

Introduction to Neuroscience: Behavioral Neuroscience

Sensory Ecology

Nachum Ulanovsky

Weizmann Institute of Science

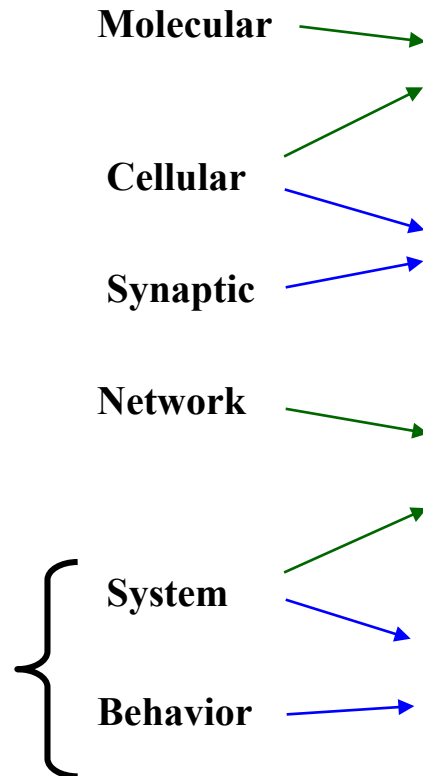
2023-2024, 2nd semester

But before we talk about sensory ecology...

Some Course Formalities

Core courses at the Weizmann Institute in Brain Sciences: Systems, Computational and Behavioral Neuroscience

Levels of Analysis of the Nervous System



Four Core Courses in Neuroscience

**Introduction to Neuroscience:
Molecular Neuroscience - Genes to Behavior**

**Introduction to Neuroscience:
Cellular and Synaptic Physiology**

**Introduction to Neuroscience:
Systems Neuroscience**

**Introduction to Neuroscience:
Behavioral Neuroscience**

Course coordinator: **Nachum Ulanovsky**

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Tel. x 6301

Email: nachum.ulanovsky@weizmann.ac.il

Course Website *(will include ALL the presentations):*

www.weizmann.ac.il/brain-sciences/labs/ulanovsky/courses

All lectures will be delivered Physically – and also video will be recorded.

Course syllabus (by week)

Characteristics of this course:

- No classical structure to courses in Behavioral Neuroscience (unlike the course in Cellular and synaptic Physiology) – as there is no Grand Theory of Behavior.
- We structured the course based on the Tradeoff between two approaches:
The Neuroethological approach and the Neuropsychological approach.

(Go over the syllabus)

www.weizmann.ac.il/brain-sciences/labs/ulanovsky/courses

Formalities

- **Grading:** 100% - Final exam (*open material*). NO compulsory reading.
→ This year in the exam we will have (i) new sets of questions, and (ii) less choice of questions than in previous years.

- **Bibliography:**

We will use three main textbooks in this course:

- *Behavioral Neurobiology, An integrative approach*, 2nd ed., Zupanc G. (Oxford, 2010)
- *Behavioral Neurobiology*, Carew J. (Sinauer, 2000)
- *Learning and Behavior*, Bouton M. (Sinauer, 2007)

Additional material for some of the lectures is covered in the following books:

- *Sensory Ecology*, Dusenbery D. (Freeman, 1992)
- *An Introduction to Behavioral Endocrinology*, 4th ed., Nelson R. (Sinauer, 2011)
- *Neuroeconomics: Decision making and the Brain*, 2nd ed., Glimcher P. and Fehr E. (Academic Press, 2013)

Dates of subsequent lectures

- Every Thursday at 13:15 until 16:00, from now until the end of the semester.
Location: FGS C.
- Special Lecture on 15/5 (Wednesday) at 14:15 until 17:00 – at FGS A ???

Sensory Ecology

Umwelt (Uexküll 1920)

Umwelt (“surrounding world”) is
The organism’s model of the world:
The perceived things in the world,
the signals emitted by both the
subject and things, and the actions
that are performed by each species.



In other words:

**Umwelt = the sensory world
and the behavioral world
of each species – *from the
perspective of the species.***

NOTE: The Umwelt of different
species can differ A LOT.

Q: What are some of the differences in the Umwelt of the following animals –
in terms of their “sensory world” ?

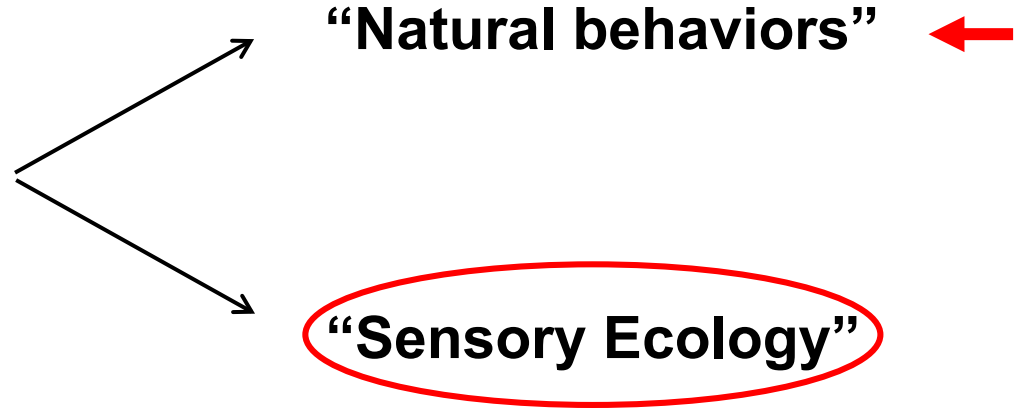
- Mouse and Rat
- Primate
- Honeybee
- Bat

→ It is crucial that we
understand the Umwelt of the
organism that we are studying!

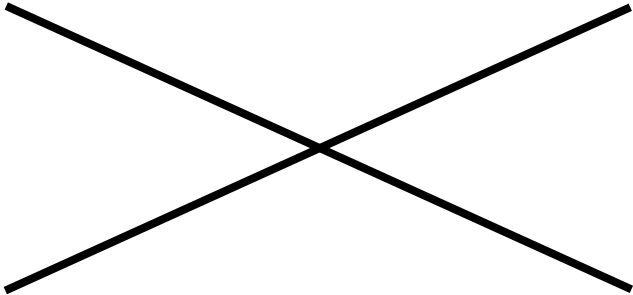
Umwelt (Uexküll 1920)

Two modern terms related to
the classical concept of Umwelt:

Umwelt = “Surrounding world”:
the sensory world and the
behavioral world of each
species – *from the perspective
of the species*

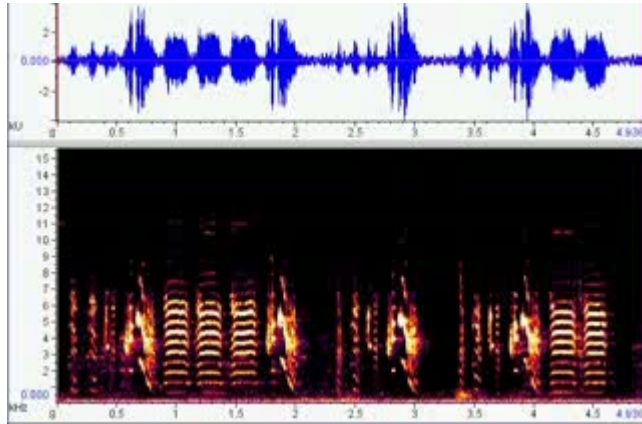


Innate/Learned vs. Natural/Artificial behaviors

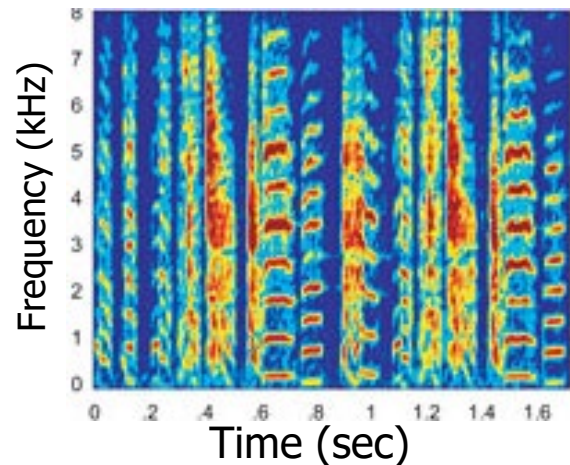
	Natural	Artificial
Learned	<ul style="list-style-type: none">• Tool use in Crows & Chimpanzees (and other animals)• Vocal learning in songbirds ←	
Innate	<ul style="list-style-type: none">• Sexual behaviors• Imprinting• Fixed Action Patterns	

Vocal learning in songbirds

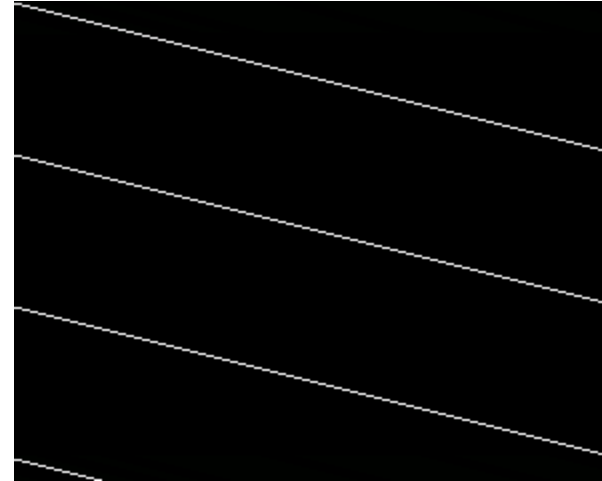
Adult zebra finch song (*Movie*)



Adult zebra finch song is complex, consisting of *syllables* and *motifs*



Song of adult birds differs from the “babbling” of juveniles (*Movie*)



Juvenile birds that are isolated and do not have a chance to learn singing from a tutor (= adult male) will *not* develop a full adult song, but will remain “babbling”

Vocal learning in songbirds

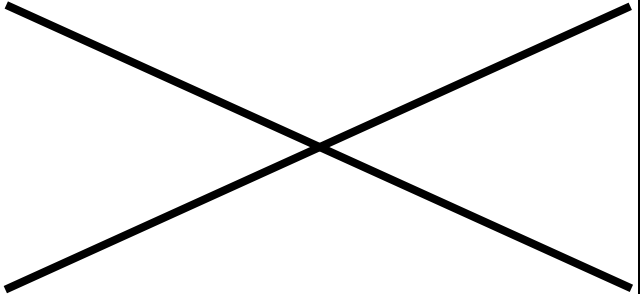
- Vocal learning in songbirds has two components, an innate component and a learned component: The tendency to “babble” is an *innate* behavior – but the full learning of a complex song is a *learned* behavior
- The study of the neural basis of vocal learning in songbirds has become popular in Behavioral Neuroscience, because:
 - It is a natural behavior – and it is complex, yet very reproducible
 - A model animal that shares many aspects with vocal learning in humans (i.e. language)
 - Has many additional interesting features: Clear critical periods ; first discovery of adult neurogenesis in vertebrates...
- *Liora Las & Yarden Cohen will talk later in the course about the bird song system.*

Artificial learned behaviors



- If you are interested in studying the neural basis of Motor Coordination in elephants, this particular behavior is probably not the best choice to focus on – because it is artificial

Innate/Learned vs. Natural/Artificial behaviors

	Natural	Artificial
Learned	<ul style="list-style-type: none">• Tool use in Crows & Chimpanzees• Vocal learning in songbirds	<ul style="list-style-type: none">• Juggling Elephants
Innate	<ul style="list-style-type: none">• Sexual behaviors• Imprinting• Fixed Action Patterns	

Innate/Learned vs. Natural/Artificial behaviors

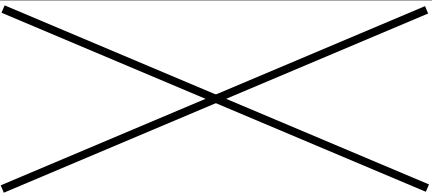
Vocal learning
in songbirds

Juggling
elephants

Continuum

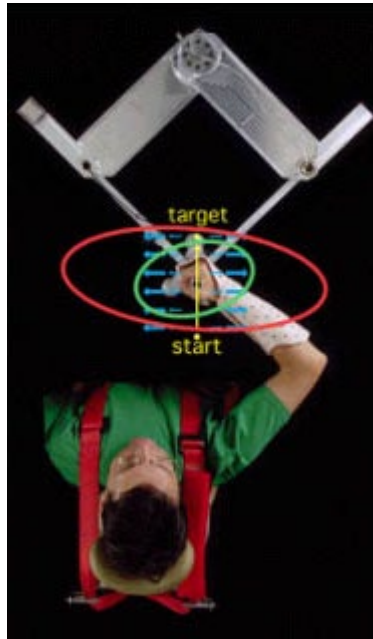
Innate vs. Learned = Fuzzy border:

