



**UNIVERSITÉ
DE GENÈVE**

Decision Making Under Uncertainty

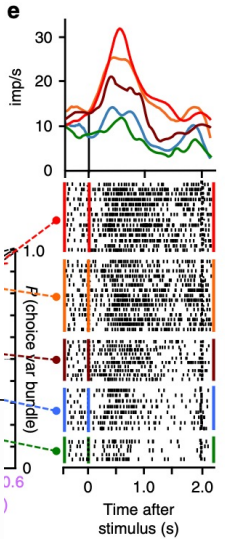
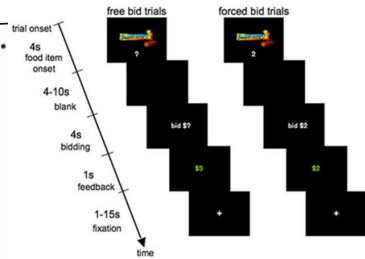
Week 3

The tools of Neuroeconomics:
Behavioral and Neural Methods

Marco Lehmann, PhD

Orbitofrontal Cortex Encodes Willingness to Pay in Everyday Economic Transactions

Hilke Plassmann, John O'Doherty, and Antonio Rangel
California Institute of Technology, Division of Humanities and Social Sciences



ARTICLE

<https://doi.org/10.1038/s41467-019-12792-4>

OPEN

Orbitofrontal signals for two-component choice options comply with indifference curves of Revealed Preference Theory

Alexandre Pastor-Bernier¹, Arkadiusz Stasiak¹ & Wolfram Schultz^{1*}

<https://doi.org/10.1038/s41562-023-01>

nature human behaviour

Article

Individual risk attitudes arise from noise in neurocognitive magnitude representations

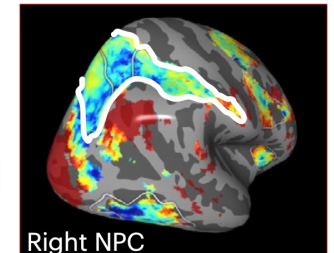
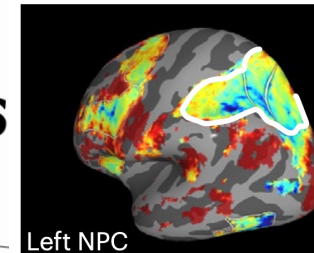
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Marcus Grueschow¹, Rafael Polanía⁴, Michael Woodford⁵ &
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Topographic number fields



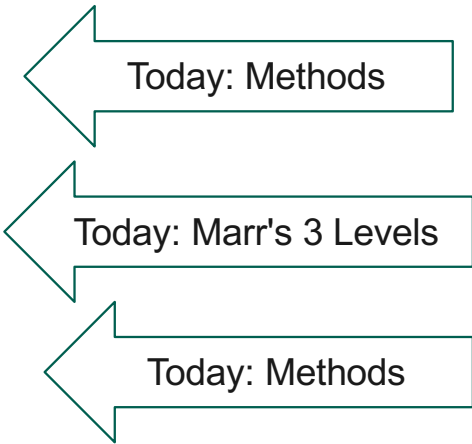
μ (preferred numerosity)

Learning Objectives

- **By the end of today, you can:**
- Explain how economists build and revise models
- Apply Marr's three levels to a decision.
- Name the main method families: behaviour, physiological measures, neural signals, interventions.
- For a given method, say what it measures, how precise it is in time and space, and whether it supports causal or only correlational conclusions.
- Locate major brain regions and describe their position with directional terms.
- Describe how neurons communicate, and why this limits processing speed.

General Scientific Approach

1. Observation
Identify a phenomenon or pattern that needs explanation.
2. Hypothesis
Formulate a testable and falsifiable statement that explains the observation.
3. Experiment
Design controlled studies or collect data to test the hypothesis.
4. Analysis
Evaluate the data using appropriate statistical or analytical methods.
5. Revision
Accept, reject, or refine the hypothesis based on results, leading to further testing.



Falsifiability: A scientific hypothesis must be structured so that it can, in principle, be proven wrong by evidence.

Replication: Findings must be reproducible by independent researchers to confirm reliability and rule out chance or bias.

Revising/Refining models: How to generate a new model

1. Identify a normative principle of judgment or choice, e.g., more is better
2. Identify anomalies that violate the principle, e.g., someone choosing less over more
3. Propose a new theory that accommodates the anomalies (preferably a generalization of the normative model)
4. Make and test new predictions generated by the new model

(for historical context and a discussion see: Camerer, C. F., & Loewenstein, G. (2004). Behavioral economics: Past, present, future. *Advances in behavioral economics*,)

How to study and understand complex SYSTEMS ?

David Marr, "Vision" 1982.

- "Trying to understand perception by studying only neurons is like trying to understand bird flight by studying only feathers; it just cannot be done. To understand bird flight, you need to understand aerodynamics, only then can one make sense of the structure of feathers and the shape of wings. Similarly, you can't reach an understanding of why neurons in the visual system behave the way they do, just by studying their anatomy and physiology." D. Marr, Vision, 1982
- freely adapted to this class:
To understand an investment decision, you need to understand the problem the investor solves (trading expected return against risk over time), only then can one make sense of the rules people use to choose and of the neural signals that carry value and risk.
You cannot understand a brain signal until you know which quantity of the decision it is supposed to encode.

A unifying frame: Marr's levels of analysis

(over-simplified, use with caution Marr's three levels are about **types of explanation**, not academic disciplines)

Marr: Information processing systems (complex systems in general) must be understood at three distinct levels:

Marr's level		Question it asks	Example domain	For our investment decision
Computational		What problem is being solved, and why this solution?	Economics	Given expected returns and risks, what allocation of savings maximizes expected utility?
Algorithmic		What representations and steps actually produce the choice?	Psychology	Loss aversion, framing, heuristic shortcuts — the actual procedure people use.
Implementational		What physical hardware carries out the algorithm?	Neuroscience	Dopaminergic reward-prediction-error signals, vmPFC valuation circuitry, etc.

Applying Marr's 3 Levels to analyse a Decision Example

in-class exercise, discuss: what is analyzed at each level?

(week 1): 💰 **The investment** → a friend calls: a new company, not public yet, no track record, but “this could be huge.” They want you to put in real money. Do you say yes?

Computational	What problem is being solved, and why this solution? (What is the Input? What is the output?)	
Algorithmic	What representations and steps actually produce the choice?	
Implementational	What physical hardware carries out the algorithm?	

