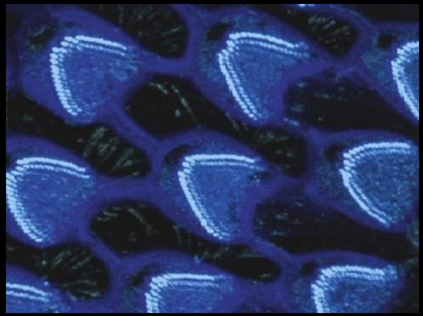
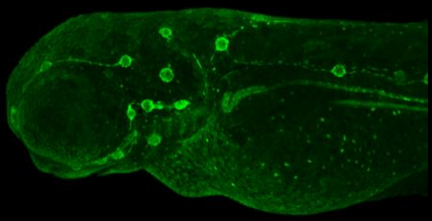
Wolfger von der Behrens, wolfger@ini.uzh.ch
Institute of Neuroinformatics, UZH & ETHZ

Structure, Plasticity and Repair of the Nervous System HS 2016



Auditory System
Purves 5th edition: Chapter 13

Vestibular System
Purves 5th edition: Chapter 14



Chemical Senses
Purves 5th edition: Chapter 15

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Structure, Plasticity and Repair of the Nervous System HS 2017

The Auditory System

1. Introduction into hearing
2. Sound
3. Anatomy of the ear
4. Mechanotransduction
5. Sound localization
6. Ascending auditory pathway
7. Music
8. Prosthesis
9. Summary & questions
10. Literature

From: Cell 2010, 141 (5)

1. Introduction into hearing: functions

Orientation

Localization & object recognition

Music

Communication

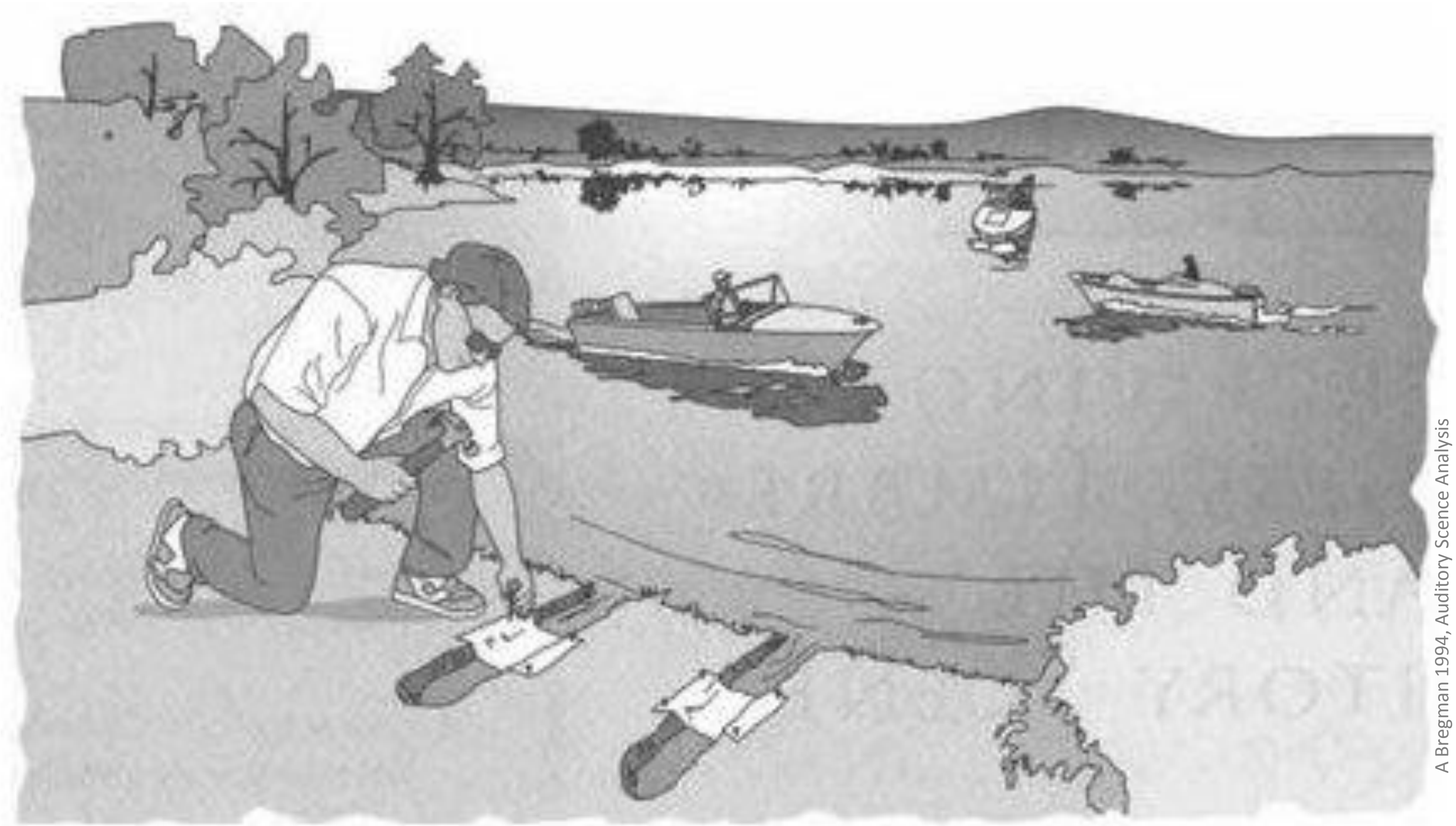
1. Introduction into hearing

Youtube.com, documentary „extraordinary people"

1. Introduction into hearing

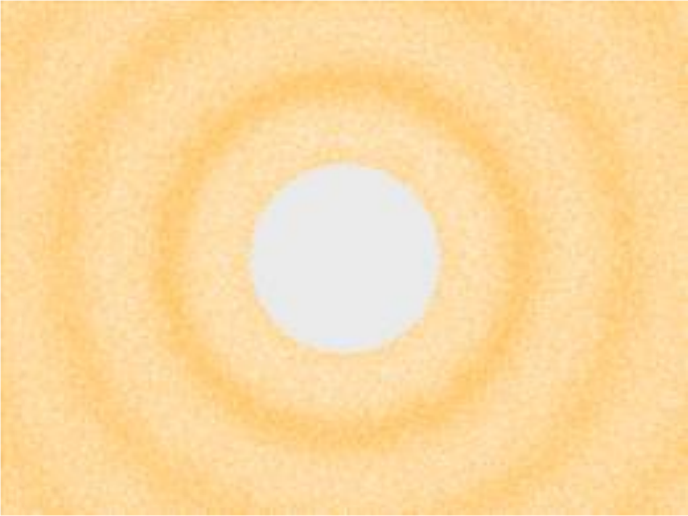
Youtube.com, documentary „extraordinary people"

1. Introduction into hearing: auditory scene analysis

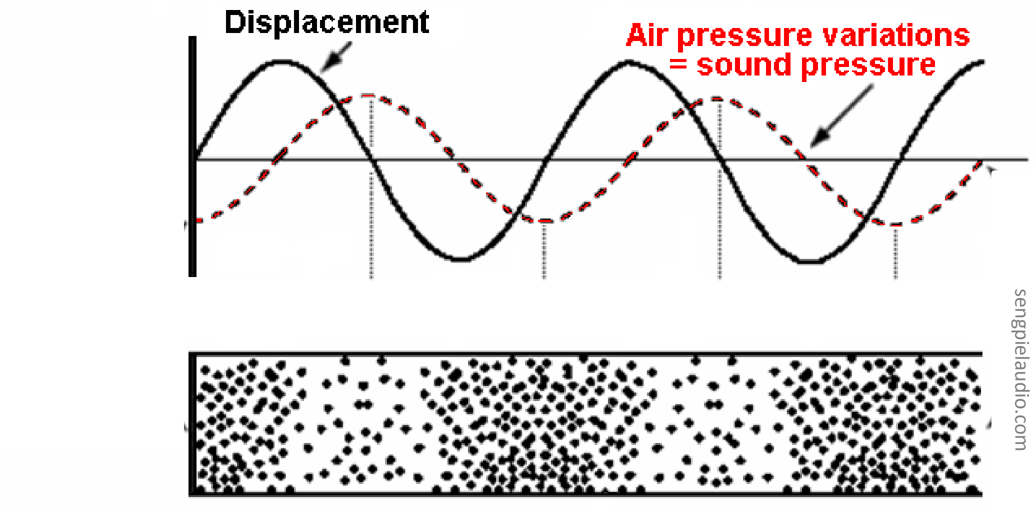


A Bregman 1994, Auditory Scence Analysis

2. Sound: physical properties



Wikipedia.com



sengpielaudio.com

- Speed of sound *c*: 343 m/s (air) or 1234.8 km/h
  1484 m/s (water)

- Wavelength λ = speed *c* / frequency *f*

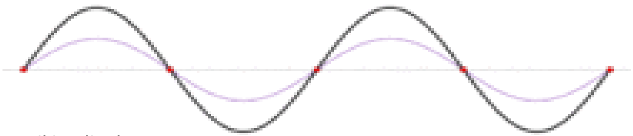
- Sound pressure *p* = N/m^2 (Pascal)

- Particle velocity *v* = m/s

- Longitudinal wave

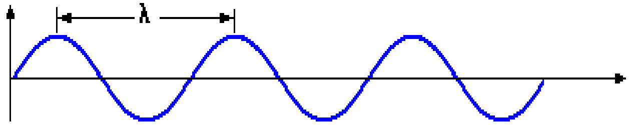
2. Sound: physical properties

Standing wave



wikipedia.de

Mechanical wave



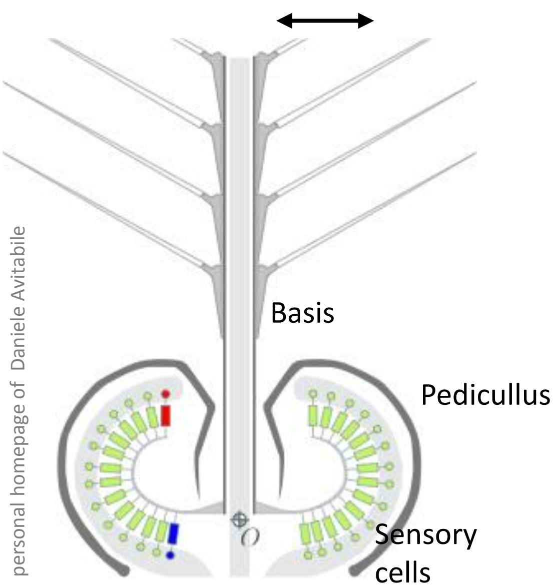
wikipedia.de

- Natural stimuli are rarely sinusoidal
- Every stimulus can be seen as a sum of sinusoidal waves
- Audible spectrum: 0.02 - 20 kHz (humans)
  20-200 kHz (some bats)
- Sound pressure level (SPL) is a logarithmic measure relative to a reference value
- 0 dB SPL = 20 µPa = human hearing threshold for 1 kHz tone (10 picometer of molecular movement)
- Dynamic range (humans): 0 – 120 dB SPL (loud rock concert, 20 Pa) = 6 orders of magnitude

2. Sound: Physical Properties

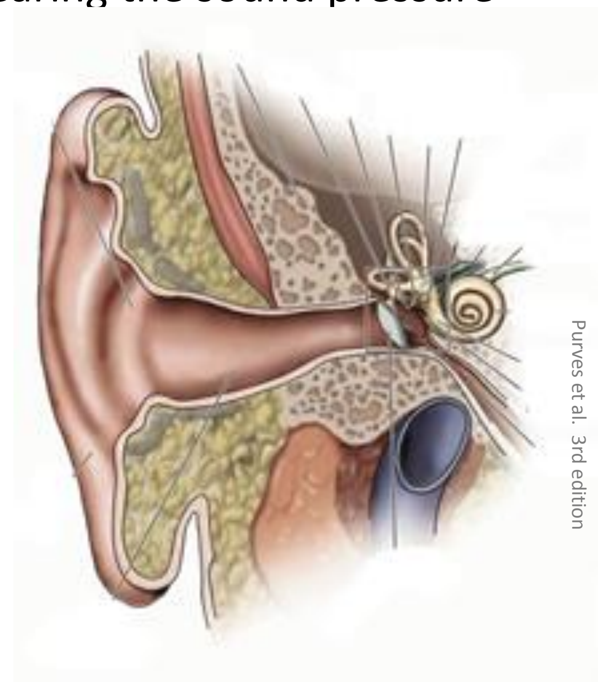
Hearing the particle velocity

.brighton.ac.uk/news/2013/130314mosquito_buzz.php

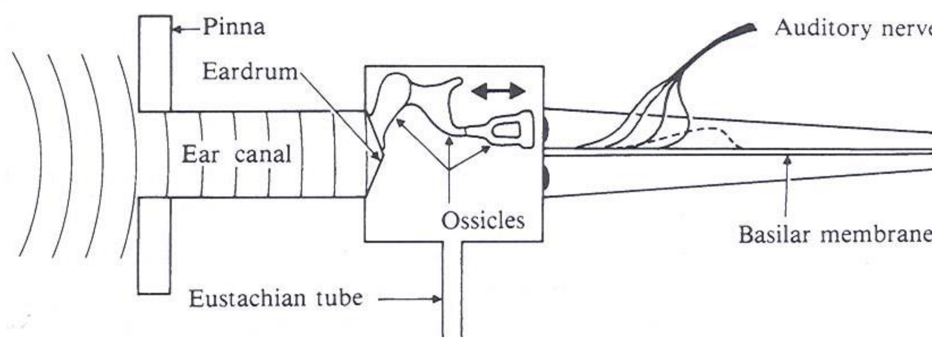


personal homepage of Daniele Avitabile

Hearing the sound pressure



Purves et al. 3rd edition



courses.physics.illinois.edu/phys406

3. Anatomy: external ear

theguardian.com

Wikipedia.com

Functions of external ear:

- focus sound waves into the ear canal
- Directionality for high frequencies

Structures:

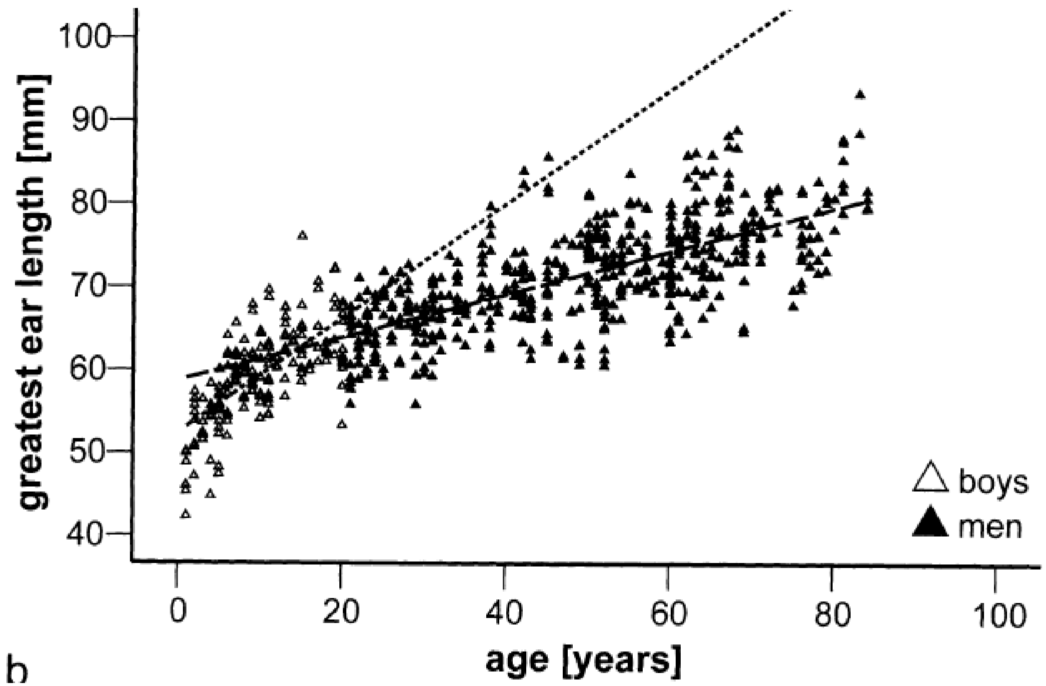
- Pinna
- Tragus
- Concha
- Ear canal (auditory meatus)