"Innate" = if develops
in all animals when
reared in isolation.
BUT, some innate
behaviors are also
followed by learning,
whereby the animal
improves with practice

	Natural	Artificial
Learned		
Innate		

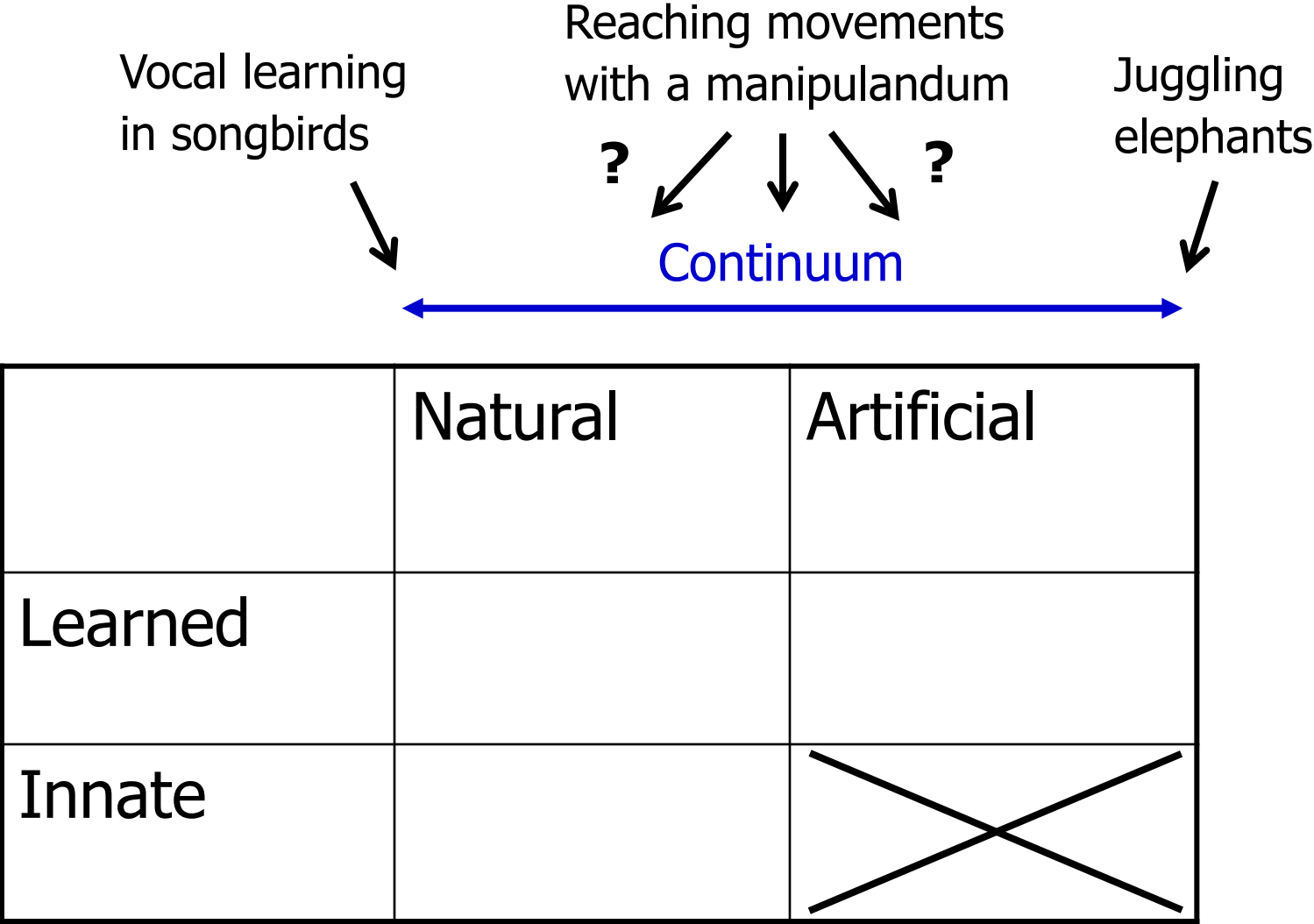
The Natural/Artificial distinction is not simple to make

What about this example?

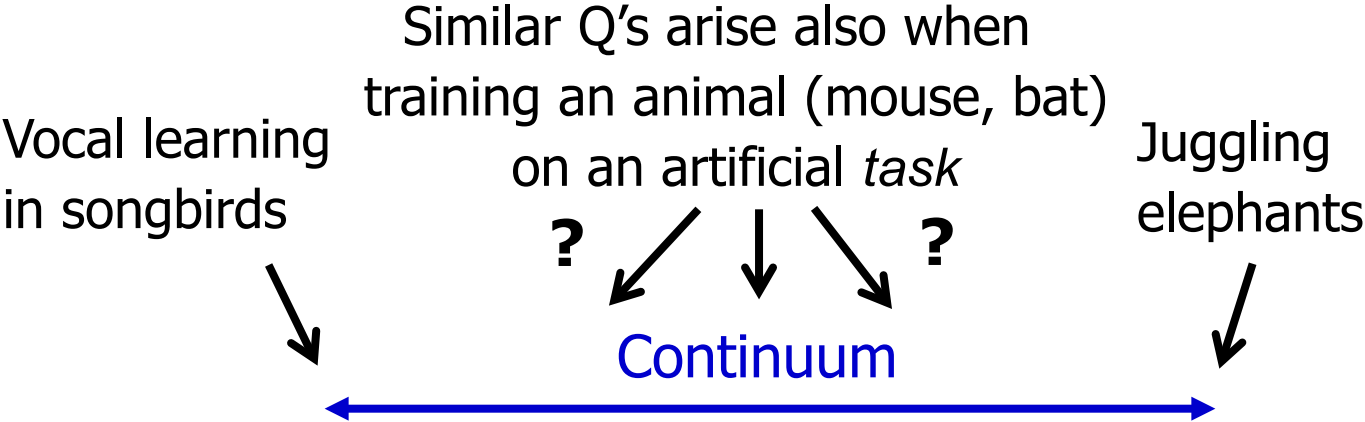


Reaching movements in humans are a natural (and important) behavior – but the setup with the manipulandum and the chin strap is artificial

Innate/Learned vs. Natural/Artificial behaviors



Innate/Learned vs. Natural/Artificial behaviors



	Natural	Artificial
Learned		
Innate		

Innate/Learned vs. Natural/Artificial behaviors

**Neuroethological
approach**

("more natural"
experiments)

**Neuropsychological
approach**

("better controlled"
experiments)

Continuum



	Natural	Artificial
Learned		
Innate		

Umwelt (Uexküll 1920)

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Umwelt = “Surrounding world”:
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behavioral world
of each species – *from the
perspective of the species*



Ecology

Ecology is the study of the interactions between an organism and its environment



“Environment”:

- The physical environment 
- Other organisms

Sensory Ecology is the study of how the physical environment affects the information available to the organism's sensory systems

Sensory Ecology – outline of today's lecture

- **Rationale:** Why should Neuroscientists care about Ecology?

Three aspects of Sensory Ecology:

- **The physics of the environment:** How it affects the sensory information available to the organism
- **Natural stimulus statistics:** A modern (and currently popular) look at the concept of “Umwelt”
- **Direct Perception** (“The ecological approach to visual perception” – Gibson): the surprisingly rich cues and clues that the Umwelt of humans supplies our visual system

Sensory Ecology – outline of today's lecture

Based (primarily) on the books:

- Sensory Ecology (Dusenbery, 1992)
- The ecological approach to visual perception (Gibson, 1986)

And a variety of more recent articles.

Sensory Ecology – outline of today's lecture

- **Rationale:** Why should Neuroscientists care about Ecology?

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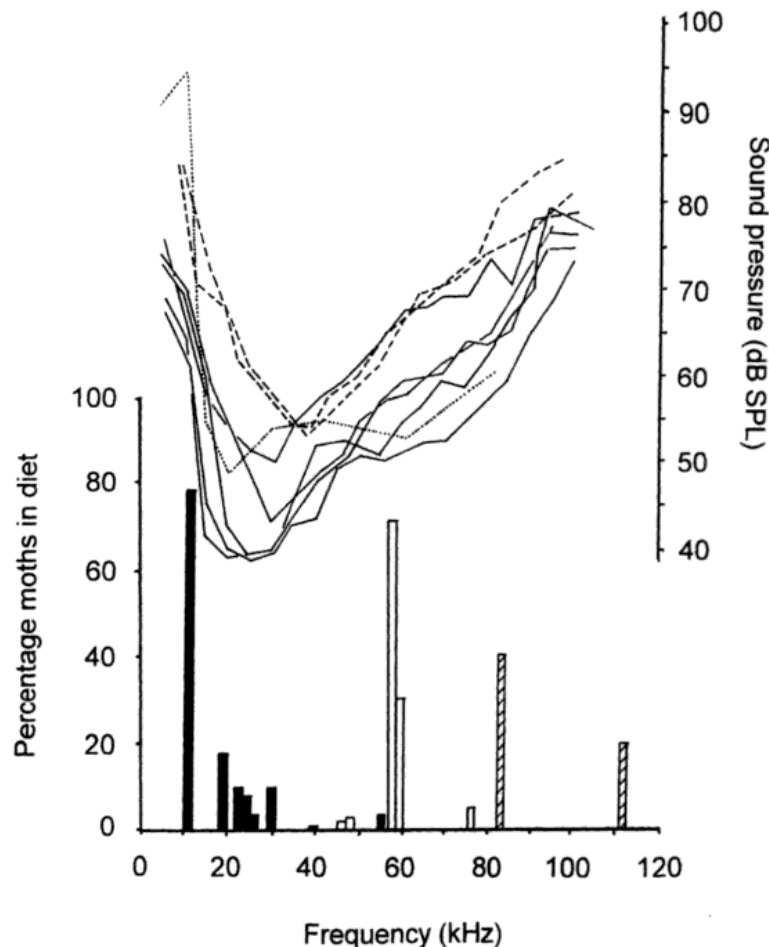
- **The physics of the environment:** How it affects the sensory information available to the organism
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Why should neuroscientists care about ecology?

- **The evolutionary argument:** Because brains in general, and sensory systems in particular, have evolved so as to maximize the animal's fitness in the face of *natural* stimuli, in the *natural* world.
- **There are many examples suggesting that ecology matters.**

Example 1: Moth hearing and bat echolocation

Co-evolution of the auditory system of moths and the echolocation calls of bats: The Umwelt of moths (which prominently includes echolocation calls of bats) strongly affected the evolution of moths' auditory system

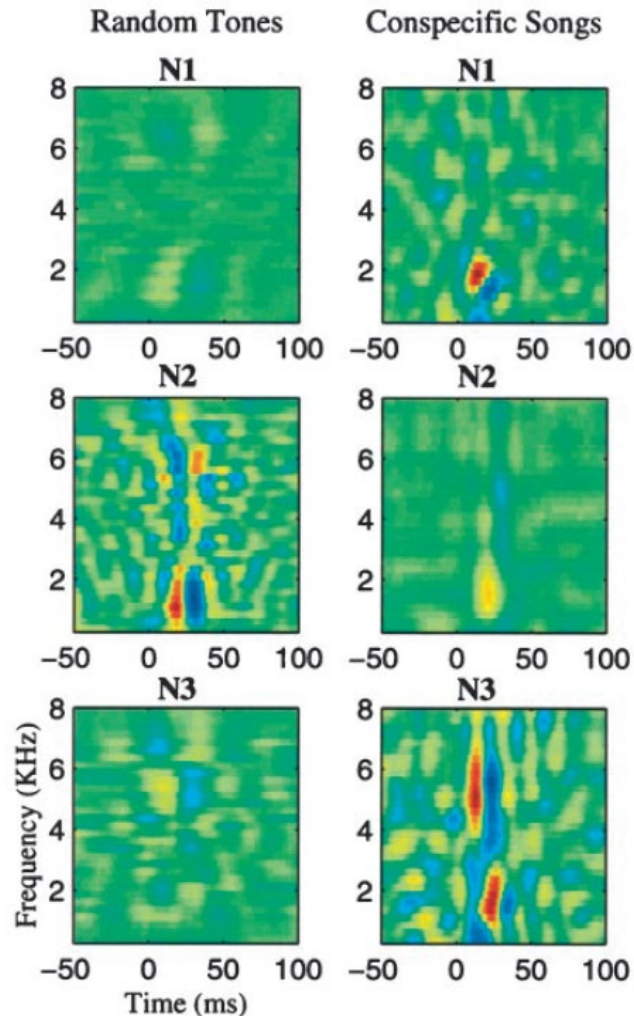


- Audiograms of 8 moth species: note that bats with echolocation freq $\sim 20\text{--}50$ kHz eat less moths; these are also the frequencies of moths' best hearing
- Moth hearing matches the local population of bats: may differ for the *same* moth/bat species in different locations (graph not shown)

... we will talk more about bat echolocation later in the course.

