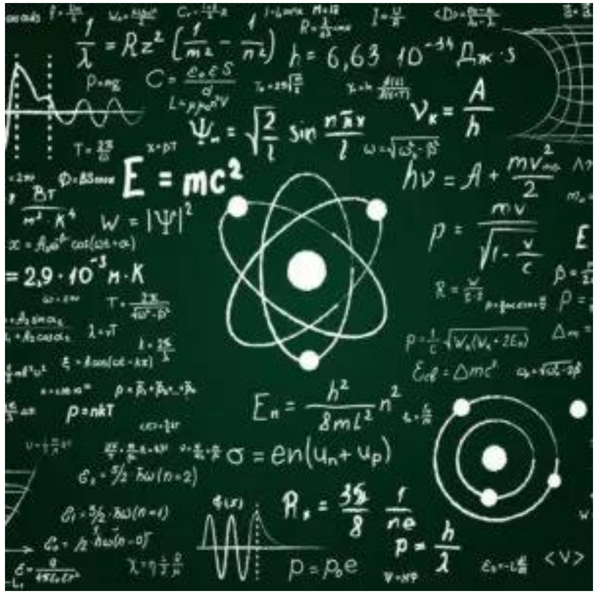
A journey of sound in the brain

A neuroscience perspective on auditory processing

CAS AI for Creative Practices 13.10.2025 Riccardo Cusinato

Introduction



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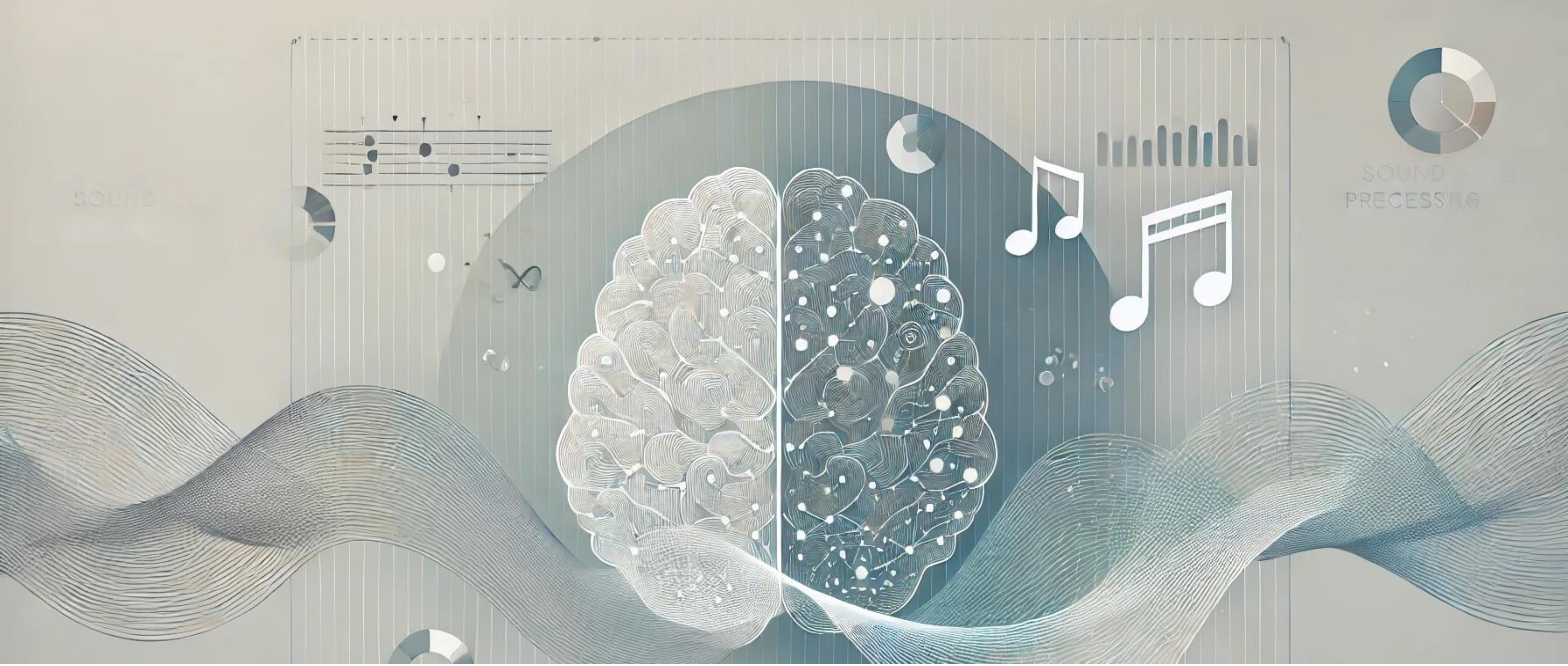
Outline

Part I: The journey of sound in the brain

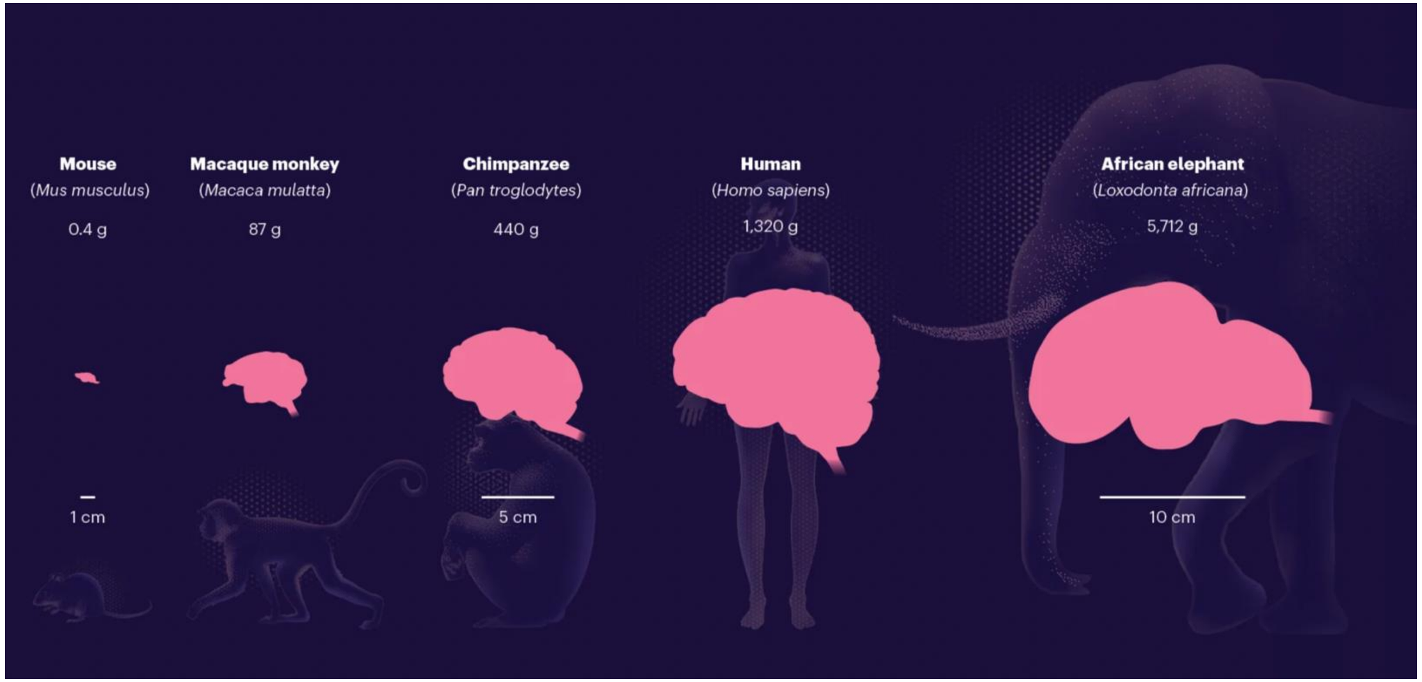
Part II: Brain responses to sound

Part III: AI in auditory neuroscience



Sound’s journey in the brain

Some facts about the brain

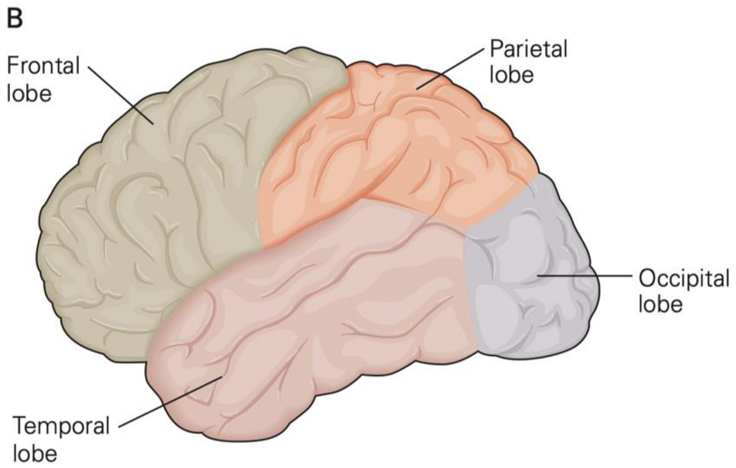


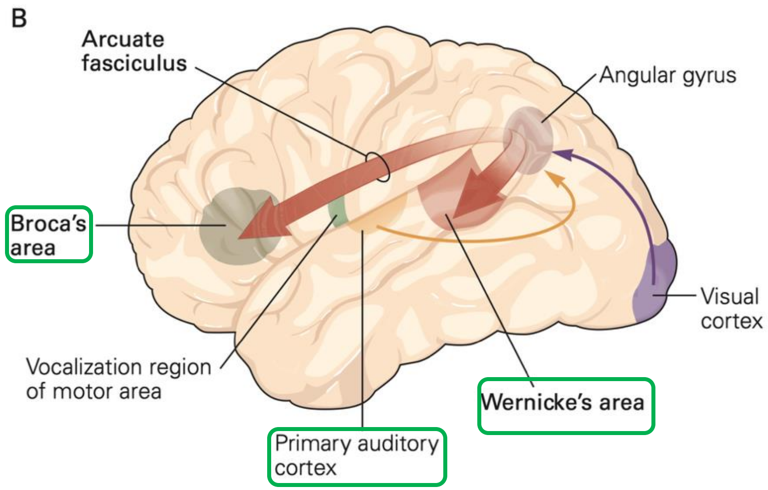
“What's so special about the human brain?”, by Kerry Smith & Nik Spencer, Nature

The human brain:

- 86 billion neurons
- Each with 1000 synapses (connections)
- Very large cortex relative to other animals

