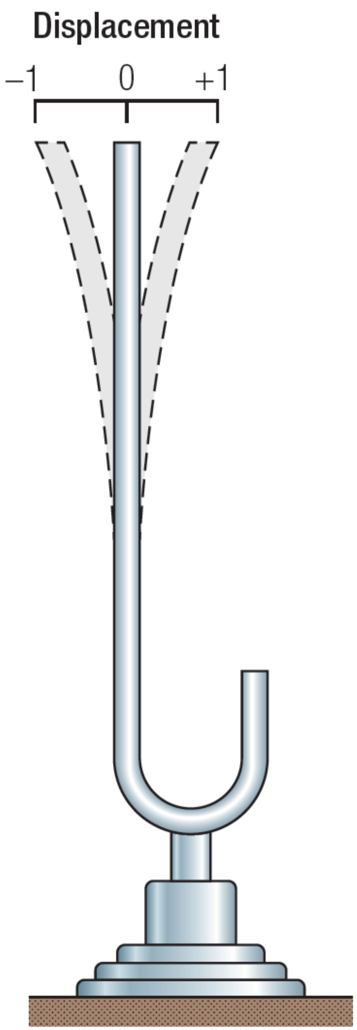
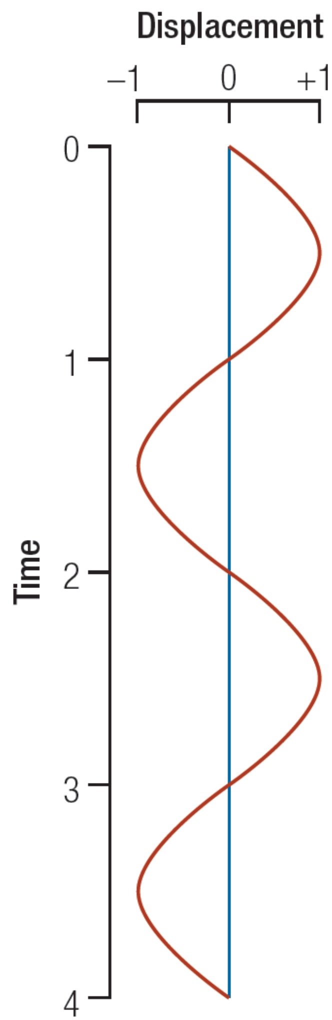
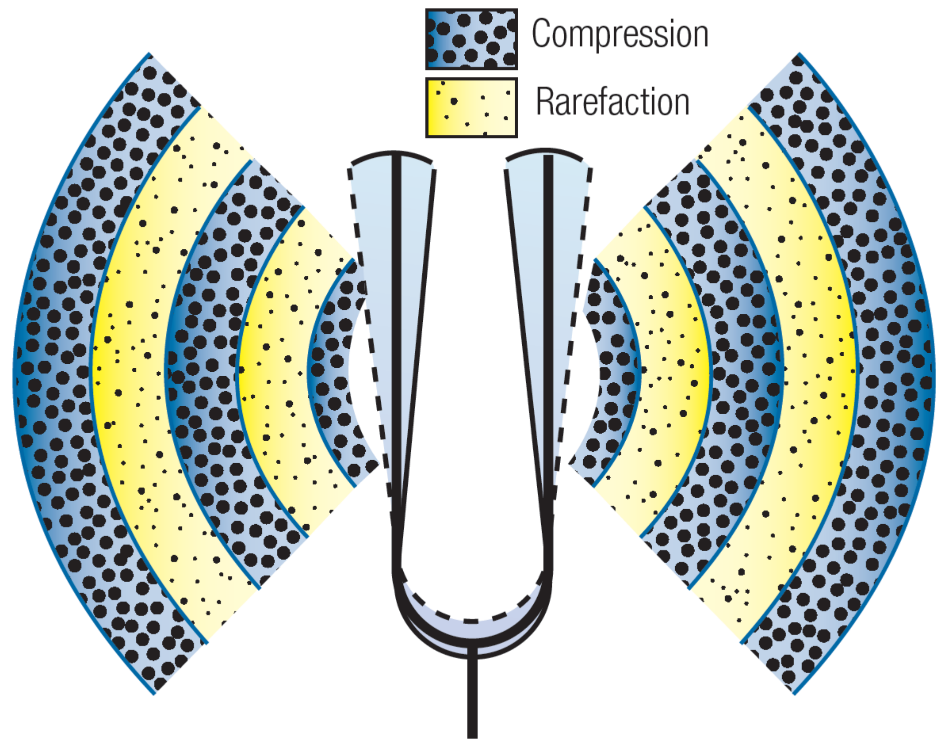
Sound and Hearing

Nature of the Sound Stimulus

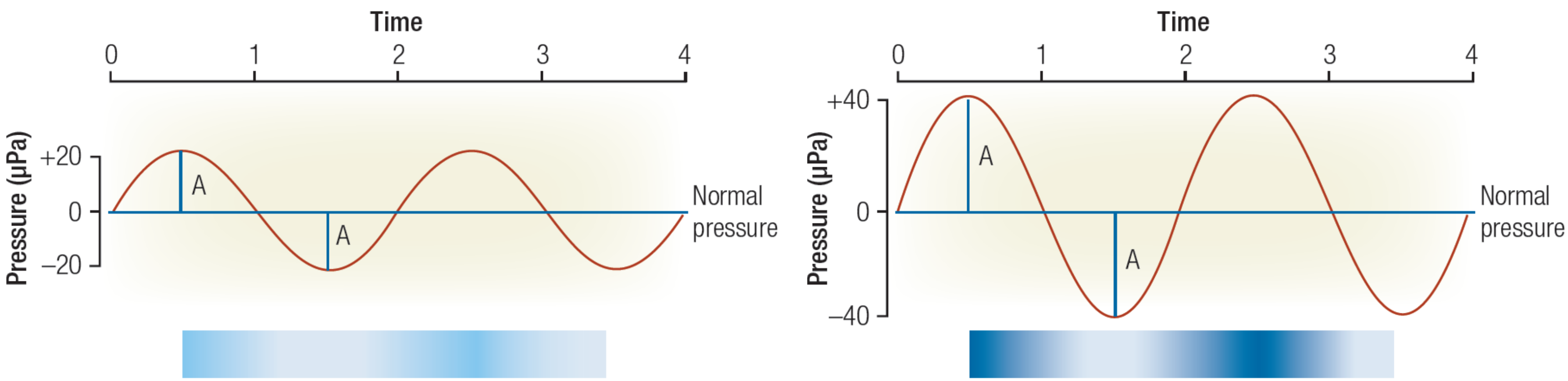






"Sound" is the rhythmic compression and decompression of the air around us caused by a vibrating object.

Sound Wave: Amplitude and Frequency (Hz)



Sound Pressure is measured in units called Pascals

1 Pascal (Pa) = 1 Newton of force/m^2

1 atmosphere = 100,000 Pa

Human absolute hearing threshold = 0.00002 Pa = **20 microPa**

(i.e., 2 ten billionths of an atmosphere)

Frequency measured in cycles/sec = Hertz (Hz)

Nominal range of sensitivity: **20 – 20,000 Hz**

The “decibel” (dB)

The **decibel** is a logarithmic unit used to describe a ratio (i.e., log (x/y))

In engineering analyses, it is used to normalize “power” measurements to a **known reference** and then compresses the resulting ratio using a $\log_{10}$ operation.

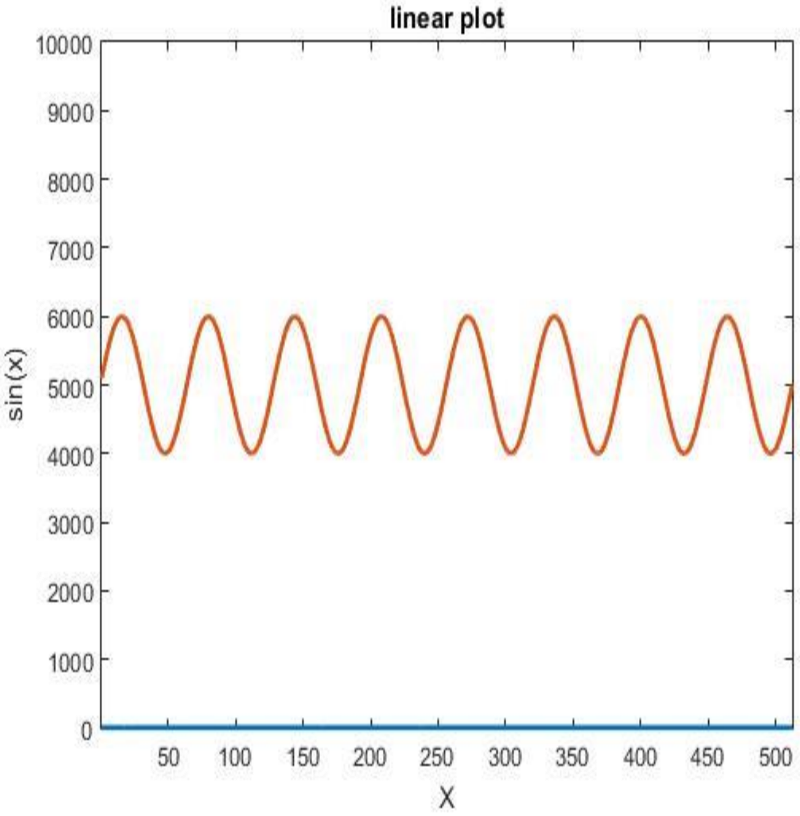
This format is convenient for engineering analyses involving wide dynamic ranges (when very small and the very large magnitudes must be considered simultaneously).

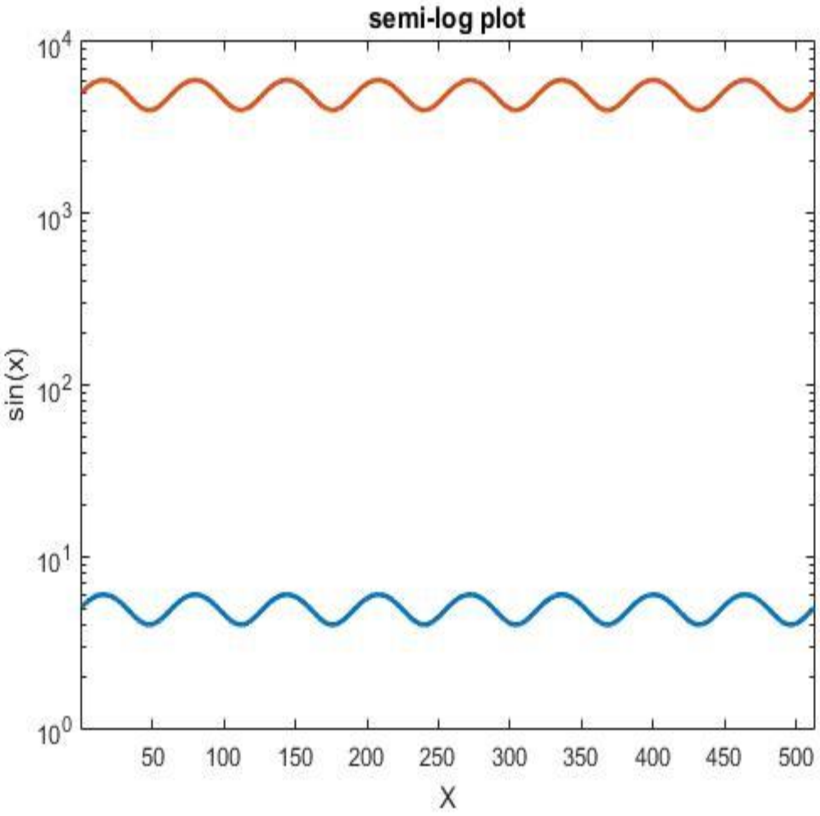
dB = 10 log(Observed Power / Reference)

Plotting Functions across a Wide Dynamic Range

(An advantage of dB scales)

Semi-Log plot allows us to see the 20% modulation in BOTH functions despite the fact that their average values differ by several orders of magnitude (i.e., 5 versus 5000)





dB_{SPL}

The transducers (microphones) on sound level meters measure sound **pressure** (i.e., N/m^2 or Pascals).

Pressure needs to be converted to **power** prior to calculation of the decibel equivalent….i.e., **acoustic power = pressure^2**

Finally, we need to agree upon a **Reference value**.
By convention, we use **20 microPa** (i.e., the hearing threshold)

Thus:
dB = 10 log (Observed Pressure^2 / 20 microPa^2)

However……..

dB_{SPL} (continued)

Prior to the advent of hand-held calculators and computers (circa 1970), performing a squaring operation was computationally expensive and prone to error.

To reduce computational demands, hearing science adopted a somewhat confusing convention in the specification of the dB_{SPL} unit:

dB_{SPL} = 20 log (Observed Sound Pressure / 20 microPa)

+3 **dB** = doubling sound intensity   +10 **dB** = 10x sound intensity

Some Typical Sound Amplitude Values

Sound	Pressure Level (pascals)	Pressure Ratio (P_s/P_r)	Intensity Ratio (I_s/I_r)	dB_{SPL}
Minimal audible sound	0.00002 (P_r)	1	1	0
Soft whisper	0.0002	10	100	20
Quiet office	0.002	10^2	10^4	40
Average conversation	0.02	10^3	10^6	60
Vacuum cleaner	0.2	10^4	10^8	80
Subway train	2	10^5	10^{10}	100
Loud thunder	20	10^6	10^{12}	120
Jet engine at takeoff (pain threshold)	200	10^7	10^{14}	140
Wind tunnel	2,000	10^8	10^{16}	160
Space shuttle	20	10^9	10^{18}	180

More about those pesky decibels

- **JND** for sound intensity is about 1 dB_{SPL} for most of normal range of hearing
- **What does 0 dB_{SPL} mean?**

  Hint: 20 log (20 microPa/20 microPA) = 0 dB_{SPL}
- If one machine emits 80 dB then what sound intensity would be expected from two machines side-by-side?

  2 x 80 = 160 dB ??? (That's pretty intense)

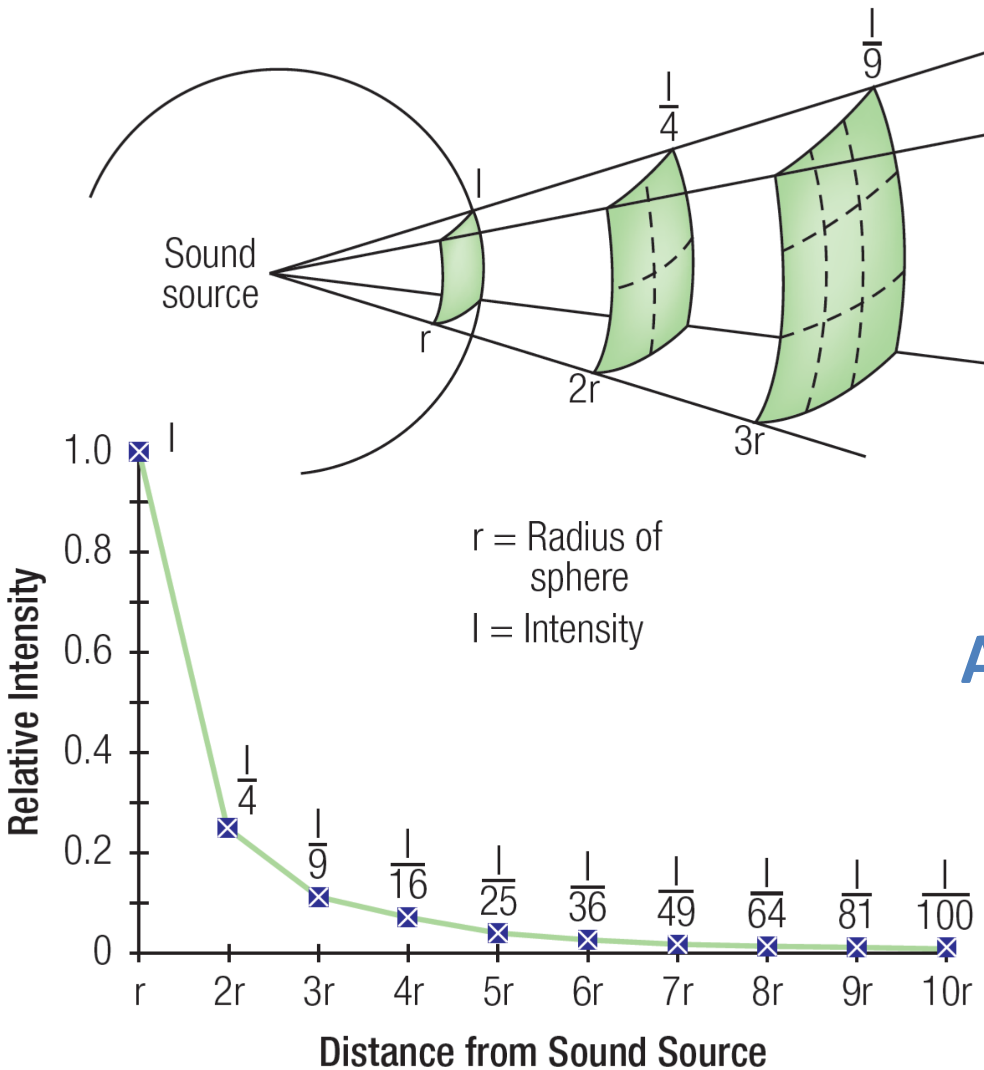
  Convert from dB back to linear units, sum the linear units, then convert sum to dB

  80 dB → antiLog(80/10) → 100,000,000

  10 log (100M+100M) = 83 dB (approx.)

+3db = doubling

Inverse-Square Law



Area of sphere = $4\pi r^2$

A "Better" Sound Amplitude Table?