Example 2: Natural stimulus statistics and neural activity

Neurons respond differently to ensembles of natural stimuli compared to artificial stimuli: example from the auditory system



Spectro-temporal receptive fields of 3 auditory neurons (Theunissen et al. 2000)

→ This means that using artificial sounds to study the auditory system – as has been done for the last half century – has a limited utility if we want to understand how the auditory system processes real-world, natural sounds.

... we will talk more about Natural Stimulus Statistics later today.

Sensory Ecology – outline of today's lecture

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Stimulus transmission

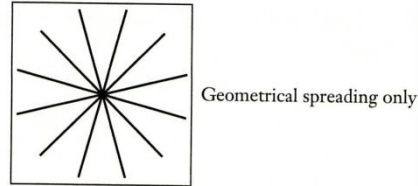
Sensory information is transmitted over long distances by one of 3 mechanisms (*“long distance” does not include touch*):

- **1. Propagation:** Light and Sound
- **2. Diffusion:** Heat and Chemicals (olfactory and gustatory)
- **3. Flow:** Heat and Chemicals (olfactory and gustatory)

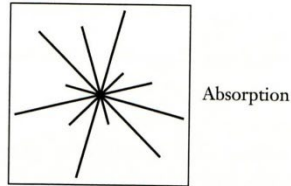
1. Wave propagation (light and sound)

Several physical properties of waves:

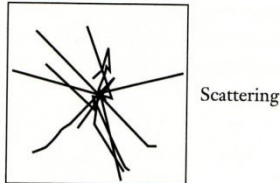
- **Geometric spreading**



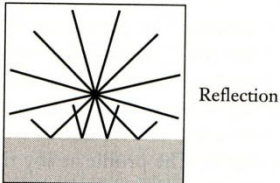
- **Absorption**



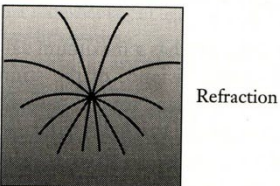
- **Scattering**



- **Reflection**



- **Refraction**



*** diffraction**

1. Wave propagation (light and sound)

Several physical properties of waves:

- **Geometric spreading**

- For point source in three dimensions (3-D), intensity (I) decreases as $1/R^2$, where R is the distance from the source: $I \sim 1/R^2$. For point source & for a spread that is limited to 2-D $\rightarrow I \sim 1/R$ (examples soon).

- **Absorption**
- **Scattering**

} **Attenuation**

- **Reflection**

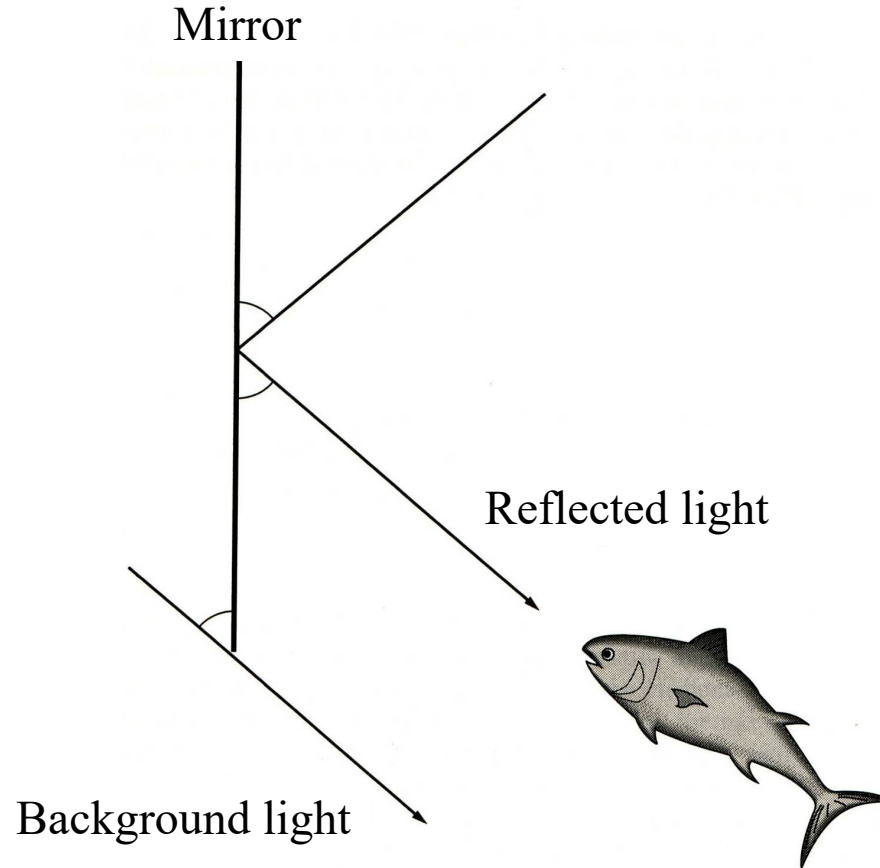
- **Refraction**

- **diffraction**

We will talk in detail about Geometric Spreading and about Attenuation when we will discuss Echolocation in Bats later in the course.

1. Wave propagation (light and sound)

Example: Implication of **Reflection** & **scattering** in the ocean's midwater. Scattering in the midwater (depth $> \sim 100$ m) is uniform in azimuth (around the vertical axis) – allowing usage of **Mirror Camouflage** by silvery fish.



1. Wave propagation (light and sound)

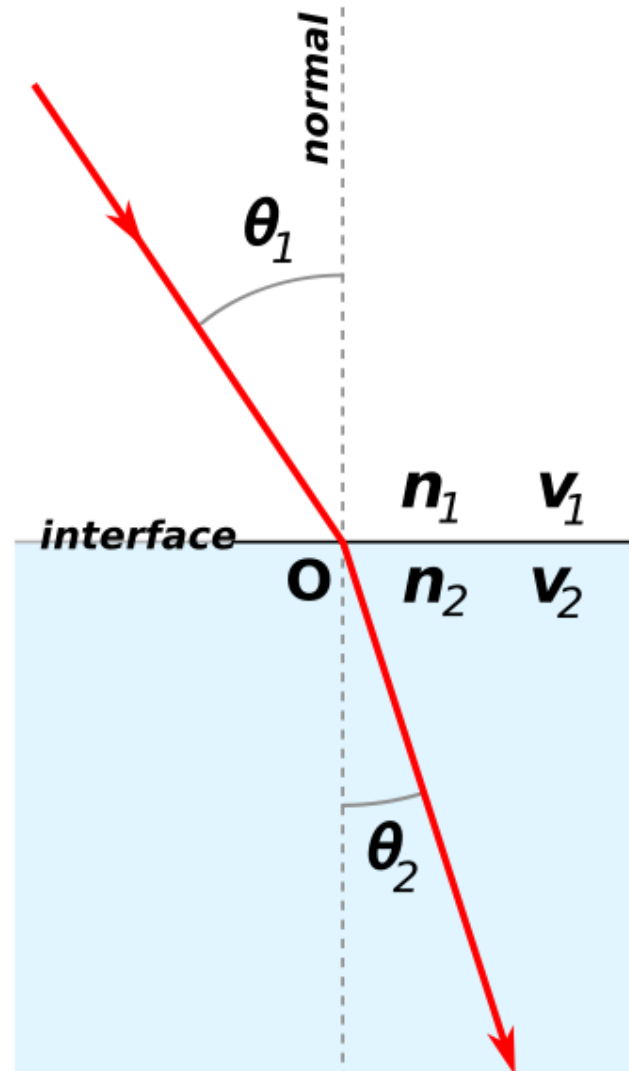
Example: Implication of **Reflection** & **scattering** in the ocean's midwater. Scattering in the midwater (depth $> \sim 100$ m) is uniform in azimuth (around the vertical axis) – allowing usage of **Mirror Camouflage** by silvery fish.



This is why fishes such as sardines and piper have silvery sides.

1. Wave propagation (light and sound)

Refraction



Snell's Law:

$$\frac{\sin \theta_1}{\sin \theta_2} = \frac{v_1}{v_2} = \frac{n_2}{n_1}$$

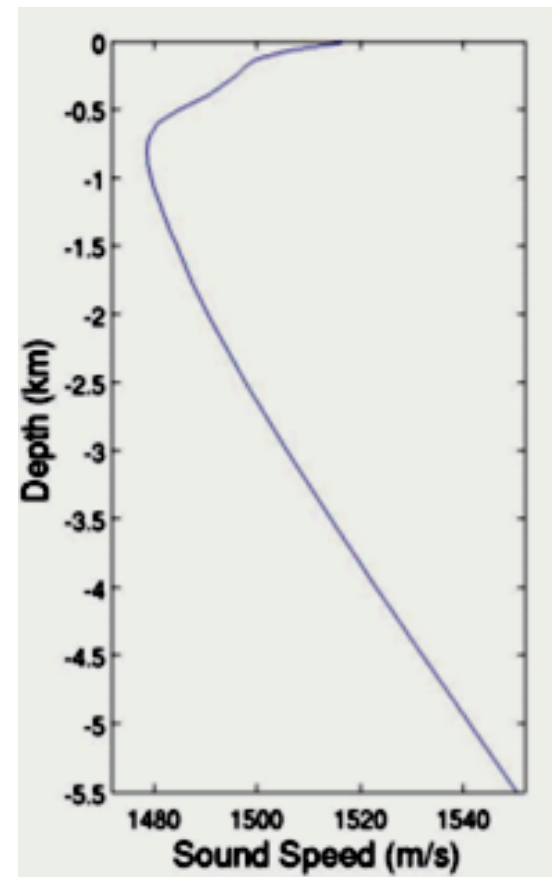
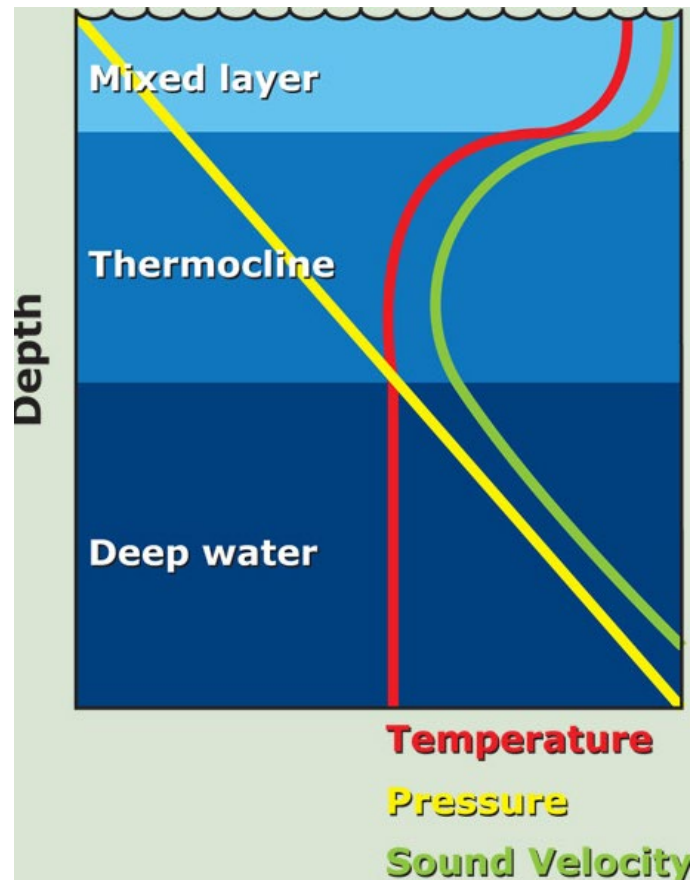
1. Wave propagation (light and sound)

