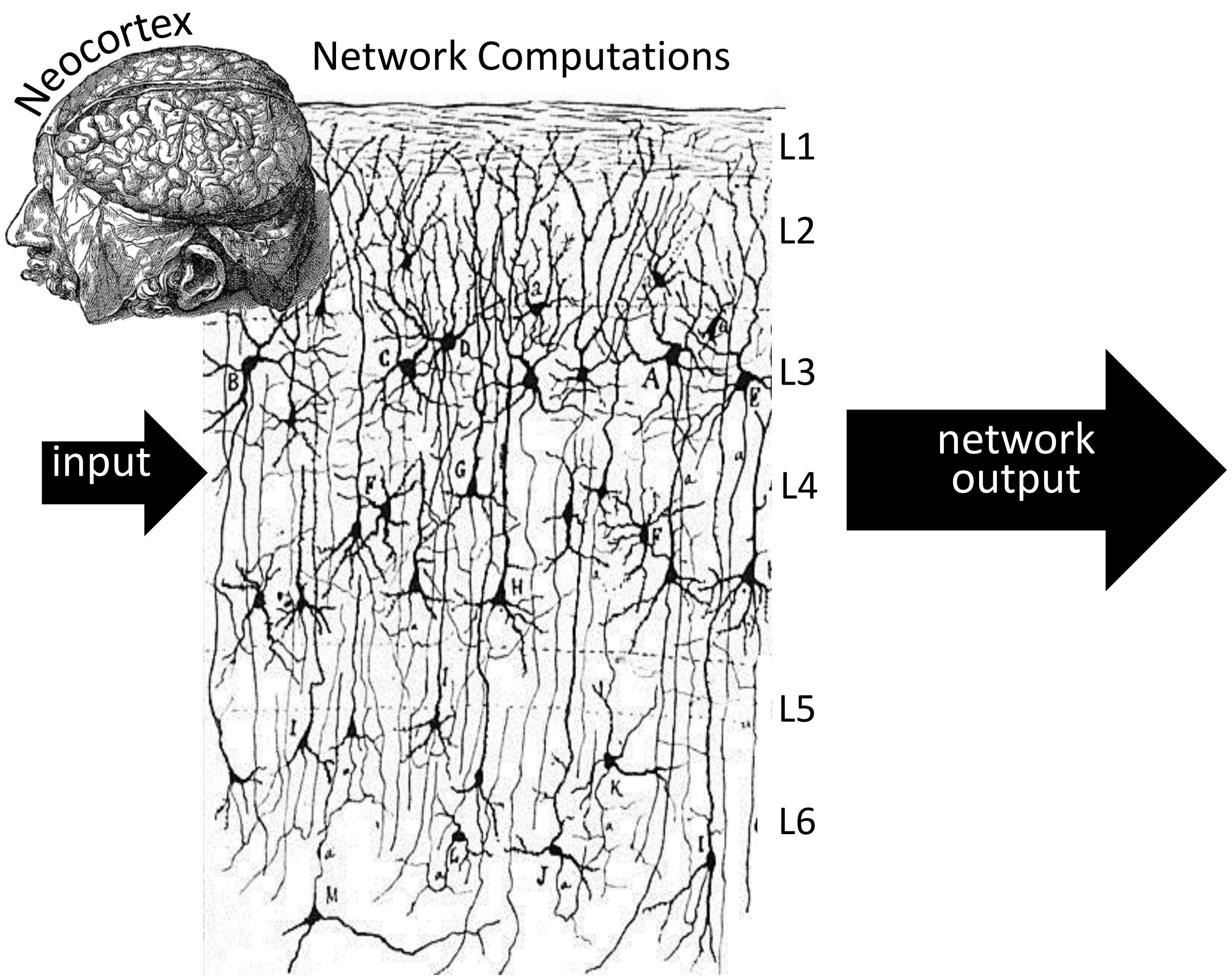


Imaged surface of visual cortex



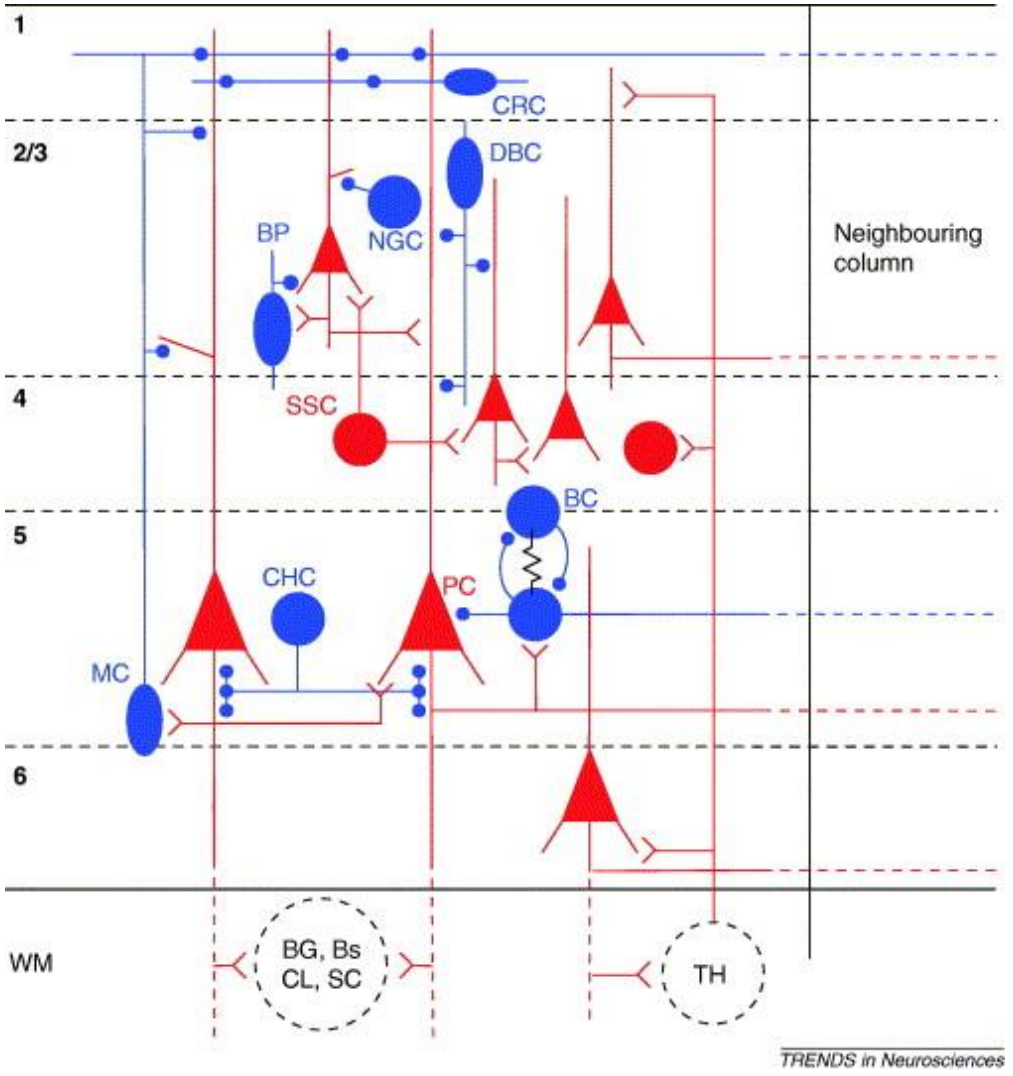
Preferred stimulus orientation of neurons at each location on cortex