Relevance of Marr's framework:

Without a computational level, a neural signal recorded during this decision cannot be interpreted

Methods. A broad categorization and characterization

- **Behaviour:** we can observe, describe, and record overt actions and derived signals (e.g. reaction-time, force, ...)
- **Physiological measures:** The body signals more than just behaviour. Scientists measure, for example, skin-conductance, pupil dilation, heart rate etc.
- **Neural signals:** Specialised tools measure brain activity directly or indirectly. Examples: fMRI, EEG, neural recordings, ...
- **Interventions:** researchers change brain function and observe the effect on behaviour, for example through lesions, brain stimulation or drugs. This allows causal conclusions.
- Every method has different **characteristics**, the choice of a suitable method depends on many factors:
 - The question the researcher is asking
 - the available equipment and skills
 - cost
 - the spatio-temporal resolution of the measured signal
 - invasive/non-invasive
 - ethical considerations / approval
 - ...

Methods 1: The behavioral toolbox

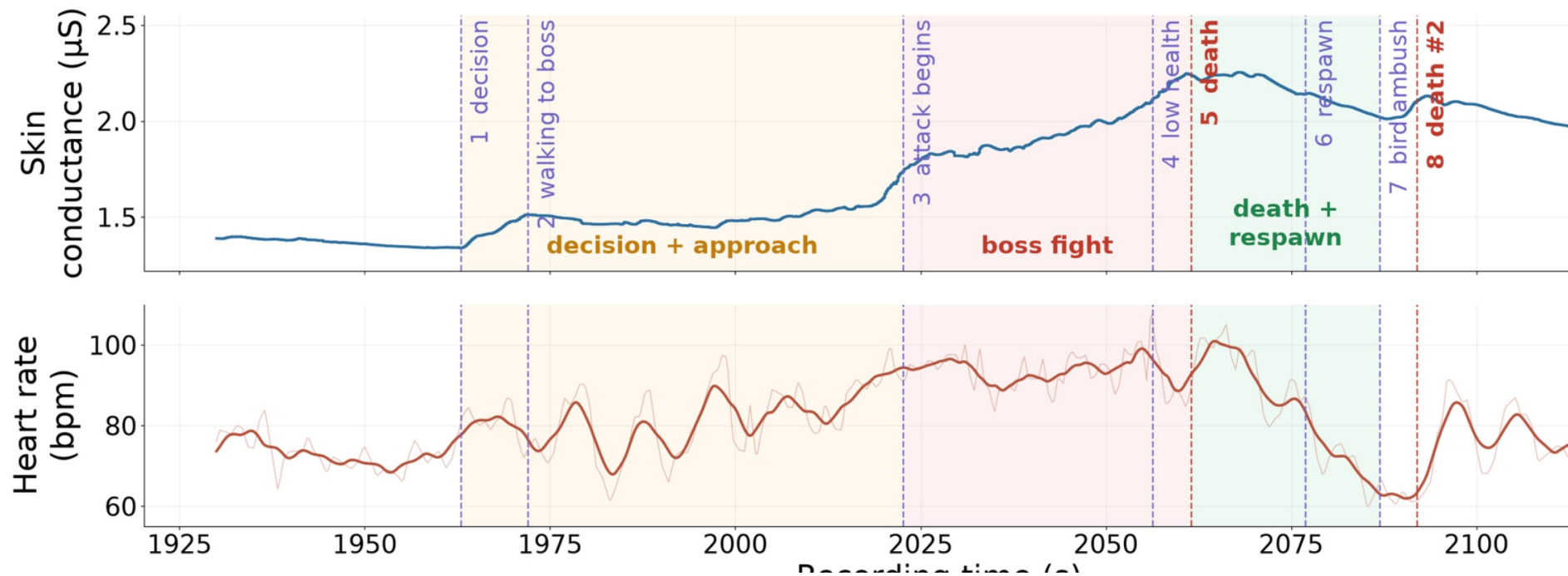
Method	What it measures	What we can learn	What we cannot learn
Lab choice tasks (single player)	Revealed choices under controlled, often incentivized conditions	Preferences, risk attitudes, consistency (WARP/GARP), effects of a manipulated variable	<i>Why</i> someone chose; whether behavior generalizes outside the lab
Games (multiple players, with or without interaction)	Choices that depend on others' choices	Strategic and social preferences, beliefs about others	Same as above, plus results depend on the exact game
Questionnaires	Self-reported attitudes, intentions, perceived risk and benefit	Stable individual differences, domain-specific attitudes, things choice data cannot reach	Whether stated attitudes match actual behavior
Field experiments	Real behavior in natural settings, sometimes with a randomized treatment	Whether effects hold in the real world	Mechanisms, since control is lower
Process data (reaction times, choice consistency, learning curves, eye tracking)	<i>How</i> choices unfold, not only what was chosen	Constraints on algorithms: does the process look like accumulation, learning, or a rule?	The physical implementation

Methods 2: Physiological measures

- In addition to behaviour (actions), researchers can measure other signals:
 - pupil dilation
 - heart rate
 - skin-conductance
 - ...

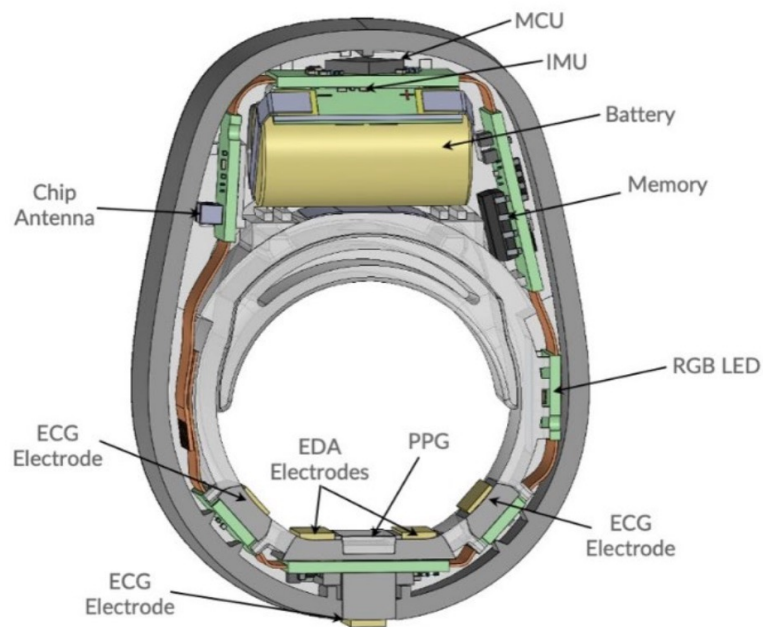
Example: Behaviour & Physiological Signals during a game

- https://unigech-my.sharepoint.com/personal/emirhan_serbest_etu_unige_ch/_layouts/15/stream.aspx?id=%2Fpersonal%2Femirhan%5Fserbest%5Fetu%5Funige%5Fch%2FDocuments%2FAttachments%2F0925%2Emp4&ga=1&referrer=StreamWebApp%2EWeb&referrerScenario=AddressBarCopied



Wearable sensor. Multiple signals.