Refraction – Implications for the hunting behavior of the Archerfish



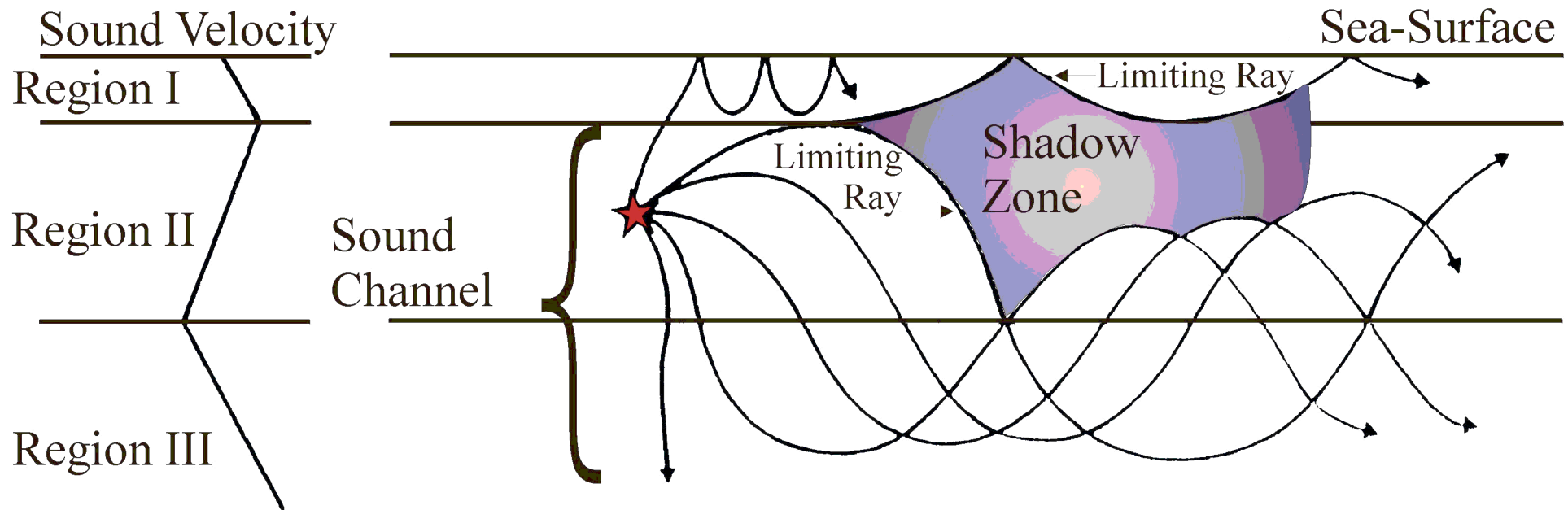
1. Wave propagation (light and sound)

Refraction – Deep Sea Sound Channel creates a \sim 2-D acoustic waveguide at a certain depth where sound velocity in the ocean is minimal.



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1. Wave propagation (light and sound)

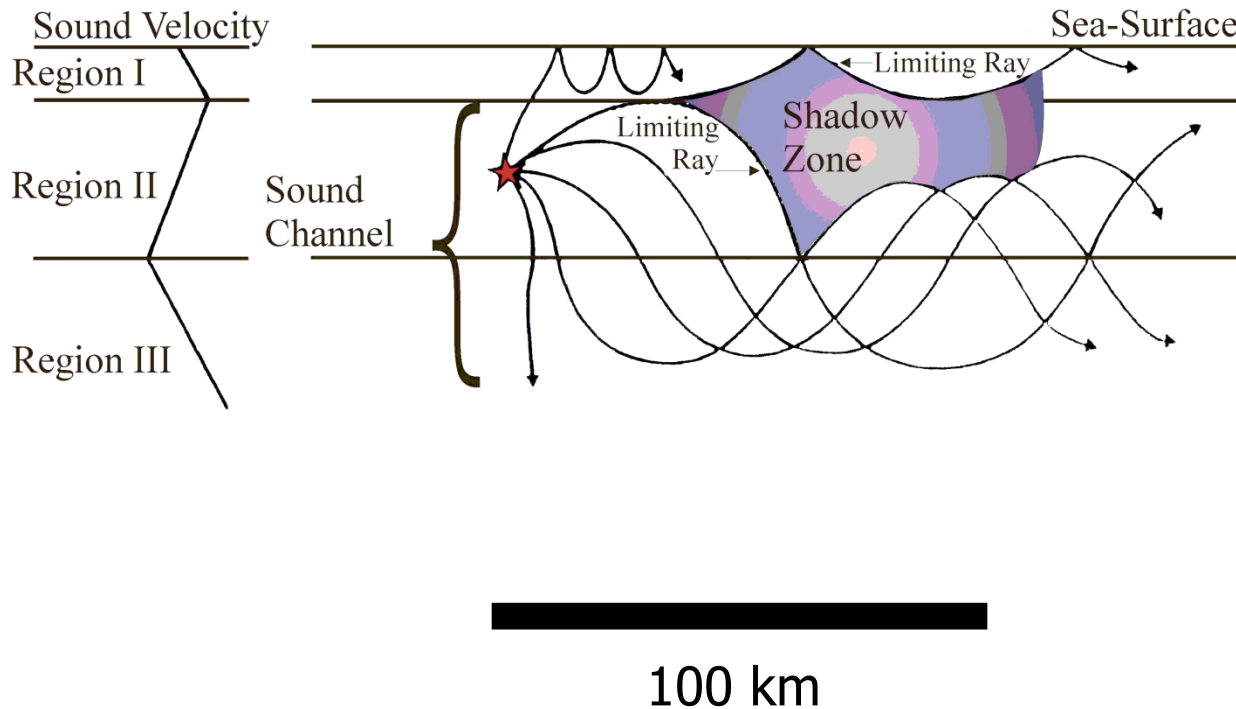
Refraction – Deep Sea Sound Channel creates a \sim 2-D acoustic waveguide at a certain depth where sound velocity in the ocean is minimal, and thus allows sound to spread for thousands of kilometers through the combined actions of **refraction** and $\sim 1/R$ **geometric spreading** (remember that for 2-D, waves spread as $\sim 1/R$ instead of the usual $\sim 1/R^2$ geometric spreading).

At high latitudes the depth of the sound channel is quite shallow, and it is thought to be important for **acoustic communication of whales**.

Another, sound channel is the surface sound channel, at the sea surface; it acts through the combined actions of **refraction** and **reflection** from the sea surface. It's also thought to be important for acoustic communication, but is less efficient due to **scattering** from the rough sea surface.

1. Wave propagation (light and sound)

Refraction – Deep Sea Sound Channel creates a \sim 2-D acoustic waveguide at a certain depth where sound velocity in the ocean is minimal.



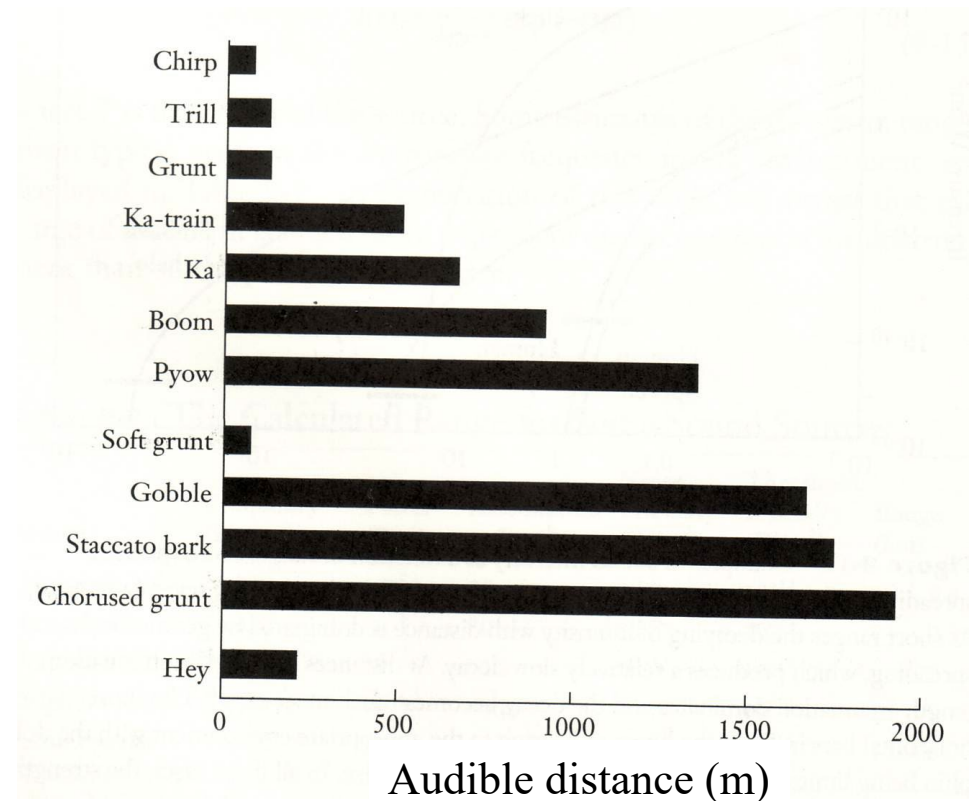
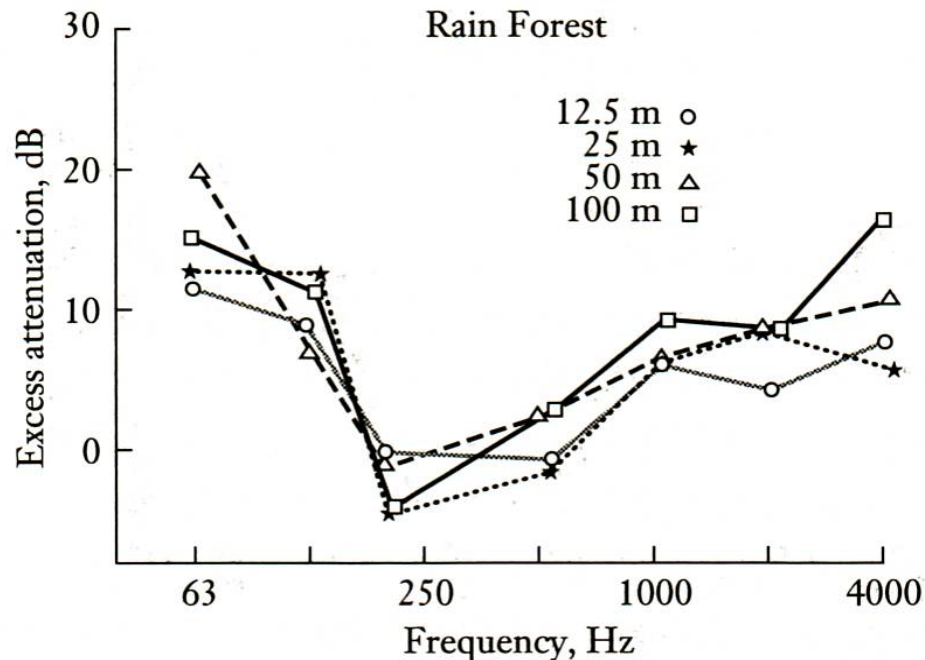
→ **Surface channel:**
Refraction + reflection +
scattering + $1/R$ spreading

→ **Deep sea channel:**
Refraction + $1/R$ spreading

1. Wave propagation (light and sound)

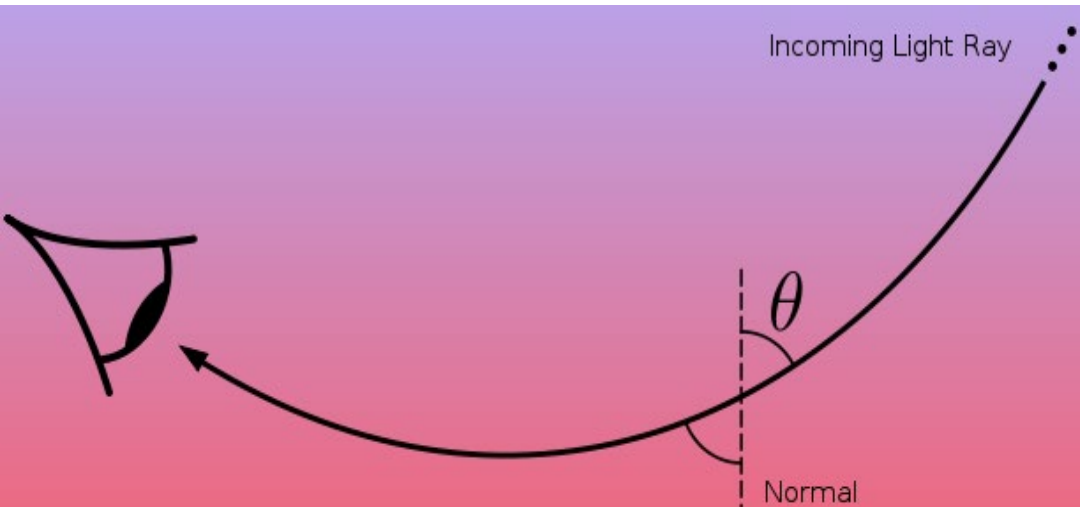
Refraction – “Sound window” @ 200 – 500 Hz in the rainforest is caused by **refraction** from the sun-heated air layer at the upper canopy – in combination with **scattering** and **diffraction** from trees and branches.