Cortical Circuits

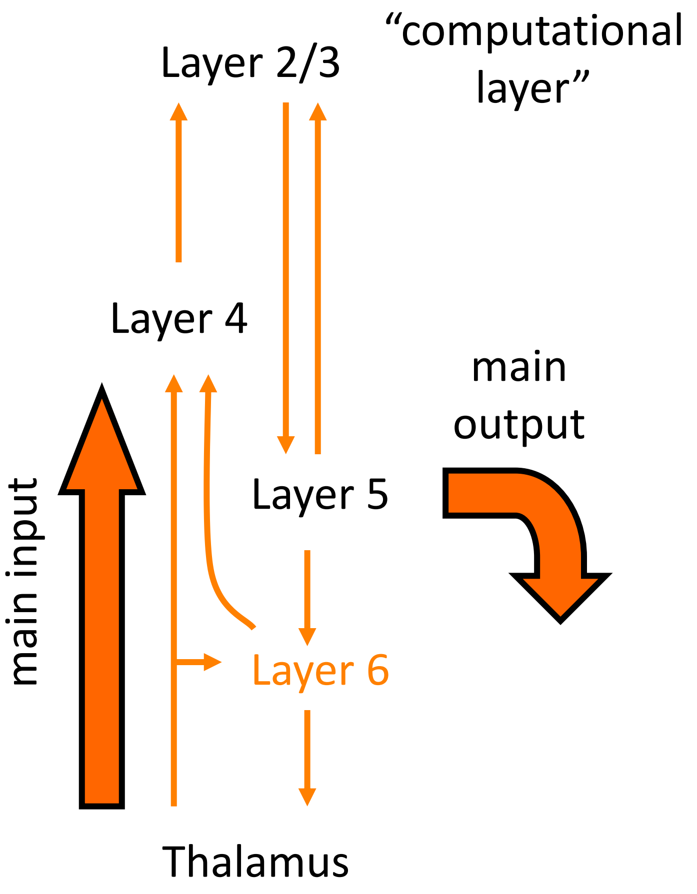


Cortical Circuits

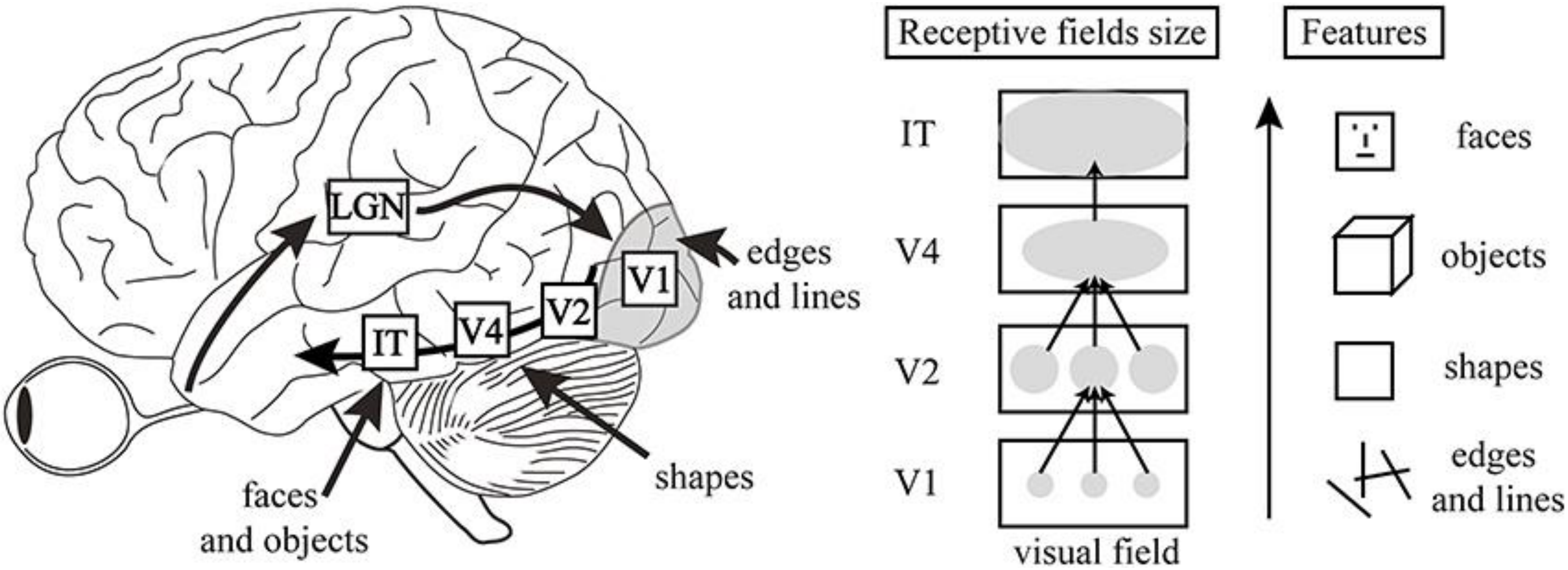