Question 4: Do human ears grow throughout the entire lifetime? yes

Anthrop. Anz. **Jg. 65** 4 391–413 Stuttgart, Dezember 2007

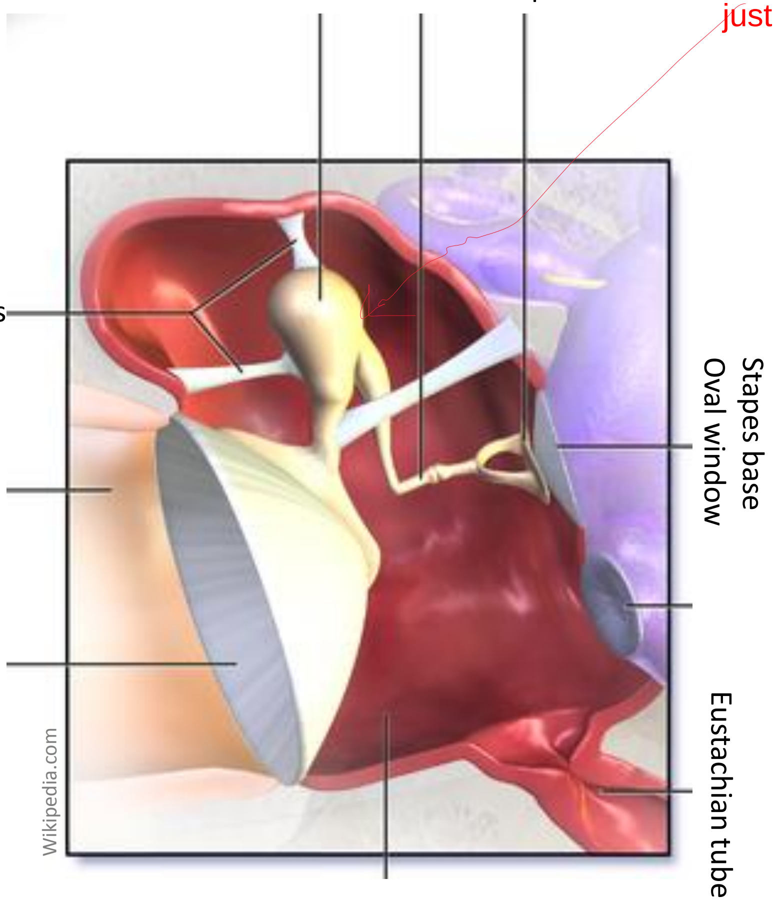
Human ears grow throughout the entire lifetime according to complicated and sexually dimorphic patterns – conclusions from a cross-sectional analysis

Carsten Niemitz, Maike Nibbrig and Vanessa Zacher



3. Anatomy: middle ear

movement is reduced but equally the force increases: no enhancenment, just a conversion

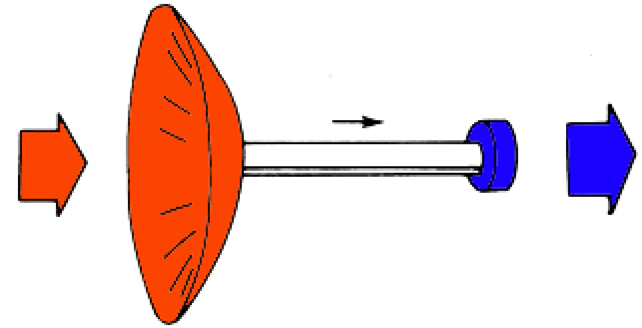


3. Anatomy: middle ear

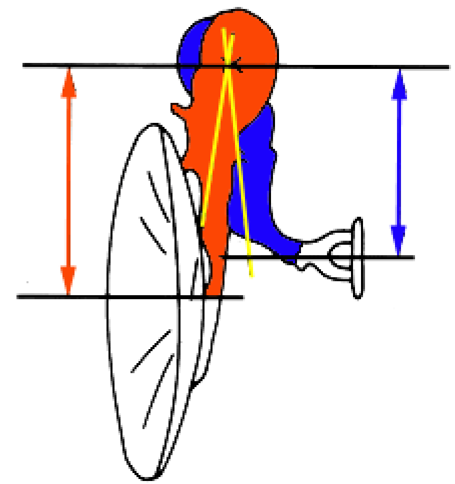
Middle ear impedance matching

- Fluids reflect 99.9% of the acoustic energy
- The middle ear increases the force ~200 times by:
    - Conversion from large to small diameter (see 1)
    - Lever action of ossicles (see 2)
    - Buckling of ear drum (see 3)
- Middle ear efficiency peaks ar ~ 1kHz
- Two muscles regulate middle ear transmisison

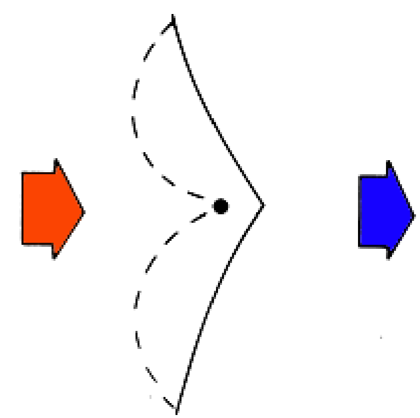
1.



2.

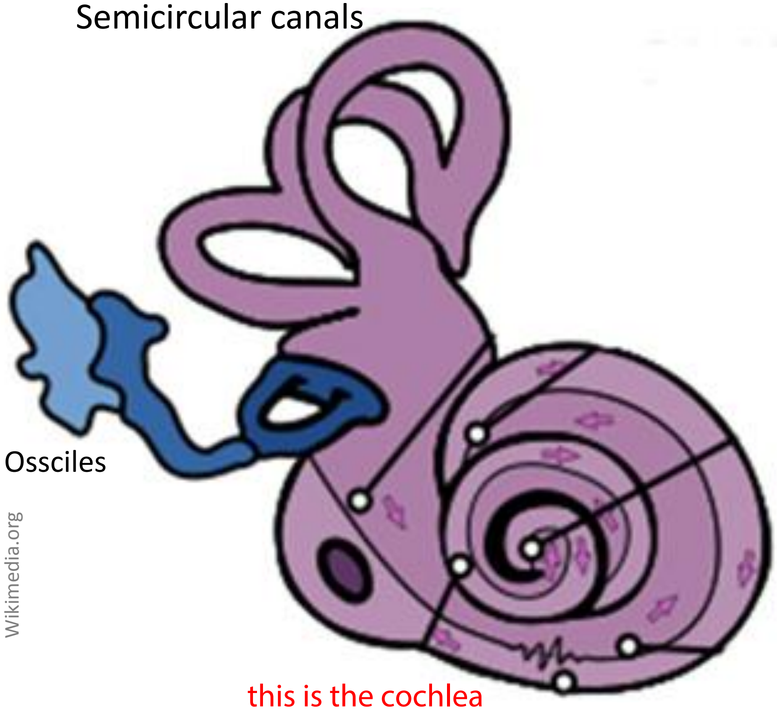


3.

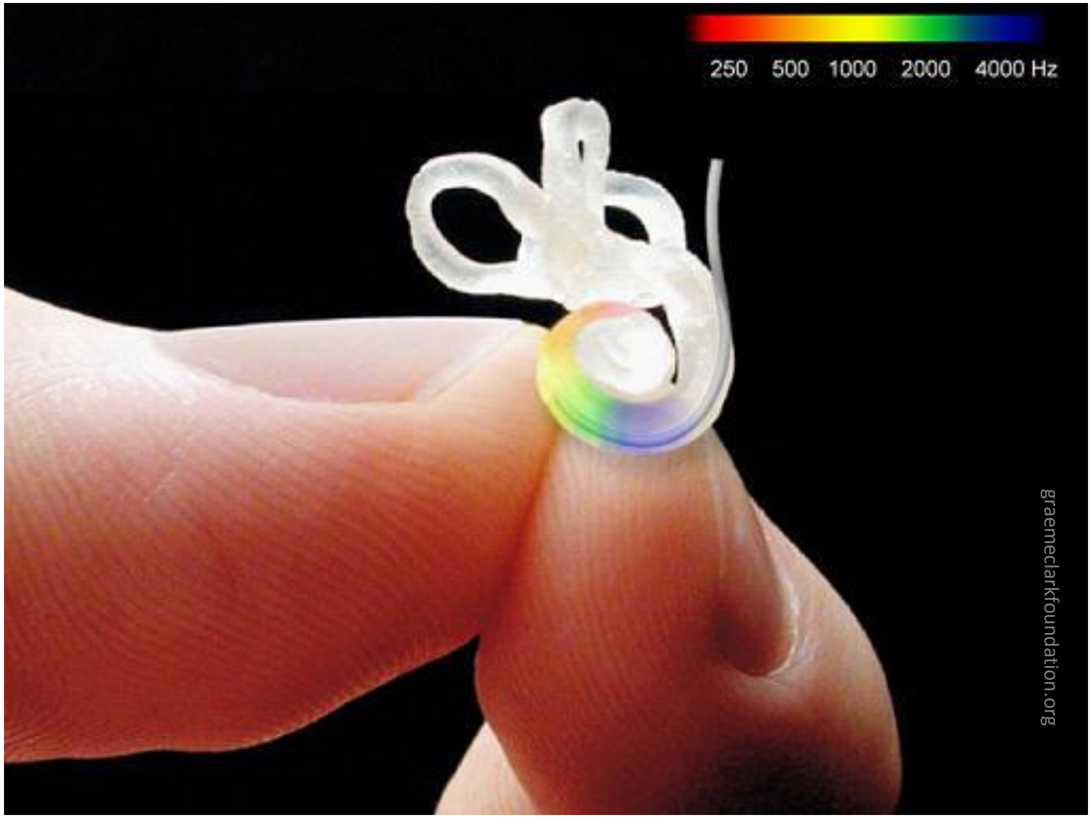


http://www.d.umn.edu/~jfitzake/Lectures/DMED/InnerEar/CochlearPhysiology/MEImpedanceMatching.html

3. Anatomy: inner ear



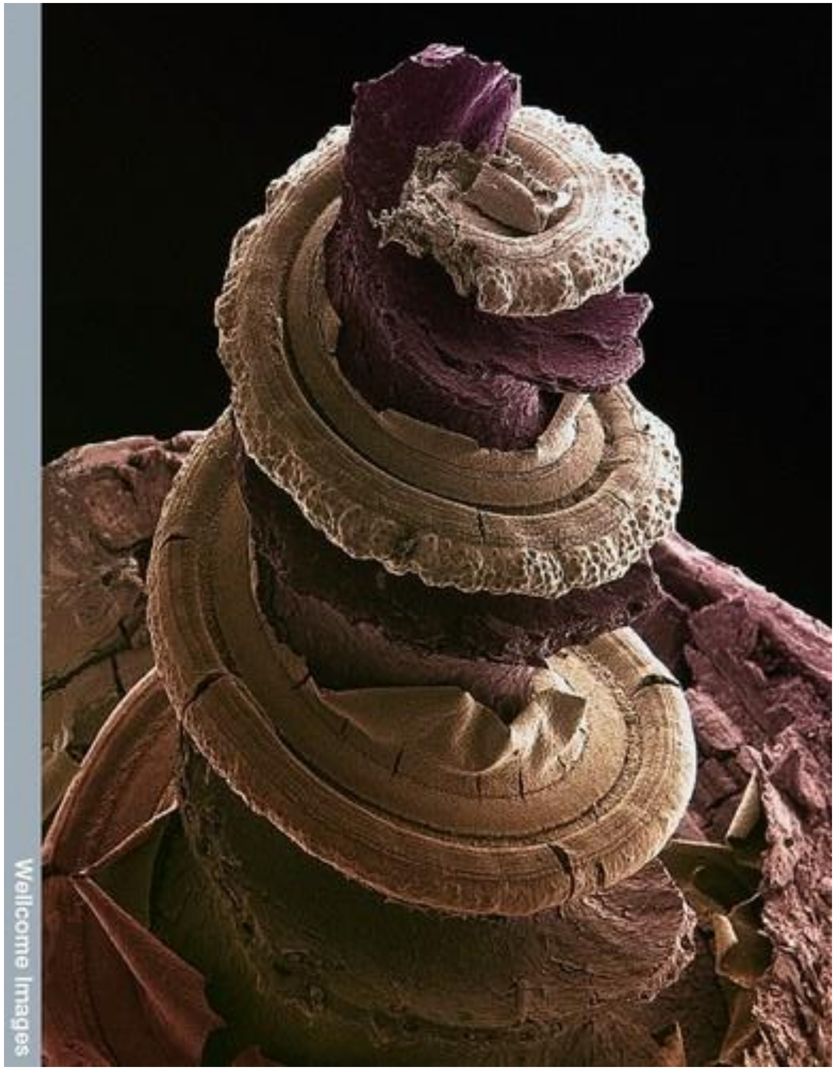
Mould of human inner ear



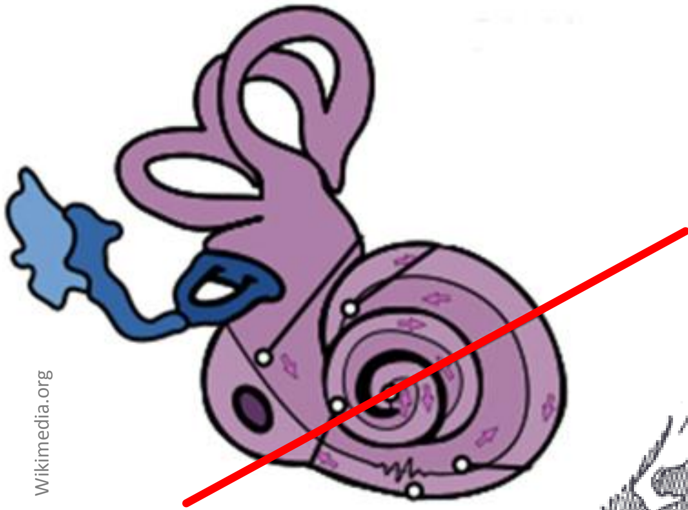
Cochlea functions:

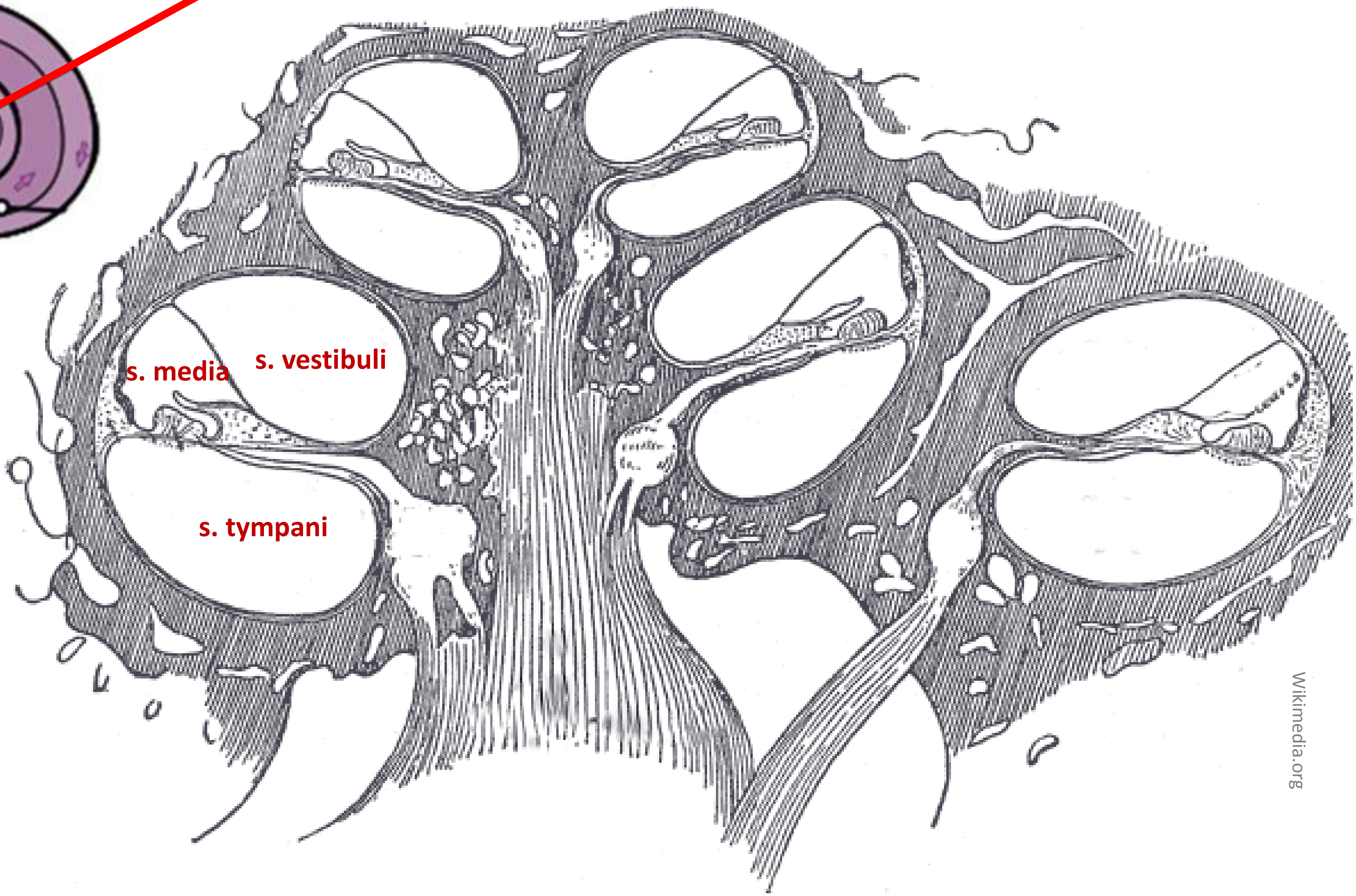
- Active sound amplification
- Conversion of sound into neural signal
- Frequency analyzer (tonotopy)