Many of the long-distance monkey vocalizations are @ 200 – 500 Hz, utilizing this sound window.



1. Wave propagation (light and sound)

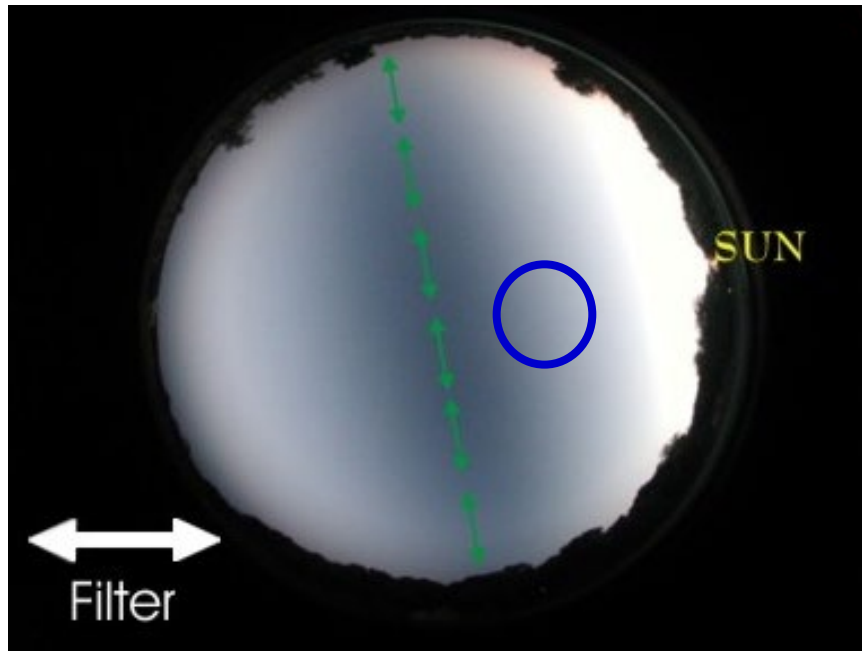
Refraction – Mirage.



1. Wave propagation (light and sound)

Scattering – creates two interesting effects:

- **Why is the sky blue?** Because scattering $\sim 1/\lambda^4$ (λ = wavelength)
- Scattering polarizes the sun's light – which forms the basis of insect's **polarization compass** (we'll discuss this later when talking about Navigation)



Even if only a patch of the sky is visible (e.g. via forest canopy), this may be enough for an insect to compute the direction of the sun = perpendicular to the polarization pattern.

Locusts were shown to have in their brain neurons that are tuned to the direction of light polarization: A neural “polarization compass”.

Fish-eye sky photo through horizontal polarization filter

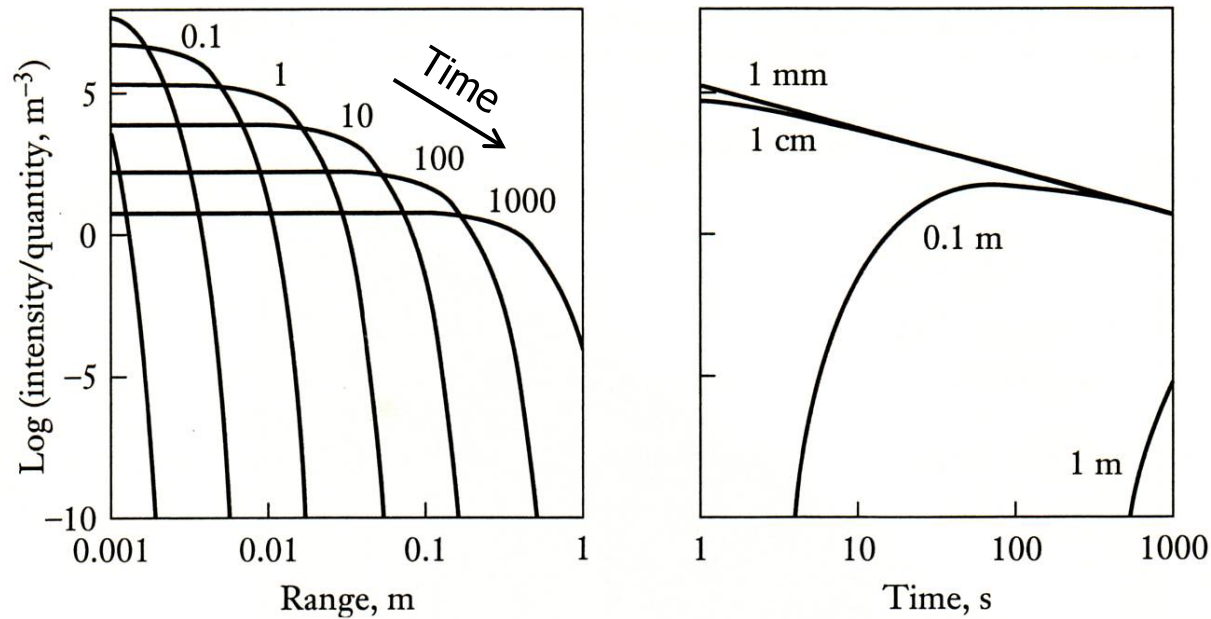
Stimulus transmission

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- ✓ • **1. Propagation:** Light and Sound
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- • **3. Flow:** Heat and Chemicals (olfactory and gustatory)

2. Diffusion

Diffusion is a very slow process: not efficient over long distances.



3. Flow

Because diffusion is inefficient, in order to transmit olfactory information over long distances it is crucial to have flow of air (or of water for aquatic animals)

- **Sniffing** = Flow created by the animal (inhaling)
- **Wind**

3. Flow

Sniffing by dogs and humans



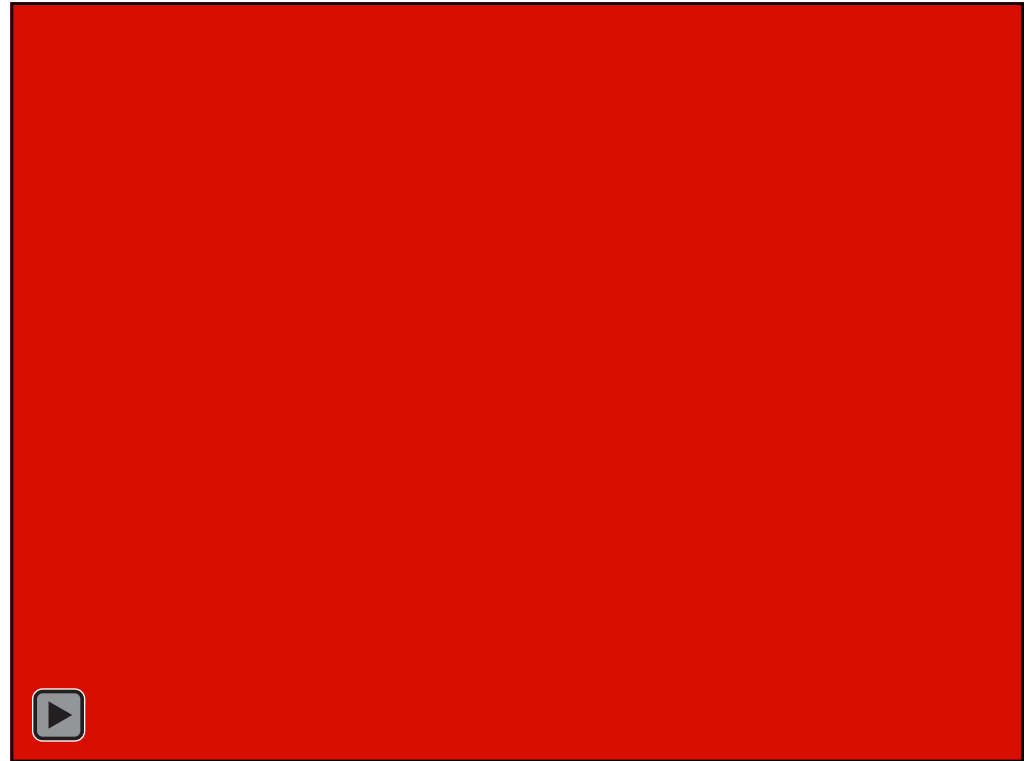
Porter et al., *Nature Neurosci.* (2007)

3. Flow

Underwater Sniffing by the star-nosed mole – using air bubbles



Movie 1



Movie 2

K. Catania, *Nature* (2006)

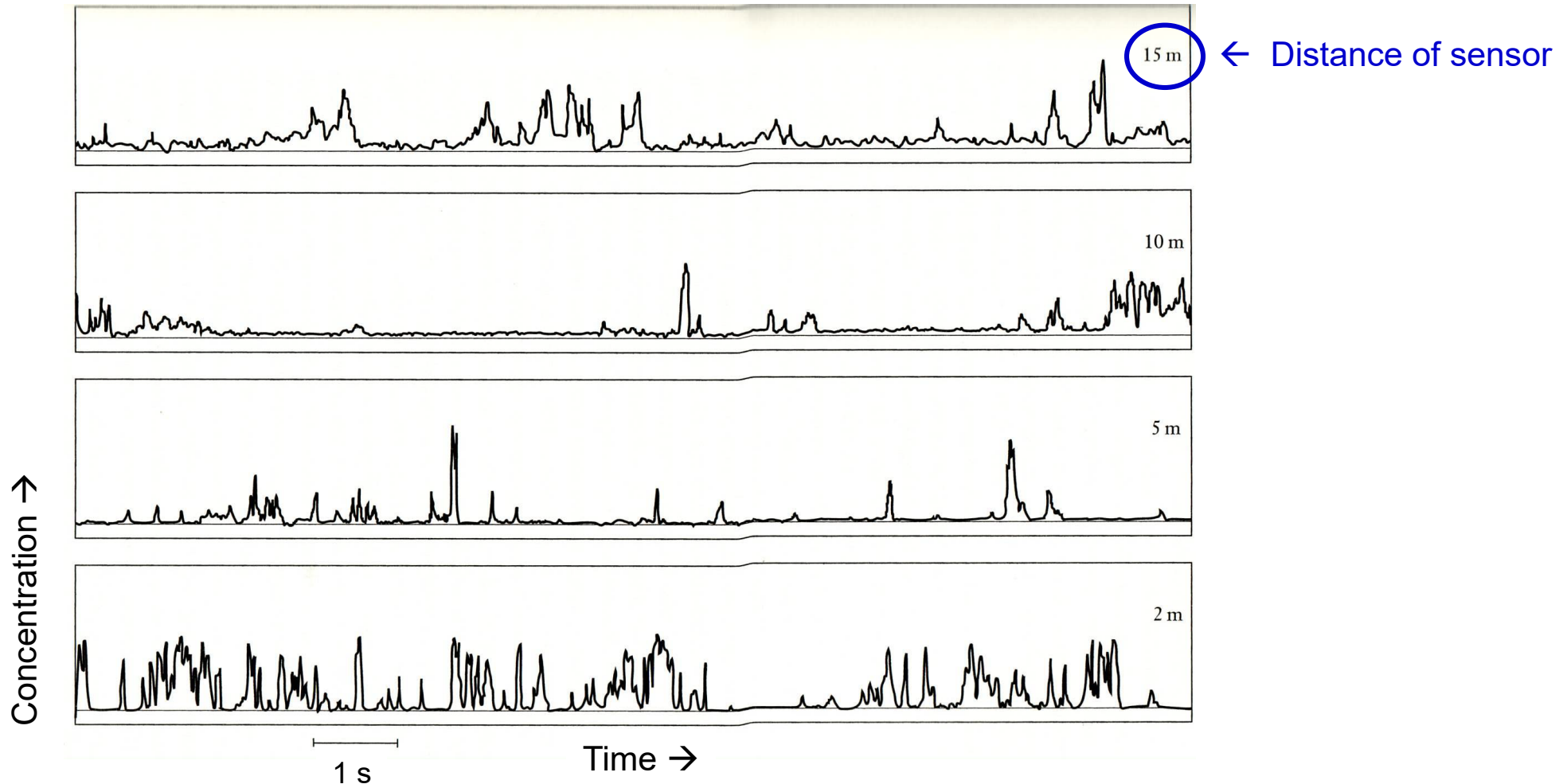
3. Flow

Wind: The problem with wind is that it creates turbulent flow = intermittent olfactory input