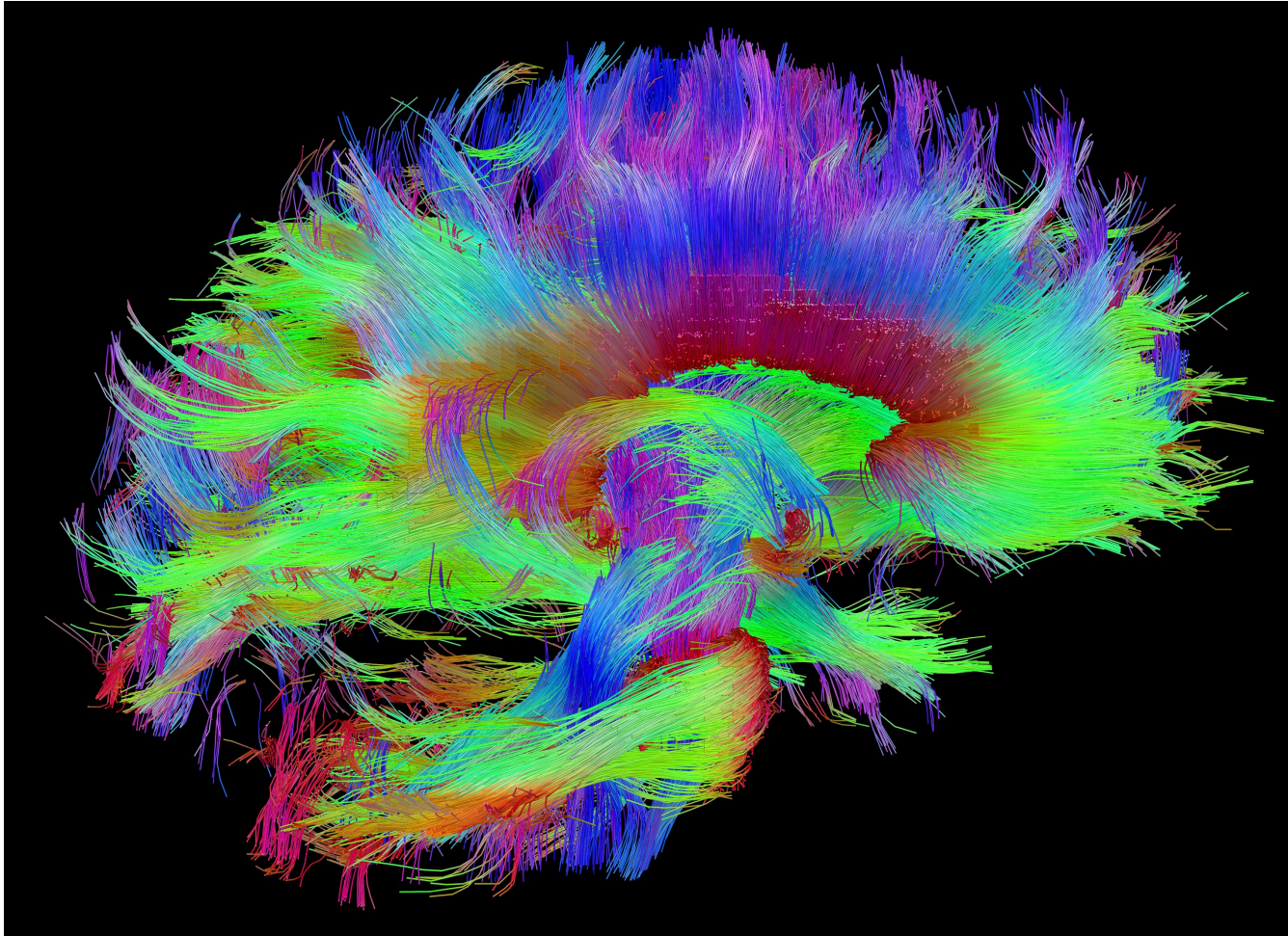
**One ring, four signals,
200 samples per second**



Senstream Research Ring: PPG, EDA electrodes, 3-axis motion, skin temperature

Images: BIOPAC product documentation

We can observe/measure behaviour. But "Who" generates the behaviour?



The human brain

Volume	1.2 L
Weight	1.3 Kg
# Neurons	~86 Billions ($86 * 10^9$)
# Synapses	~100 Trillions ($100 * 10^{12}$)
Memory capacity	? Gigabytes to Terabytes
Power consumption	20 Watts !



https://en.wikipedia.org/wiki/Human_brain#/media/File:Brain_autopsy_lateral_view.jpg
CC BY-SA 4.0

Aristotle, 4th century BC

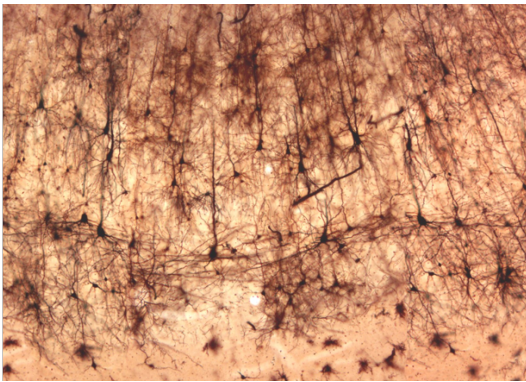
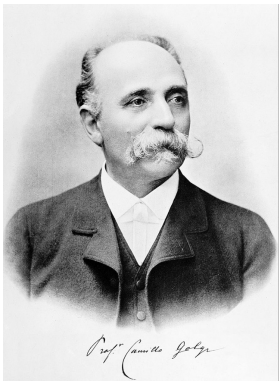
"The brain is the coldest part of the body... its function ... is to cool the blood that arrives through the aorta from the heart and is distributed through the vessels surrounding the brain."

"This preservation consists in tempering by the brain the heat and the boiling that take place in the heart."



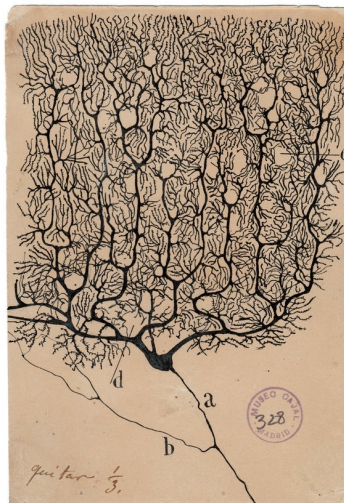
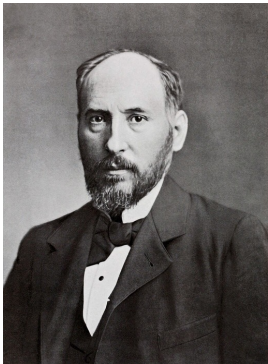
Modern Neuroscience started ~ 150 years ago

- In 1906, the Nobel Prize in Physiology or Medicine was awarded jointly to Camillo Golgi and Santiago Ramón y Cajal "in recognition of their work on the structure of the nervous system".



