



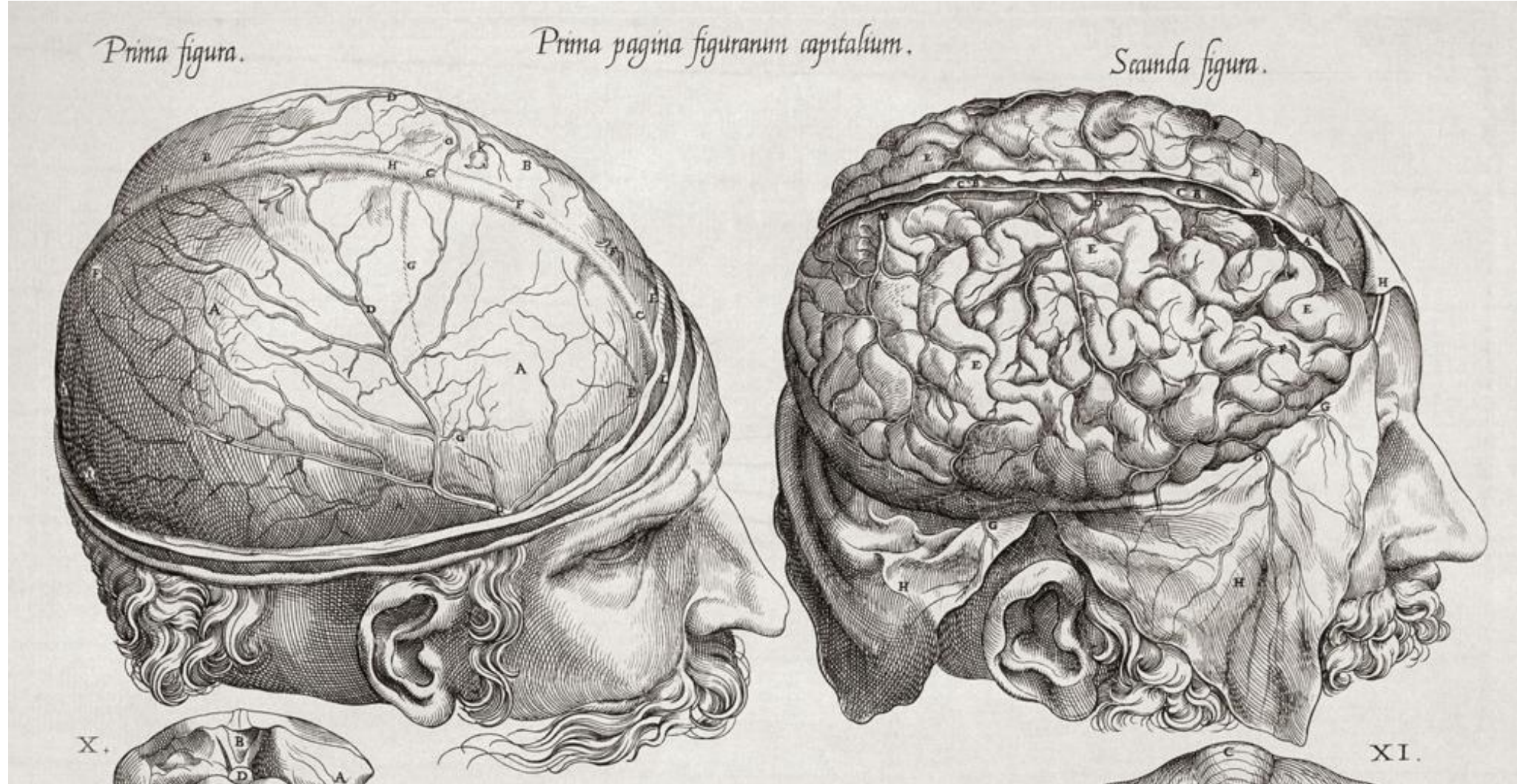
Introduction to Neuroscience

Angus Chadwick, ANC

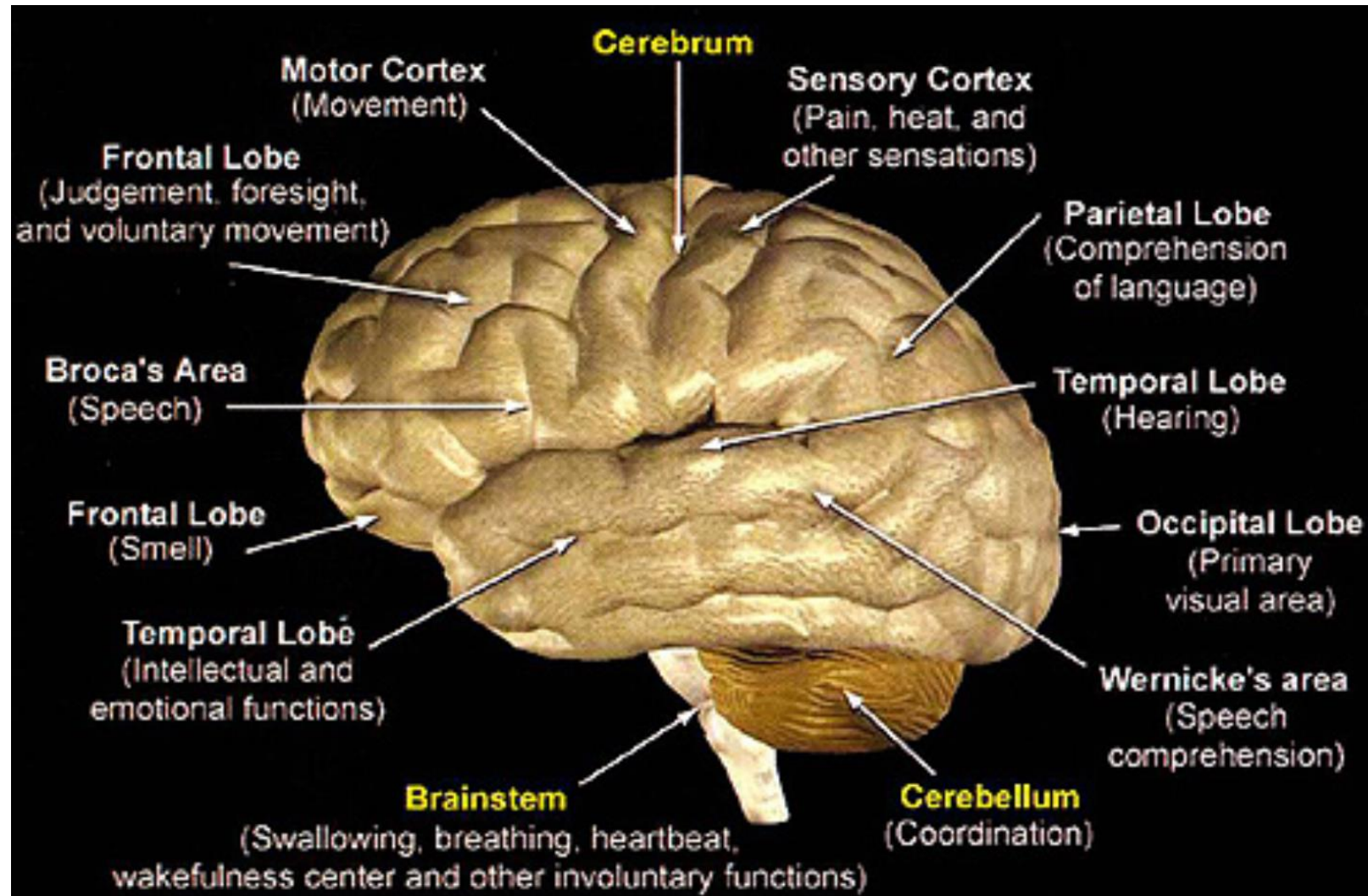
School of Informatics, University of Edinburgh, UK

Computational Neuroscience (Lecture 2, 2024/2025)

The Brain



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)

Damage to hippocampus (memory region)

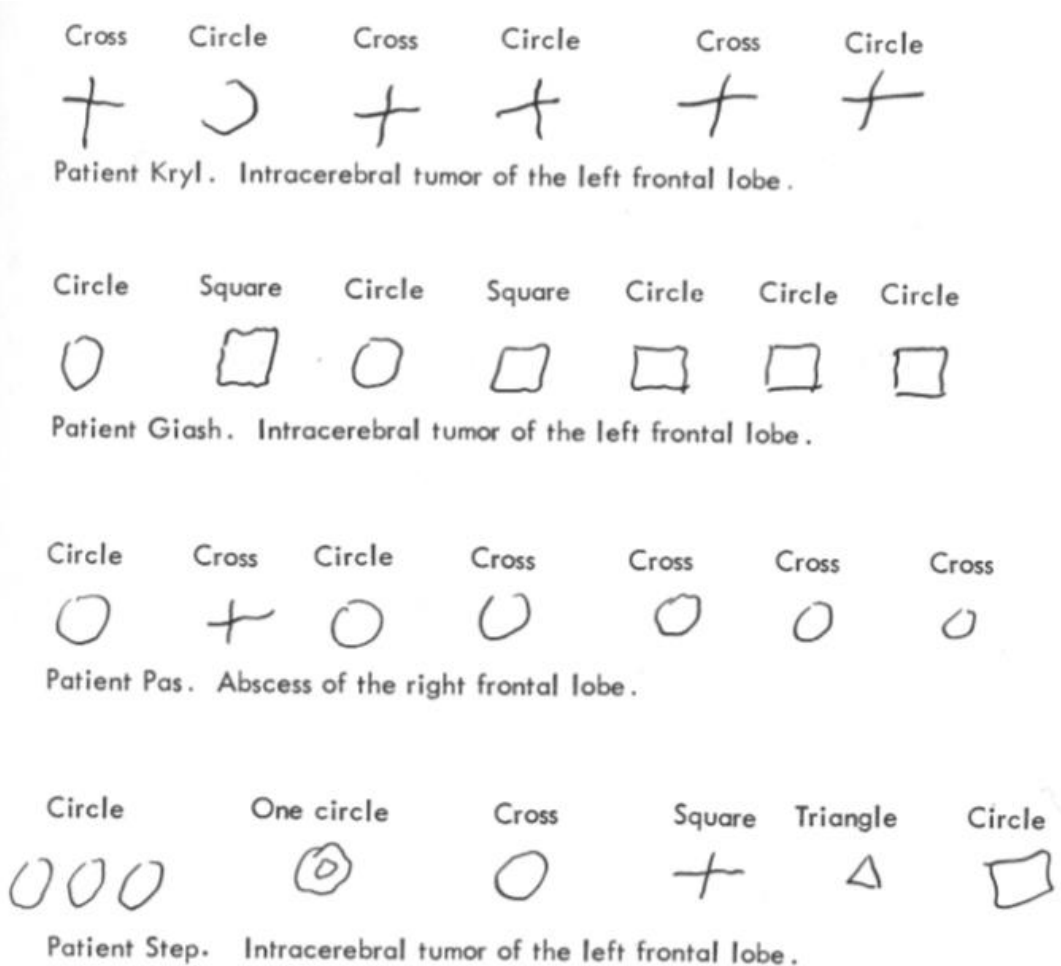


FIGURE 66 Disturbance of the performance of single tasks as a result of pathological inertia of action in patients with extensive lesions of the frontal lobes.

