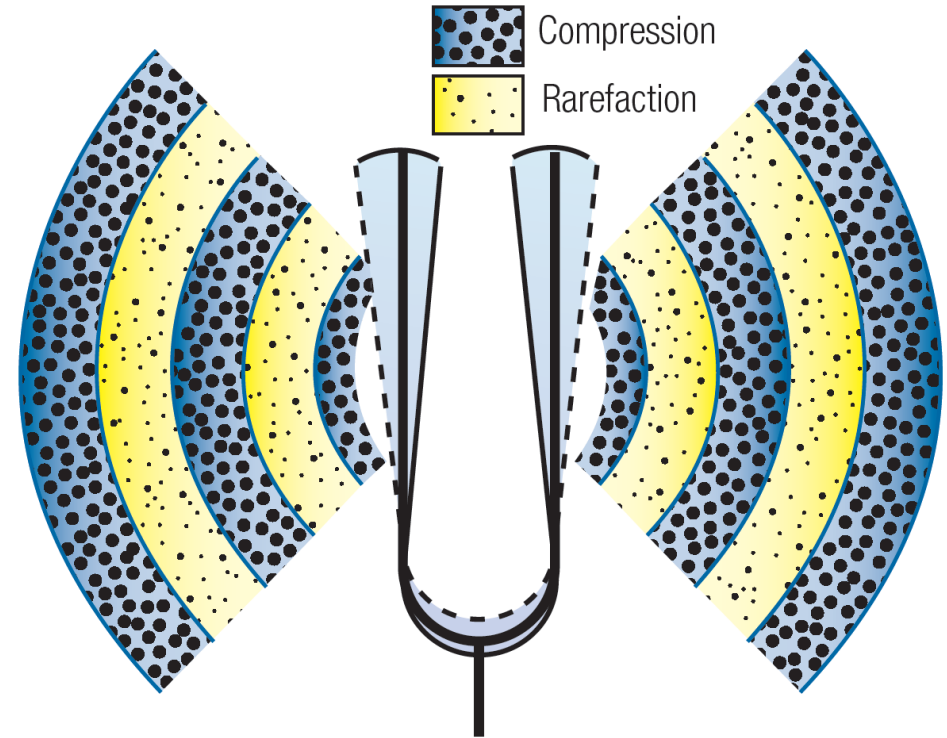
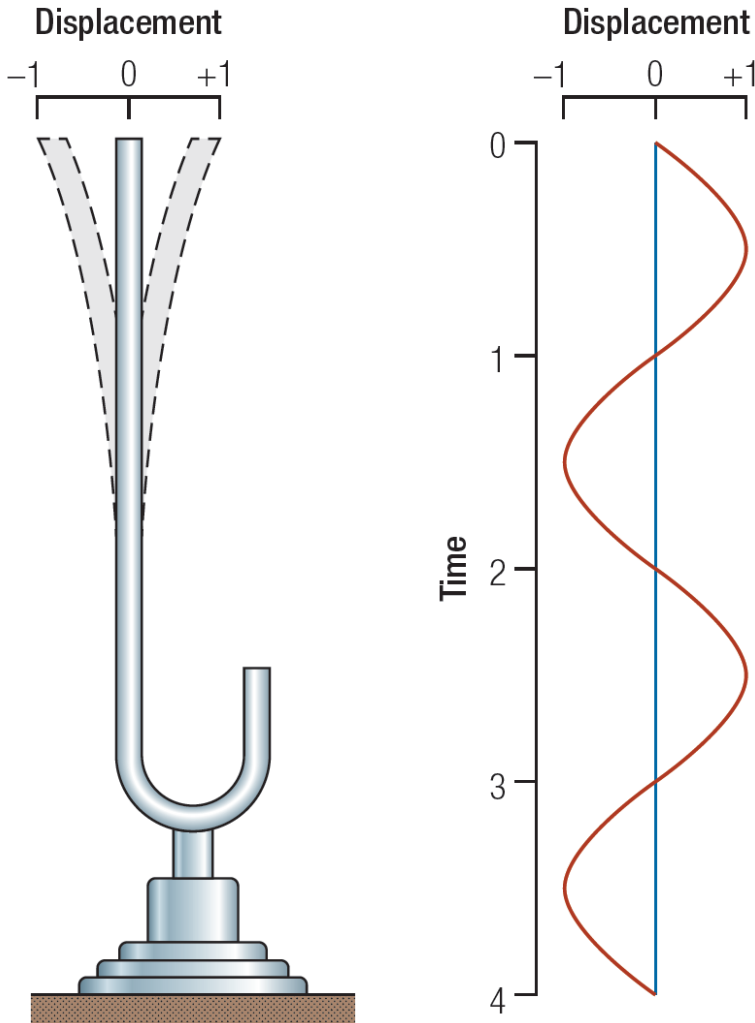


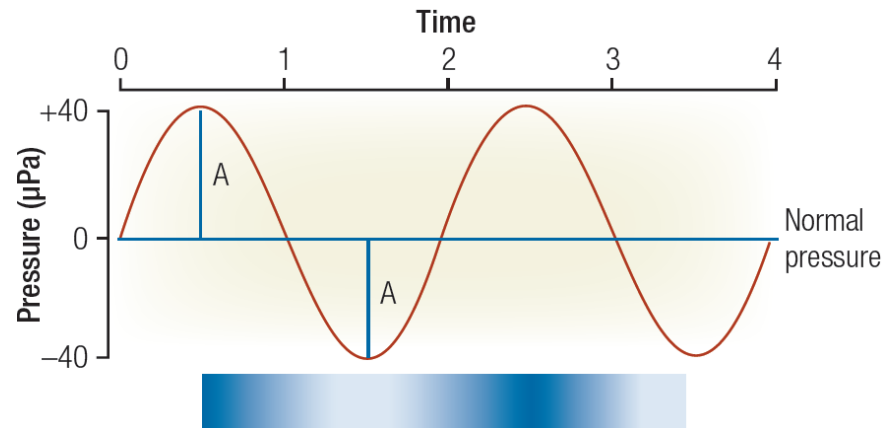
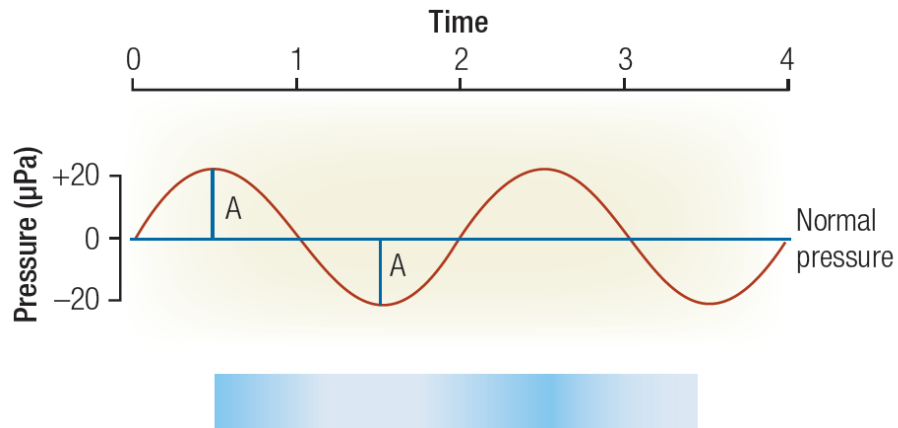
Sound and Hearing

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/m²

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).

$$\text{dB} = 10 \log(\text{Observed Power} / \text{Reference})$$

dB_{SPL}

The transducers (microphones) on sound level meters measure sound **pressure** (i.e., N/m² or Pascals).

Pressure needs to be converted to **power** prior to calculation of the decibel equivalent....i.e., **acoustic power = pressure²**

Finally, we need to agree upon a **Reference value**.

By convention, we use **20 microPa** (i.e., the hearing threshold)

Thus:

$$\text{dB} = 10 \log (\text{Observed Pressure}^2 / 20 \text{ microPa}^2)$$

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:

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

+6 **dB_{SPL}** = doubling sound pressure

+20 **dB_{SPL}** = 10x pressure

+3 **dB_{SIL}** = doubling acoustic power

+10 **dB_{SIL}** = 10x acoustic power

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 $1 \text{ dB}_{\text{SPL}}$ for most of normal range of hearing
- **What does $0 \text{ dB}_{\text{SPL}}$ mean?**

Hint: $20 \log (20 \text{ microPa}/20 \text{ microPa}) = 0 \text{ dB}_{\text{SPL}}$

- If one machine emits $80 \text{ dB}_{\text{SPL}}$ then how much sound amplitude would be expected from two machines side-by-side?