Camillo Golgi (1843–1926)

Golgi staining 1873: a few single neurons become visible under the light microscope.



Santiago Ramón y Cajal (1852 – 1934)

Neuroanatomy.

Neuron Doctrine: the idea that the nervous system is composed of discrete cells (neurons) rather than a continuous network.

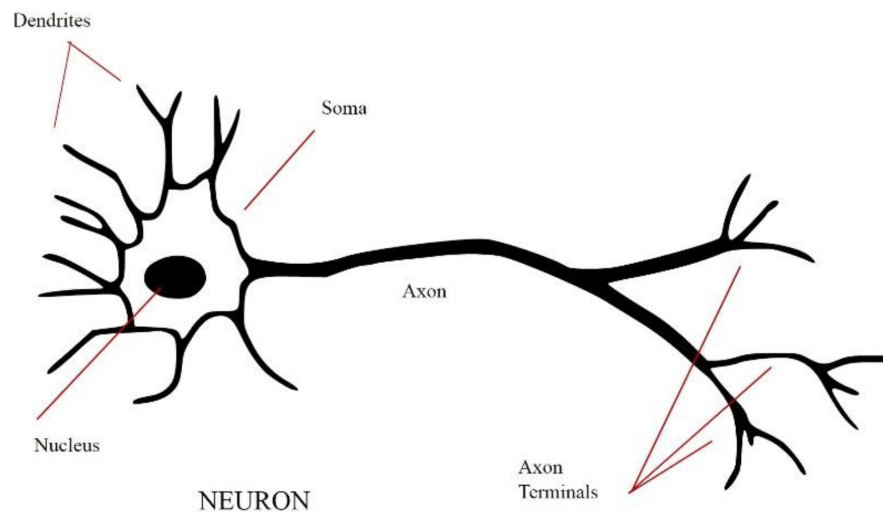
Public Domain

https://en.wikipedia.org/wiki/Camillo_Golgi

https://en.wikipedia.org/wiki/Santiago_Ram%C3%B3n_y_Cajal

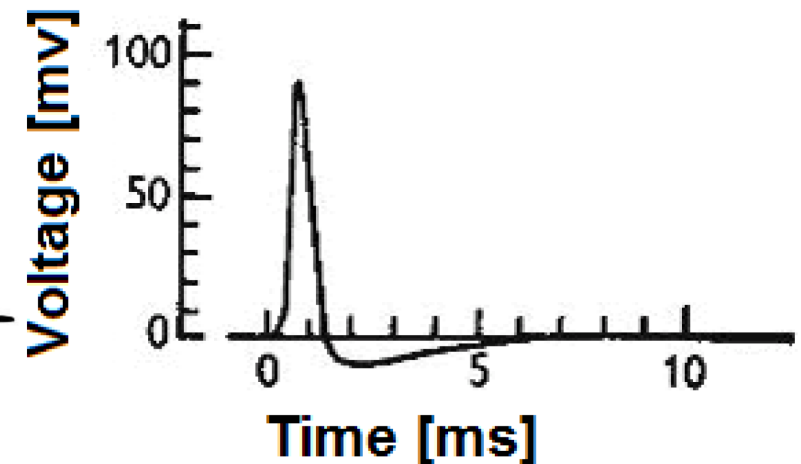
Neurons integrate information and send signals

- A neuron is a specialized eukaryotic cell that processes and transmits information through electrical and chemical signals. It is the basic computational unit of the nervous system.
- *Dendrites*: Collect (chemical) **input** from (many) other neurons.
- *Cell Body (Soma)*: If the collective input signal reaches a (voltage) threshold, an electrical **output** signal, called "action potential" or "spike" is generated.
- *Axon*: a long extension. The electrical pulse (spike) travels along the axon to other neurons.



(a)

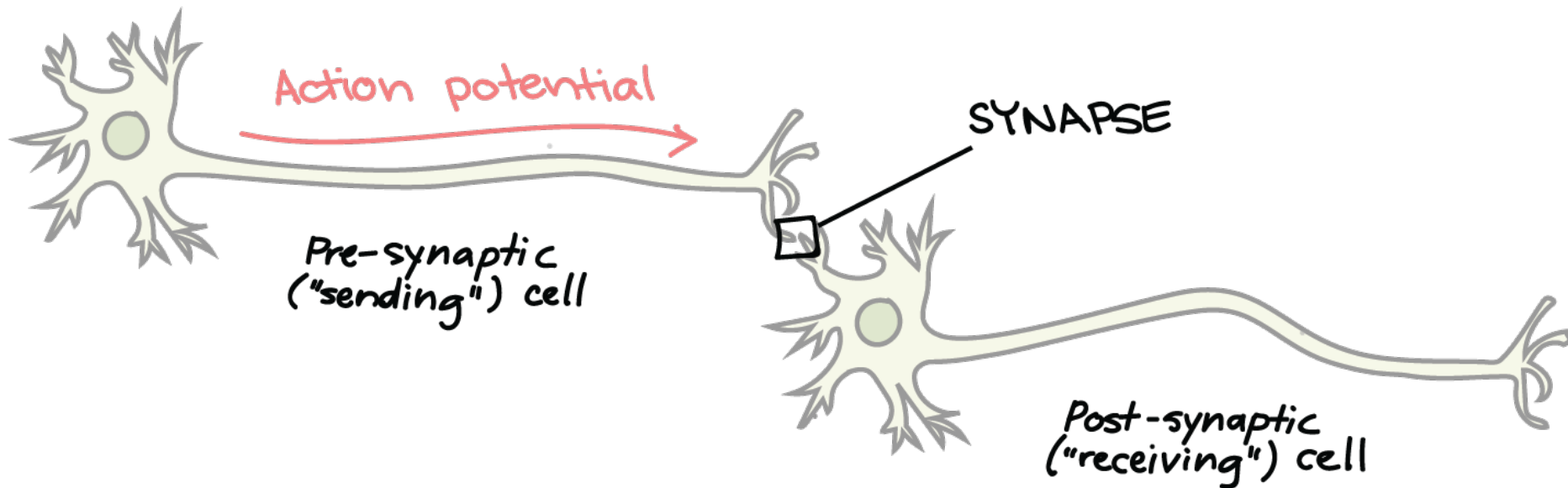
<https://www.mdpi.com/2079-9292/8/12/1479/htm>



(b)

Synapses: Where neurons connect (and learning happens)