Auditory brain areas

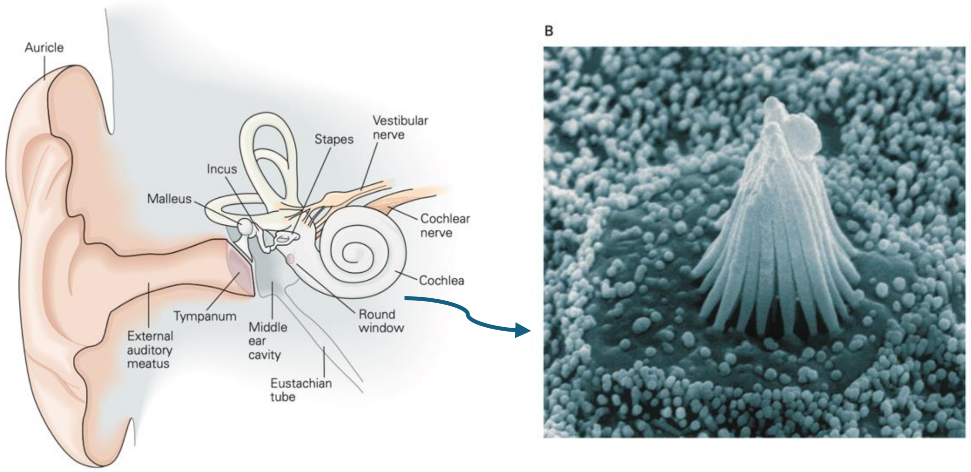


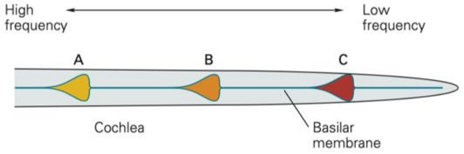


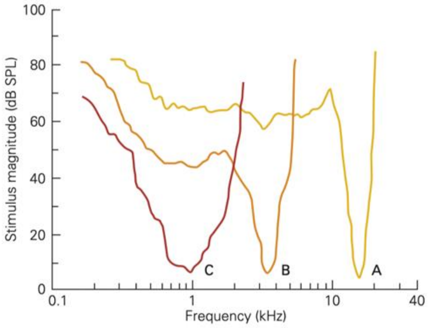
Kandel, E.R., et al., Principles of Neural Science (2013)

- Cerebral cortex responsible for cognition
- Major organization: 4 lobes
- Specialized cortex for auditory and language perception, vision, motor commands

The cochlea and frequency responses



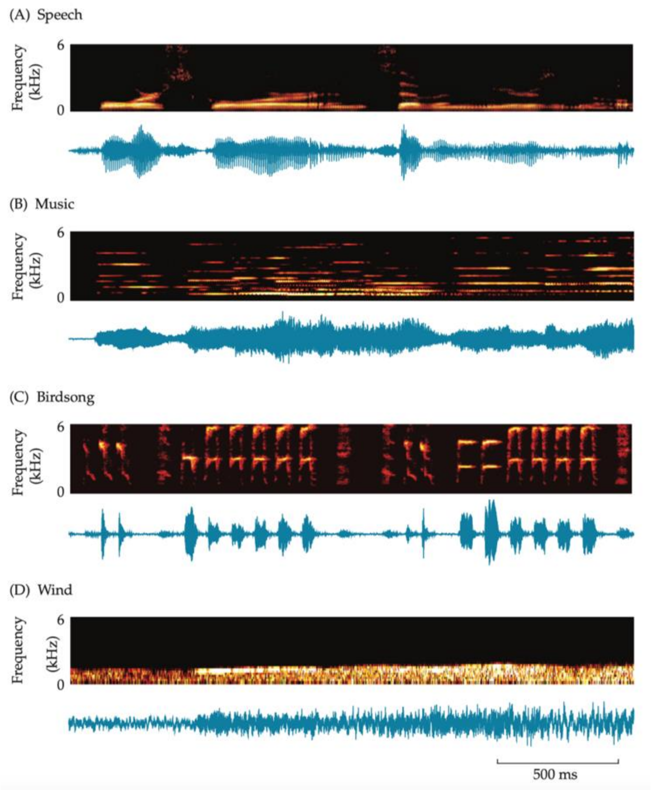




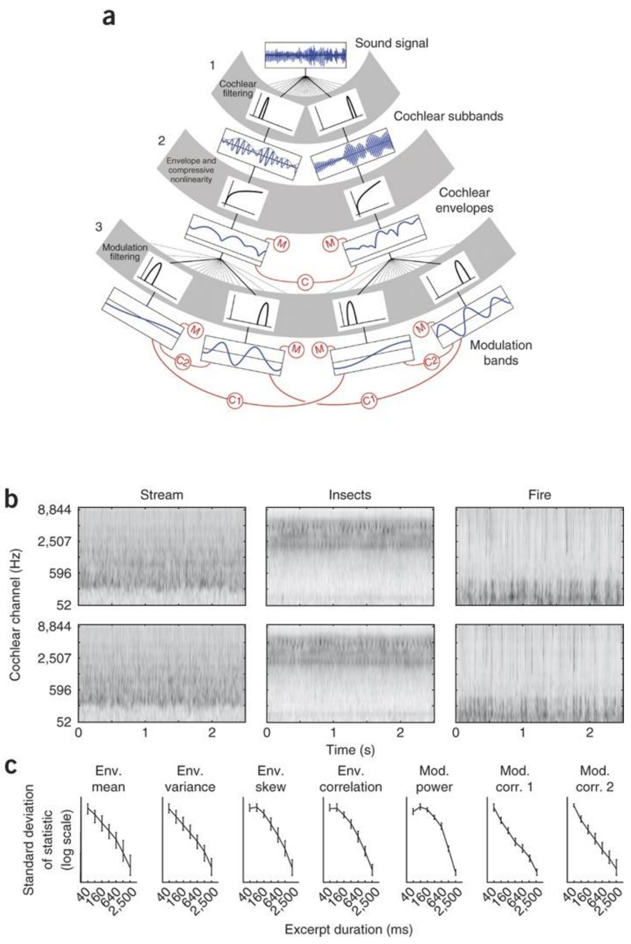
Kandel, E.R., et al., Principles of Neural Science (2013)

- Sound begins its journey in the ear
- Air pressure stimulates the Tympanum
- The cochlea is the hearing organ, with hair cells detecting different frequencies

Brain representations of sounds



Purves, D., et al., Neuroscience (2018)

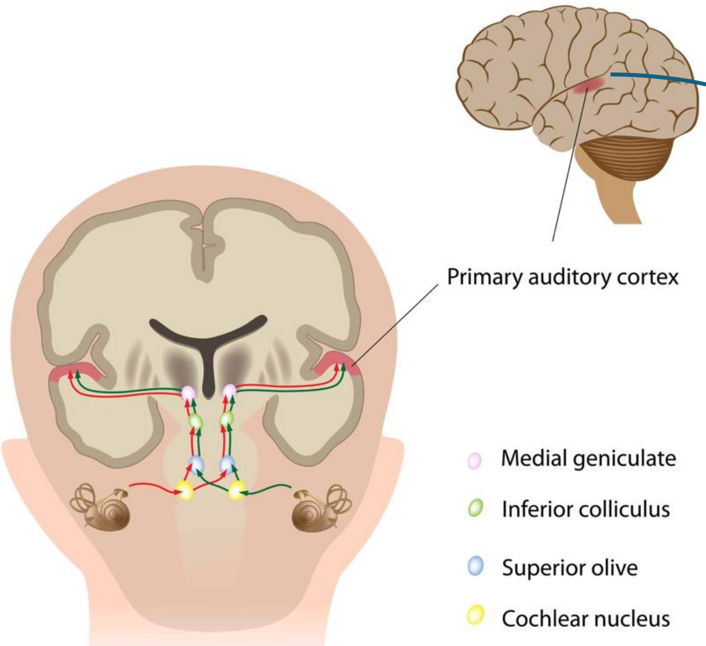


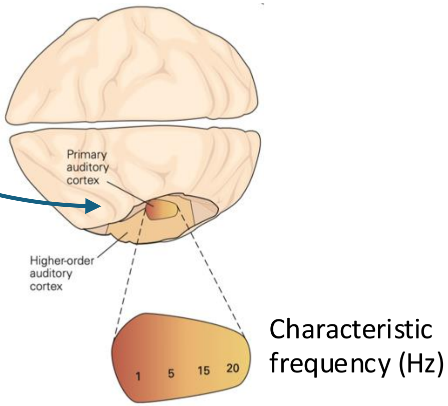
McDermott, J., et al., Nature Neuroscience (2013)

- Sound is naturally represented as decomposed into frequencies → spectrogram

- Studying the responses in the cochlea, we can get a spectrogram of the ear → cochleogram

Climbing up to the cortex



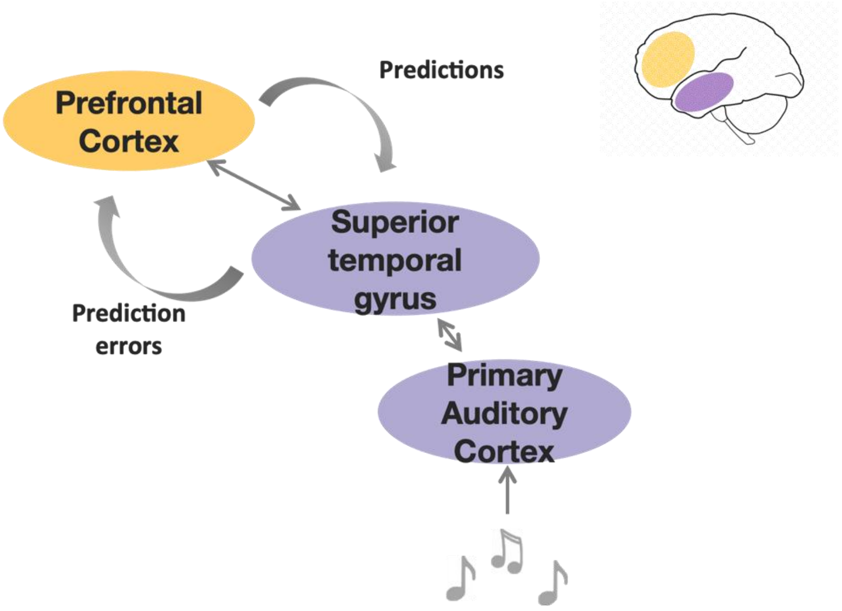


Kandel, E.R., et al., Principles of Neural Science (2013)