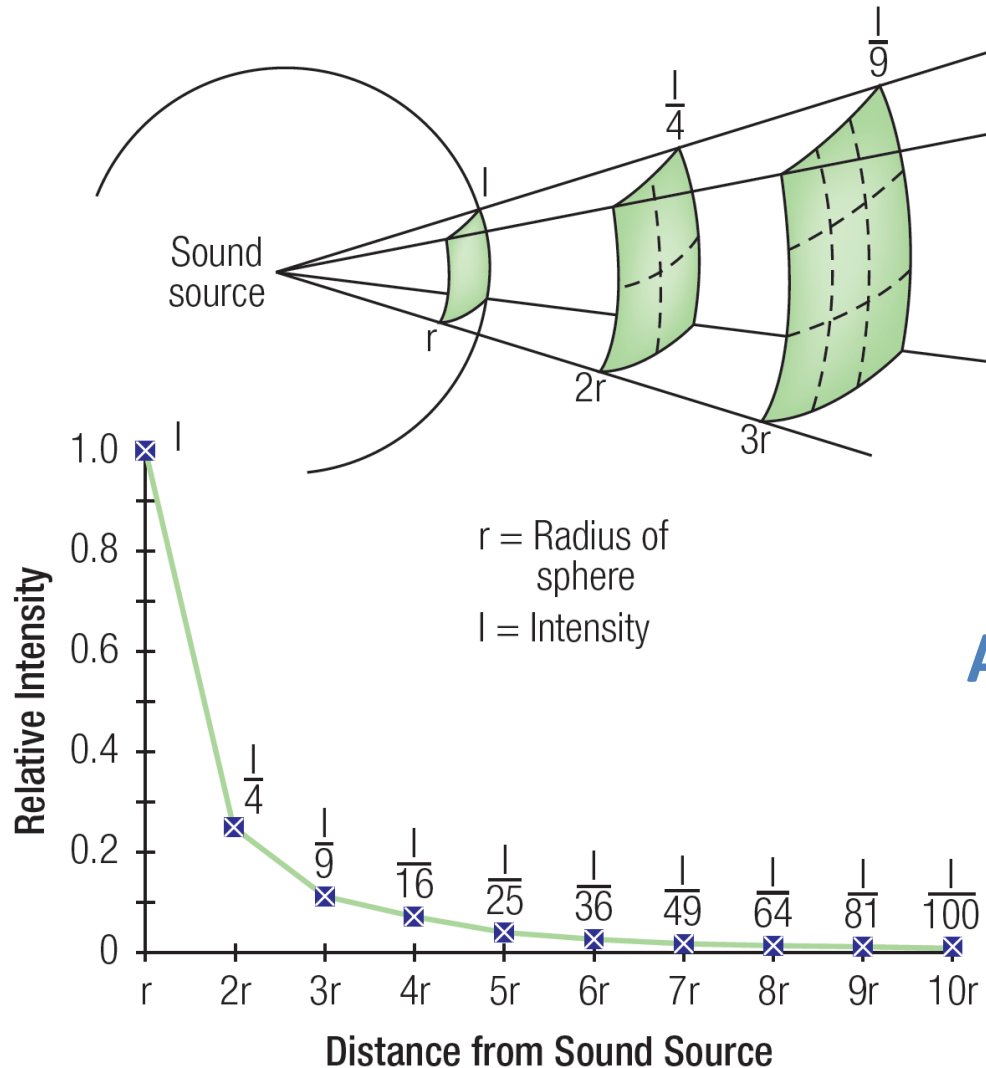
$2 \times 80 = 160 \text{ dB}_{\text{SPL}}$??? (That's pretty intense)

Convert from dB_{SPL} back to raw pressure, sum the pressures, then convert sum to dB_{SPL}

$80 \text{ dB}_{\text{SPL}} \rightarrow \text{antiLog}(80/20) \rightarrow 10,000$

$20 \log (10,000+10,000) = 86 \text{ dB}_{\text{SPL}}$ (approx.)

Inverse-Square Law

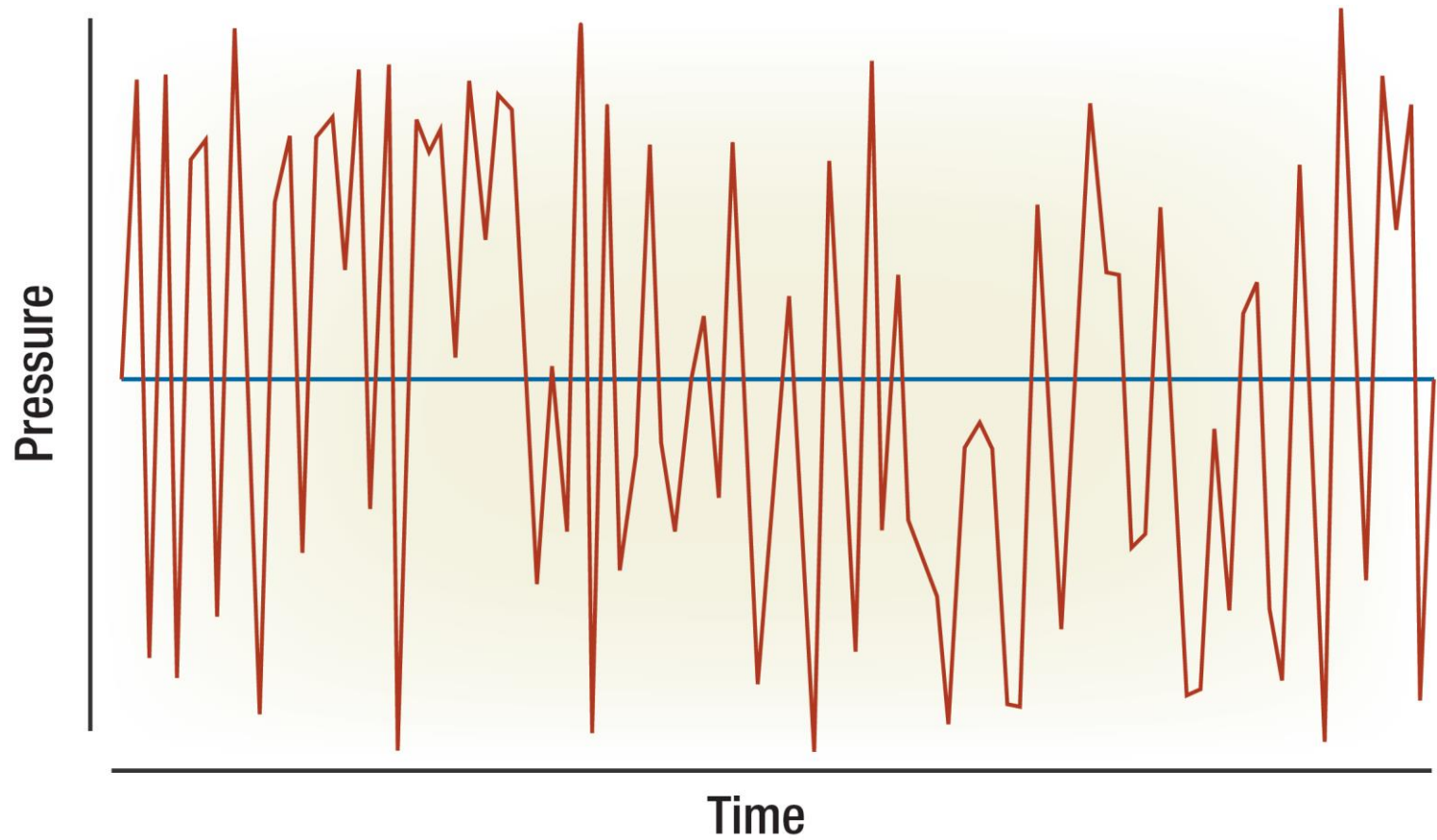


A “Better” Sound Amplitude Table?