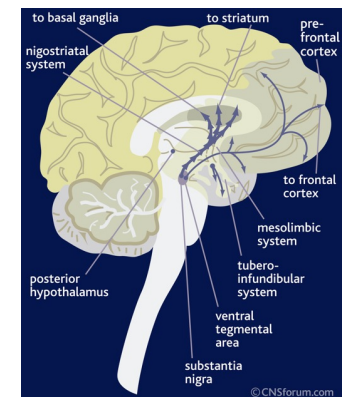
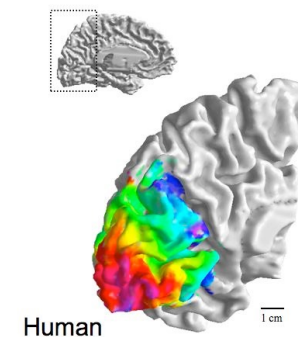
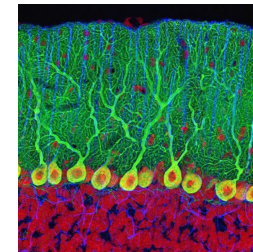
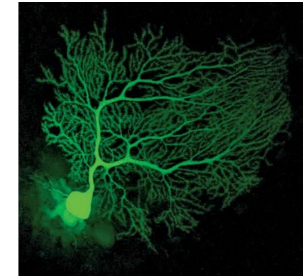
- Each neuron receives input from up to 10^4 other neurons. The connections are called synapses.
- When a brain "learns", the synapses are strengthened (they can grow).



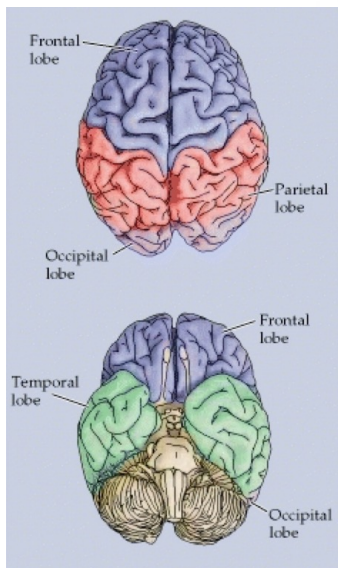
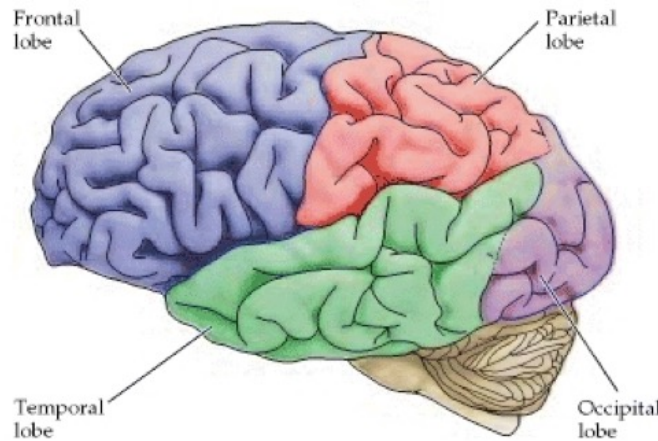
<https://www.khanacademy.org/science/biology/human-biology/neuron-nervous-system/a/the-synapse>

Levels of brain anatomy

- Molecules/Synapses
e.g., neurotransmitters and their receptors
- Neurons/Layers
e.g. neuronal firing
- Networks/Maps
e.g., small local circuits
- Systems
e.g. interconnected brain regions representing decision-relevant variables



Neocortical lobes

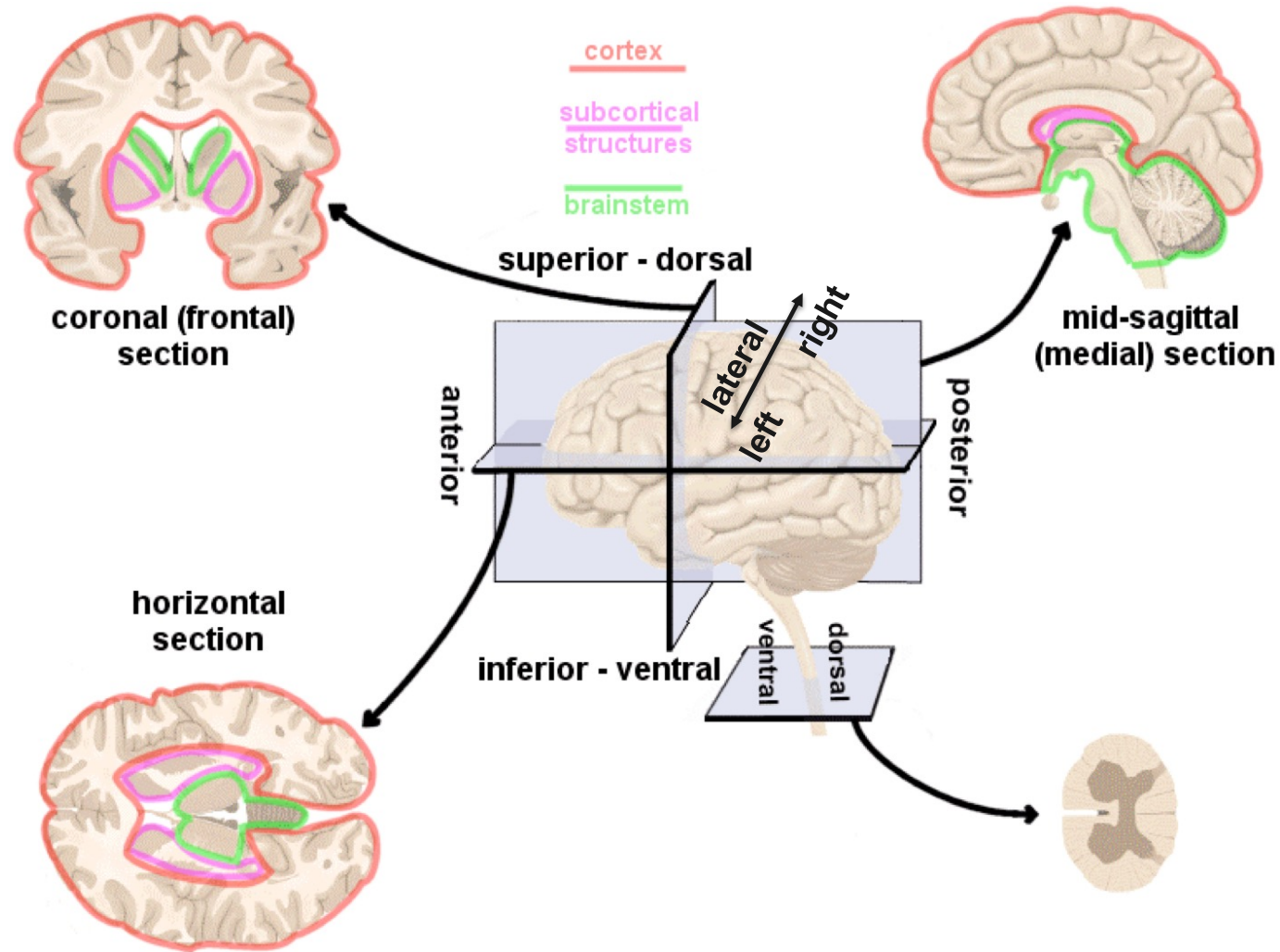


Four lobes on external surface of the cortex:

- Frontal lobe: Planning and complex thought
- Parietal lobe: Sense of touch, attention, space
- Temporal lobe: Audition, language and memory
- Occipital Lobe: Vision

Each lobe contains sulci and gyri (often labelled in logical fashion: superior, middle, inferior, etc.)