3. Anatomy: cochlea

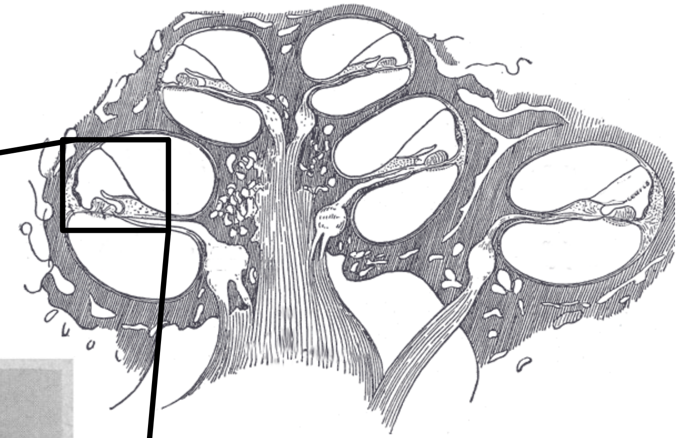


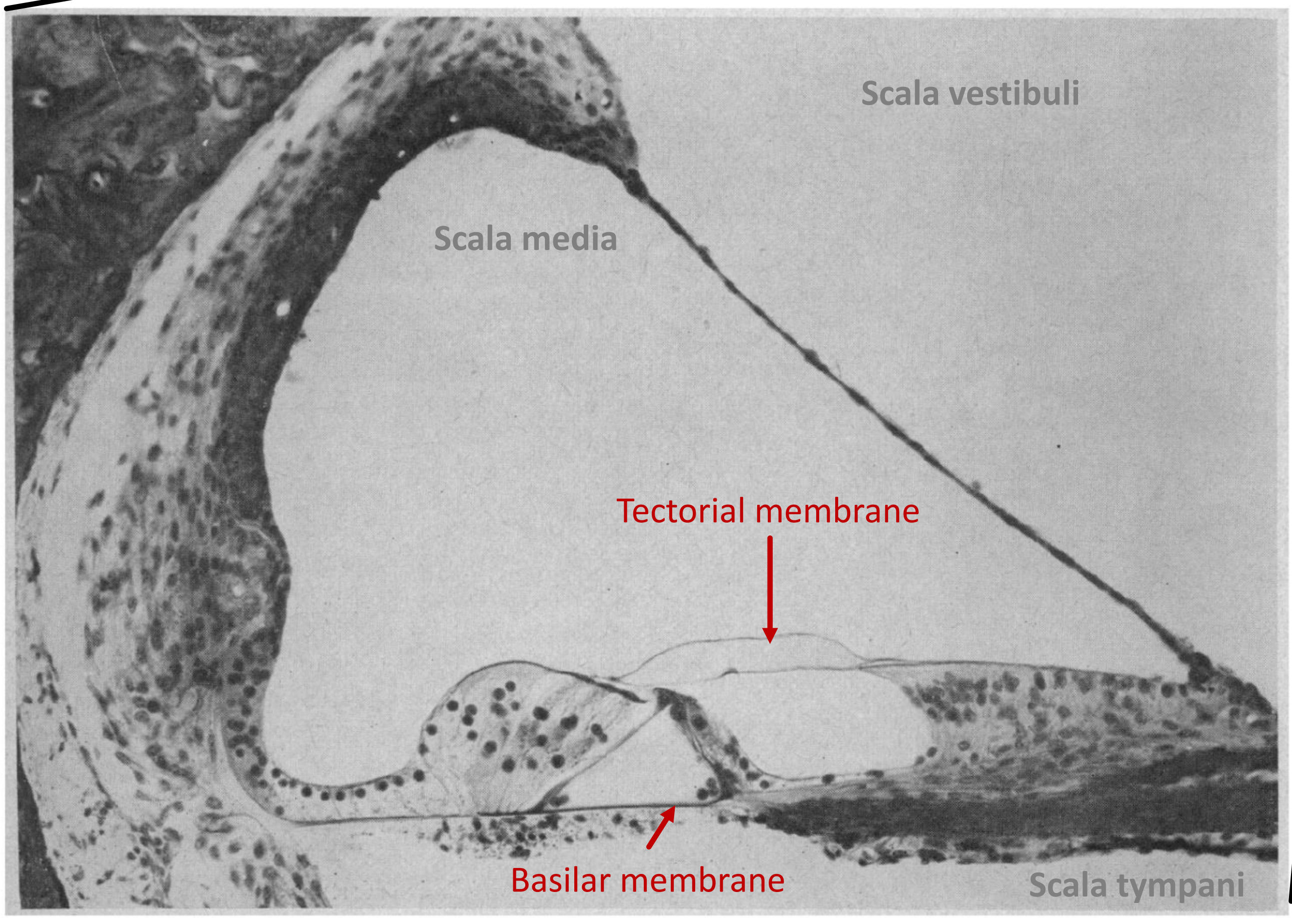
3. Anatomy: cochlea





3. Anatomy: organ of corti

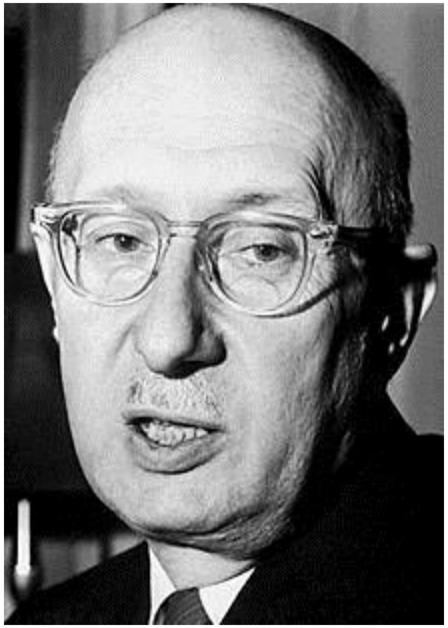




Squirrel monkey

Arch Otolaryng—Vol 82, Nov 1965

3. Anatomy: organ of corti

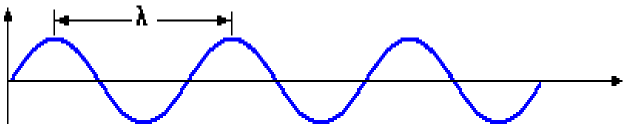


From: wikipedia.de

Georg von Békésy (1899-1972)