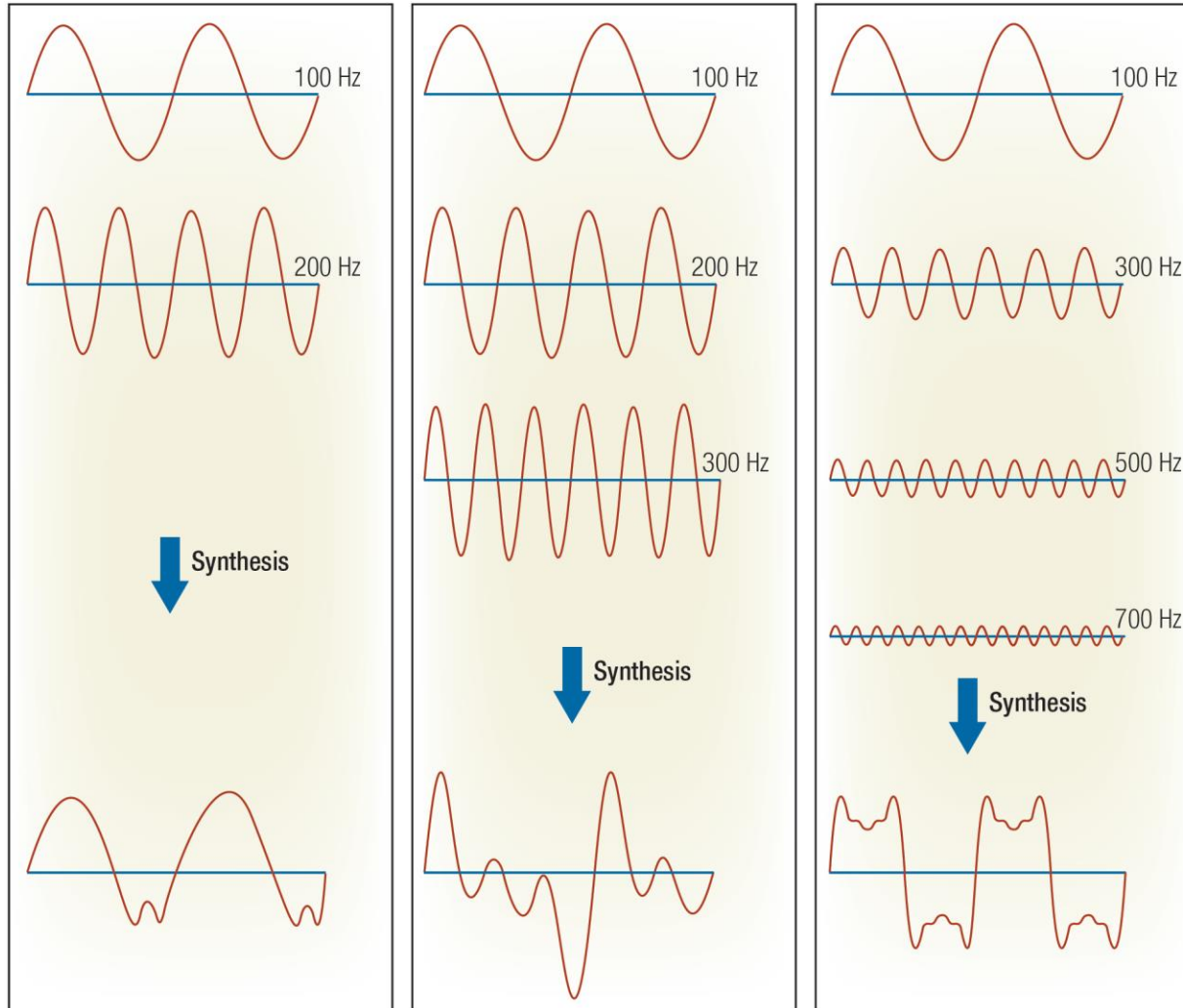
dB_{SPL}

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

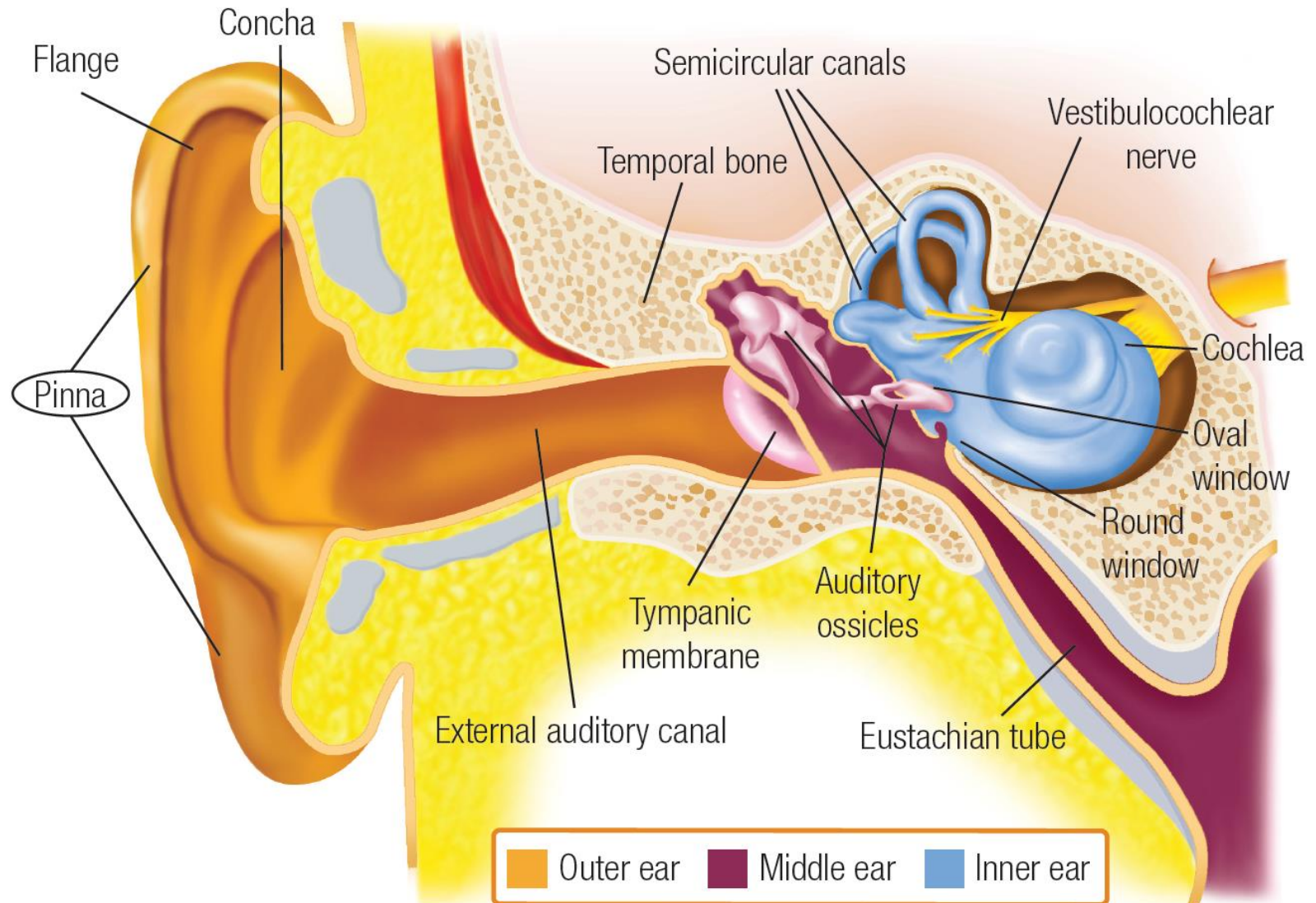
Acoustic energy results from a traveling wave of rhythmic “compression” through a physical medium (e.g., air; water; steel).

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).

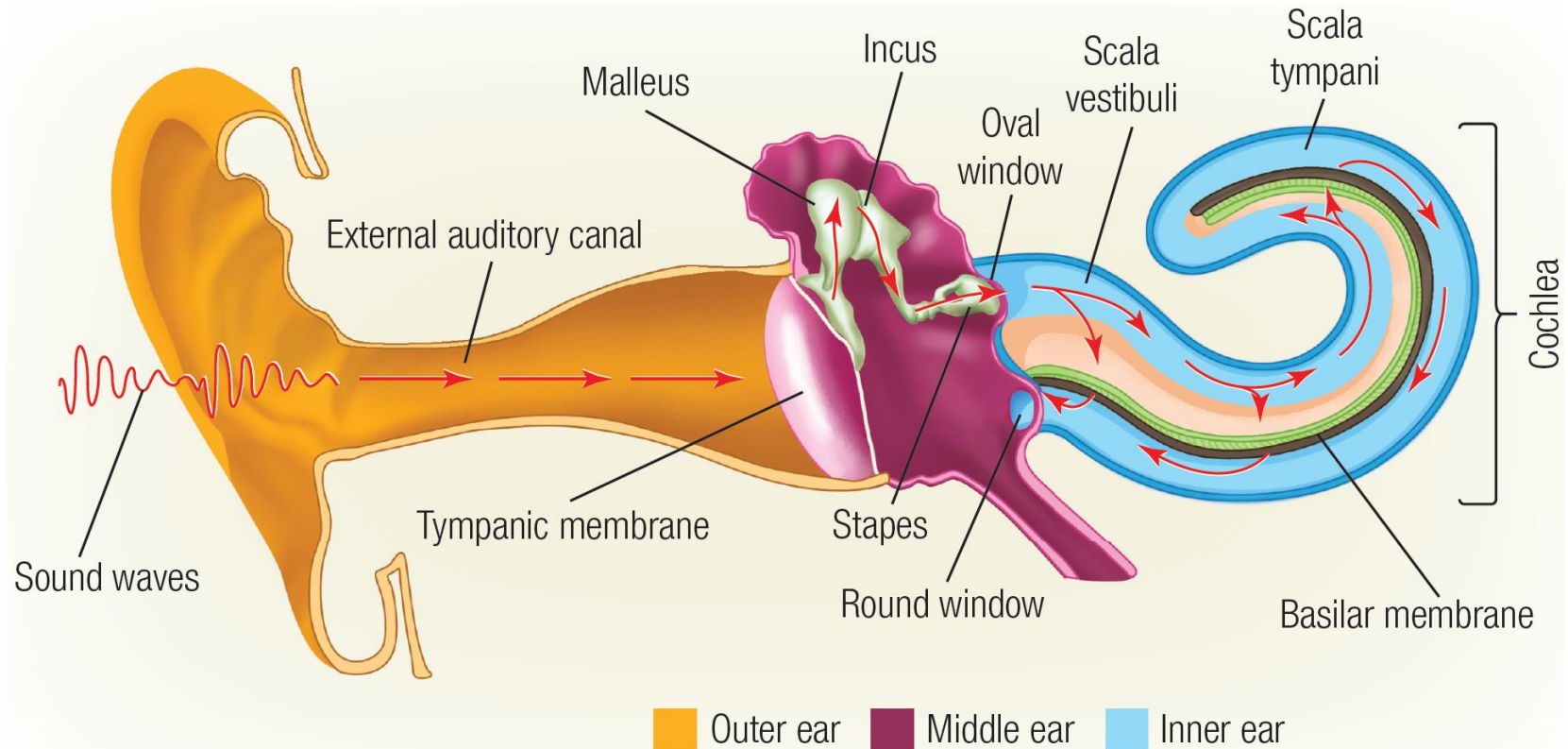
The speed of acoustic energy through the air (aka “sound”) is 331 m/sec (or **742 MPH**) at 0-deg C (Faster at higher temperatures).