Source: TeachMeAnatomy

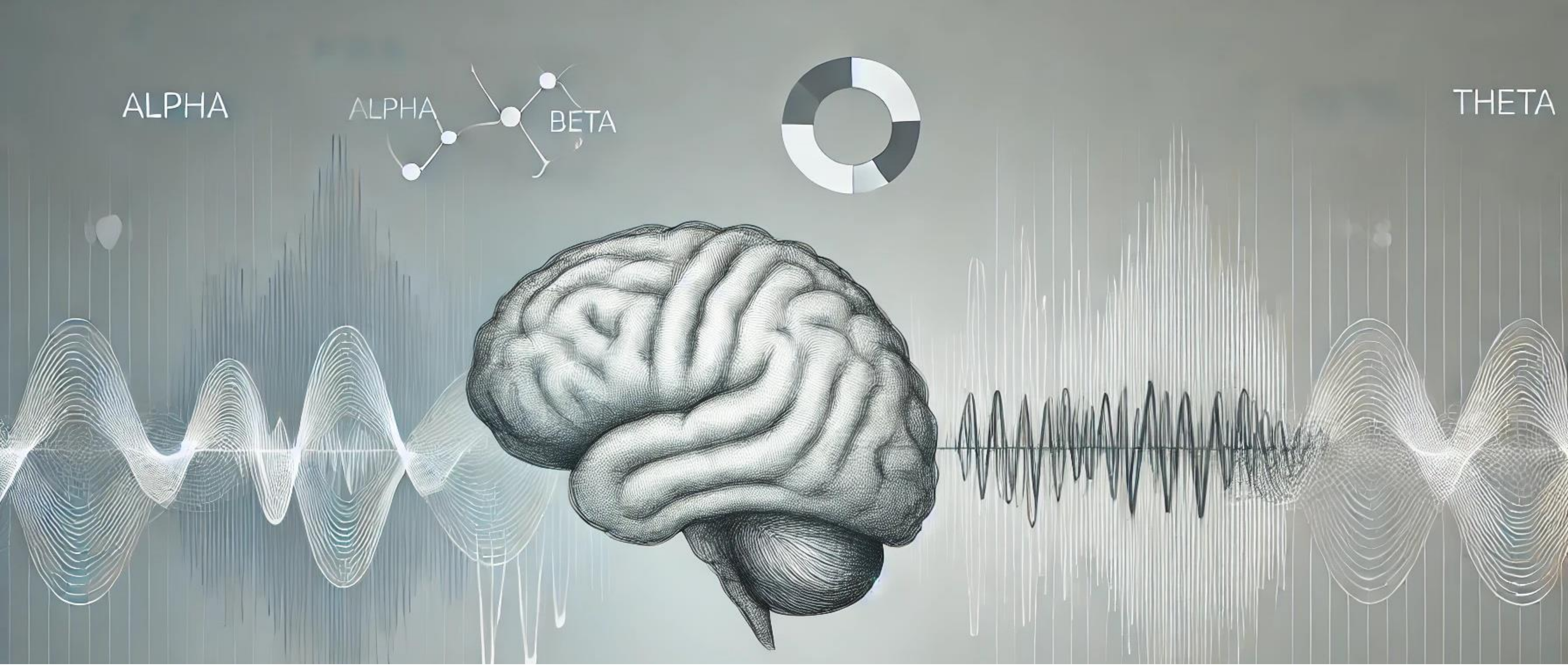
- From the ear, sounds arrive at the brain stem and from there to the auditory cortex in the temporal lobe
- The auditory cortex is organized “tonotopically”: specific parts map to particular frequencies

Not just auditory cortex



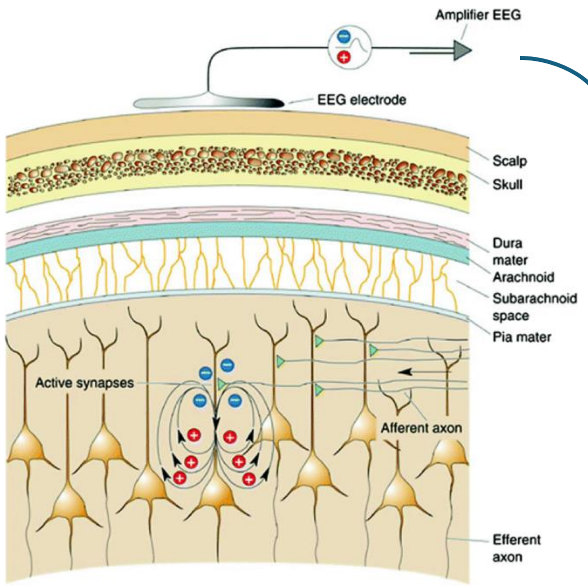
Garrido et al., 2009; Boly et al., 2011; Auksztulewicz & Friston, 2015; Chennu et al., 2016; Durschmidt et al., 2016

- Sounds are then processed by a widespread network of areas in temporal and frontal lobes
- They are further processed according to “predictive coding”: predictions and prediction errors

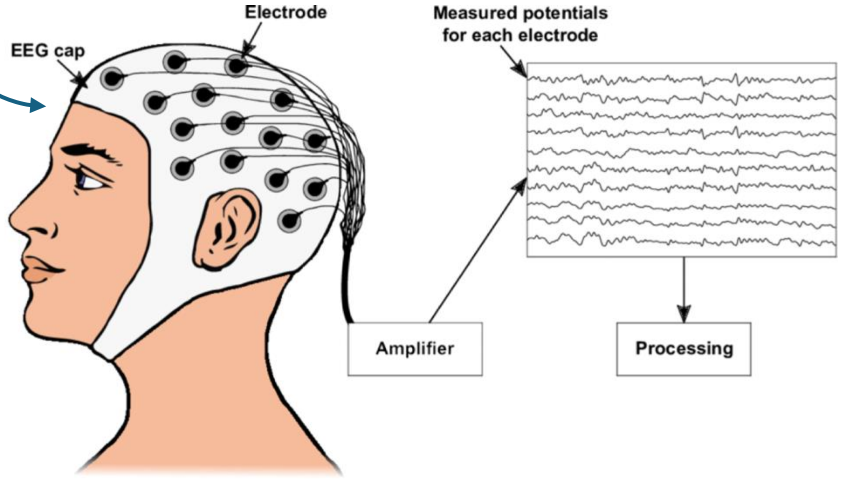


Brain responses to sound

EEG: measuring brain signals



Siuly et al. (2017)

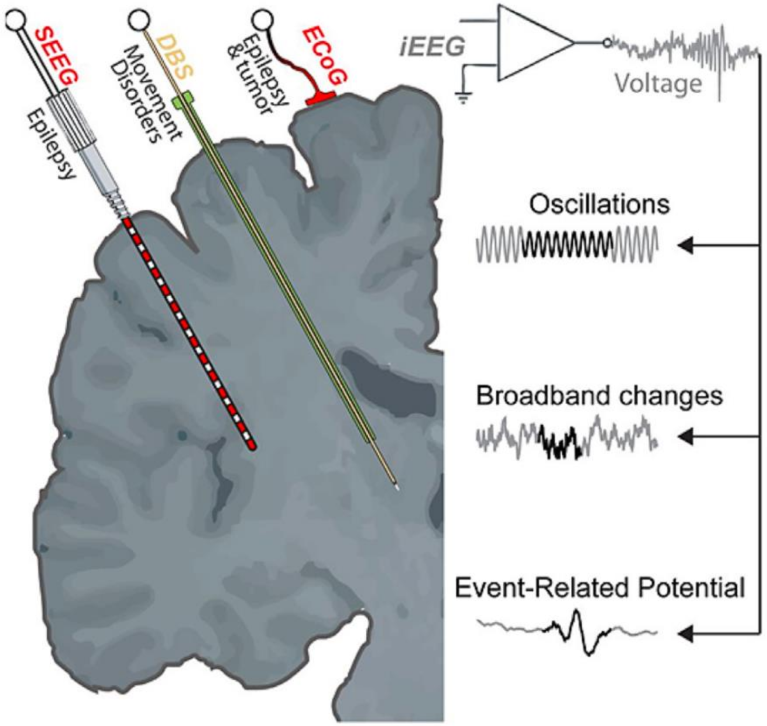


Nagel et al. (2019)

- Neural activity generate electrical currents that can be picked up by electrodes

- The electroencephalogram (EEG) measures this signal at different locations

Intracranial EEG

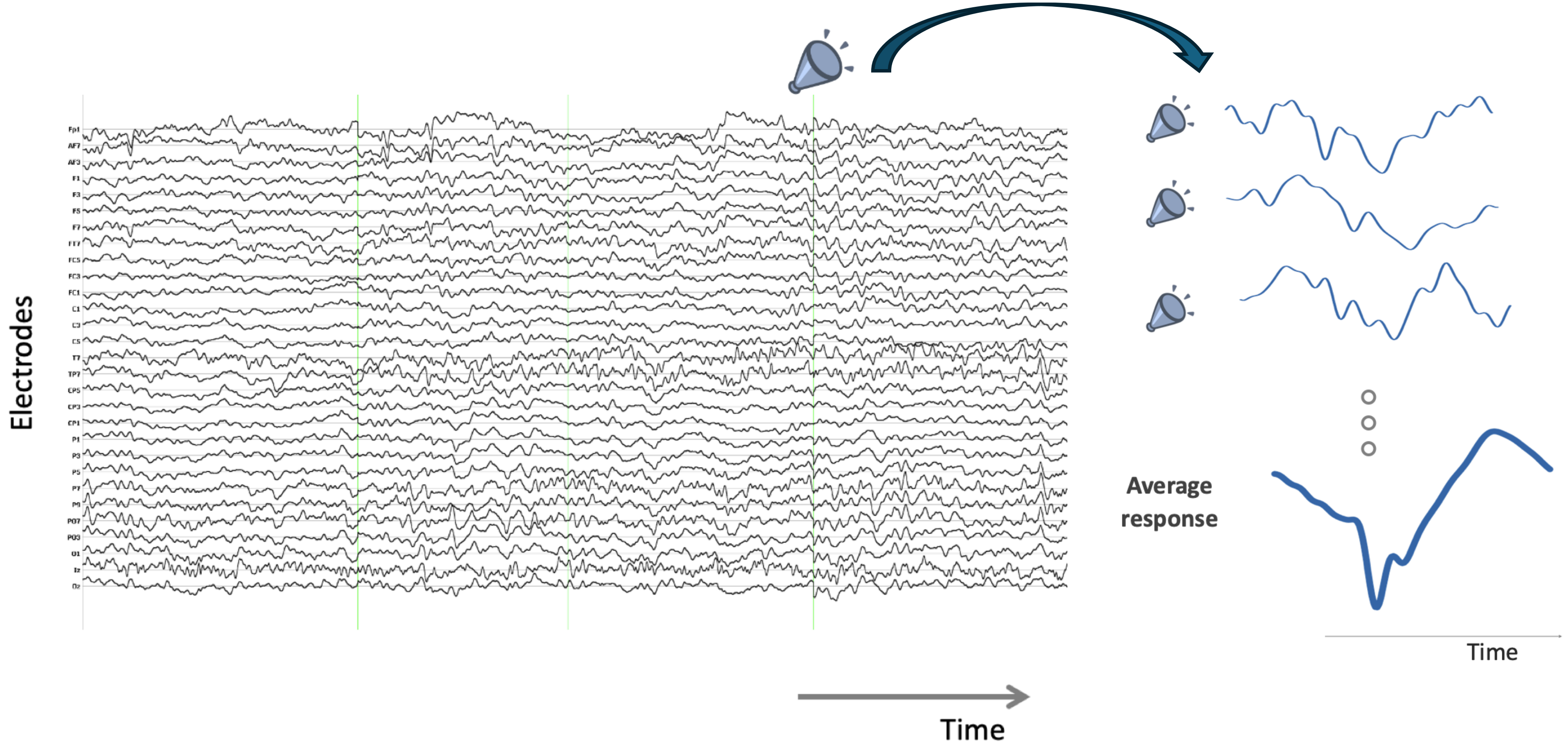


Mercier et al. (2022)