Wiring diagram of cortical circuit



Information flow through circuit

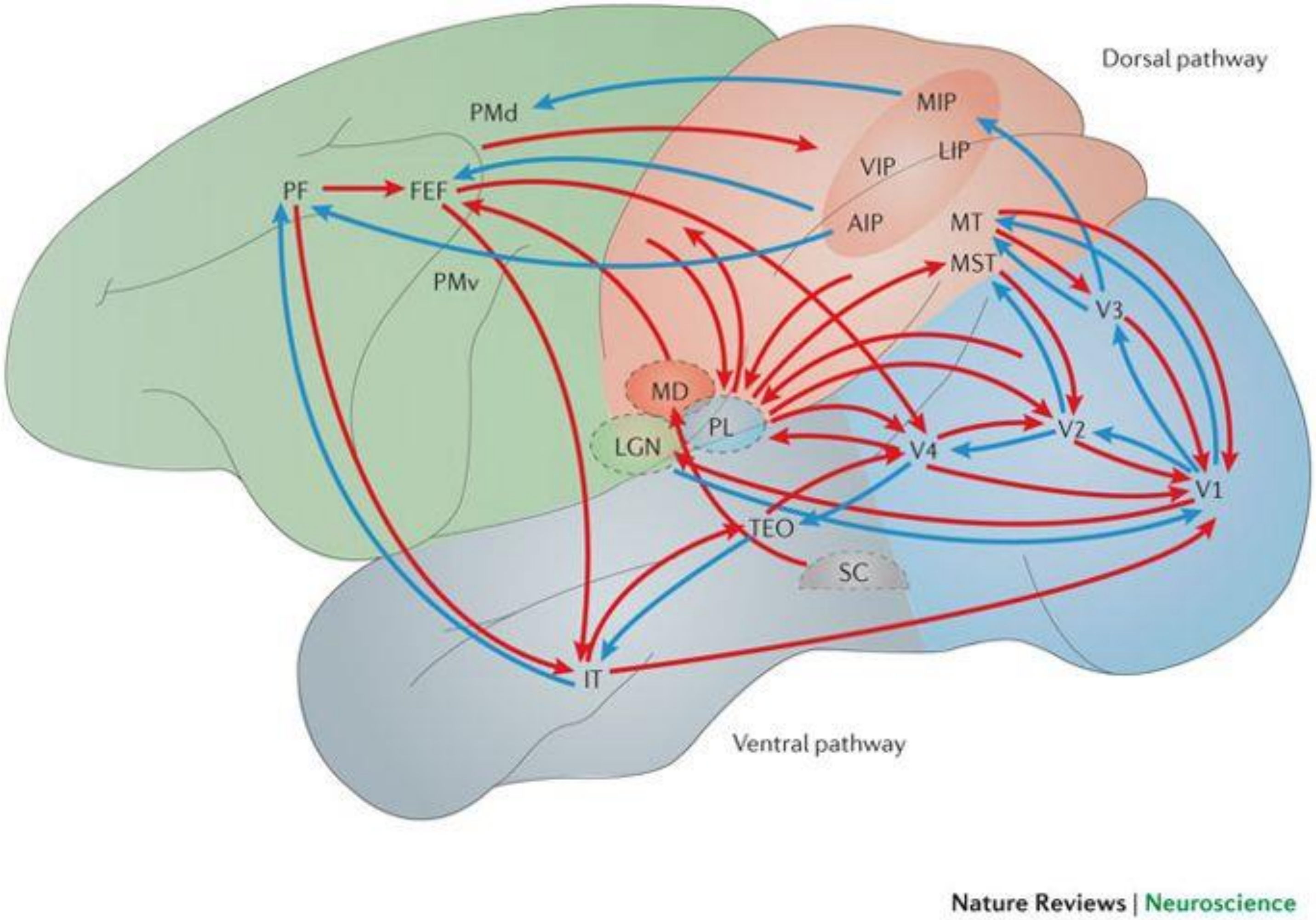


Feedforward Computations in the Visual System