Gross Anatomy of the Ear



Flow of Acoustic Energy

(The “Impedance Problem”)



The “Impedance Problem”

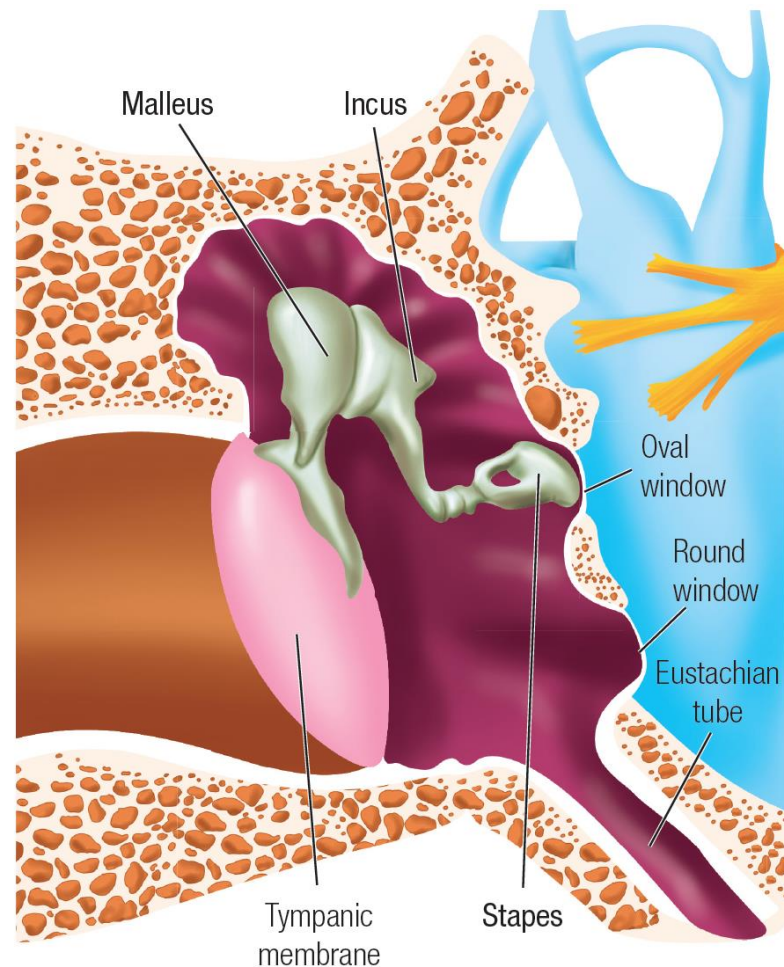
99.9% of sound energy in the air is reflected at the air:water boundary
 $(10 \log(0.1/100)) = \text{-30 dB loss}$ **(1/1000x)**

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

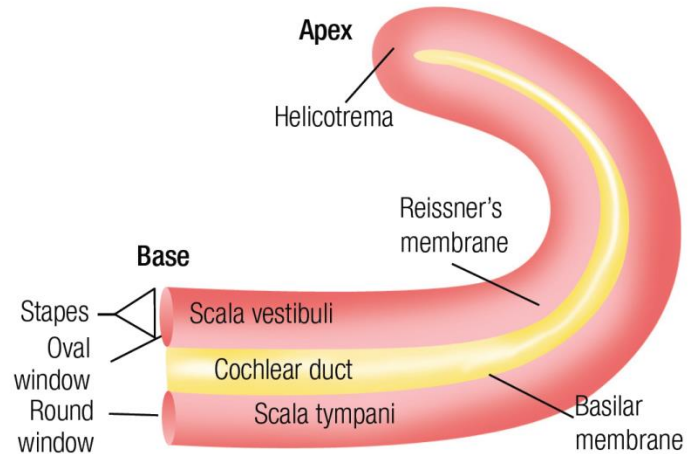
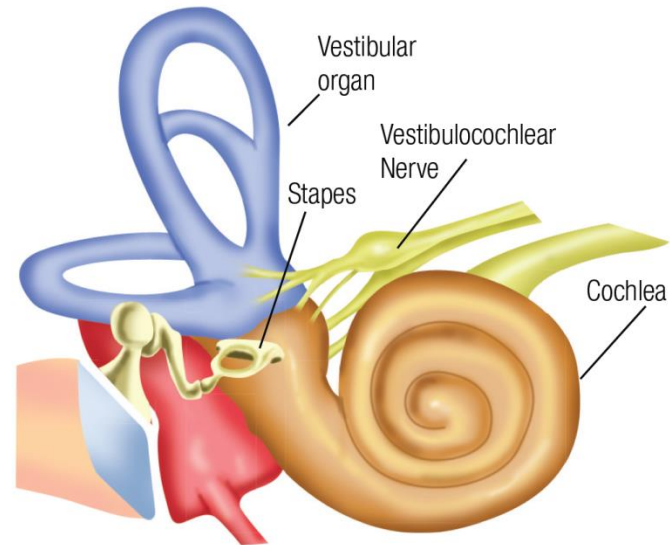
2 dB gain via ossicular leverage **(1.6x)**

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

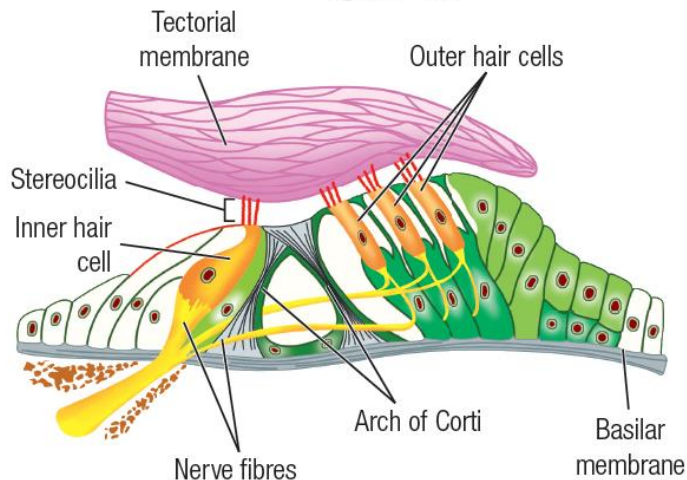
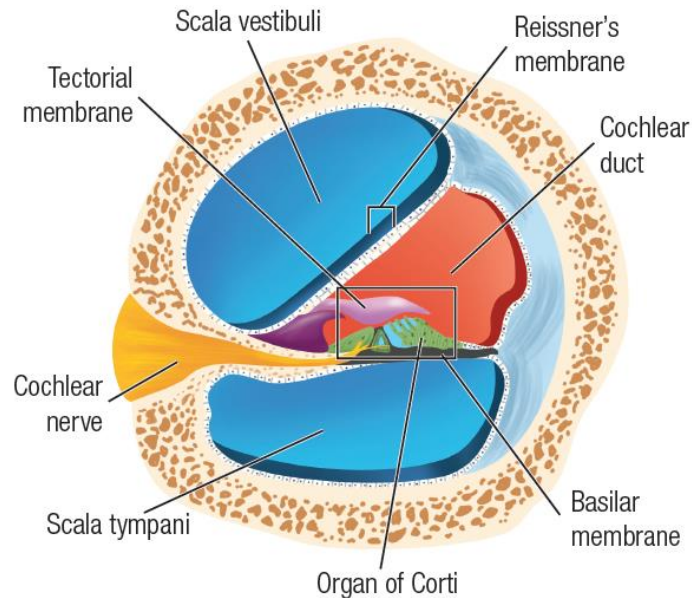
~5 dB gain at mid-frequencies **(3x)** due to pinna and auditory canal resonance



The Cochlea



The Organ of Corti



3000-3500 Inner Hair Cells (IHC)

12,000 Outer Hair Cells (OHC)

