Cognitive Science and AI

Introduction

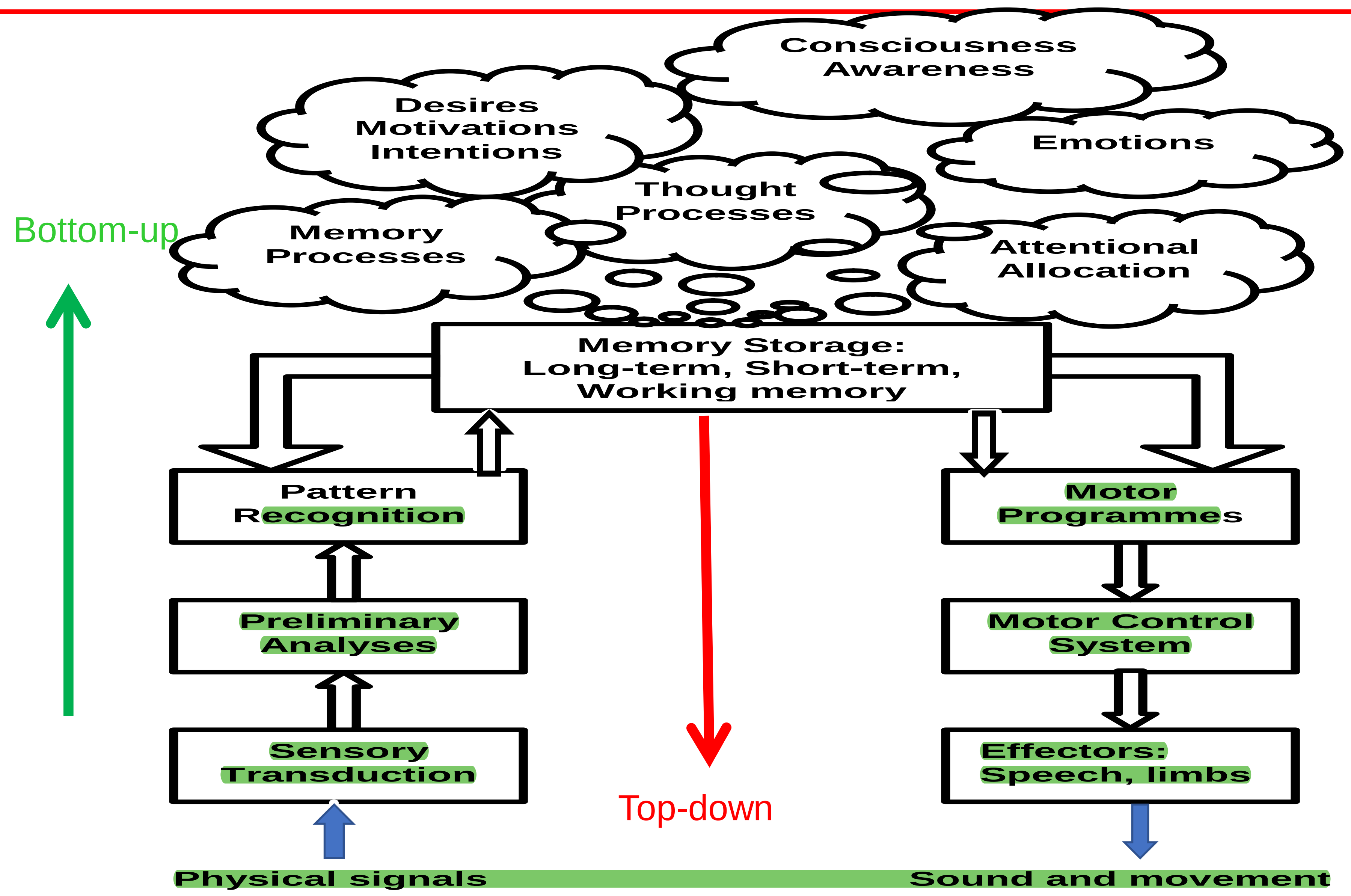
Preamble

- The goal of cognitive science is to understand the principles of intelligence with the hope that this will lead to a better comprehension of the mind and of learning and to develop intelligent devices. [Wikipedia: Cognitive Science]

- To elucidate the principles of organization in the brain and how they translate to algorithms for building intelligent systems

- Computational Representational Understanding of Mind (CRUM)
    - The central hypothesis of cognitive science is that thinking can best be understood in terms of representational structures in the mind and computational processes that operate on those structures. (Thagard)

Human Information Processing System



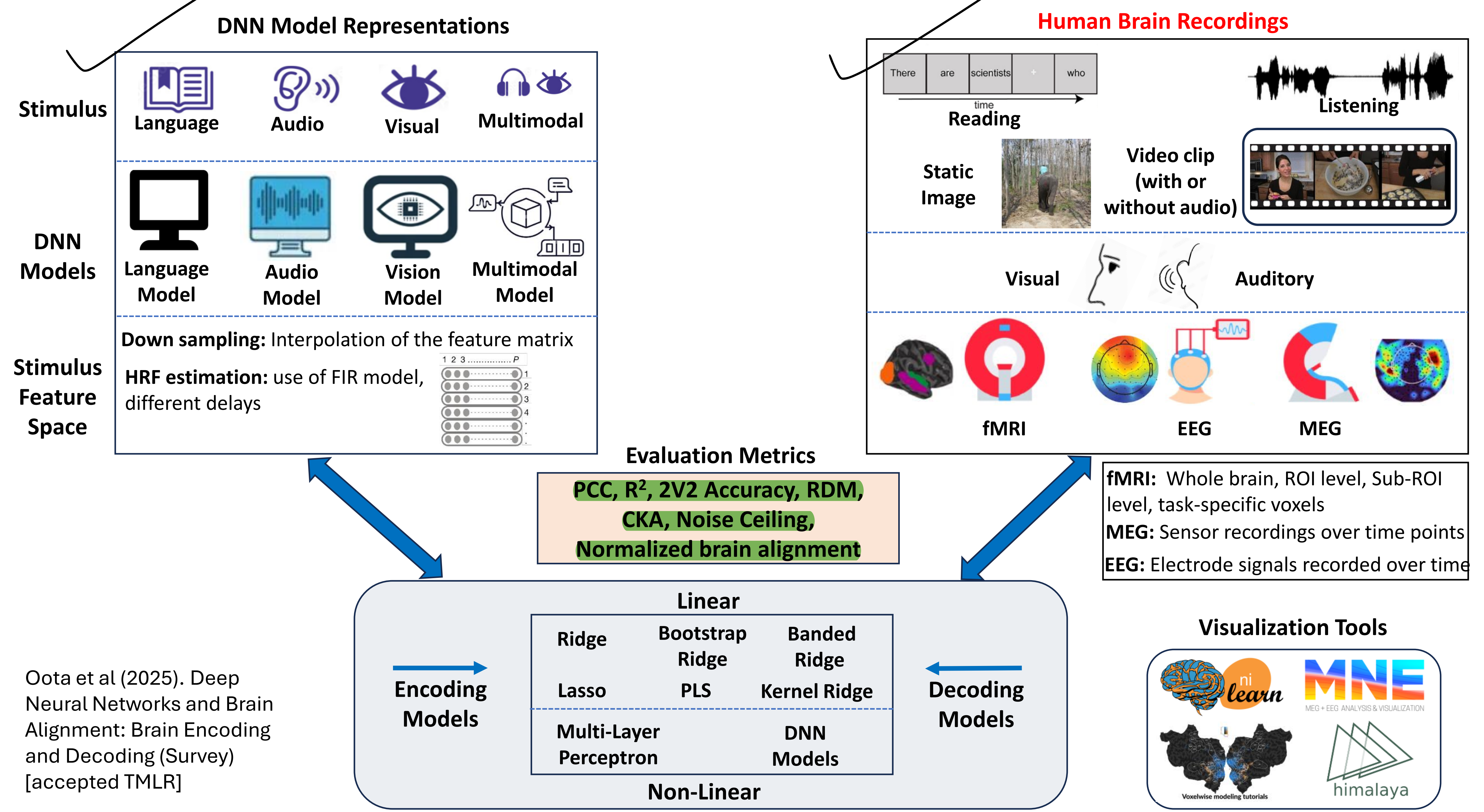
What are the representations and computations that operate between the stimulus and the response?

