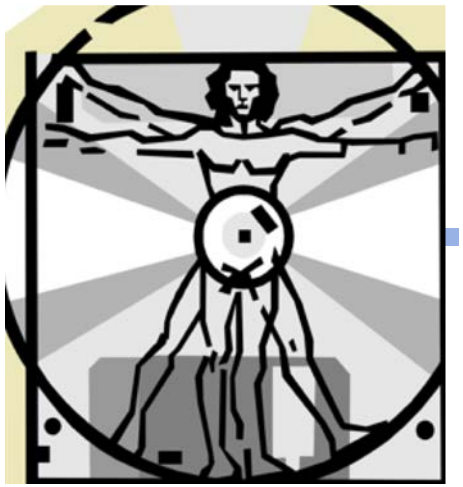


Auditory System

What's the frequency Kenneth…?

Overview

- Intro
- Physical Stimulus: Sound
- Perceptual Attributes
- Anatomy of the Auditory System
- Functioning of the Cochlea
- Auditory Cortex
- Upcoming

Physical Stimulus: Sound

- Physics of sound: vibrations
- Frequency (Hz)
- Wavelength (m)
- Amplitude (dB)

$$\text{deciBel} = 20 \log \frac{P_{sound}}{P_{threshold}}$$

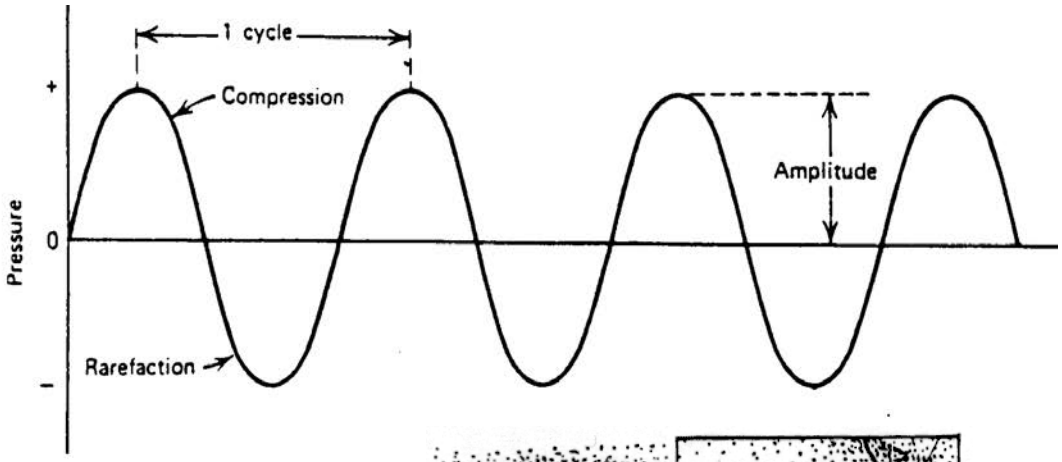
$$\text{deciBel} = 20 \log \frac{20}{0.0002} \quad \text{<-- 20 μPa}$$

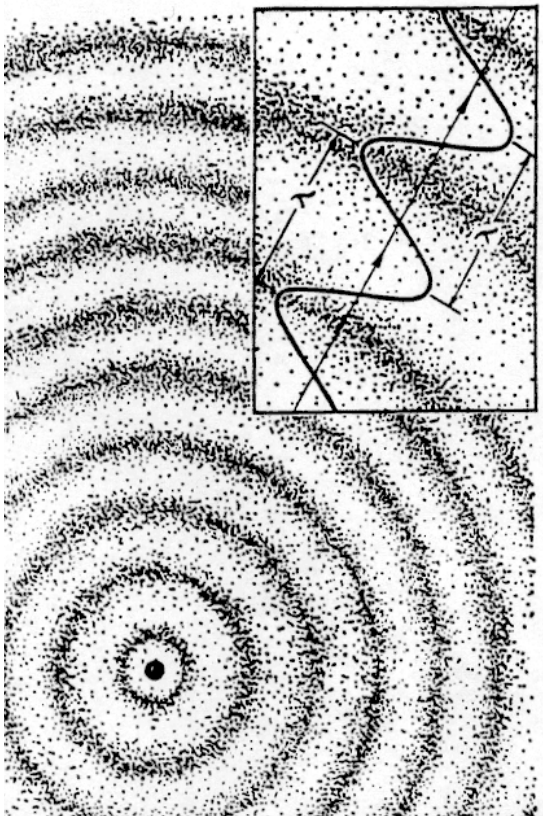
deciBel = 20 log 100000

deciBel = 20 x 5 = 100

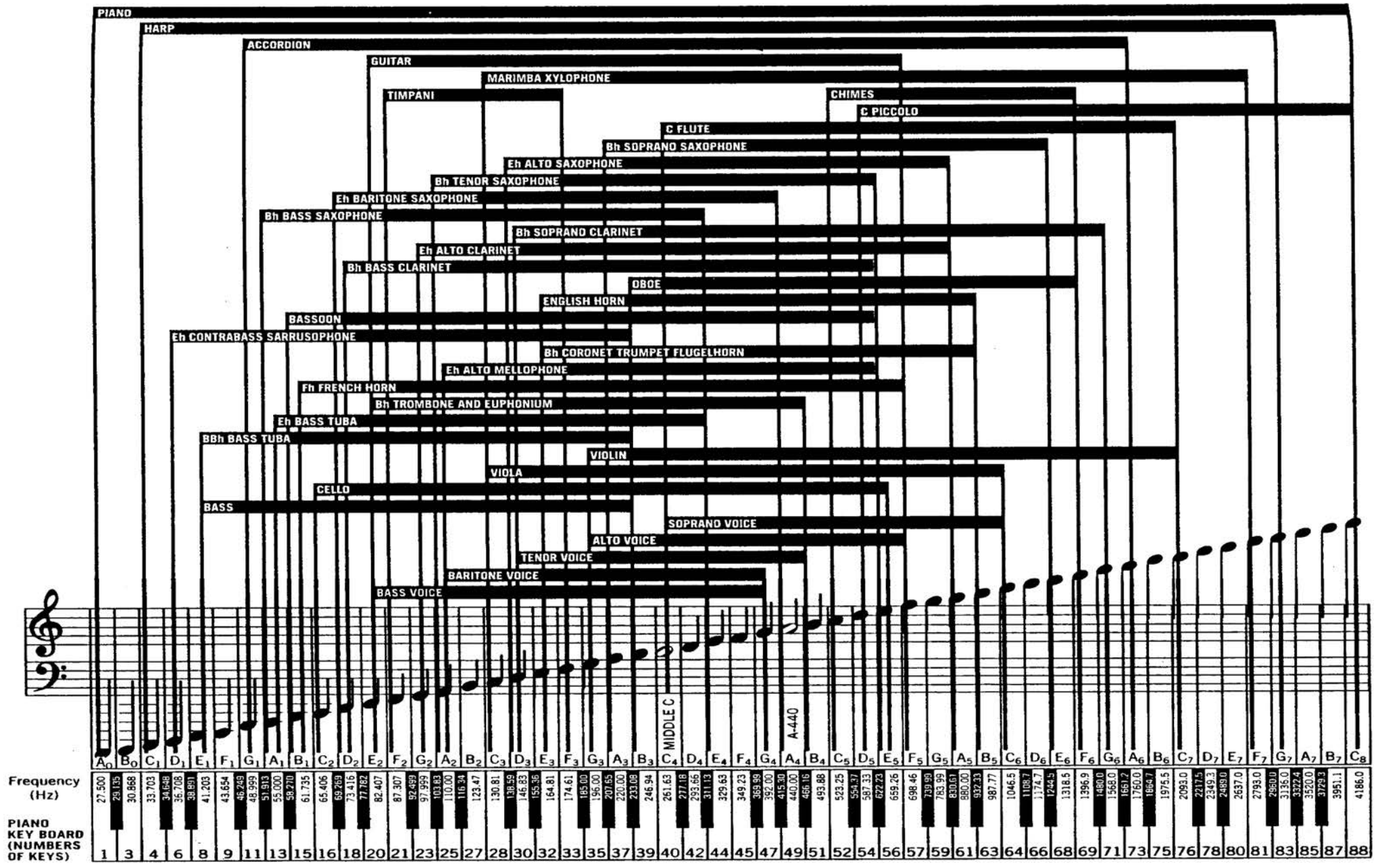
Amplitude = 100 dB SPL

- Complexity
  - Harmonics
  - What about Ohm's Acoustical Law?