Source: ketteringhealth.org

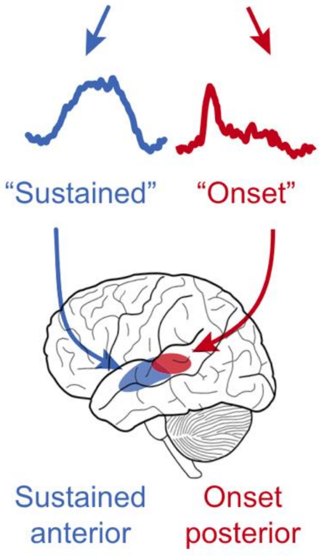
- Epilepsy patients who need surgery are implanted with electrodes directly in the brain
- We can study neural activity in greater detail

Average responses

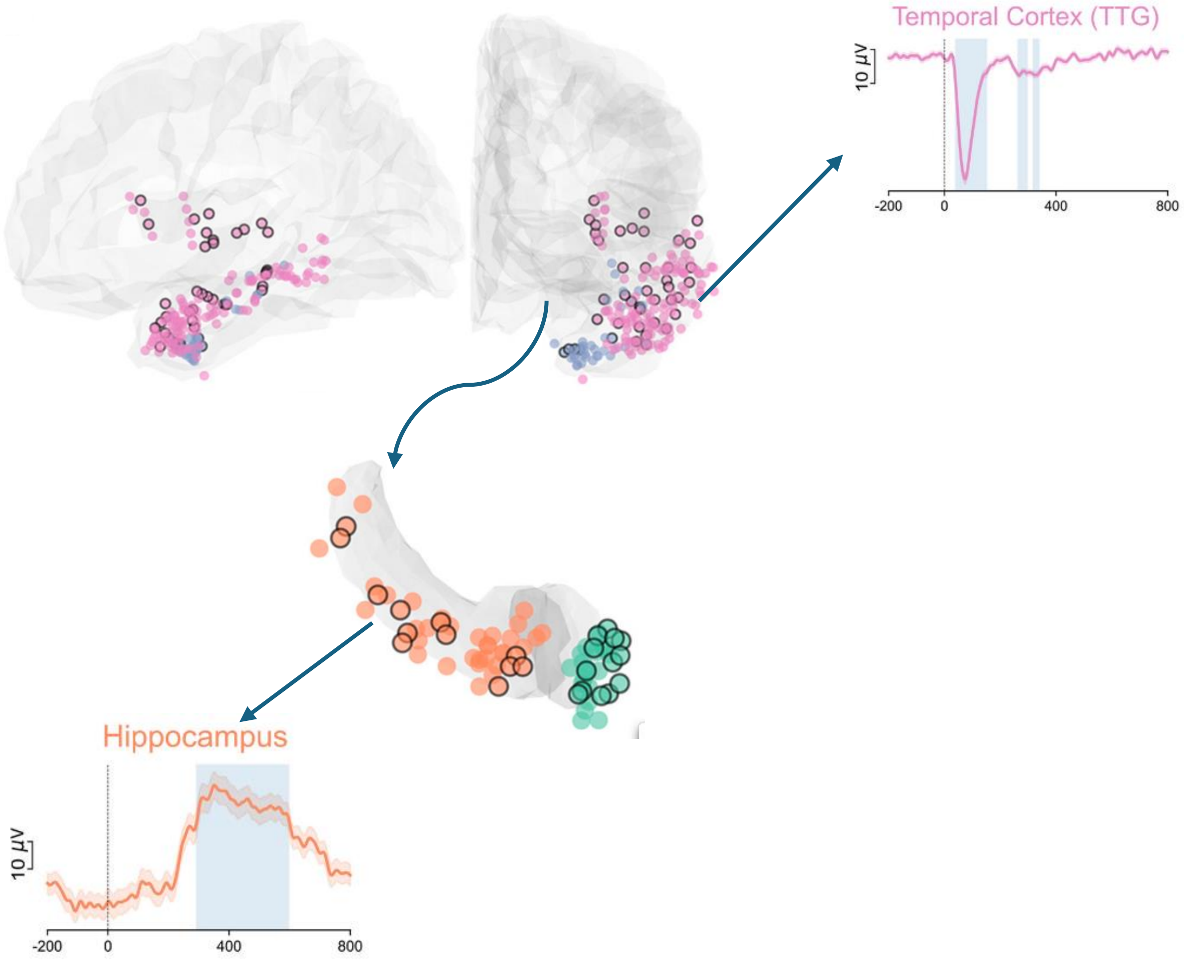


- Brain signals are noisy and complex
- We need to collect many trials and average the response

Auditory responses across the brain



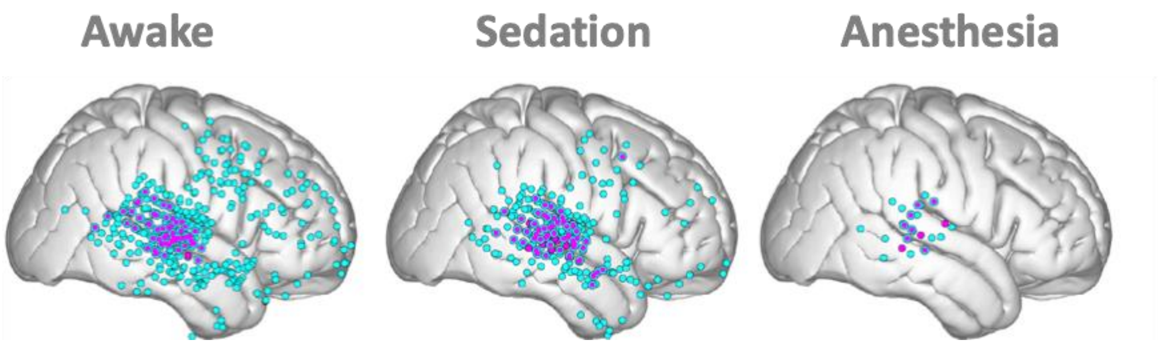
Hamilton et al. (2018)



- We can study the properties of auditory responses in different brain areas
- Understand which areas are involved and the characteristics of a healthy brain

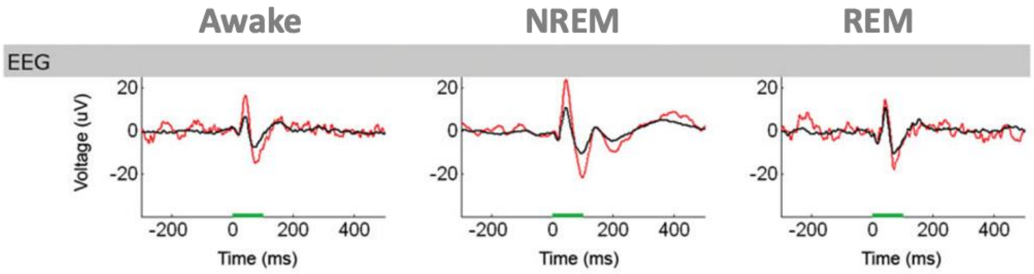
Cusinato et al. (2023)

Study of consciousness



Nourski et al. (2018)

Sleep

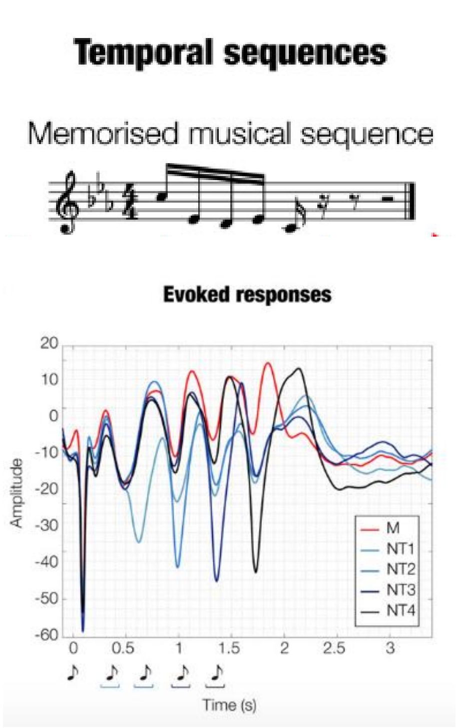


Nir et al. (2015)

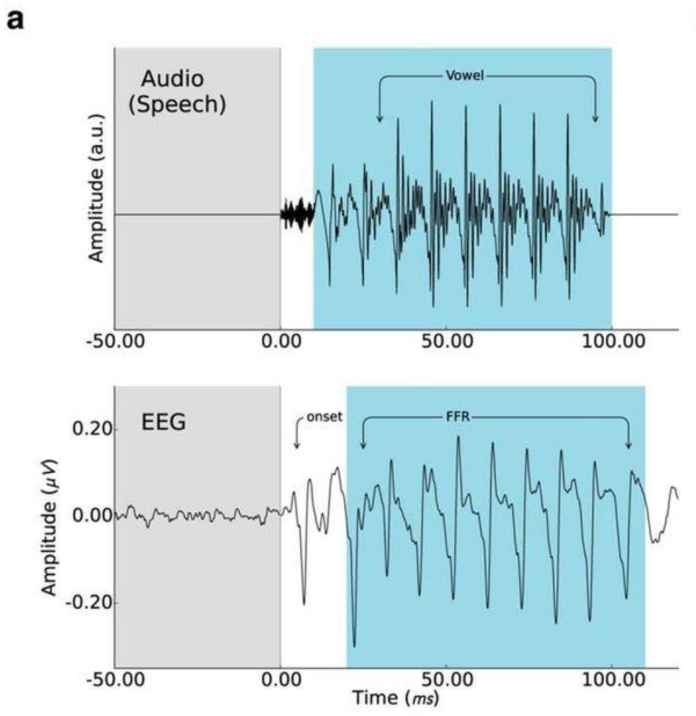
- Auditory responses are a useful tool to study auditory processing in altered states of consciousness, e.g. , anesthesia and sleep