Aim of the Course

- * What are the representations and computations that the brain/mind performs and
- ** how do they compare with AI solutions?
- *** What is the gap? Is there an opportunity?
- Course Goals:
  - Emphasis on understanding the current status on * (Lectures)
  - Open exploration and Reflection on ** and *** and debates thereof (Presentations, Project)
  - Give hands-on experience in addressing these questions on real brain data

Course Outline

- Sensation-Perception
- Vision
- Language and Speech
- Motor Systems
- Other topics:
  - Learning & Memory, Attention, Decision Making, Emotions, Consciousness
  - Compositionality, Causality, Learning-to-learn (Meta Learning)
  - Structure-to-Function, Development and Ageing
  - Representational Similarity Analysis (RSA)
  - Predictive Coding and Bayesian Brain



Oota et al (2025). Deep Neural Networks and Brain Alignment: Brain Encoding and Decoding (Survey) [accepted TMLR]

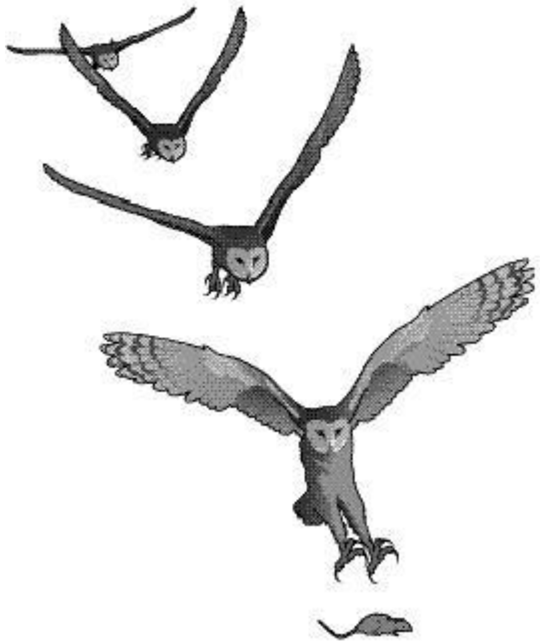
https://openreview.net/pdf?id=YxKJihRcby

Course Logistics

- Assignments (6-7): 35%
  - ~4-5 using NILearn (fMRI) and MNE-Python (EEG/MEG)
  - ~2 on Brain Encoding and Decoding
- Presentations: 5% (Presentation + Summary Report)
  - 2 Presentations per class (starting from 3rd week)
  - 20 mins each presentation.
  - Groups of 2 per presentation.
- Project: (30%)
  - Groups of 3 per project (Stimulus Repr; NI response; Model & Eval)
- Quizzes (2x5): 10%
- Mid-Sem: 20%

Marr’s Three Levels of Understanding

- Marr & Poggio program for understanding cognitive/computational systems (including brains).
- Example: sound localization in the barn owl (*Tyto alba*)



Example from: Shimon Edelman, Computing the Mind: : How the Mind Really Works, OUP, 2008 (Ch 4.2: pp 69-77)

The barn owl: hunting behavior

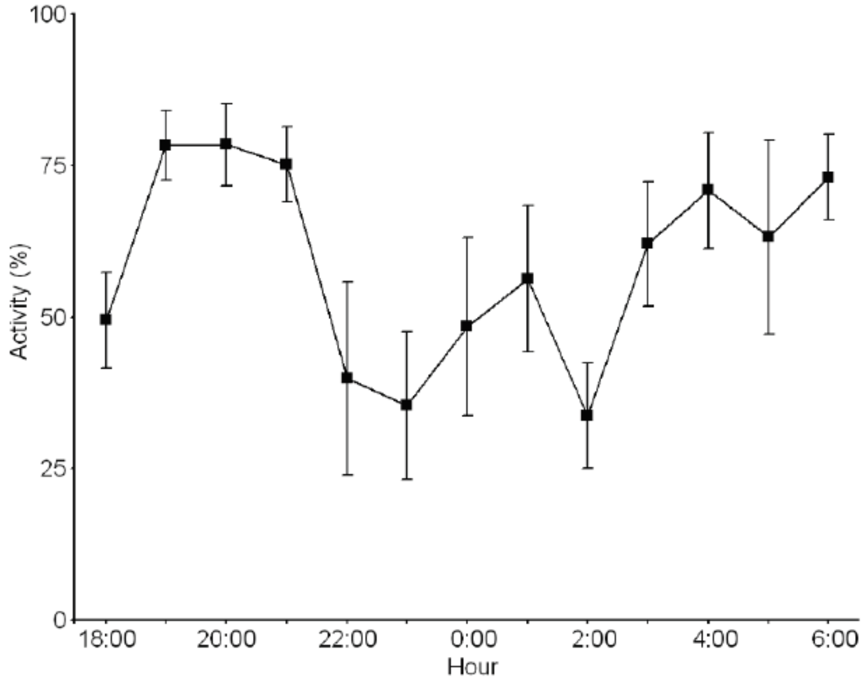


Figure 3. Mean (± SE) activity level of a Common Barn-owl (*Tyto alba*) instrumented with a GPS pet tracker device in an agroecosystem in Argentinean's rolling pampas during the period of data collection.