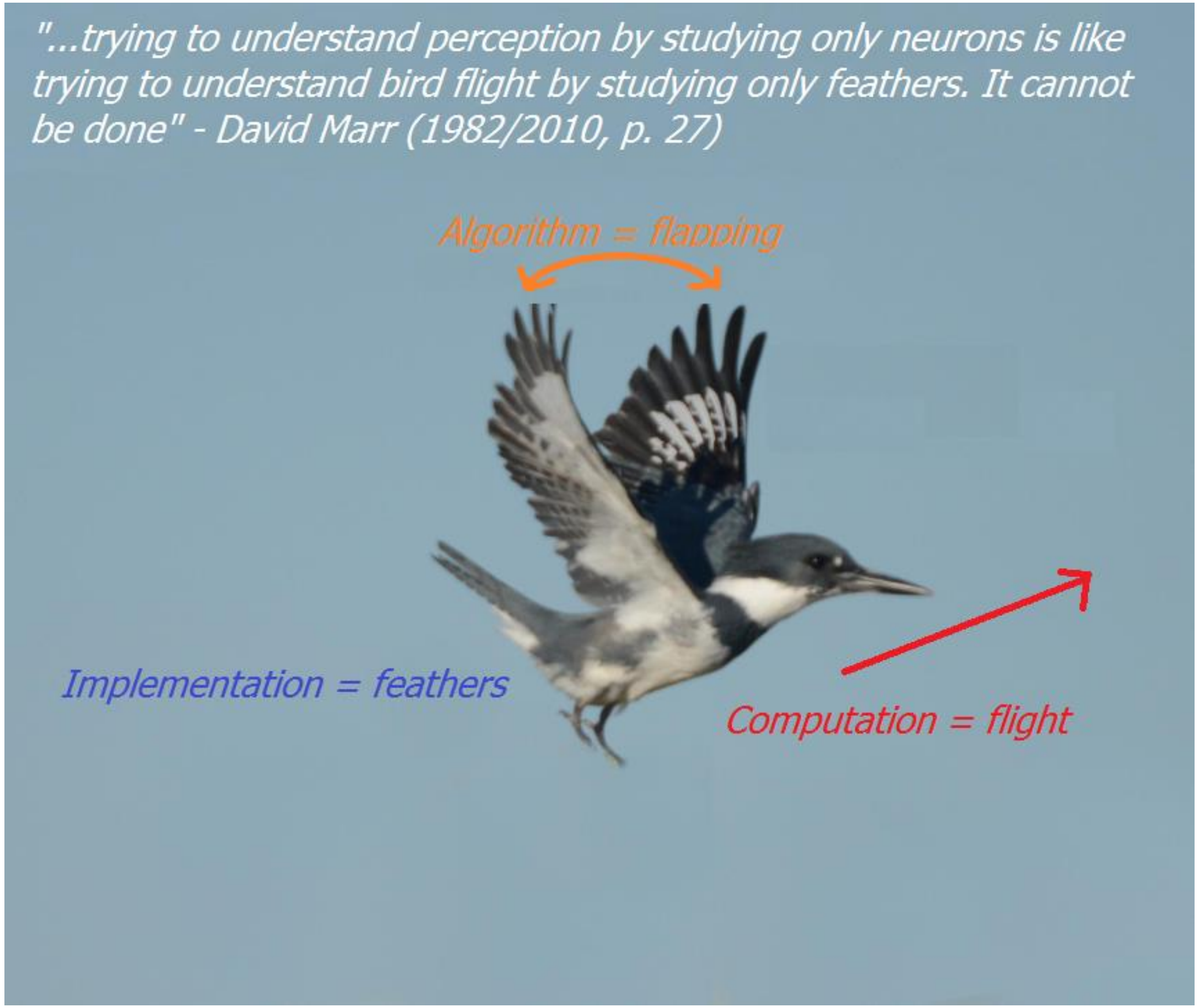
Feedforward computations can perform categorisation, object recognition, etc.