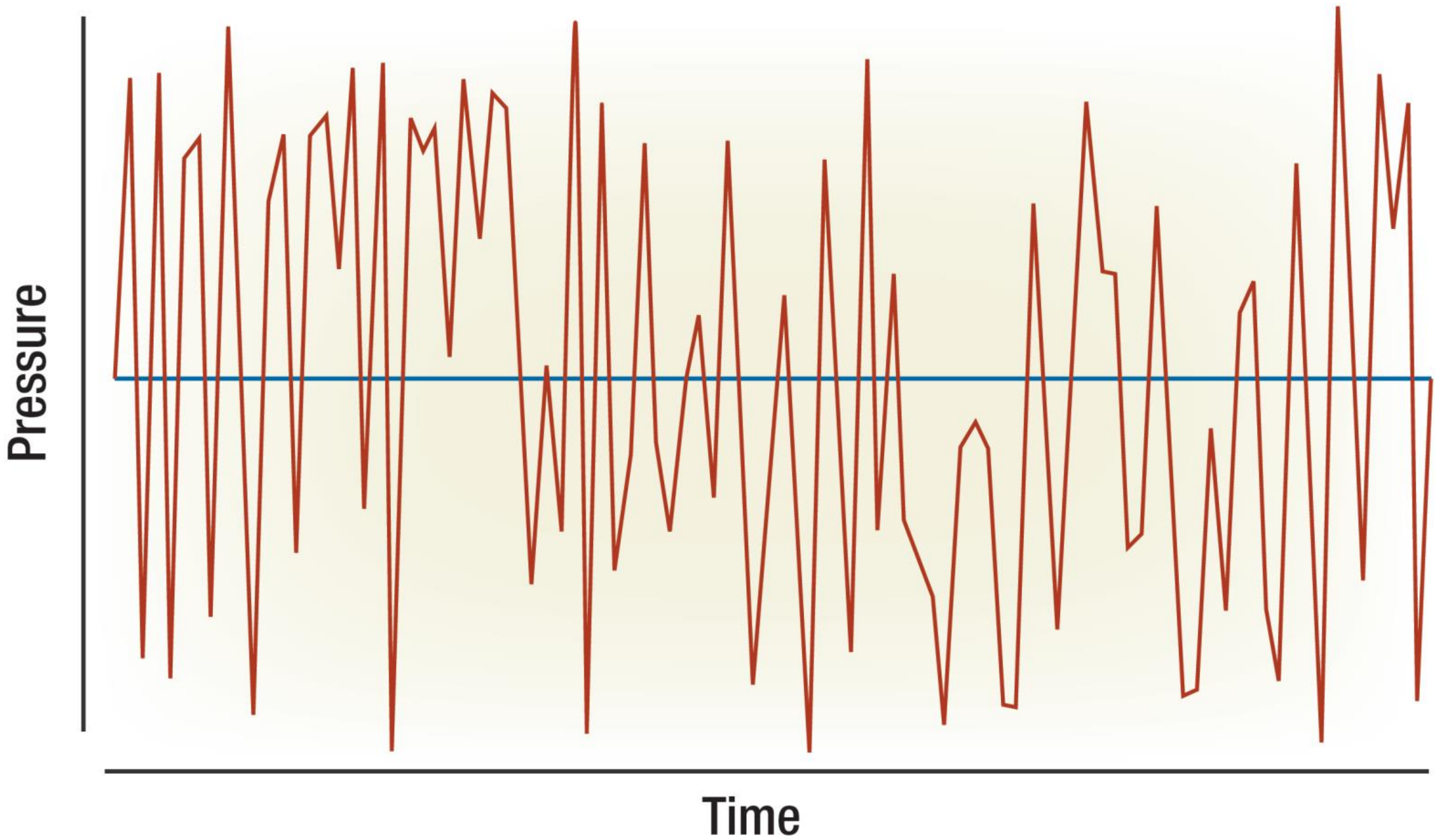
(Always specify the measurement distance)

Because of the inverse-square law

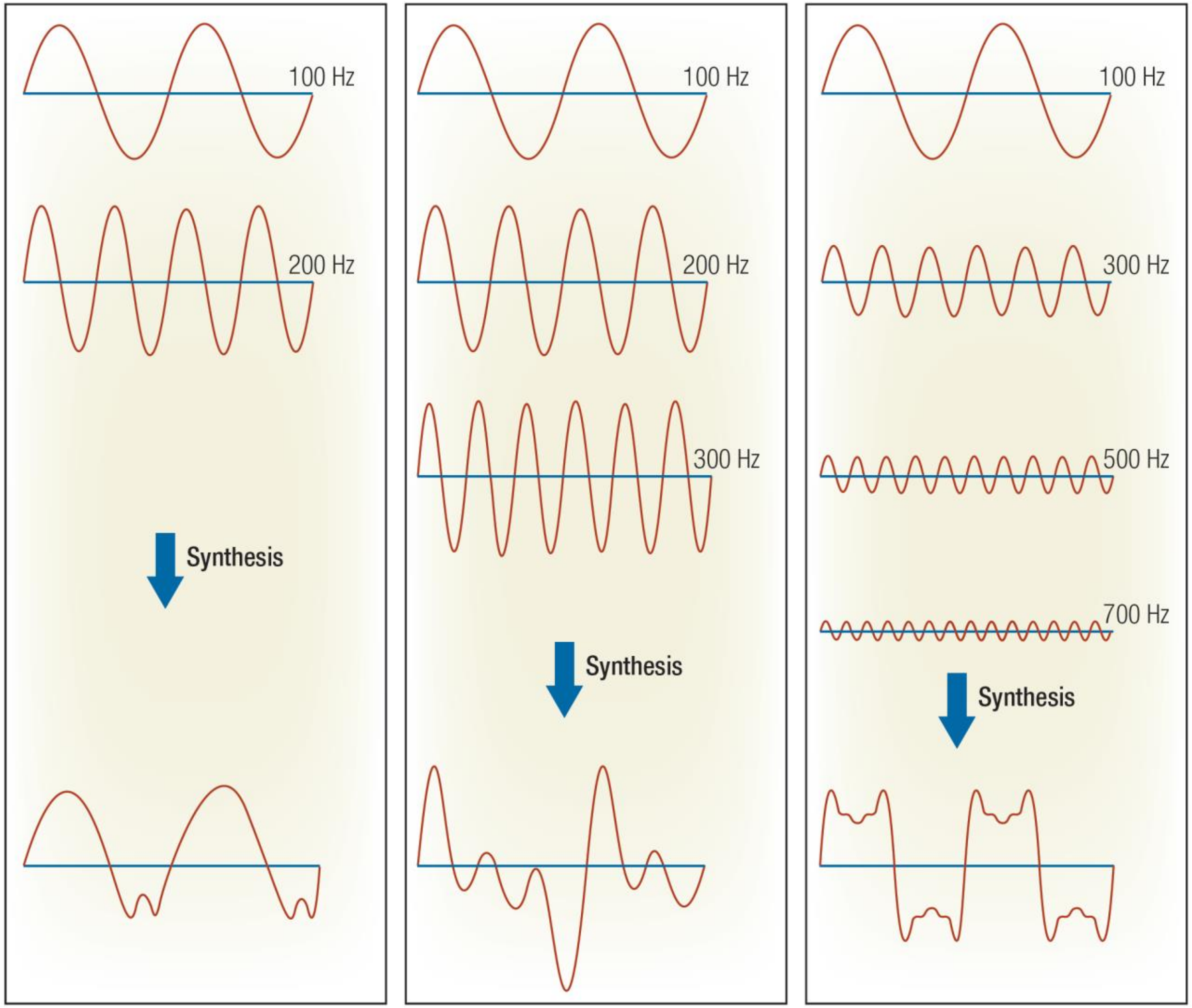
dB_{SPL}

130 Loud hand clapping at 1 m distance
110 Siren at 10 m distance
95 Hand (circular) power saw at 1 m
80 Very loud expressway traffic at 25 m
60 Lawn mower at 10 m
50 Refrigerator at 1 m
40 Talking; Talk radio level at 2 m
35 Very quiet room fan at low speed at 1 m
25 Normal breathing at 1 m
0 Absolute threshold

Most Sound Stimuli are Complex



Complex Sound = Sum of Sines (Fourier Theorem Revisited)



J.B.J. Fourier
(1768-1830)

Fourier Sound Applet

Speed of Sound

Medium	Sound Speed (metres/second)
Gas	
Carbon dioxide	268
Air	331
Helium	972
Liquid	
Ethanol	1,130
Fresh water	1,402
Sea water	1,522
Solid	
Brass	4,700
Steel	5,790
Aluminum	6,420

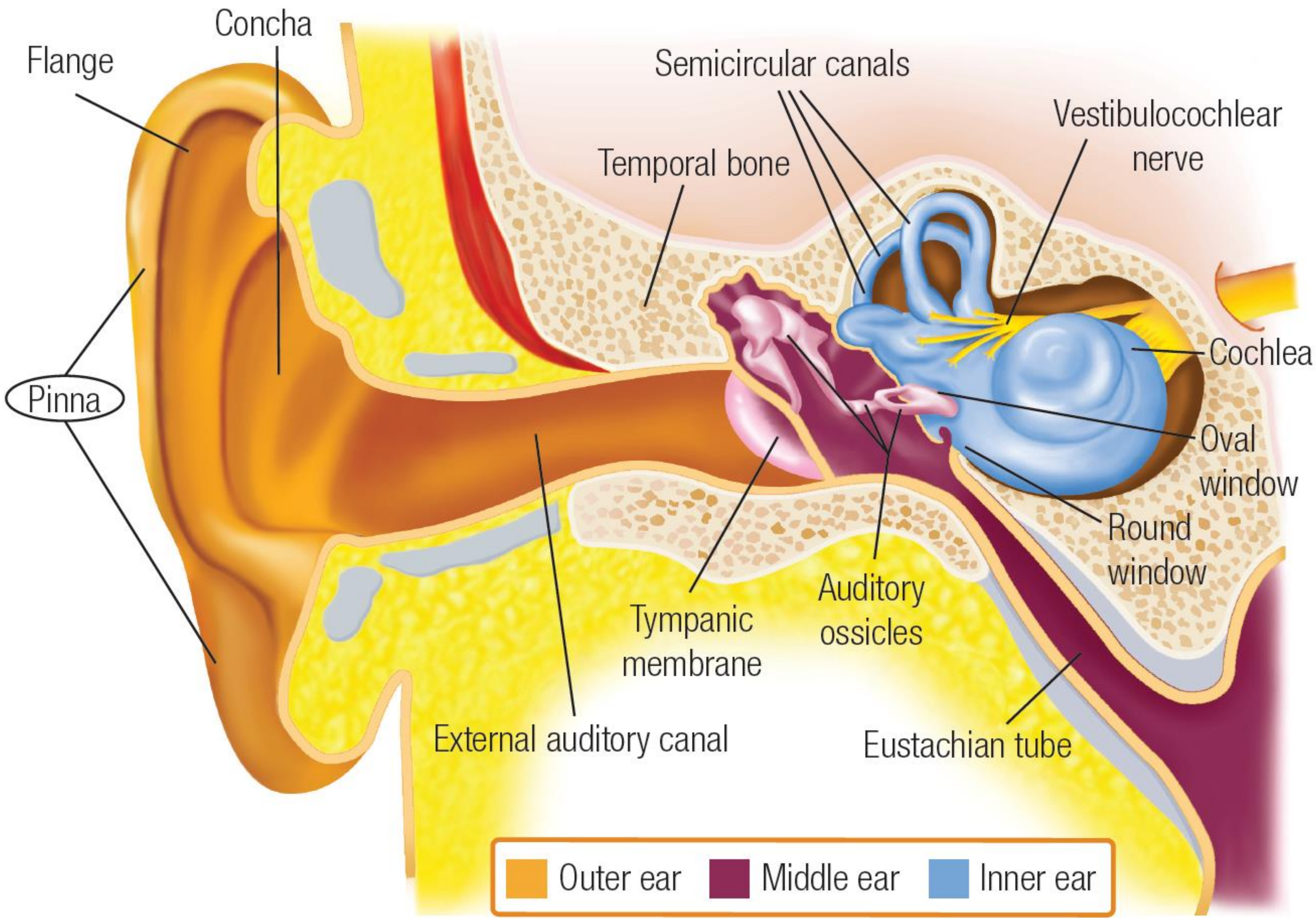
Acoustic energy results from a traveling wave of rhythmic "compression" through a physical medium (e.g., air; water; steel).

It is the "compression" that travels not the medium, *per se*.

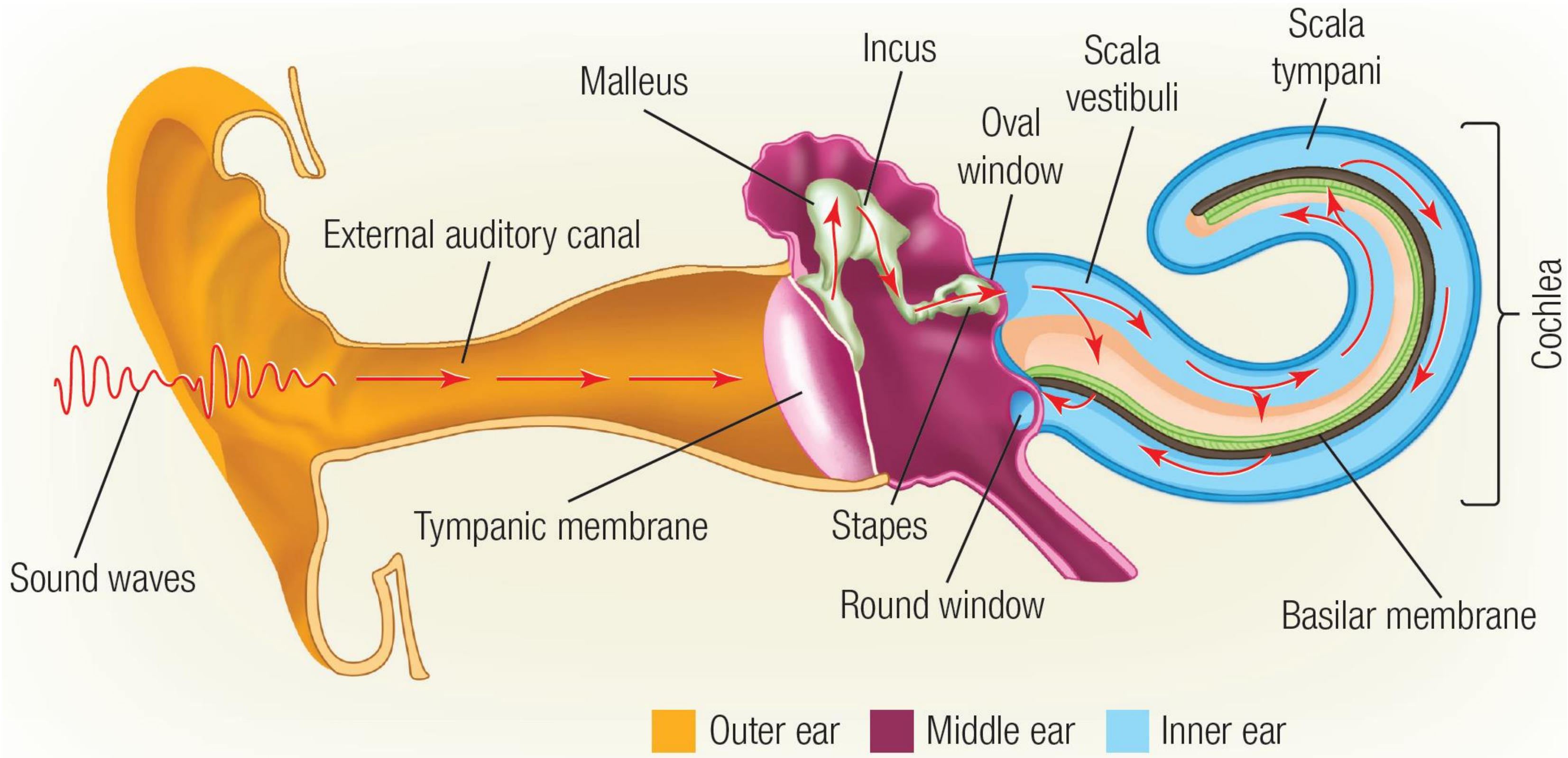
The characteristic speed of this travelling wave varies as a function of the medium (elasticity; density).

The speed of acoustic energy through the air (aka "sound") is 331 m/sec (or **742 MPH**) at 0-deg C (Faster at higher temperatures).

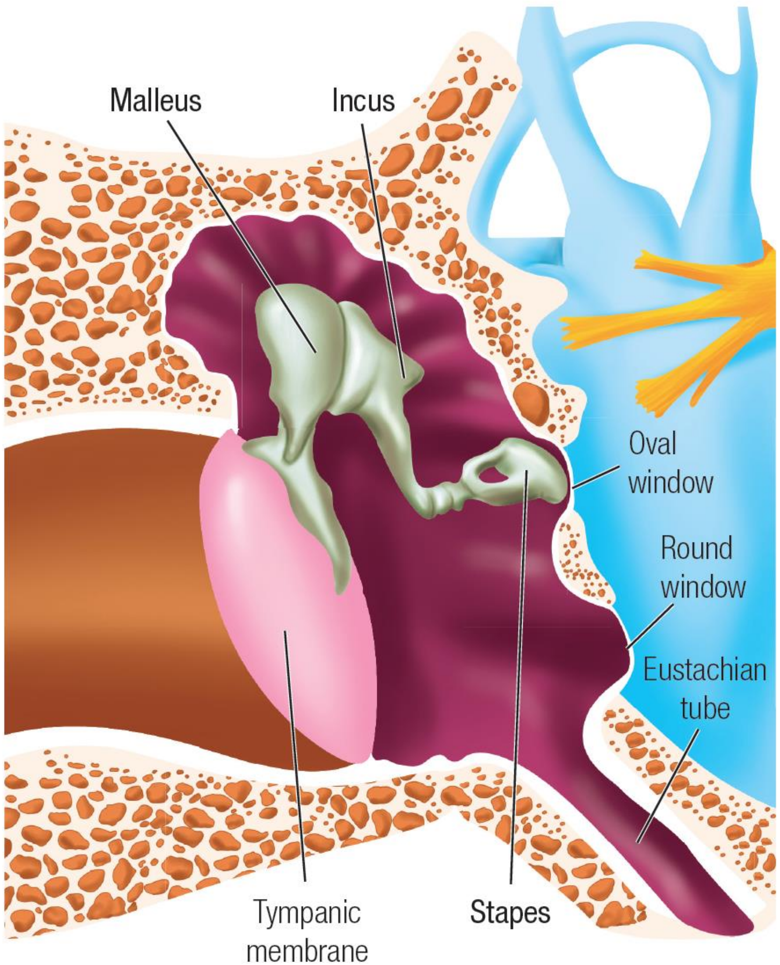
Gross Anatomy of the Ear



Flow of Acoustic Energy
(The "Impedance Problem")



The "Impedance Problem"



99.9% of sound energy in the air is reflected at the air:water boundary (10 log(0.1/100)) = **-30 dB loss**) (1/1000x)

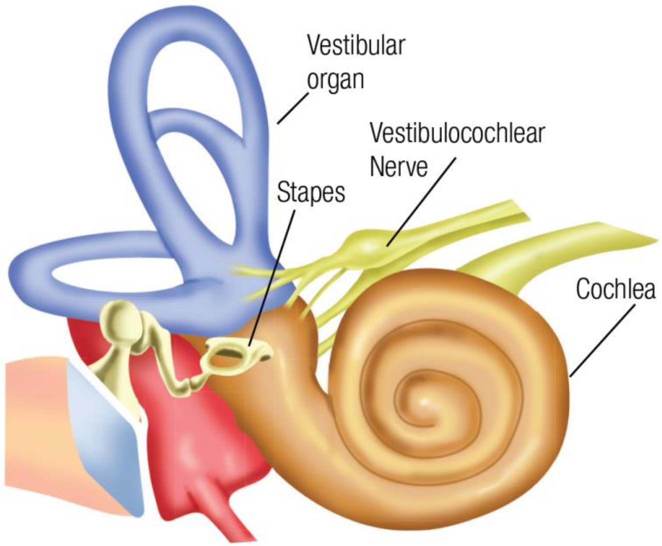
How does the ear compensate for this loss as sound energy is transmitted from the air to the fluid that filled the cochlea?