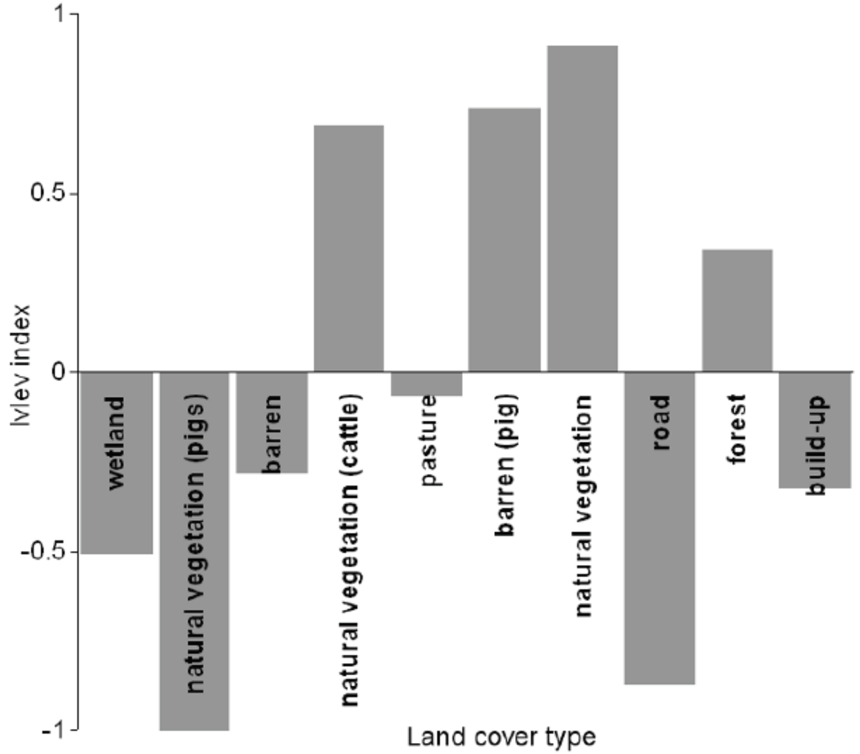


Figure 4. Values of the Ivlev's Electivity Index estimating land cover type selection by a Common Barn-owl (*Tyto alba*) instrumented with a GPS pet tracker device in an agroecosystem in Argentinean's rolling pampas.

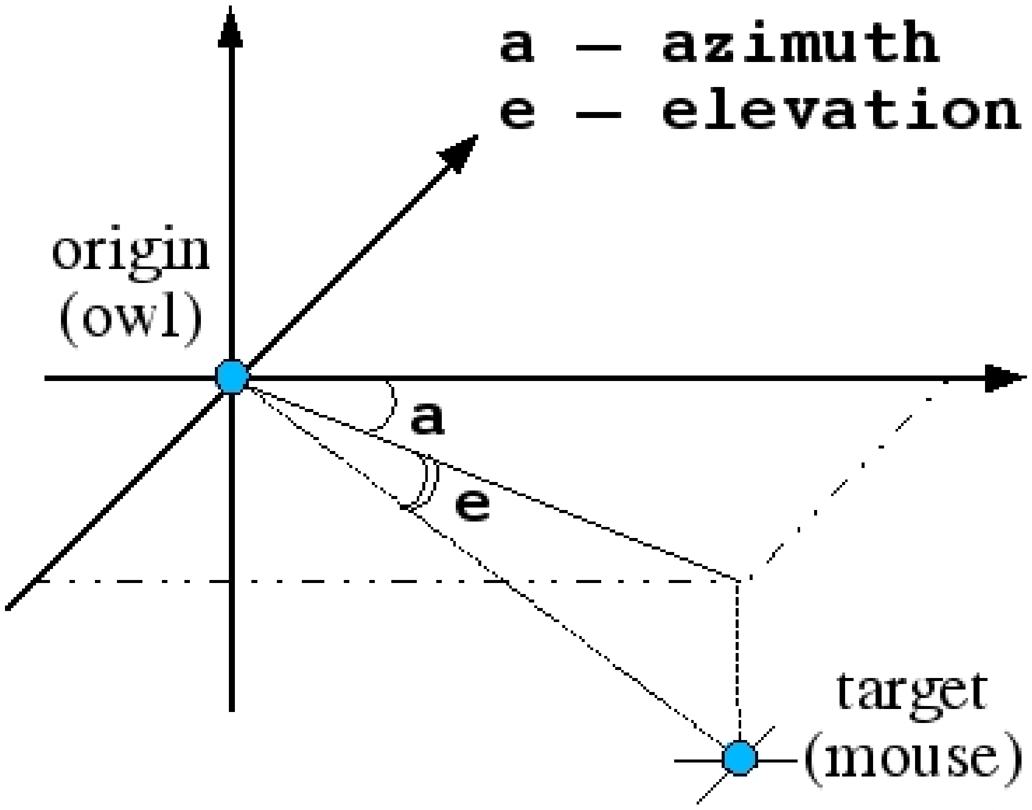
Tracking owls with GPS (Massa et al., 2015). Left: activity by time of night. Right: preferred terrain type.

The hunting owl

In the wild, the barn owl finds and catches mice in total darkness, presumably by homing in on the sound of their movement.

barn owl — posing the computational challenge

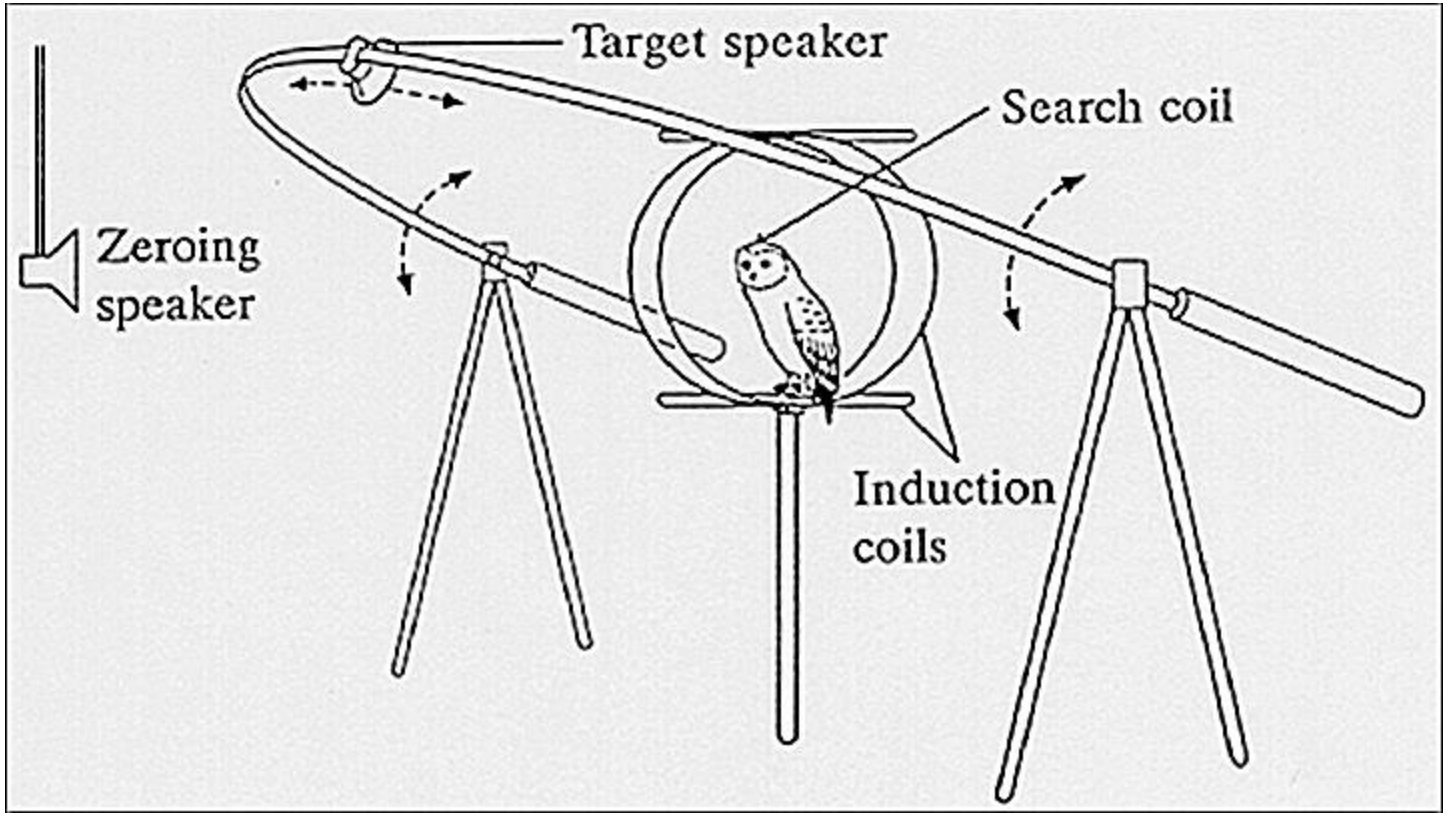
- Level 1 (the computational problem):
  - What is it that needs to be done for the hunting behavior to succeed?
    - **find target coordinates (azimuth, elevation)**



barn owl — a classical experimental setup for behavioural study of sound localization