Feedforward, Lateral, and Feedback Pathways



The brain is not feedforward!

How Should We Study the Brain?



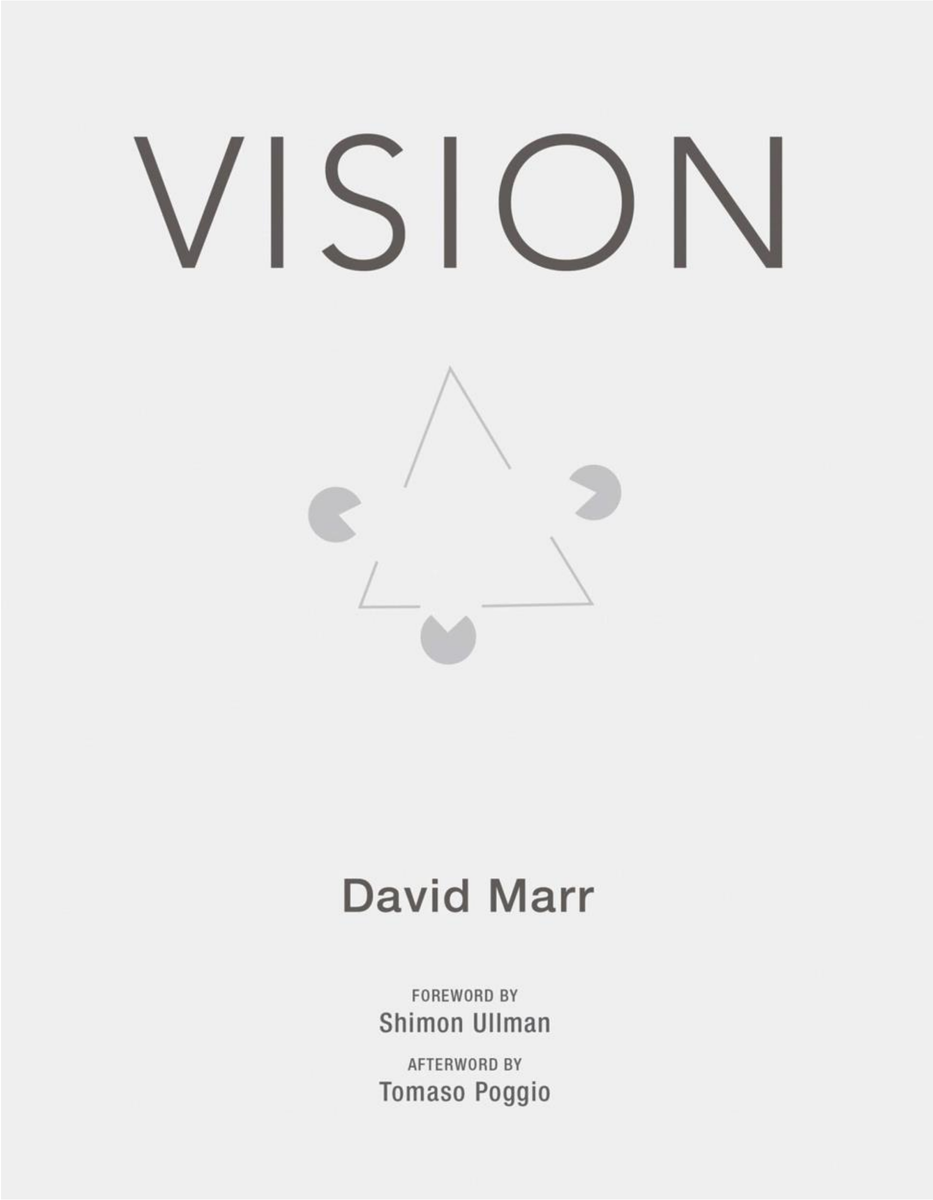
David Marr

Marr’s Three Levels

Computational theory	Representation and algorithm	Hardware implementation
What is the goal of the computation, why is it appropriate, and what is the logic of the strategy by which it can be carried out?	How can this computational theory be implemented? In particular, what is the representation for the input and output, and what is the algorithm for the transformation?	How can the representation and algorithm be realized physically?

Figure 1–4. The three levels at which any machine carrying out an information-processing task must be understood.