Frequency Ranges



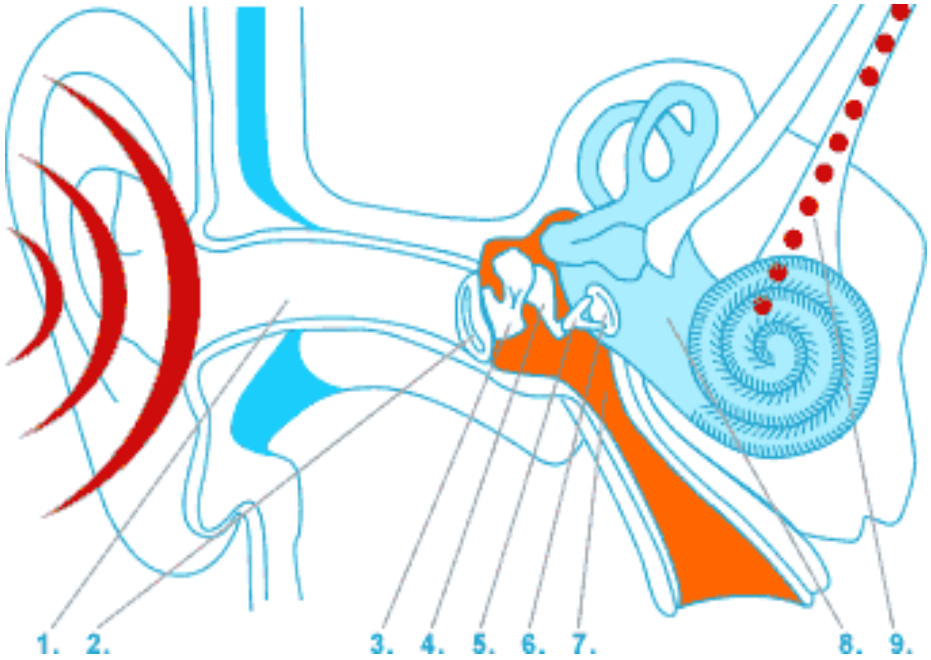
Perceptual Attributes

- Frequency --> Pitch
- Amplitude --> Loudness
- Complexity
  - Richness - number of harmonics
  - Brightness - relative power of harmonics in different parts of the spectrum
  - Timbre - perceptual signature of the sound
    - Essentially everything that is not already noted above
    - Makes trumpets different from clarinets
- Key: physical stimulus is measurable, unchanging, but perception of it can (and does) differ
- (Perception is not the same as sensation)

Demo

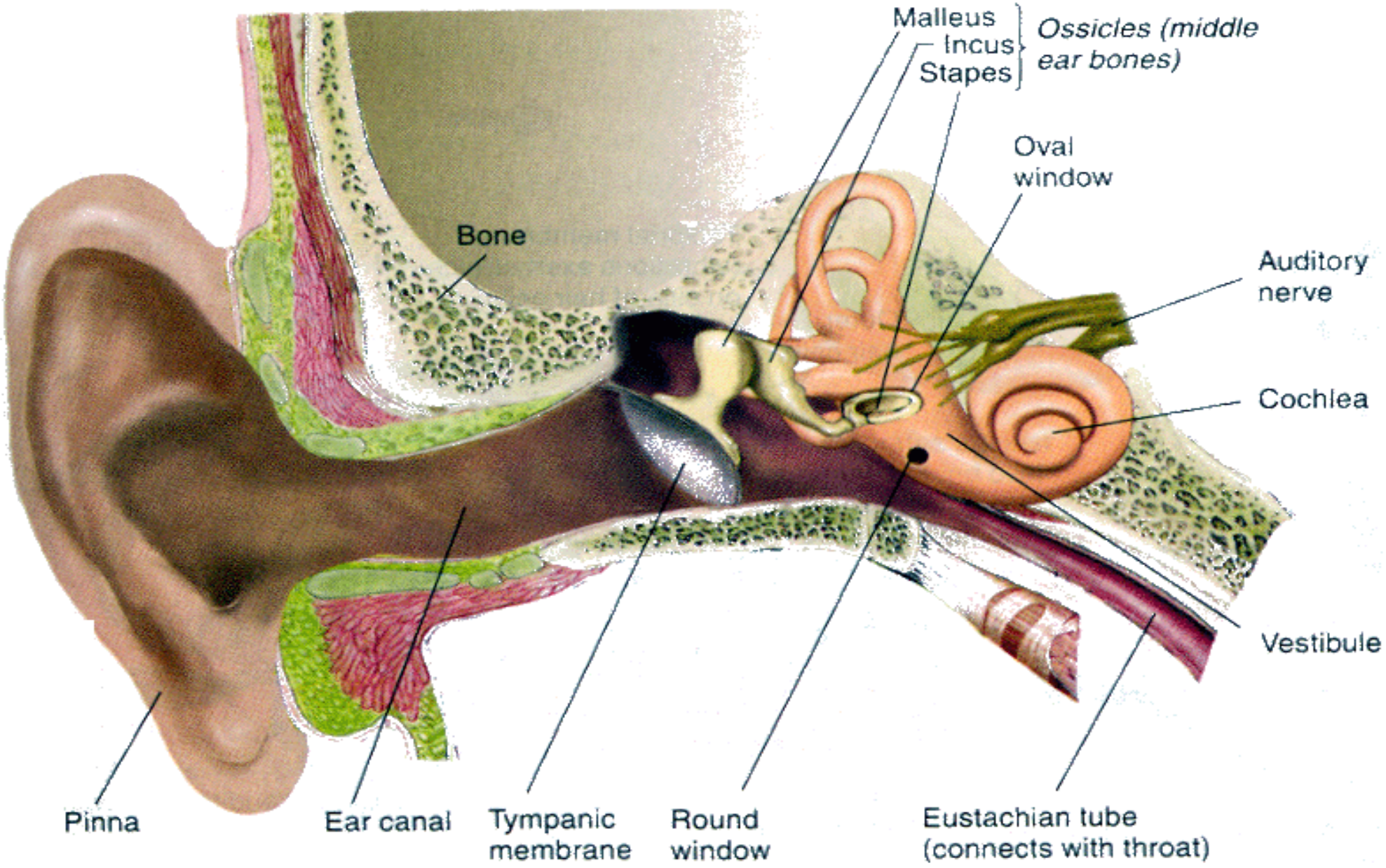
Anatomy of the Auditory System

- Includes:
  - outer ear
  - middle ear
  - inner ear (cochlea)
  - auditory nerve
  - auditory pathway
  - auditory cortex



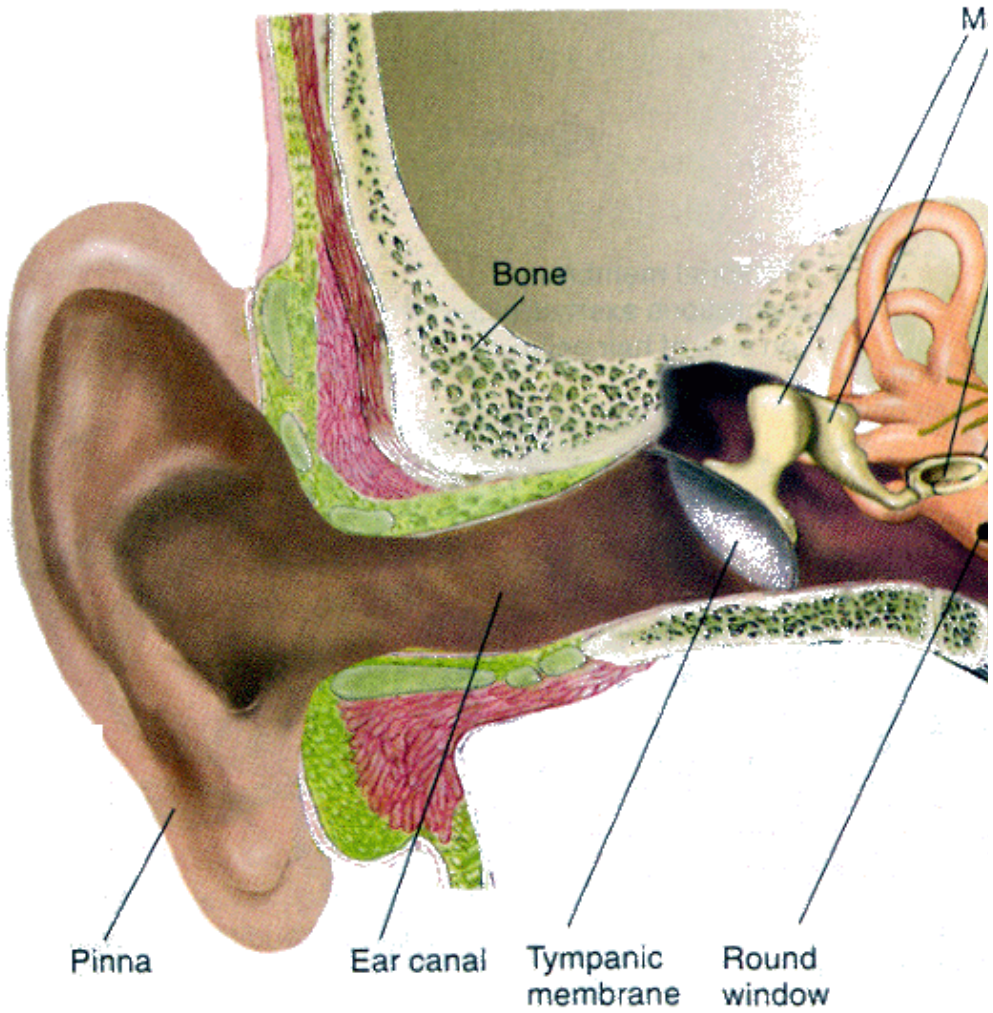
- Question: What is the most important part of the auditory system? Where are the "receptors" of sound?