Where is "north" on the map?



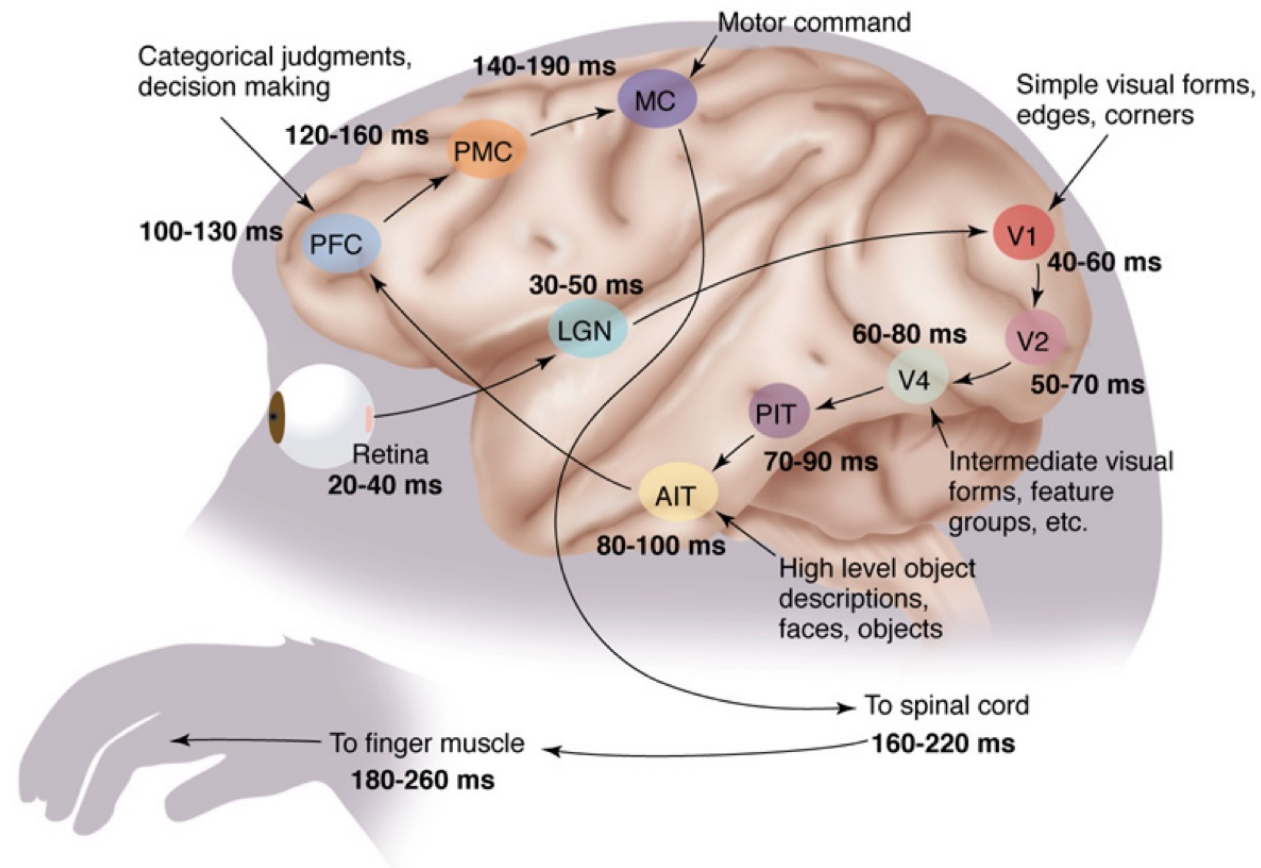
Navigating Brain Structures (in-class)

- go to: [https://www.brainfacts.org/3d-brain - intro=false&focus=Brain](https://www.brainfacts.org/3d-brain-intro=false&focus=Brain)
- Find the following brain structures. Try to locate them in your brain by pointing with two fingers:
 - Orbitofrontal Cortex
 - Prefrontal Cortex
 - Dorsolateral Prefrontal Cortex
 - Thalamus

Information for this week's assignment:

- use the "annotate" button.
- use the "camera" (snapshot) button.

From perception to decision making: a basic view



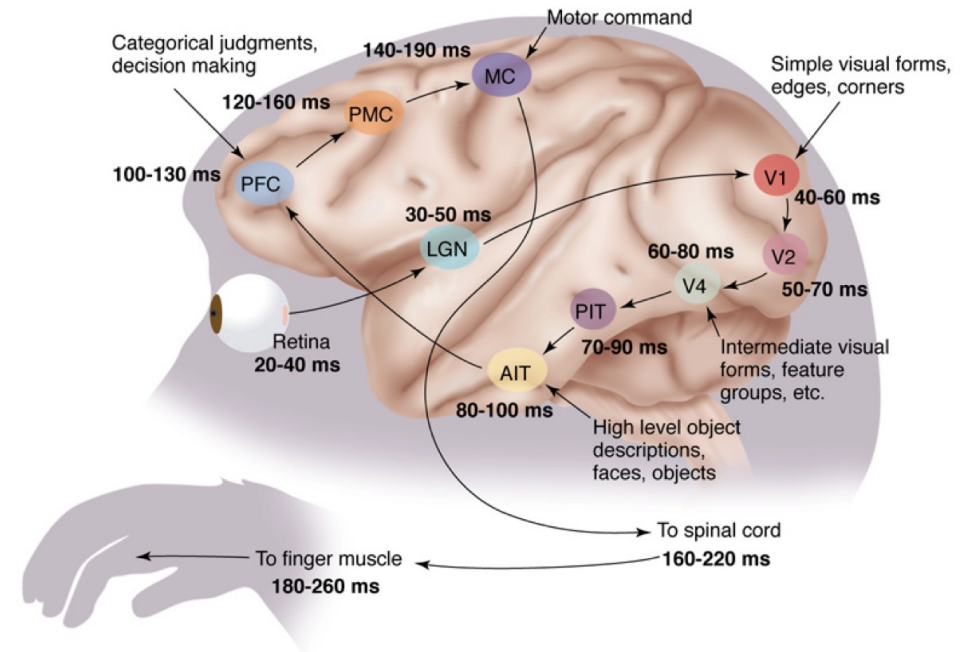
- Question: A visual "Start" signal is given. What is the shortest reaction time?