“…trying to understand perception by studying only neurons is like trying to understand bird flight by studying only feathers: It just cannot be done. In order to understand bird flight, we have to understand aerodynamics; only then do the structure of feathers and the different shapes of birds' wings make sense”

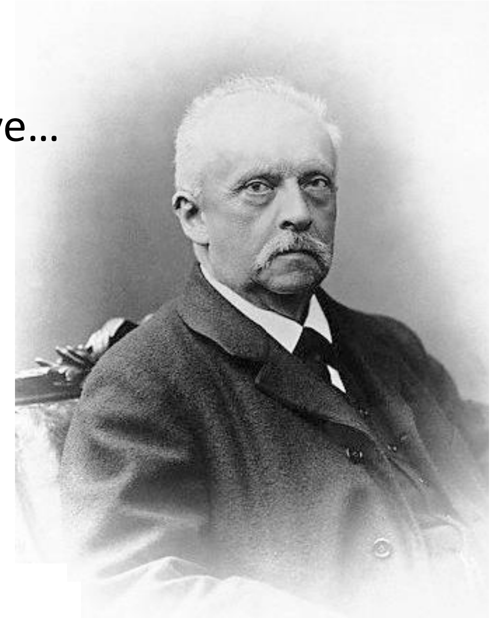


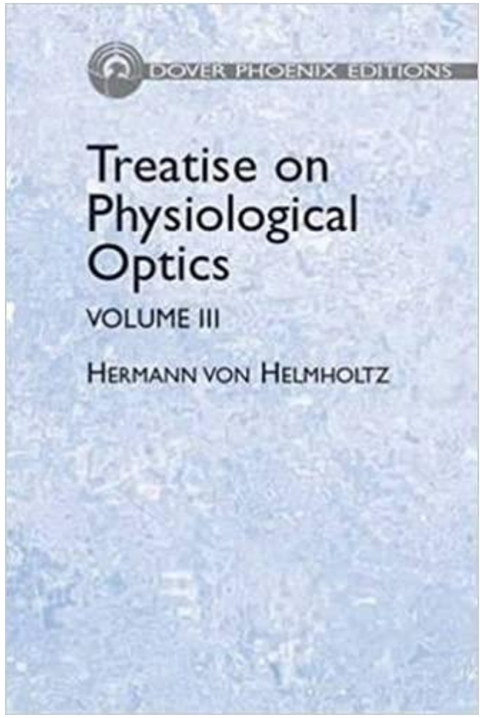
Perception as Inference

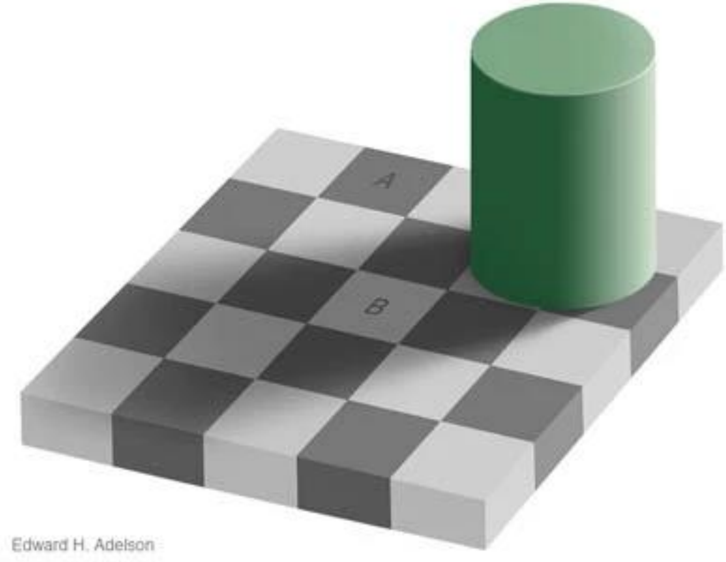
Helmholtz: Perception is “unconscious inference”

Our brain infers the likely physical causes of the sensory inputs we receive…

Other statements: “Perceptions are hypotheses” (Richard Gregory), “Perception is controlled hallucination” (unknown attribution)