Auditory System Graphic



Outer Ear

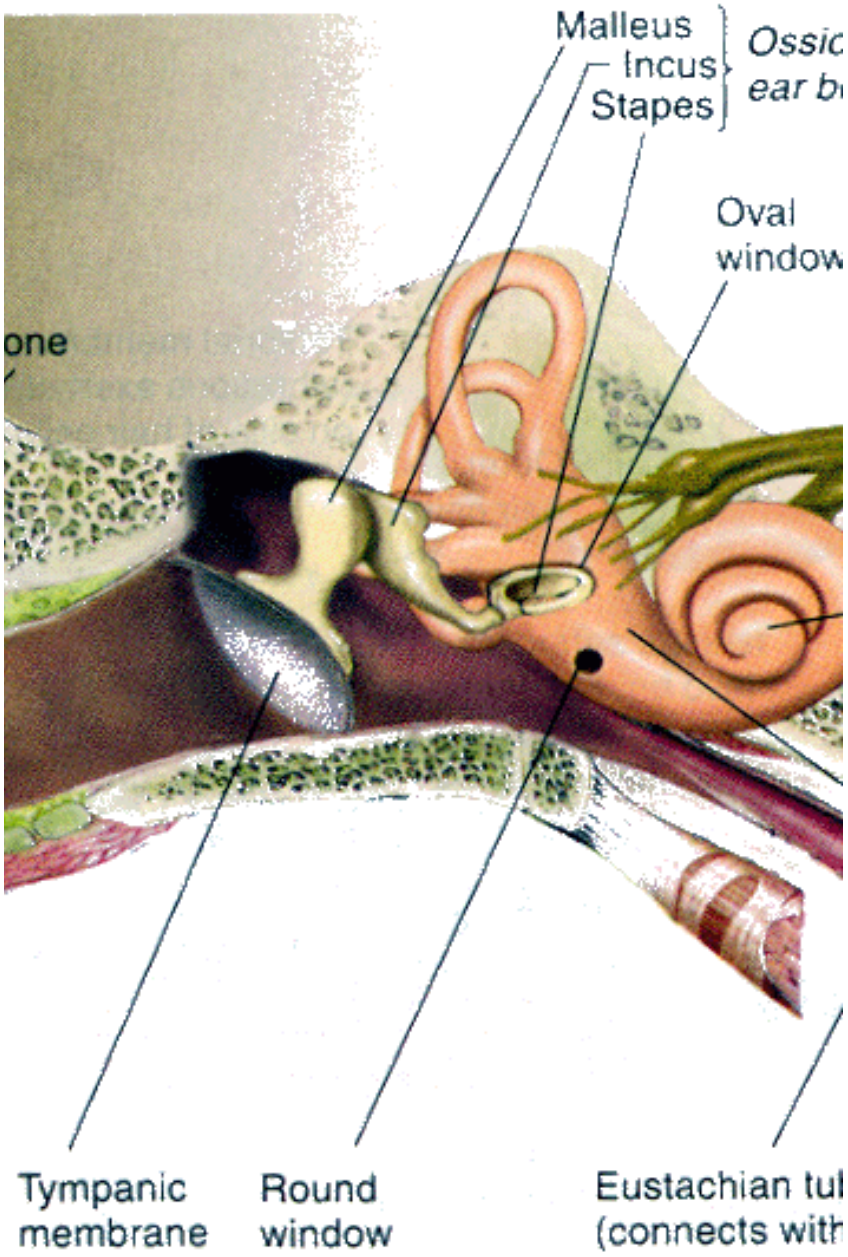
- Pinna
- External Aud. Canal
- Eardrum
  - (tympanic membrane)



Pinnae

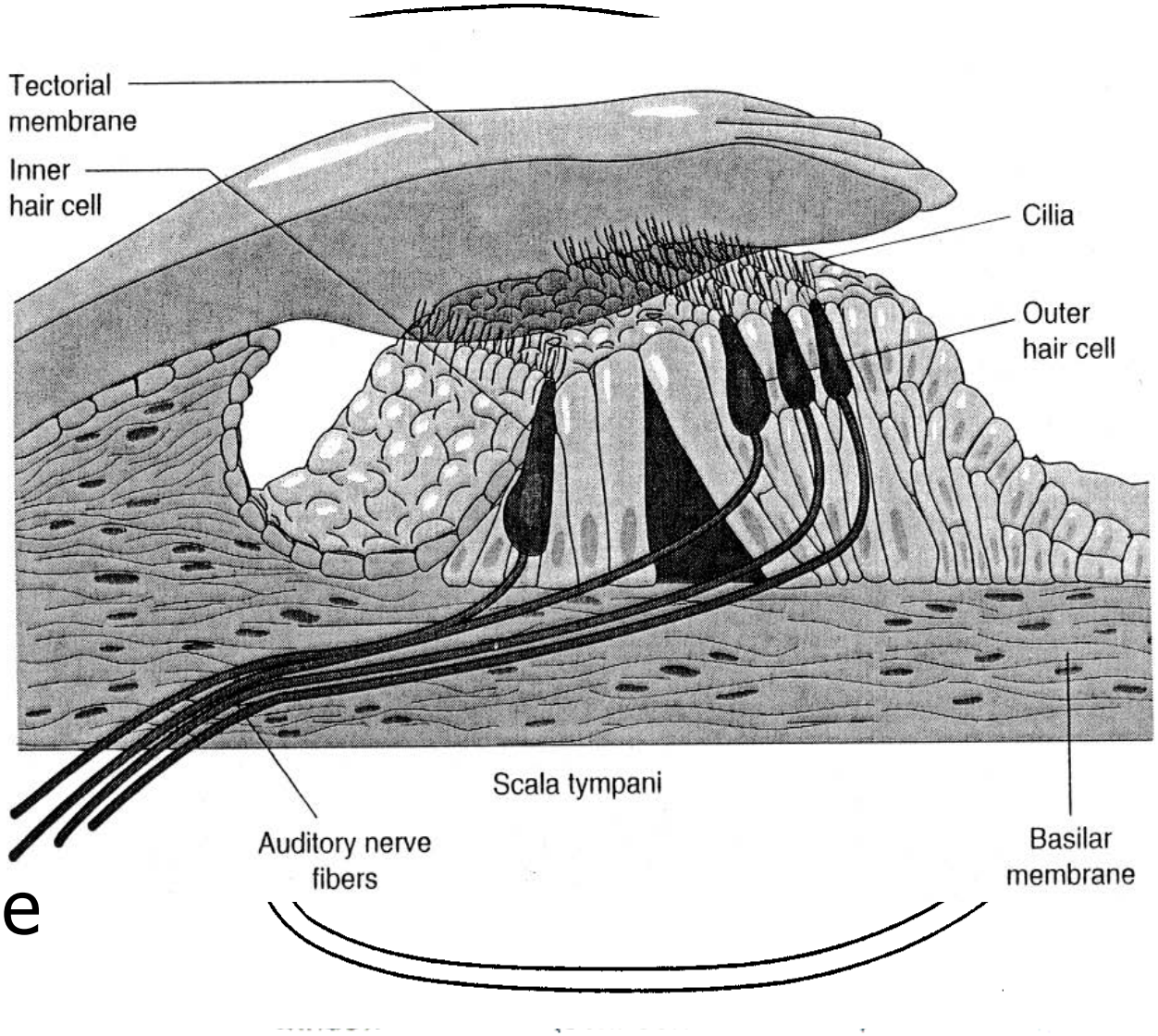
Middle Ear

- Ossicles
  - Malleus
  - Incus
  - Stapes
  - Impedance matching
- Acoustic reflex
  - Tensor tympani & stapedius muscles



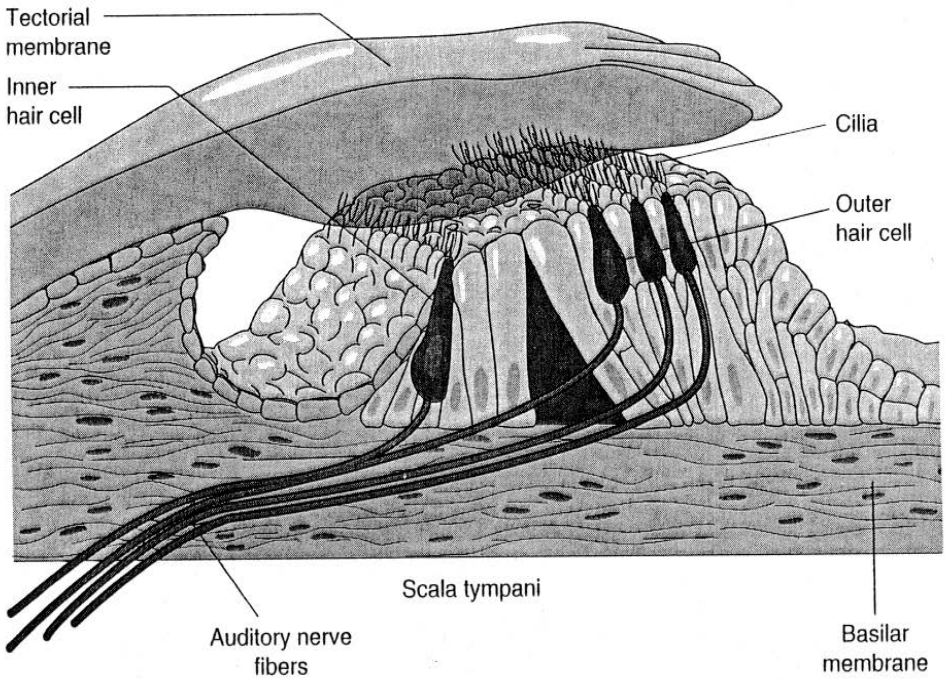
Inner Ear (Cochlea)

- 3 chambers
  - Vestibular canal
  - Cochlear duct
  - Tympanic canal
- Basilar membrane
- Oval window
- Hair cells
  - Inner (3500)
  - Outer (12,000)
- Tectorial membrane
- Auditory nerve