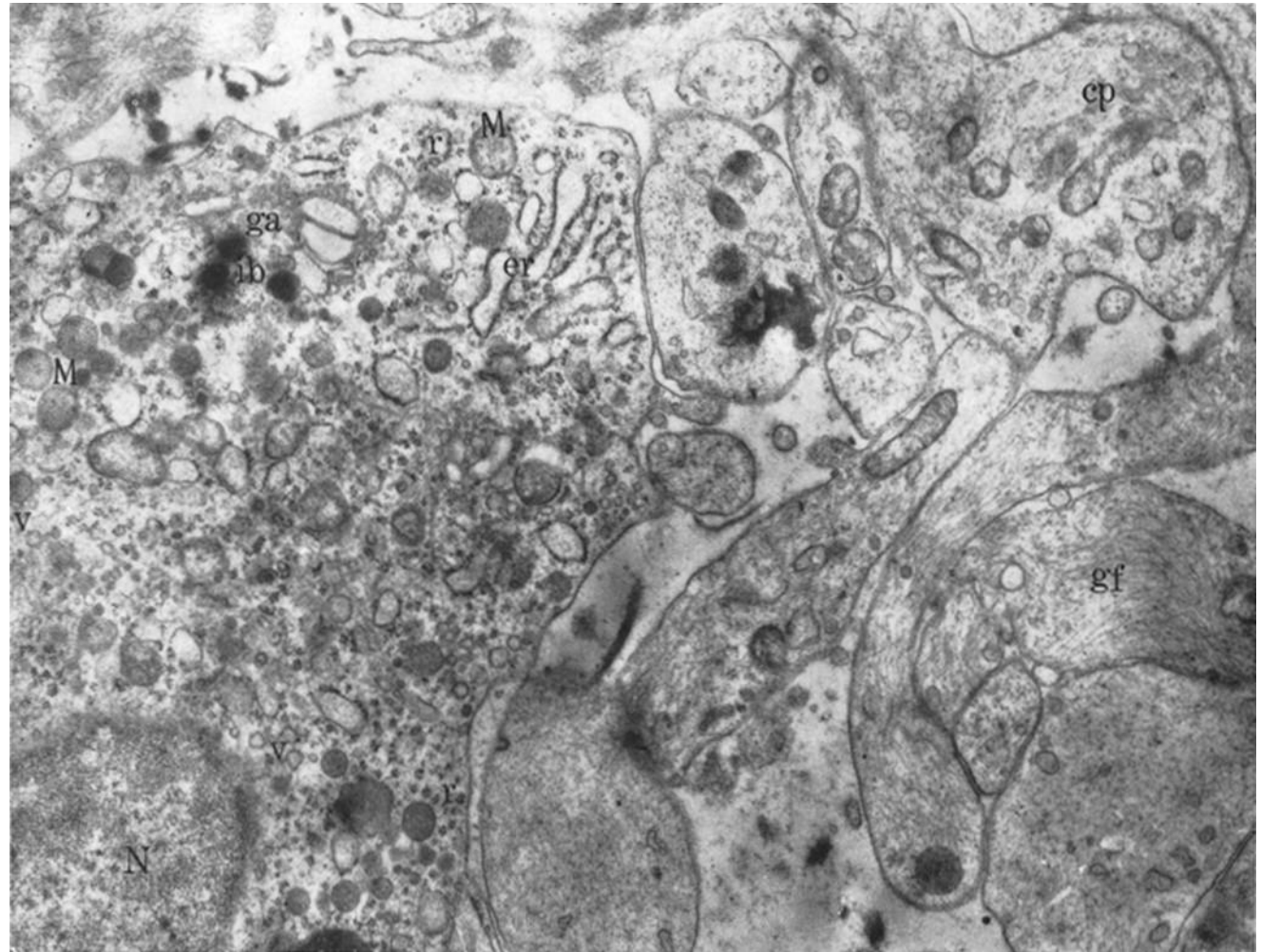
The Brain – In Numbers

10^{11} neurons

10^3 connections per neuron

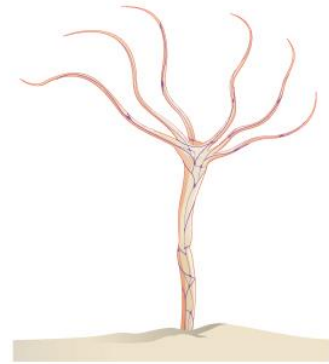
10^{14} connections (synapses)

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

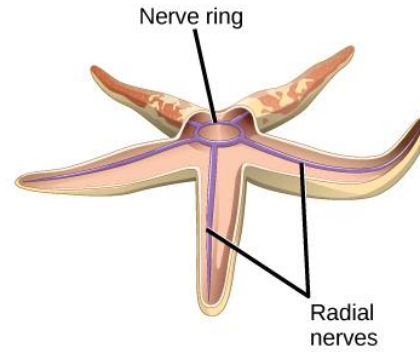


Electron microscopy scan of human brain tissue

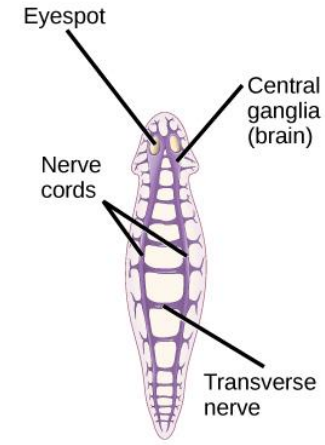
Evolution of the Nervous System



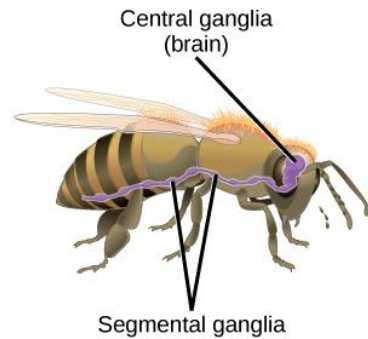
(a) Cnidarian (hydra)



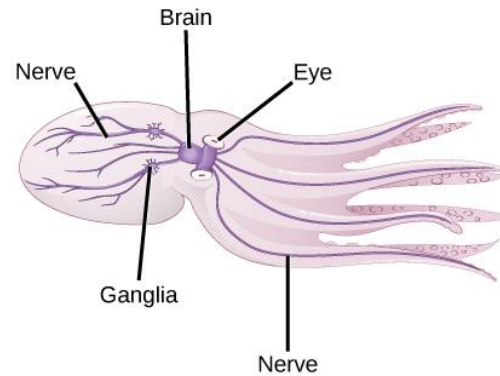
(b) Echinoderm (sea star)



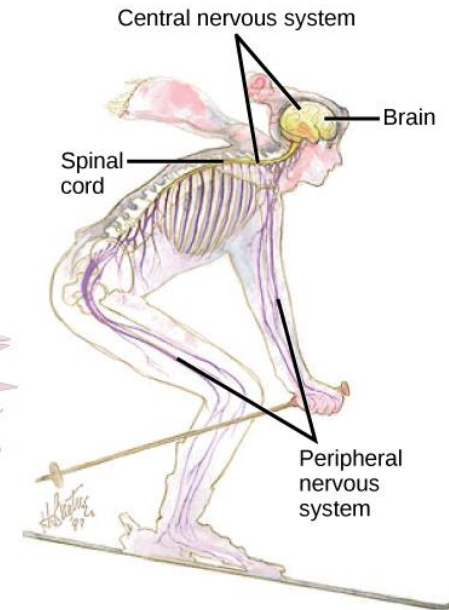
(c) Planarian (flatworm)



(d) Arthropod (bee)



(e) Mollusk (octopus)



(f) Vertebrate (human)

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...

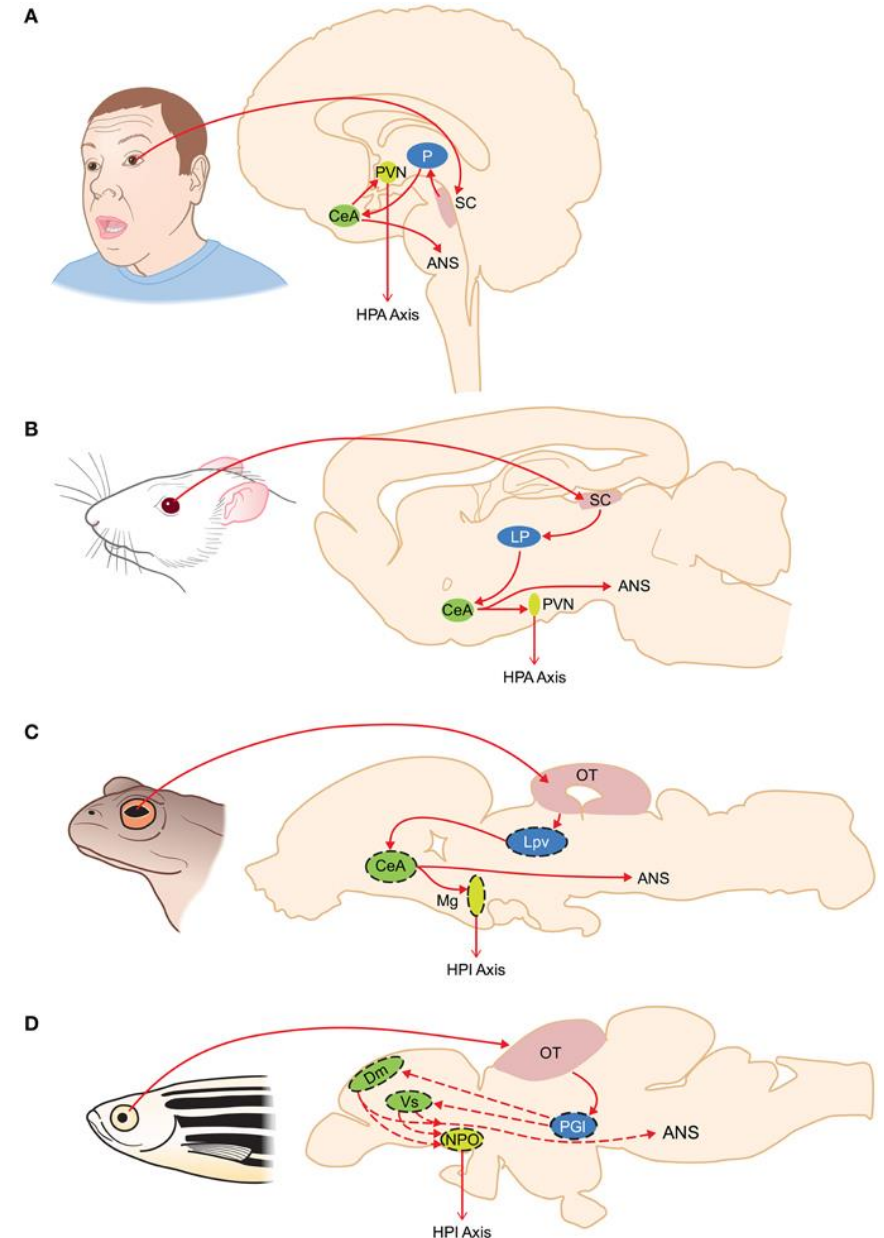
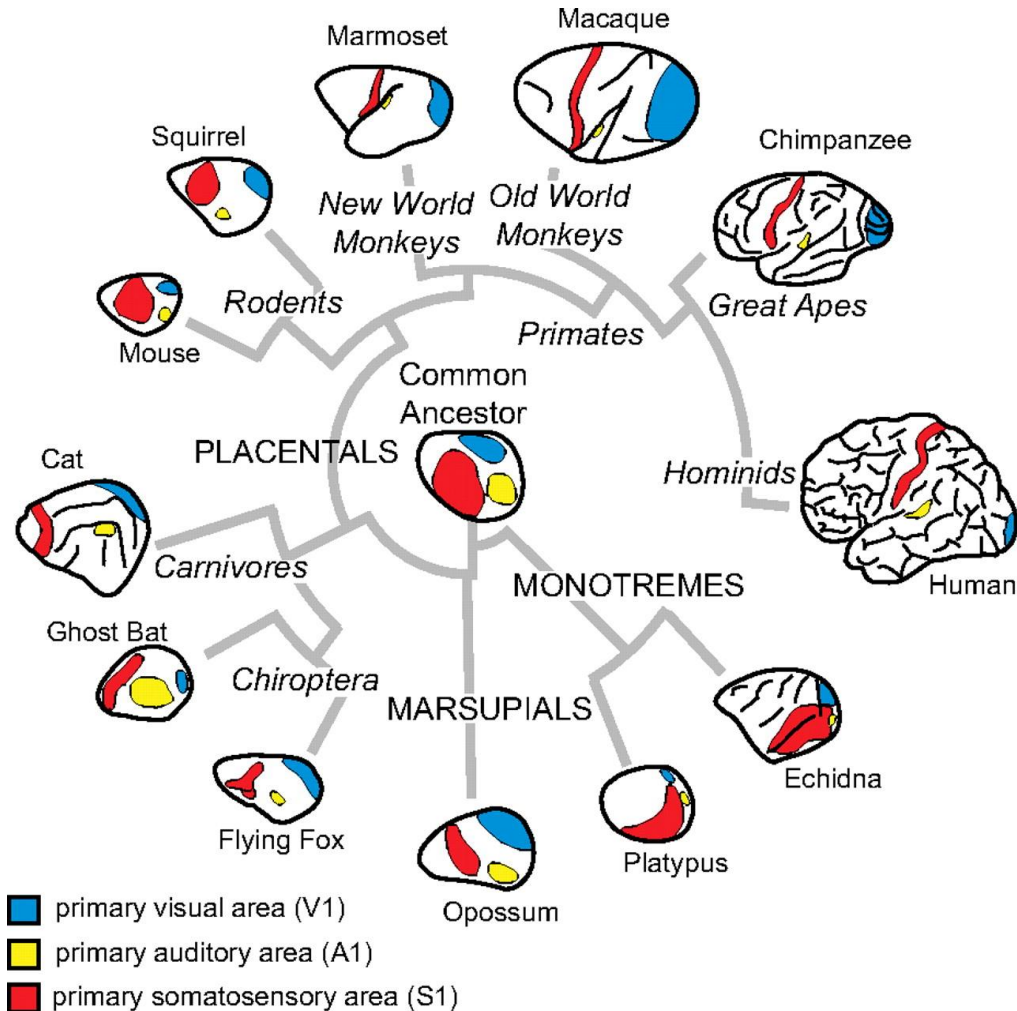
UNBELIEVABLE FACTS



The Tunicate (sea squirt), once finding a suitable rock, will attach itself for life. At this point, it eats its own brain, deciding that it no longer needs it.

Evolution of the Mammalian Cortex

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



What Challenges do Brains Face?