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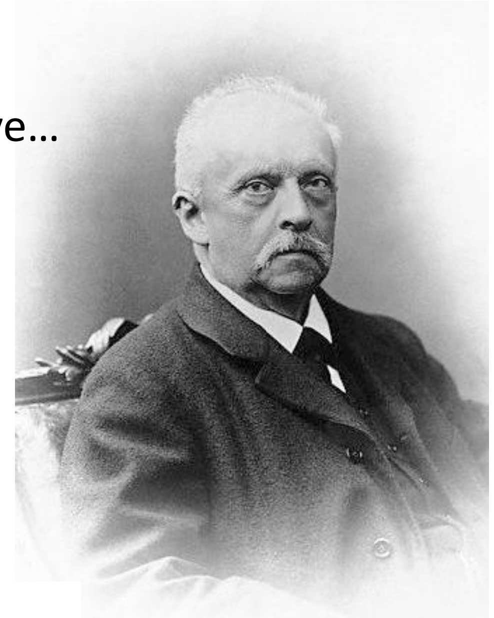
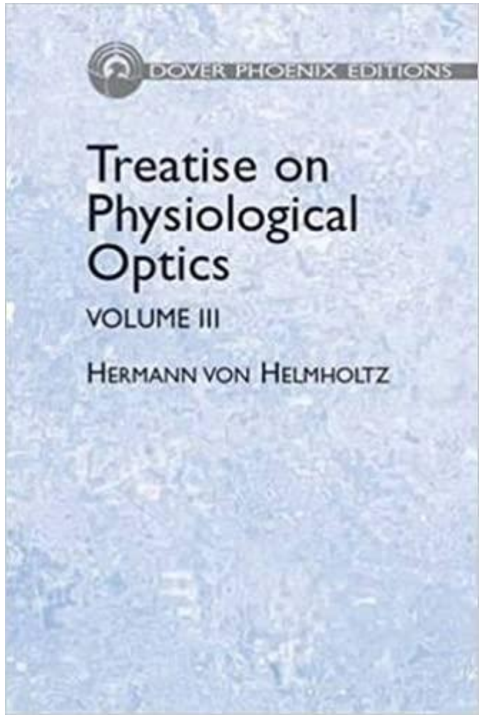
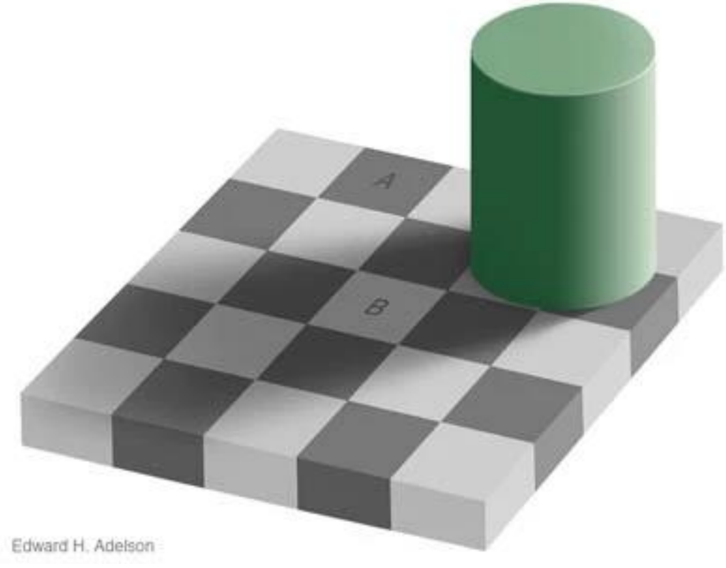
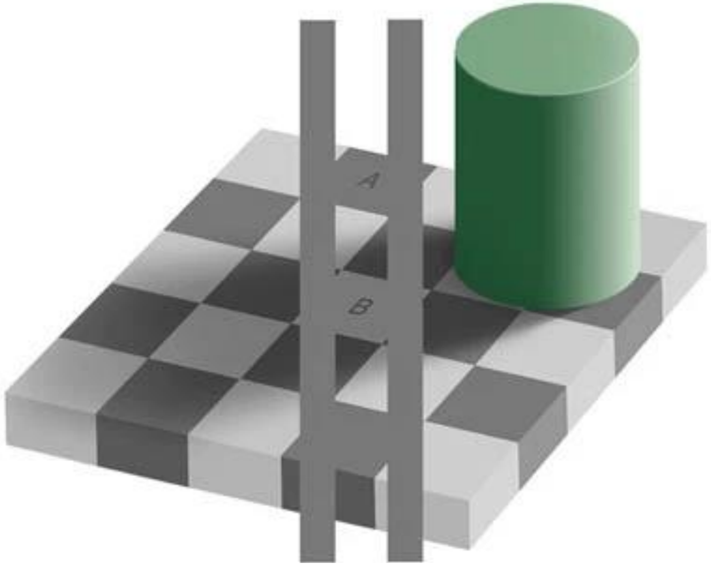
Unconscious prior beliefs about surface reflectance properties overcome raw sense data to construct an interpretation of the colour of the surface being illuminated….