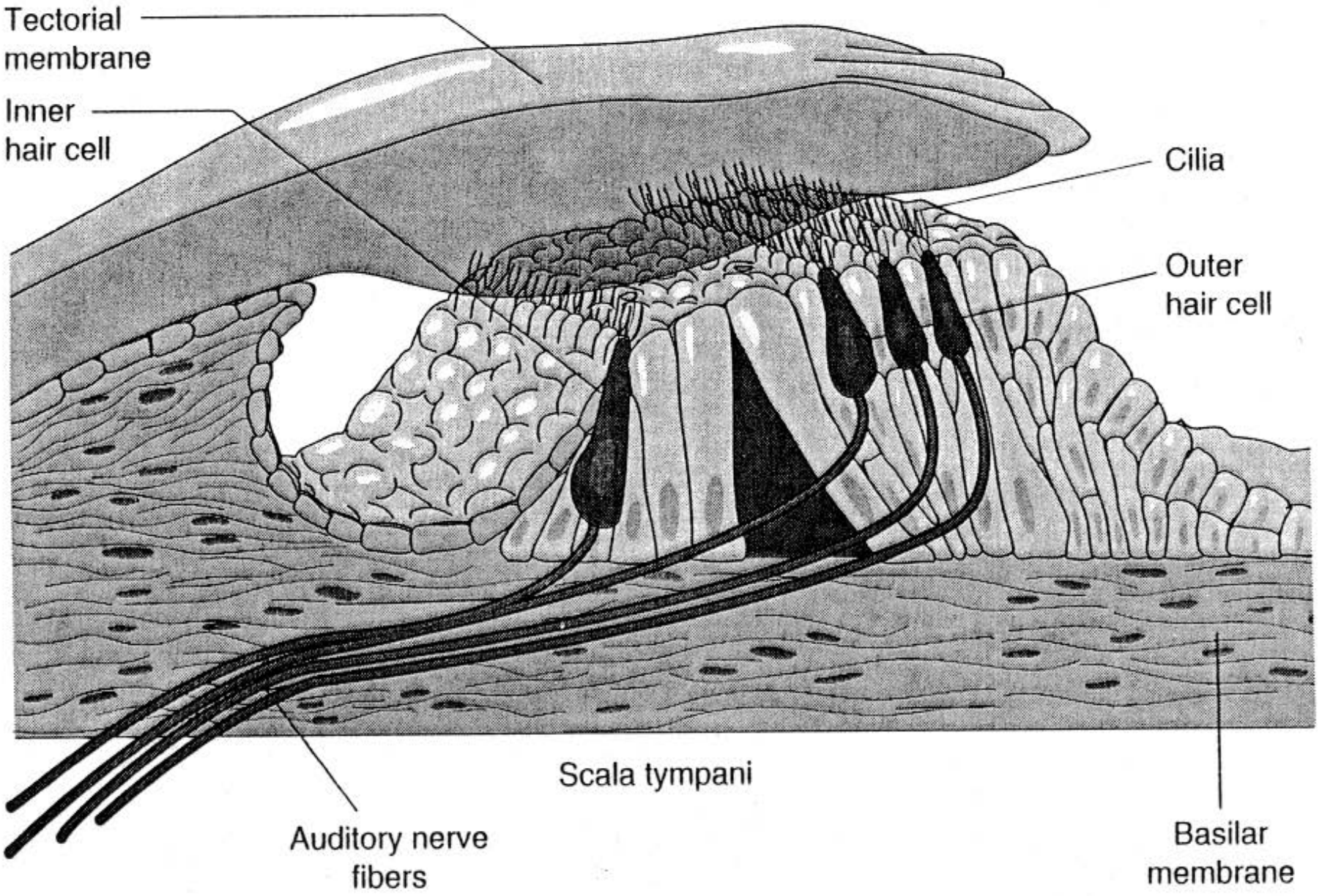


Functioning of the Cochlea

- Transduce movement (physical energy) into nerve firing (electrochemical energy)
- Note the complicated transduction process is NOT exactly as described in most textbooks (we'll come back to that in a few slides)



Hair Cells (General Location)

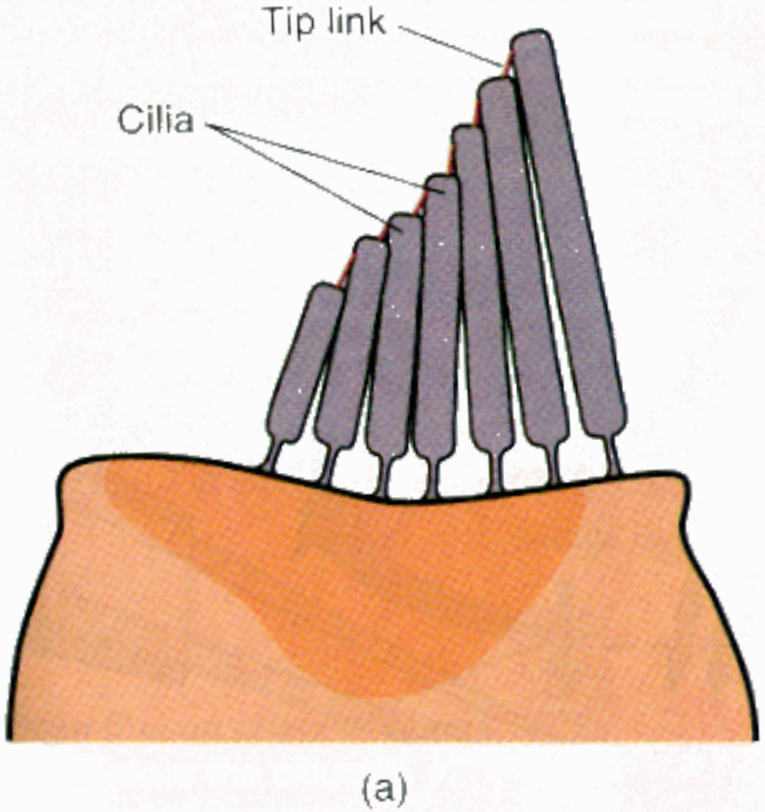


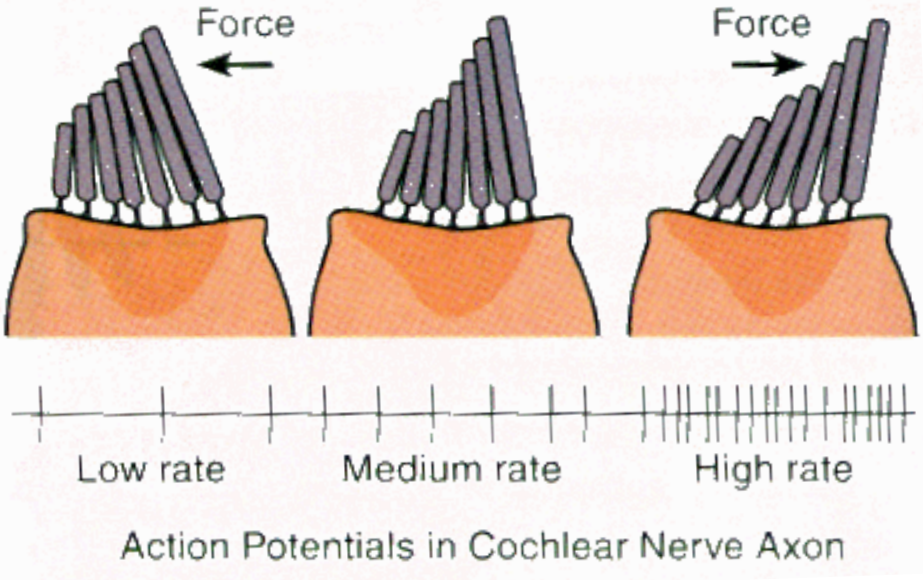
Hair Cells (Details)

- Inner hair cells
  - ~3500
  - Connected to each other with tip links
  - Synapse onto 48,000 (95%) of fibers in cochlear nerve (one-to-many)
- Outer hair cells
  - ~12,000
  - Only connect to ~2000 (5%) of aud. nerve fibers (many-to-one)
  - Can change length, which results in fine-tuning the frequency response of a region of the cochlea by stiffening or loosening the movement of the basilar and tectorial membranes (feedback mechanism)

Hair Cells (Functioning)

- Sets of stereocilia connected by tip links
- Movement of basilar membrane leads (indirectly, via fluid movement) to "leaning" of cilia bundles
  - Firing rate depends on force and direction