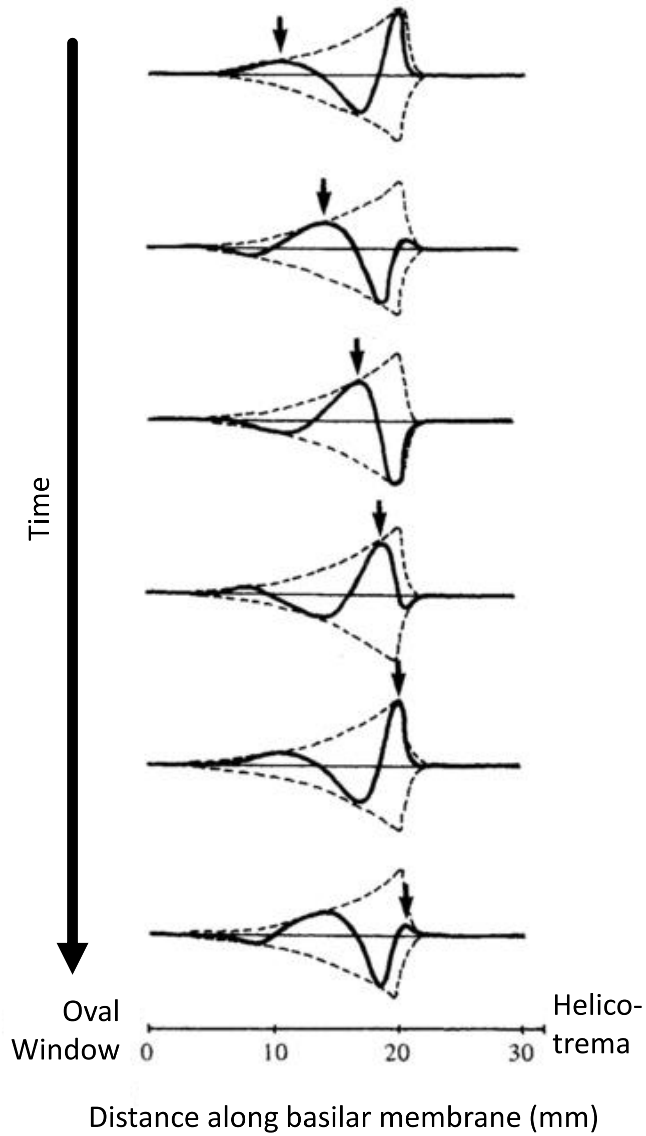
3. Anatomy: organ of corti

Mechanical wave



wikipedia.de

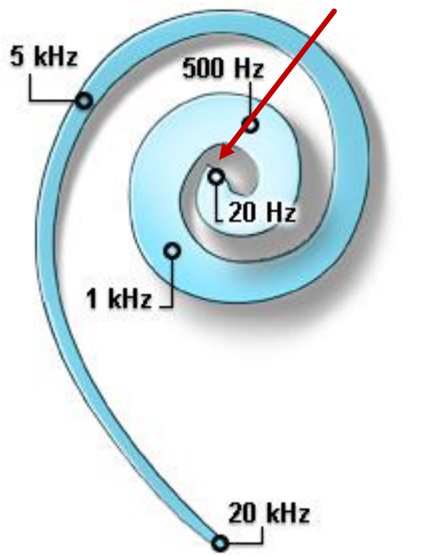
Travelling wave along the cochlea



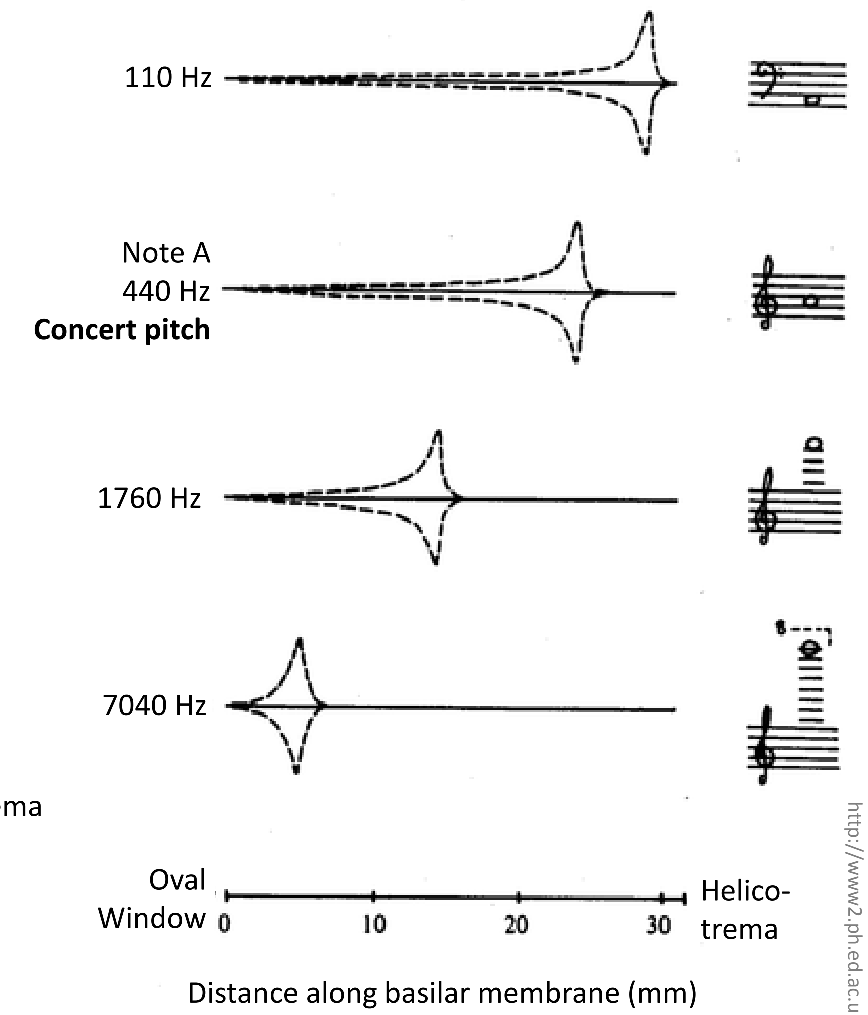
http://www2.ph.ed.ac.uk

3. Anatomy: organ of corti

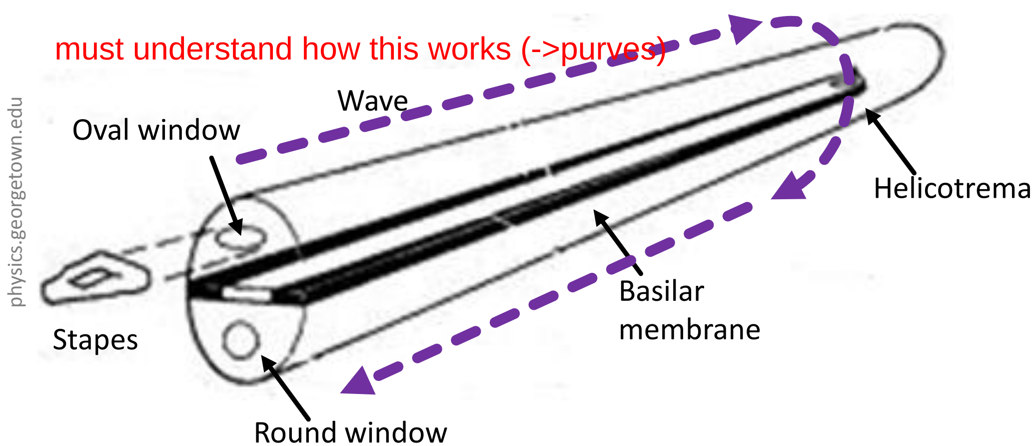
Tonotopy along the cochlea



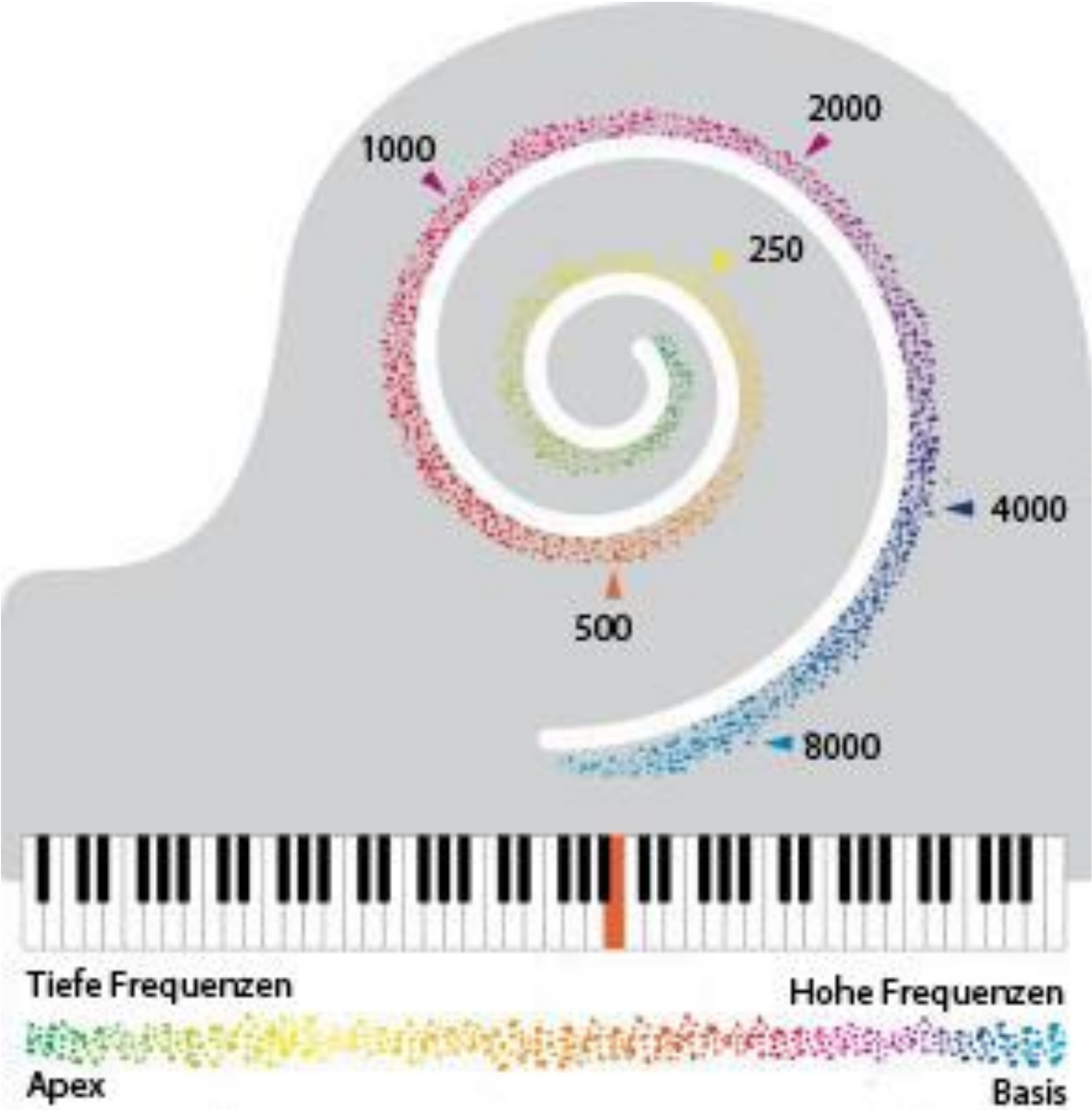
Tonotopy along the basilar membrane



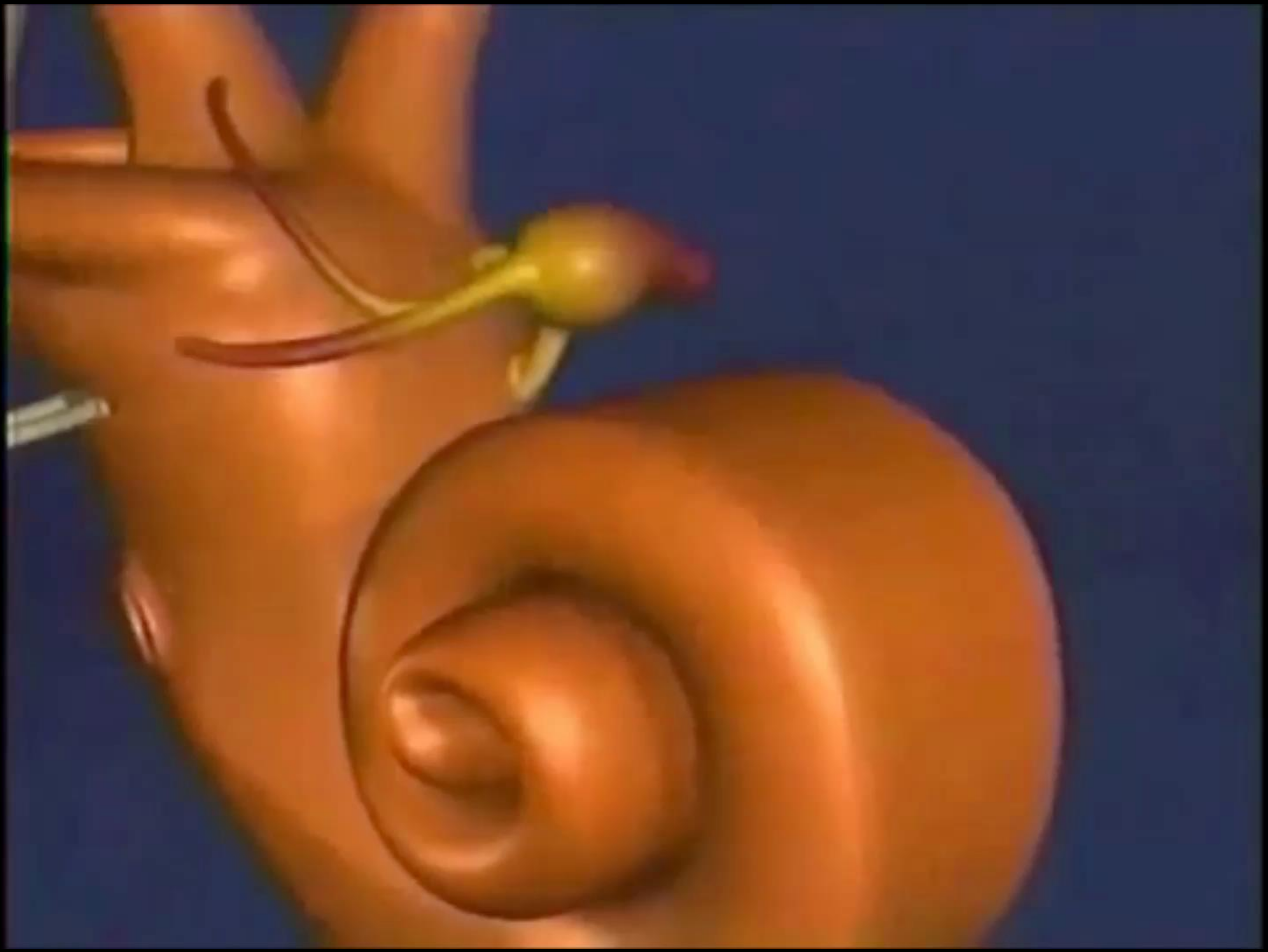
must understand how this works (->purves)