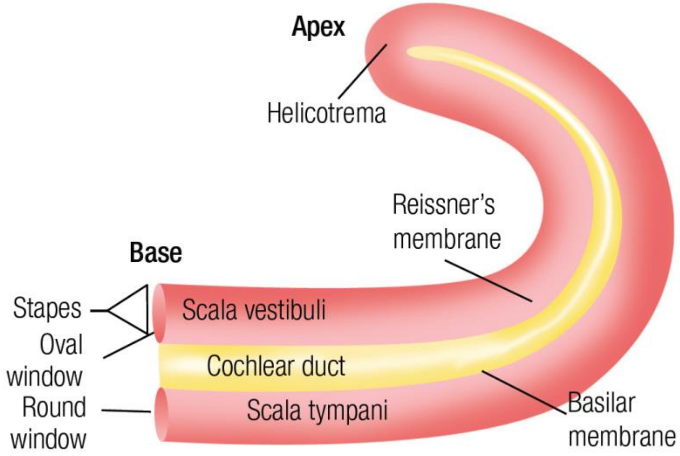
2 dB gain via ossicular leverage (1.6x)

25 dB gain via surface area condensation (eardrum → stapes) (316x)

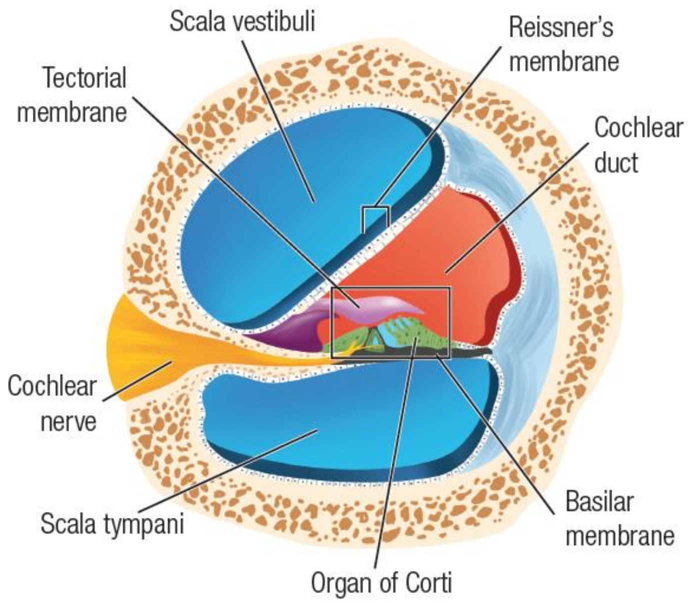
~5 dB gain at mid-frequencies (3x) due to pinna and auditory canal resonance

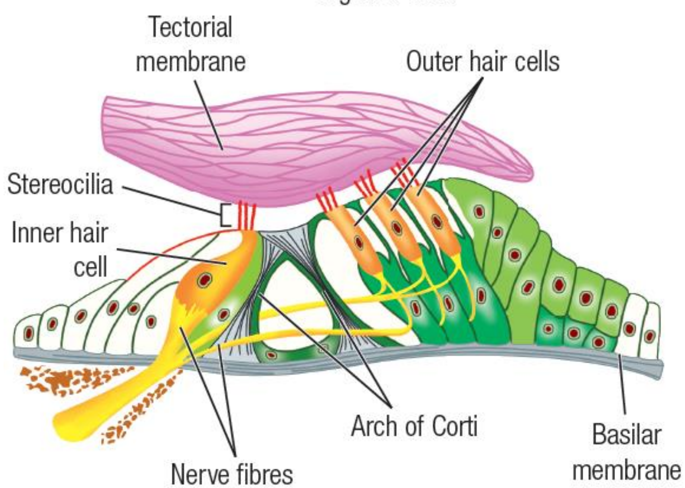
The Cochlea


Vestibular organ
Vestibulocochlear Nerve
Stapes
Cochlea


Apex
Helicotrema
Reissner's membrane
Base
Stapes
Oval window
Round window
Scala vestibuli
Cochlear duct
Scala tympani
Basilar membrane

The Organ of Corti





3000-3500 Inner Hair Cells (IHC)

12,000 Outer Hair Cells (OHC)

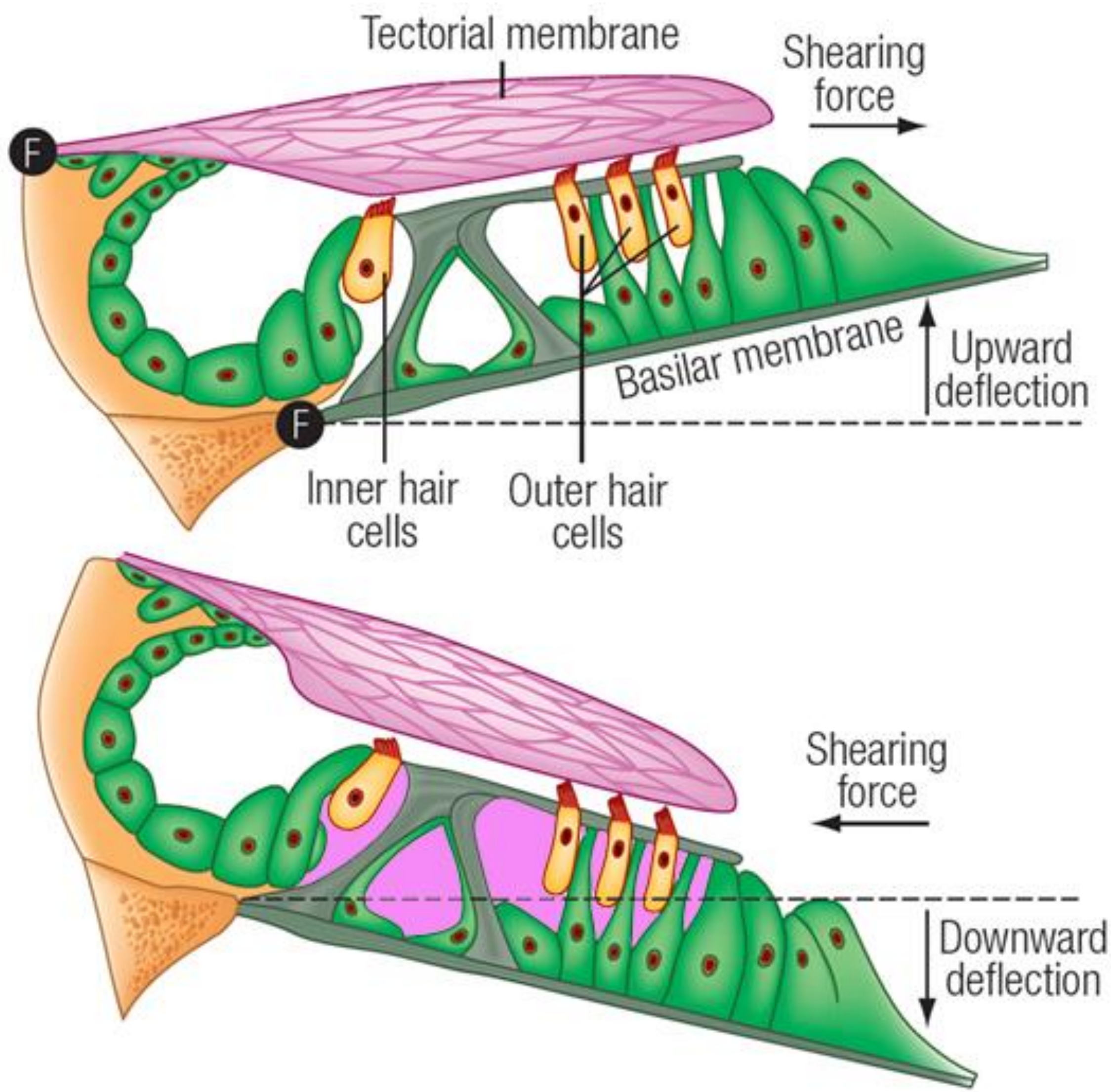
Photomicrograph: Sensory Hair Cells

Three rows of Outer Hair Cells

One Row of Inner Hair Cells

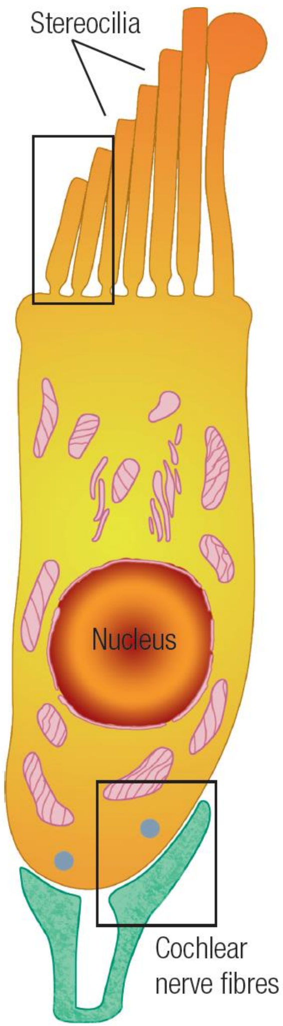
Auditory Transduction

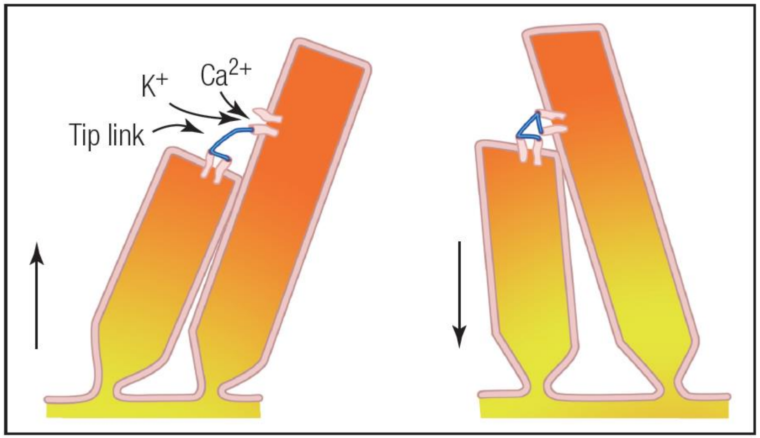
Basilar Membrane Modulation Effects upon Sensory Hair Cells



Note: K^+ ion concentration gradient across sensory hair cells (see pink cavities)

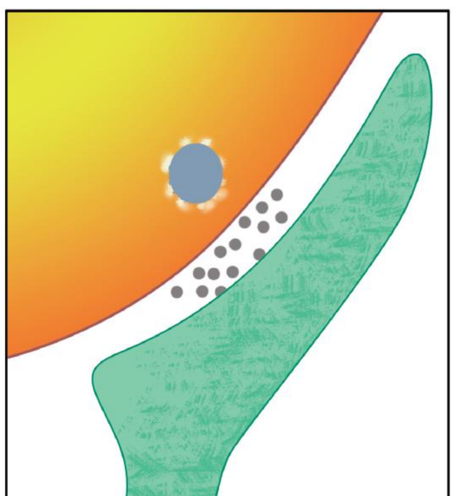
IHC Stereocilia “Tip Links”





“tip link” connects gate to adjacent cilia.

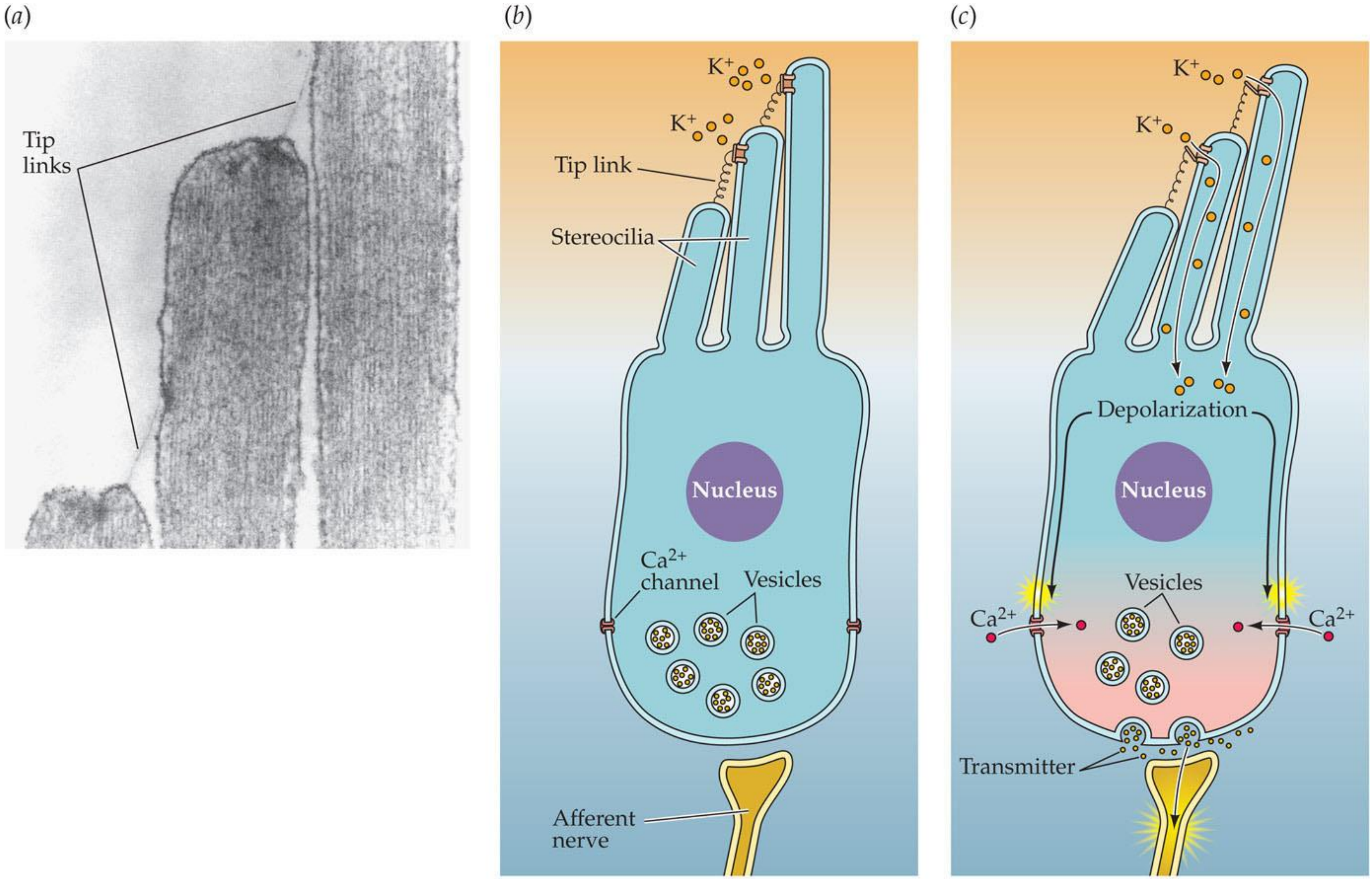
Shearing motion forces gate to open.



Mechanical open-and-close of gate modulates <u>influx of potassium</u> ions (much FASTER than slow chemical cascade in visual transduction).

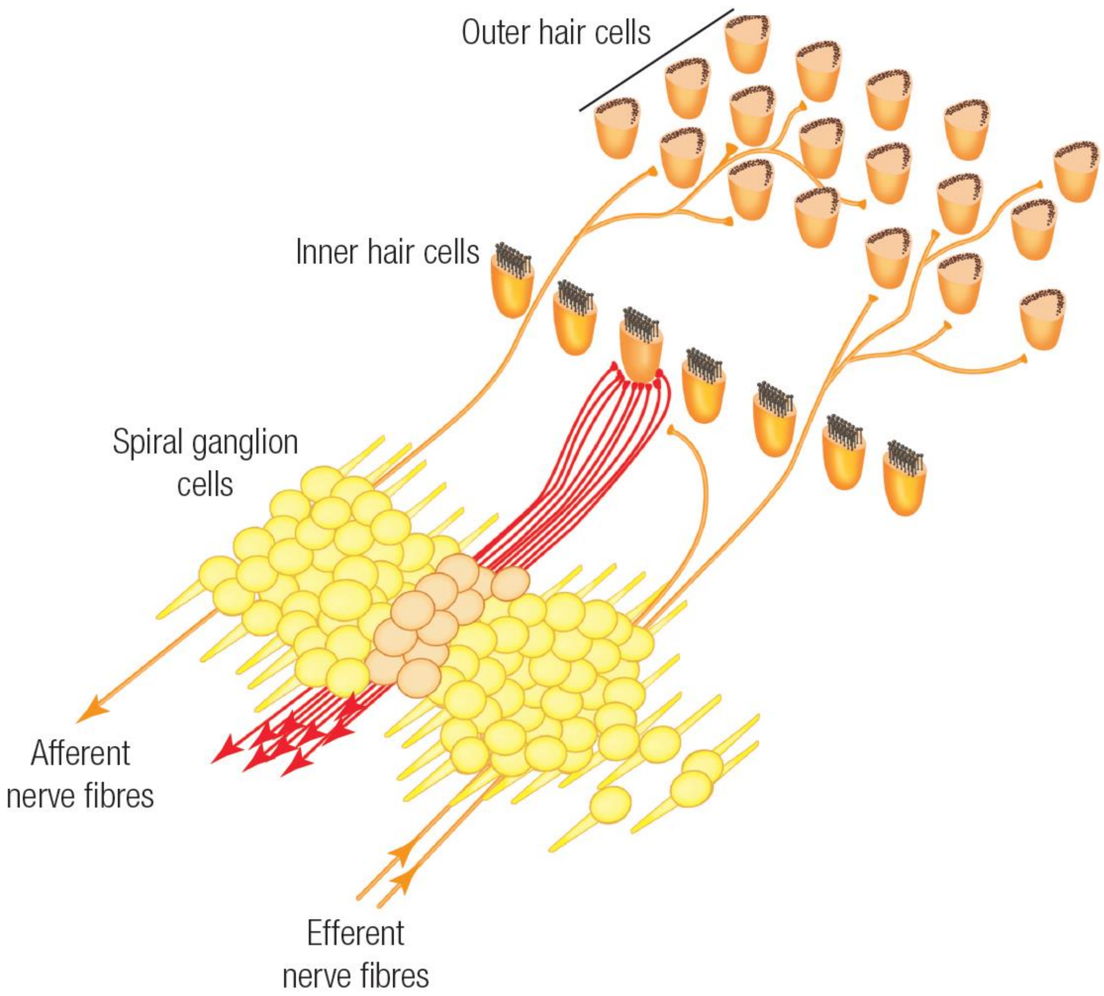
K^+ depolarization of IHC triggers release of **glutamate** at cochlear nerve fiber synapse.

IHC Auditory Transduction



SENSATION & PERCEPTION 4e, Figure 9.11

Innervation of 3000 IHCs versus 12,000 OHCs



30,000+ fibers in cochlear nerve. Nearly 10:1 fiber-to-IHC innervation ratio.

Sparse number of fibers carry info from OHC to brain.

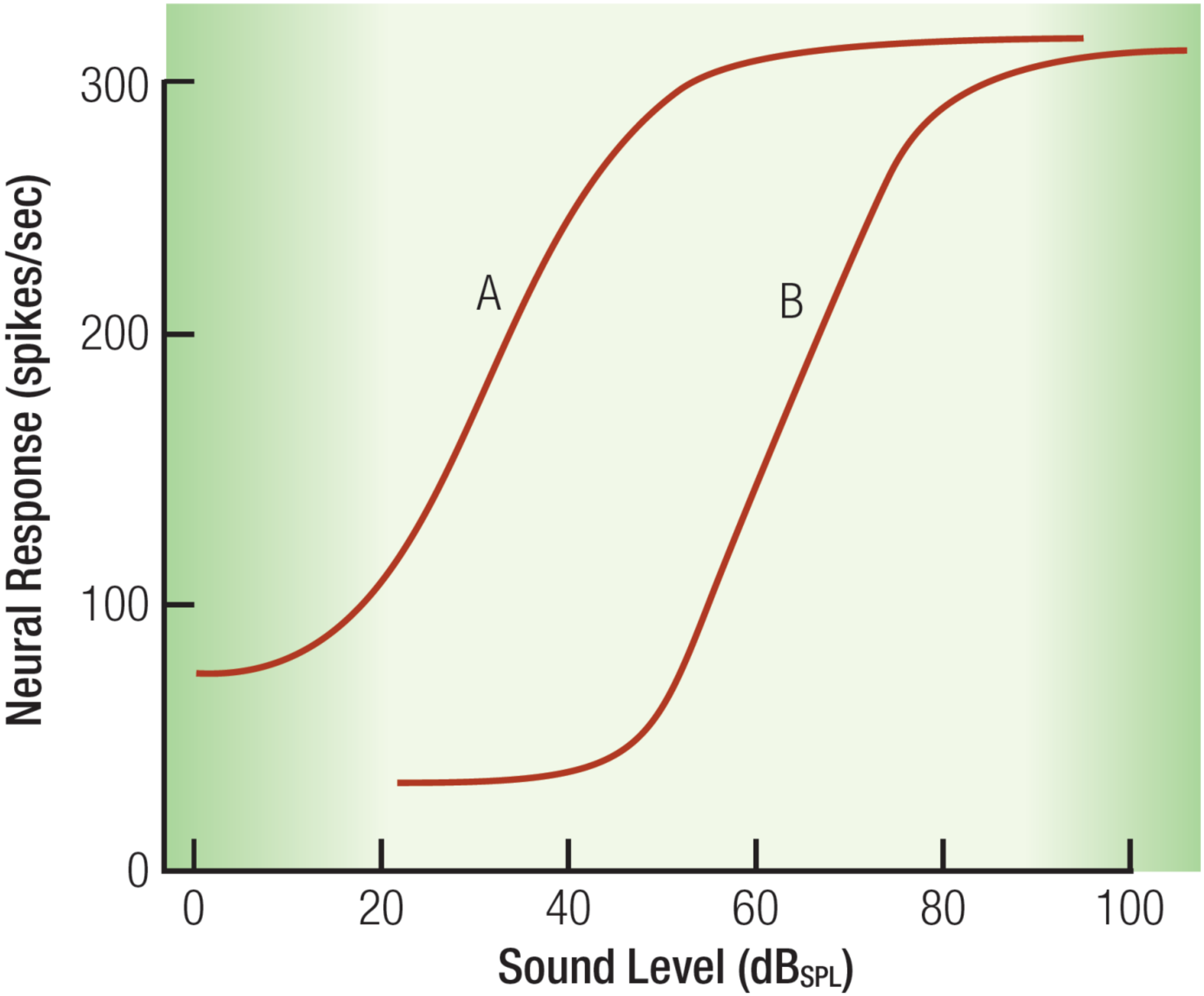
Small number of fibers descend from brain to OHCs.

Role of OHC's?