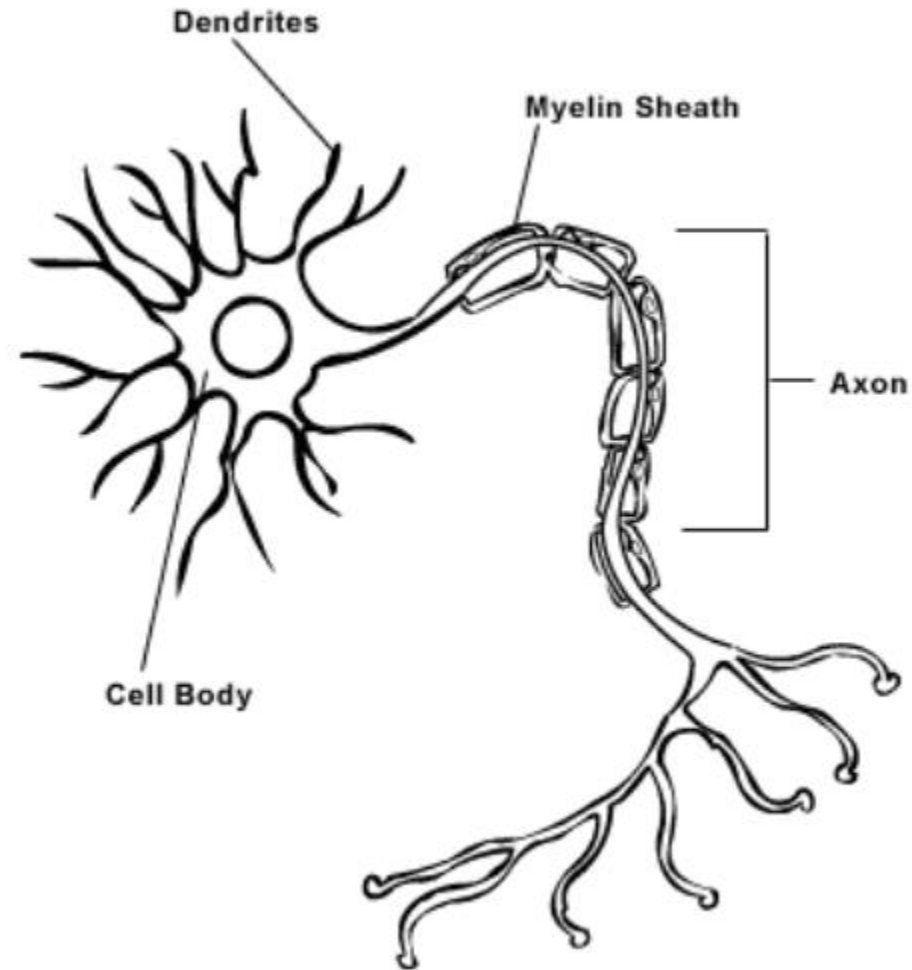
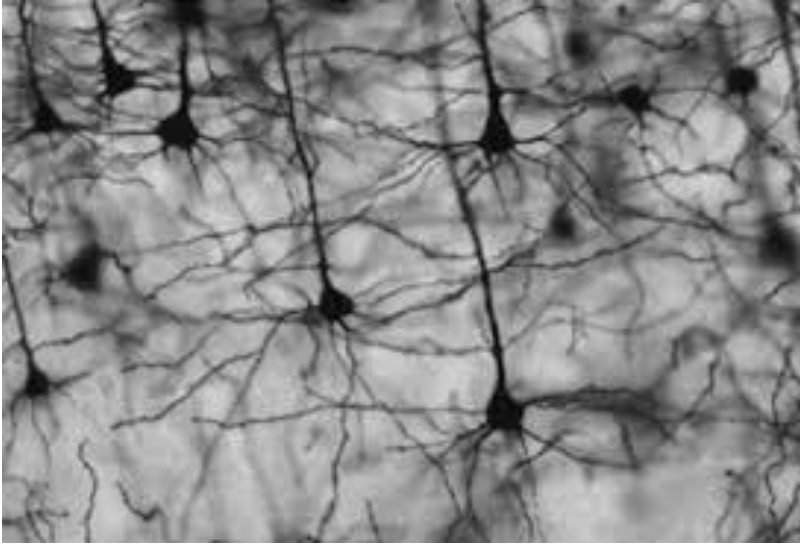
What challenges do brains face?

- **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 that matter for behaviour 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 (not enough genes to specify all connections in most species)

Neurons



Brain is made of **neurons** (and glial cells!)

Dendrites: receive inputs from other neurons

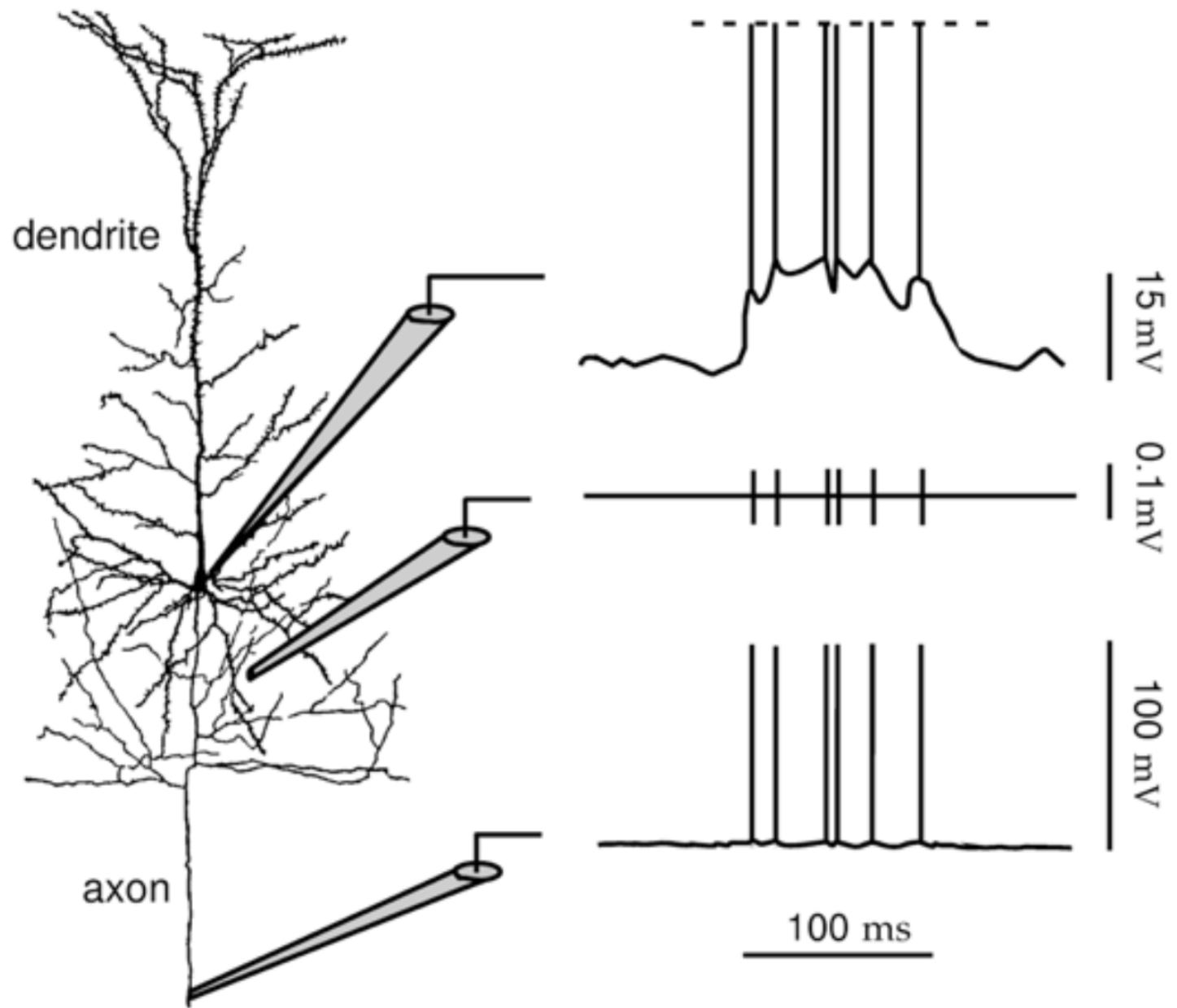
Soma (cell body): Collects signals from dendrites

Axon: sends signals to other neurons

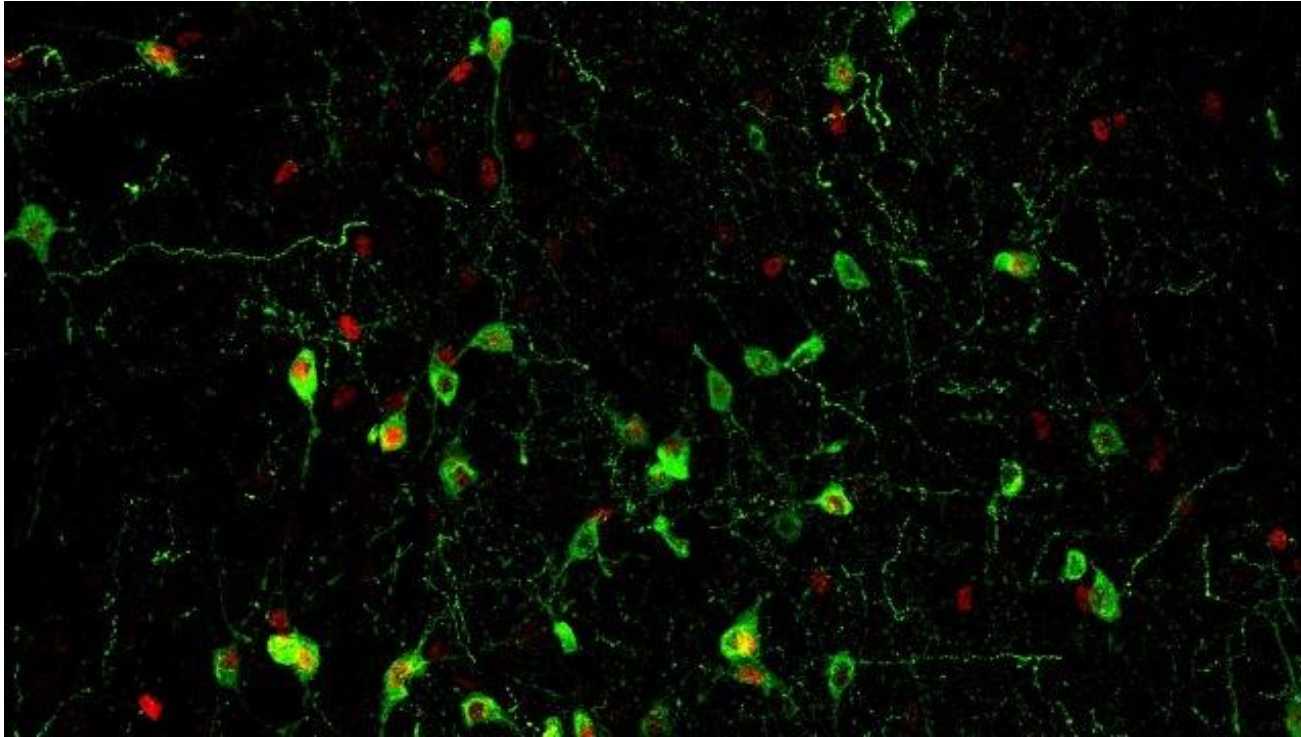
Synapse: Connection from axon to dendrite (usually)

Action potential (spike): Pulse signal sent down axon to another neuron (unit of communication)