Cilia Bundles of Hair Cells

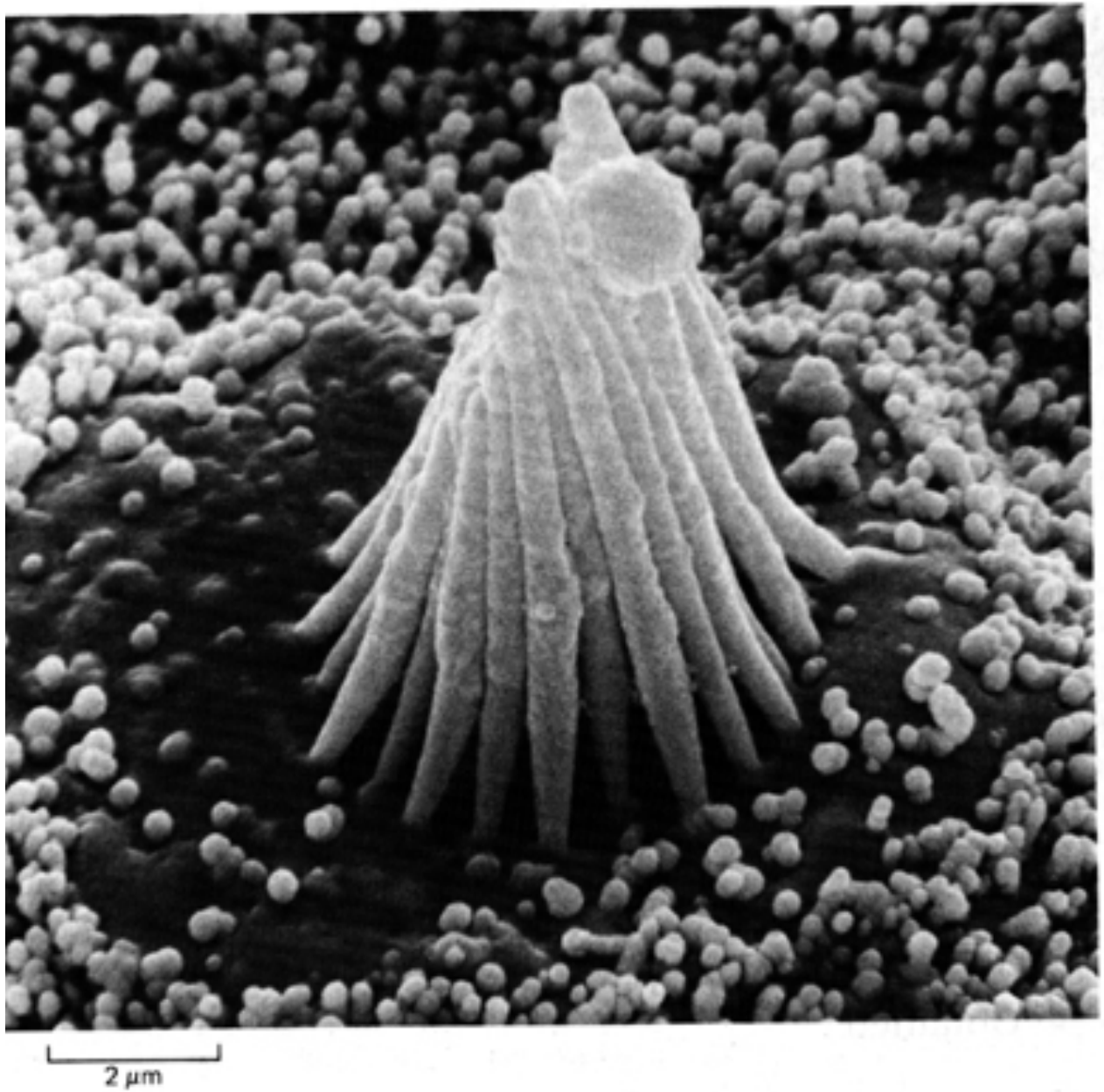
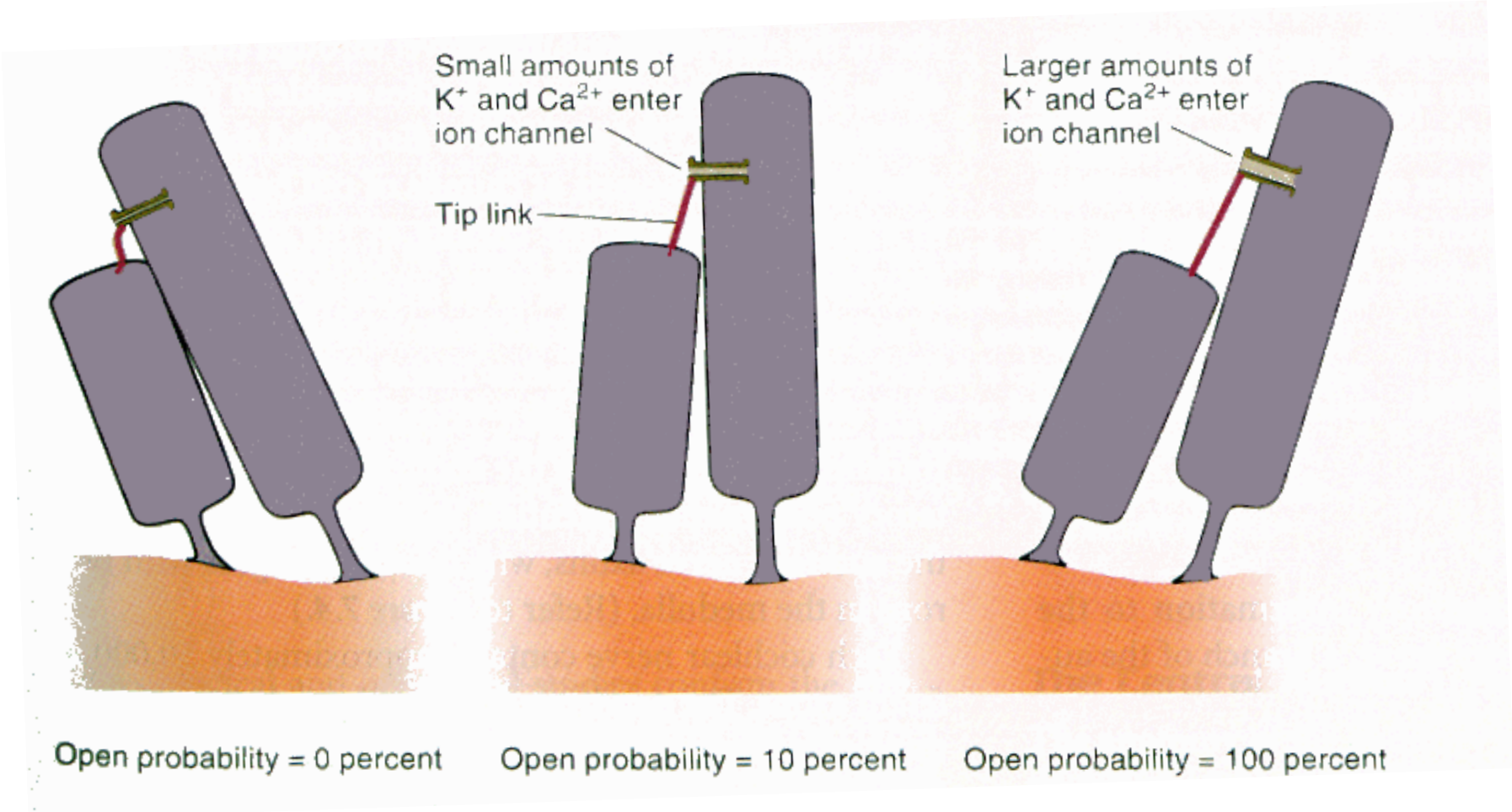


Figure 4–14 Scanning electron micrograph of the organ-pipe-like arrangement of stereocilia projecting from the surface of hair cells in the inner ear. (Courtesy of R. Jacobs and A. J. Hudspeth.)