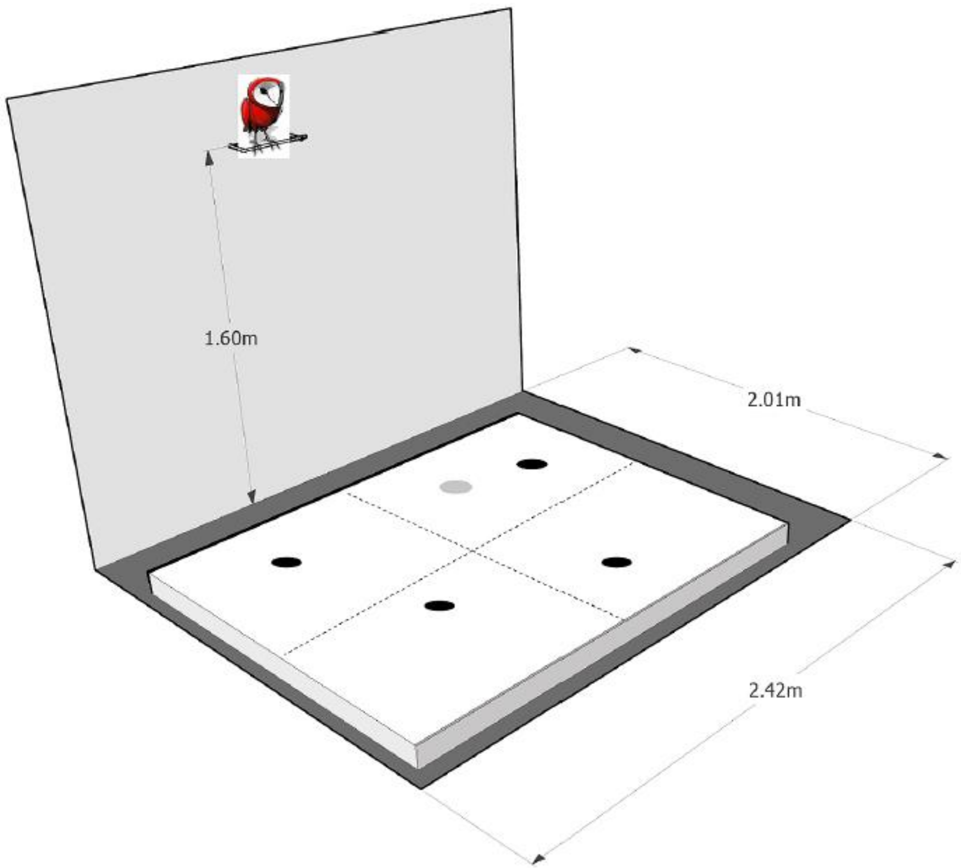
To address Levels 2 (representation and algorithm) and 3 (mechanism), controlled experimentation is required.

The diagram on the right illustrates the behavioral testing setup.



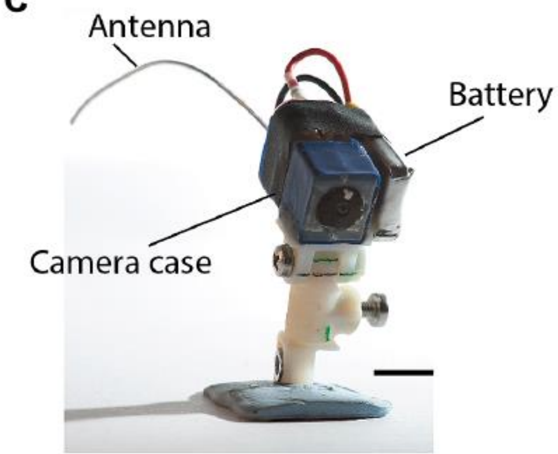
the barn owl: a recent behavioral study of sound+vision localization IN THE LAB

A



B

C



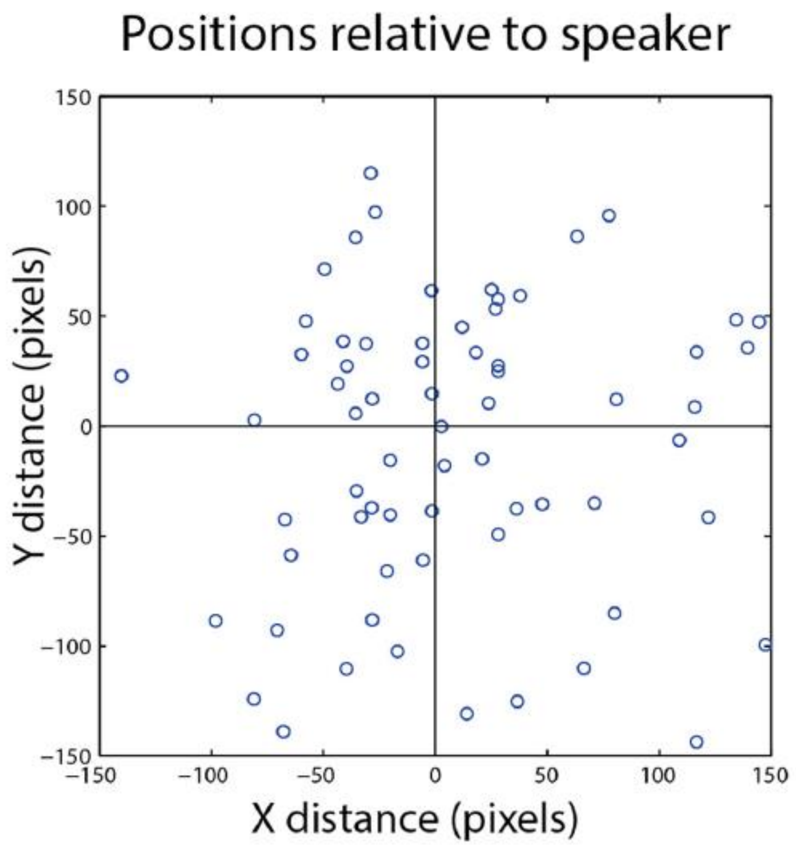
(B) An owl with the OwlCam attached to its head.