Excitatory vs Inhibitory neurons: activate vs inactivate other neurons



Networks/Circuits of Neurons

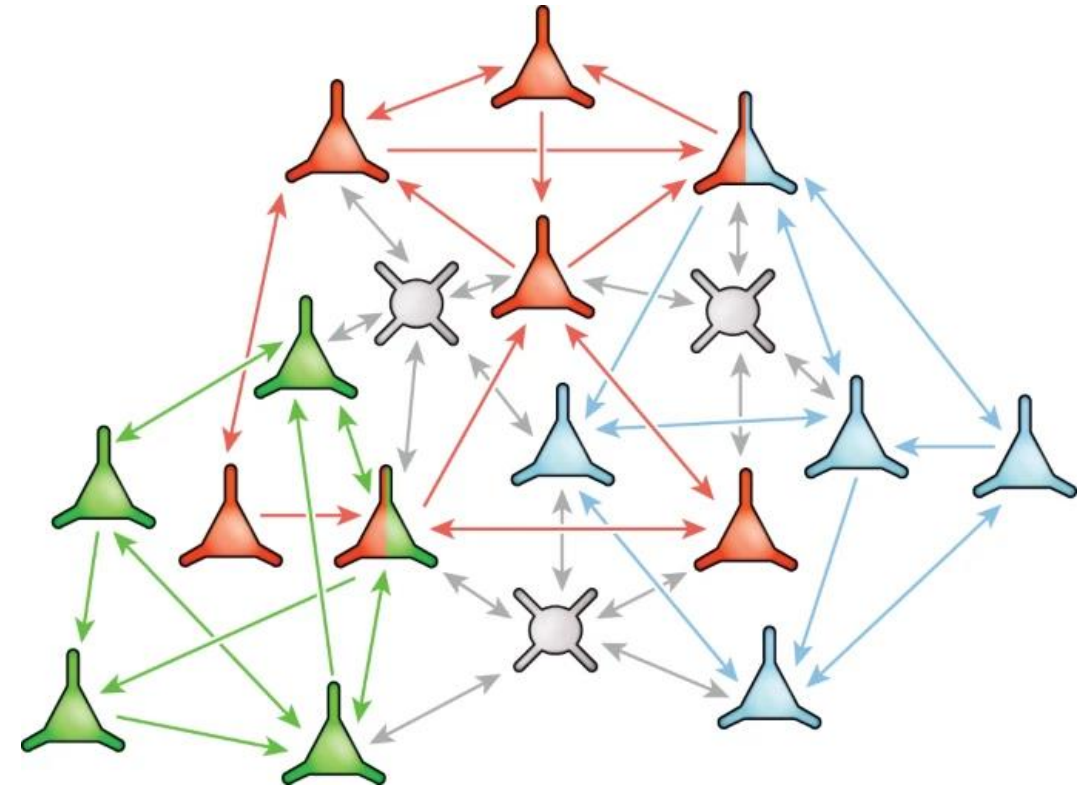


Staining of neuron cell bodies and axons/dendrites

Neurons form networks/circuits via synaptic connections

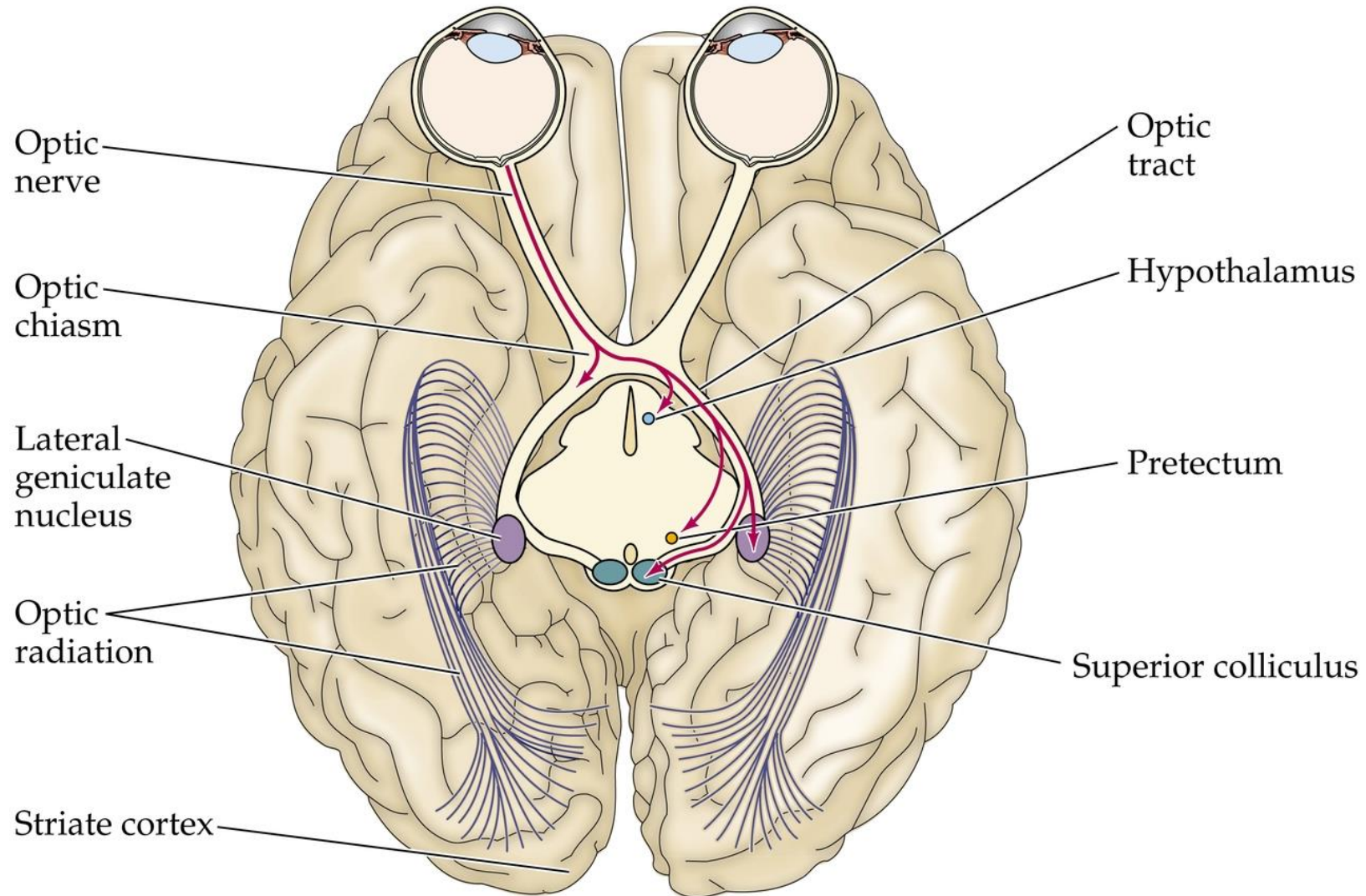
The collective behaviour of a network of neurons may be complex

It is thought that these circuits carry out particular computations

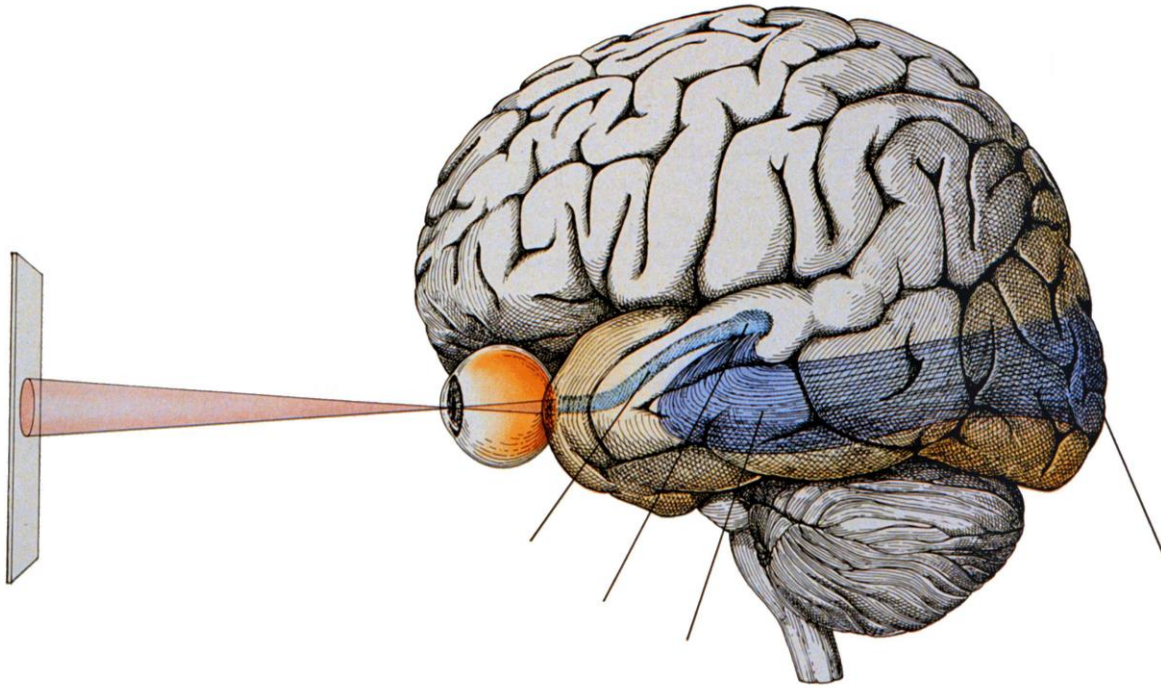


Schematic of different neuron types wired together to form a network/circuit

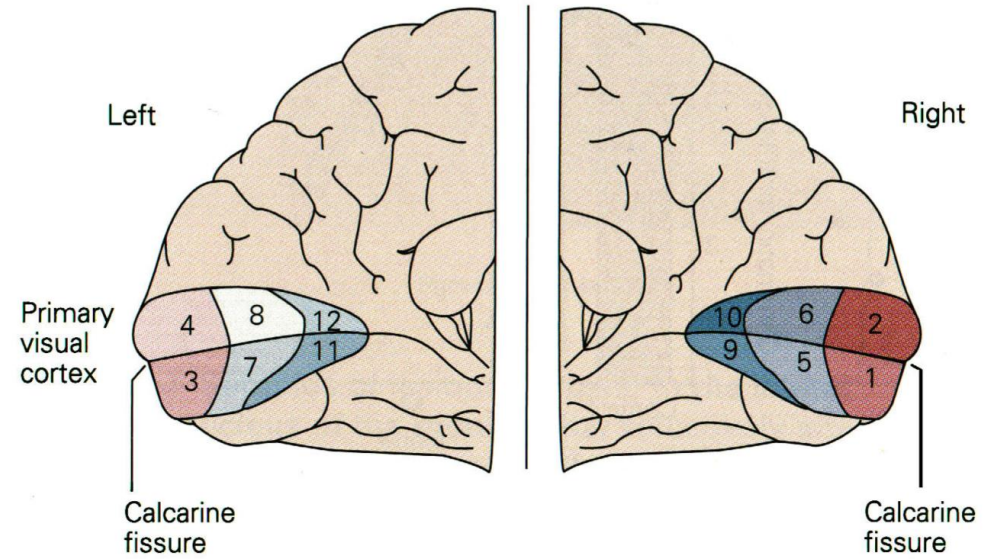
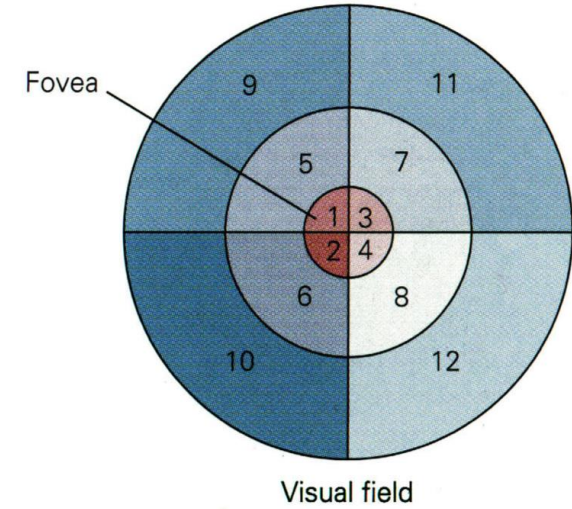
The Early Visual System