But where's the decision?

An additional "circuit runs in parallel":

- Modulate: Which action should we take?
- Evaluate/Reinforce: was it a successful action?

A model of the "decision-making"- and "learning"-circuits will be discussed in a few weeks.



Methods 3: Neural signals

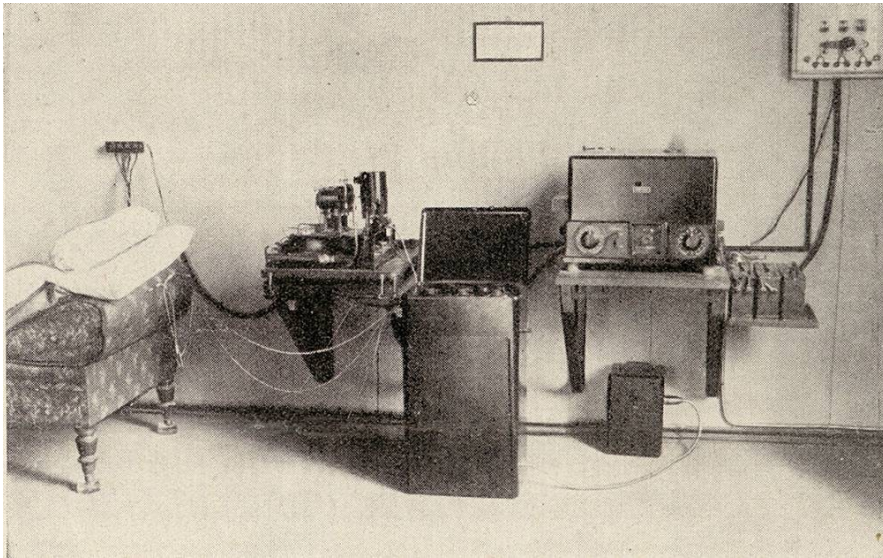
- Different methods exist to measure **neural activity** directly or indirectly. Non-invasive methods allow the observation of the brain (activity) during a task (correlation brain $\leftrightarrow$ behaviour).

Method	What it measures	Direct or indirect	Time	Space	What we can learn	What we cannot learn
fMRI	Blood oxygenation changes (BOLD) following neural activity	Indirect	Slow (seconds)	Good (millimeters), whole brain	Which regions' activity varies with a task variable (value, risk, surprise)	Fast dynamics, direct neural firing, whether a region is necessary
EEG	Summed electrical activity at the scalp	Fairly direct, but mixed sources	Excellent (milliseconds)	Poor (centimeters)	<i>When</i> processing happens, and in what order	Precisely where it comes from

More methods in the self-study section

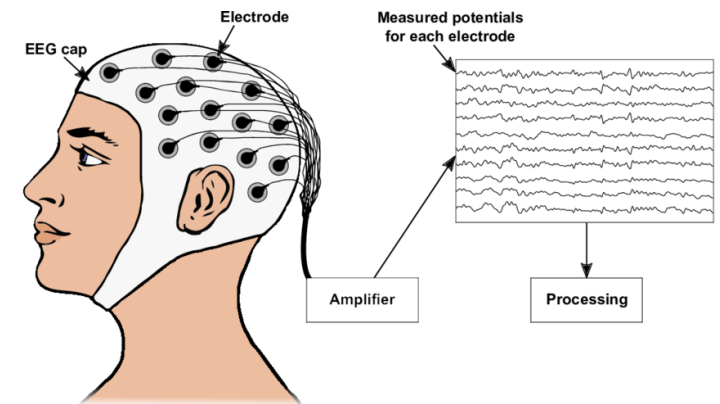
Electroencephalogram EEG

- German physiologist/psychiatrist Hans Berger (1873–1941) recorded the first human EEG in 1924.
- EEG records voltage changes generated by synchronous activity of neural populations.
- High temporal resolution (milliseconds). Low spatial resolution (centimeters)
- **ERP = event-related potential**: small voltage change in the EEG that is **time-locked to a specific event**, such as a stimulus, decision, or response



<https://youtu.be/nPaTG1f-JBU?si=leZRqJ9qF6GOBrh1&t=66>

First electroencephalogram (EEG). This prototype of the EEG developed by Hans Berger was the only model in the Jena Psychiatric Hospital for many years. (Published by Rudolf Lemke, 1954, Jena University Archives, fonds V, section XLVI, no. 43, sheet 1r), <https://link.springer.com/article/10.1007/s10309-024-00704-6/figures/3>



Sebastian Nagel, 2019, "Towards a home-use BCI: fast asynchronous control and robust non-control state detection"

functional Magnetic Resonance Imaging fMRI

- Measures brain activity **indirectly** through changes in blood oxygenation
- Uses the Blood-Oxygen-Level-Dependent signal (**BOLD**): more active brain regions receive more oxygen-rich blood.
- Requires complex data analysis, sophisticated equipment, and trained personnel.
- High spatial resolution (millimeters), but low temporal resolution (seconds).

Putting a Participant in the Scanner



<https://youtu.be/ofwm4lc7RgE?si=WS1dhxKIgOoPKgMF&t=330>

How to perform an fMRI experiment

 Cognitive Neuroscience Compendium
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 149 