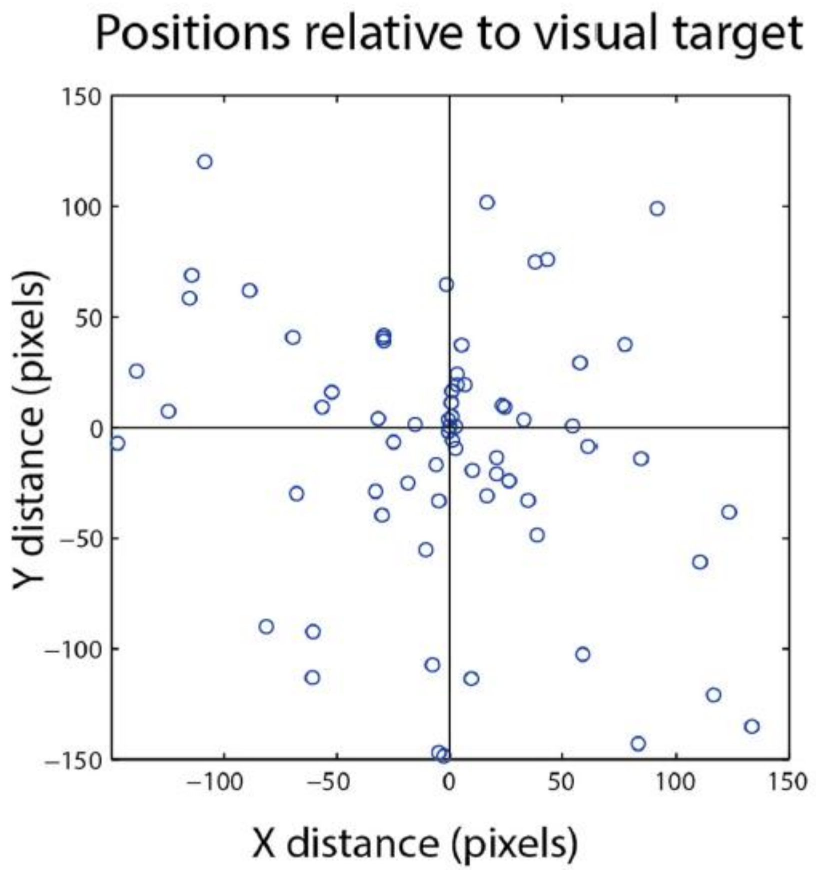
(C) A close view of the OwlCam with the attachment unit and the battery in place. The scale bar designates 10mm.

A) The dark spots on the arena designate possible positions of four food items. Items were spread so that each quadrant will contain one item. The gray spot on the arena designates a possible location of the loudspeaker.

Studying owl auditory-visual cue integration in the lab (Hazan et al., 2015)

the barn owl: a recent behavioral study of sound+vision localization IN THE LAB

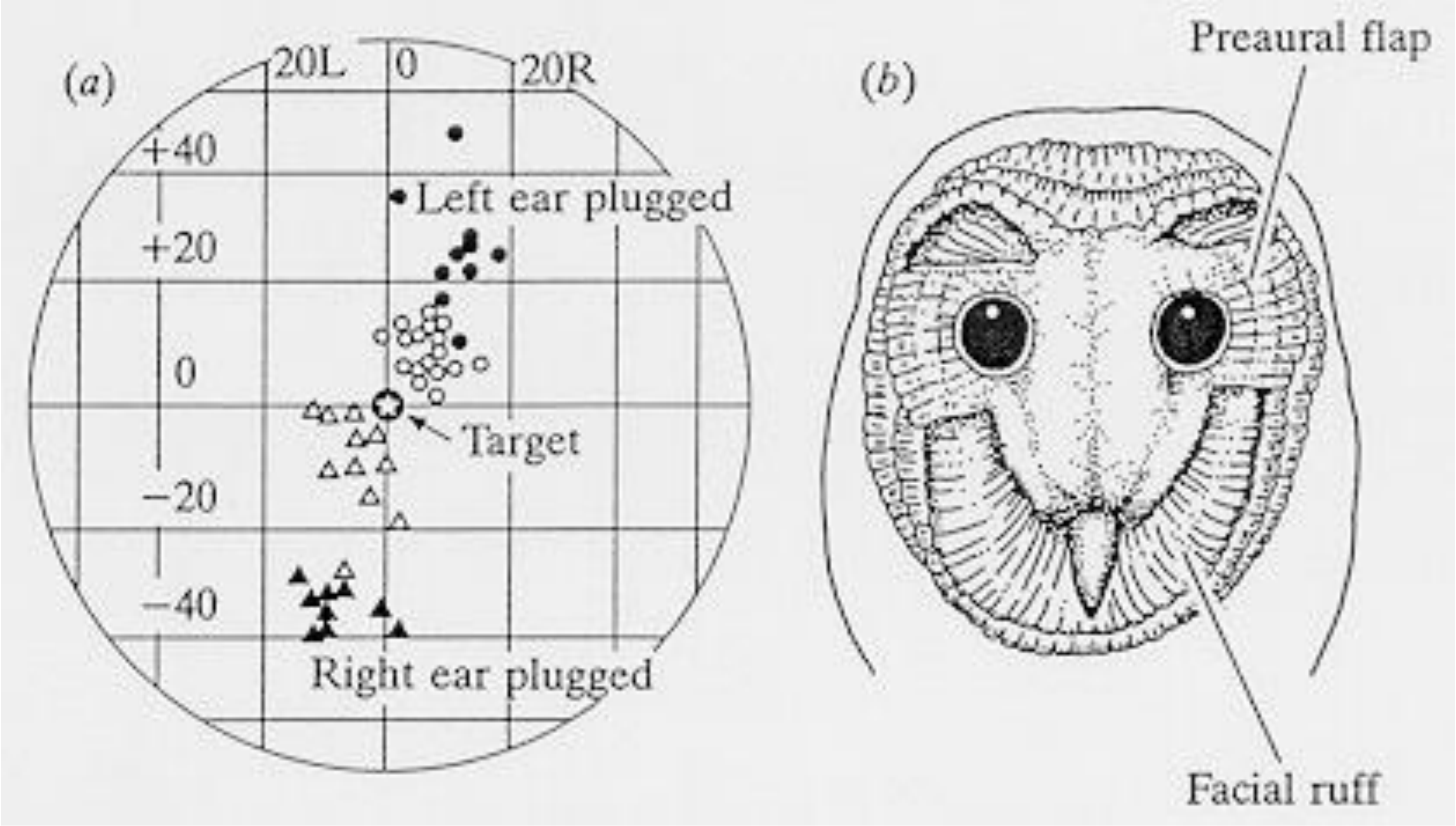




Note how bad auditory orienting (left) is, compared to visual (right)
Conducting the experiment in darkness approximates better (but not perfectly) the natural hunting conditions IN THE WILD!