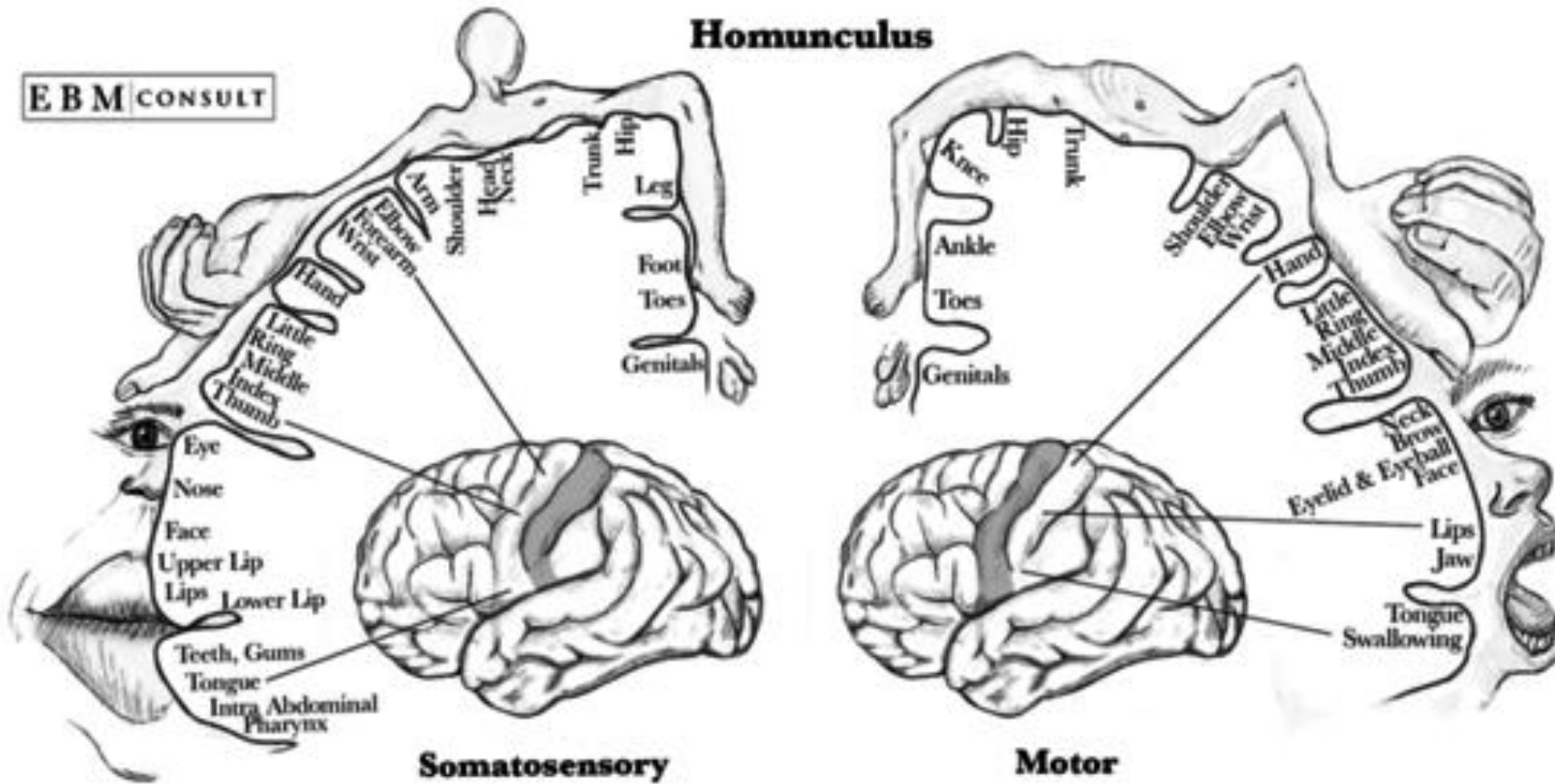
Representation of Visual Space



Retinotopic Organization



Representations of Bodily Space



Representations in Single Neurons – Tuning Curves

Tuning Curves: Vary stimulus and plot mean response of neuron

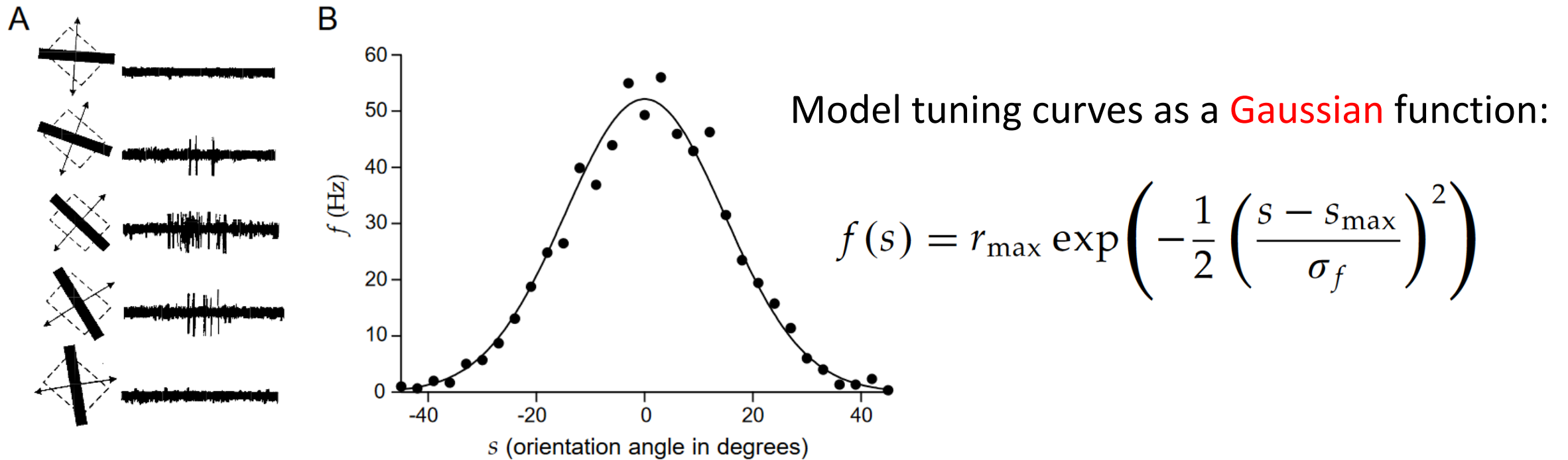
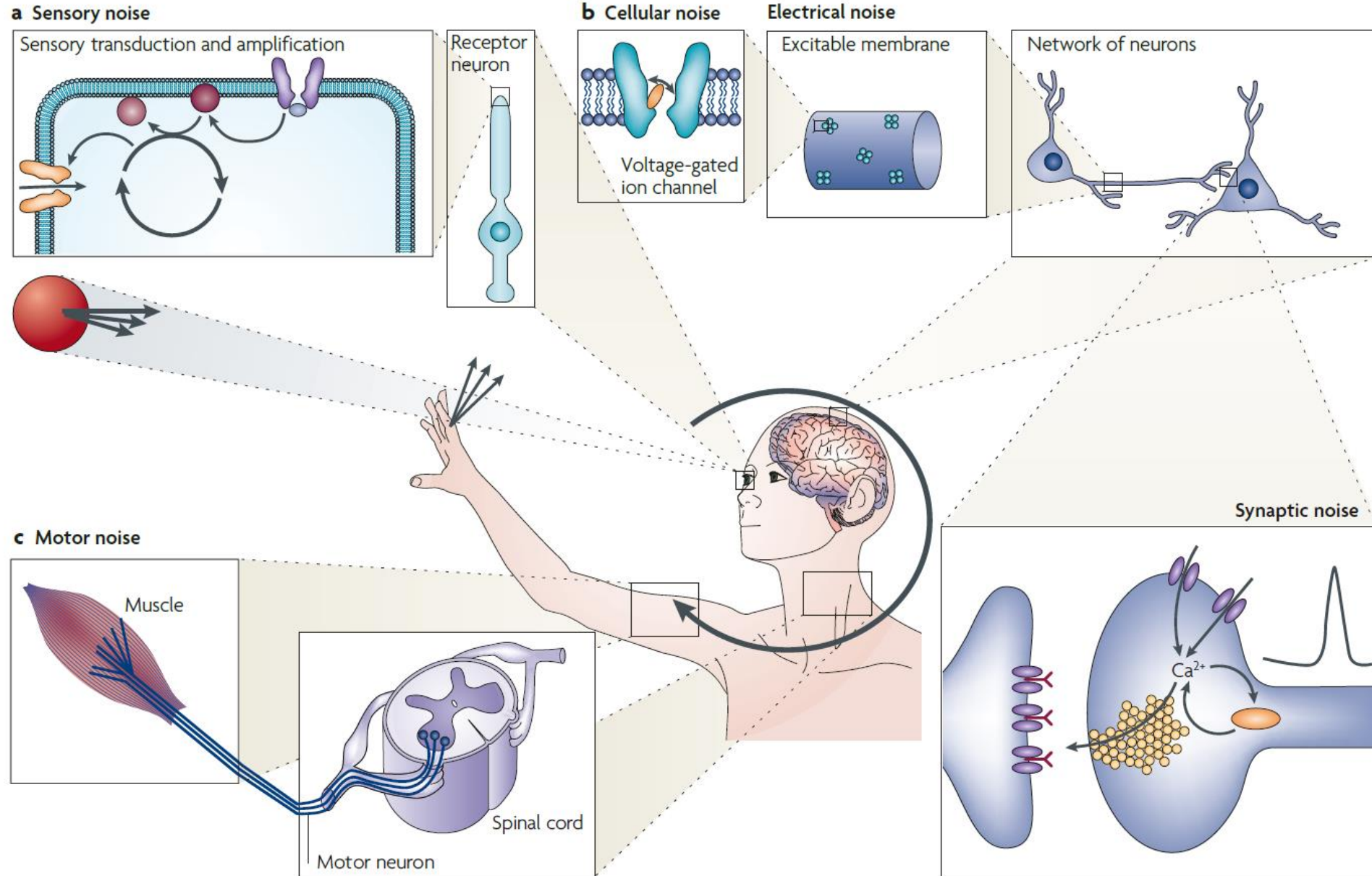


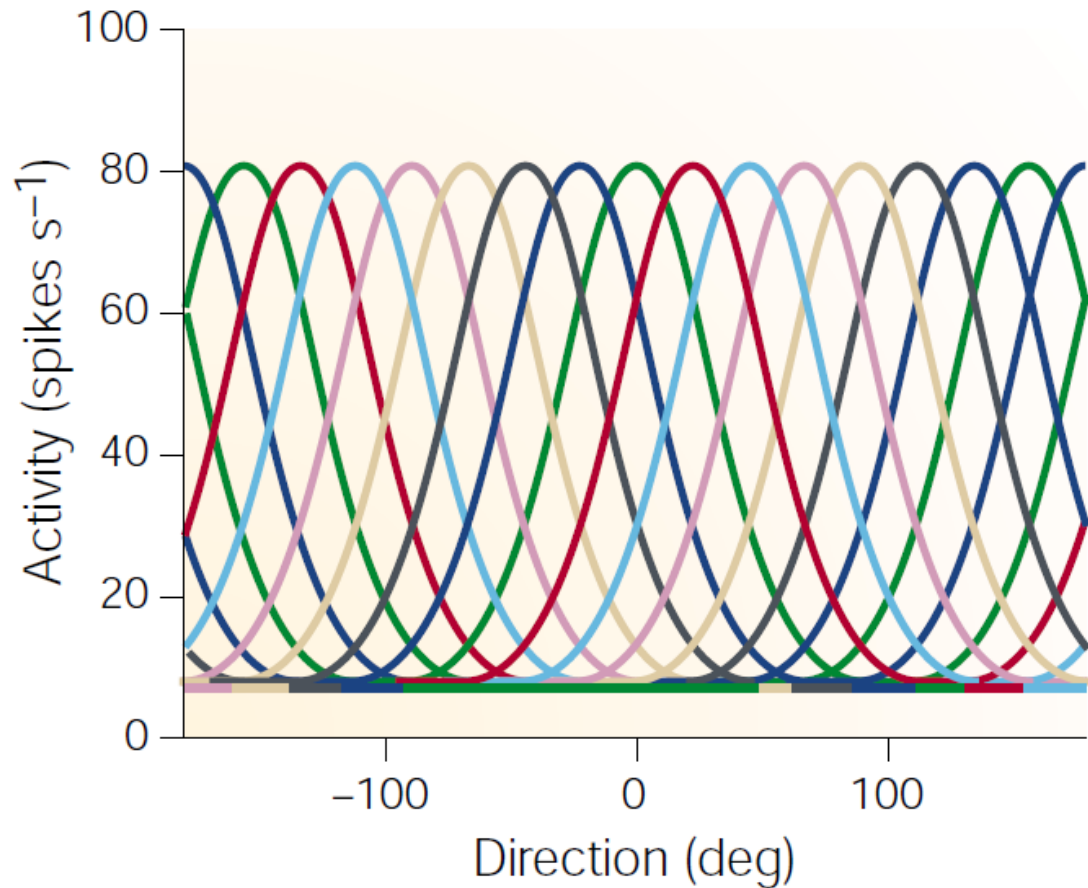
Figure 1.5 (A) Recordings from a neuron in the primary visual cortex of a monkey. A bar of light was moved across the receptive field of the cell at different angles. The diagrams to the left of each trace show the receptive field as a dashed square and the light source as a black bar. The bidirectional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