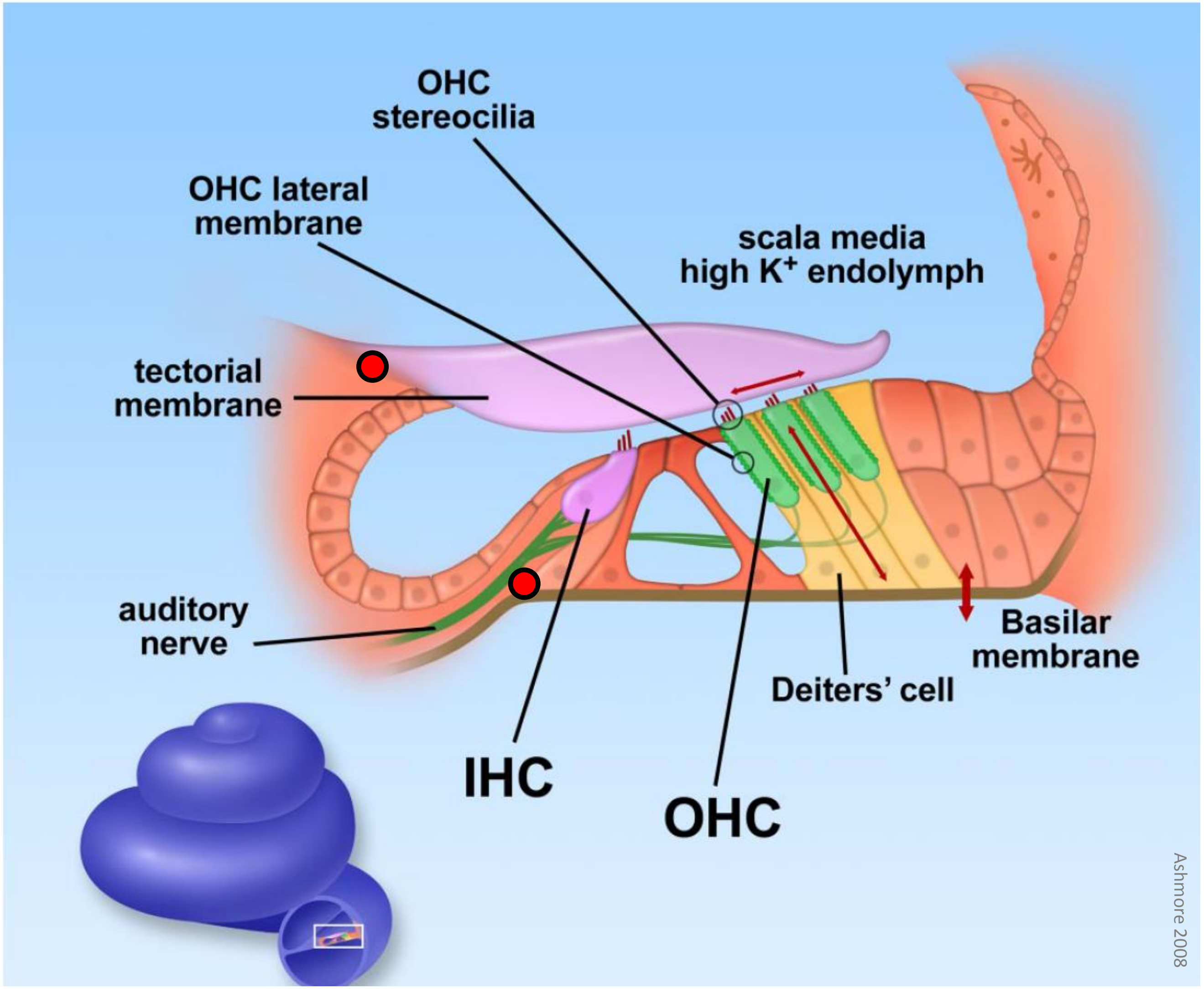
3. Anatomy: organ of corti



3. Anatomy: spectral decomposition in organ of corti



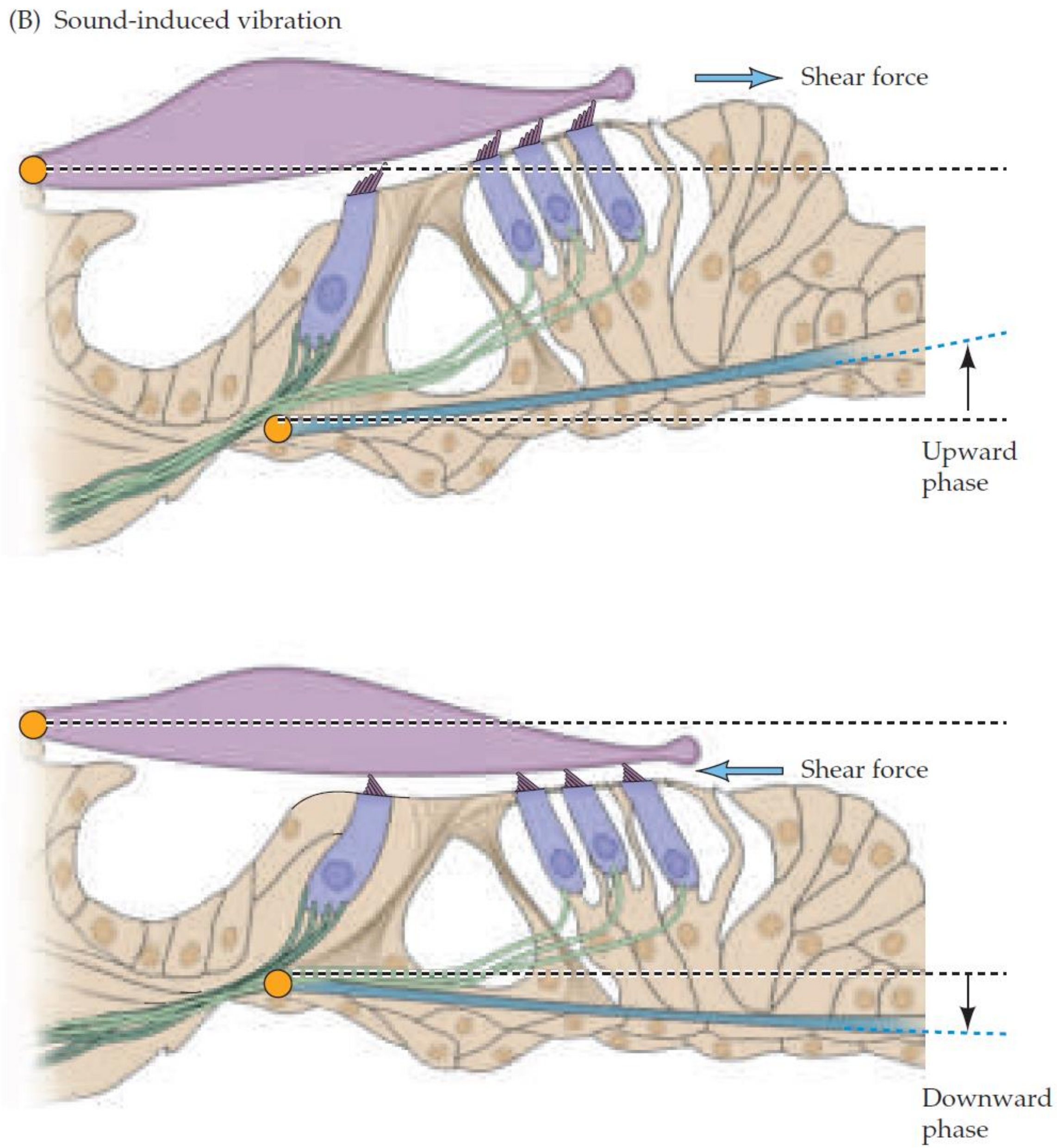
3. Anatomy: organ of corti



1. Inner hair cells (IHC)
2. Outer hair cells (OHC)
3. Endolymph (high K^+)
4. Tectorial membrane
5. Basilar membrane

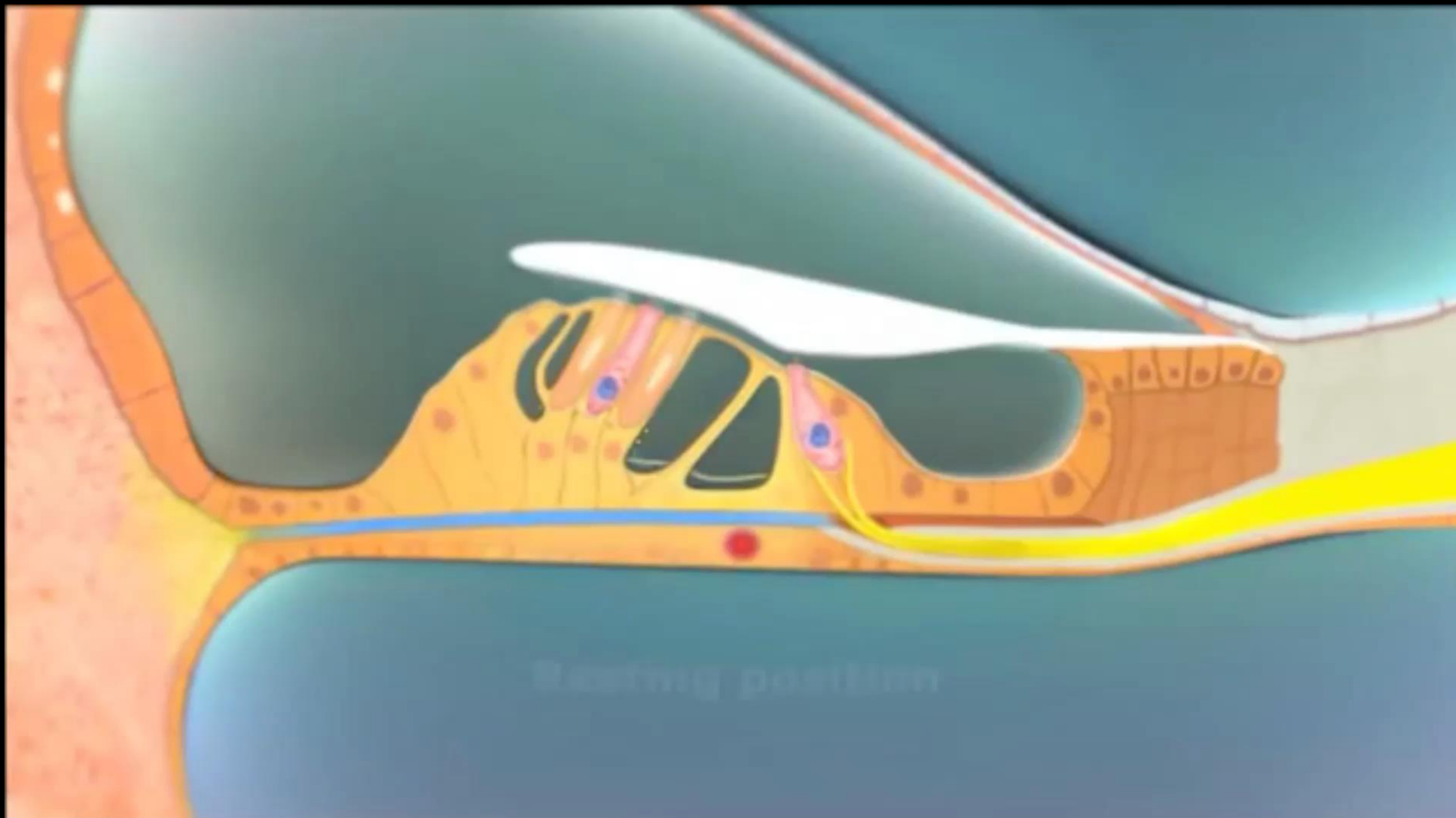
= Pivot point

3. Anatomy: organ of corti



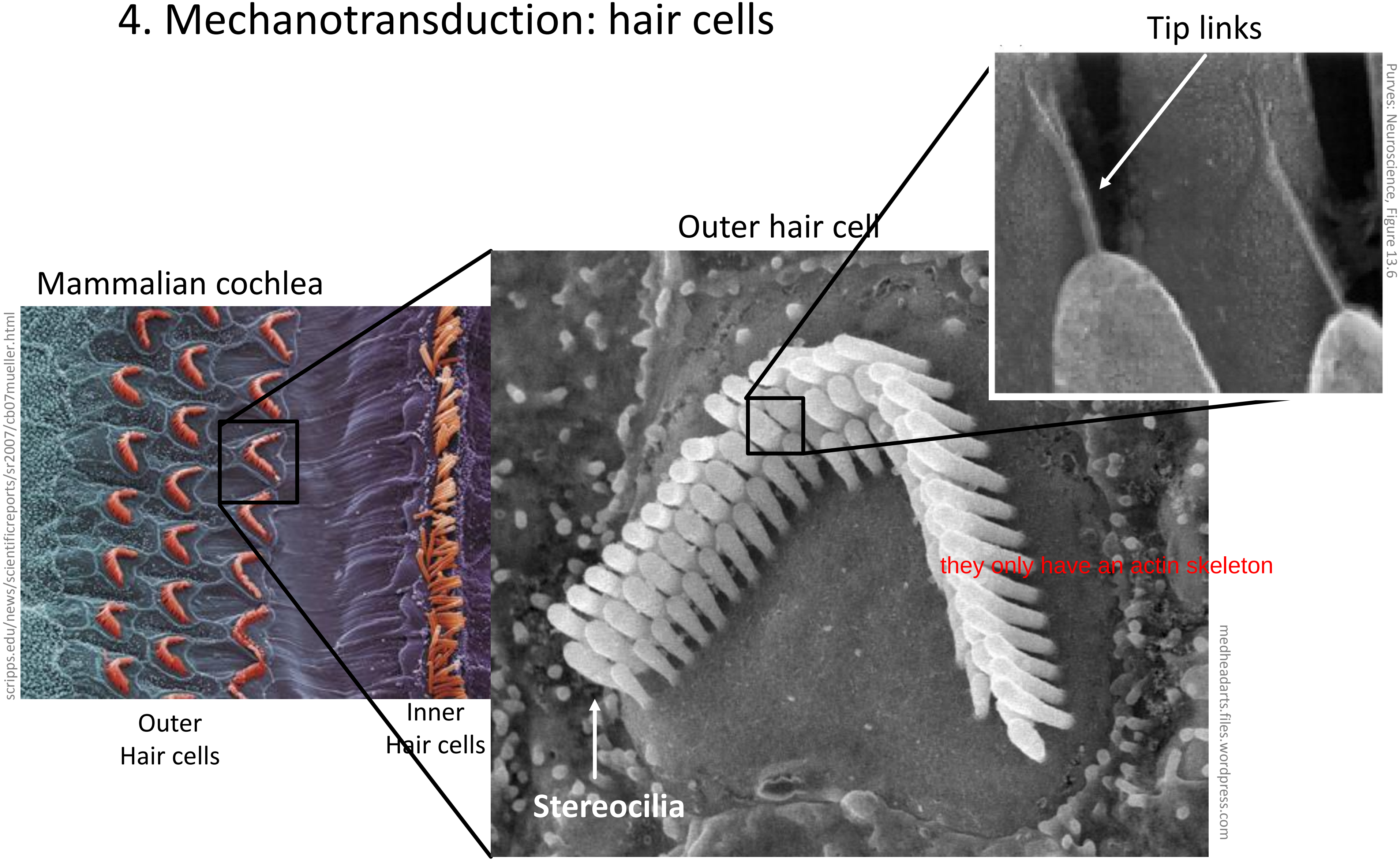
Purves: Neuroscience, Figure 13.6

3. Anatomy: organ of corti

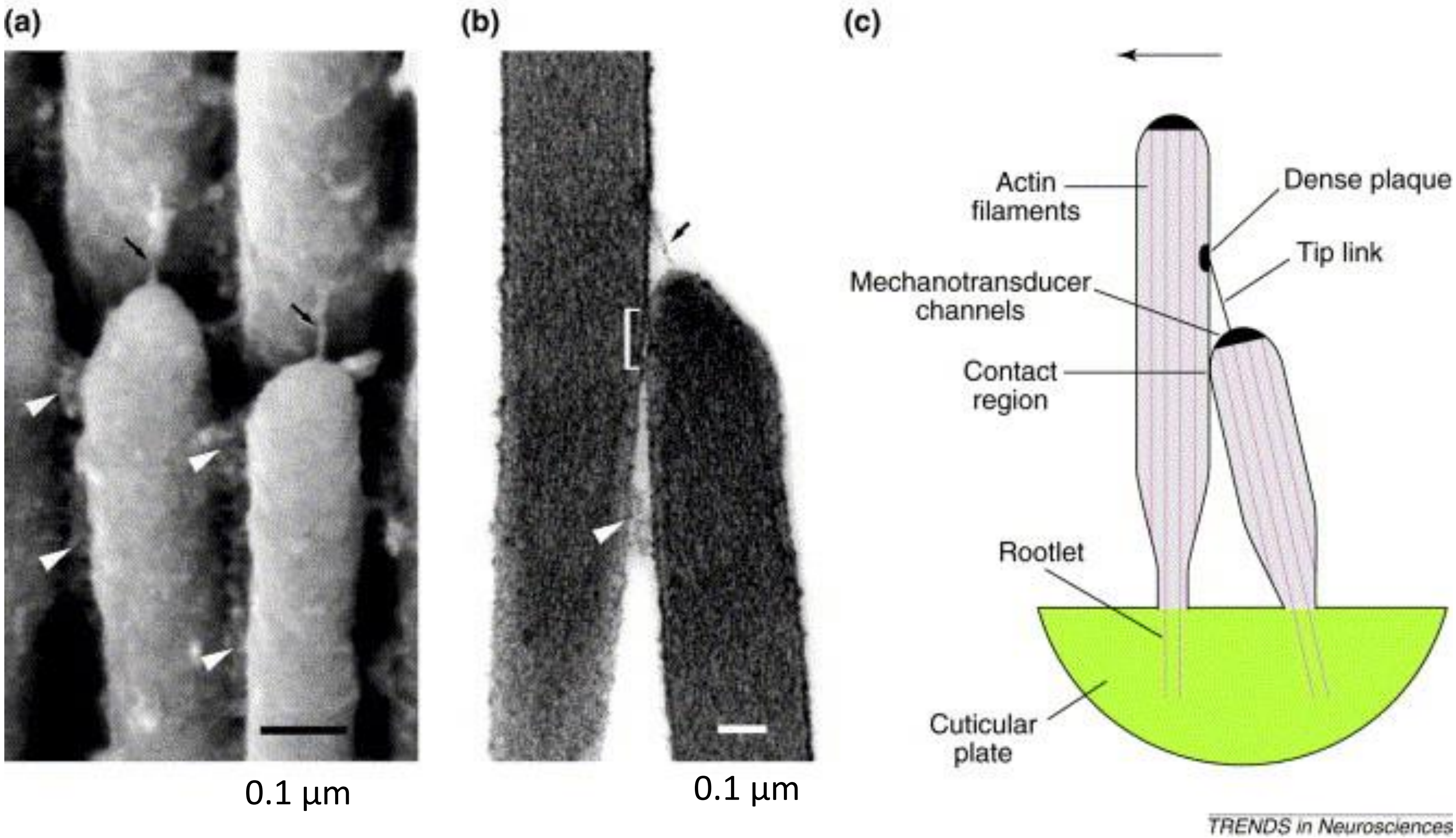


Youtube.com

4. Mechanotransduction: hair cells



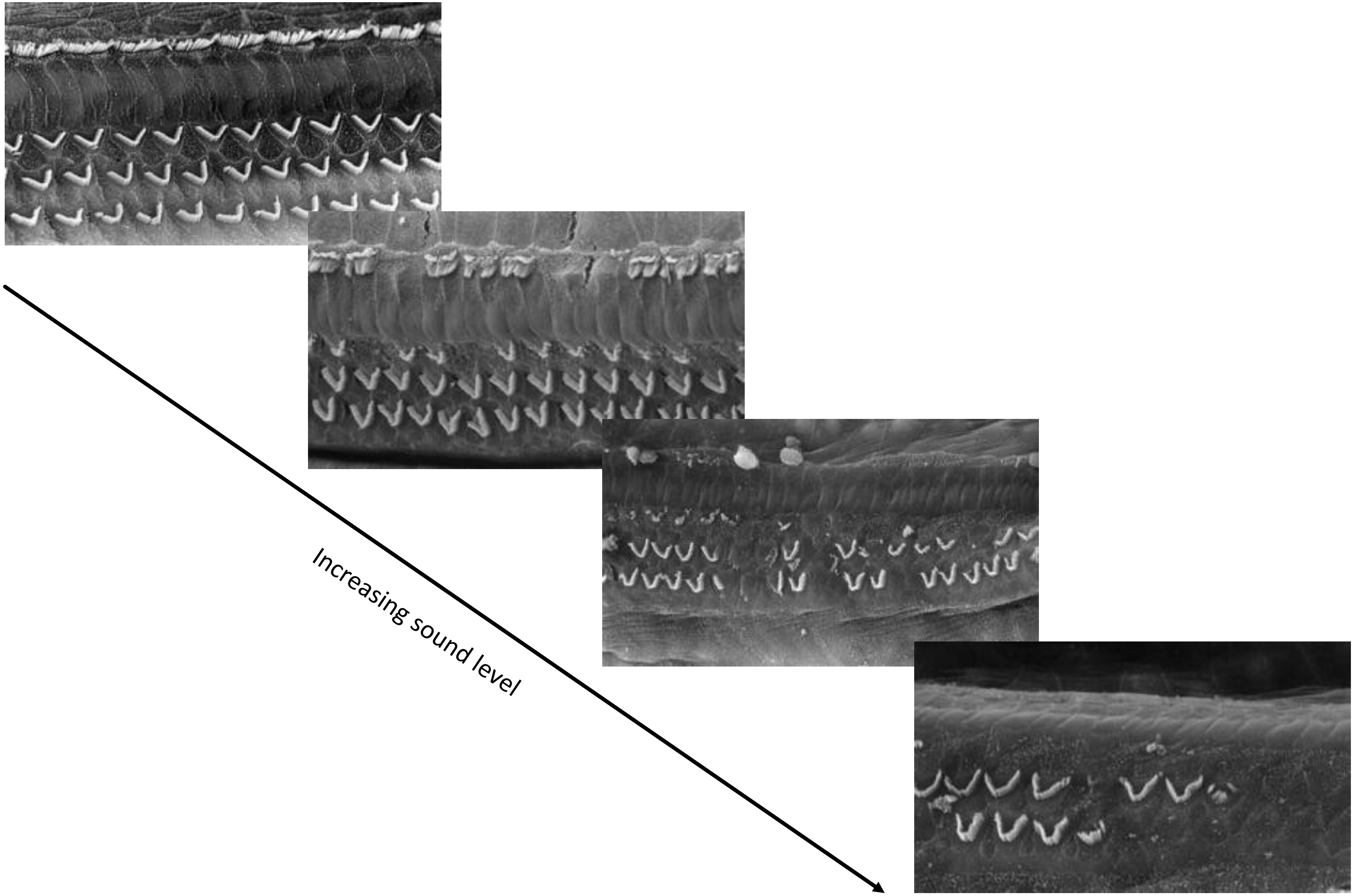
4. Mechanotransduction: hair cells



0.1 µm

0.1 µm

4. Mechanotransduction: hair cell trauma



Question 1: How do some drugs damage hair cells (ototoxicity)?

1. Antibiotics
   - Aminoglycoside (e.g. gentamycin)
   - Excitotoxicity?
   - Free radicals ?

2. Chemotherapeutic agents
   - Cisplatin, Carboplatin
   - Damage through the production of reactive oxygen species -> oxidative stress

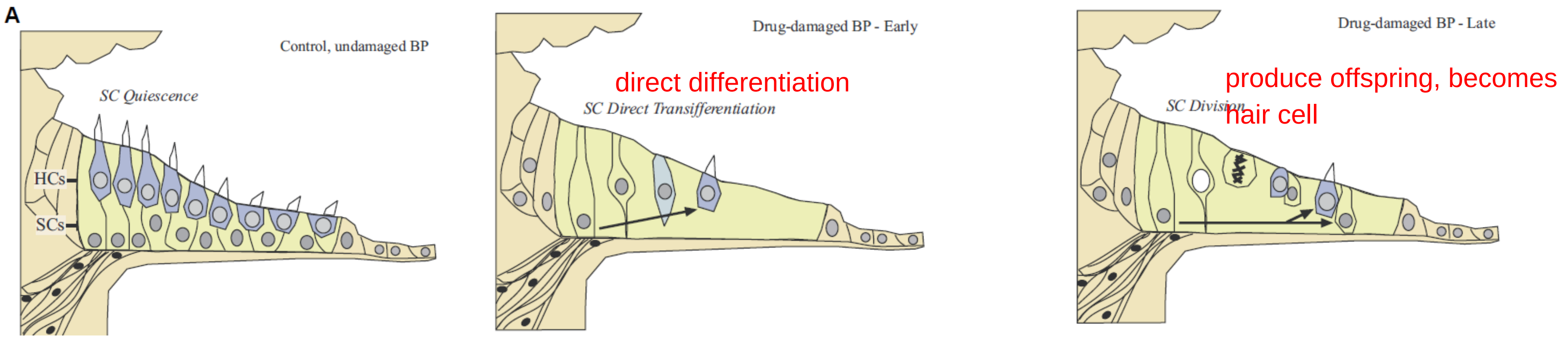
3. Others
   - Aspirin
   - Quinine
   - Heavy metals
   - Viagra?

Question 3: Why/how do haircells in birds regenerate but not mamals

Int. J. Dev. Biol. 51: 633-647 (2007)
doi: 10.1387/ijdb.072408js

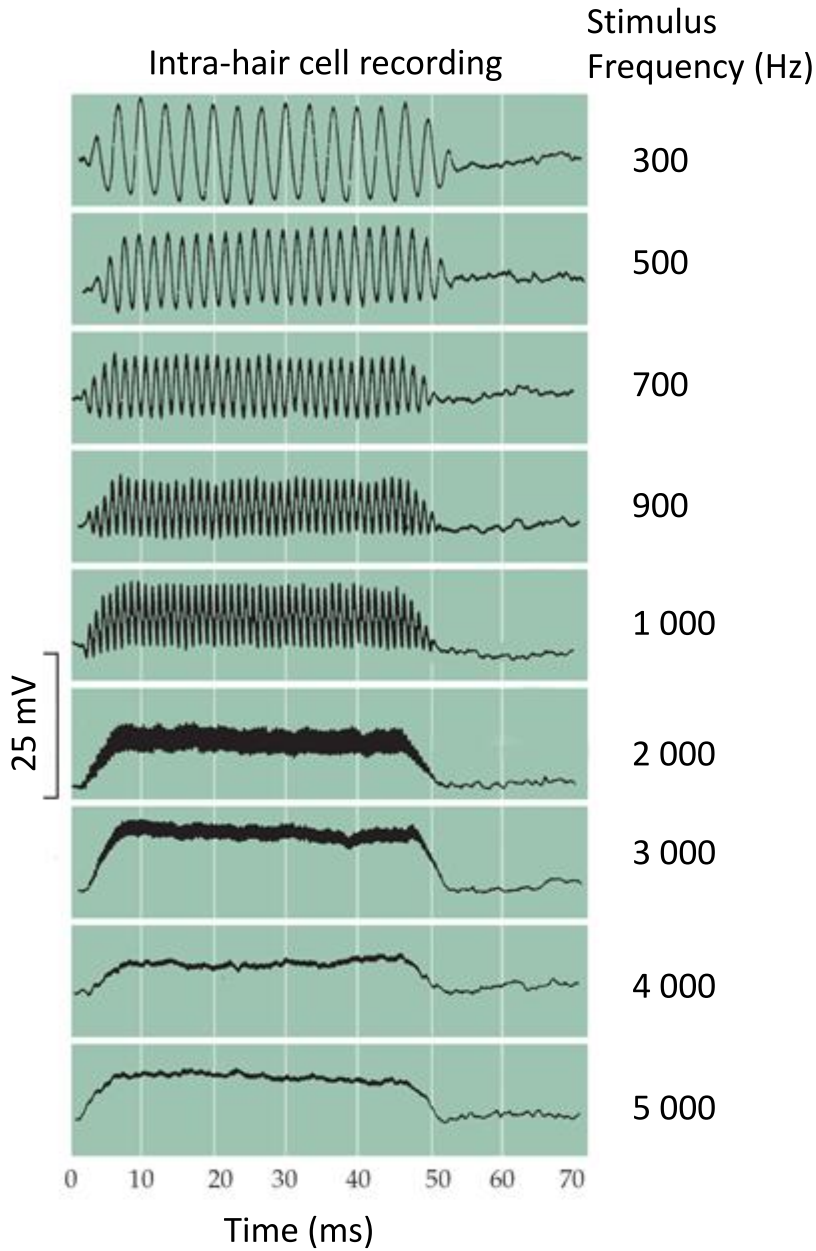
Hair cell regeneration in the avian auditory epithelium

JENNIFER S. STONE[1,*] and DOUGLAS A. COTANCHE[2]