- Can give scientific and clinical insights

Responses to complex sounds – music & speech



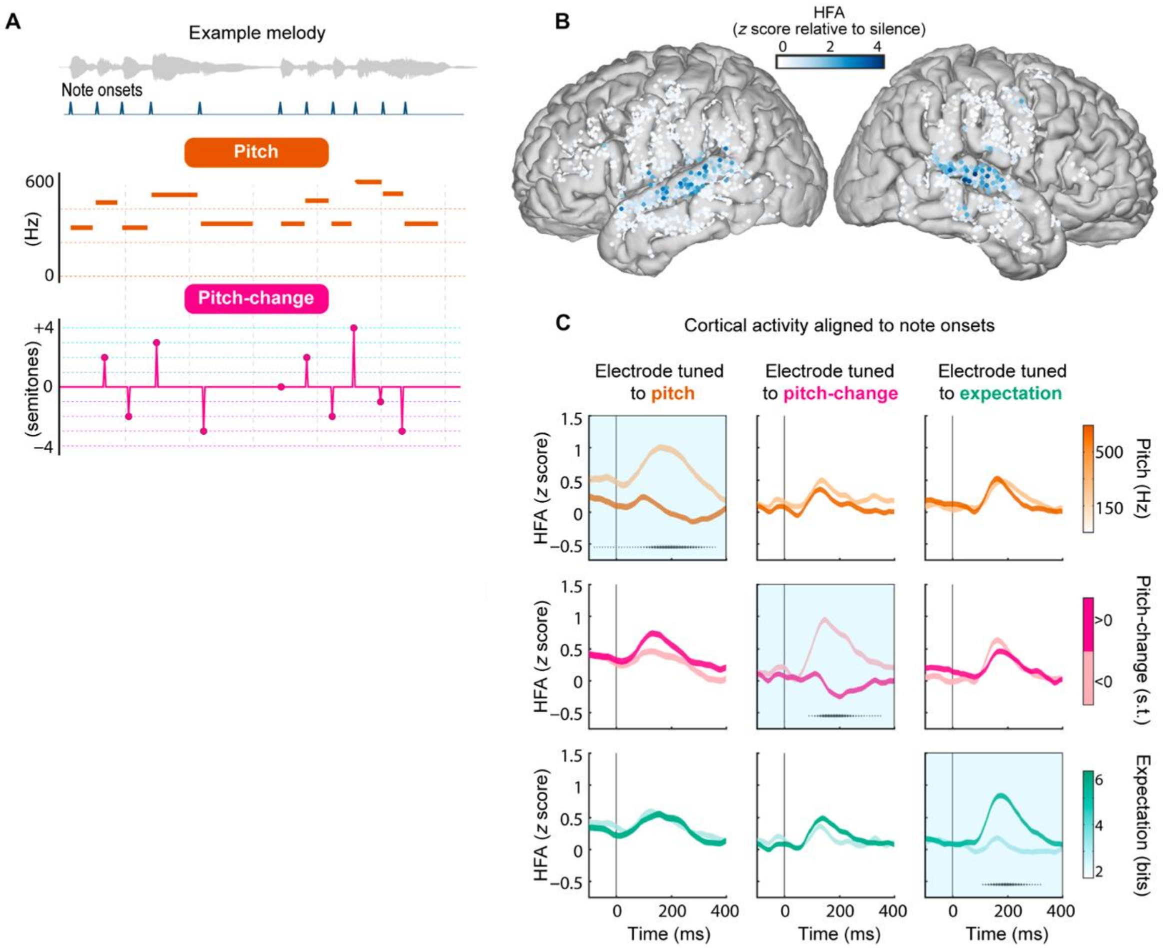
Bonetti et al. (2023)



Coffey et al. (2017)

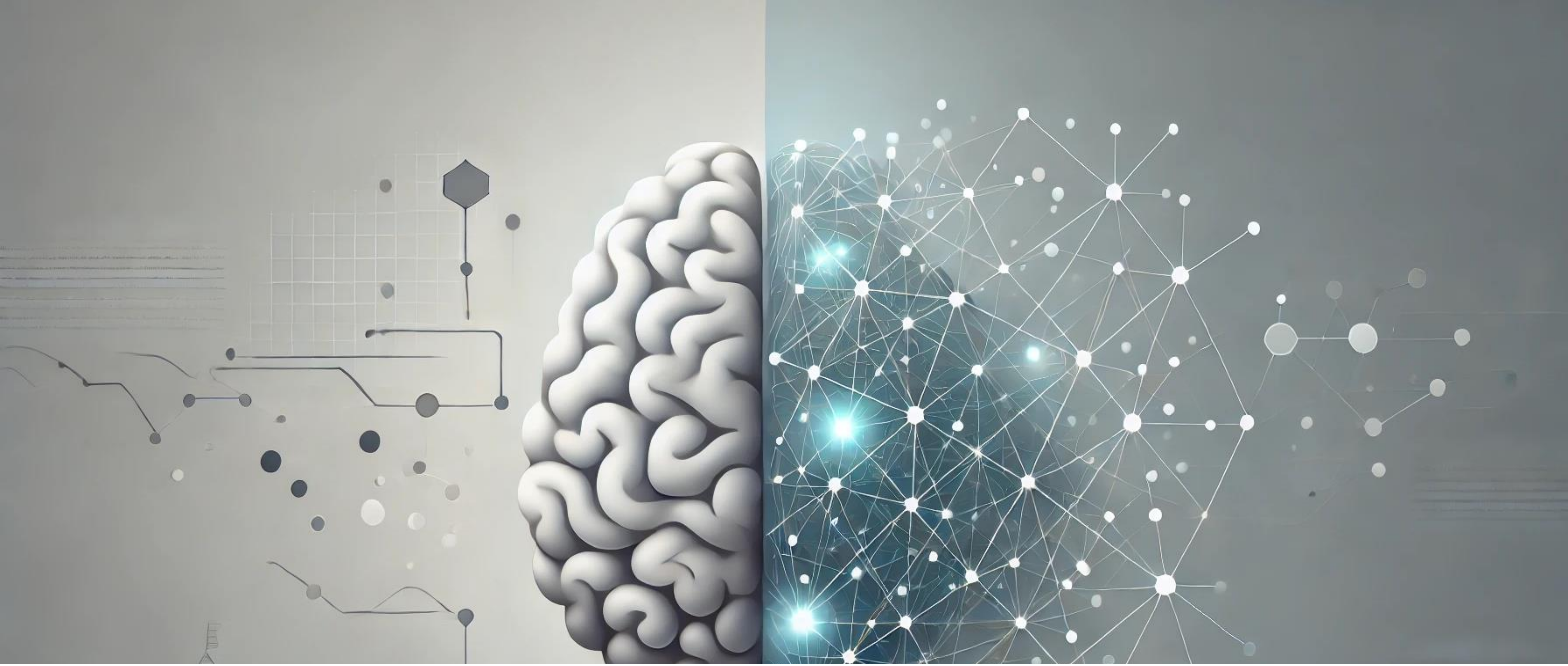
- Music and speech possess many more acoustic components, but also some regularities
- In certain cases, we might see responses to each note/letter ...

Responses to complex sounds – music & speech



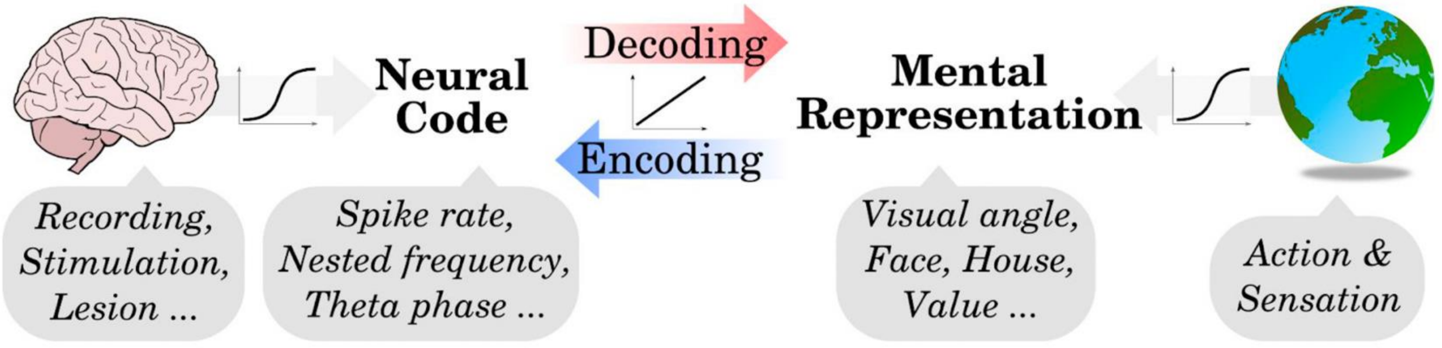
- But more often brain responses are complicated and influenced by many features
- E.g. pitch, changes, expectations (predictions)

Sankaran et al. (2024)