Photomicrograph: Sensory Hair Cells

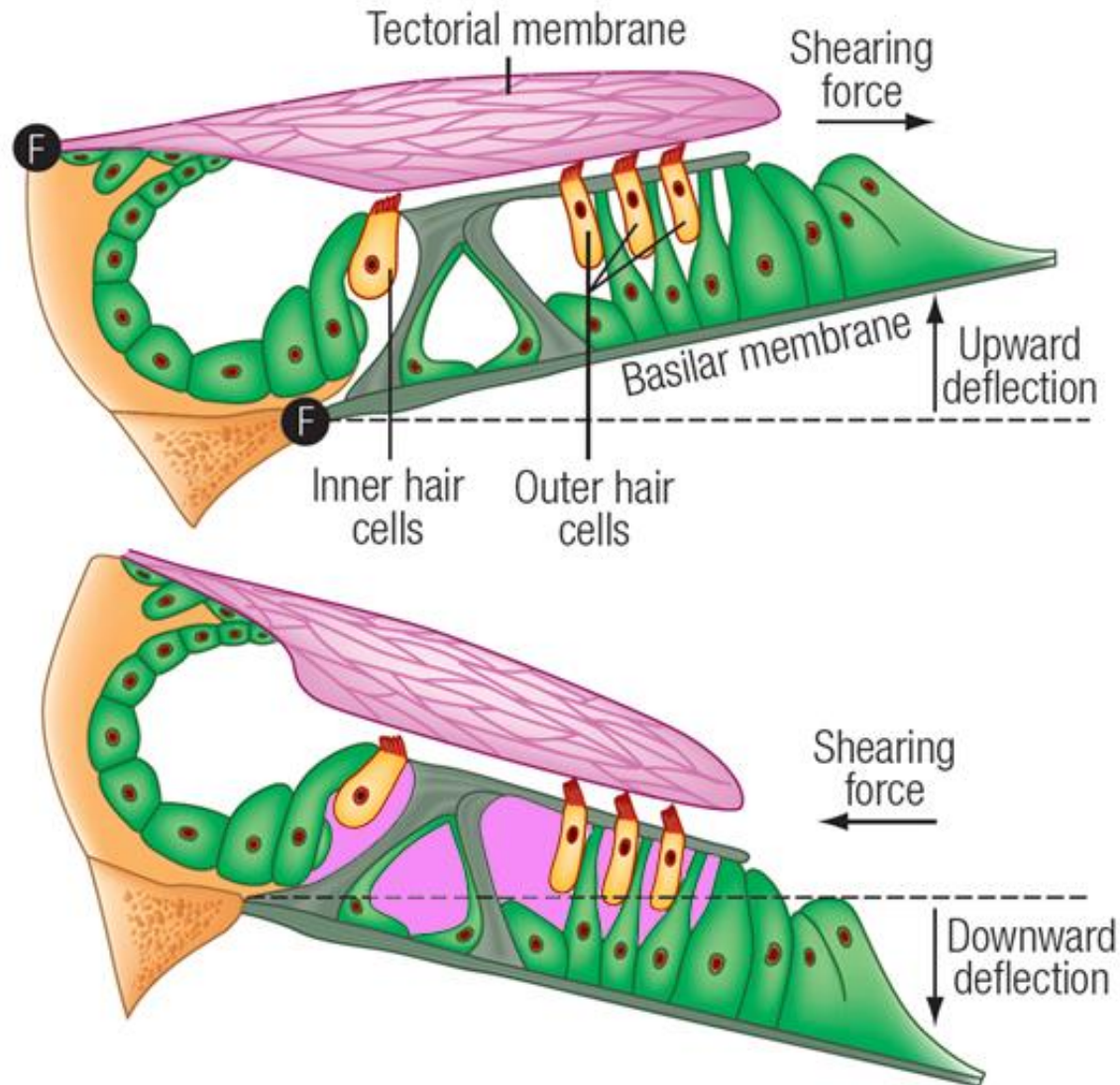


Three rows of
Outer Hair Cells

One Row of
Inner Hair Cells

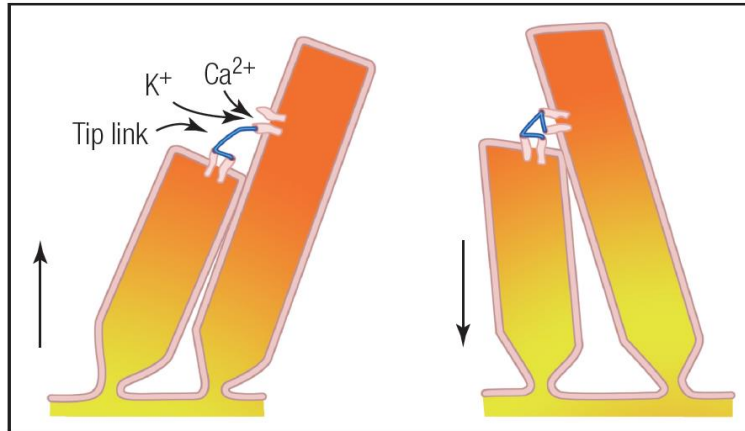
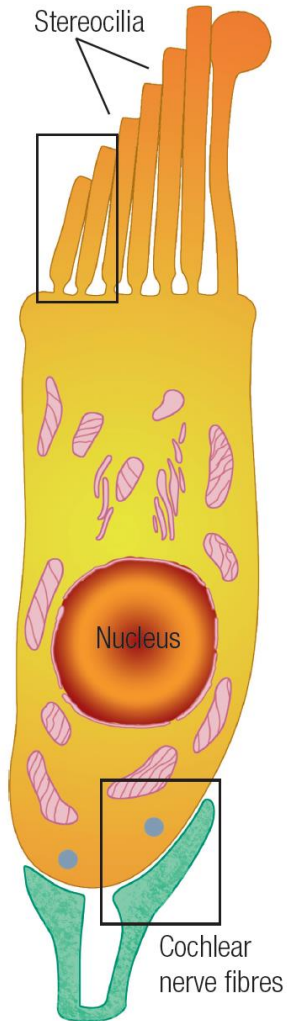
Auditory Transduction

Basilar Membrane Modulation Effects upon Sensory Hair Cells



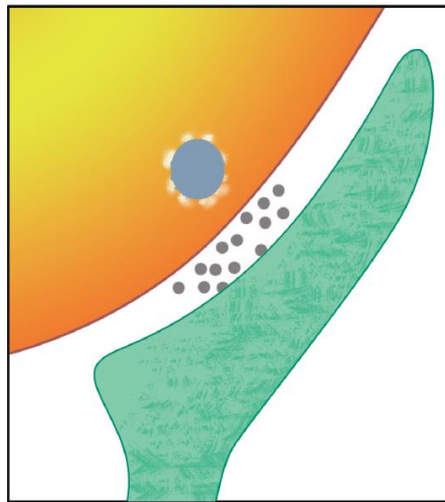
Note: K⁺ ion concentration gradient across sensory hair cells (see pink cavities)

IHC Stereocilia “Tip Links”



“tip link” connects gate to adjacent cilia.

Shearing motion forces gate to open.

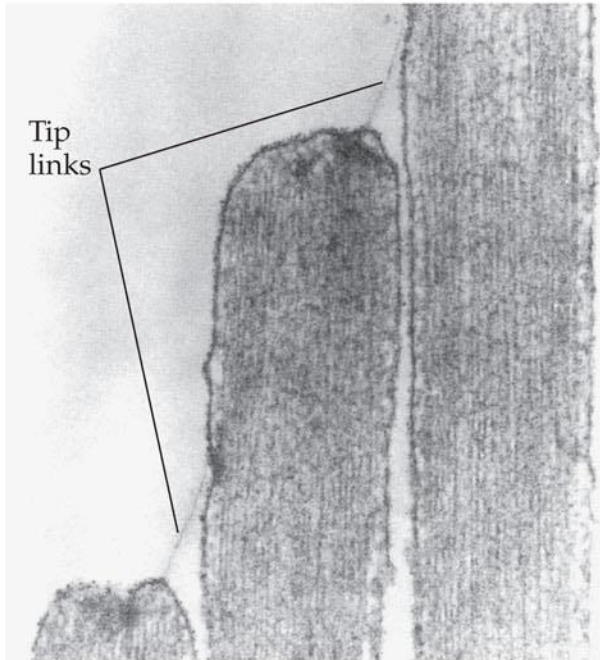


Mechanical open-and-close of gate modulates influx of potassium ions (much FASTER than slow chemical cascade in visual transduction).