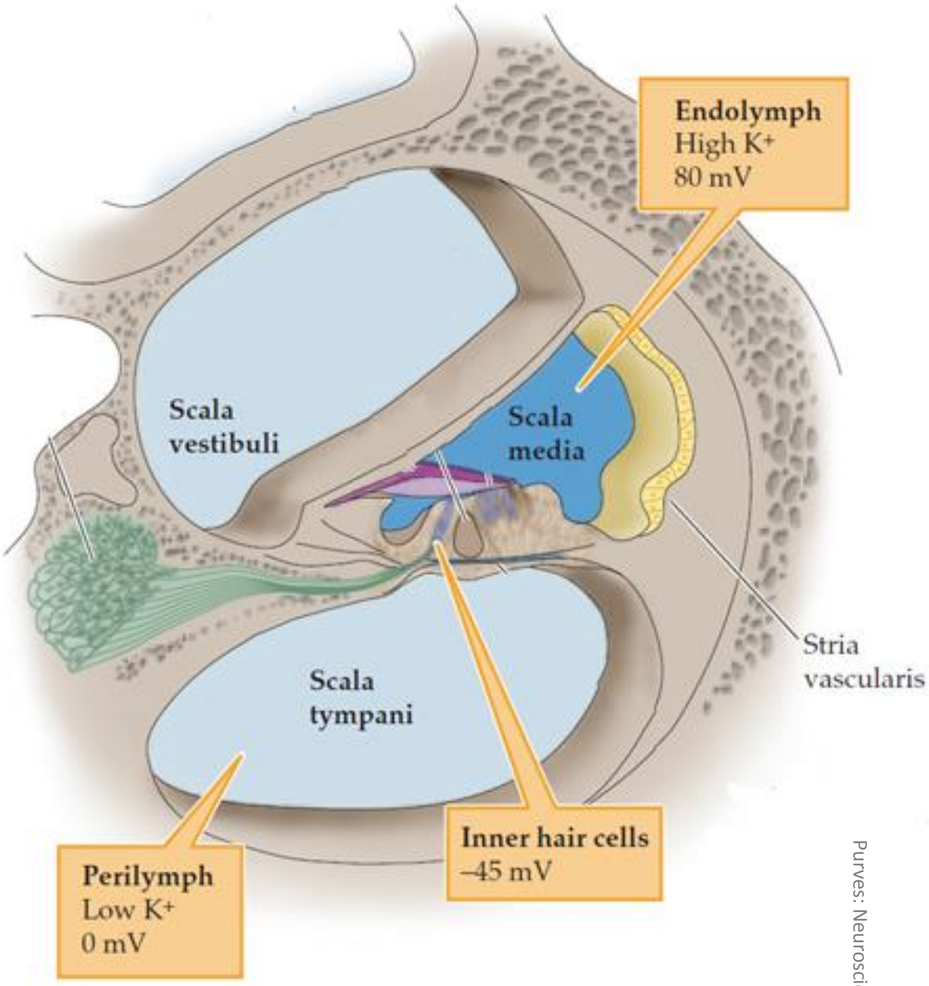


birds can regenerate their hearing organs/hearing mechanism

4. Mechanotransduction: receptor potential

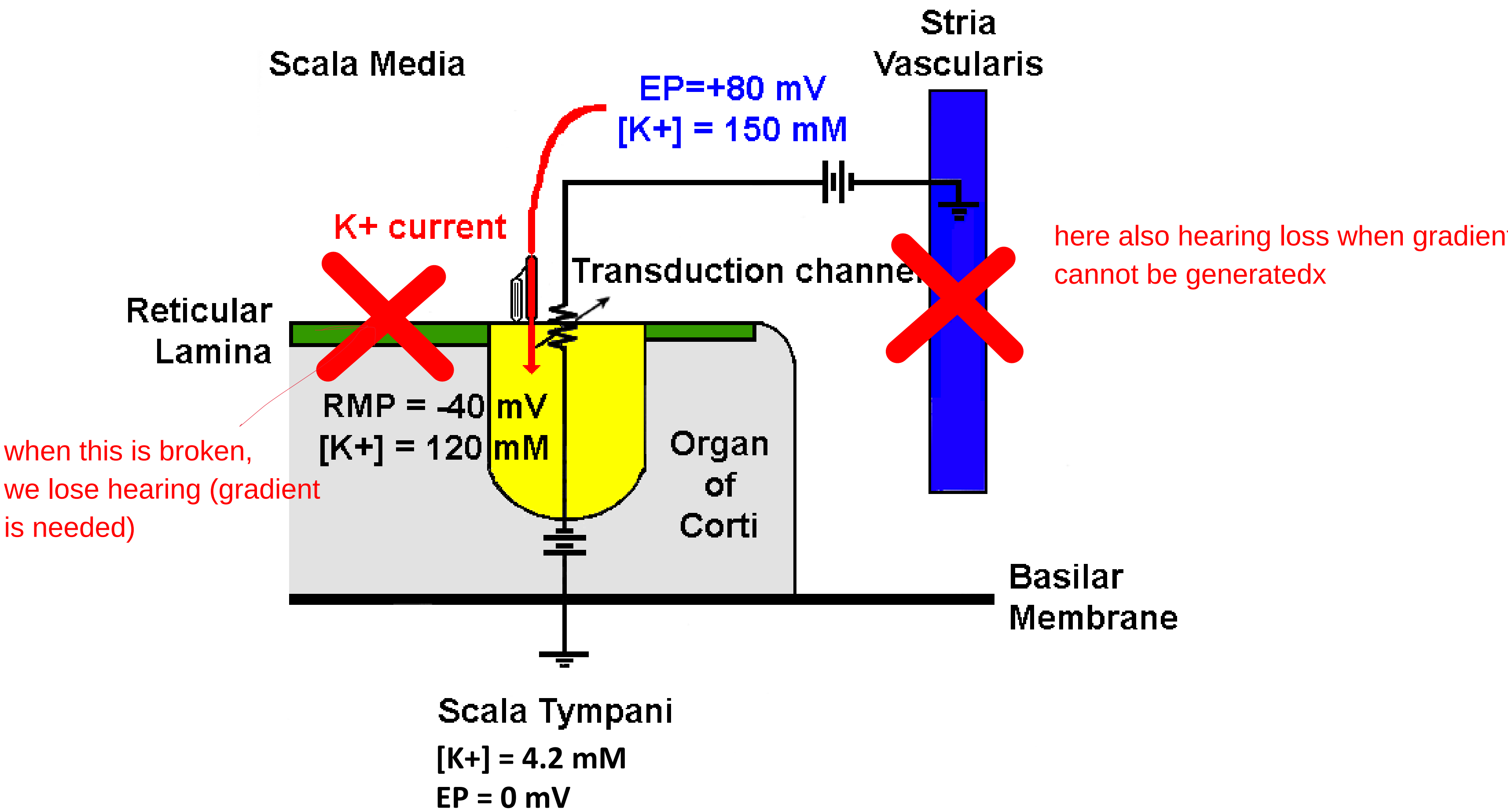


Purves: Neuroscience, Figure 13.9



Purves: Neuroscience, Figure 13.10

4. Mechanotransduction: receptor potential



Two forces are defining the receptor potential:

- K^+ concentration gradient 150 mM vs 120 mM
- Electrical gradient (+80 mV vs -40 mV)

Damage of stria vascularis of reticular lamina (red cross) leads to sensorineural hearing loss

d.umn.edu/~jfitzake/Lectures/DMED/InnerEar/CochlearPhysiology/EP.html

4. Mechanotransduction: receptor potential

about 50% of these cells are always open

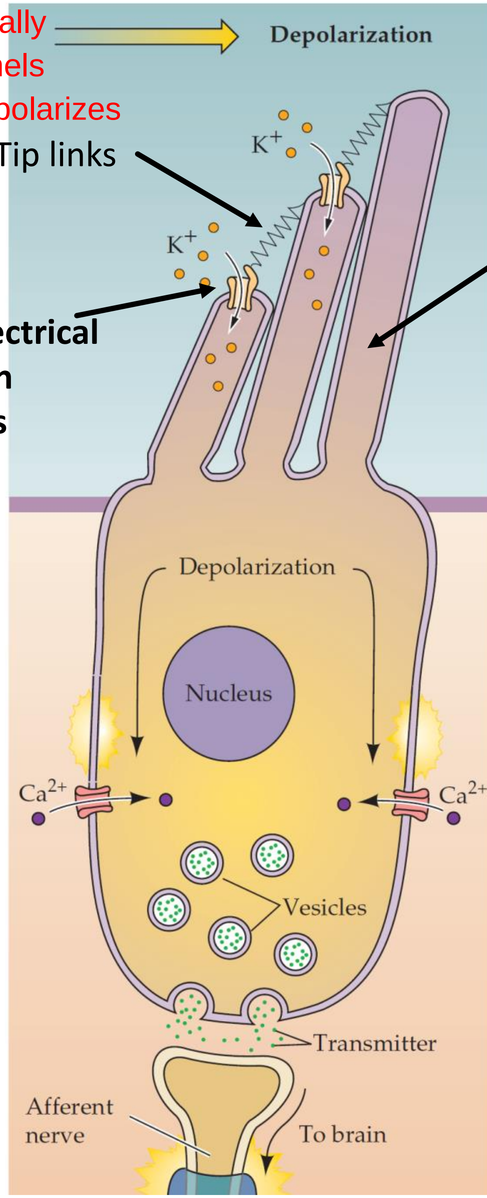
Depolarization

the tip links mechanically pull open the K-channels and the whole cell depolarizes

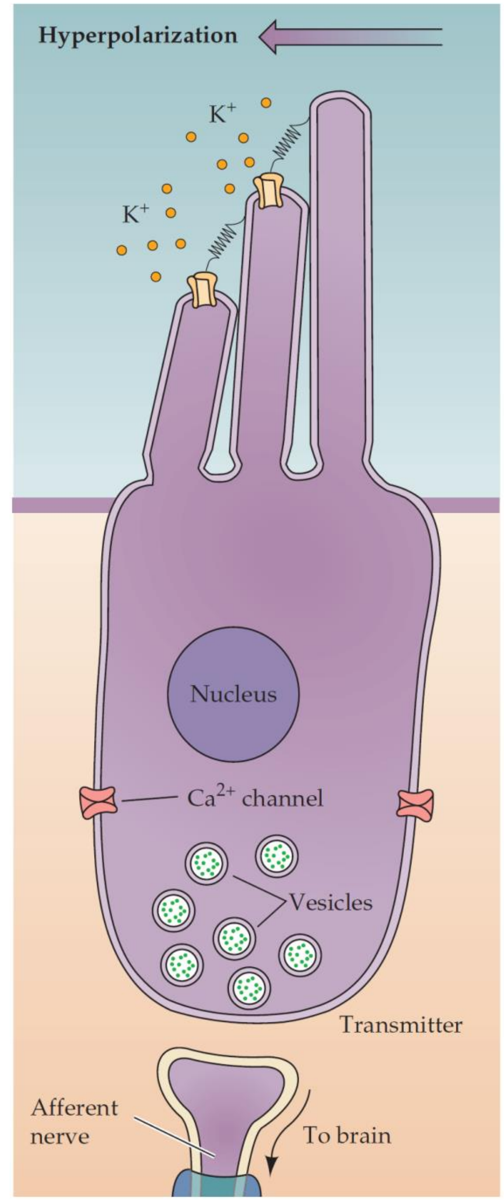
Tip links

Mechanoelectrical Transduction ion channels (MET)

Stereocilium



Hyperpolarization



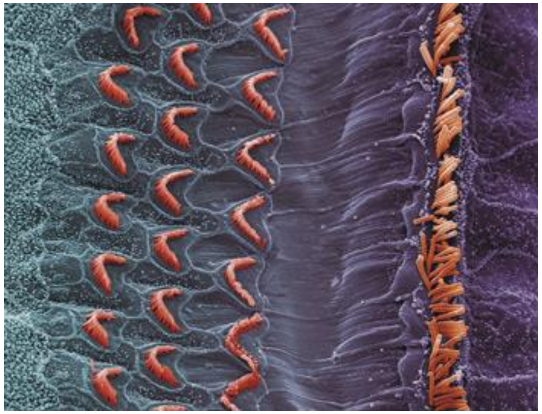
Purves: Neuroscience, Figure 13.8

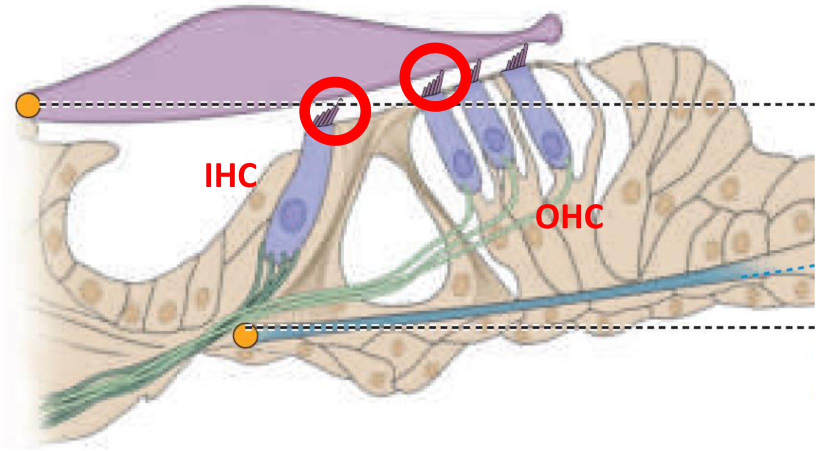
4. Mechanotransduction: outer and inner hair cells

scripps.edu/news/scientificreports/sr2007/cb07mueller.html

Outer Hair cells

Inner Hair cells





Outer hair cells (OHC)

- attached to tectorial membrane
- Electromotility
- Active amplification

Inner hair cells (IHC)

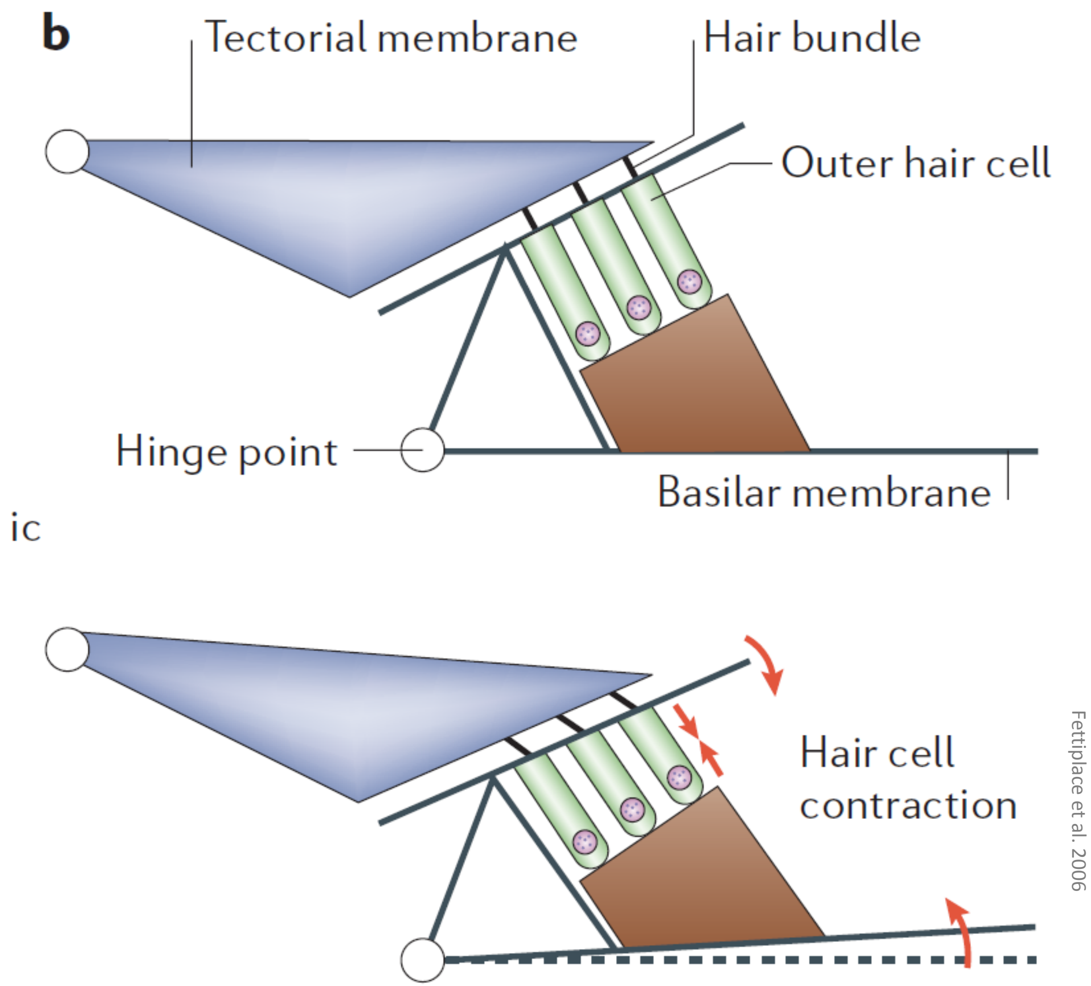
- NOT attached to tectorial membrane
- Sensory transduction

4. Mechanotransduction: cochlear amplifier

A purely passive cochlea cannot explain:

- The sharp tuning of the auditory nerve
- The strong vibrations of the basilar membrane at low sound intensities
- Otoacoustic emissions