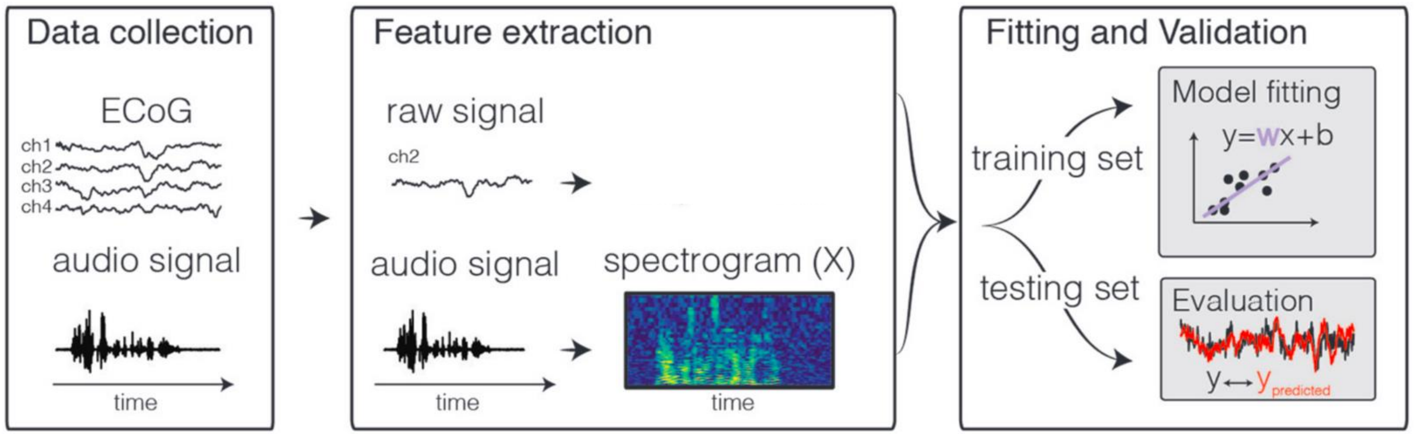


AI in auditory neuroscience

Encoding and decoding models



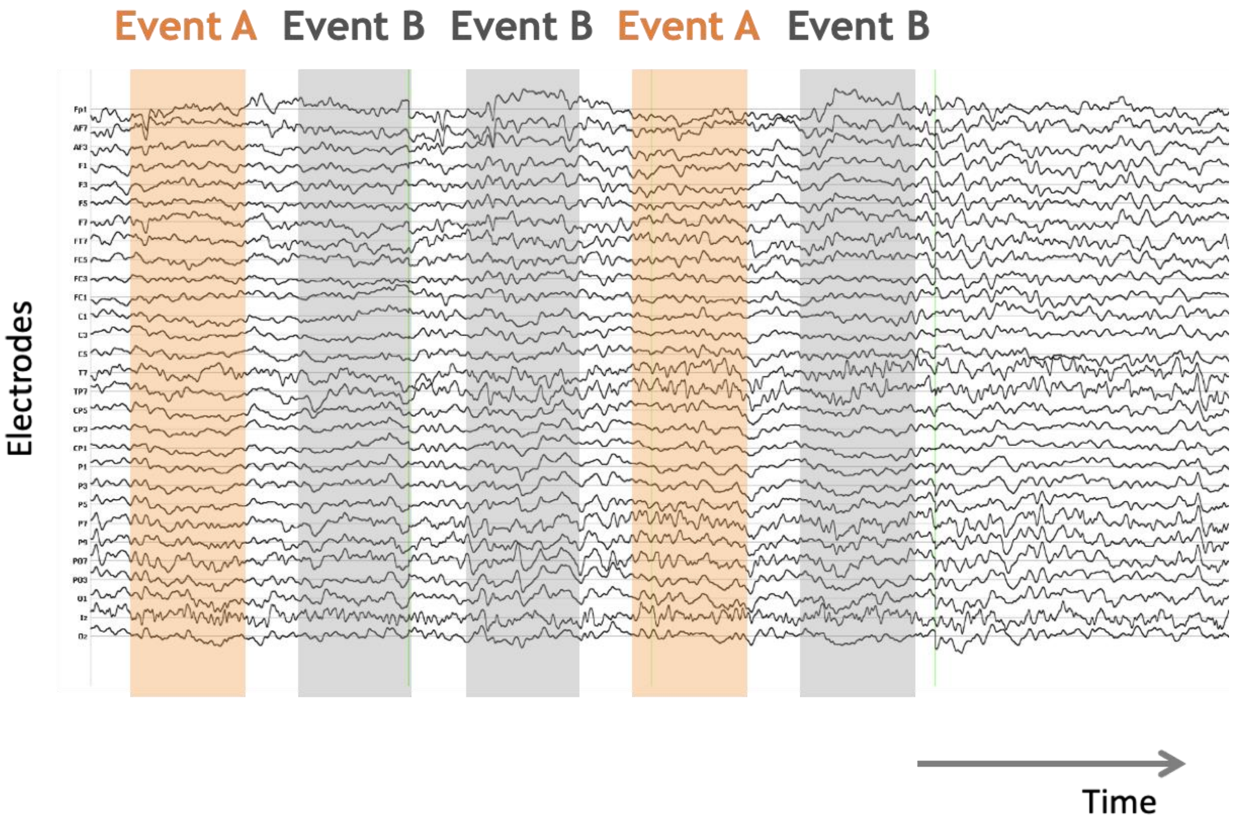
King et al. (2018)



Holdgraf et al. (2017)

- A big goal of neuroscience is understanding the “neural code”: how the brain represents objects and abstractions
- Machine learning can help linking brain processes to representations
- Quick ML recap:
    - we train a model on some data...
    - ...and test the performance on other data

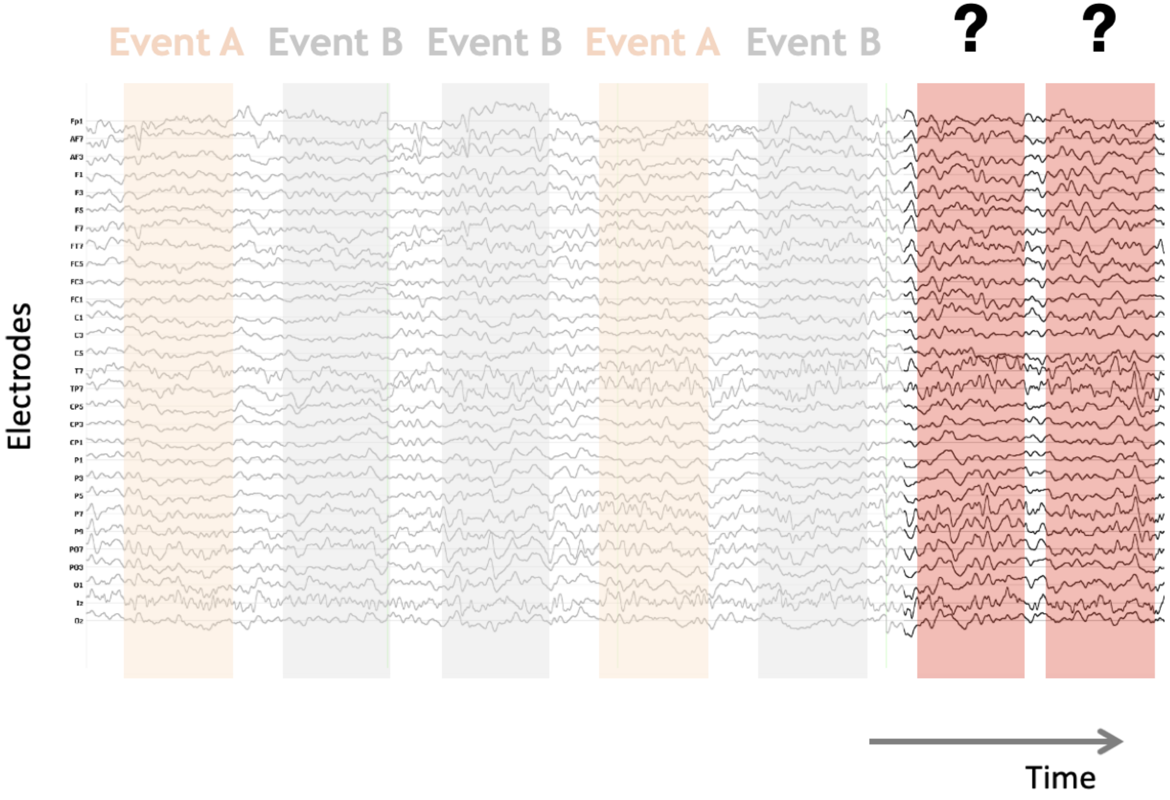
Quick machine learning recap

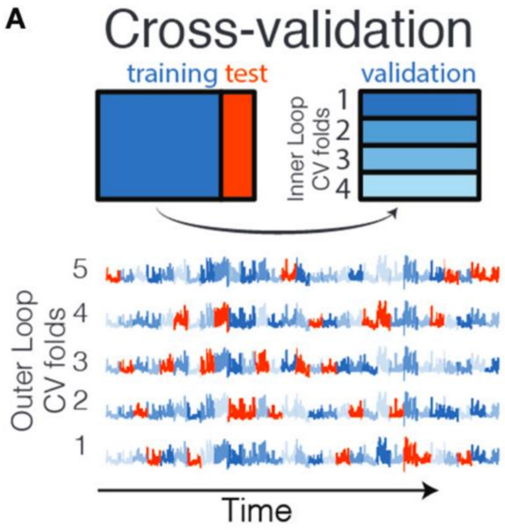


- We detect events in our data
  - sounds
  - visual stimuli
  - healthy vs pathological

- Focusing on known labels we build a mathematical model representing data patterns

Quick machine learning recap

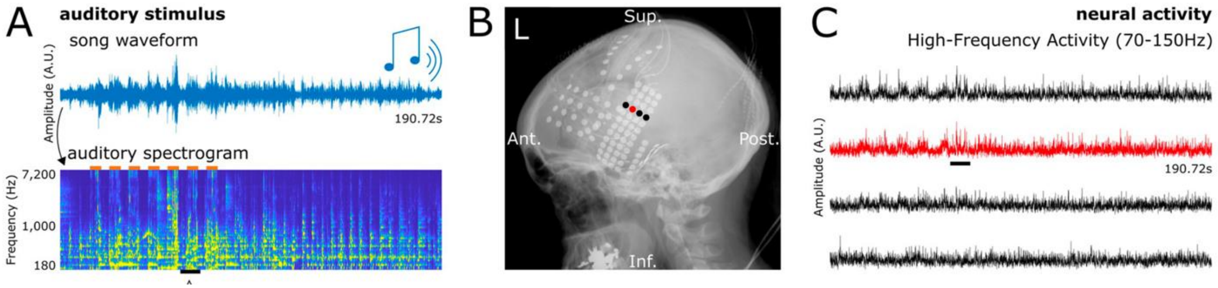


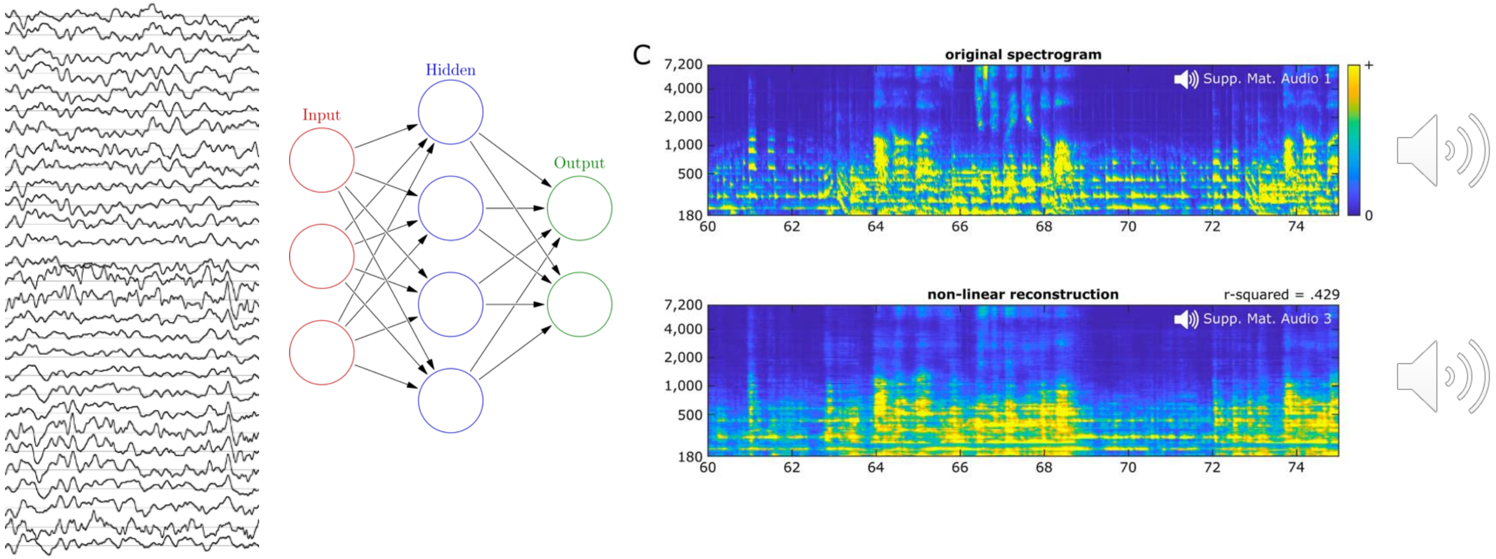


Holdgraf et al. (2017)

- We then always test the model on unseen data
- And ask it to predict new labels