Mechanical gain

otoacoustic emission

Sound Amplitude Coding ("Divide and Conquer")

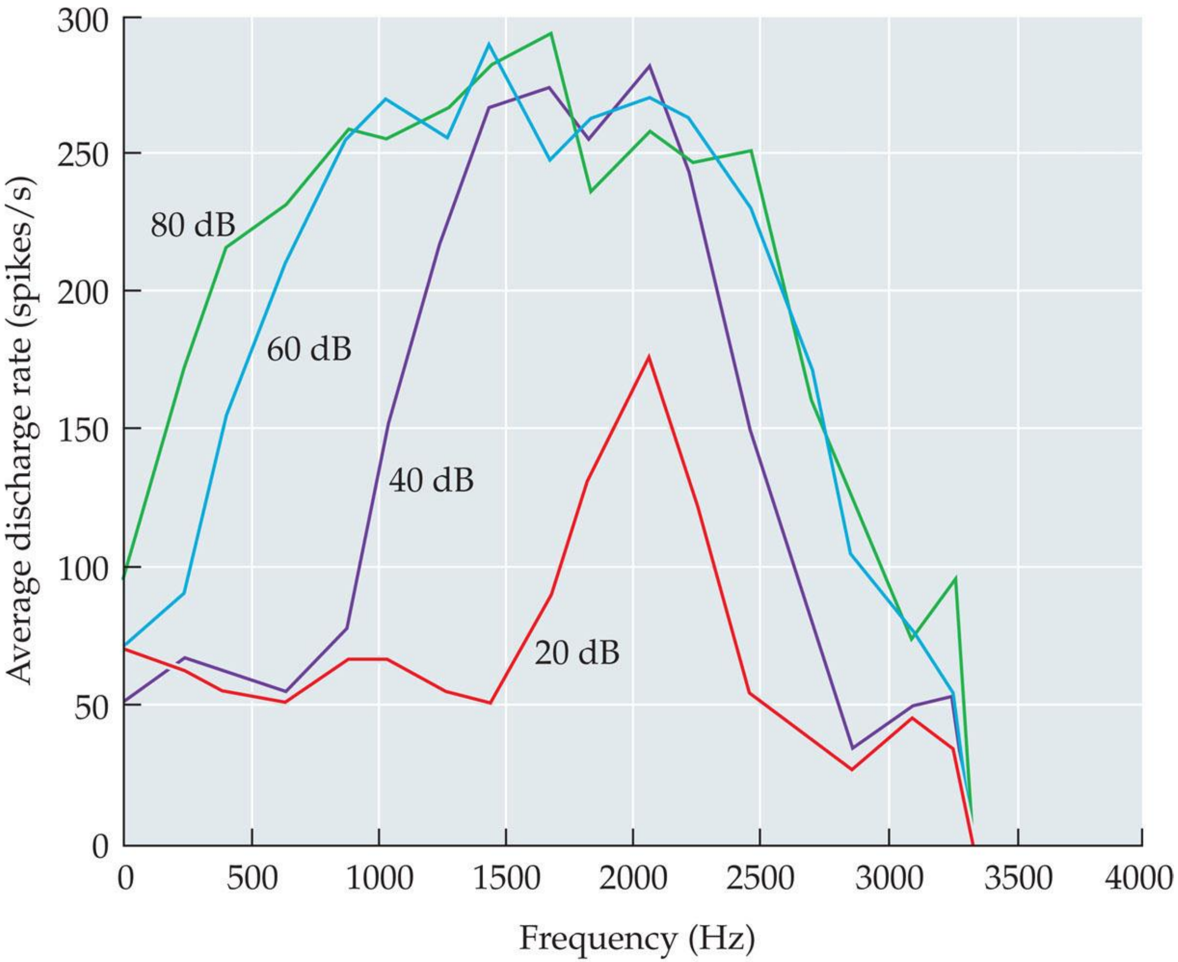


Multiple nerve fibers for each IHC.

Each nerve fiber tuned to a different 40 dB "range" of stimulus intensity.

Intensity-level multiplexing

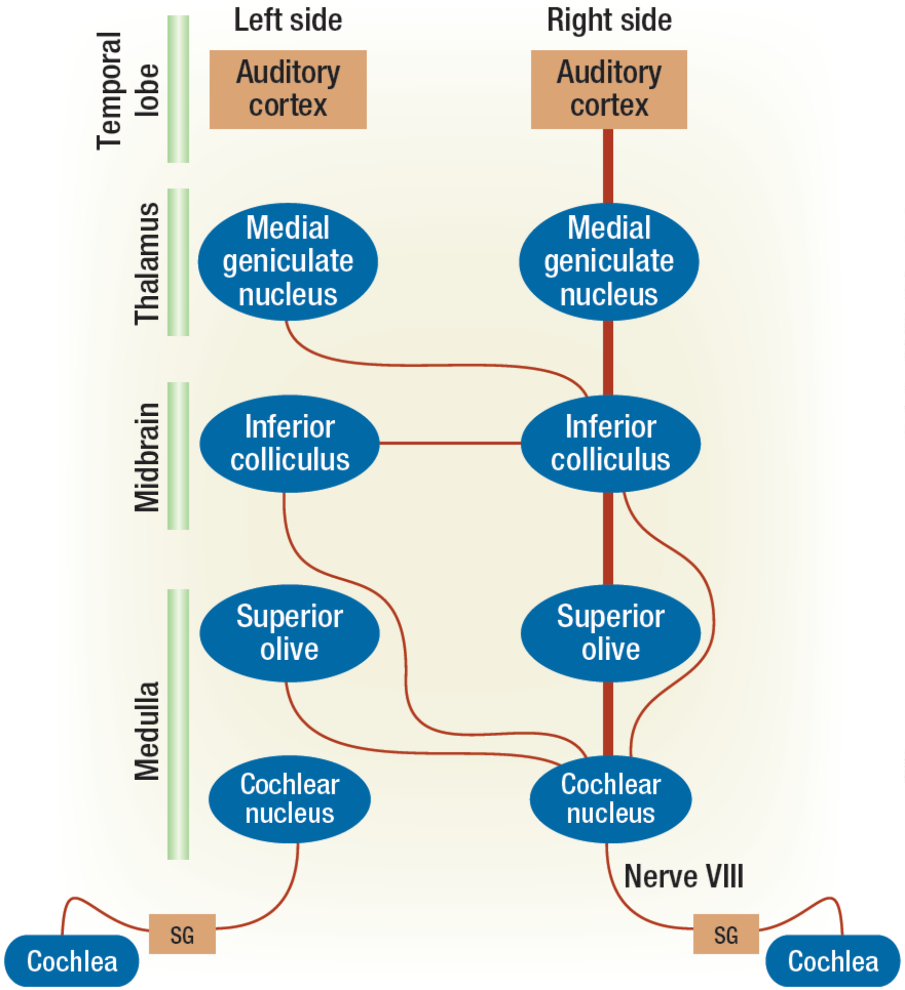
Tuning Specificity of Cochlear Nerve Fibers "Broadens" with Increased Intensity

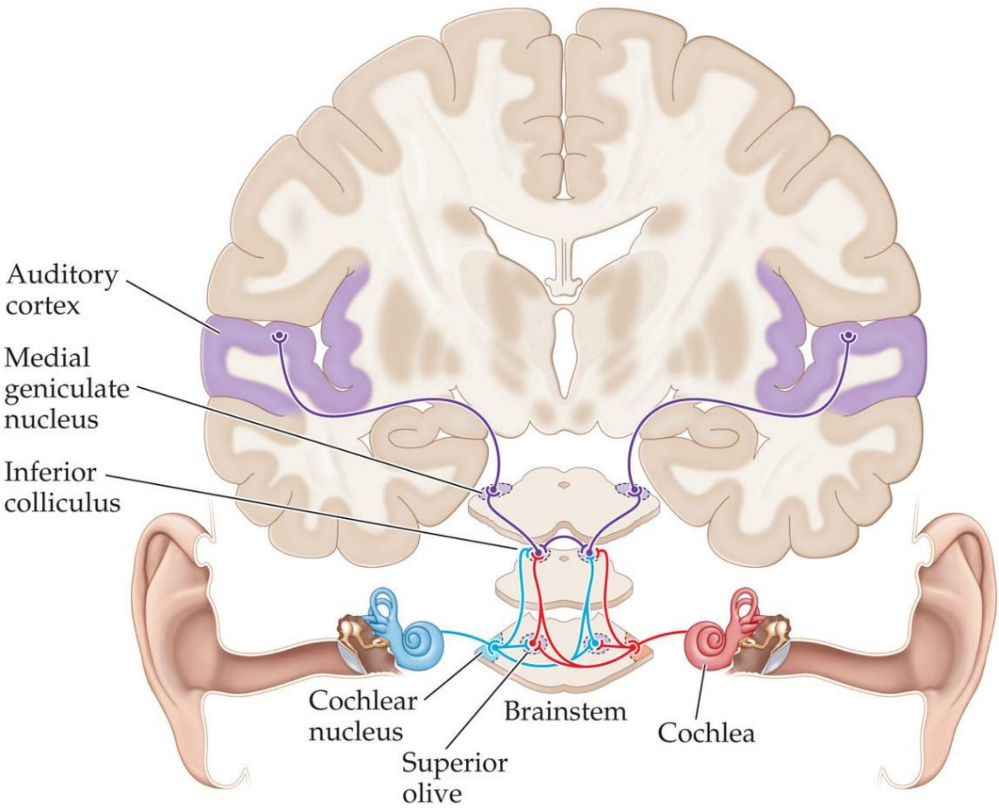


SENSATION & PERCEPTION 4e, **Figure 9.16**

<u>Q</u>: Why the broadening and asymmetry? <u>A</u>: Look to the Basilar membrane's response

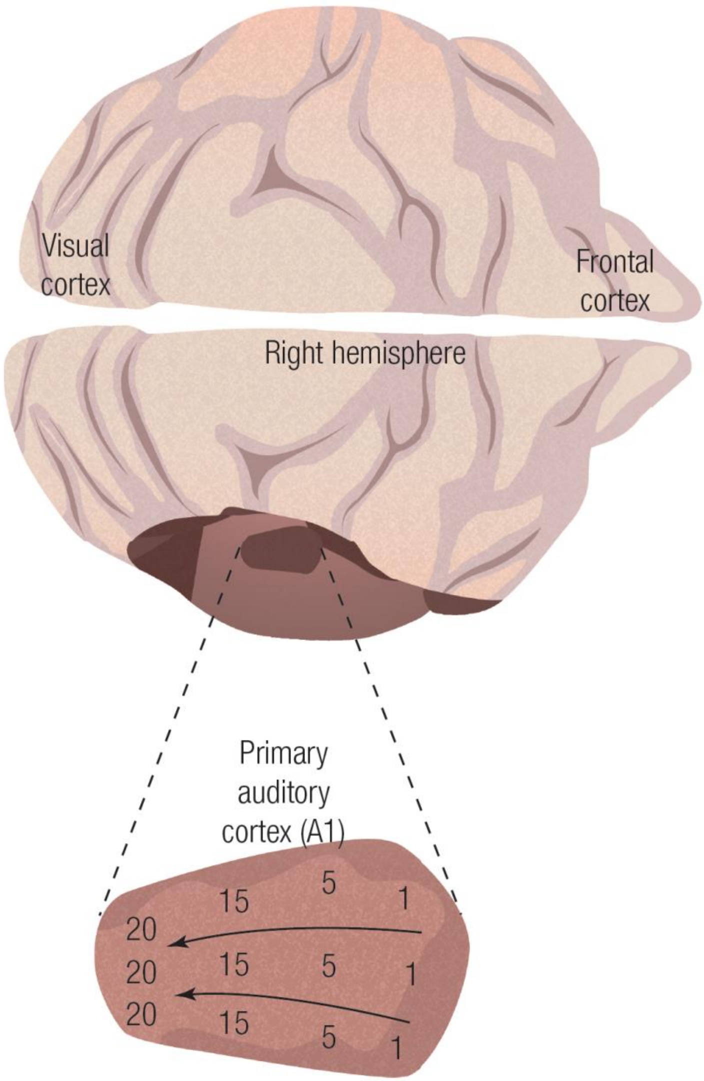
Ascending Pathways





SENSATION & PERCEPTION 4e, Figure 9.20

Tonotopic Organization of Primary Auditory Cortex (A1)



<u>Also note</u>:

Segregation of monaural versus binaural cells is maintained.

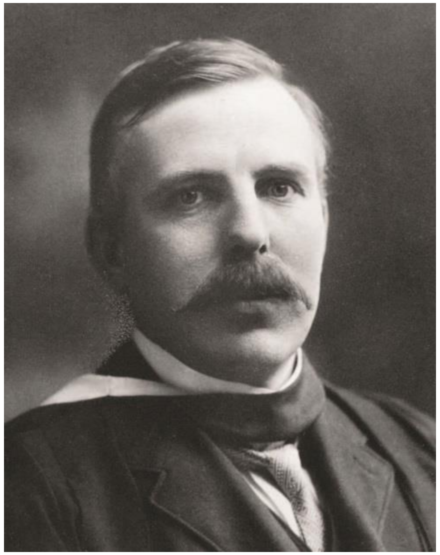
Binaural cells loosely organized according to spatial location of stimulus source.

Auditory Frequency Coding

(What is the neural code for “pitch”?)

Temporal Mechanism versus Place Mechanism

Temporal Theory



Ernest Rutherford
(1871-1937)

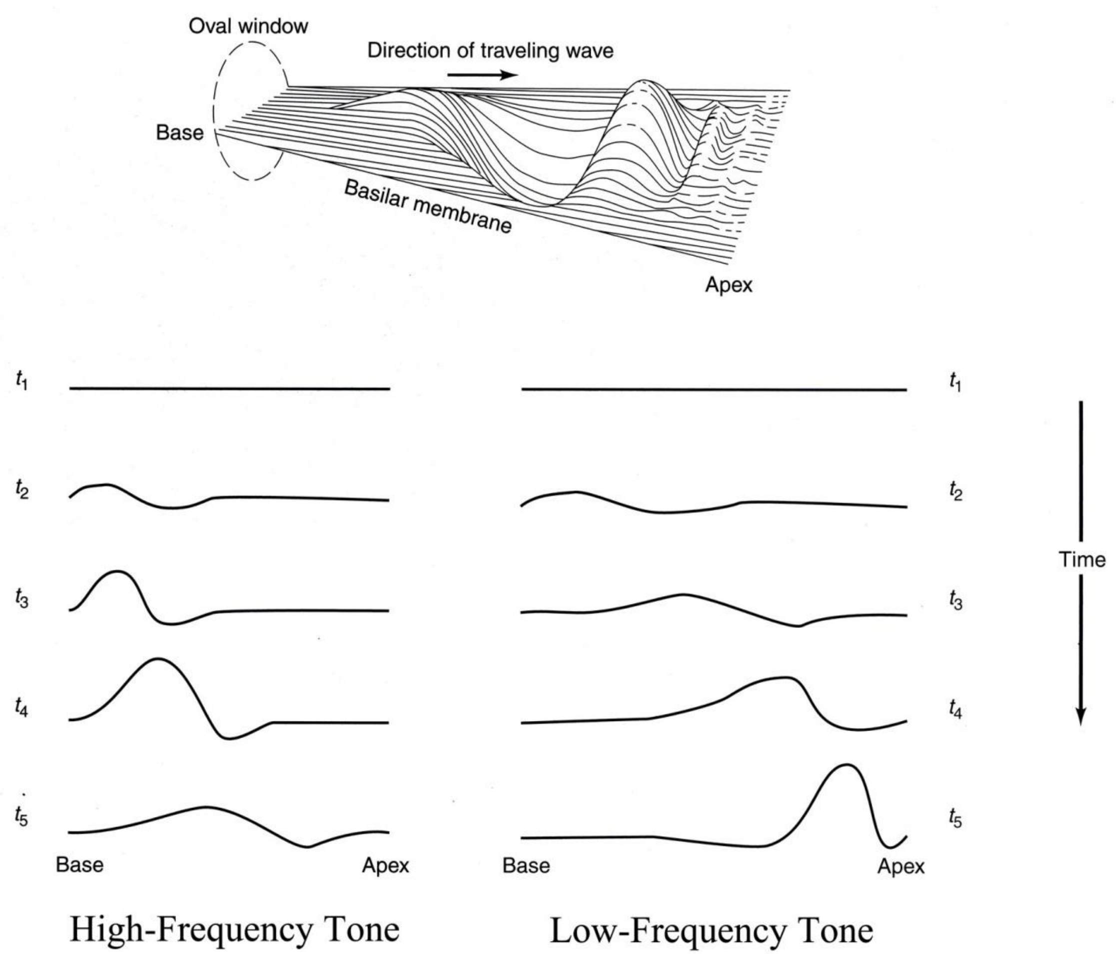
Place Theory

Georg von Békésy
(1899-1972)

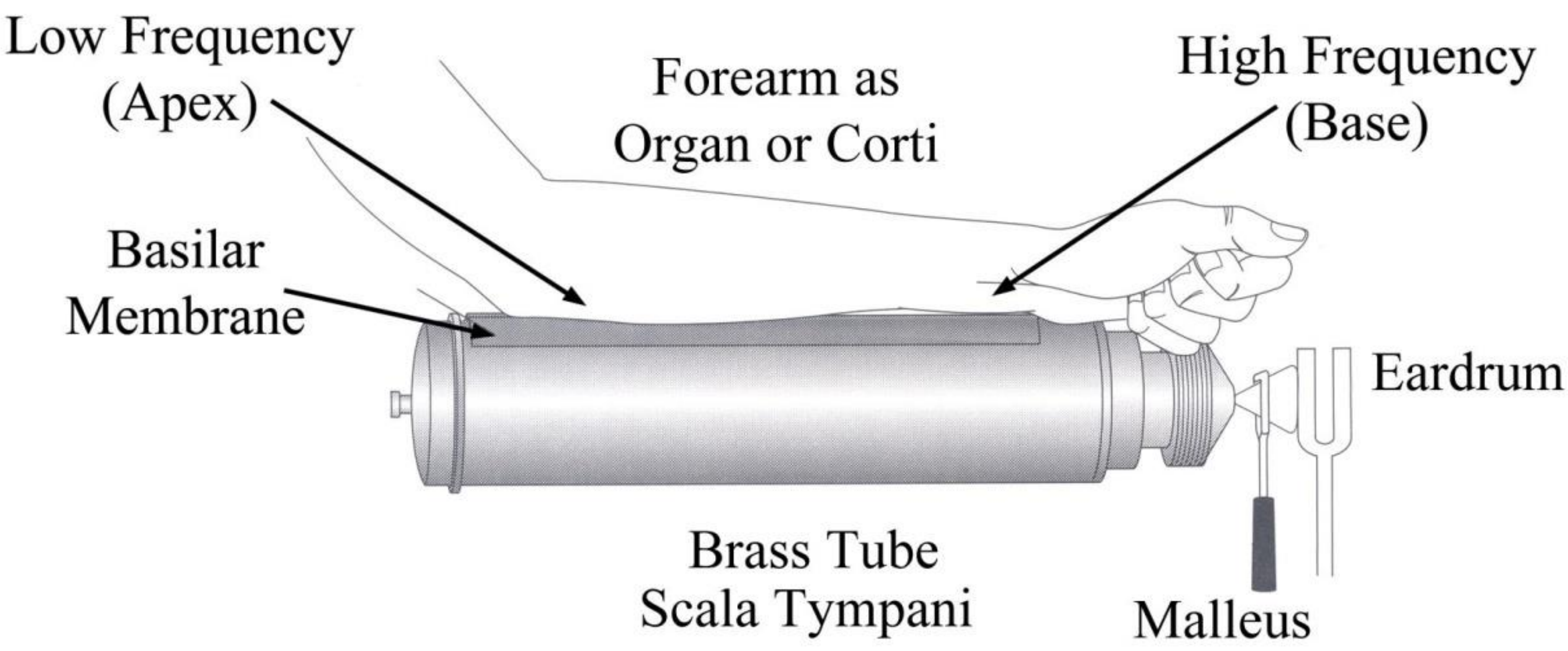
Temporal Theory (Rutherford)

- Basilar membrane analogy to microphone diaphragm
- Each oscillation yields nerve pulse
- Problem: Max. neural response approx. 500 Hz
- Solution: Time division multiplexing
  (aka **"Volley Principle"**)
  Supported by **"cochlear microphonic"**
  (Wever & Bray; but consider *Botox* results)