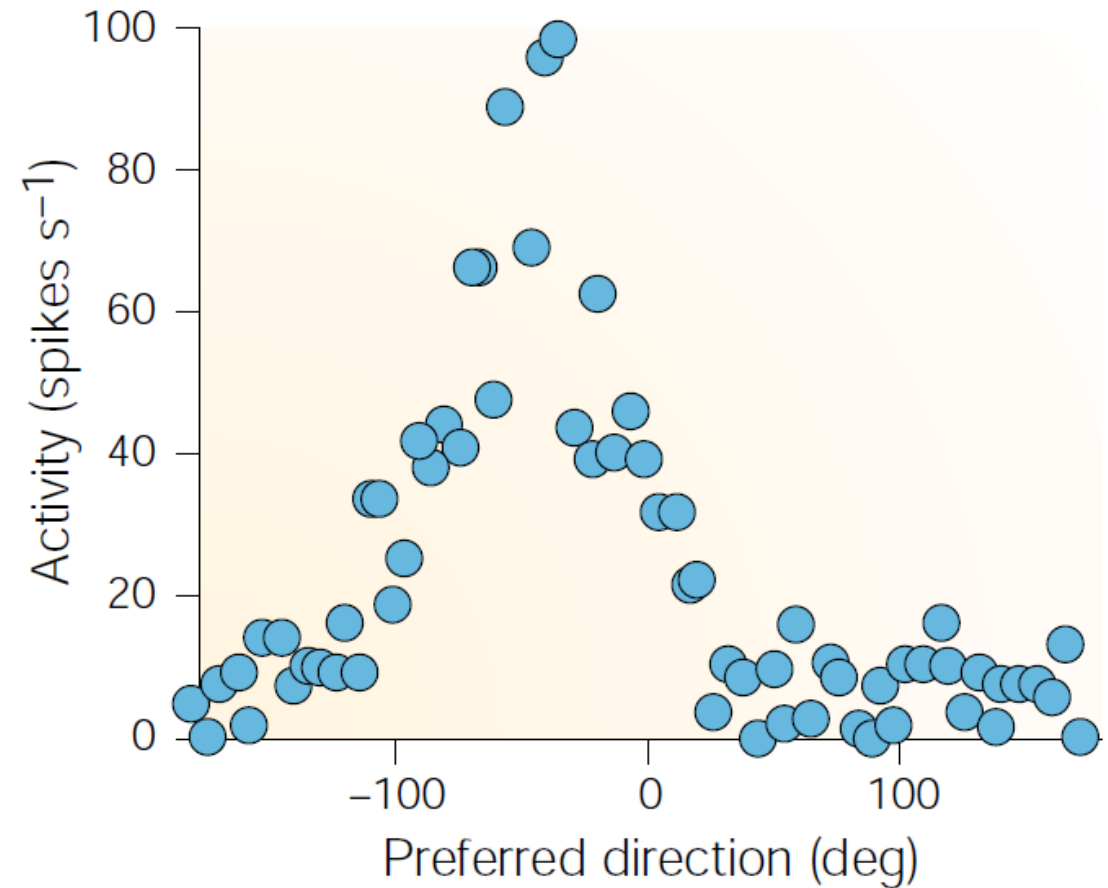


Representations in Populations of Neurons

Many neurons, each with a different preferred orientation

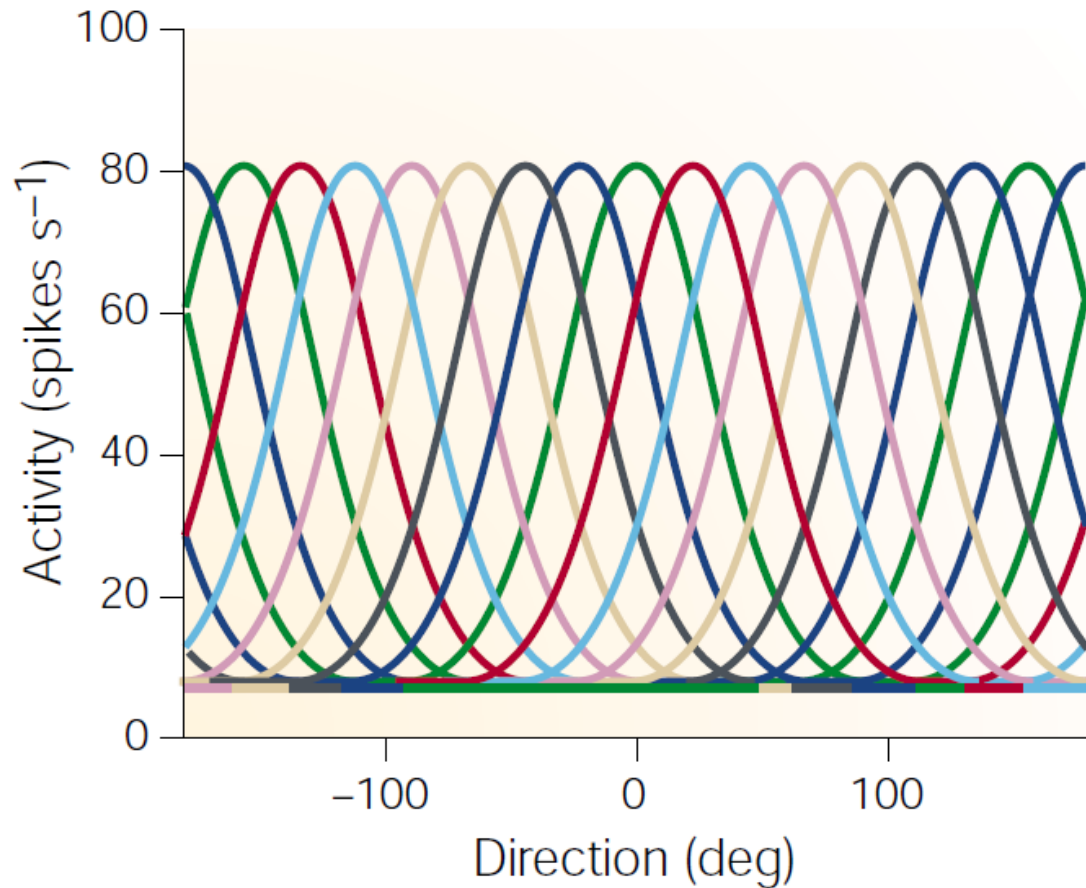


Noisy response of population to a single stimulus presentation

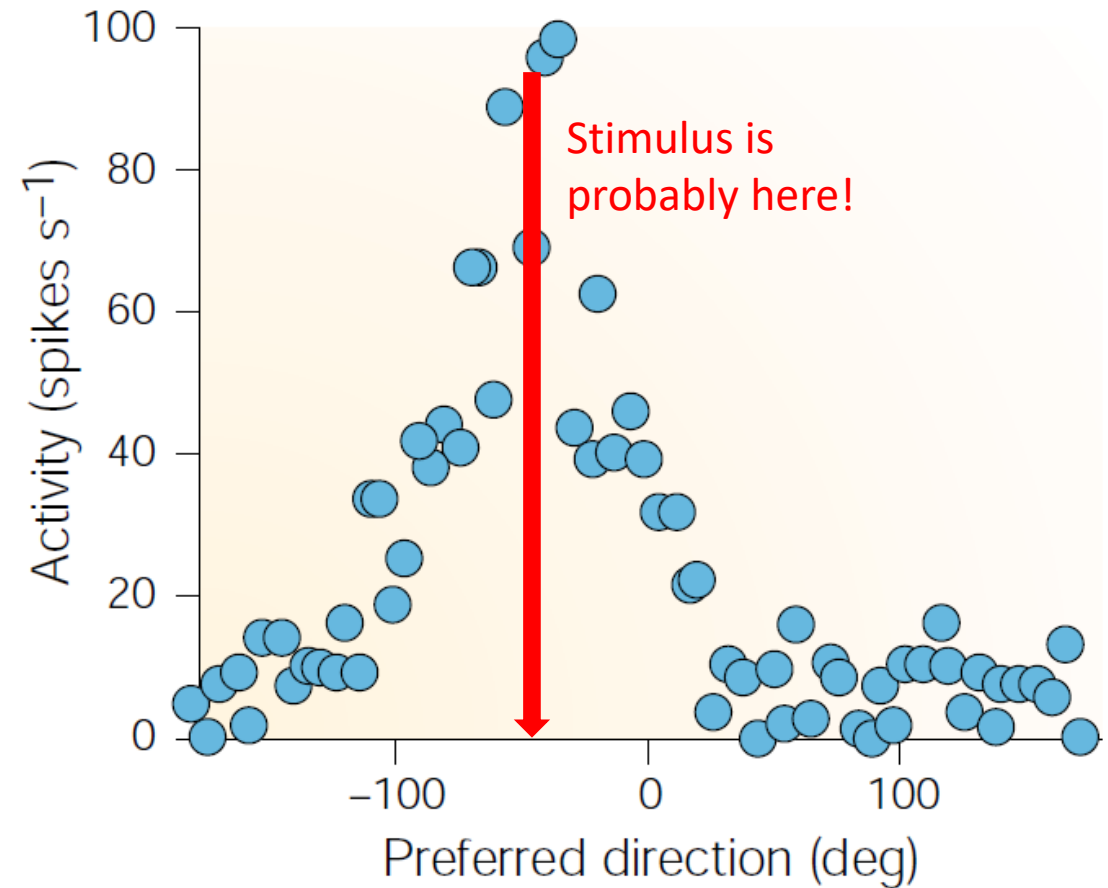


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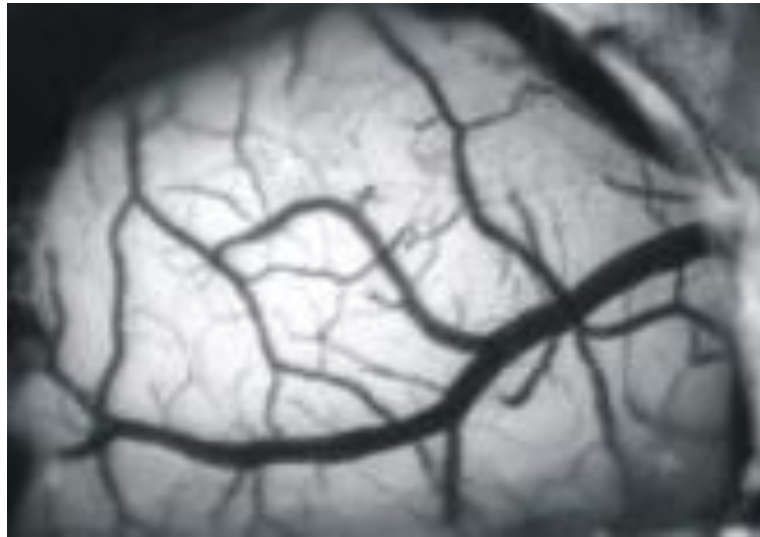


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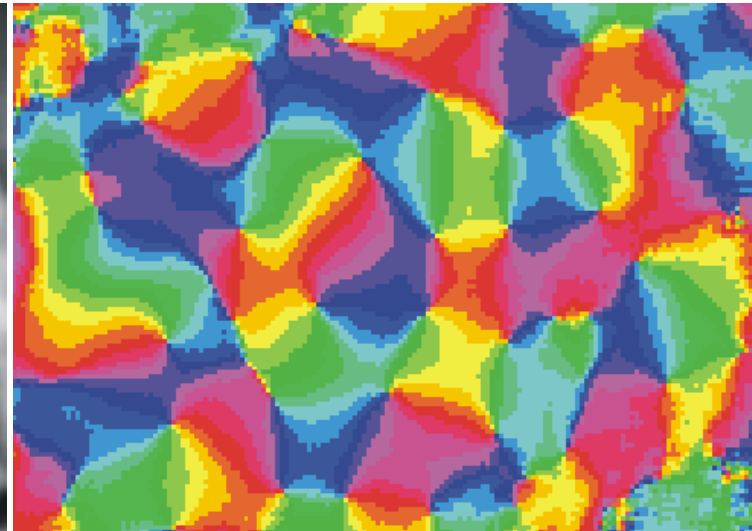