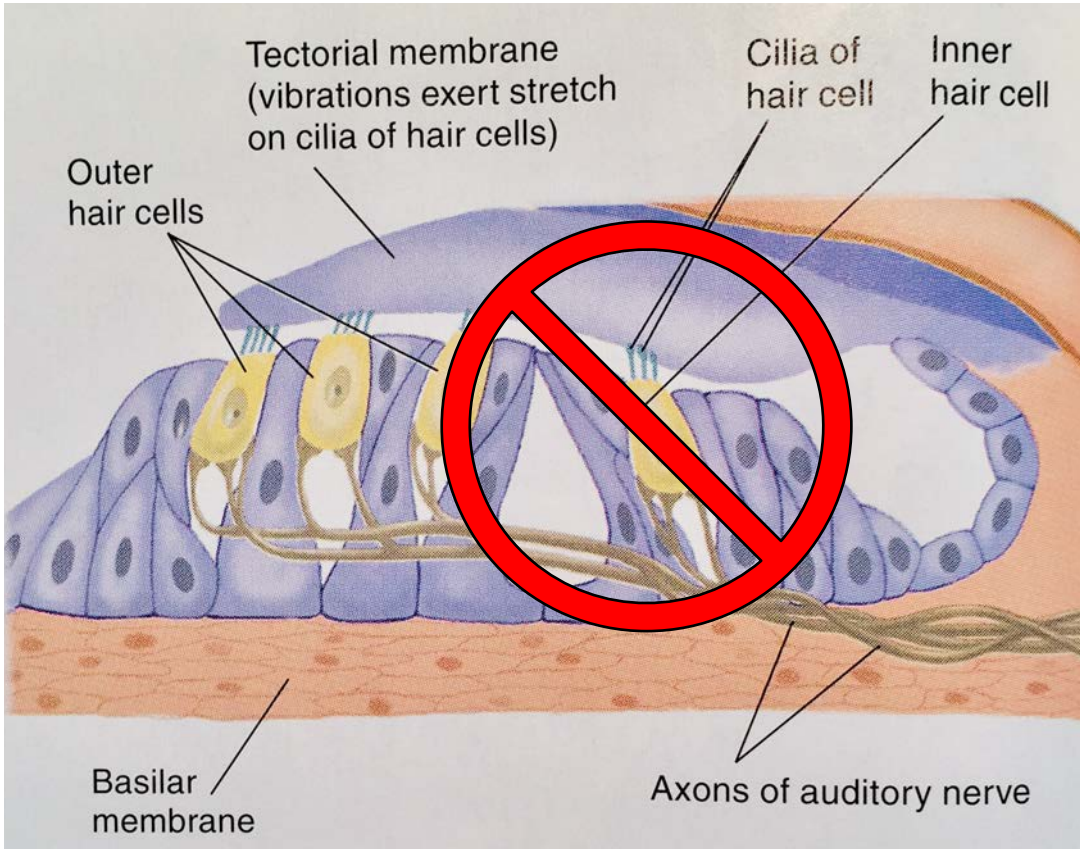
Hair Cell Functioning

- Tip links pull open ion channel
  - Basically a physical system



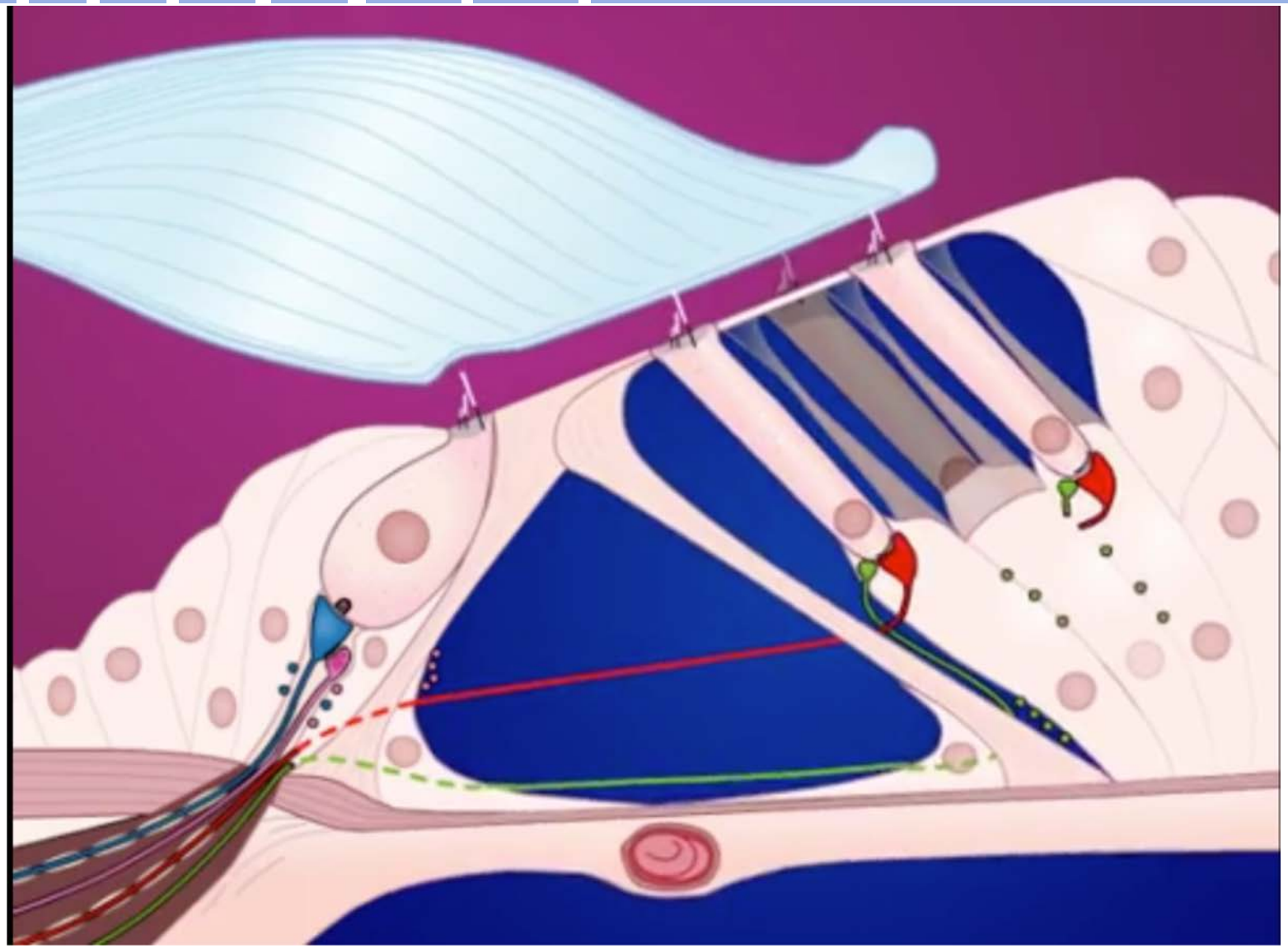
Transduction (Detail)

- Inner hair cells **NOT** connected to tectorial membrane
- Only outer hair cells are connected/embedded
- Figures and text are usually wrong (simplified)
- Tectorial membrane does NOT rest on IHCs



- Movement of membranes leads to "sloshing" of perilymph fluid, which leads to bending of hair cells
- Just like in semicircular canals
- See video, next slide

Transduction (In Action)



https://youtu.be/OwwcSLb3eNo

Characteristic Frequency

- Each fiber of the auditory nerve fires maximally to a particular frequency
- Basically related to the location along the cochlea (basilar membrane) that the nerve connects to
- "Tonotopic" layout along the basilar membrane
  - In general terms, the fiber represents the frequency (frequencies) in the sound

Rate (Frequency-Matching) Theory

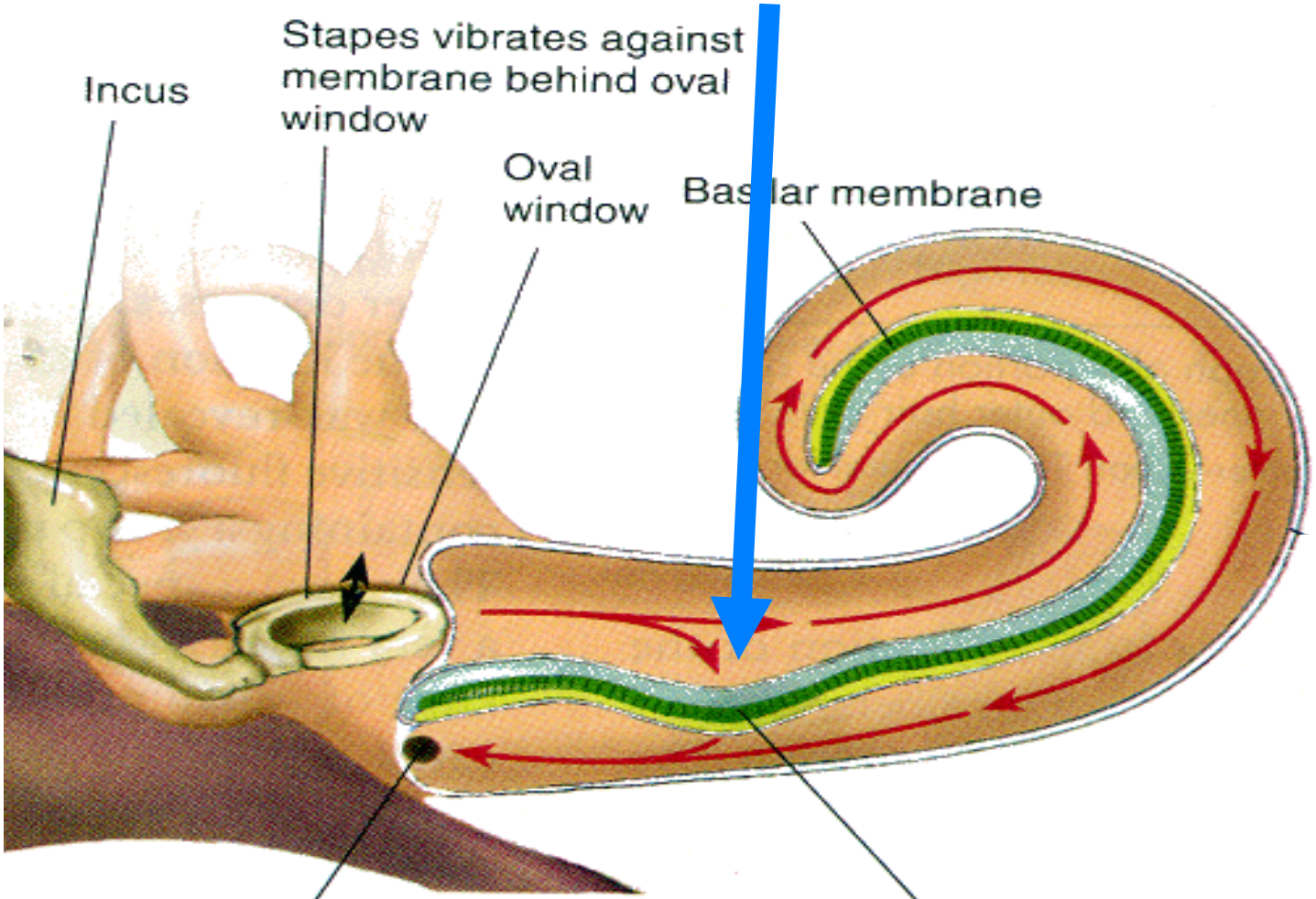
- Frequency of movement of the basilar membrane leads to matching rate of firing
  - e.g., every bend of a hair cell leads to a signal
- 100 Hz tone --> 100 hz neural firing
- Sometimes only 1 neuron, sometimes a volley is required to keep up the firing frequency
- Only works up to about 1000 Hz (but we hear ~20kHz)
  - "low-rate work will get you fired!"
  - Note: Volley principle

Place Theory

- Since the afferent nerve fibers from the auditory nerve connect to different places along the cochlea, perhaps the place that is stimulated most by a sound will lead to firing of specific nerve fibers
- "Region of maximum displacement" on basilar membrane
- So close to one end might be low frequencies, and close to the other end might be high frequencies