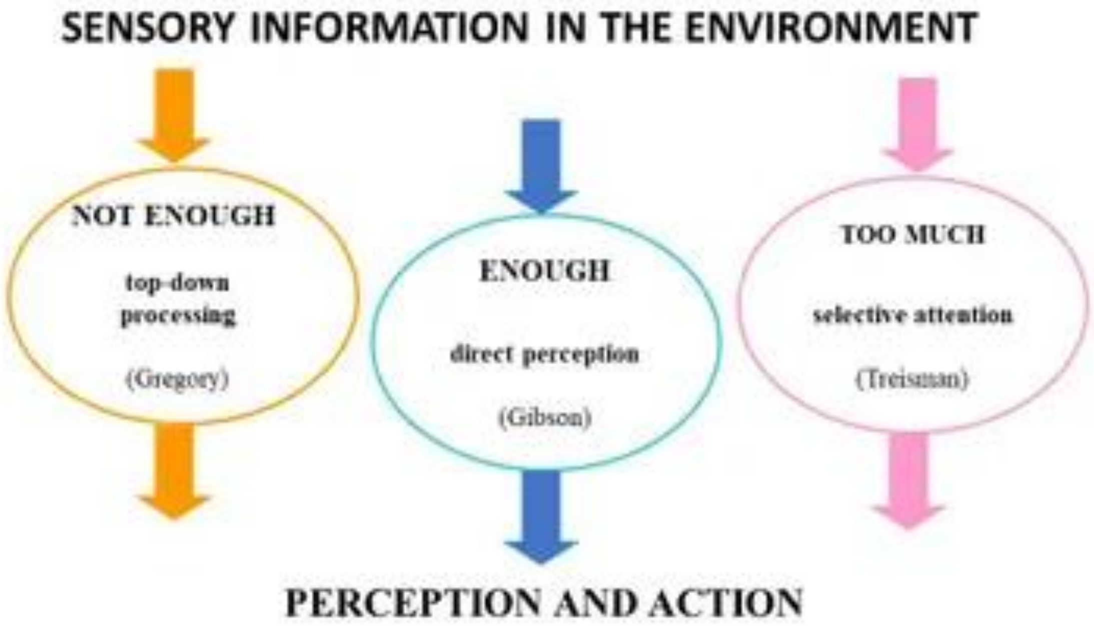


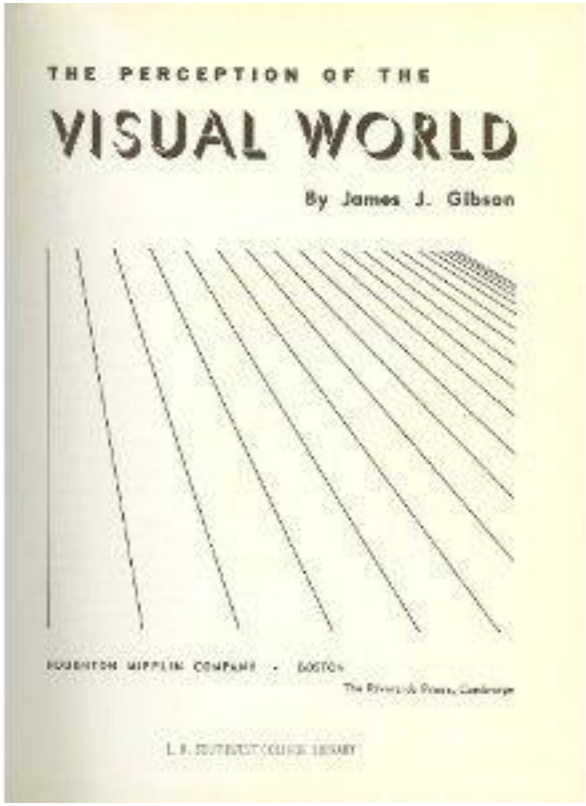
Alternative Theory: Direct Perception

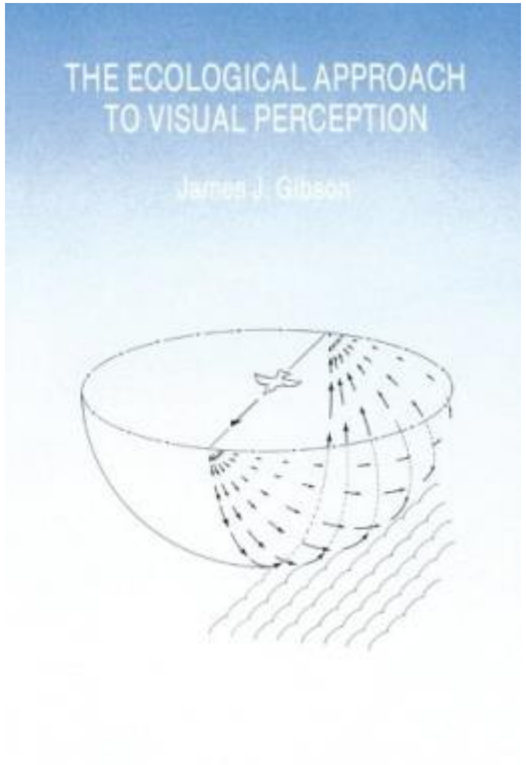
JJ Gibson: We perceive the world as it is – movement of sense organs provides enough information to specify our environment (no “top-down” inference required)

Perception and action are deeply intertwined – we perceive our environment in terms of “affordances” for action (e.g., objects that can be manipulated)

Predict sensory consequences of actions using “motor-efference copies”
(did I move or did the world move?)







Summary

- The brain evolved for perception and action
- The brain is formed of networks of neurons, which self-organise through development and learning to process information and perform computations (cognition)
- The brain is divided into different systems: cortical/subcortical, sensory/motor/cognitive/affective
- In each system, we find “representations” of the outside world (or of internal mental states)
- Perception may be viewed as a form of inference
- How do neurons work? How do networks perform computations? How are neural representations formed? Subject of upcoming lectures!