Representations in Populations of Neurons

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



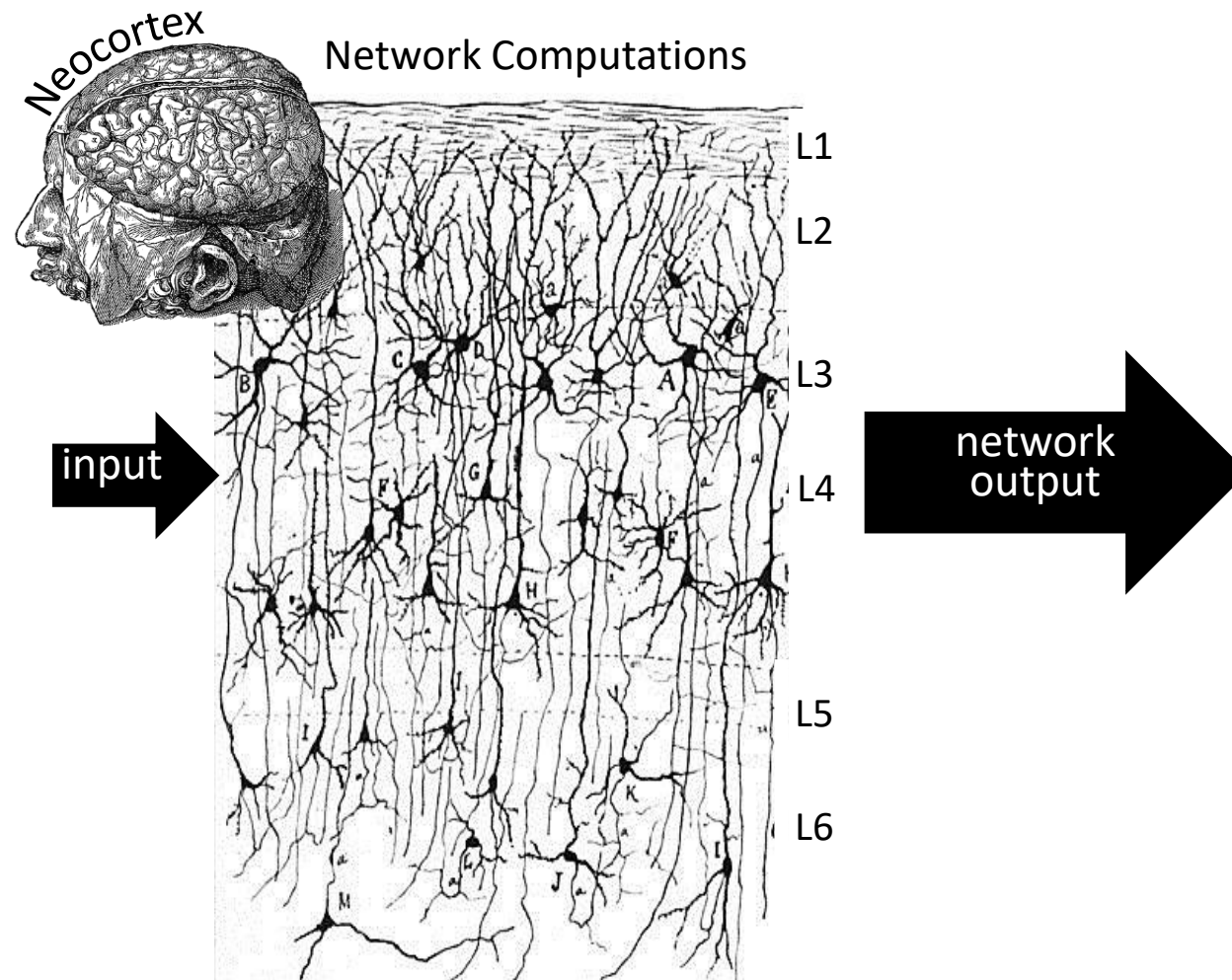
Imaged surface of visual cortex



Preferred stimulus orientation of neurons at each location on cortex

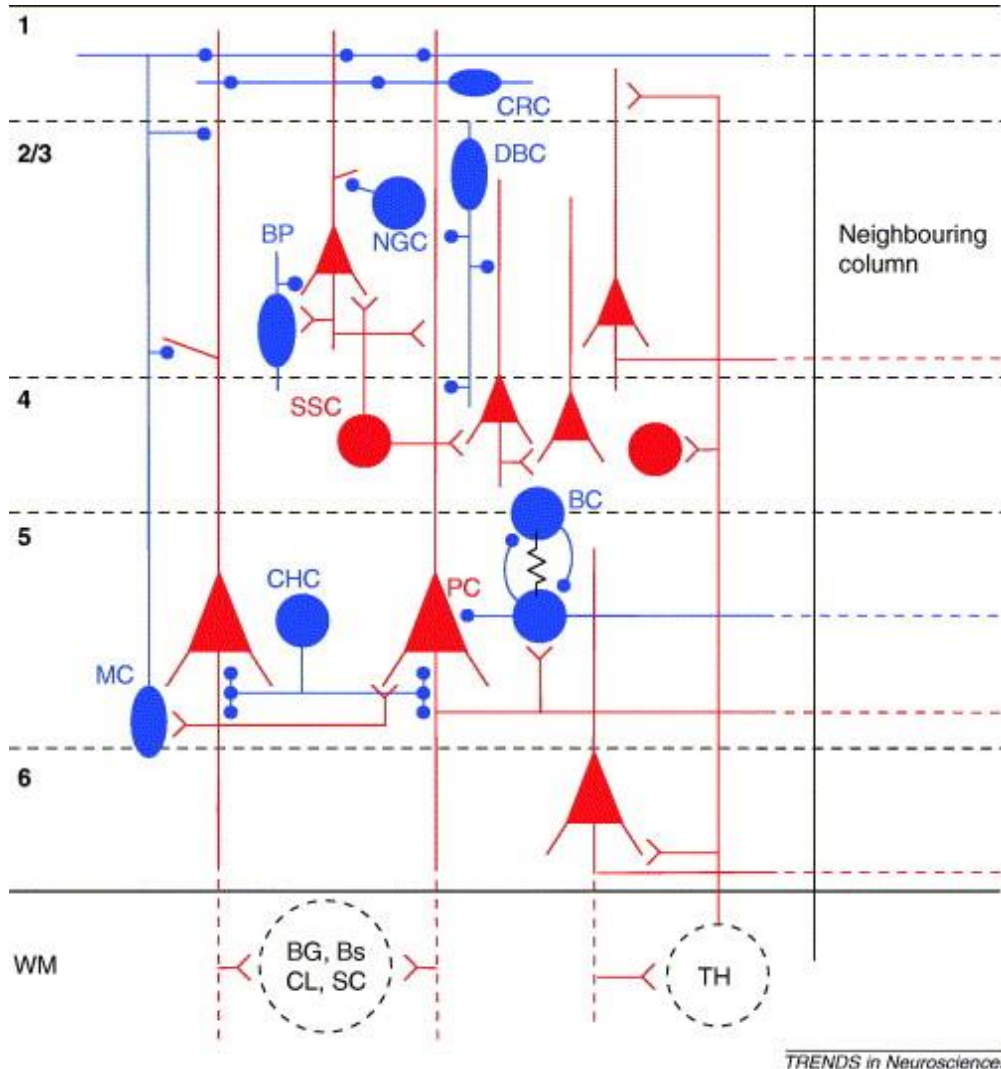


Cortical Circuits

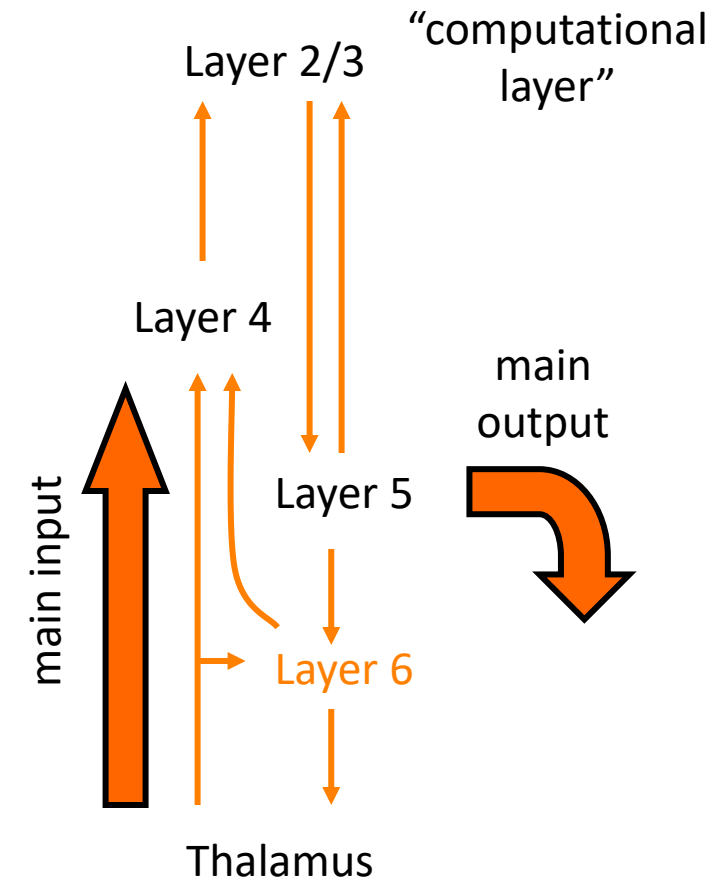


Cortical Circuits

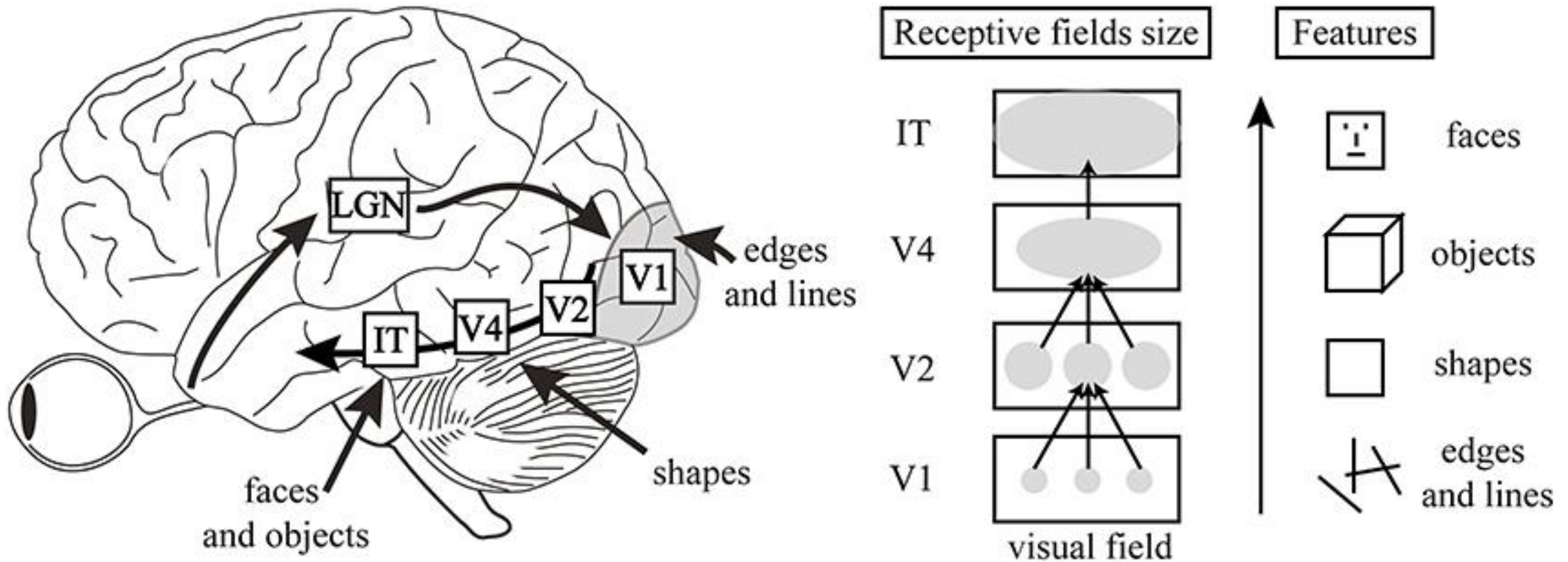
Wiring diagram of cortical circuit



Information flow through circuit

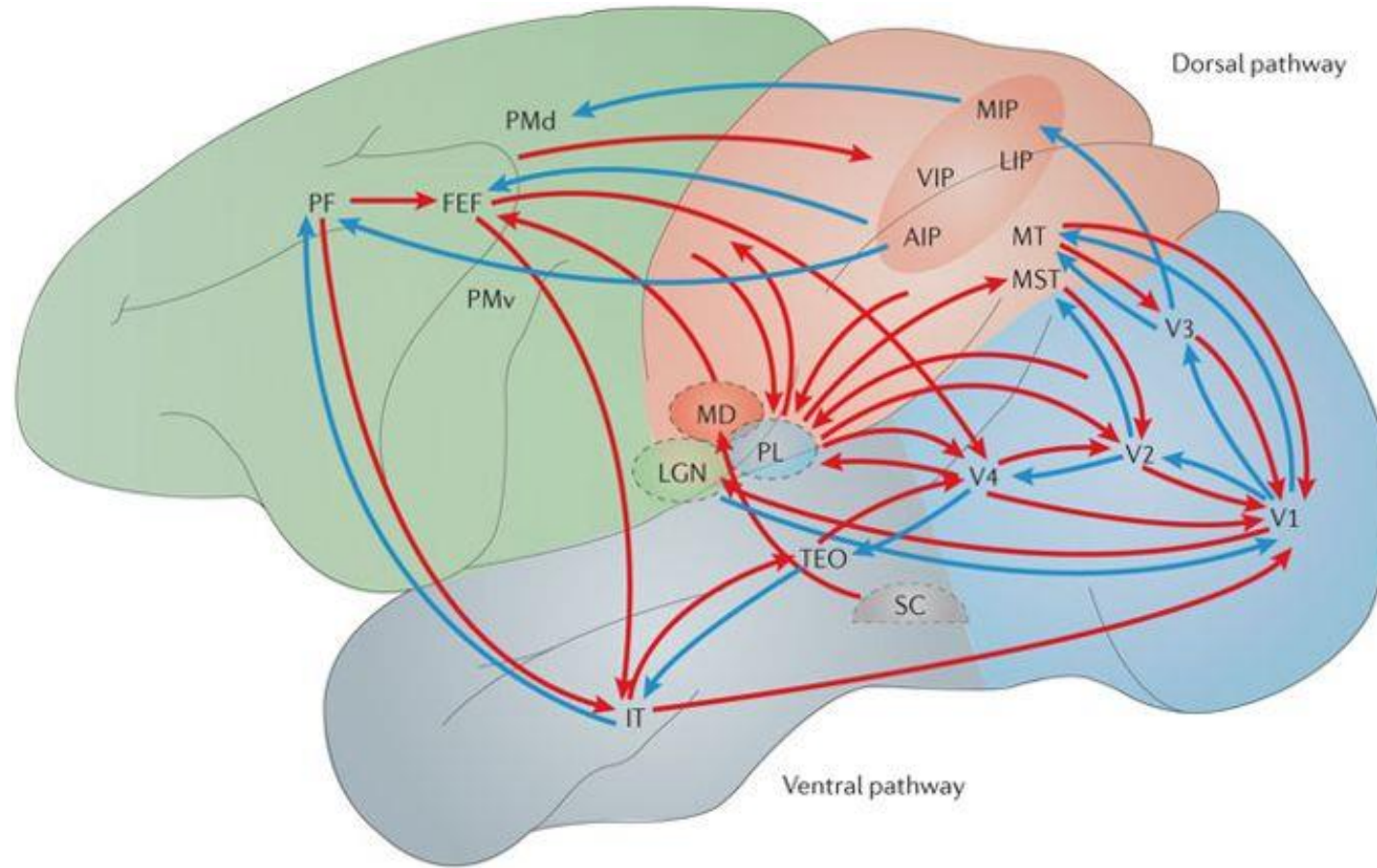


Feedforward Computations in the Visual System



Feedforward computations can perform categorisation, object recognition, etc.