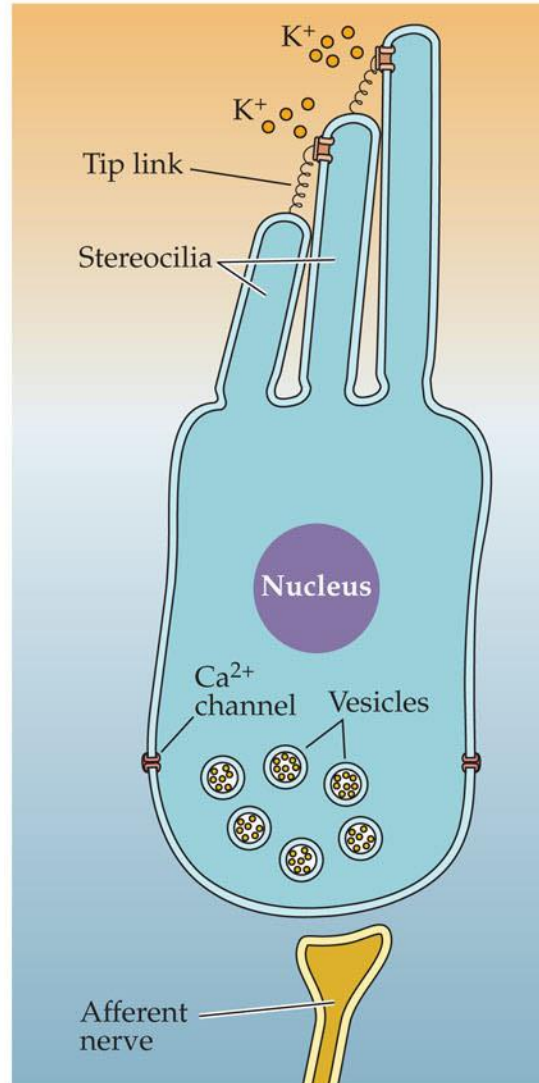
K^+ depolarization of IHC triggers release of **glutamate** at cochlear nerve fiber synapse.

IHC Auditory Transduction

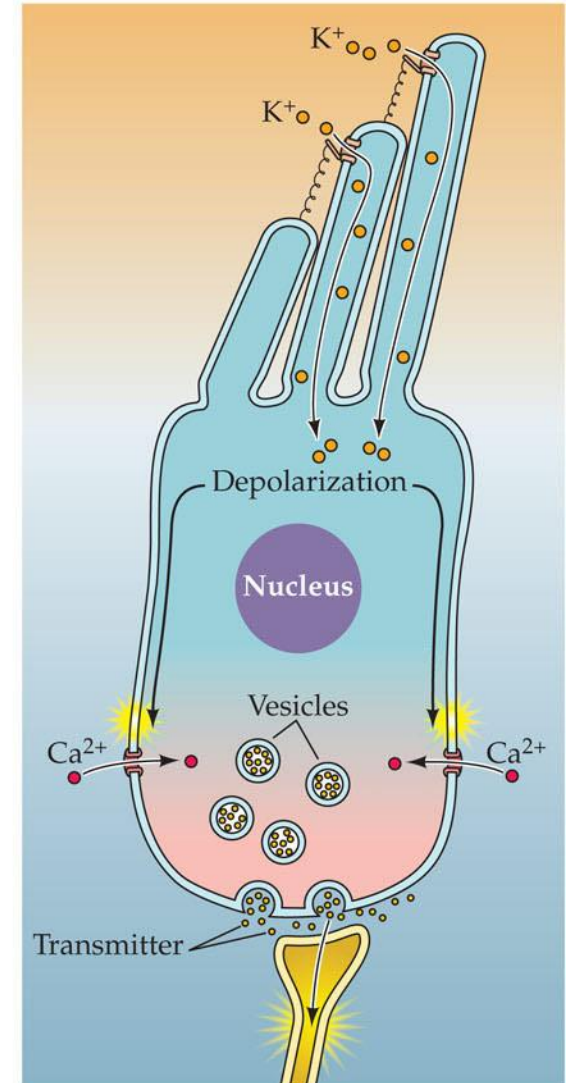
(a)



(b)



(c)



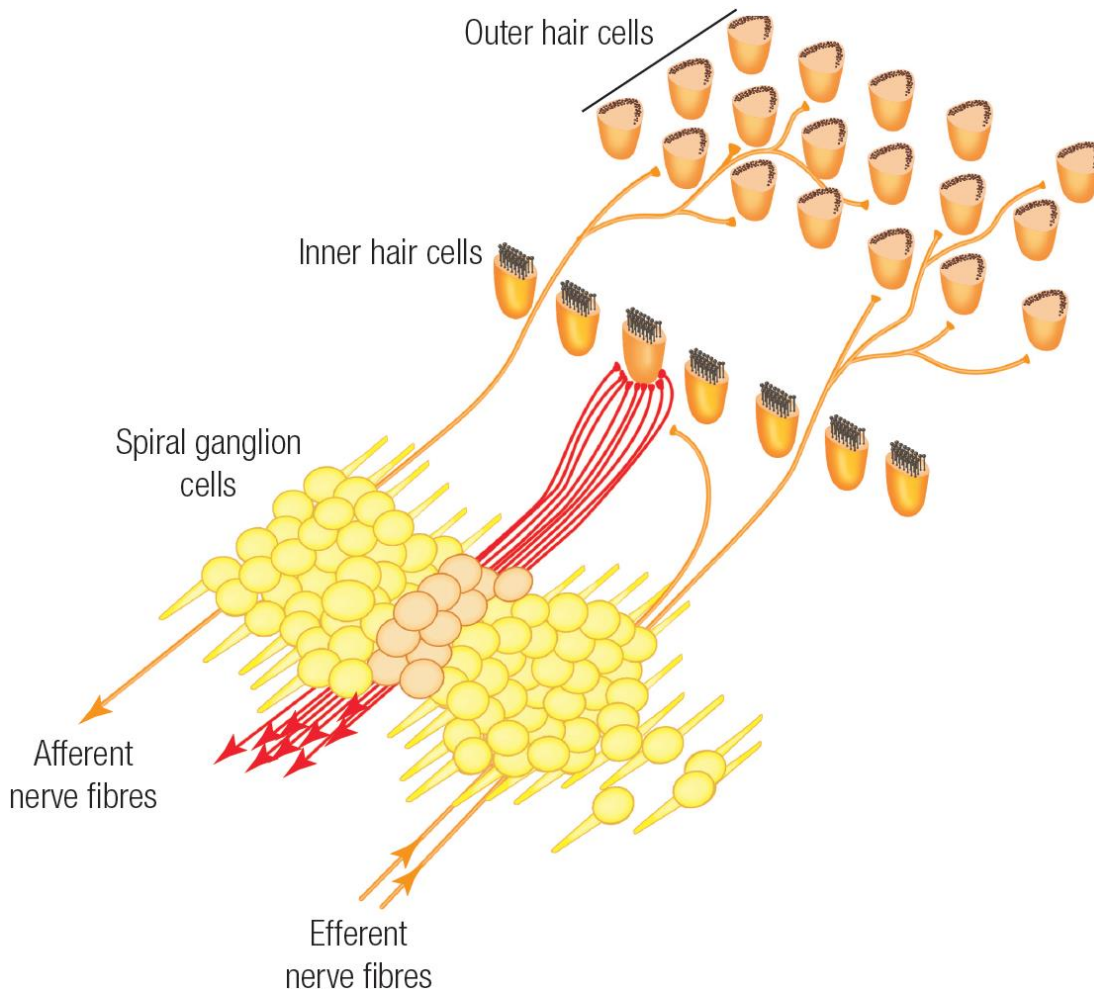
Innervation of 3000 IHCs versus 12,000 OHCs

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

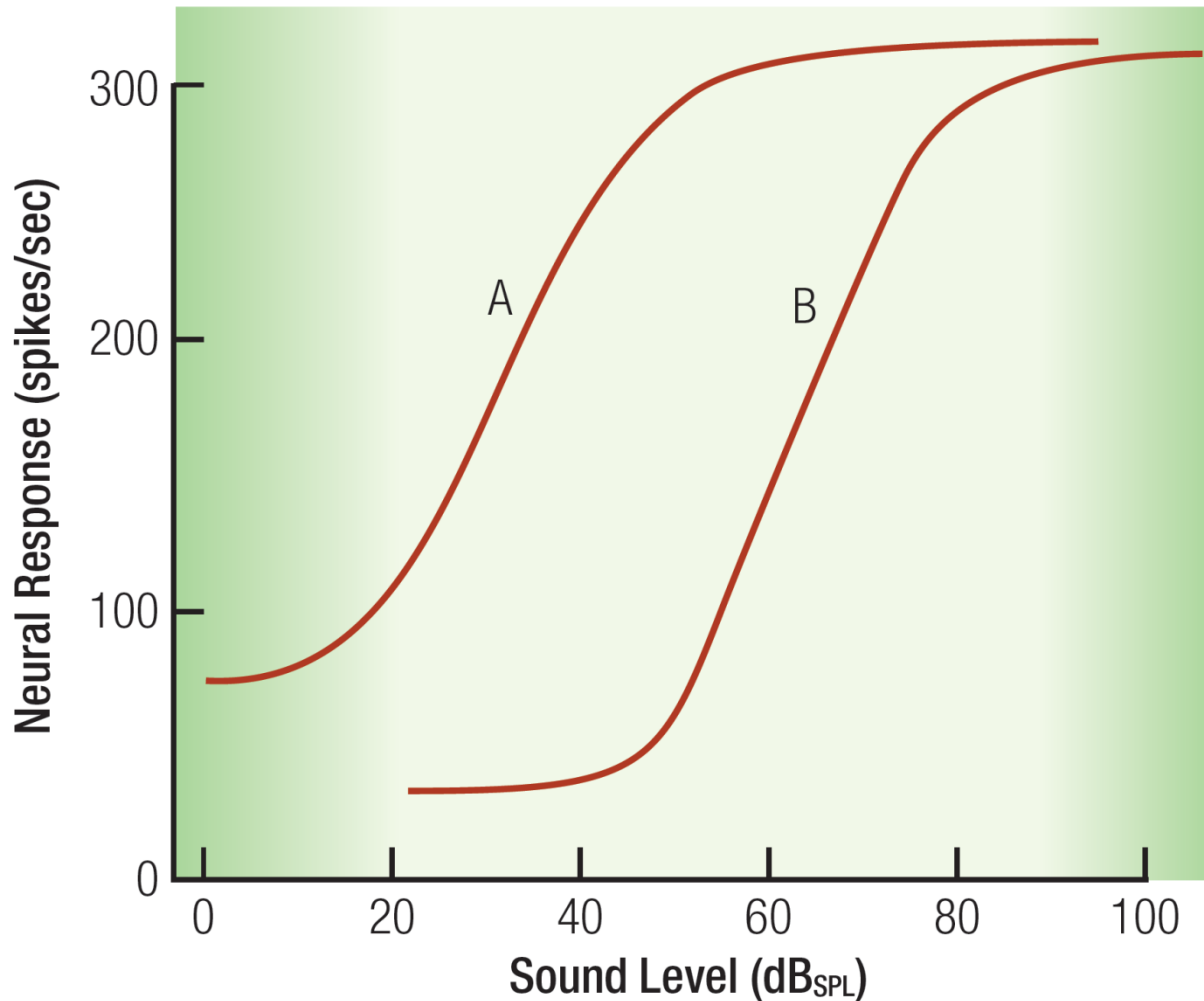
Sparse number of fibers carry info from OHC to brain.