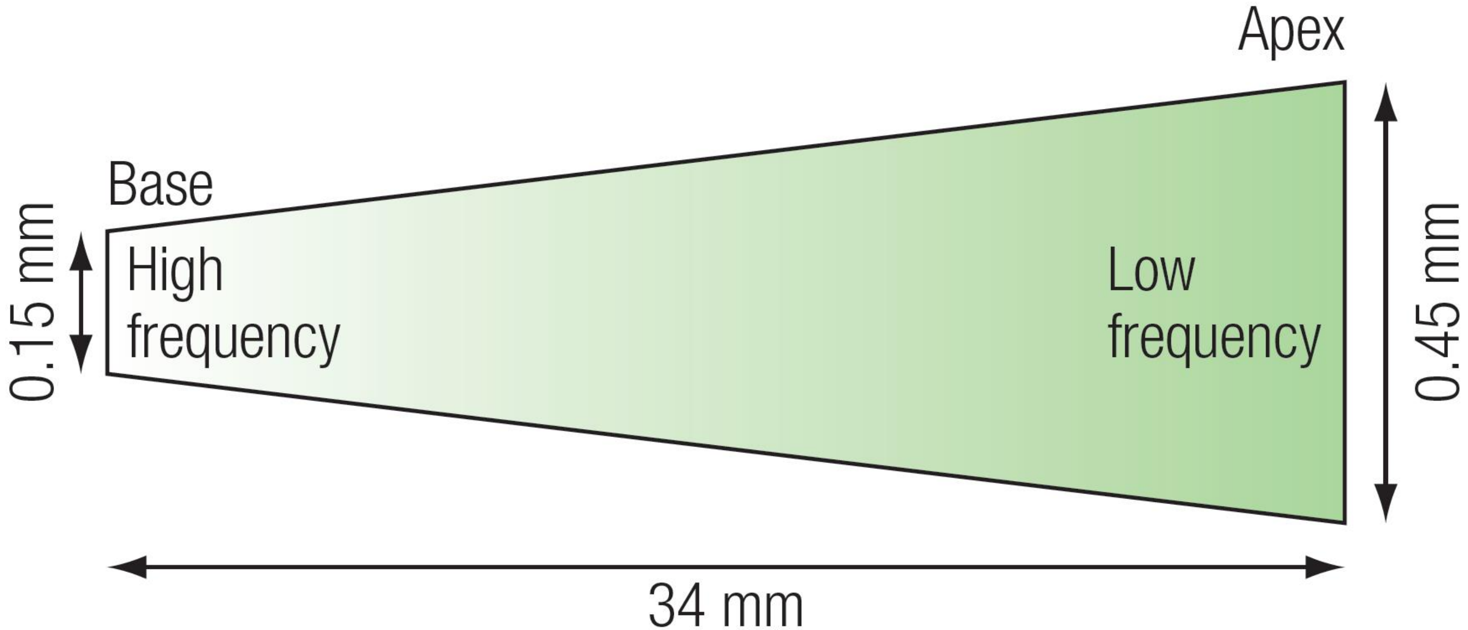
von Békésy Place Theory: Focus on Basilar Membrane Dynamics

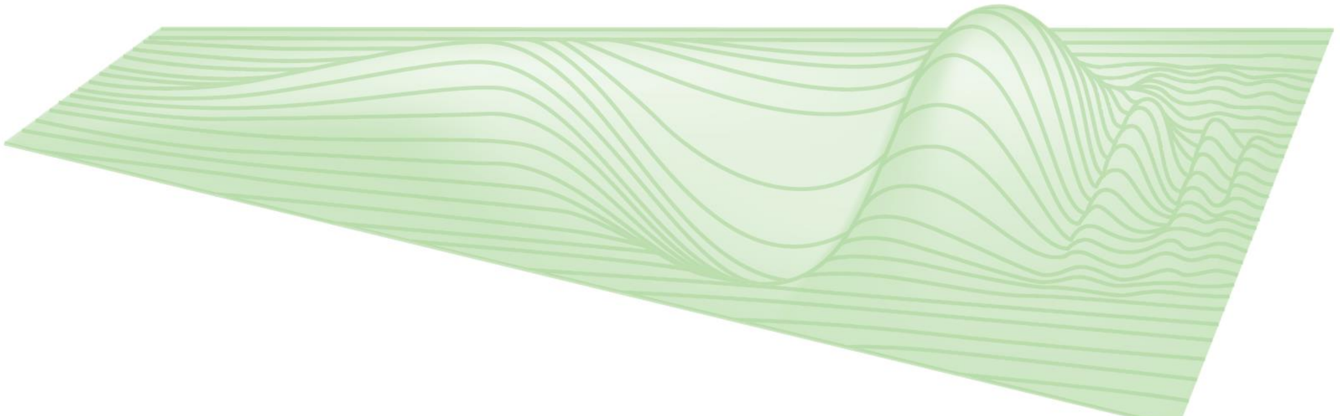


The Simple Beginnings for von Békésy's Nobel Prize

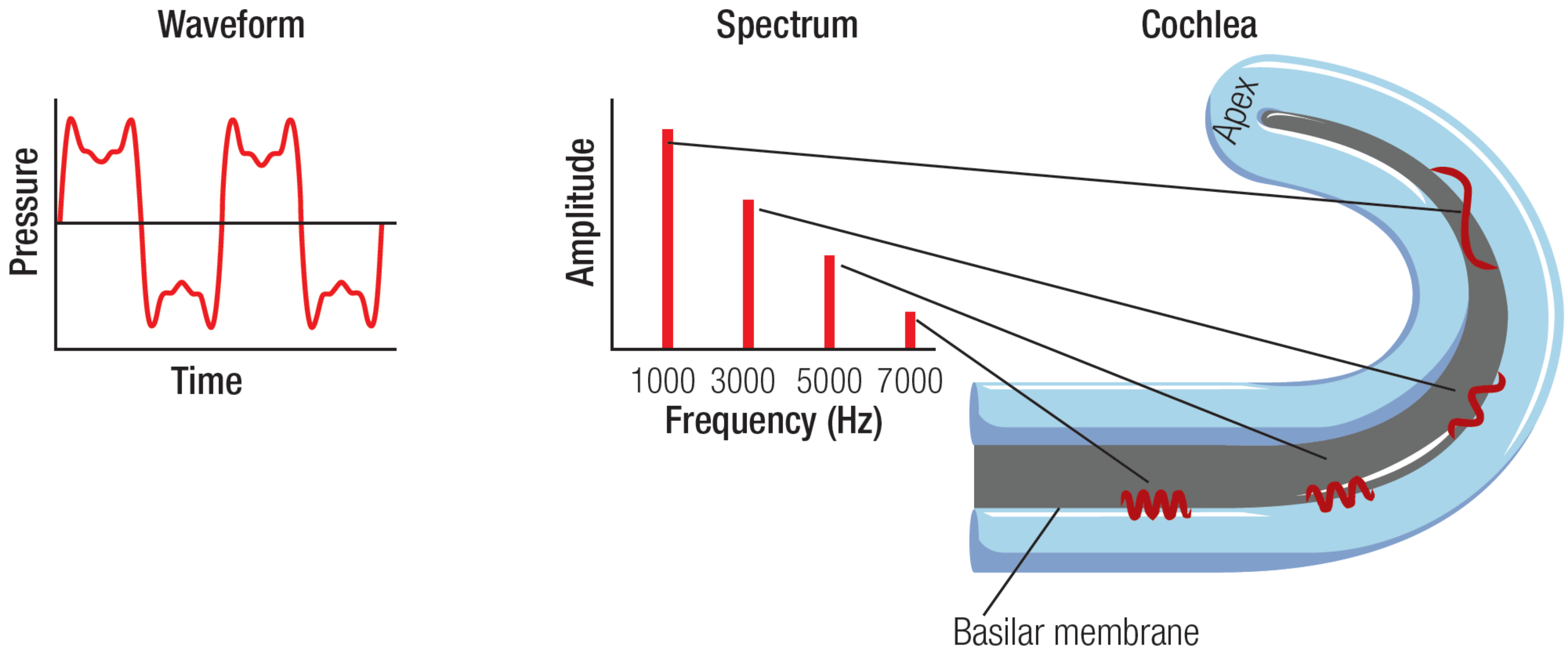


Basilar Membrane Response to Pure Tone Stimulus





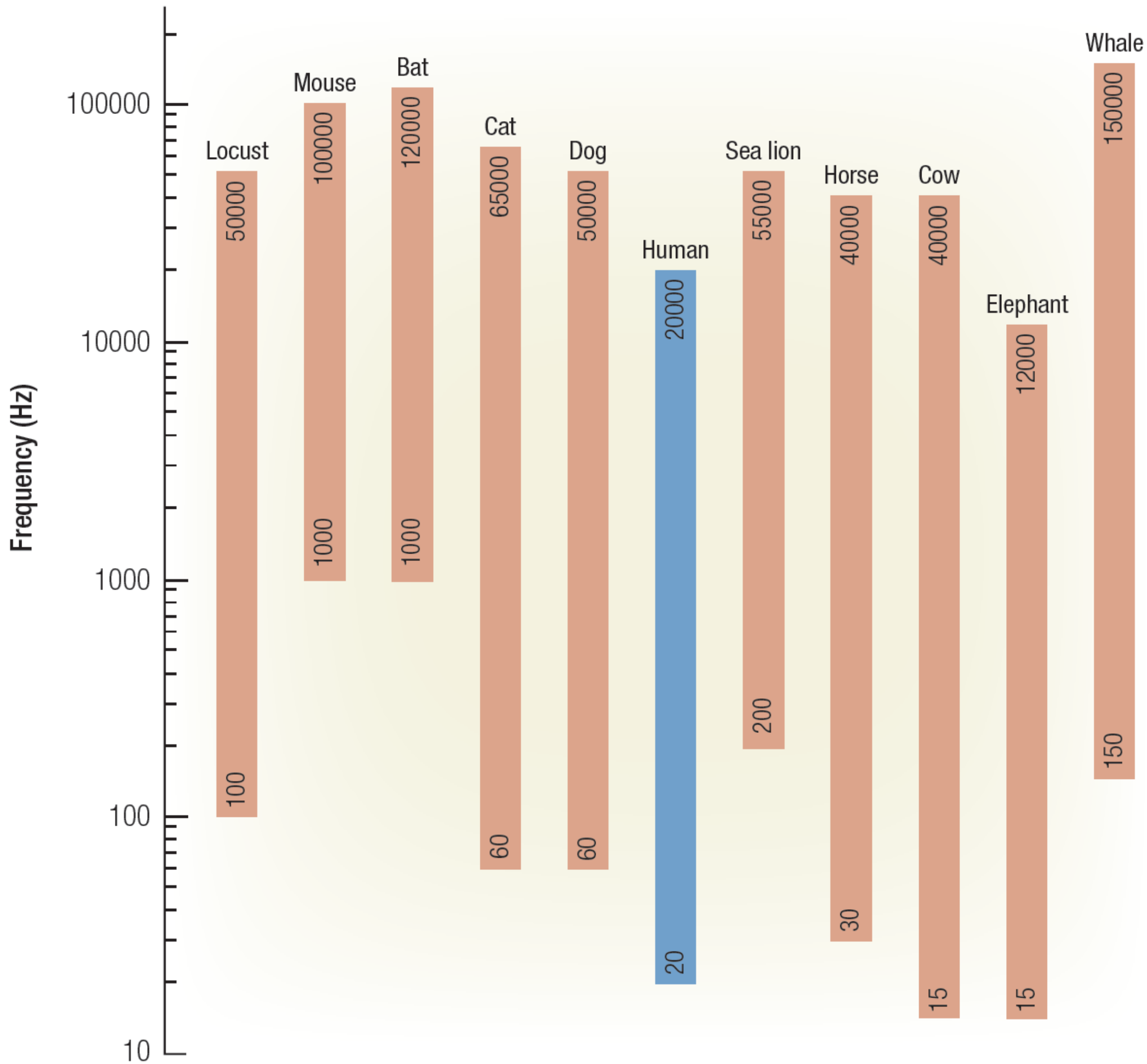
Von Békésy's "Place Mechanism" as Biological Fourier Analyzer



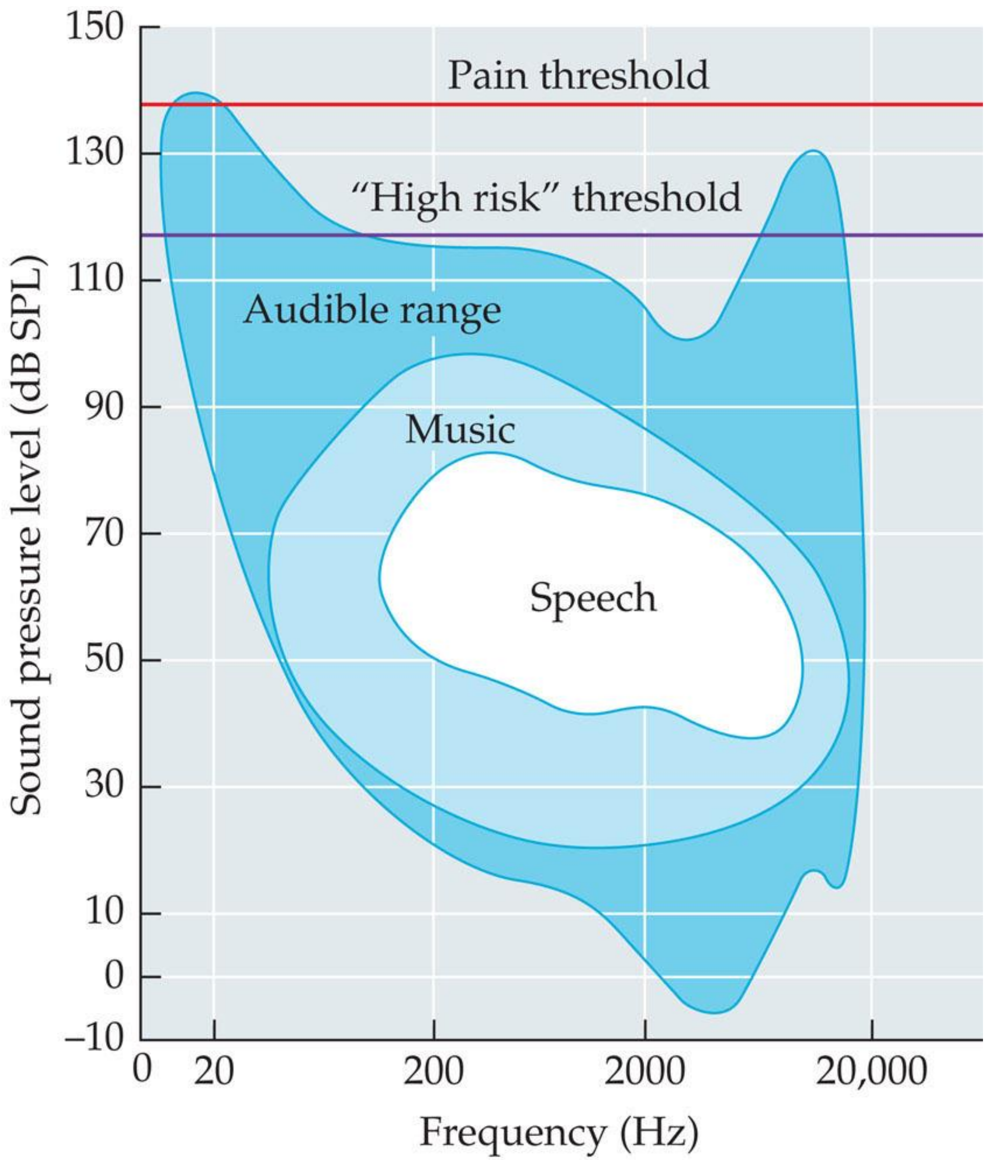
[Basilar Membrane Dynamic Simulation](#)
(animation)

Functional Aspects of Hearing

Species-Specific Frequency Range

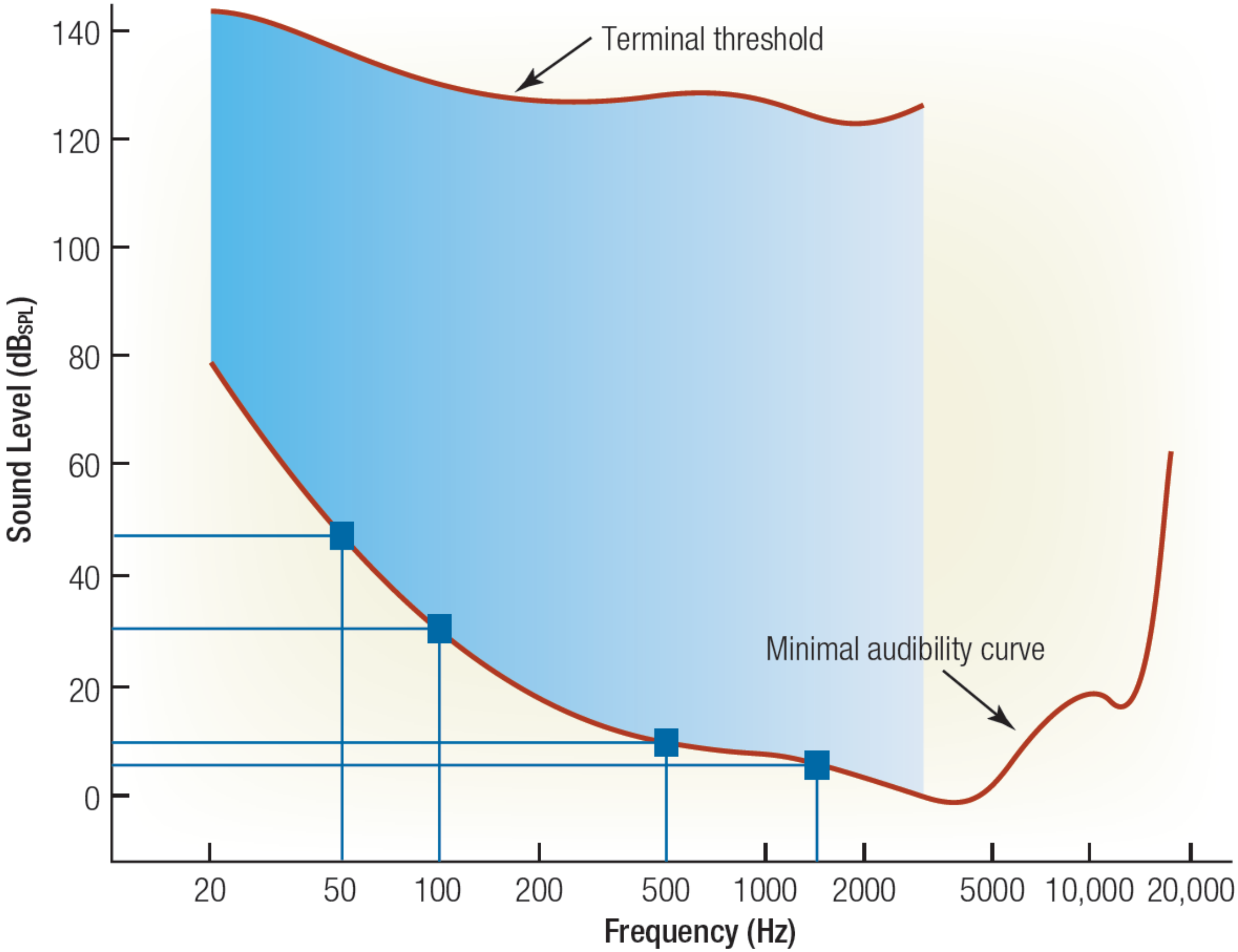


Human "Earscape"