4. Mechanotransduction: cochlear amplifier

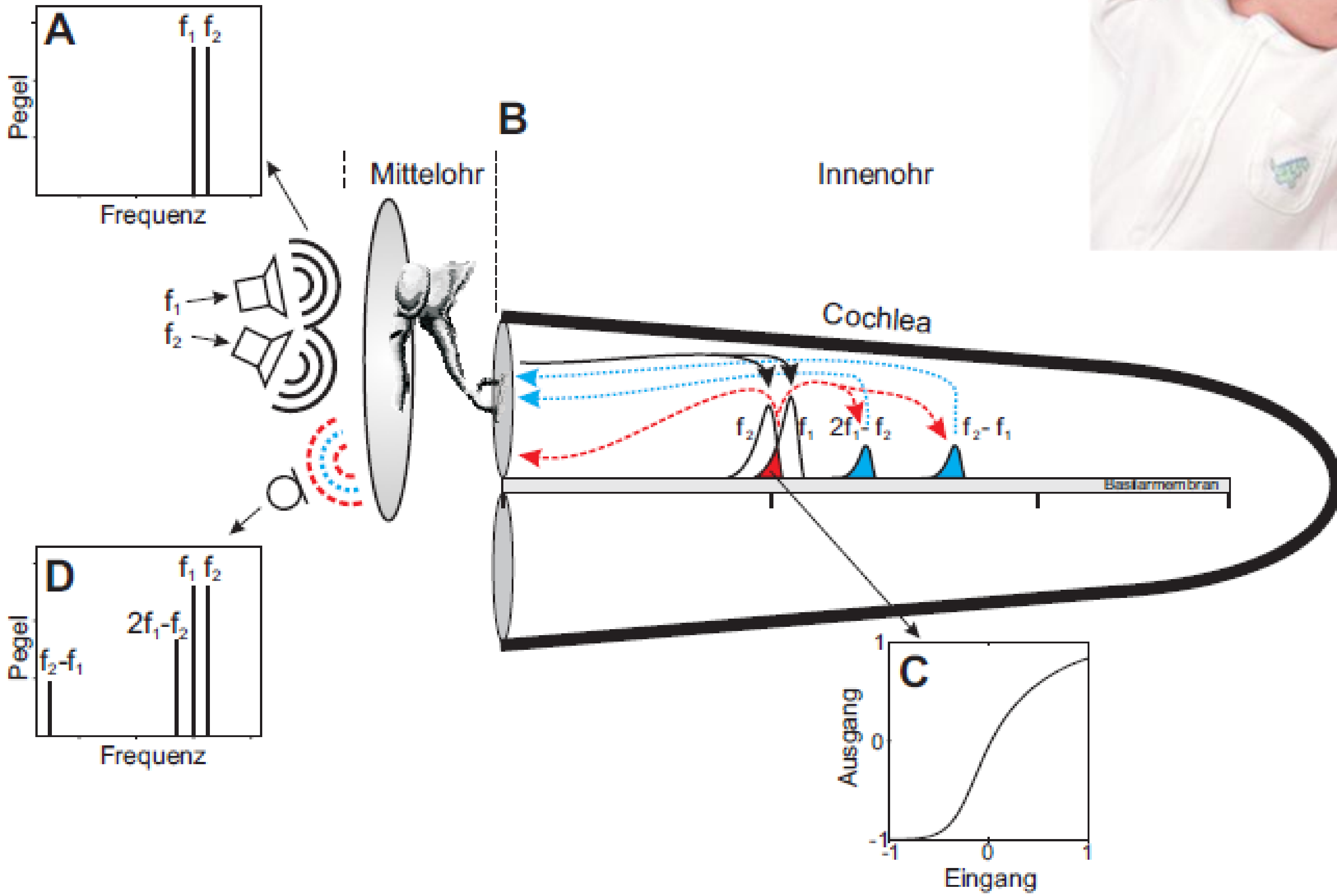


A purely passive cochlea cannot explain:

- The sharp tuning of the auditory nerve
- The strong vibrations of the basilar membrane at low sound intensities
- Otoacoustic emissions

4. Mechanotransduction: otoacoustic emisions

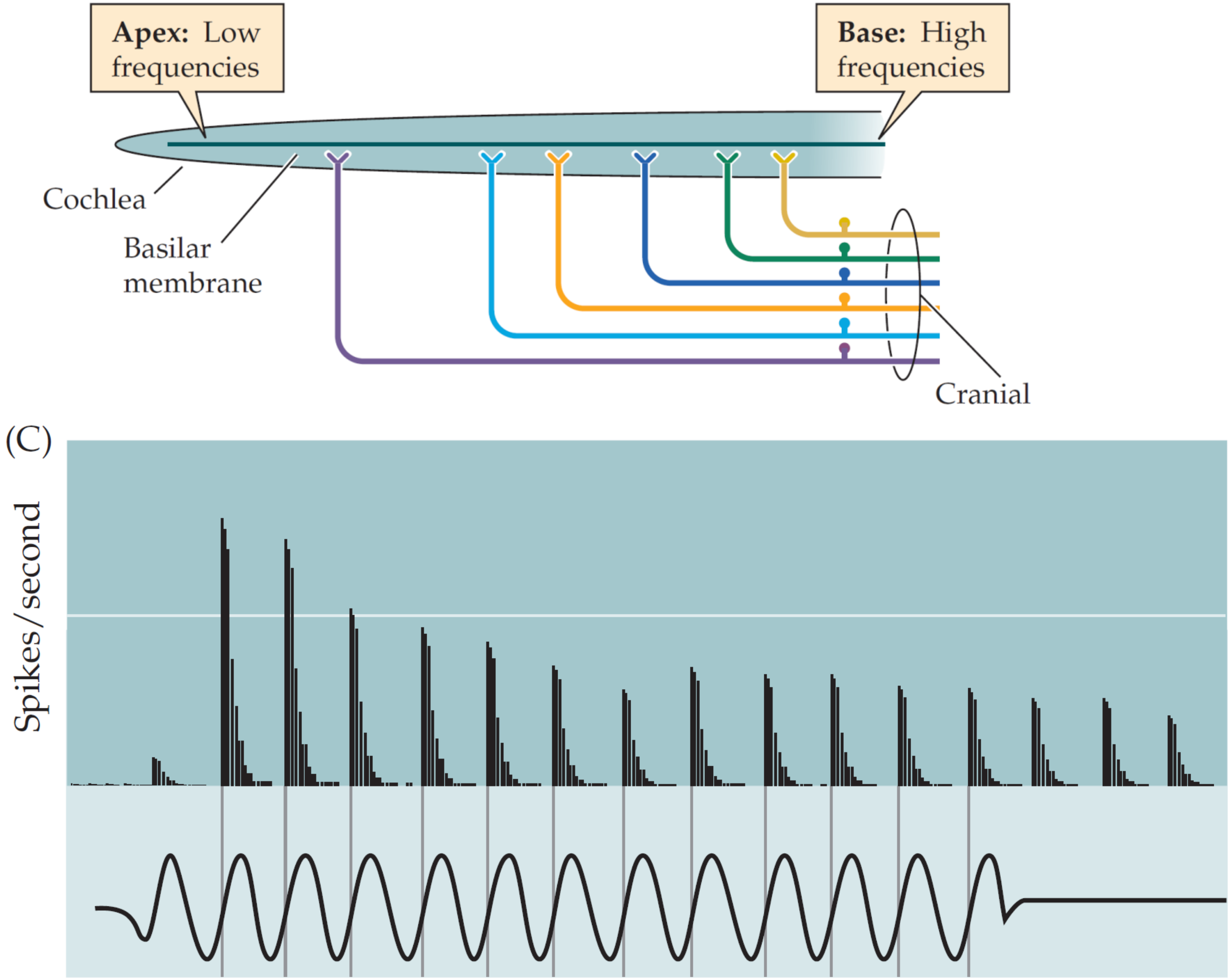
From: Anna Wiltekindt 2009



4. Mechanotransduction: Neuronal signal

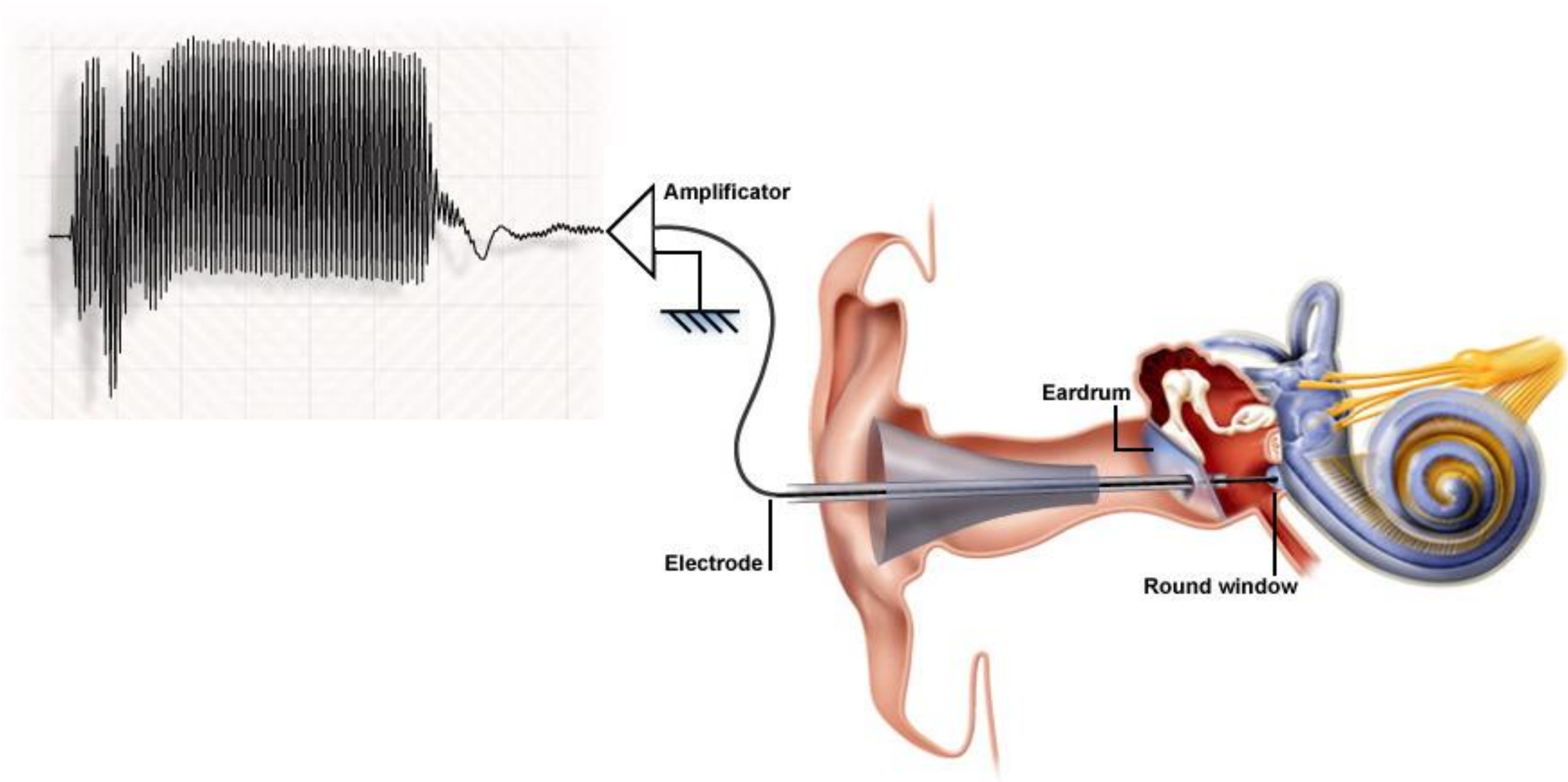
Two posibilities to transduct the frequency information

- Activity locked to the stimulus (phase locking)
- „Place code“ of frequencies along the cochlear tonotopy



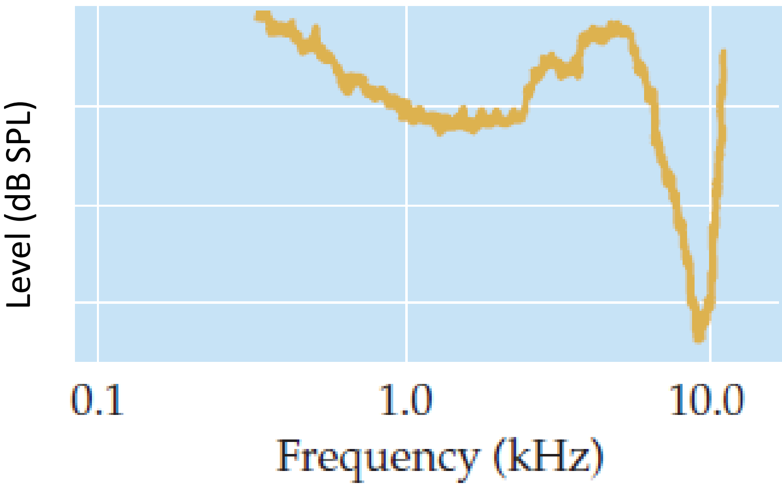
Purves: Neuroscience, Figure 13.11

4. Mechanotransduction: microphone potential



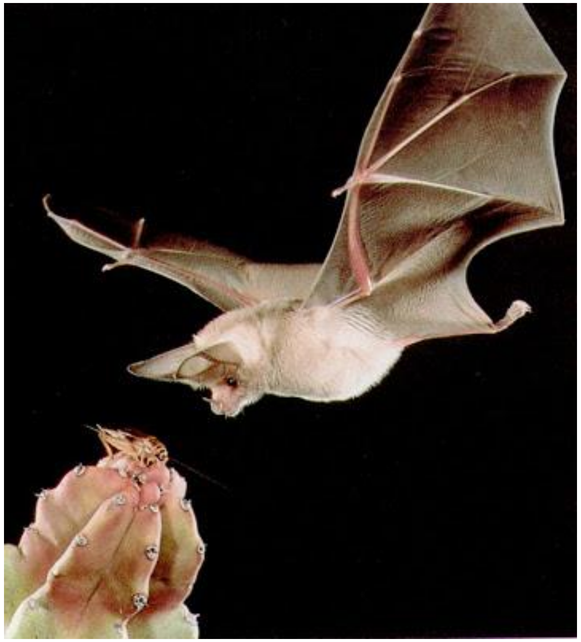
From: http://www.neuroreille.com/promenade/english/audiometry/ex_cochlea/explo_cochlea.htm

4. Mechanotransduction: Neuronal signal

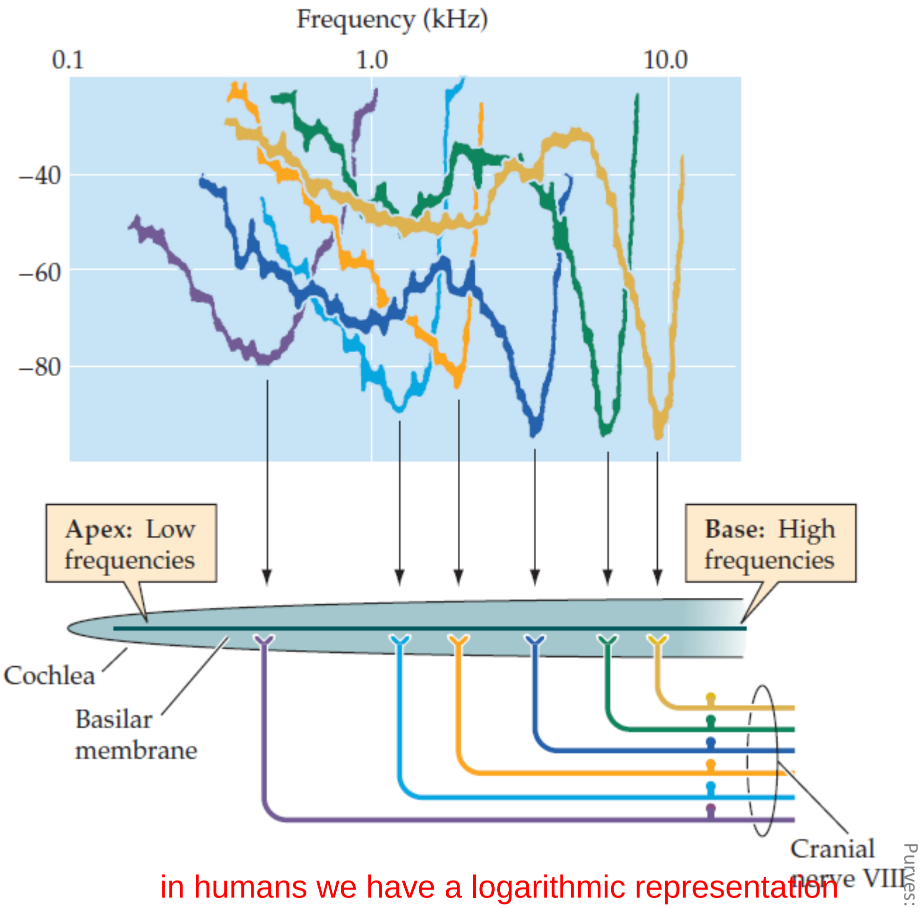


Purves: Neuroscience, Figure 13.11

Mustached bat (*Pteronotus parnellii*) have an auditory fovea



http://behavioralethology.blogspot.ch/2008/05/mustached-bat.html



in humans we have a logarithmic representation

Purves: Neuroscience, Figure 13.11

5. Sound localization: Direction

5. Sound localization: Direction

en.valka.cz/files/naslouchadlo_131.jpg

https://lh5.googleusercontent.com/-qkGYgFZhmmM/TY48iNZaNkI/AAAAAAAAB_w/TszmBMVMboI/s1600/b4radar-1.jpg

5. Sound localization: Direction

Directional hearing relies mostly on the differential input from both ear:

Interaural **time** difference (ITD)

Interaural **level** difference (ILD)

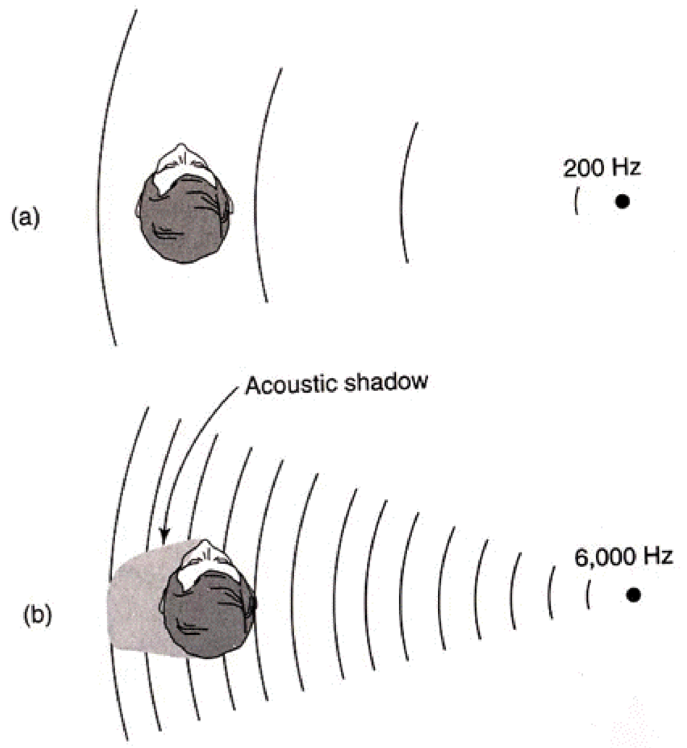
Monaural cues

Human localization (horizontal plane):