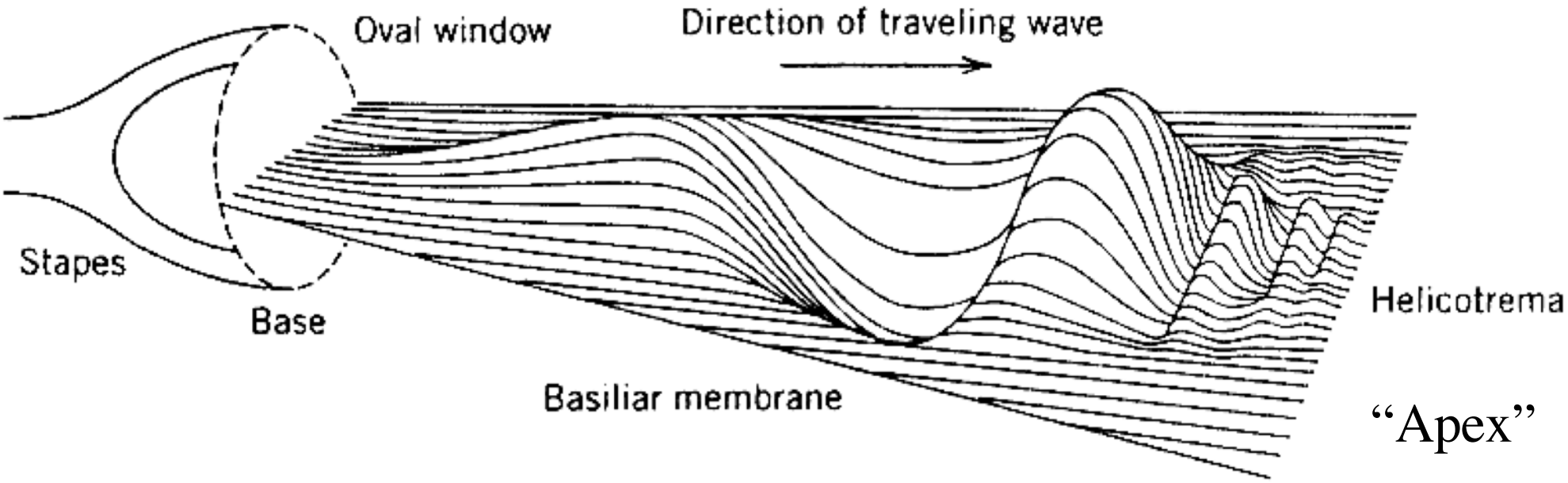
Place Theory

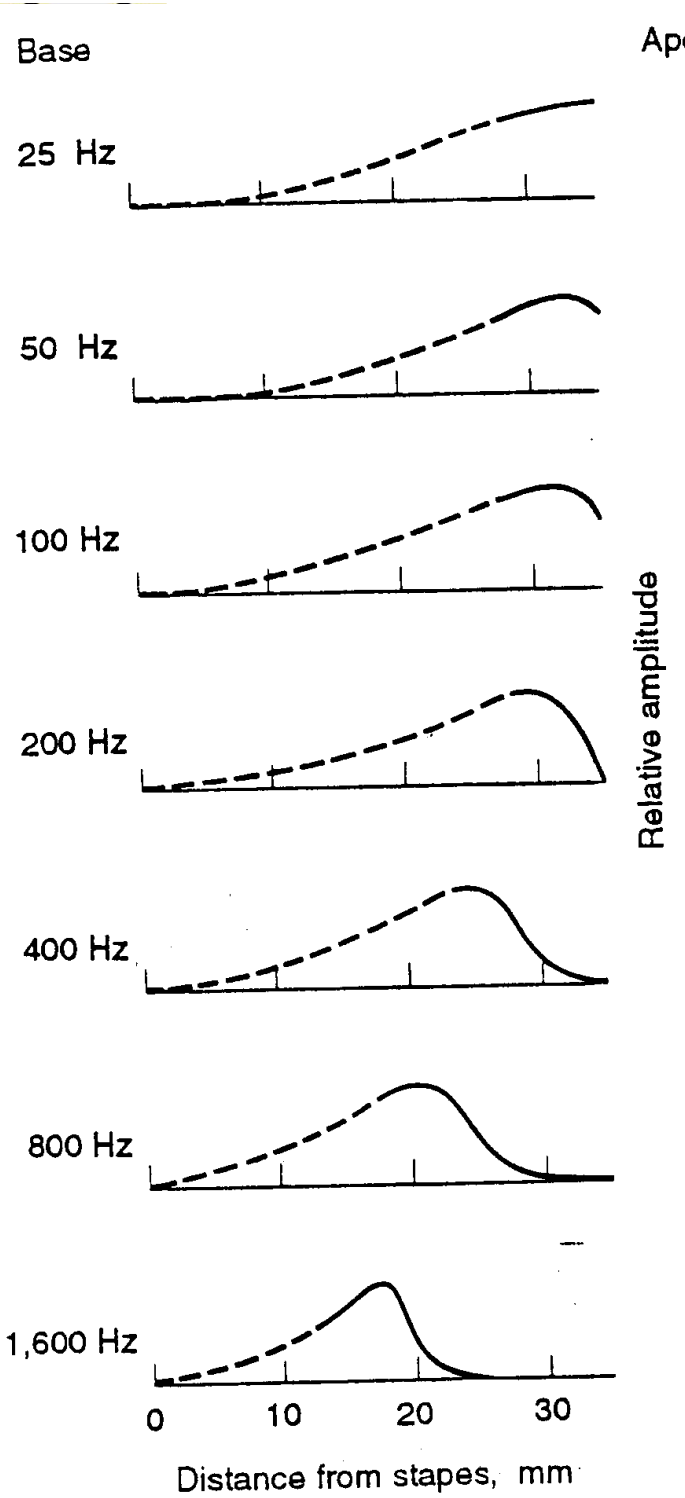
- "Region of maximum displacement"



Place Theory

- Traveling wave
  - Complex signal will decompose into smaller peaks (automatic Fourier analysis)



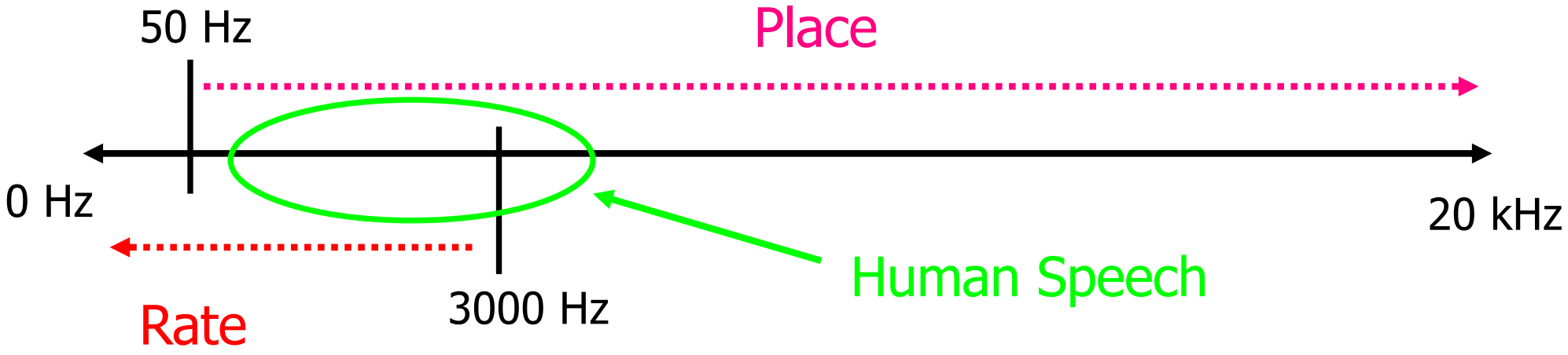


Place Theory

- Low frequencies stimulate apex
- High frequencies stimulate base of cochlea (near stapes)
  - "Bass is not at the base"
- Works best for high frequencies (above ~800 Hz)

Rate + Place (Combo) Theory

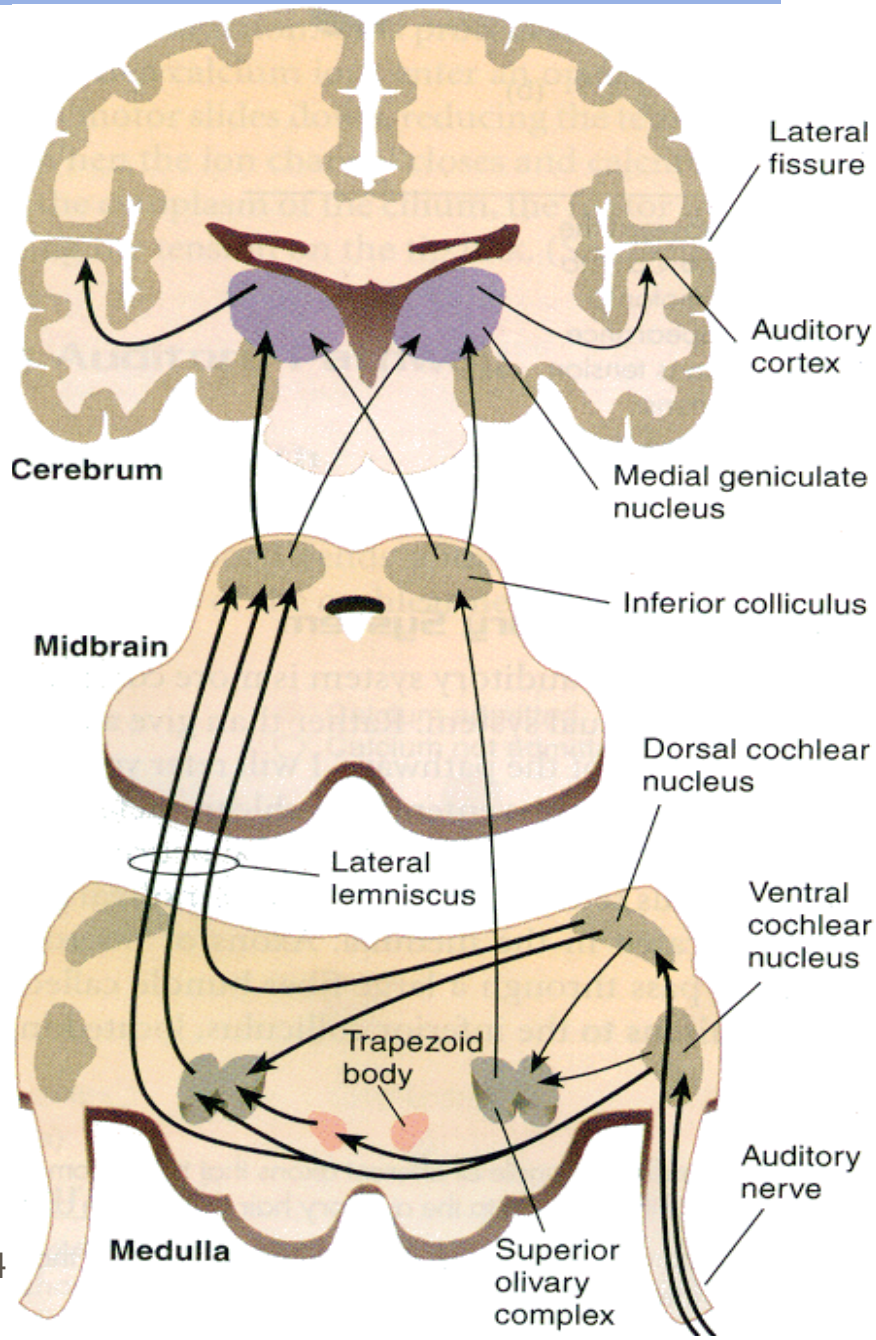
- Rate works best for low frequencies
- Place works best for high frequencies
- There is an overlap between about 50-3000 Hz, where both work
  - Note, this is the region central to human sounds