3. Flow

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3. Flow

Wind: The problem with wind is that it creates turbulent flow = intermittent olfactory input

- Nevertheless, moths can detect pheromone odors from > 1 km
- It may be better NOT to use a **chemotaxis** strategy, which tries going up the gradient – as there is *no* continuous gradient – but to use an **infotaxis** strategy for olfactory search (Vergassola et al., *Nature* 2007)
- When studying the neural basis of olfaction, you need to understand the **natural stimulus statistics** of odors

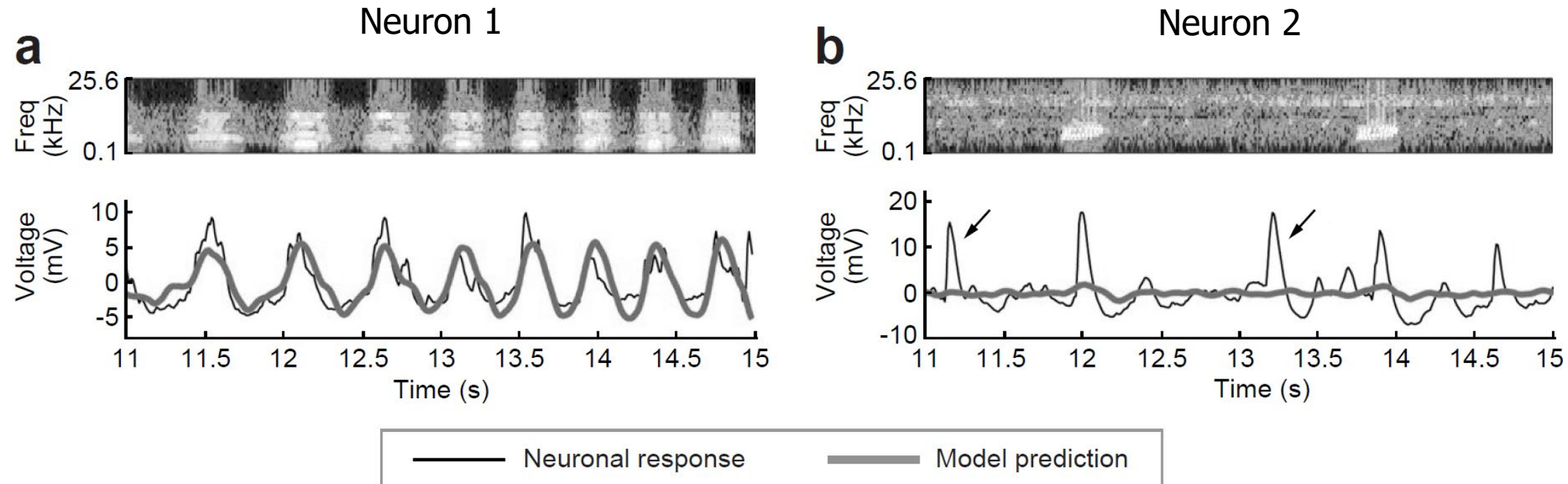
Sensory Ecology – outline of today's lecture

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- **The physics of the environment:** How it affects the sensory information available to the organism
- **Natural stimulus statistics:** A modern (and currently popular) look at the concept of “Umwelt”
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Natural stimulus statistics and neural activity



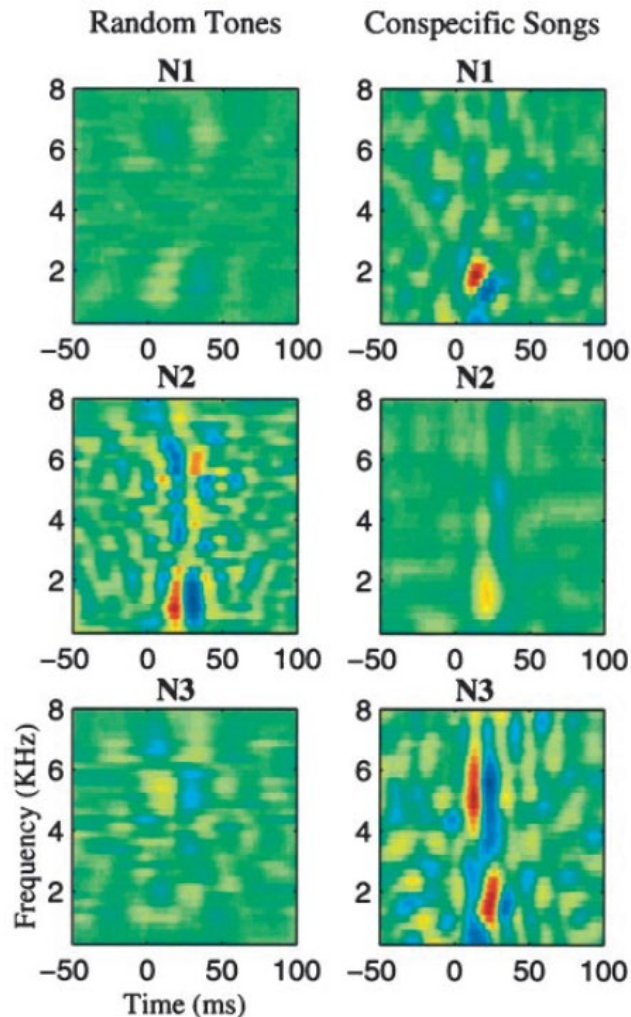
The average prediction success for neuronal responses to natural sounds – using linear models based on standard artificial sounds – is typically $\sim 10\%$ (like in Neuron 2).

Why ?

Neurons are nonlinear, sensitive to stimulus history, and to (spectral) context.

Natural stimulus statistics and neural activity

Neurons respond differently to ensembles of natural stimuli compared to artificial stimuli: example from the auditory system



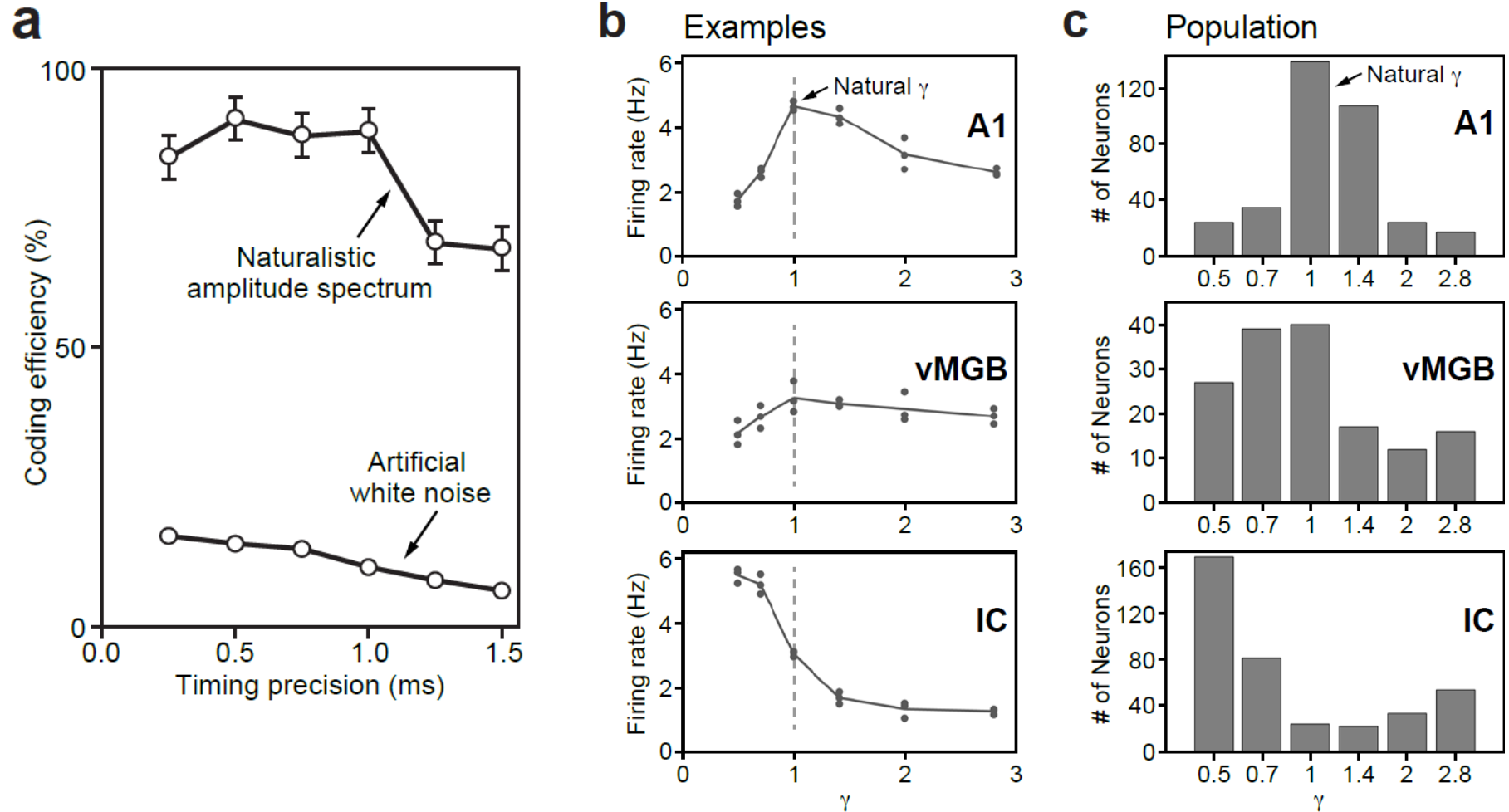
Spectro-temporal receptive fields of 3 auditory neurons (Theunissen et al. 2000)

→ This means that using artificial sounds to study the auditory system – as has been done for the last half century – has limited utility if we want to understand how the auditory system processes real-world, natural sounds.

→ We must understand in-depth the natural stimulus statistics of auditory soundscapes.

→ similar results were found also for Vision.

Neurons may be tuned to natural stimuli

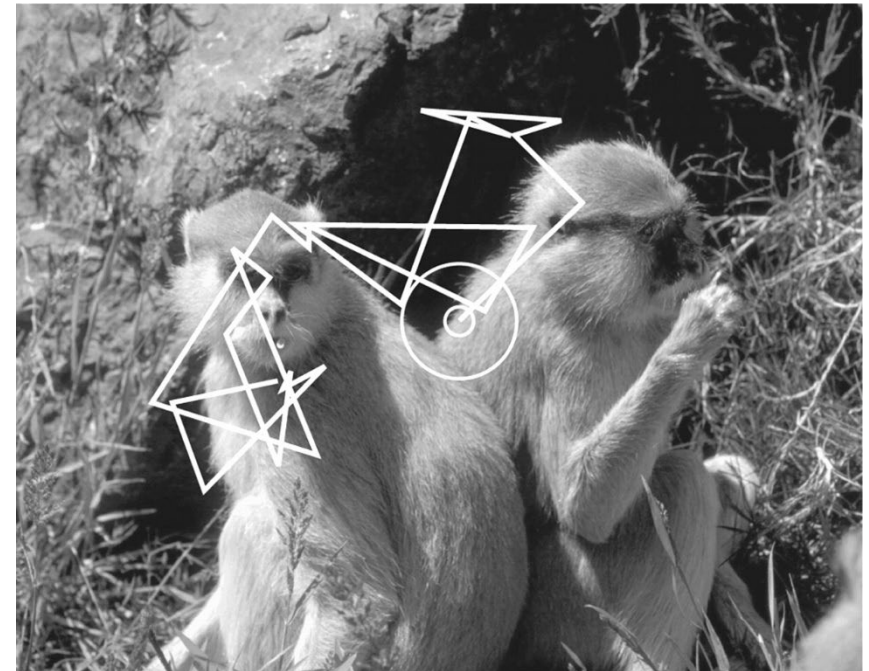


In b,c: Amplitude Spectra of sounds $\sim 1 / f^\gamma$

Natural stimulus statistics and neural activity

Natural vision has complex statistics – due to the long-range correlations within the images themselves, and the complex scanning movements by the eyes – both of which turn out to have important implications for:

- **Responses** of visual neurons.
- Modeling the **development** of response properties (receptive fields) of visual neurons.
- Visual system **function**: The large eye movements (saccades) and microsaccades pose a serious problems for classical theories of vision – while active-sensing theories suggest that vision works *through* the eye movements.