Studying owl auditory-visual cue integration in the lab (Hazan et al., 2015)

Barn owl – Localization performance



Experiments in the wild showing how the owl uses binaural hearing

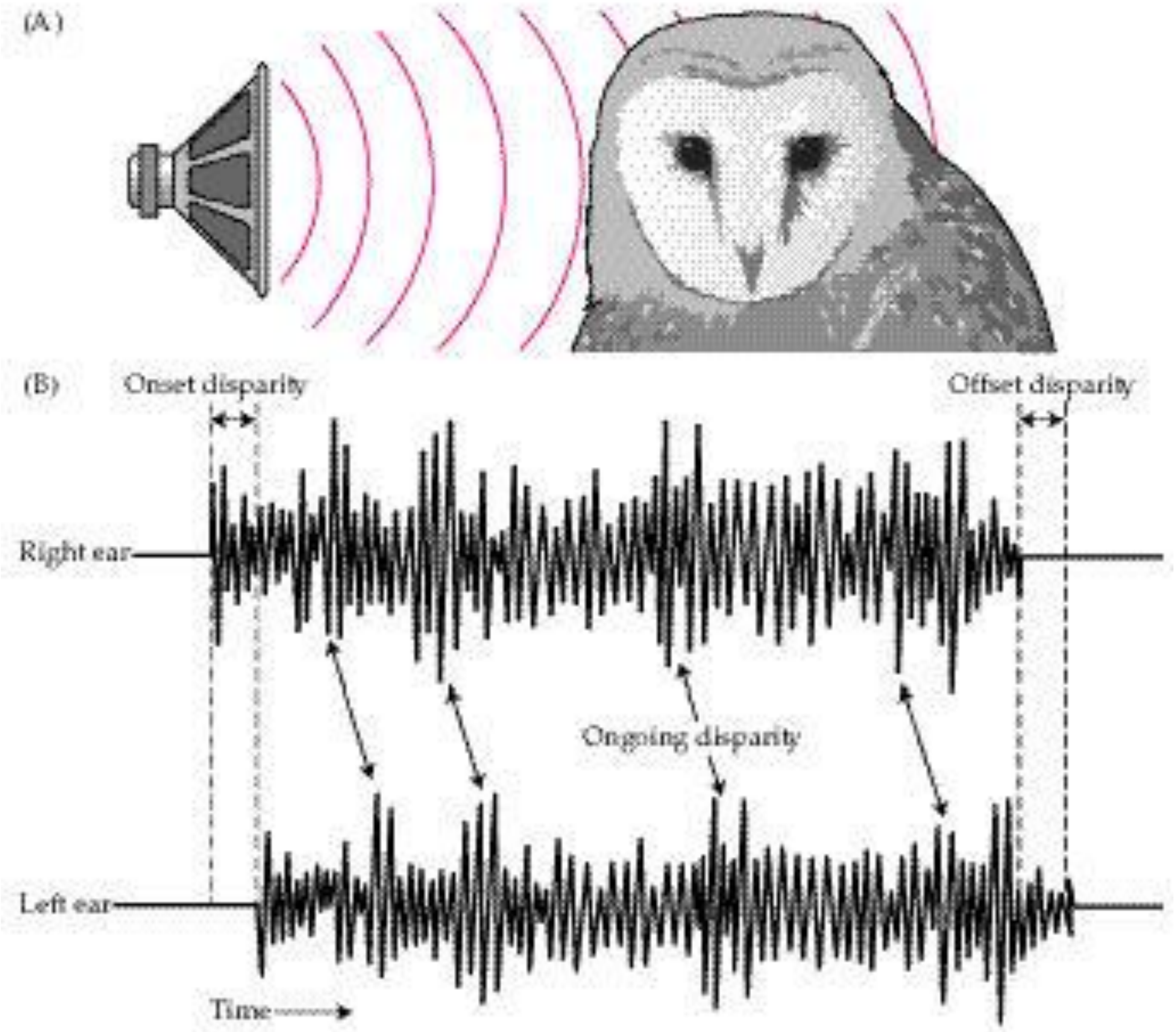
Barn owl — from problem to algorithm

How could binaural audio information be used to localize sound source?

Barn owl — from problem to algorithm

How could binaural audio information be used to localize sound source?

1. by noting **intensity difference** between the two ears;
2. by noting **timing difference** between the two ears.

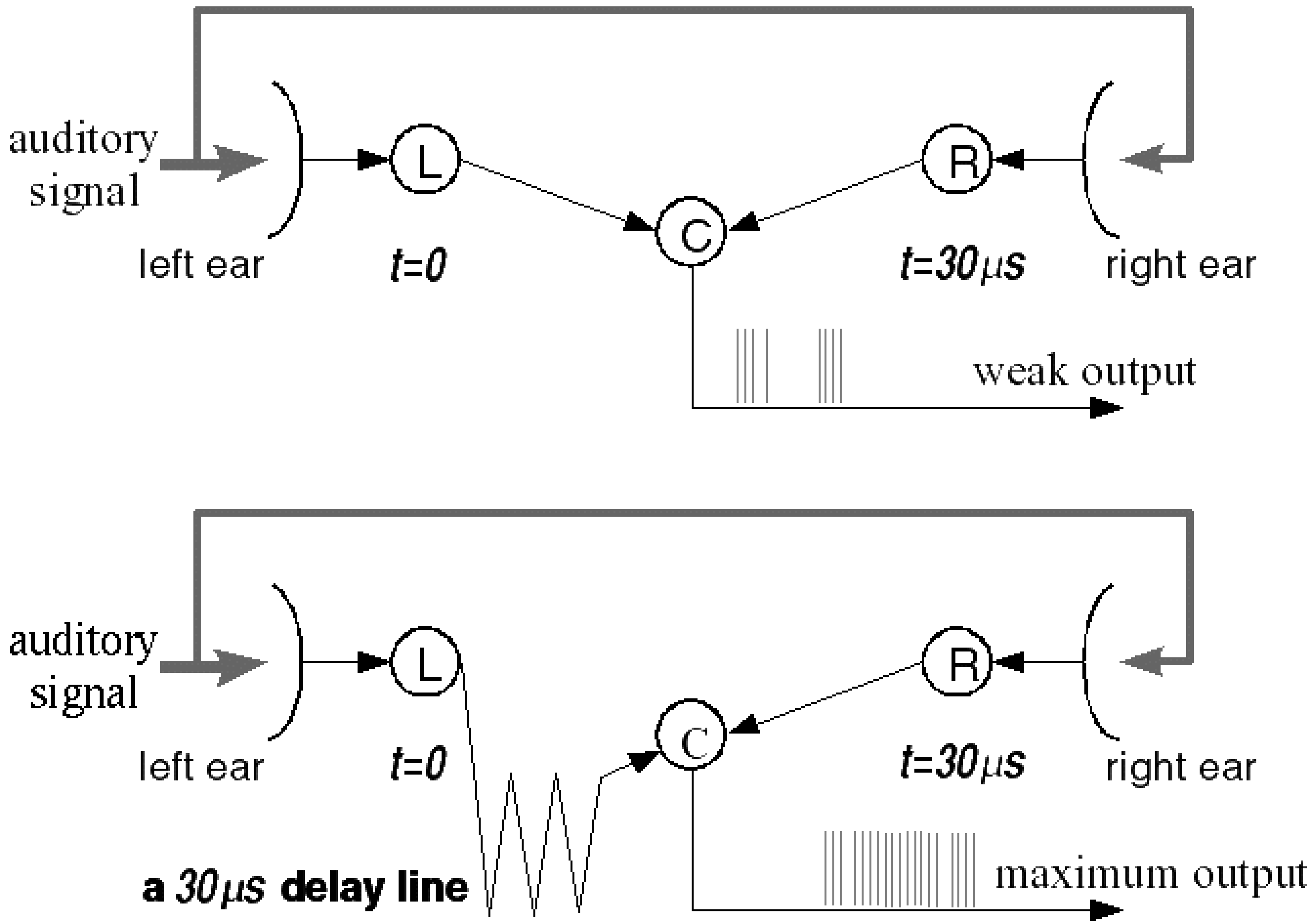


barn owl — algorithm, implementation (focusing on time difference)

A possible way of computing time difference (Jeffress, 1948) using:

a coincidence detector
and
a calibrated time delay line

(in air, a distance of 1 cm = 30 μs time delay).