Reconstruction music from EEG

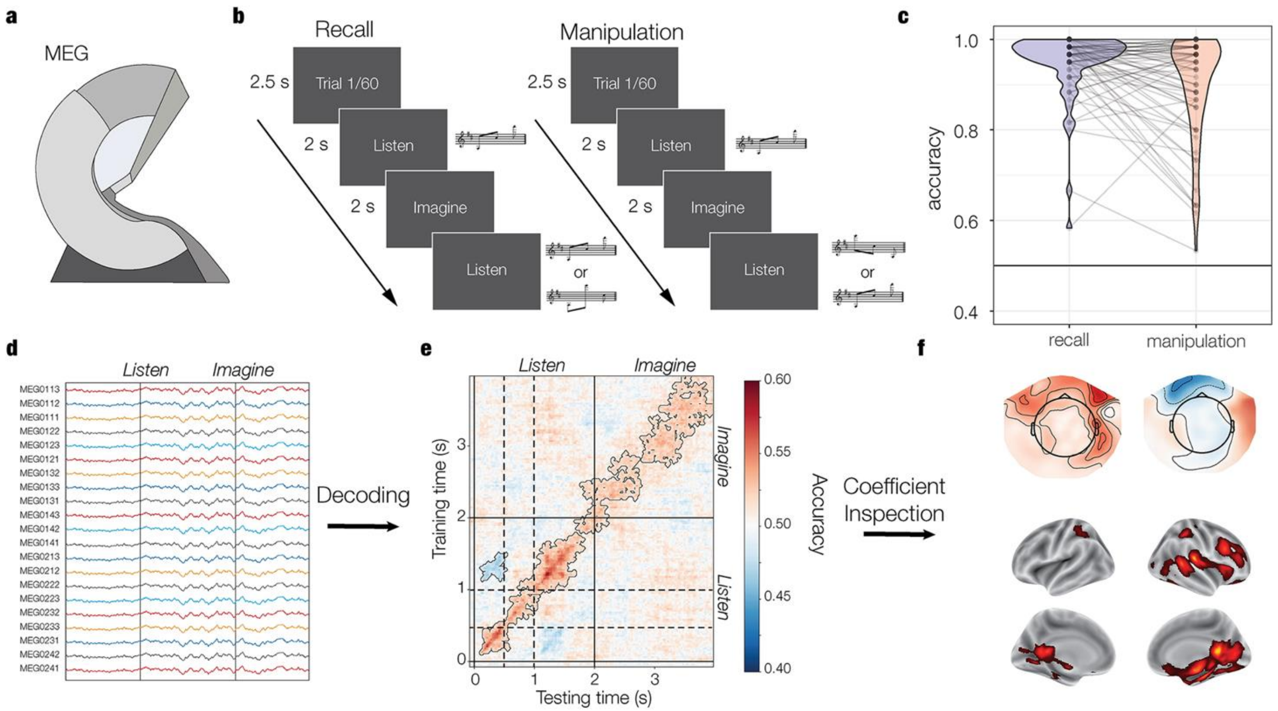




- Using a song as our “events” (stimulus), we can train a model to link audio and brain activity
- Brain activity recorded with intracranial EEG

Bellier et al. (2023), Plos Biology

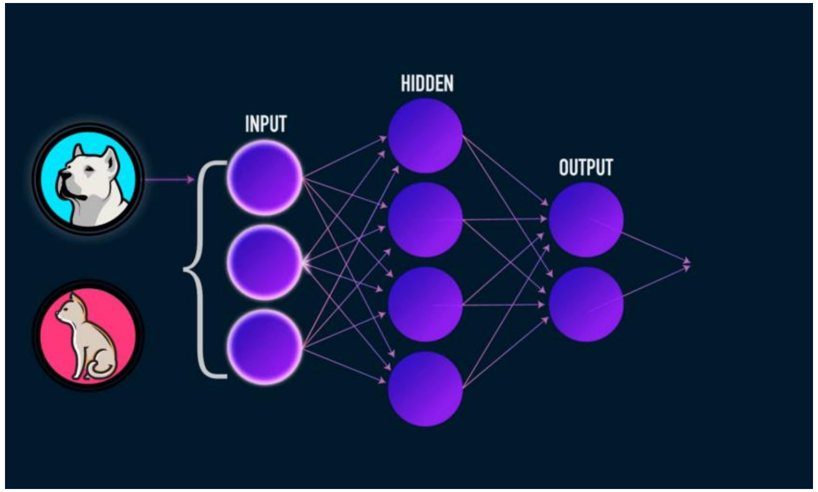
Decoding imagined sounds



Quiroga-Martinez et al. (2024), Plos Biology

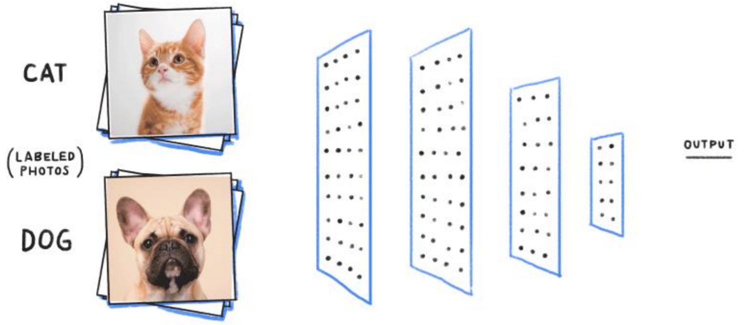
- We can also go as far as decoding people's "thoughts"
- Here, people listened and imagined 3 notes
- Model coefficients allow to localize activation patterns

Artificial neural networks

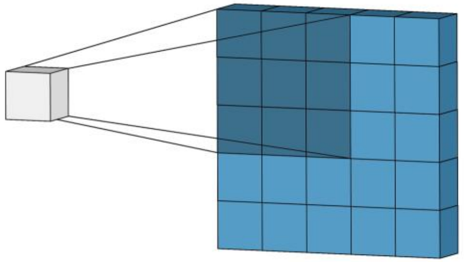


Source: Medium.com Terry-Jack

Convolutional NN



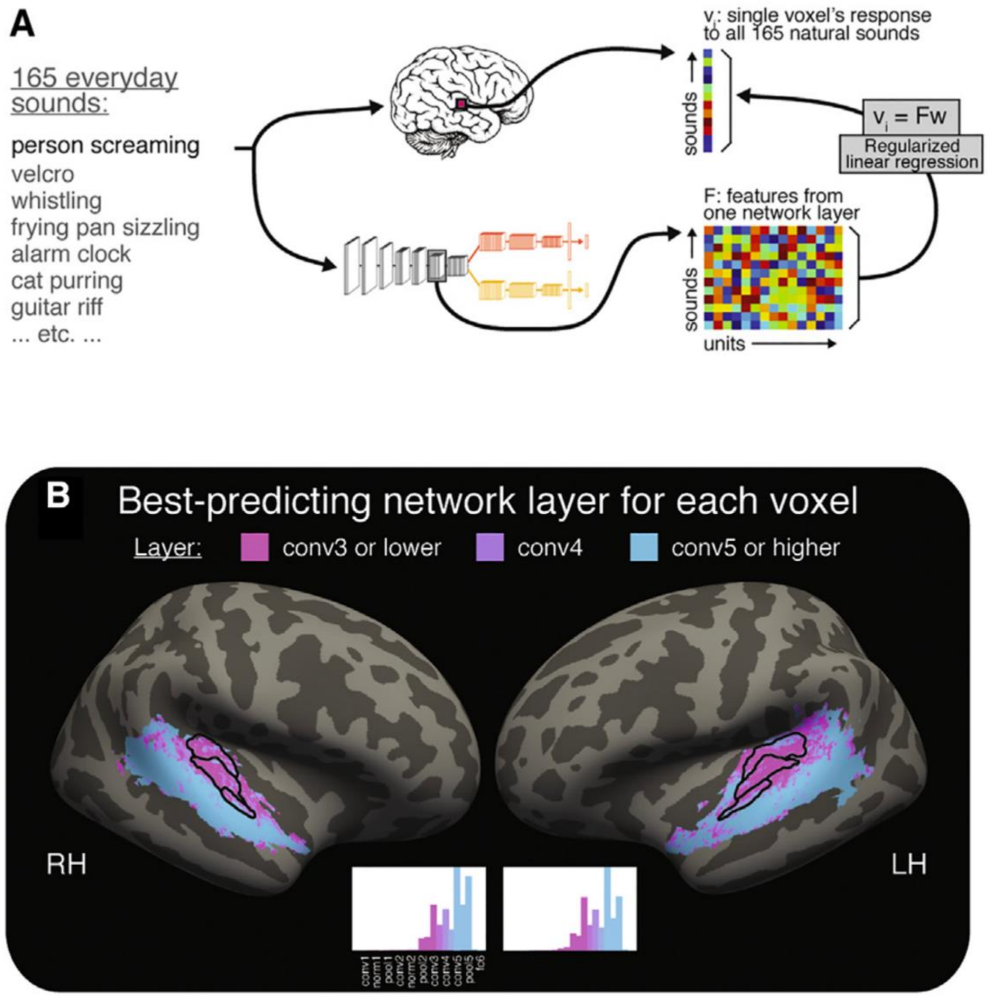
Source: Towardsdatascience.com Jiwon Jeong



Source: Towardsdatascience.com Mayank Mishra

- Artificial neural networks are powerful models that contain many “layers” and map inputs to outputs

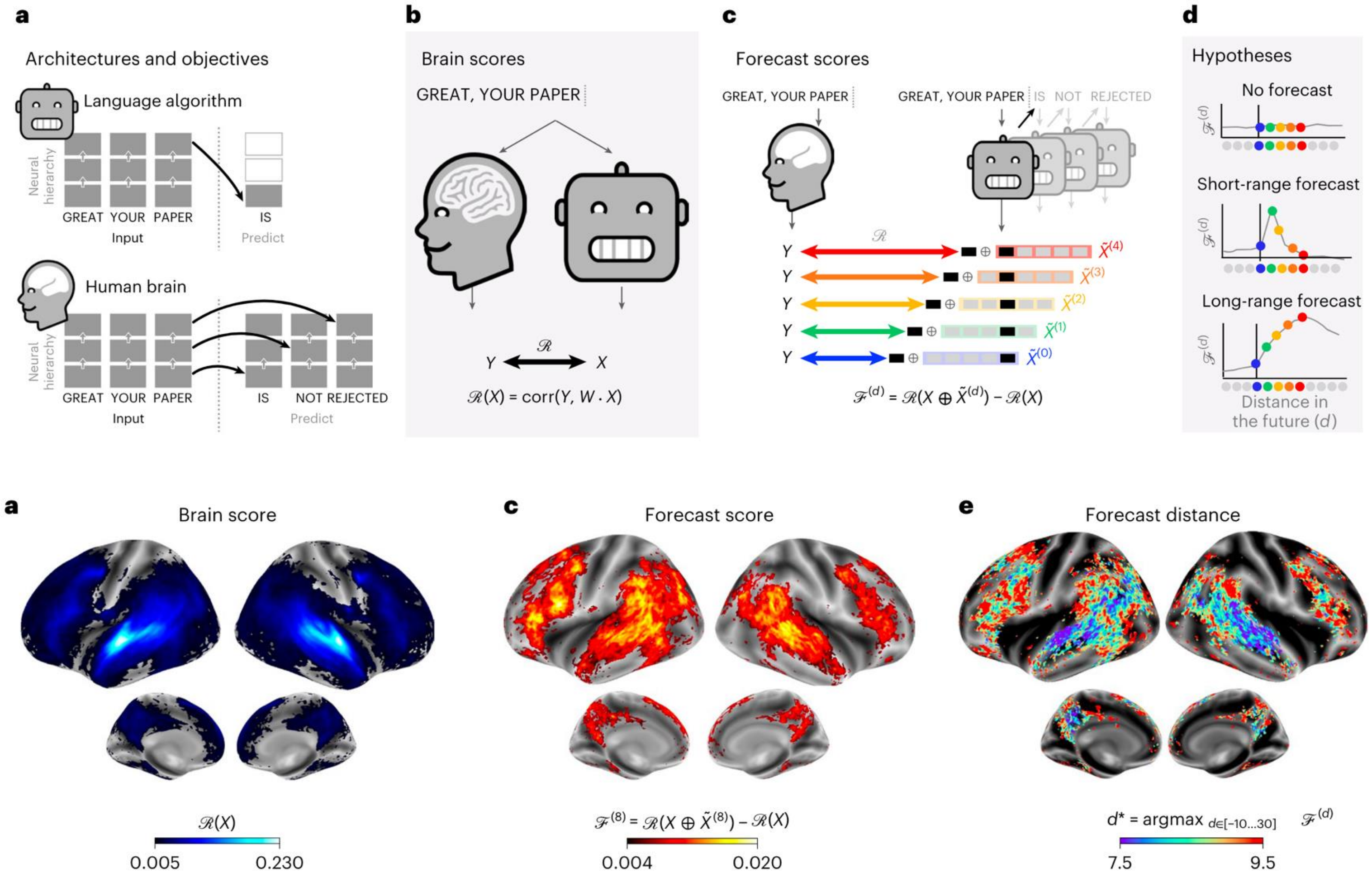
Artificial neural networks as sensory models