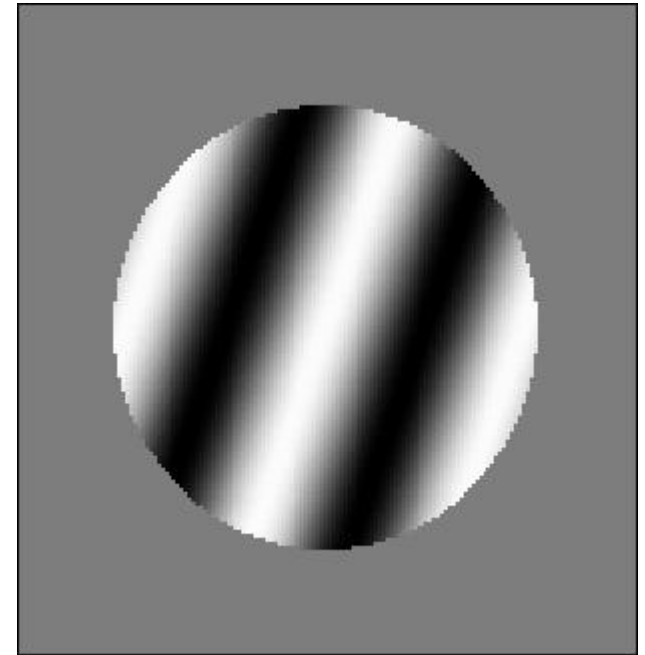
Vinje and Gallant, *J. Neurosci.* (2002)

... you will learn more about Natural Stimulus Statistics and about Active Sensing in the course “Systems Neuroscience”.

Natural *stimulus* statistics is also tightly linked to natural *movement* statistics

Question: When do you ever have, in the natural environment, moving-grating or moving-bar stimuli as were used by Hubel & Wiesel, and as used to this day in most studies of visual neuroscience ?

Answer: Almost exclusively due to the animal's *own* movements. It is only then that the trees, houses and other line-elements in the scenery start moving coherently on the retina.



→ Perhaps, then, motor signals are represented in V1 ?

Natural *stimulus* statistics is also tightly linked to natural *movement* statistics

Dissociating visual inputs from movements in a virtual (VR) setup:



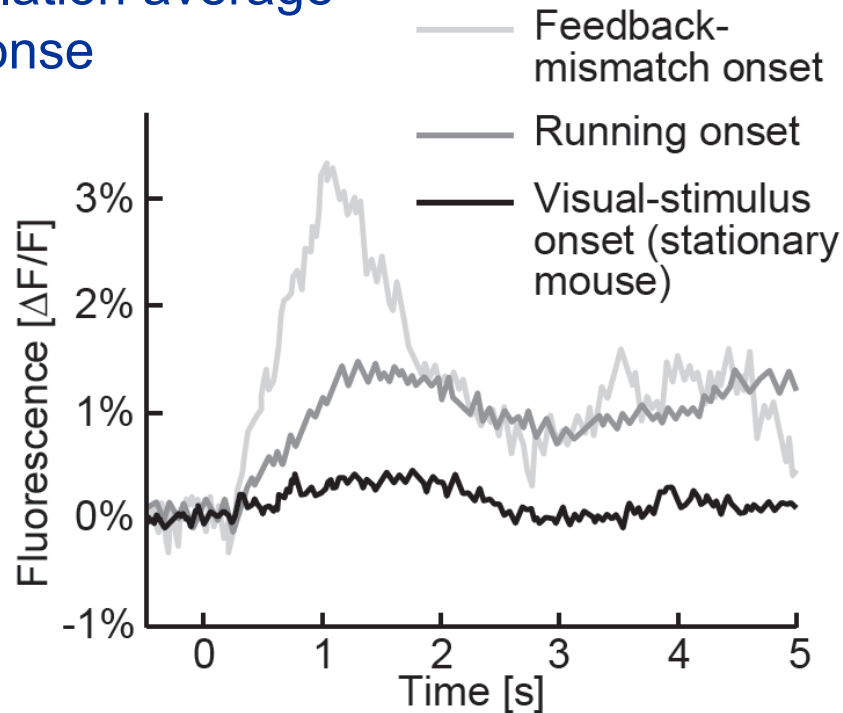
Movie 1 – Mouse behavior in VR



Movie 2 – Calcium imaging of neural activity

Natural *stimulus* statistics is also tightly linked to natural *movement* statistics – and this coupling affects neurons

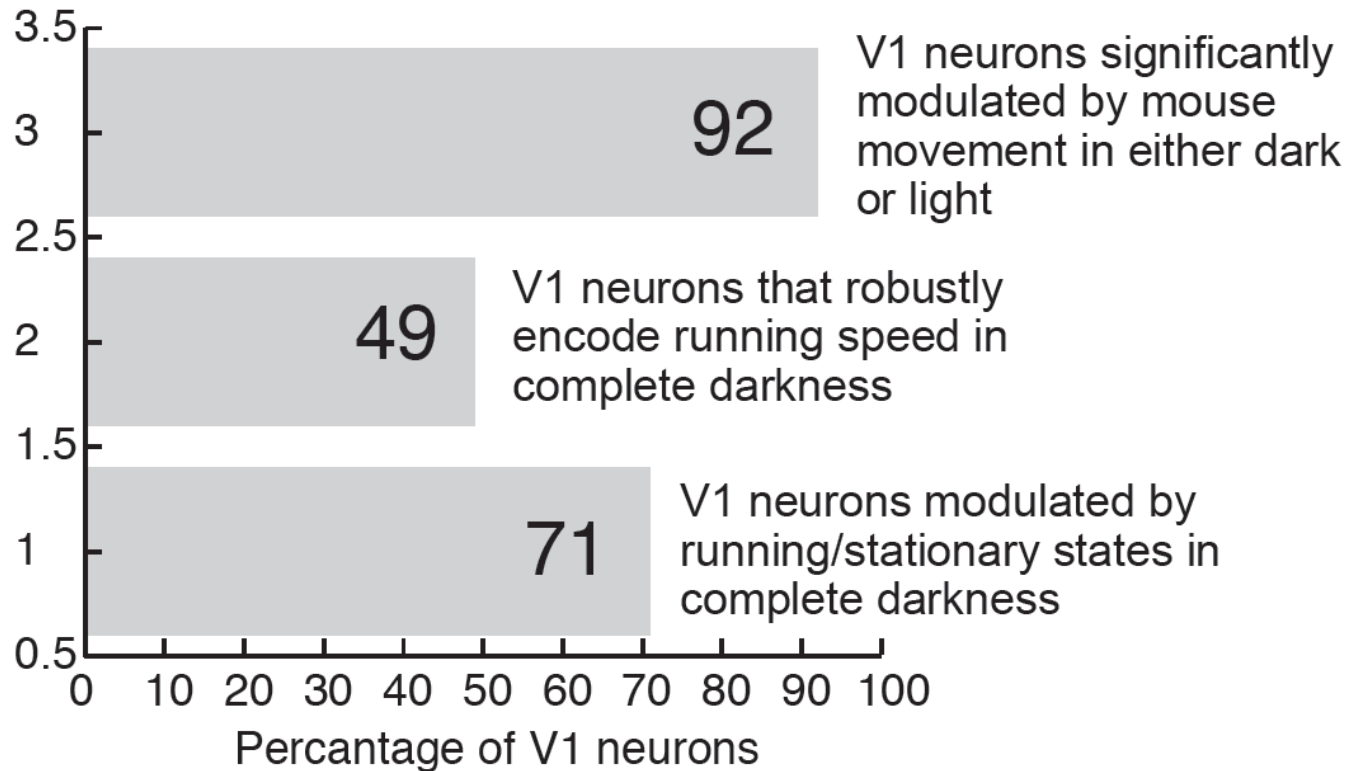
Population average response



→ Surprisingly, the majority of neurons in mouse V1 did *not* encode purely passive visual stimuli, but responded to either congruence or incongruence (“feedback-mismatch”) between vision and the animal’s own movements.

→ How many of Hubel and Wiesel’s original neurons were in fact Mismatch cells – and *not* pure visual cells ?!

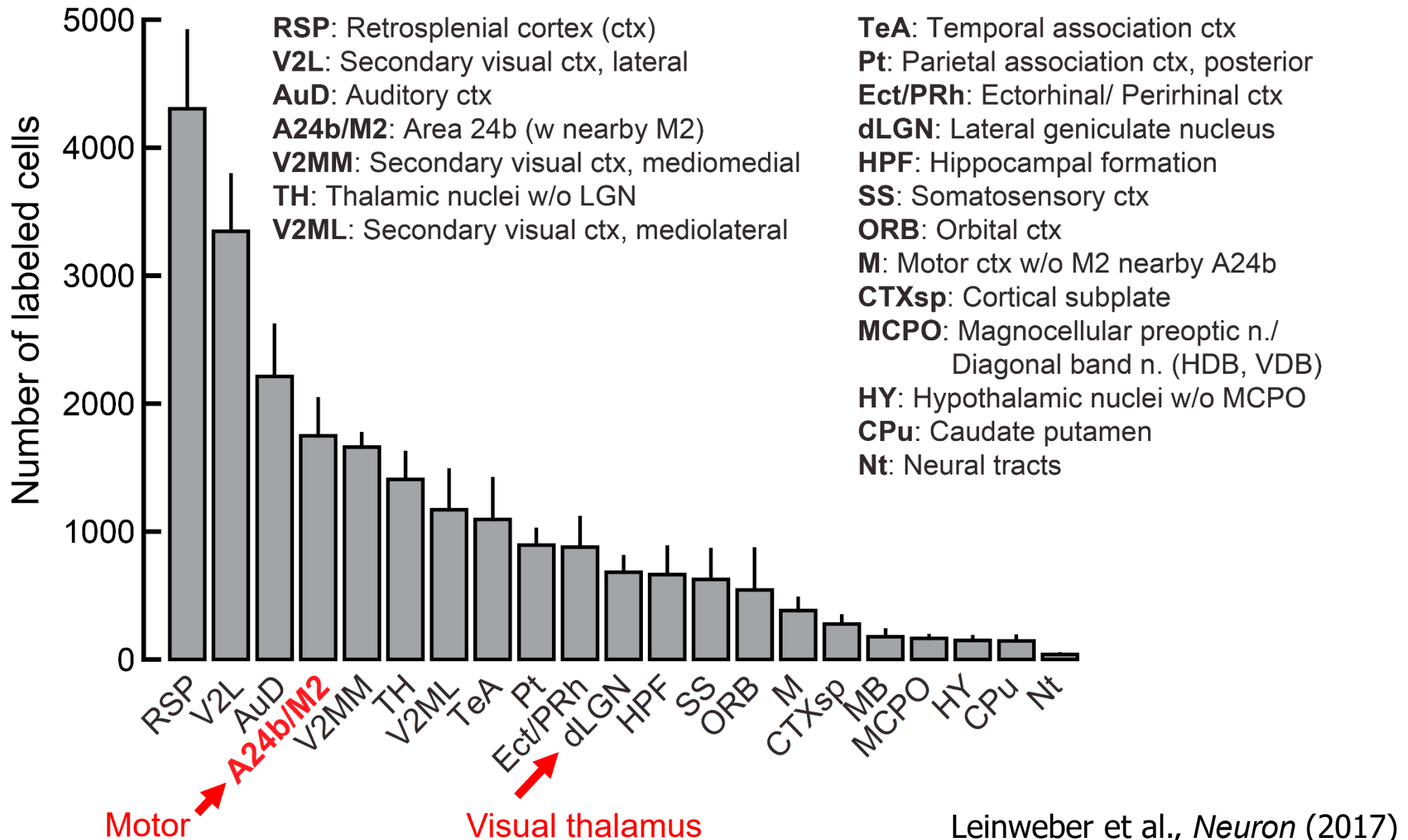
Natural *stimulus* statistics is also tightly linked to natural *movement* statistics – and this coupling affects neurons



→ Several additional VR studies showed similarly strong effects of locomotion on V1 responses: e.g. Saleem et al. (2013).