SENSATION & PERCEPTION 4e, **Figure 9.3**

Minimum Audibility Curve

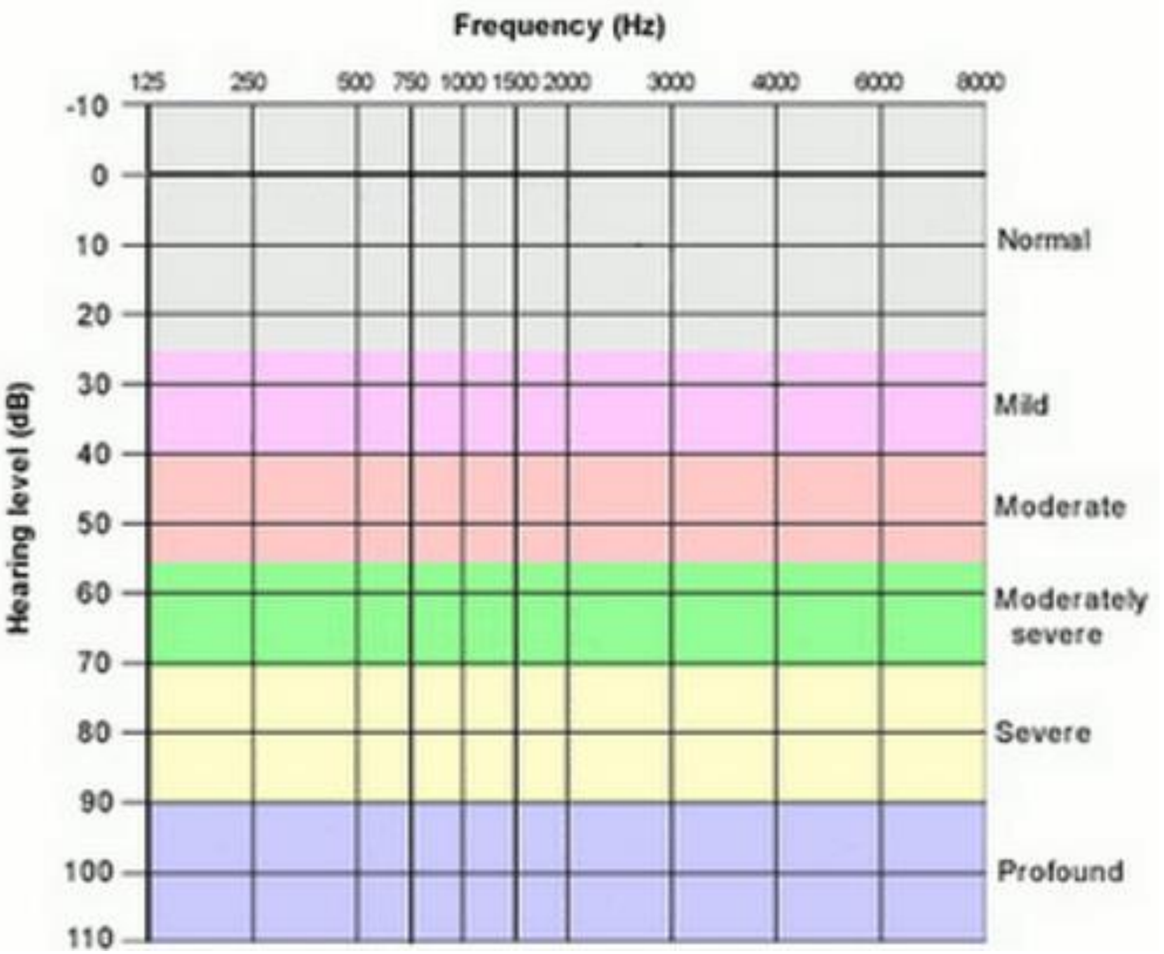


Average detection threshold for 18-yr-olds for 1KHz tone at sea level is **20 microPa (µPa)**

Minimum occurs at approx. 3 KHz

Binaural intensity thresholds are 3 dB lower than mono

Clinical Audiogram (dB_{HL})

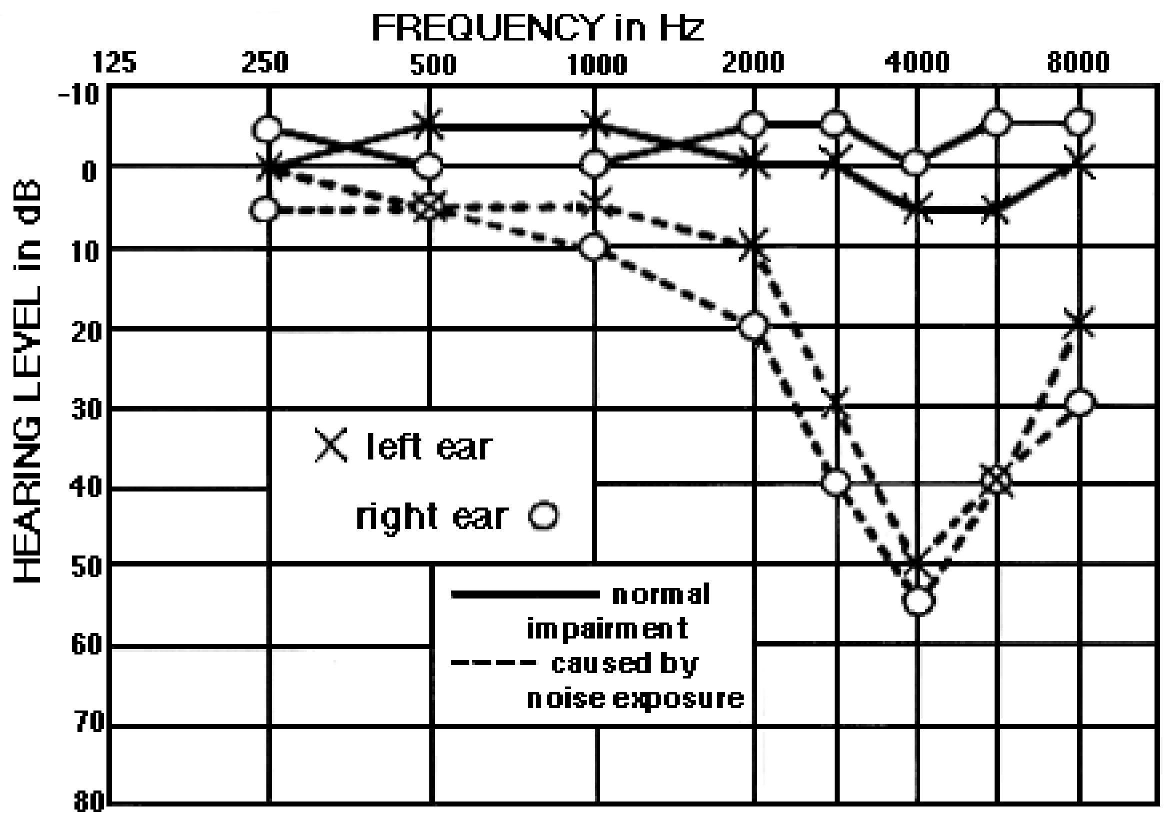


dB-HL (Hearing Level) uses a different reference level for each test frequency.

That reference level represents the average threshold (18 yr-olds) demonstrated at that frequency.

Hence, a value of **0 dB-HL** means "average" hearing level at the frequency under test.

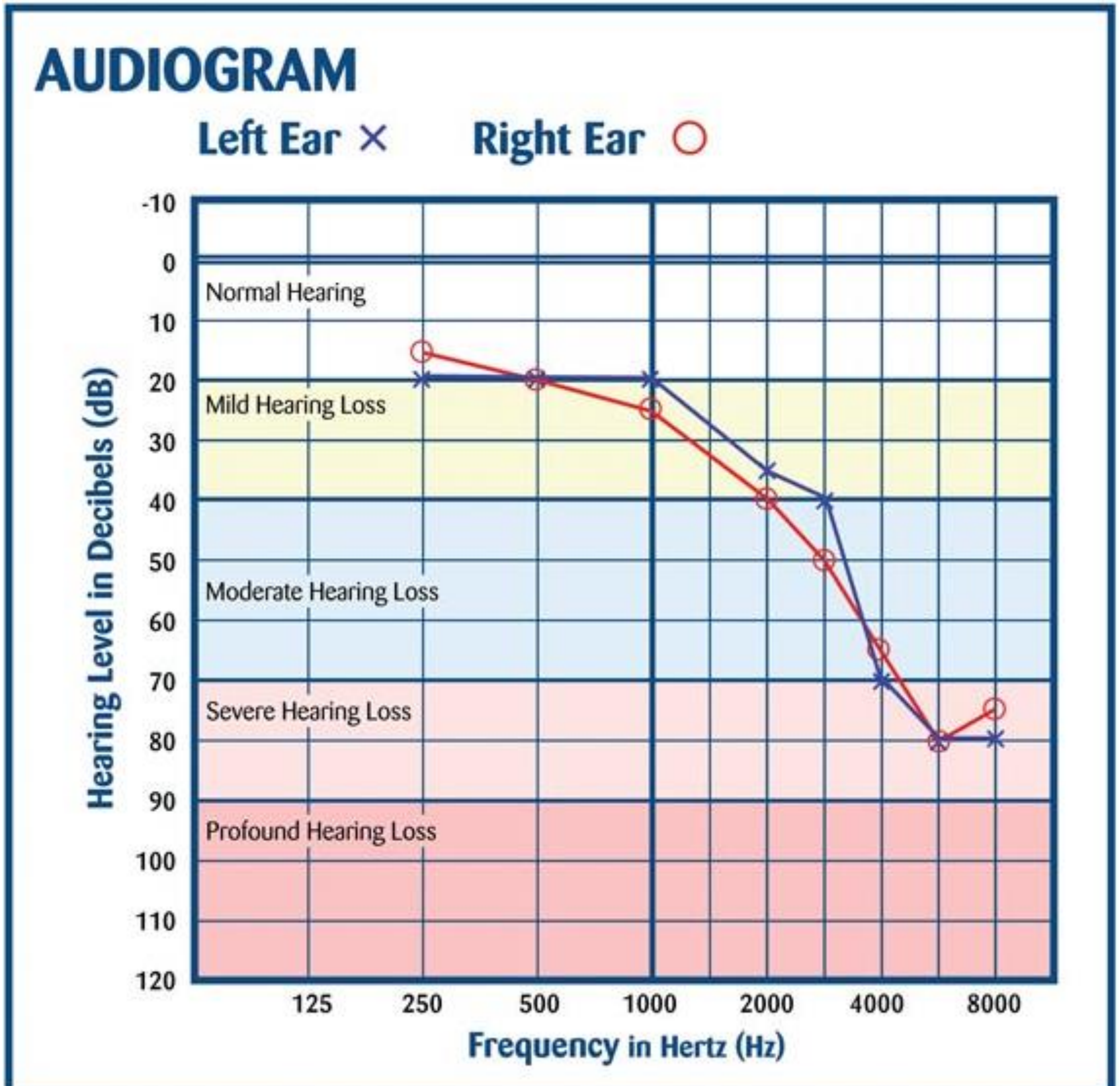
Normal vs. Noise-Induced Hearing Loss



Note "notch"
At 4 KHz.

Source: http://mustelid.physiol.ox.ac.uk/drupal/?q=acoustics/clinical_audiograms

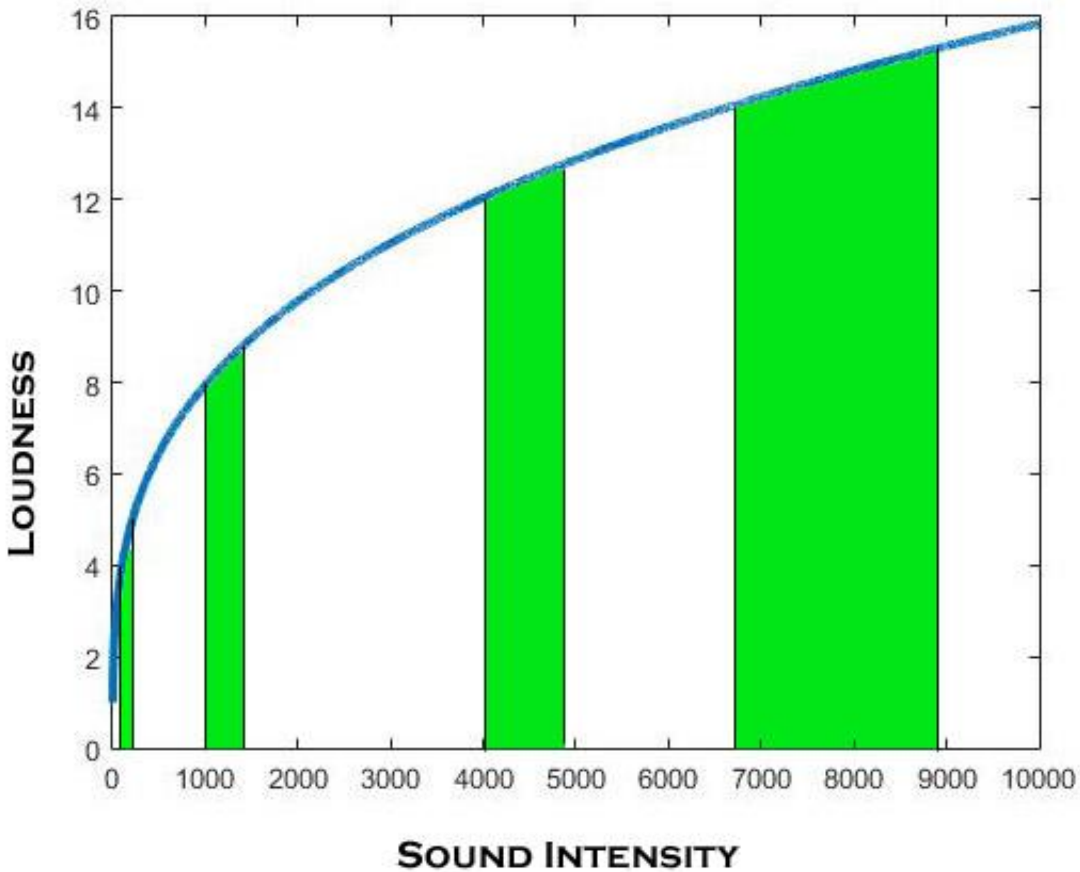
Age-related Hearing Loss (Presbycusis)



Inevitable or preventable?

Loudness

- **Sound Intensity** expresses the physical power of a sound stimulus and is usually measured in units of dB_{SPL}
- **LOUDNESS** represents the subjective experience that varies as a function of sound intensity
- Capturing the nature of this psychophysical relationship is quite complex



Early 20th century research in psychoacoustics demonstrated that the relationship between sound intensity and subjective loudness was <u>highly non-linear</u>

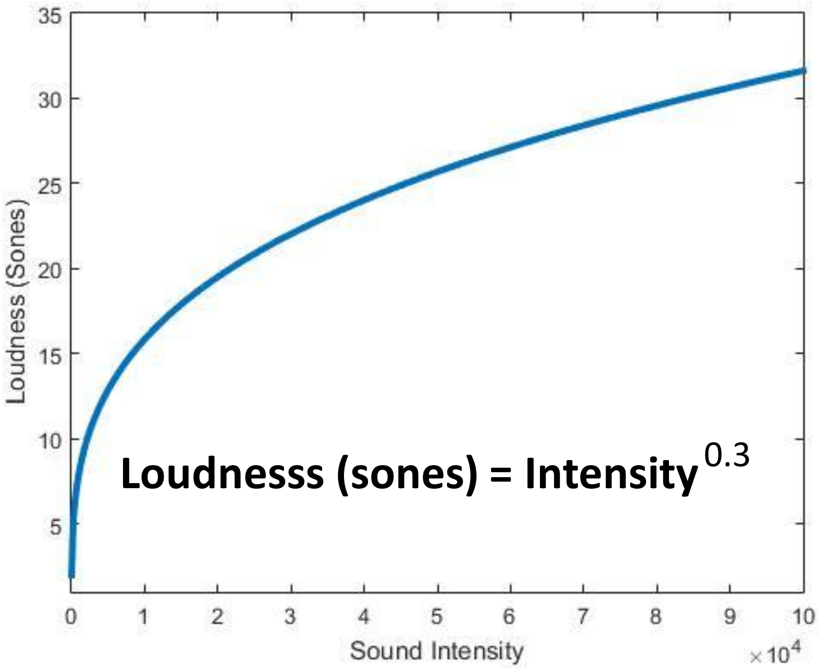
Stevens' Law of Loudness

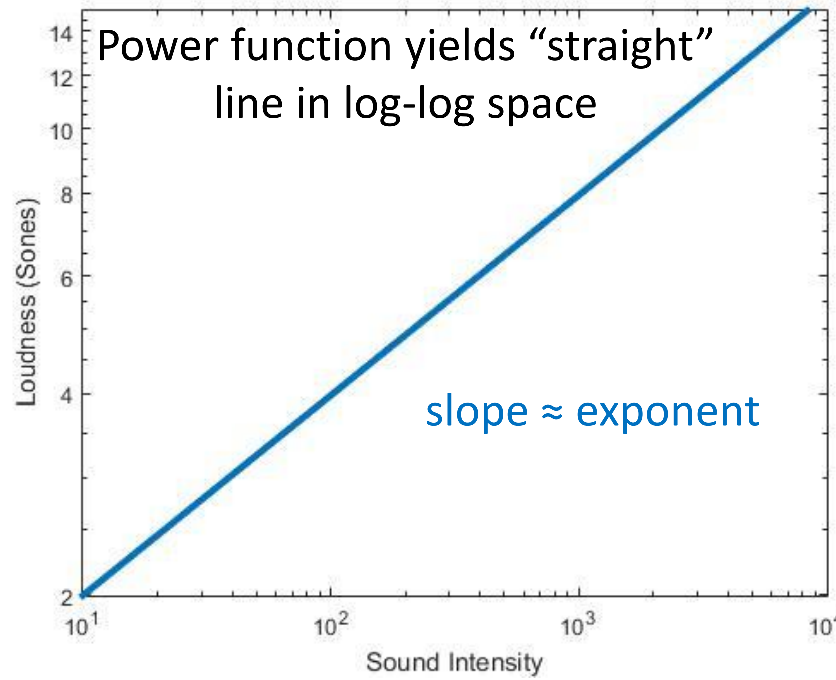
- S.S. Stevens used magnitude estimation techniques to quantify psychological loudness
- This work was based upon subjective comparisons of a range of sound intensities to an arbitrary **reference standard**:

  viz.,
  40 phon = 1 KHz tone @ 40 dB_{SPL}
  1 sone = 40 phon
- **Phon scale** represents the equivalent loudness of a 1 KHz standard tone
- **Sone Scale** models the relationship between phons and psychological loudness on a ratio scale (according to Stevens)

Results of Magnitude Estimation Studies

(Loudness of 1 sone = 40 phon reference)





Quick 'n Dirty Computational Formula:

$$L\ (\text{sones}) = (\text{phons}/40)^{2.86}$$

Stevens' Law:

$$L = I^{0.3}$$

A tone with an equivalent loudness of 60 phons (1 KHz @ 60 dB) = 3.18 sones

$$(60/40)^{2.86} = 3.18$$

Stevens'
Sone Scale of Loudness

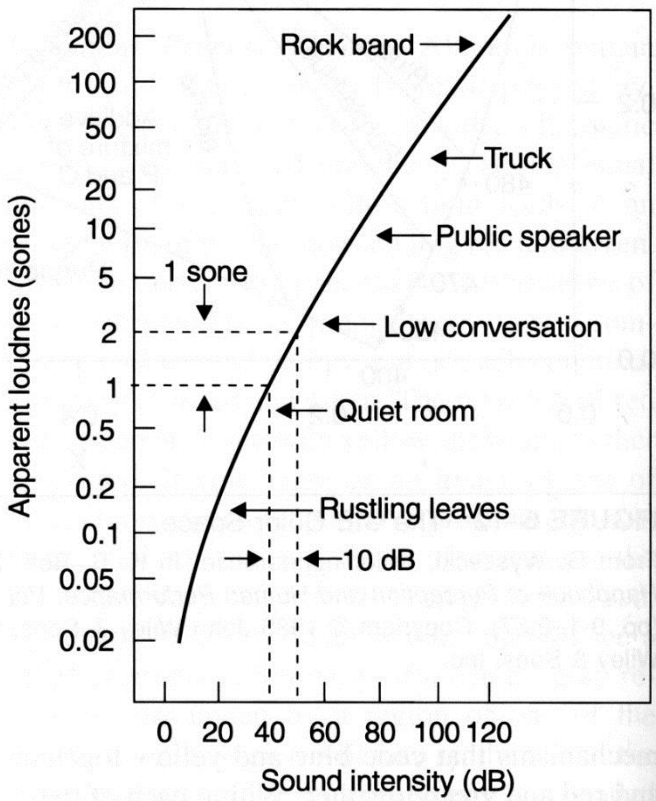


FIGURE 6–13 The Sone Scale of Loudness.
From Stanley Coren and Lawrence M. Ward, *Sensation and Perception*, Third Edition. Copyright © 1989 by Harcourt Brace Jovanovich, Inc. Reprinted with permission.

With some representative stimulus exemplars

In the linear range (40 dB+):
You need to **increase stimulus intensity by 10 dB to double perceived loudness…**

There is a “fly in the ointment” when it comes to modeling and measuring loudness.