Feedforward, Lateral, and Feedback Pathways



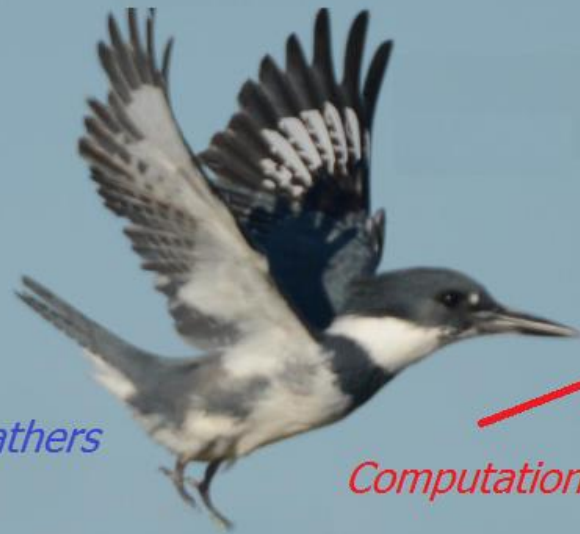
Nature Reviews | Neuroscience

The brain is not feedforward!

How Should We Study the Brain?

"...trying to understand perception by studying only neurons is like trying to understand bird flight by studying only feathers. It cannot be done" - David Marr (1982/2010, p. 27)

Algorithm = flapping



Implementation = feathers

Computation = flight



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”

VISION



David Marr

FOREWORD BY
Shimon Ullman

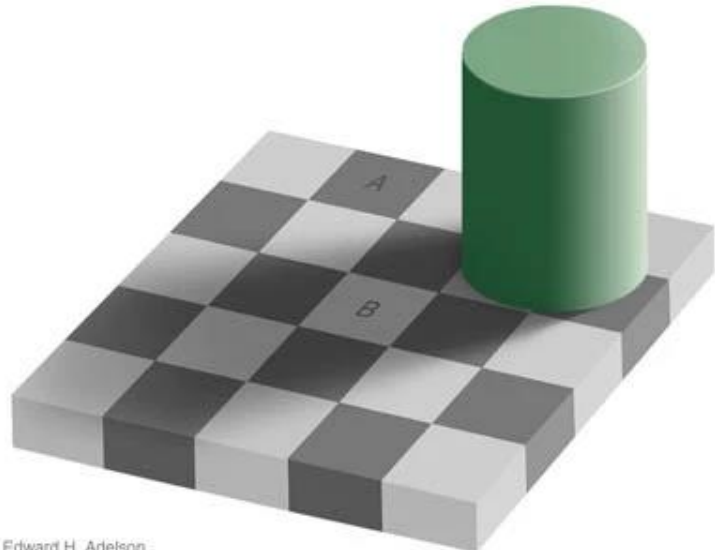
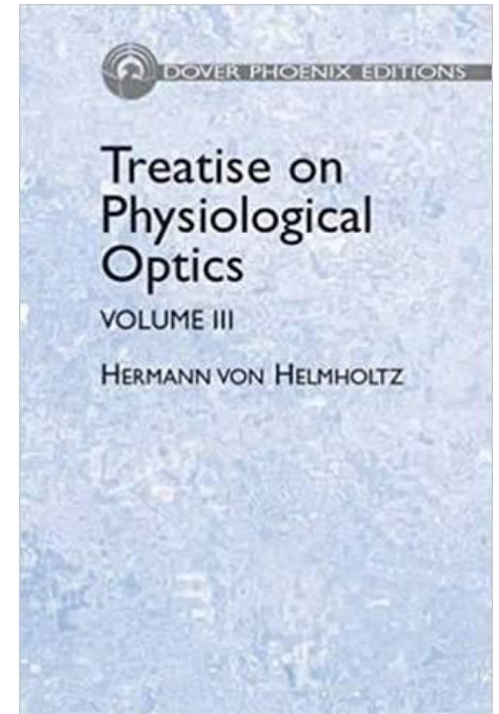
AFTERWORD BY
Tomaso Poggio

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)

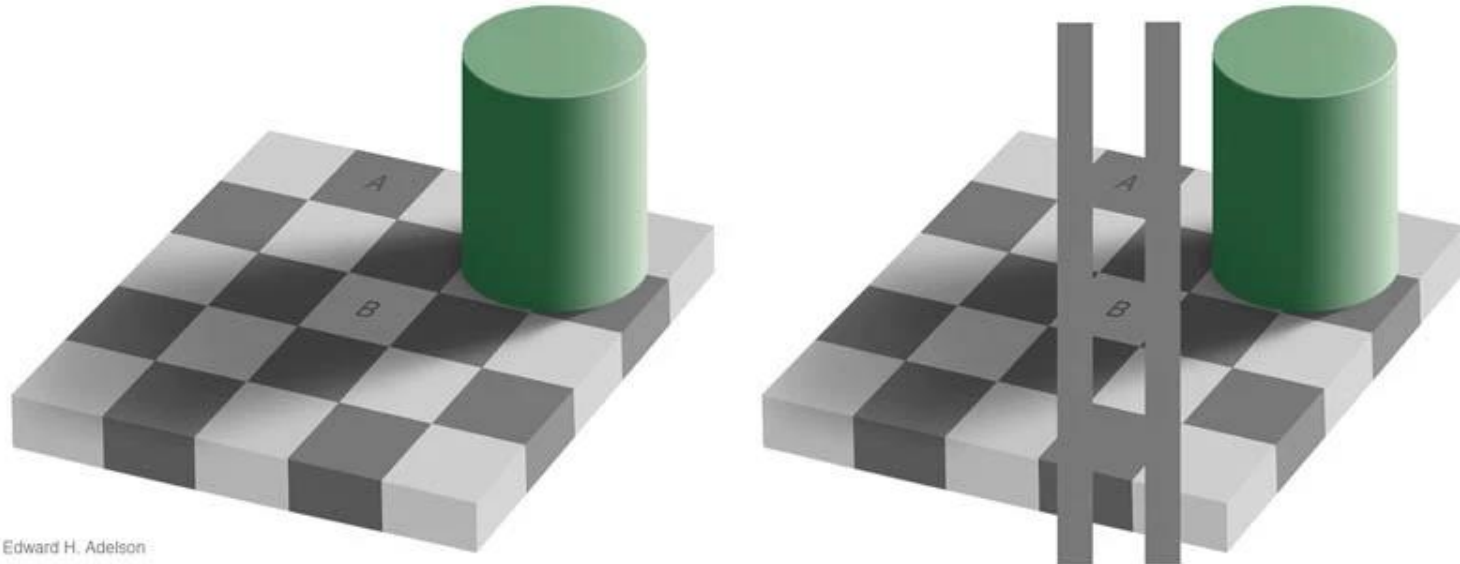
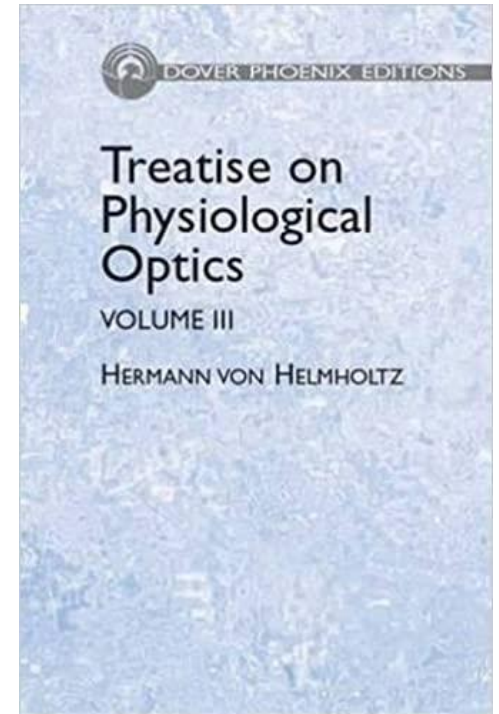


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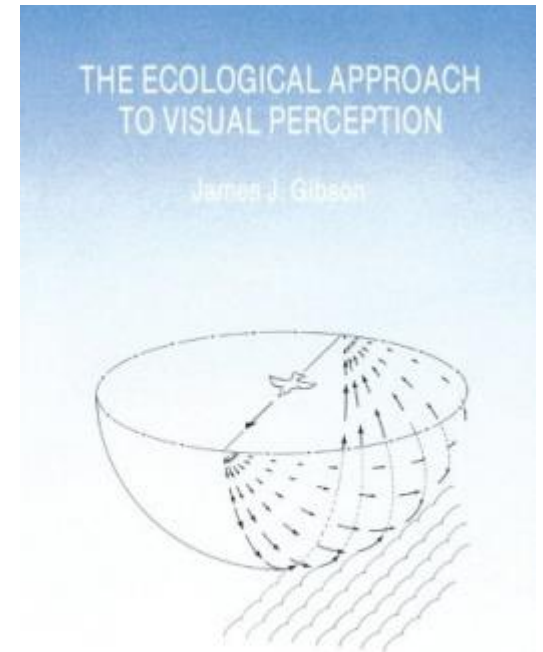
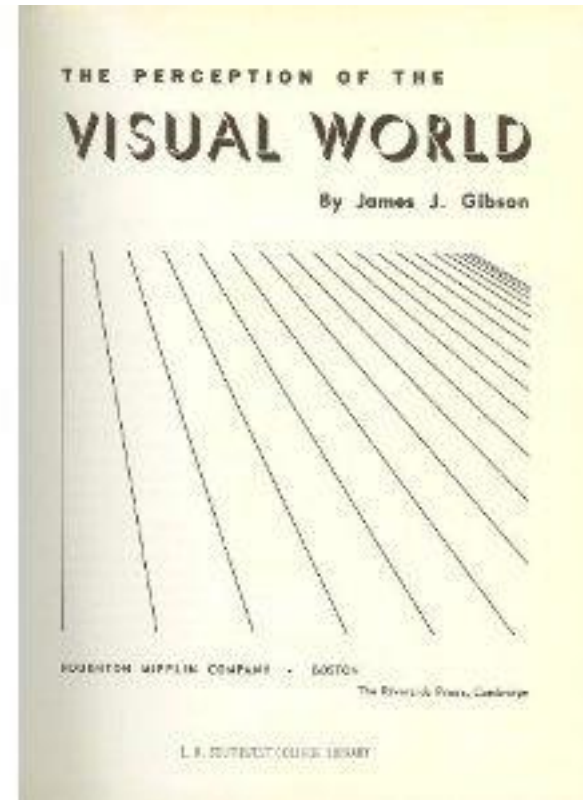
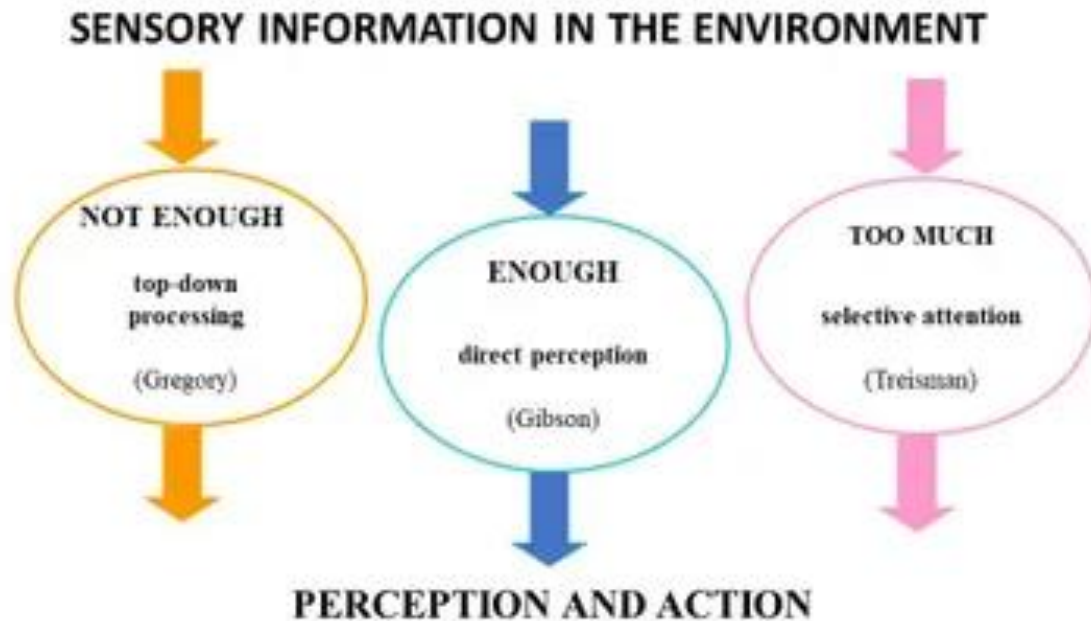


Alternative Theory: Direct Perception

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!