Kell et al. (2018)

- Given their power, artificial neural networks can be used as computational models of auditory processing, especially with complex stimuli
- Different layers can be mapped to different regions of the cortex
- Striking similarity between neural networks and brains

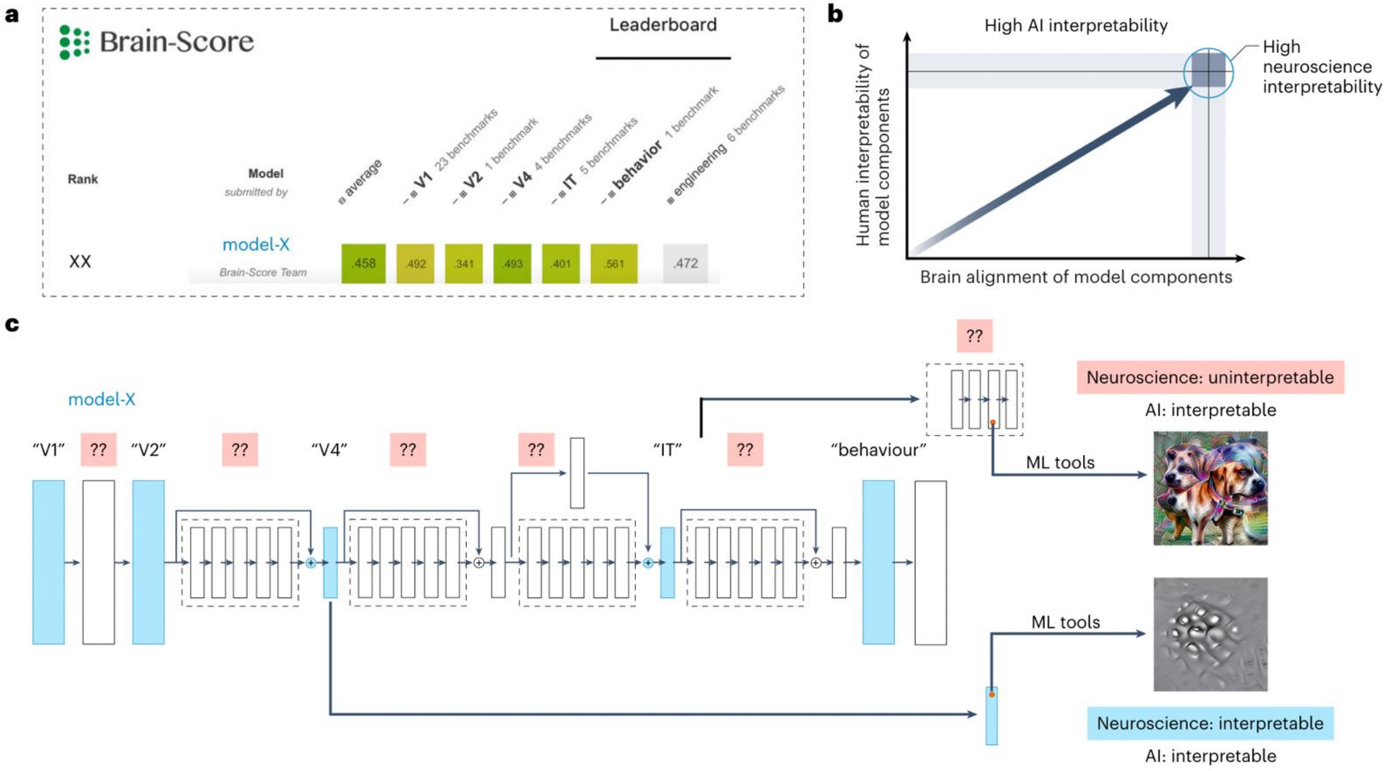
Hypothesis testing with artificial neural networks



Caucheteux et al. (2023)

- Artificial neural networks can also be used to test hypotheses about how the brain works
- With language, to map the language network
- Understand if the brain predicts next words and how far ahead

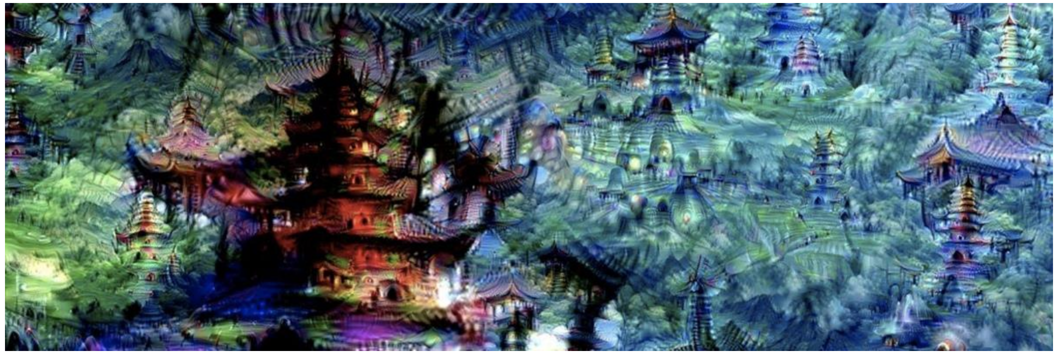
Artificial neural networks challenges: interpretability

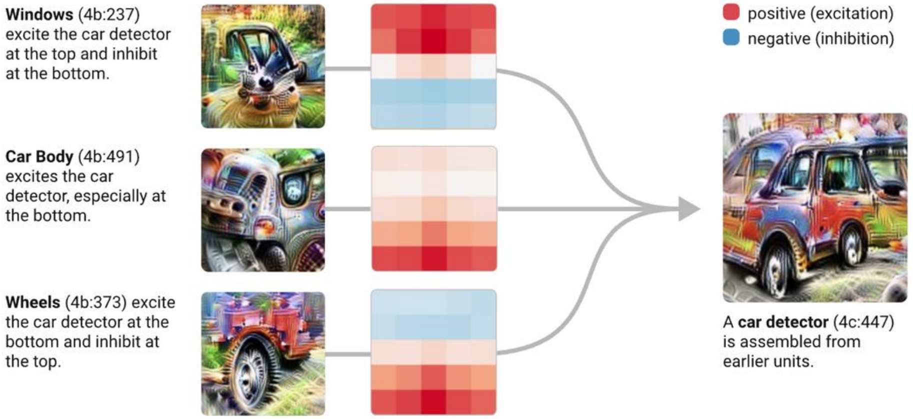


Kar et al. (2022)

- Although very powerful, artificial neural networks are still very incomplete models of the brain
- They are limited to some domains and have limited predictive power
- No one-to-one mapping between brain areas and network layers

Artificial neural networks challenges: interpretability





Olah et al. (2020)

- Progress is being made by studying the network's internal features
- And the mechanisms by which they get combined

See also: https://transformer-circuits.pub/2023/monosemantic-features/index.html#comment-nanda

Conclusions

- Neuroscientists can study how the brain processes sounds in great detail
- Different responses have been mapped to different cortical areas and can be studied with EEG
- New tools and approaches are needed to study more complex sounds (language, music...)
- Machine learning and artificial neural networks offer promising models...
- ...but research is still needed to validate them in the scientific context

Thank you for your attention!

Questions?

References / Further Reading

General encoding/decoding approach:
Encoding and Decoding Models in Cognitive Electrophysiology

Decoding for imagined sounds:
Decoding reveals the neural representation of perceived and imagined musical sounds (this is the one showed in the slides)
Imagined speech can be decoded from low- and cross-frequency intracranial EEG features (a similar study with speech, done by researchers in Geneva)
Decoding Imagined Sound (a longer tutorial)

Some efforts being done to decode speech:
A high-performance neuroprosthesis for speech decoding and avatar control
The speech neuroprosthesis (review article)
Brain implants that enable speech pass performance milestones (layman commentary)
Decoding speech perception from non-invasive brain recordings

Neural networks as sensory/cognitive models:
Using goal-driven deep learning models to understand sensory cortex (review article)
Cognitive computational neuroscience (review article, quite broad)
A Task-Optimized Neural Network Replicates Human Auditory Behavior, Predicts Brain Responses, and Reveals a Cortical Processing Hierarchy (a paper I presented)
Evidence of a predictive coding hierarchy in the human brain listening to speech (the other paper I showed, with hypotheses about speech predictions)
Driving and suppressing the human language network using large language models (very interesting study, showing how you can "change" brain activity based on networks predictions)
Shared functional specialization in transformer-based language models and the human brain (comparison of brain with transformers)

Adversarial attacks and sounds:
Learning from brains how to regularize machines (paper on how to use neural data to improve network's robustness)
Imperceptible, Robust, and Targeted Adversarial Examples for Automatic Speech Recognition (adversarial attacks can be done on audio)
Subtle adversarial image manipulations influence both human and machine perception (also humans get fooled sometimes)

Something on movies:
Slow Cortical Dynamics and the Accumulation of Information over Long Timescales
Movie reconstruction from mouse visual cortex activity

Something on emotions:
Visual and auditory brain areas share a representational structure that supports emotion perception (ML used to decode activity related to emotional content)

Other:
Large language models surpass human experts in predicting neuroscience results (nice recent papers showing how neural networks are much better predicting the content of a neuroscience paper)