Small number of fibers **descend** from brain to OHCs.

Role of OHC's?
Mechanical gain
otoacoustic emission



Sound Amplitude Coding ("Divide and Conquer")

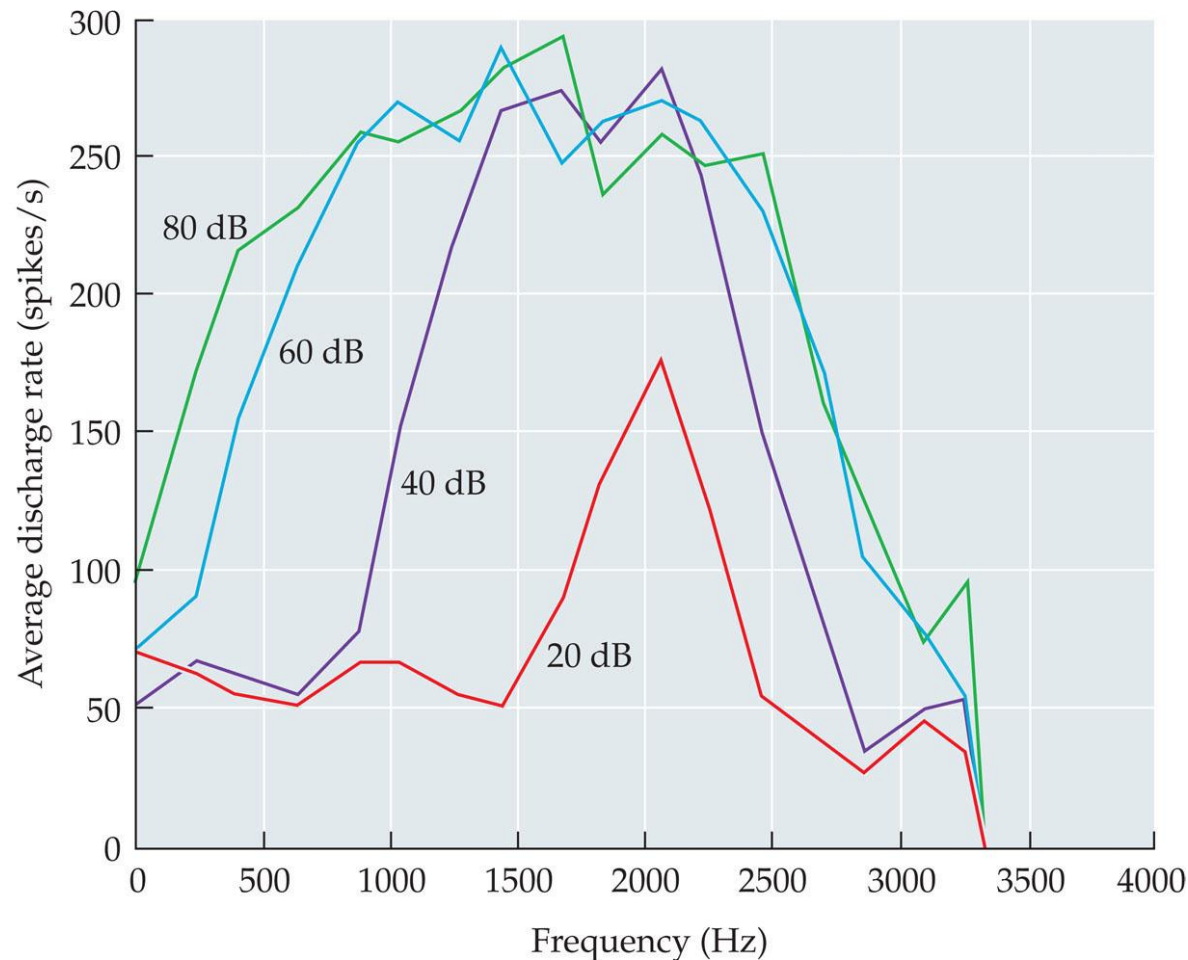


Multiple nerve fibers for each IHC.

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

Intensity-level multiplexing

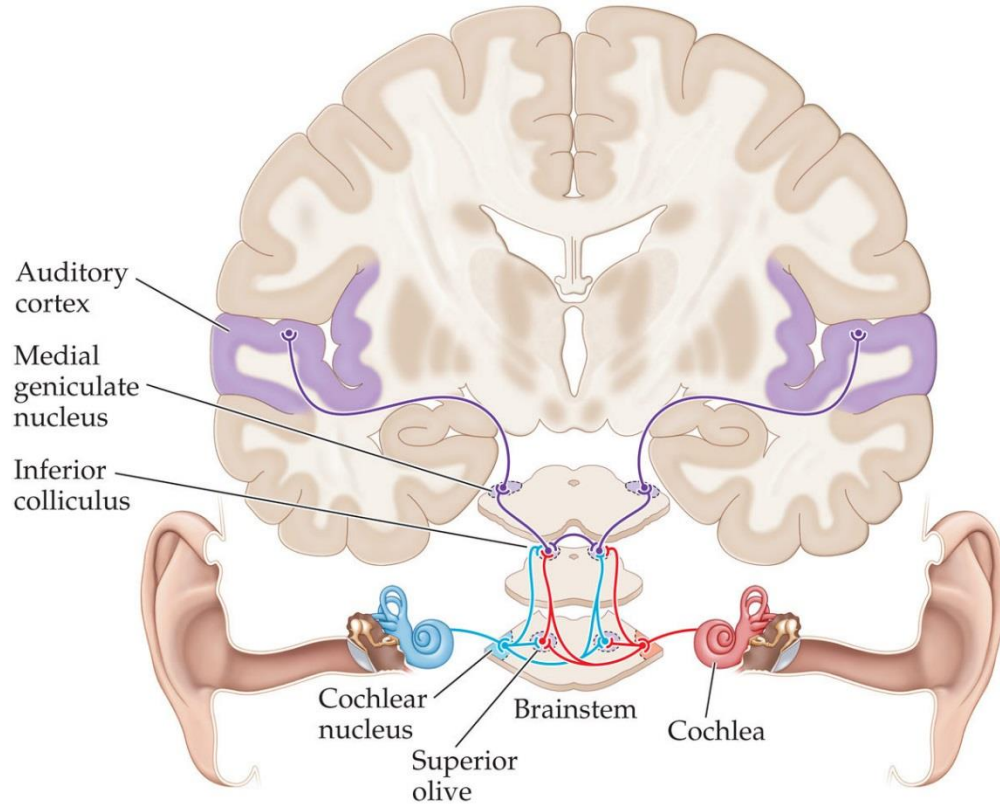
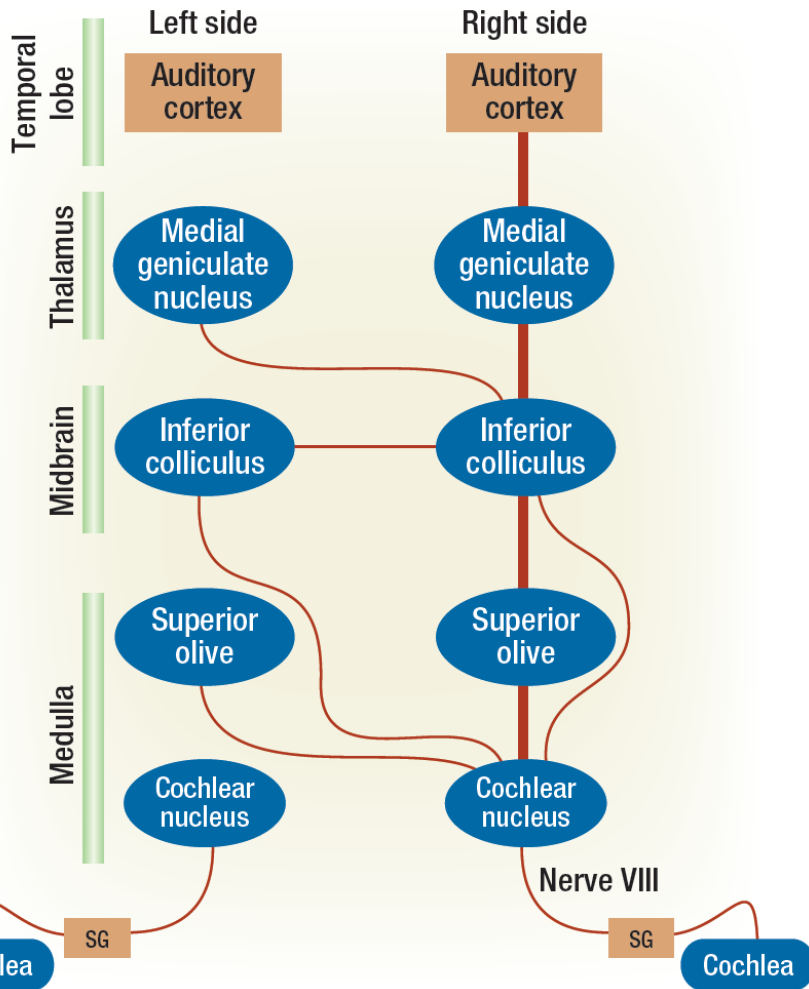
Tuning Specificity of Cochlear Nerve Fibers “Broadens” with Increased Intensity