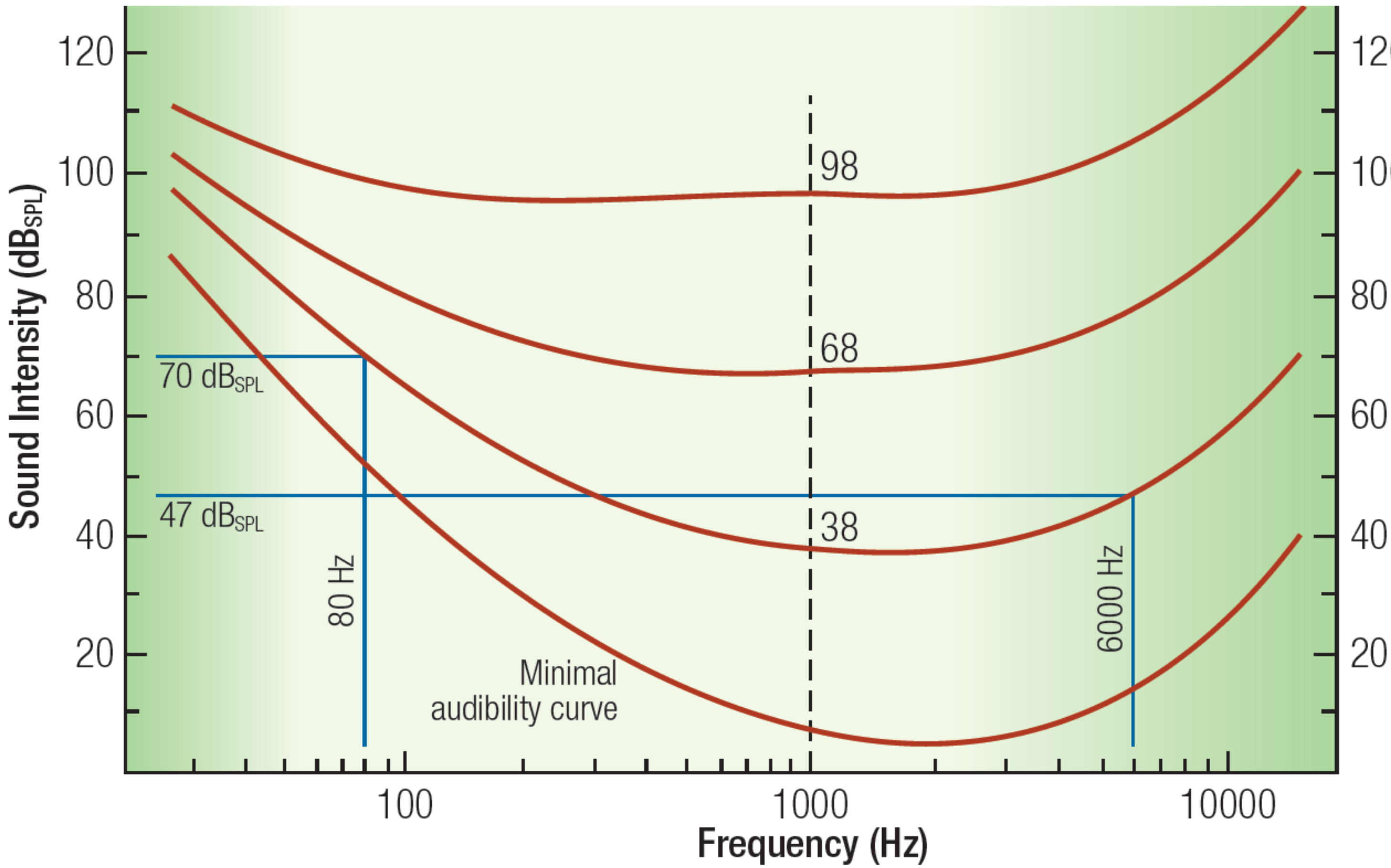
Perceived loudness at a given dB level varies with frequency.

Q: How does one generalize from a model of loudness based upon a 1-KHz standard stimulus to sounds at other frequencies?

A: Apply the Iso-Loudness Contour functions

See next slide …

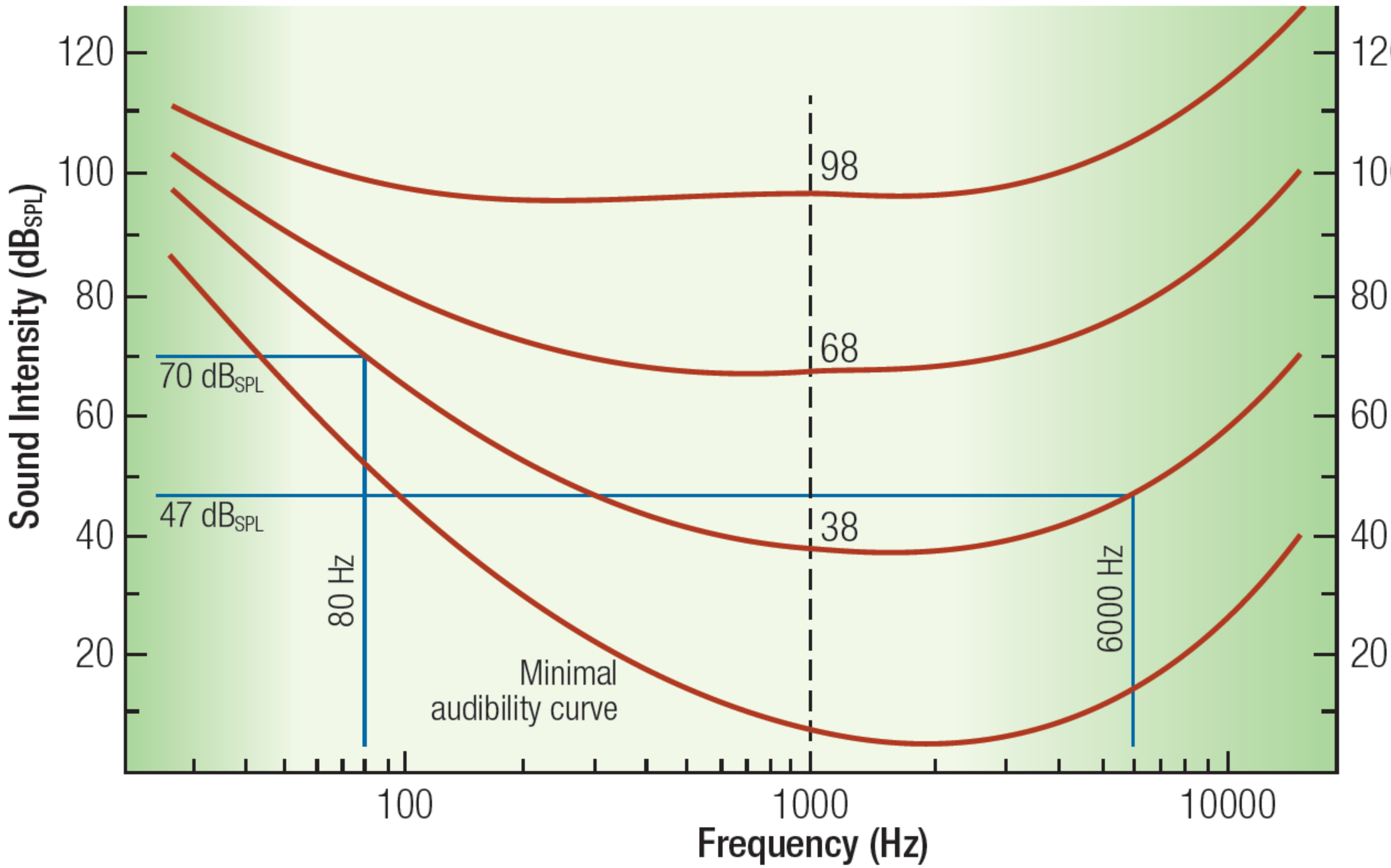
Equal Loudness Contours



Case study:
Background "hum" in sound system = 70 dB @ 80 Hz
What is its loudness in Sones?
(1)Find equivalent loudness in phons.
(2) Convert phons to sones using Stevens' Law

$$L_{SONES} = (L_{PHONS}/40)^{2.85}$$
$$= (38/40)^{2.85}$$
$$= 0.86$$

Equal Loudness Contours



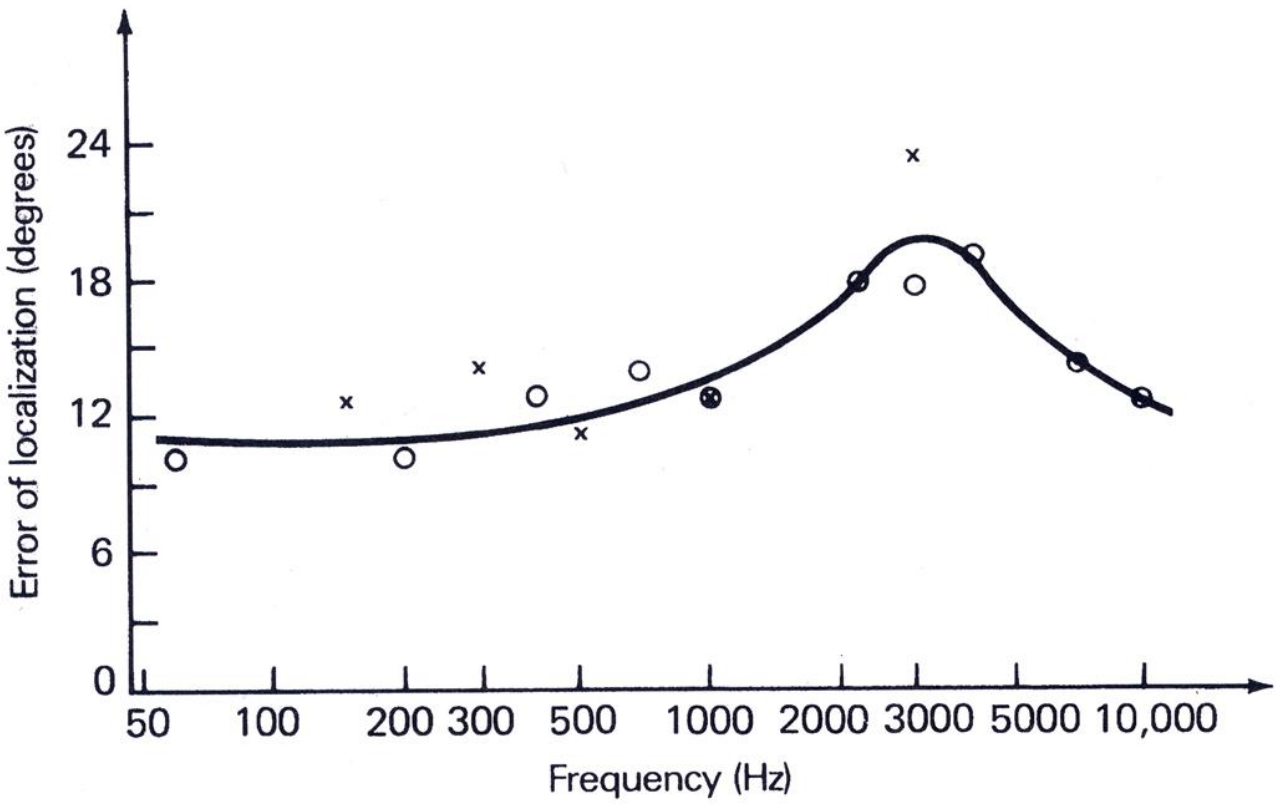
Frequency differentiation is flattened at high amplitudes; Speech and music sounds “tinny” at high loudness levels; Remember change in cochlear nerve tuning at higher intensity levels.

Sone Scale Landmarks

Normal conversation	1-4
Automobile @ 10m	4-16
Vacuum cleaner	16
Major roadway @ 10 m	16-32
Long-term hearing damage dosage	32+
Jackhammer @ 1m	64
Brief-exposure hearing damage	256
Pain threshold	676

Sound Localization

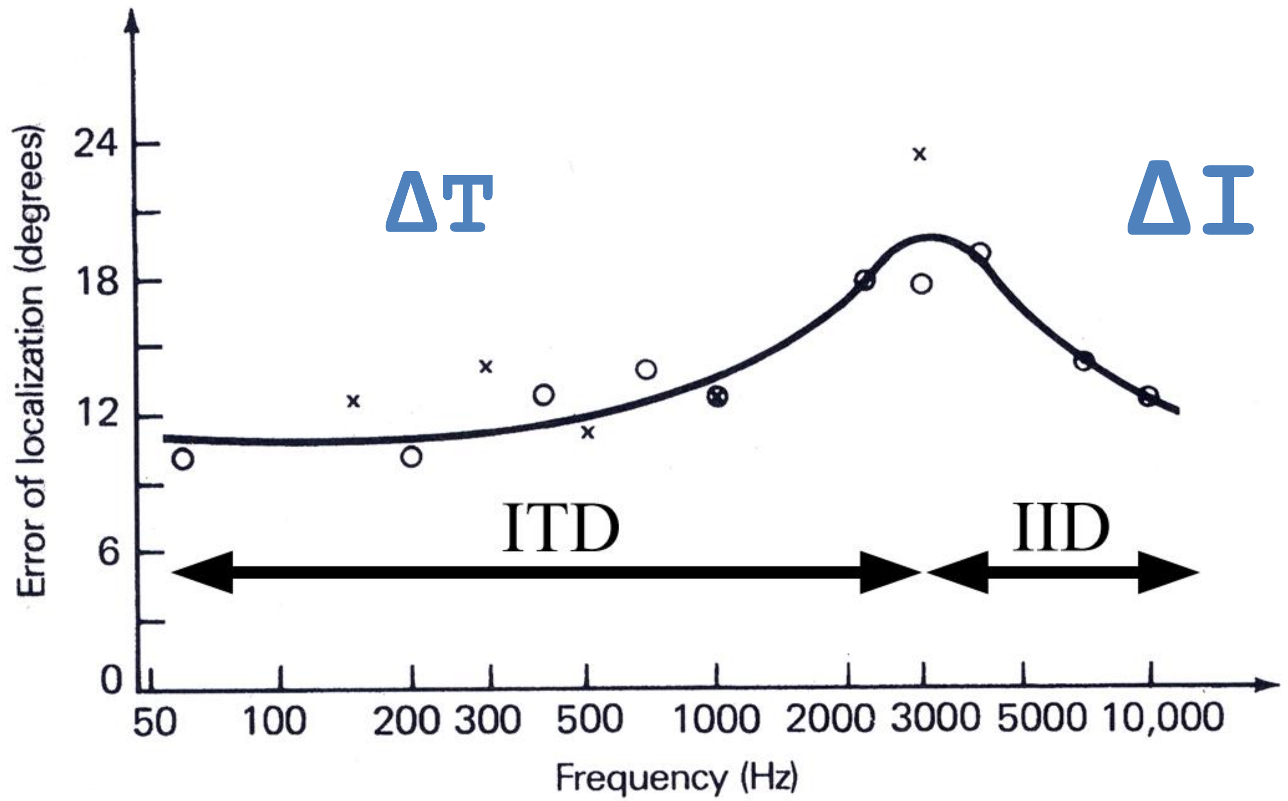
Localization Accuracy vs. Frequency



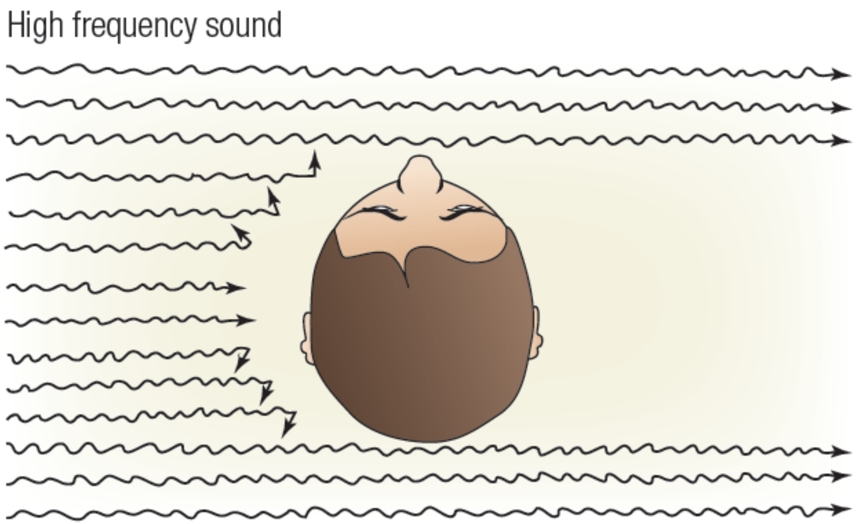
Signature of a dual-mechanism process?

Localization Accuracy vs. Frequency:

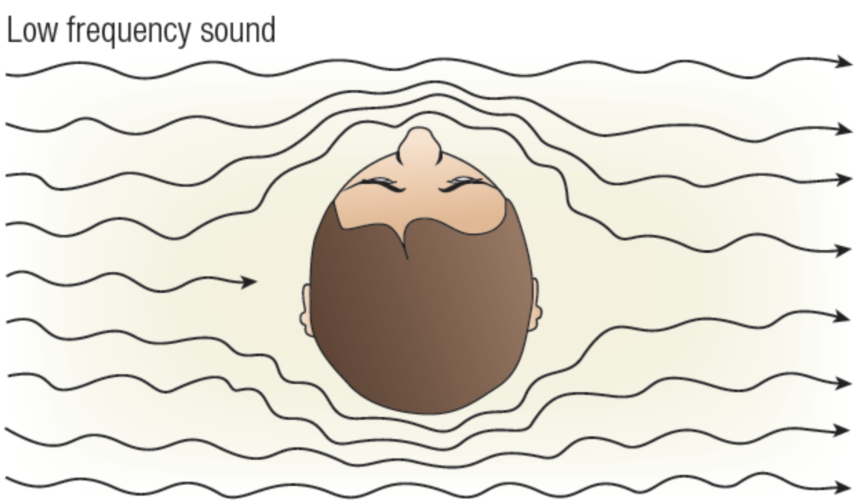
Low Freq – Interaural Time Difference
High Freq – Interaural Intensity Difference



Sound Shadowing
(Interaural Intensity Difference –IID)



High-frequency sound waves are “blocked” by the human head and cast a “shadow” at the far ear **(Strong IID cue)**

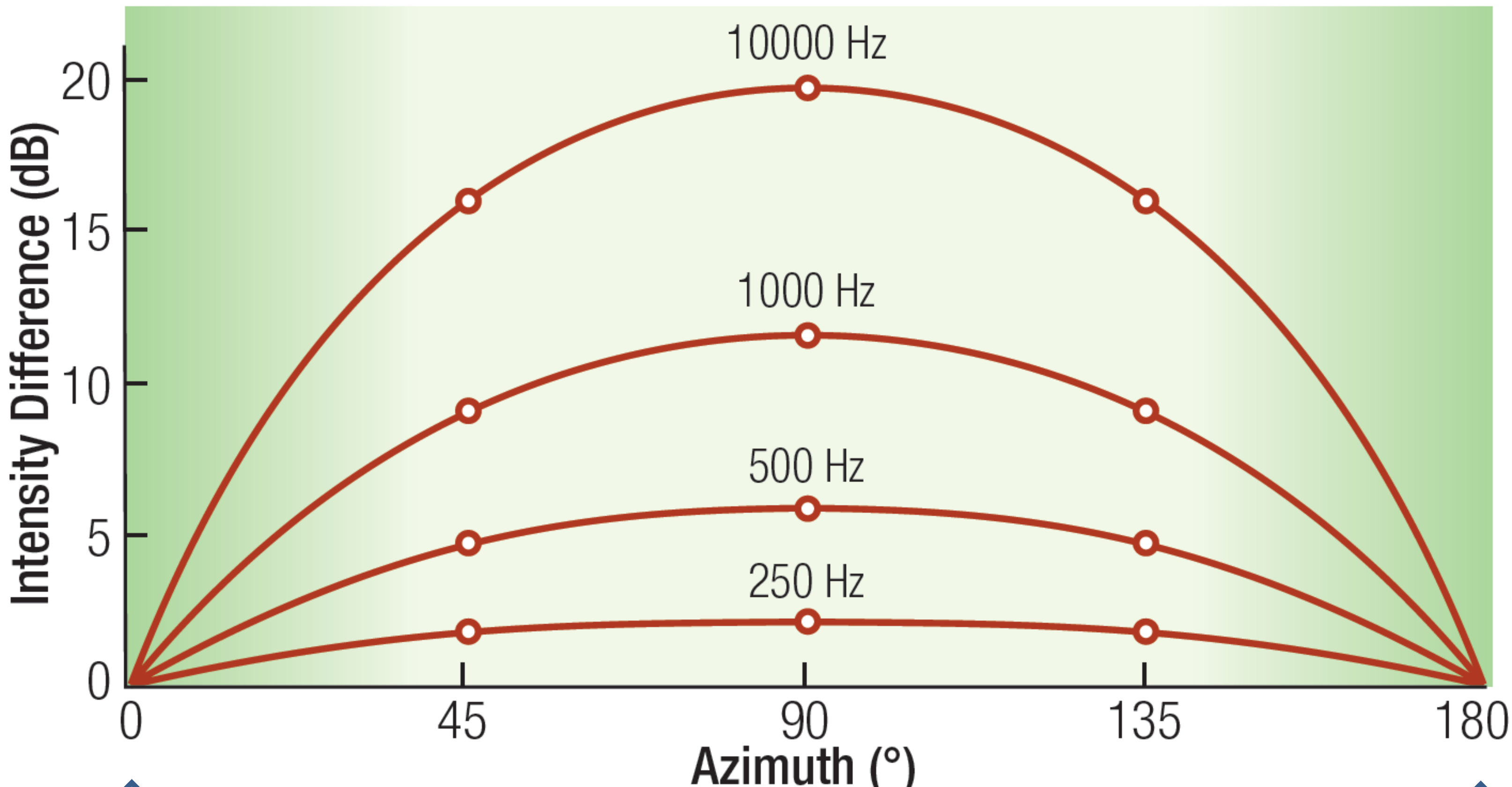


Low-frequency sound waves wrap easily around the head and cast little or no sound shadow **(Weak IID Cue)**