- 1 degree (frontal)
- 15 degree (at the side)

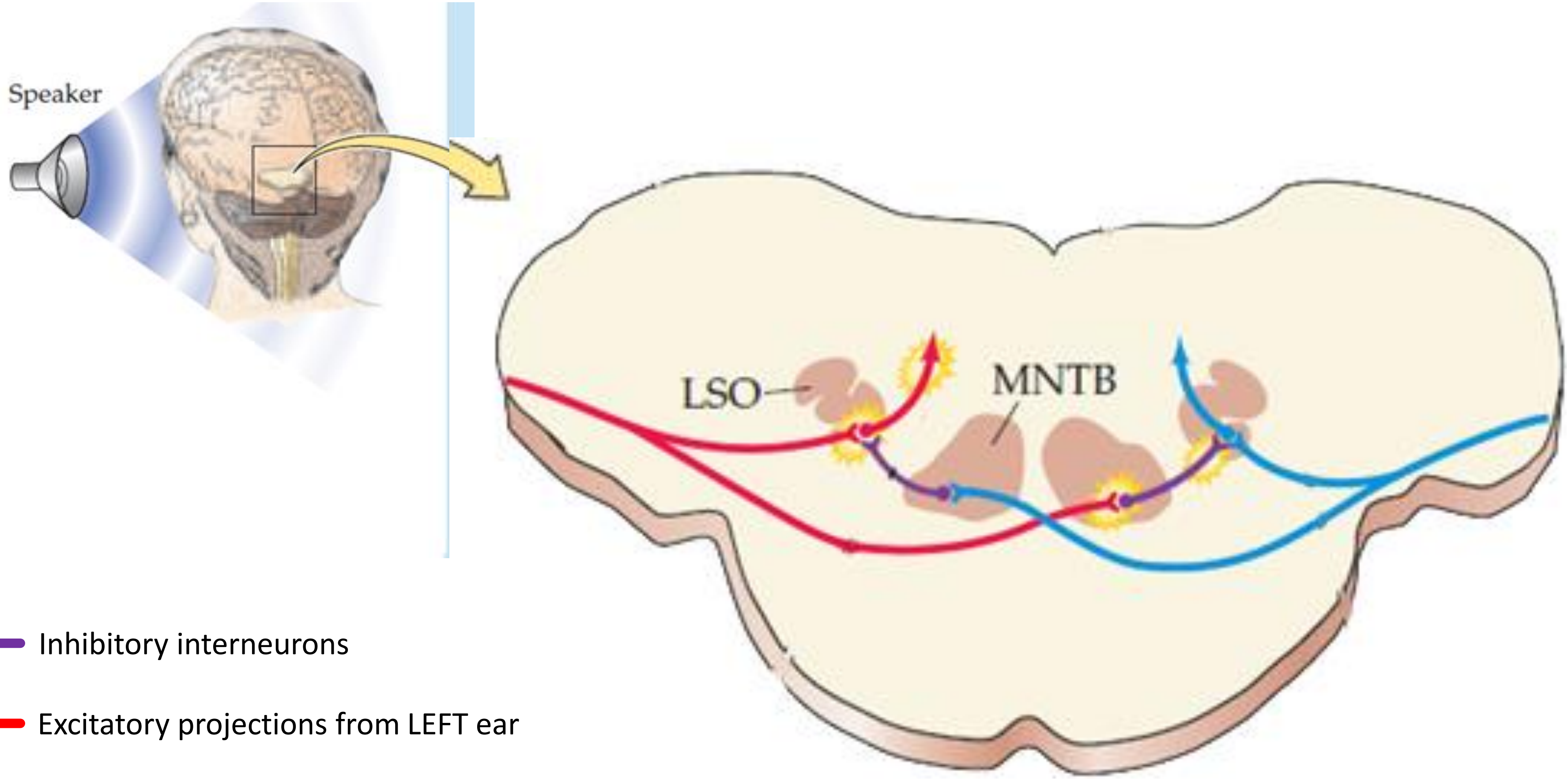
5. Sound localization: Direction, interaural **LEVEL** difference (ILD)

- Operates at higher frequencies
- In humans: > 1600 Hz
- The head shadows one ear
- Differences are frequency dependend (more at higher freq.)
- Depends on the ratio of head diameter and frequency (at 10 kHz ist 20 dB in humans)
- Approx. 3 degree resolution (differences of 0.5-0.8 dB)



www.ssc.education.ed.ac.uk/courses/deaf/dnov10i.html

5. Sound localization: Direction, interaural **LEVEL** difference (ILD)



Inhibitory interneurons

Excitatory projections from LEFT ear

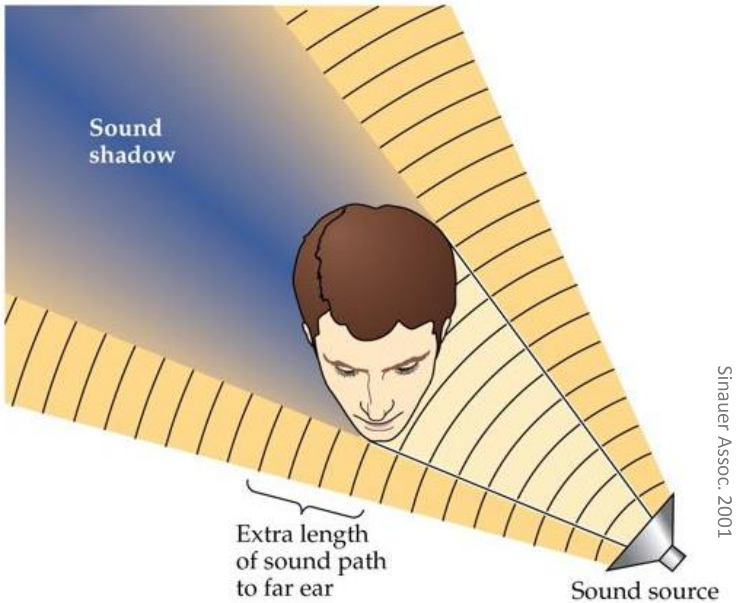
Excitatory projections from RIGHT ear

LSO= Medial Superior Olive
MNTB=Medial Nucleus of the Trapezoid Body

Purves: Neuroscience, Figure 13.14

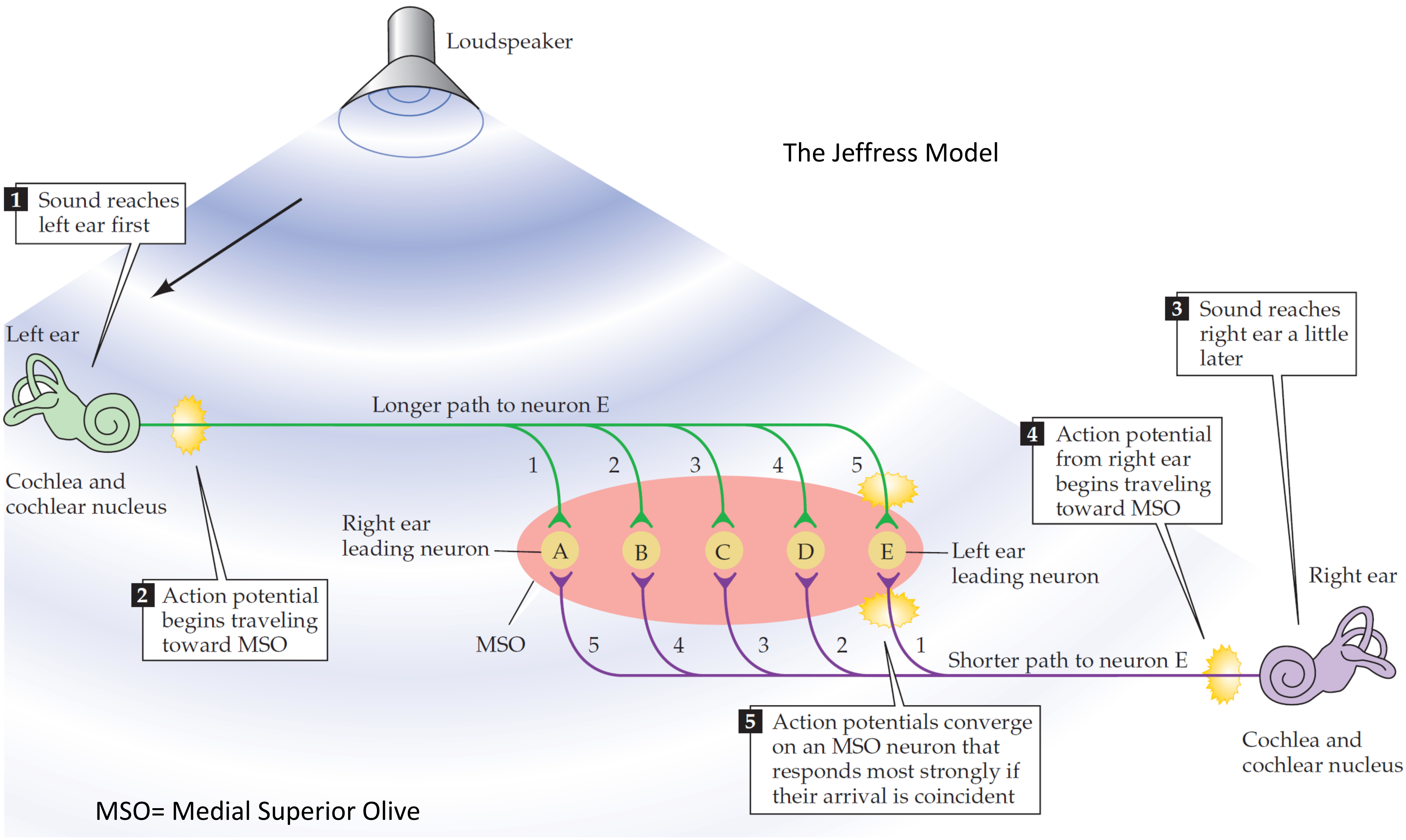
5. Sound localization: Direction, interaural **TIME** difference (ITD)

- Operates at lower frequencies (< 800 Hz in humans
- Interaural time delay max. 625 µs (humans)
- Minimal detectable difference approx. 10 µs



Sinauer Assoc. 2001

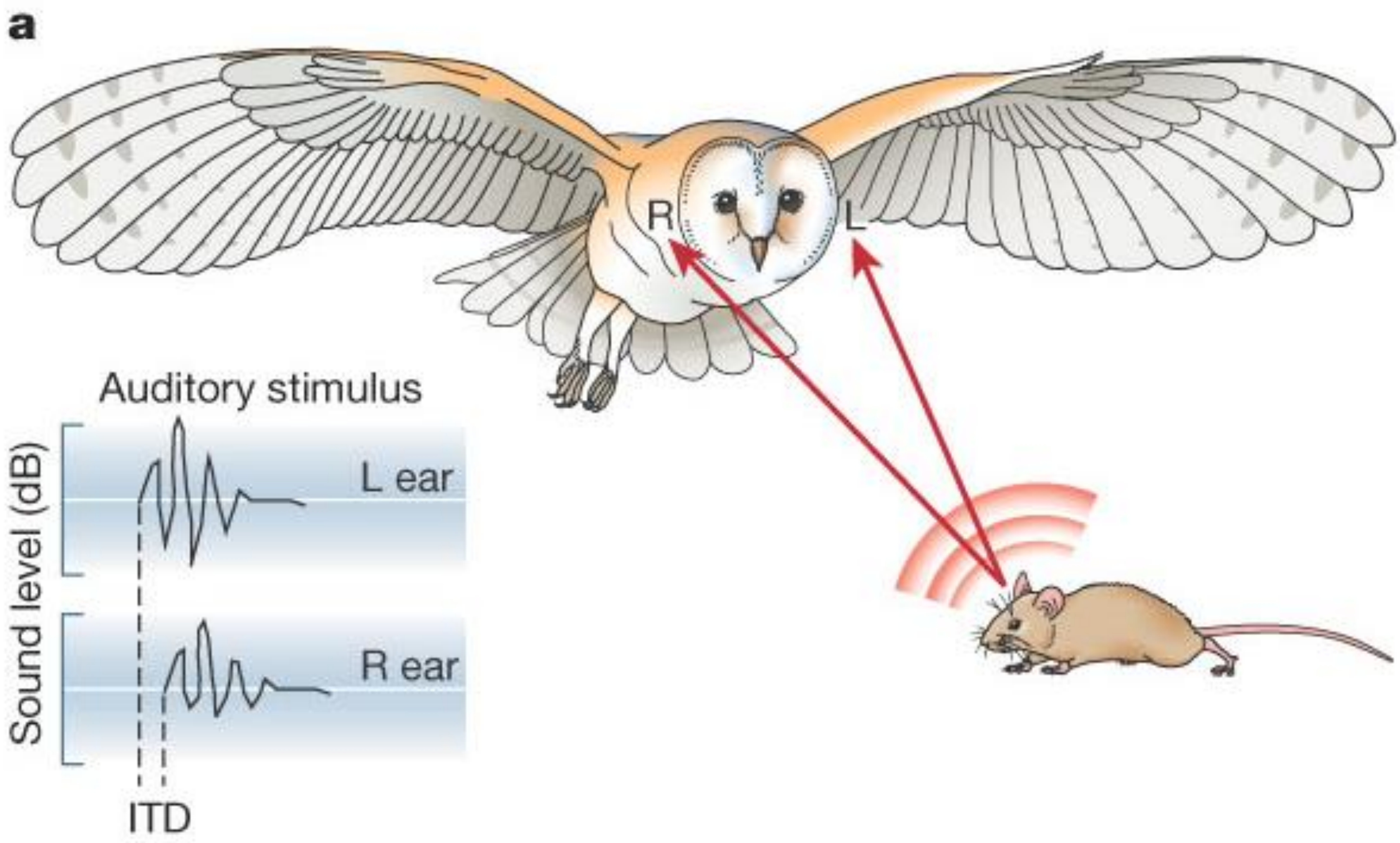
5. Sound localization: Direction, interaural **TIME** difference (ITD)



MSO= Medial Superior Olive

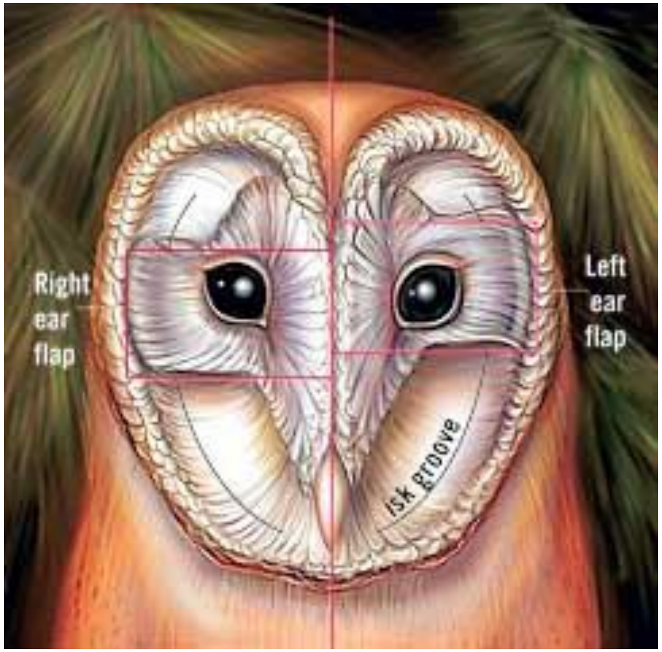
Purves: Neuroscience, Figure 13.13

5. Sound localization: Barn owl



From: knudsen 2002 nature

5. Sound localization: Barn owl



http://owls-perch.blogspot.ch/2012_09_01_archive.html

8. Summary

1.) The mammalian hearing is an exquisitely sensitive pressure sensor

2.) The sound is amplified linearly in the middle ear and non-linearly in the cochlea

3.) The cochlea can be considered as a filter disassembling different frequencies

4.) Frequencies are represented by a place code along the cochlea (tonotopy)

5.) Sound localization relies on the comparison of the binaural input (time and level)

8. Questions answer these as exam prep

Through which passive and active mechanisms in the ear is the sound transmission amplified?

Which are the two main mechanisms for sound localization?

How can vertical auditory localization work?

How would the hearing threshold change after a rupture of the tympanic membrane?

Which mechanisms give rise to the tonotopy along the cochlea?

Cisplatin and carboplatin are chemotherapeutics that can excert ototoxic ("toxic to the ear") effects on the sensory auditory receptors of the inner ear (hair cells). Cisplatin inactivates the outer hair cells, carboplatin the inner hair cells of the inner ear. (A) Draw/describe the main structures of the inner ear that contains the hair cells (organ of corti) together with the outer and inner hair cells, (B) what is the main function of the inner and outer hair cells, (C) what effect of a high-dosage cisplatin and carboplatin on the hearing would you expect?

9. Literature

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