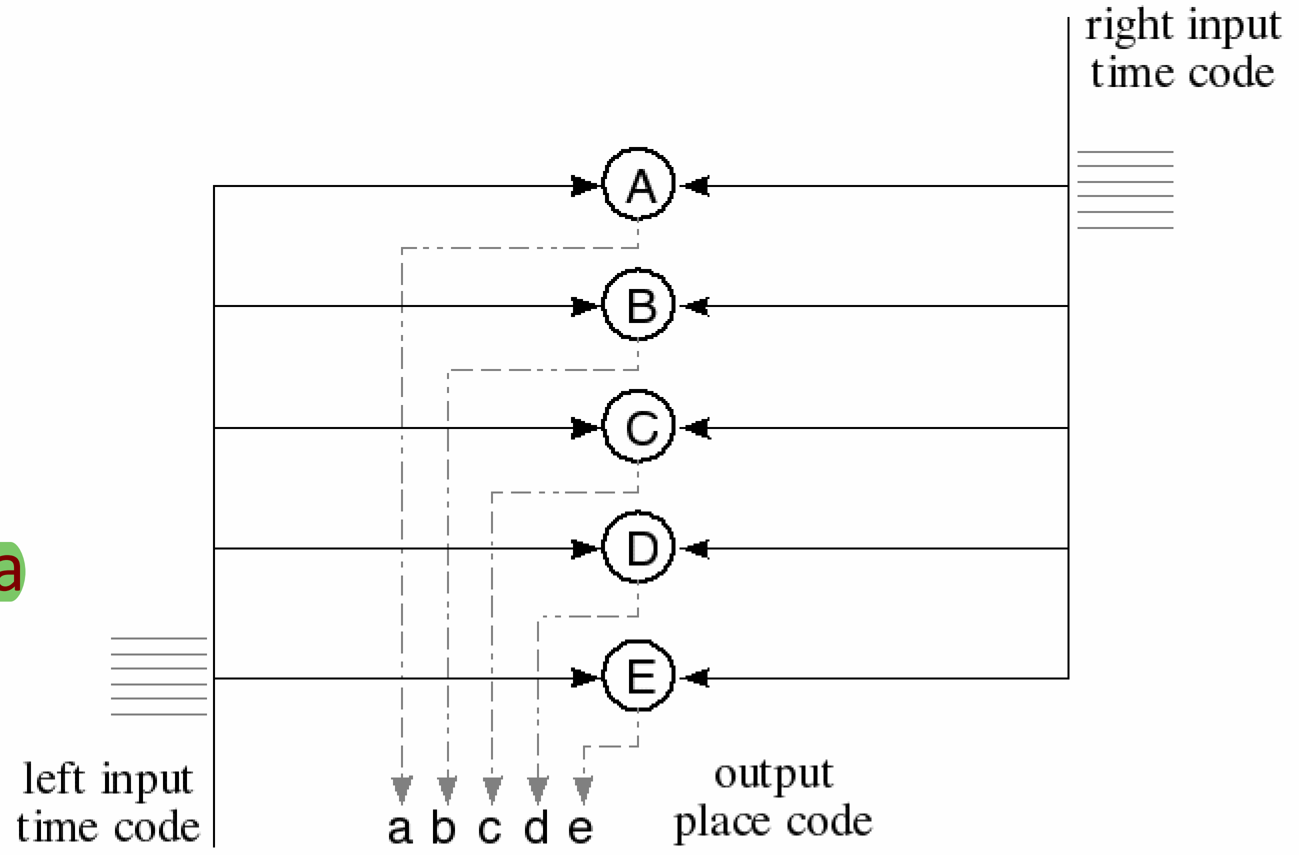


barn owl — implementation

An elaboration of the coincidence + calibrated delay model by Masakazu Konishi —

The key idea:
convert time delay information into a place code.

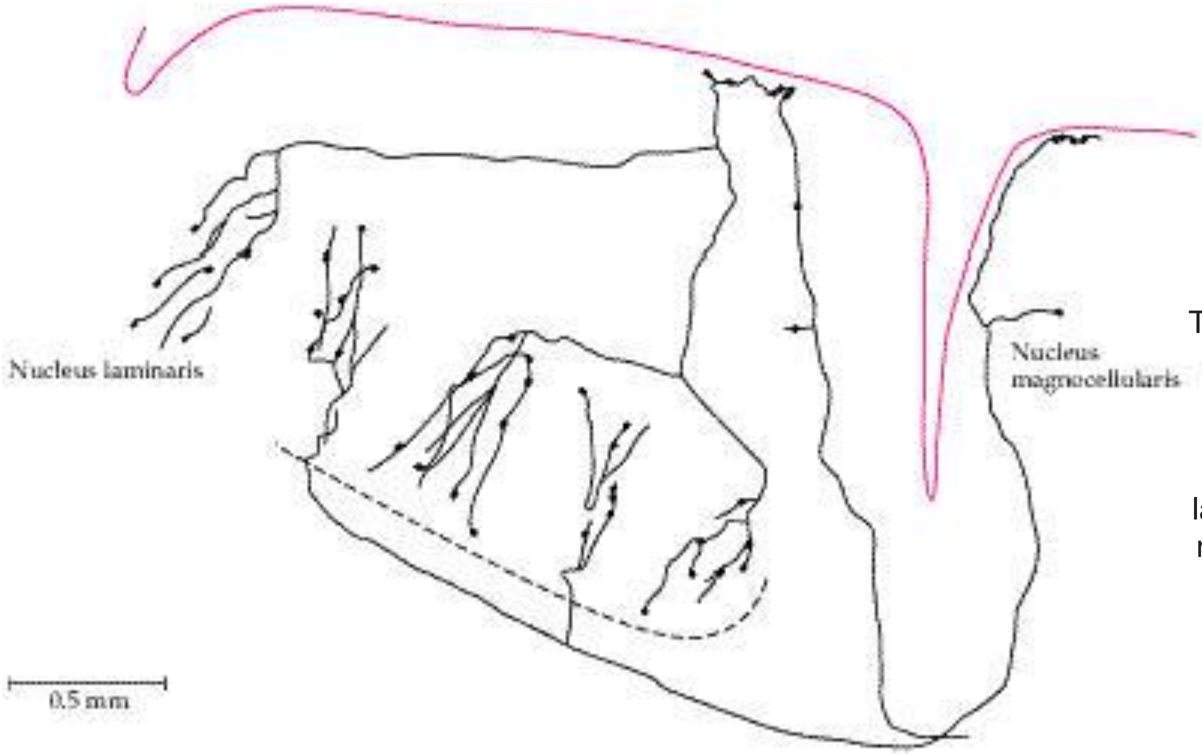
Does the barn owl use this method?
Yes!