Methods 4: Interventions

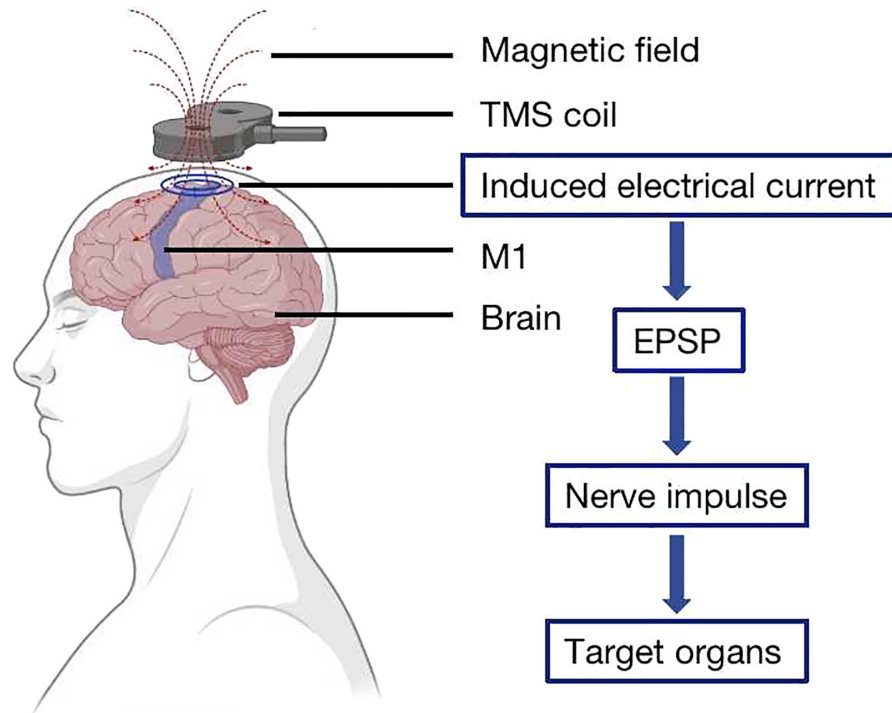
- Interventions (perturbations) stimulate or change a neural activity. It's like probing a complex system: *"What happens if I turn this knob"?*
- Using controlled interventions, **causality** can be studied. Measuring and observing often gives only correlations. Using a hypothesis-driven intervention, **cause** (the intervention) and **effect** (the observation made using one of the previous methods) can be studied.
- Historically, accidents ("uncontrolled interventions") have been a source of information:
 - Phineas Gage (accident) Harlow, J. M. (1868). *Recovery from the passage of an iron bar through the head*. Publications of the Massachusetts Medical Society 2, 327–347.
 - **Method**: a physician's case report, based on observing Gage's **behaviour before and after the injury** (left frontal lobe largely damaged).
 - **Finding**: Gage's intellect survived, but his **planning and social conduct** did not. Harlow wrote that Gage was "no longer Gage".
https://en.wikipedia.org/wiki/Phineas_Gage



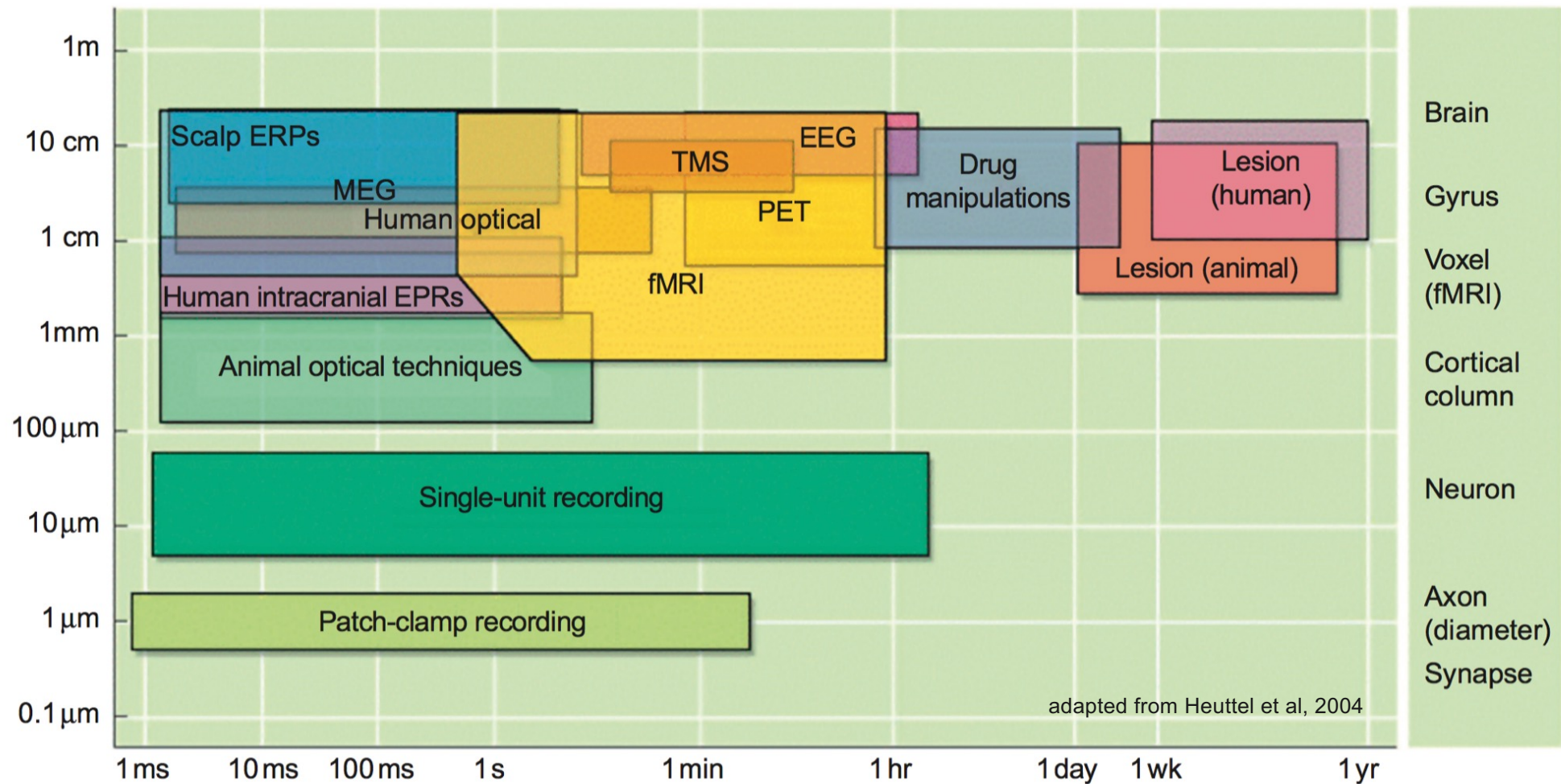
The left frontal lobe (red), with Ratiu et al.'s estimate of the iron's path^[R1]

• Methods: Transcranial Magnetic Stimulation (TMS)

- TMS non-invasively modulates brain activity using magnetic pulses.
- Lab example https://youtu.be/qkNbYHu_STU?si=BG126FnCfoFqrMiS&t=50



• Comparison of Methods: temporal and spatial resolutions



ERP = event-related potential: small voltage change in the EEG that is **time-locked to a specific event**, such as a stimulus, decision, or response

Back to our starting point: Economic Model Building

1. **Normative principle (Theory):** How a rational agent should choose. Example: maximise expected value.
(this is what we did last week)
 - ↓ **Prediction (Theory)**
Translate the model into a prediction about **observable behavior or a neural signal**.
 - ↓ **METHODS / Experiment design**
The scientist designs an experiment that creates the relevant decision situation and **measure the predicted behavior or neural signal**.
2. **Anomaly.** Find choices that systematically violate the principle. Example: people pay little for the St. Petersburg lottery.
3. **New model.** Propose a model that accounts for the anomaly, preferably as a generalisation of the old one. Example: Bernoulli's expected utility.
4. **Test.** Derive new predictions and test them. The cycle restarts when a new anomaly appears.