ΔI

IID = f(Location, Frequency)

ΔI



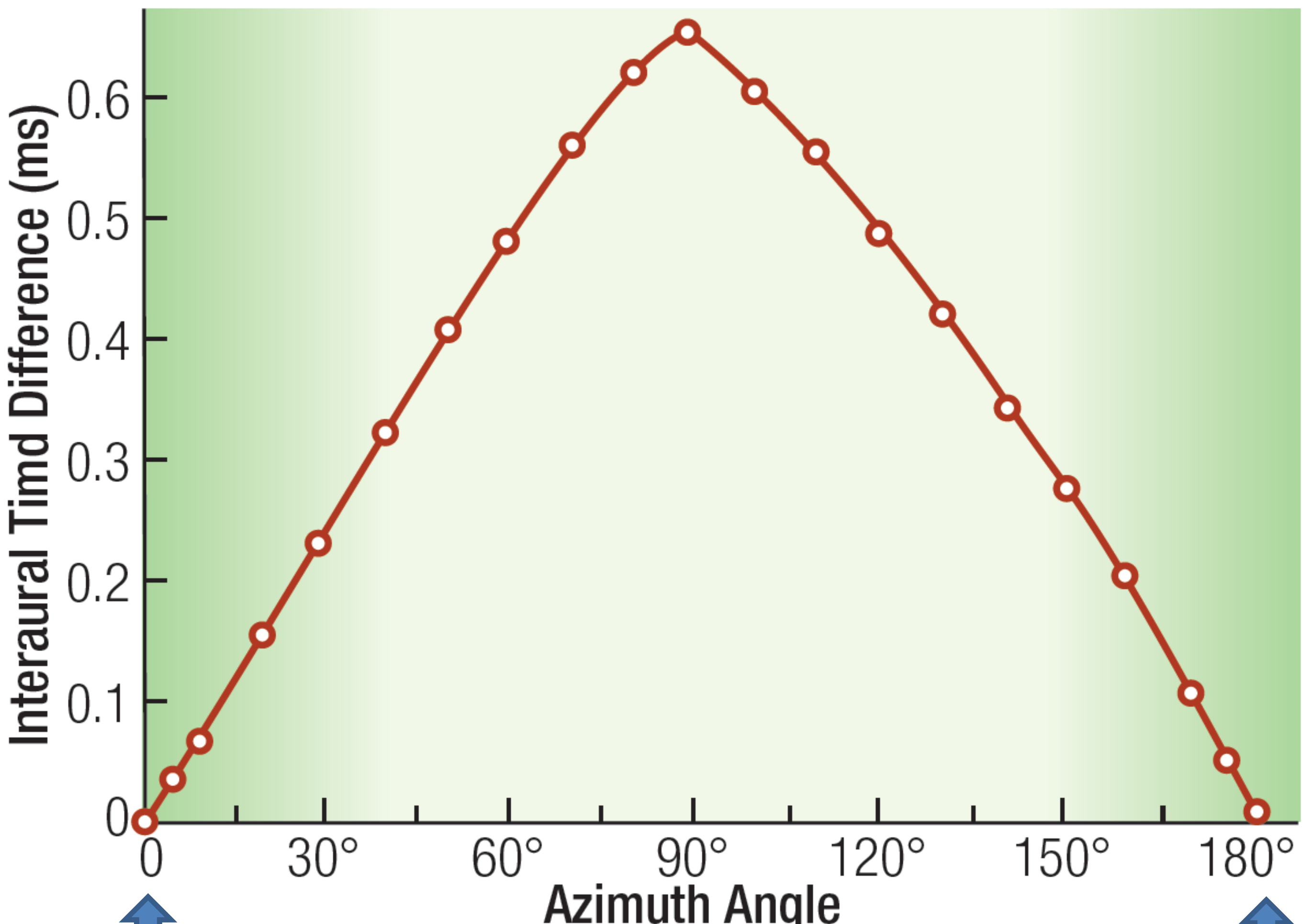
Straight Ahead

Right Ear (Perpendicular)

Straight Behind

ITD versus Location

ΔT



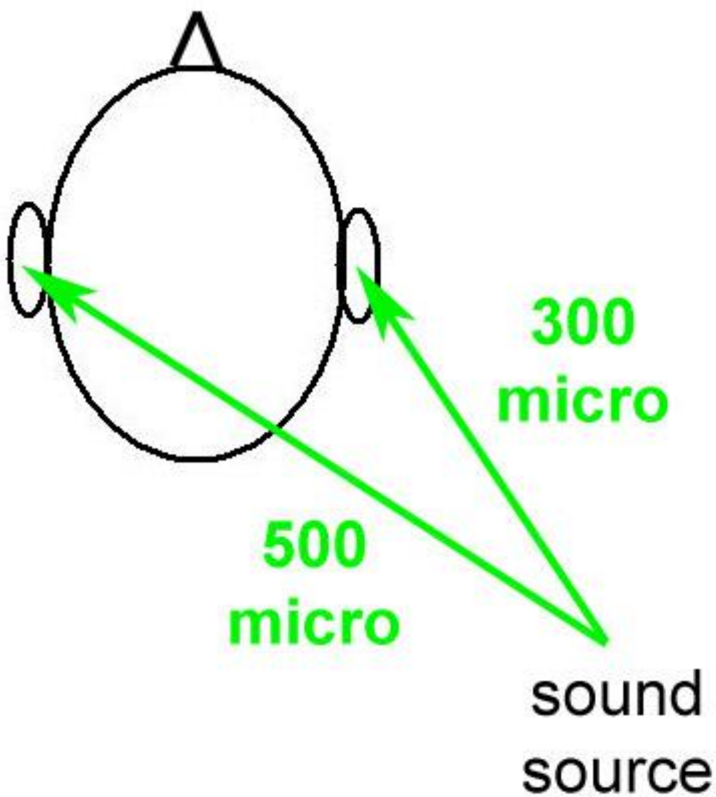
Straight Ahead

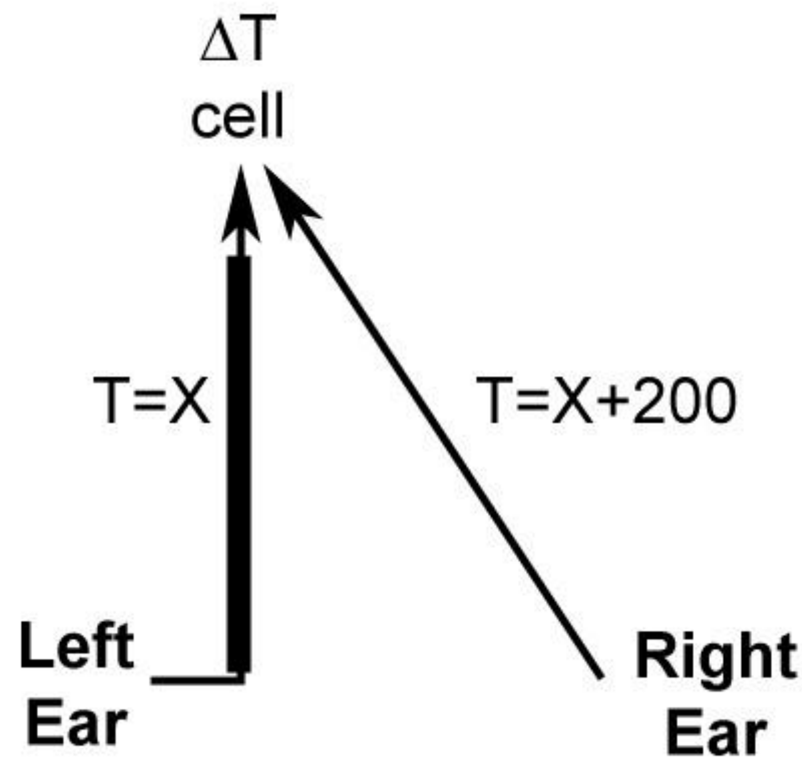
Right Ear (Perpendicular)

Straight Behind

Delay Line Theory

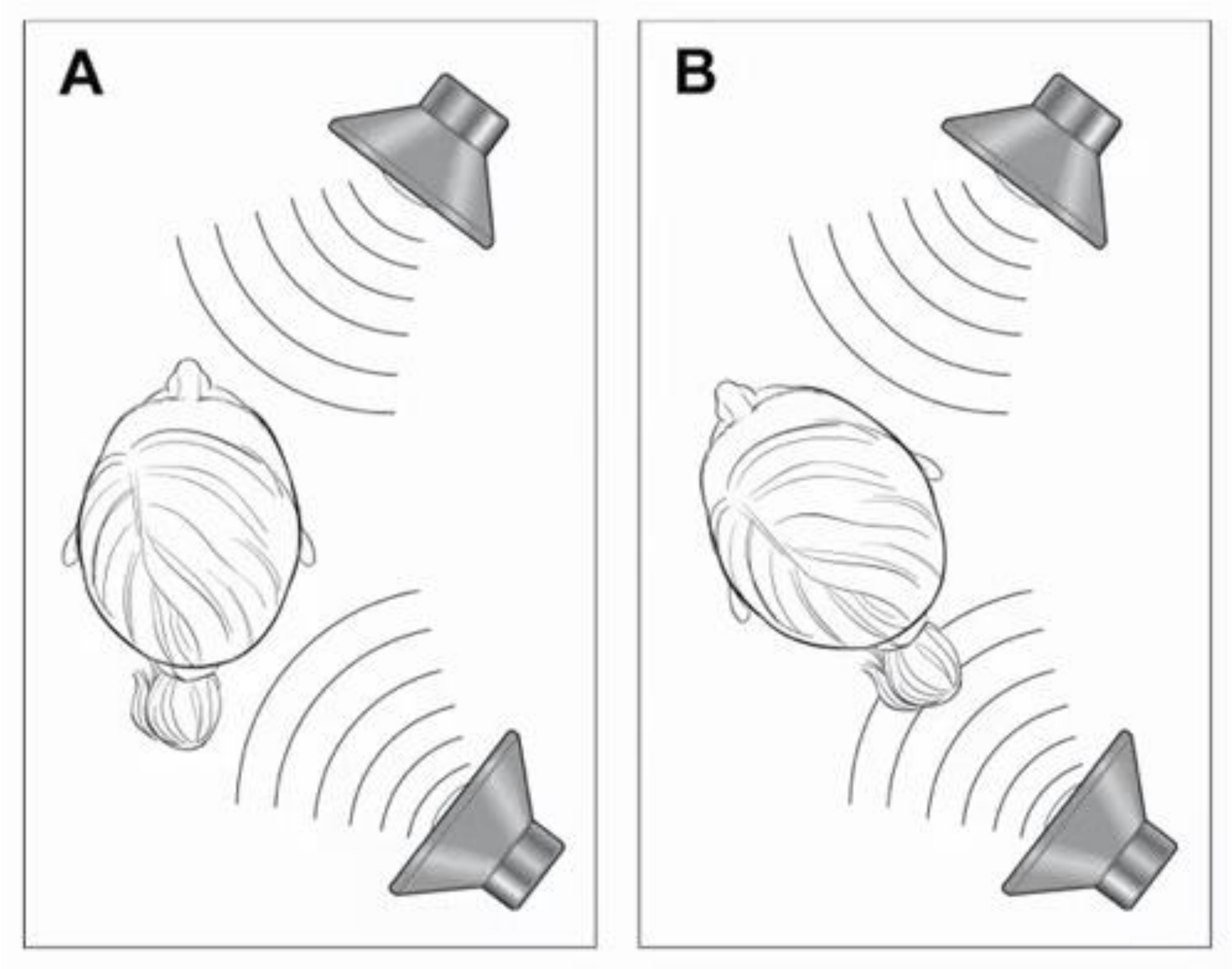
(How to Build a Cell tuned to delta-T Signals)





Delta-T = 200 microsec

“Active” Localization
(Continuous Sound Sources)



Straight Ahead vs. Straight Behind

Relatively good localization performance despite same IID and ITD levels (i.e., zeros)

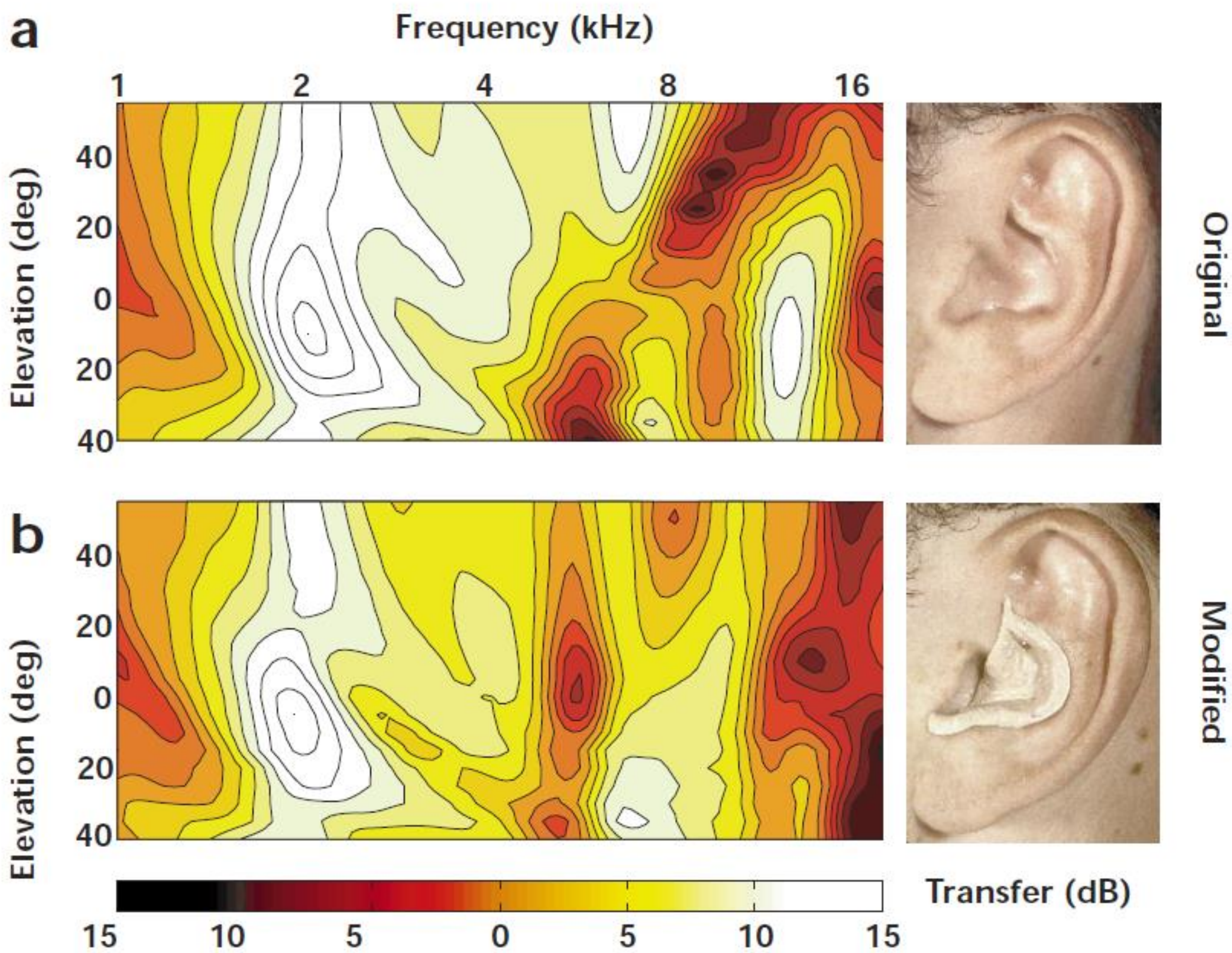
Differential sound distortion ("coloration") introduced by interaction with pinna

Modifying shape of pinna causes immediate reduction in localization accuracy (Hoffman, et al., 1998)

Listening through the ears of another yields "ahead" vs. "behind" confusion (chance performance)

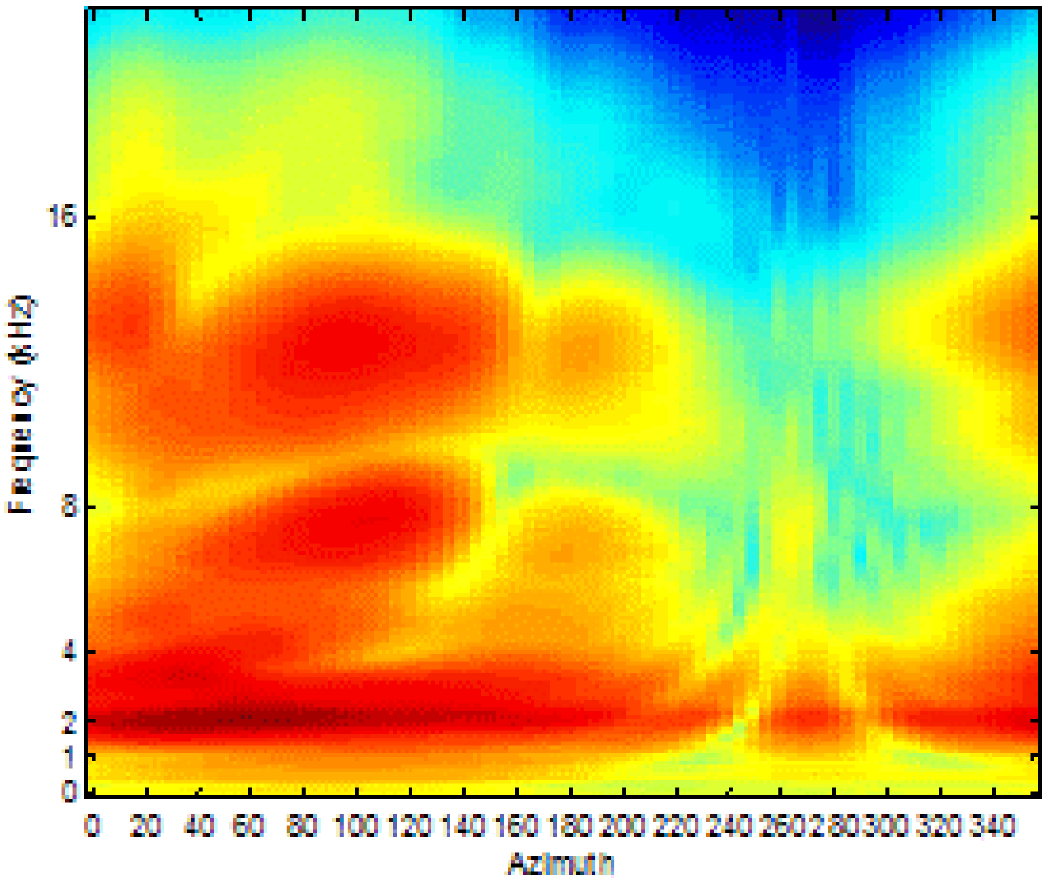
Modifying the Pinna Transfer Function

(Hoffman, et al., 1998) **Earprints?**



Cross-Section of a Head-Related Transfer Function

(Spectral Coloration by Head, Torso & Pinnae)



Auditory/Visual Integration

Ventriloquism Effect
Visual capture of sound localization

McGurk Effect
"Compromise" between conflicting sound and visual cues in speech understanding

What you hear is what you see

Problem capturing this video for online lecture so see the link below

Visit:
http://www.michaelbach.de/ot/mot_bounce/index.html
to see how sound effects can influence what we see