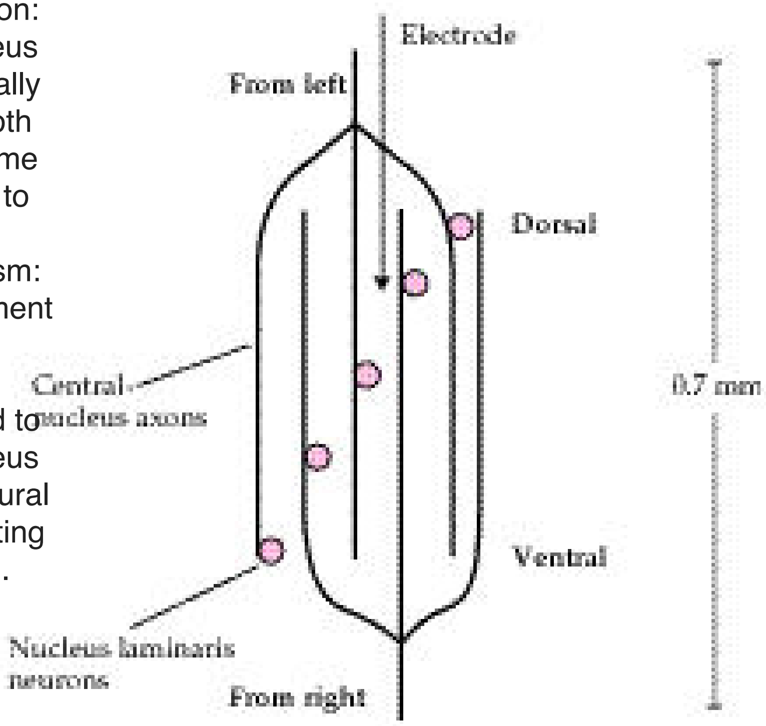
Auditory information from the two ears enters the nucleus laminaris (NL), a structure in the brainstem involved in processing binaural cues for sound localization.

barn owl — neural circuitry

nucleus laminaris acts as a neural delay line system.



Coincidence Detection: Neurons in the nucleus laminaris fire maximally when inputs from both ears arrive at the same time, allowing them to encode ITDs.
Delay Line Mechanism: The parallel arrangement of axons and the systematic shift in response times (lead to lag) across the nucleus laminaris create a neural map of ITDs, supporting the Jeffress model.



anatomy: axons carrying information from the two ears enter the nucleus laminaris from opposite sides, and run parallel to each other.

physiology: neurons at the top of nucleus laminaris show response time LEAD to the ipsilateral ear, changing to LAG as the recording electrode descends into NL.

Jeffress/Konishi model supported!!

Update: on the algorithmic & evolutionary levels

B. J. Fischer and J. L. Peña (2011). Owl's behavior and neural representation predicted by Bayesian inference. Nature Neuroscience 14:1061-1067.

"Spatial hearing in birds and mammals is more alike than previously thought in its patterns of developmental plasticity, physiological responses, and the computations employed to interpret binaural cues and map the environment" (Shamma, 2015).

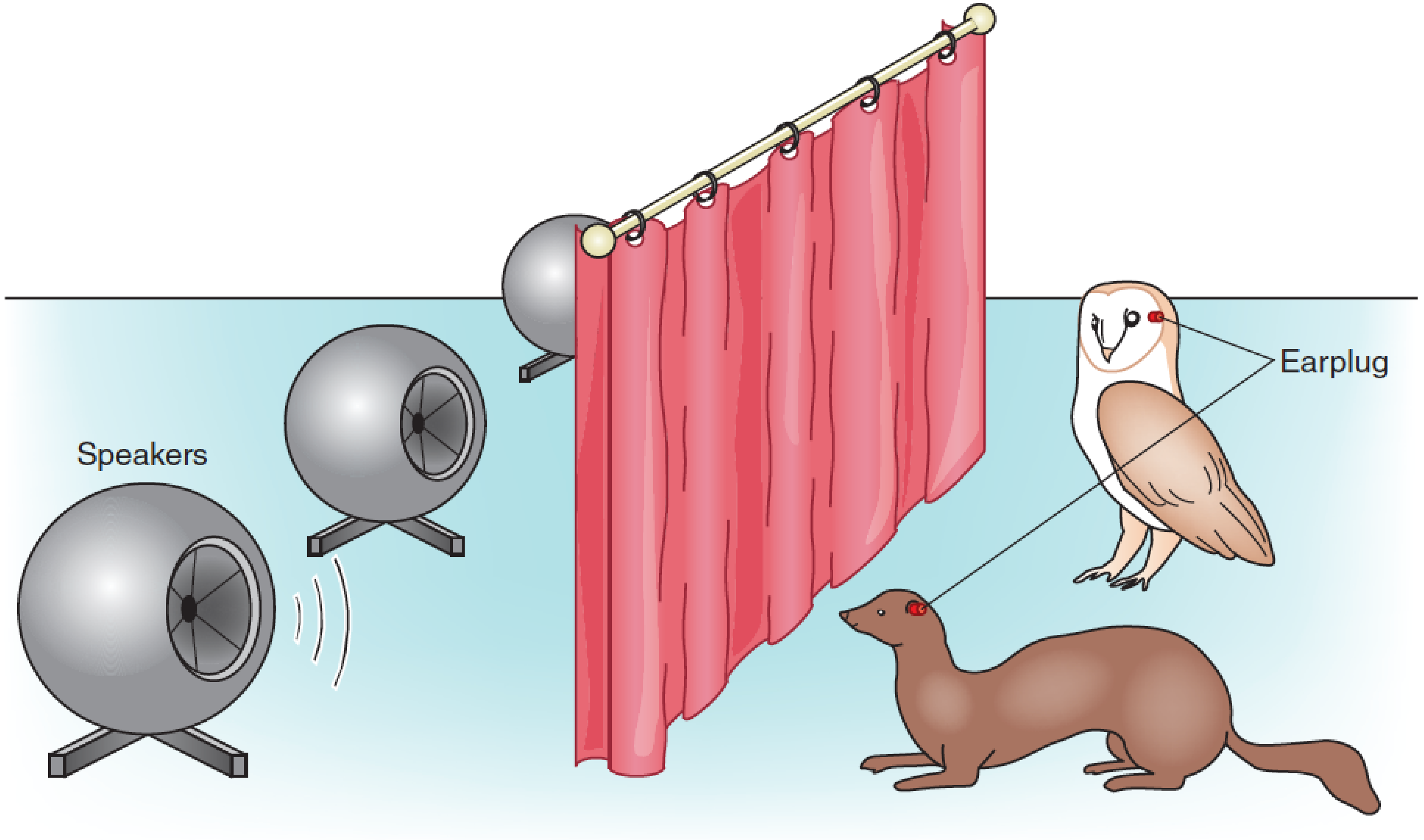


Figure 1 Sound localization with one ear plugged. Although once thought to employ different strategies, barn owls and ferrets utilize similar interaural level difference–based cues to localize a sound[5].

Summary of the Barn Owl Case Study

The multiple levels of analysis, applied to sound localization by the owl:

0. The evolutionary and behavioral context:
    - In the ecological niche they reside in, owls employ passive sound localization to pinpoint prey, by using interaural time (and intensity) differences.

1. The computational problem:
    - given timing (and intensity) differences measured at two locations, pinpoint the source of the sound.

2. Representation and algorithm:
    - use coincidence detection and delay lines to transform time difference into a place code in the brain.

3. The mechanism/implementation:
    - arrange the neurons and wire them up via delay lines to reflect the algorithmic solution.