Introduction to Neuroscience

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Computational Neuroscience (Lecture 2, 2023/2024)
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...

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 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
Networks/Circuits of Neurons

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.

Staining of neuron cell bodies and axons/dendrites

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

- **Homunculus**
  - Somatosensory: Eye, Nose, Face, Upper Lip, Lips, Lower Lip, Teeth, Gums, Tongue, Intra Abdominal Pharynx
  - Motor: Eyelid & Eyeball, Jaw, Tongue, Swallowing

- **Brain Diagrams**
  - Left: Nose, Eye, Face, Upper Lip, Lips, Lower Lip, Teeth, Gums, Tongue, Intra Abdominal Pharynx
  - Right: Eyelid & Eyeball, Jaw, Tongue, Swallowing
**Representations in Single Neurons – Tuning Curves**

**Tuning Curves**: Vary stimulus and plot mean response of neuron

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Model tuning curves as a **Gaussian** function:

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

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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

a) Sensory noise
- Sensory transduction and amplification

b) Cellular noise
- Receptor neuron
- Voltage-gated ion channel

Electrical noise
- Excitable membrane
- Network of neurons

c) Motor noise
- Muscle
- Spinal cord
- Motor neuron

Synaptic noise
Representations in Populations of Neurons

Many neurons, each with a different preferred orientation

Noisy response of population to a single stimulus presentation
Representations in Populations of Neurons

Many neurons, each with a different preferred orientation

Noisy response of population to a single stimulus presentation

Stimulus is probably here!
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

Neocortex

Network Computations

input

network output

L1
L2
L3
L4
L5
L6
Cortical Circuits

Wiring diagram of cortical circuit

Information flow through circuit

Layer 2/3

“computational layer”

Layer 4

Layer 5

Layer 6

main output

main input

Thalamus
Feedforward Computations in the Visual System

Feedforward computations can perform categorisation, object recognition, etc.
Feedforward, Lateral, and Feedback Pathways

The brain is not feedforward!
"...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)
…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.”
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)
Perception as Inference

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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!