Numbers Based on:
Saleem et al., *Nature Neurosci.* (2013)

Major motor inputs and other non-visual inputs into mouse V1



Sensory Ecology – outline of today's lecture

- **Rationale:** Why should Neuroscientists care about Ecology?

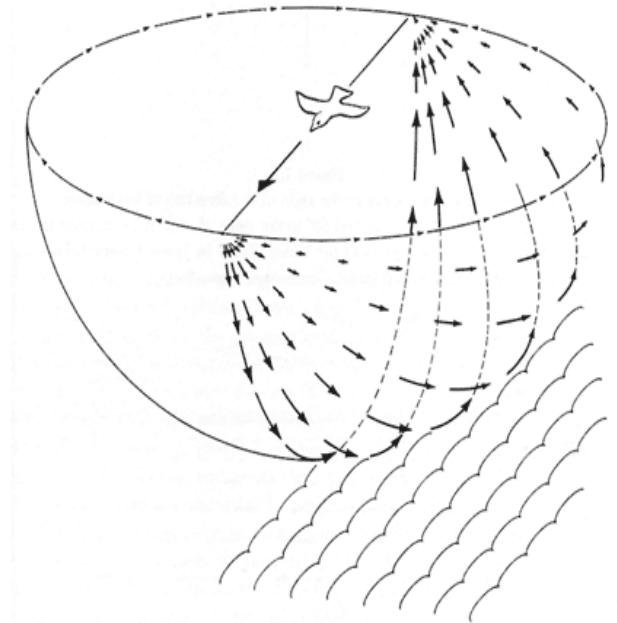
Three aspects of Sensory Ecology:

- **The physics of the environment:** How it affects the sensory information available to the organism
- **Natural stimulus statistics:** A modern (and currently popular) look at the concept of “Umwelt”
- **Direct Perception** (“The ecological approach to visual perception” – Gibson): the surprisingly rich cues and clues that the Umwelt of humans supplies our visual system

"The ecological approach to visual perception" – Gibson

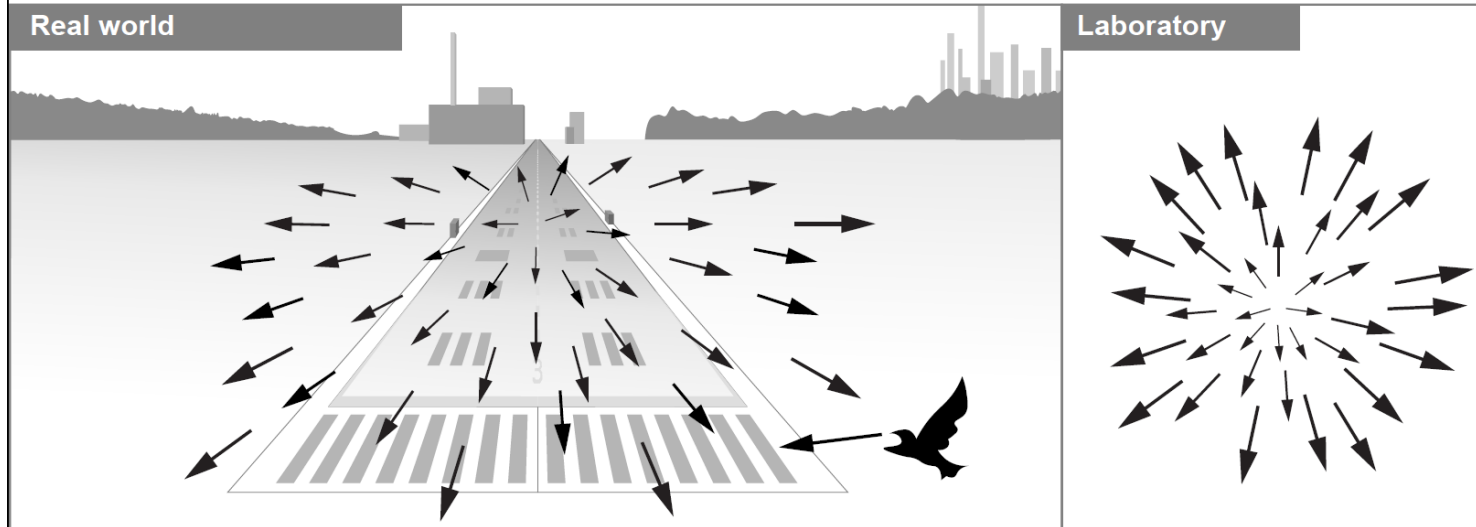
Example #1: Optic Flow :

- The zero-point of optic flow allows estimating the **point of collision**, independent of cross-winds
- Geometric methods for directly estimating **time-to-collision** without complex calculations
 - Birds use it, behaviorally !
 - Neurons in the bird brain encode time-to-collision.
- Optic flow is the main cue used by:
 - Honeybee odometer (distance meter)
 - Pilots landing on aircraft carriers in rough seas

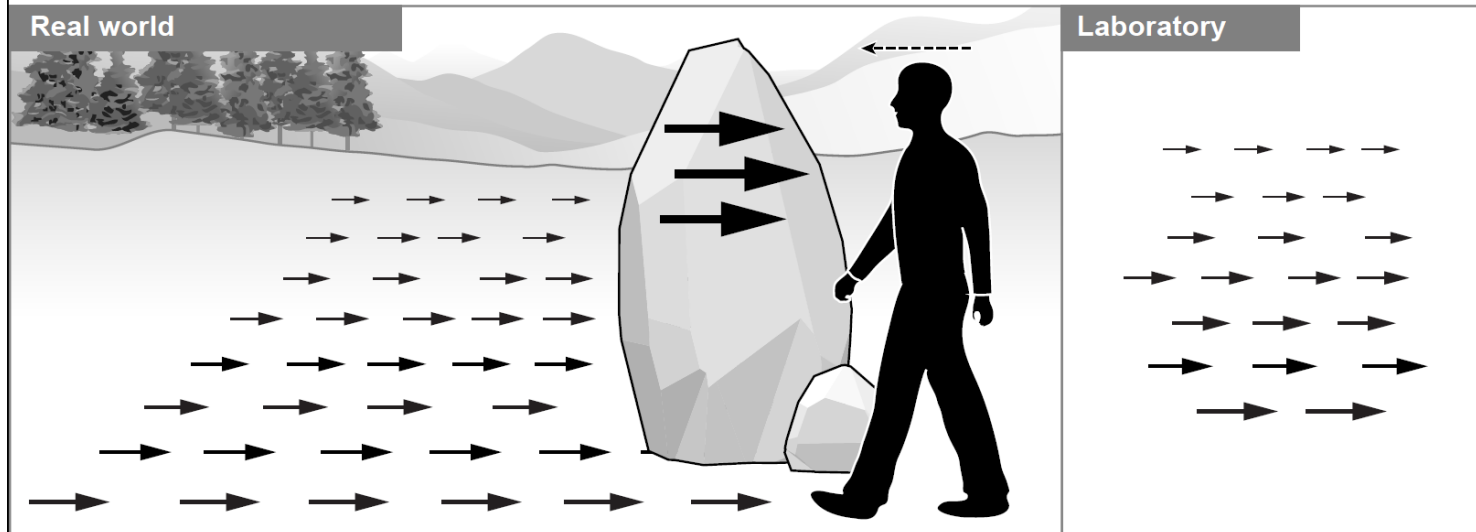


"The ecological approach to visual perception" – Gibson

b Translational optic flow: 0°

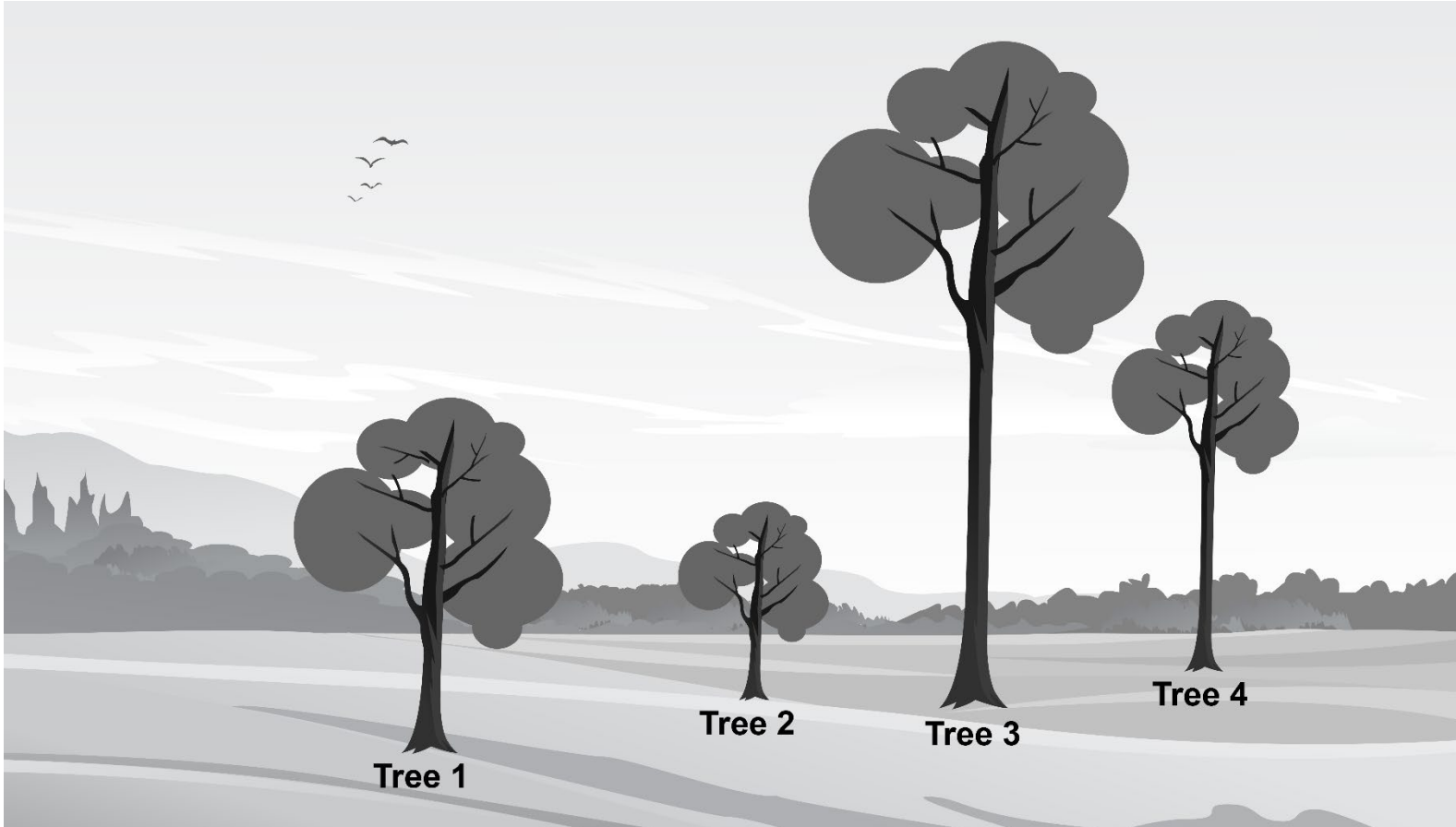


c Translational optic flow: 90°



"The ecological approach to visual perception" – Gibson

Example #2: The invariant horizon ratio of terrestrial objects



- Can you estimate the trees' heights?

- The line where the horizon cuts the object is just as high above the ground as your eye. Note that trees 1+2 are "cut" at the same height, and their above:below horizon ratio is $\sim 2:1$, implying a total height of 5 m. For trees 3+4, we can likewise estimate height of 15 m.

Take home message

When studying the neural basis of behavior in a certain animal species, it is important to control the animal's Umwelt (surrounding world) in the laboratory – but it is also very important to fully understand this animal's Umwelt in its natural environment → because: (1) the natural environment is what the animal's brain evolved to cope with, and (2) neurons care about this !
Hence: we must incorporate these considerations when studying brain function.