Auditory Neural Pathway

- Cochlear nerve
  - Branch of Aud. Nerve 8th cranial nerve
  - 50,000 afferent axons
    - 95% connect to inner cells
    - 5% connect to outer
- Central aud. Pathway
  - Cochlear nucleus
  - Superior olivary nucleus
  - Inferior colliculus
  - Medial geniculate nucleus
  - (Primary) auditory cortex

    ("SONIC MG")

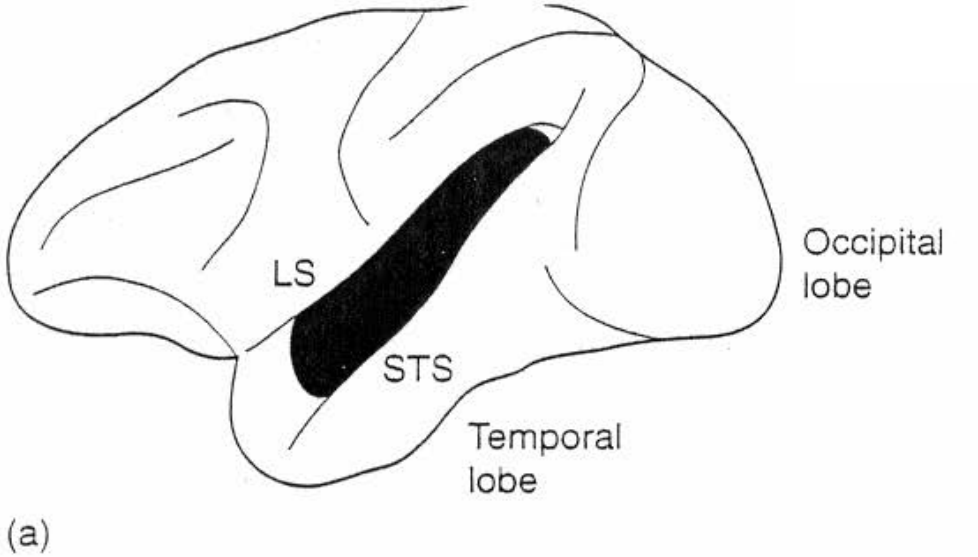


Auditory Cortex Areas

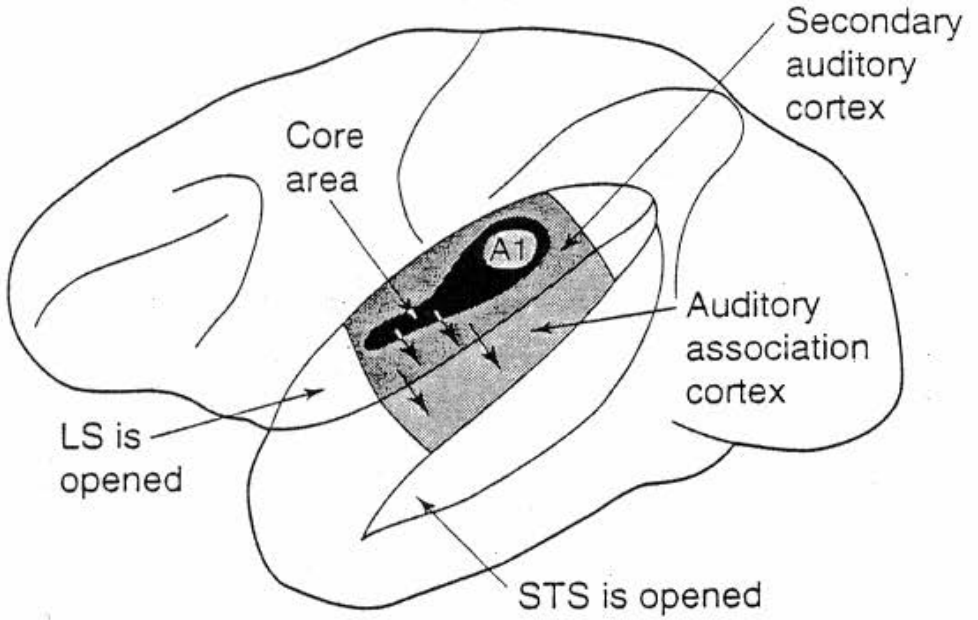
- Primary Auditory Receiving Area (A1)
  - Temporal lobe, both hemispheres
  - Buried inside lateral sulcus (LS)
  - Receives input from medial geniculate nucleus of the thalamus
  - Note: Visual signals synapse in the *lateral* geniculate nucleus of the thalamus. Thalamus is a central receiving area for all sensory information
- Core: A1 + some surrounding cortex ("belt")
- Secondary auditory cortex
- Auditory association cortex

} "parabelt"

Auditory Cortex Layout



(a)



(b)

Auditory Cortex Attributes

- Tonotopic map
  - Each area of cortex corresponds to one characteristic frequency, preserving the tonotopic arrangement from the auditory nerve fibers
- Columnar arrangement
  - Descending down into the brain from the surface, neurons share same characteristic freq., but respond to different aspects of the sound
    - e.g., location in space

Cortical Tonotopy

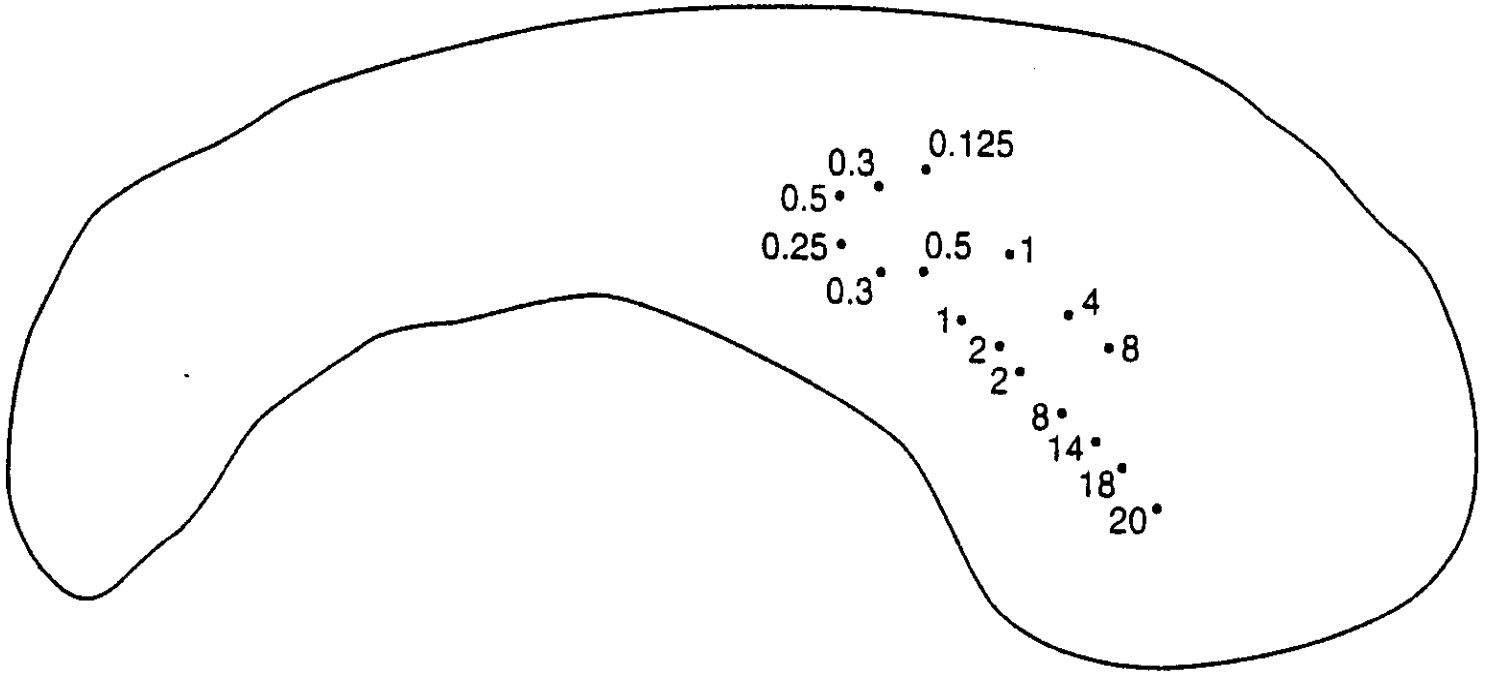


Figure 10.45

The outline of the core area of the monkey auditory cortex, showing the tonotopic map on the primary auditory receiving area, A1, which is located within the core. The numbers represent the characteristic frequencies (CF) of neurons in thousands of Hz. Notice that CFs range from 250 Hz on the left to 20,000 Hz on the right. (Adapted from Kosaki et al., 1997.)

Plasticity of Perception

- Area of the cortex (# of neurons) can change with differential usage.
- More usage --> more neurons being "recruited"
  - e.g., monkey trained on 2500 Hz tone had a larger region of auditory cortex devoted to 2-4 kHz sounds
  - Musicians have larger auditory processing area

Upcoming

- Basic Auditory perception functions