SENSATION & PERCEPTION 4e, Figure 9.16
© 2015 Sinauer Associates, Inc.

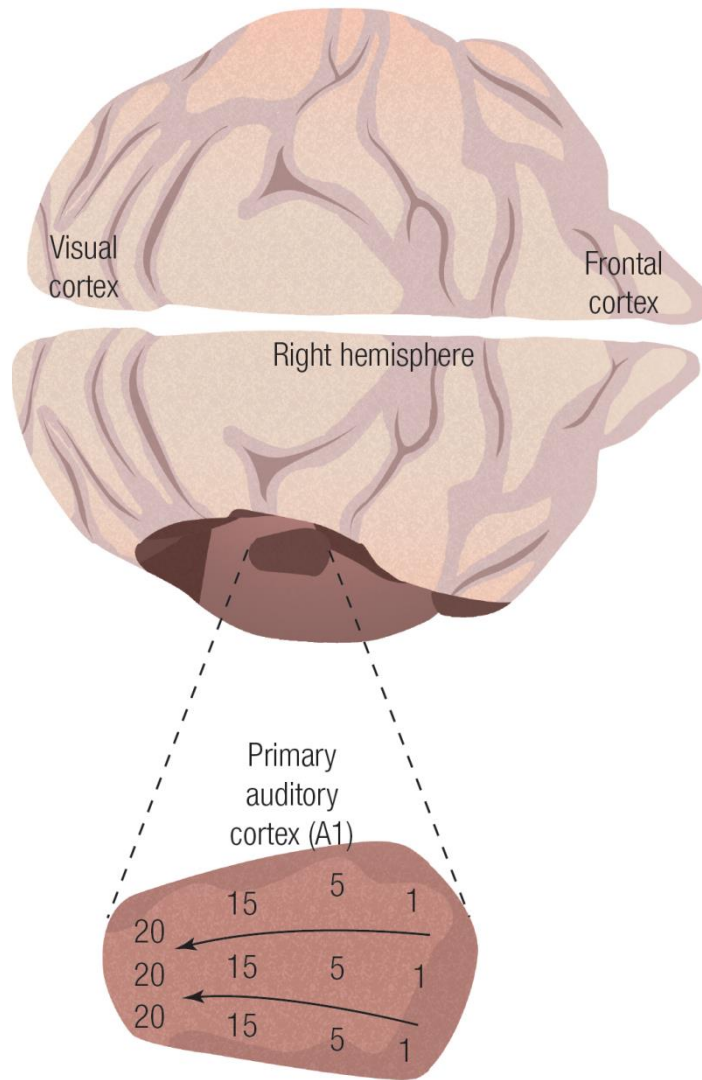
Q: Why the broadening and asymmetry? A: Look to the Basilar membrane's response

Ascending Pathways



SENSATION & PERCEPTION 4e, Figure 9.20
© 2015 Sinauer Associates, Inc.

Tonotopic Organization of Primary Auditory Cortex (A1)



Also note:

Segregation of monaural versus binaural cells is maintained.

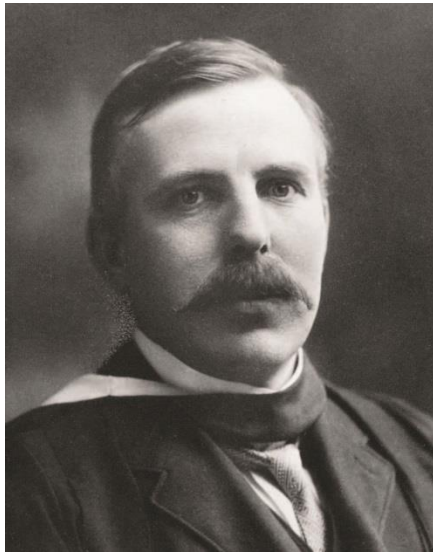
Binaural cells loosely organized according to spatial location of stimulus source.

Auditory Frequency Coding

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

Frequency Mechanism versus Place Mechanism

Frequency Theory



Ernest Rutherford
(1871-1937)

Place Theory

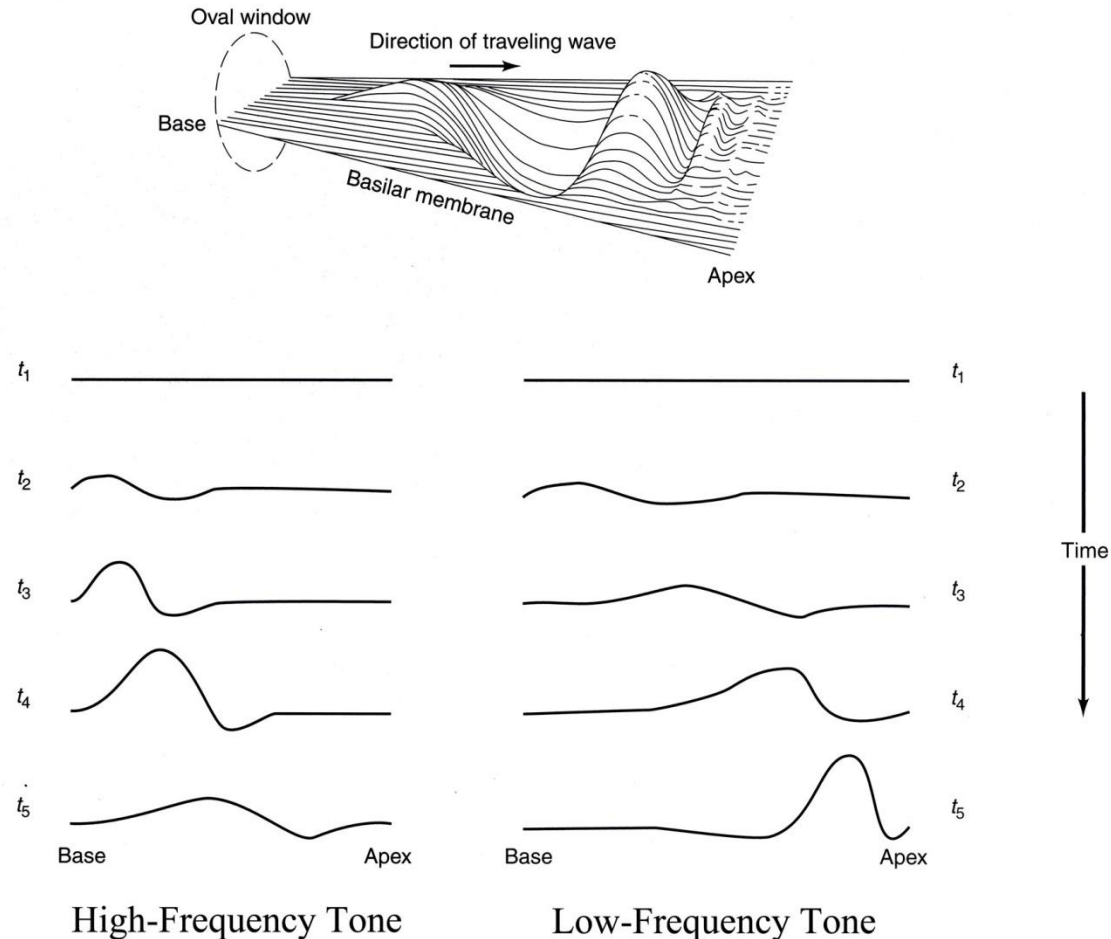


Georg von Békésy
(1899-1972)

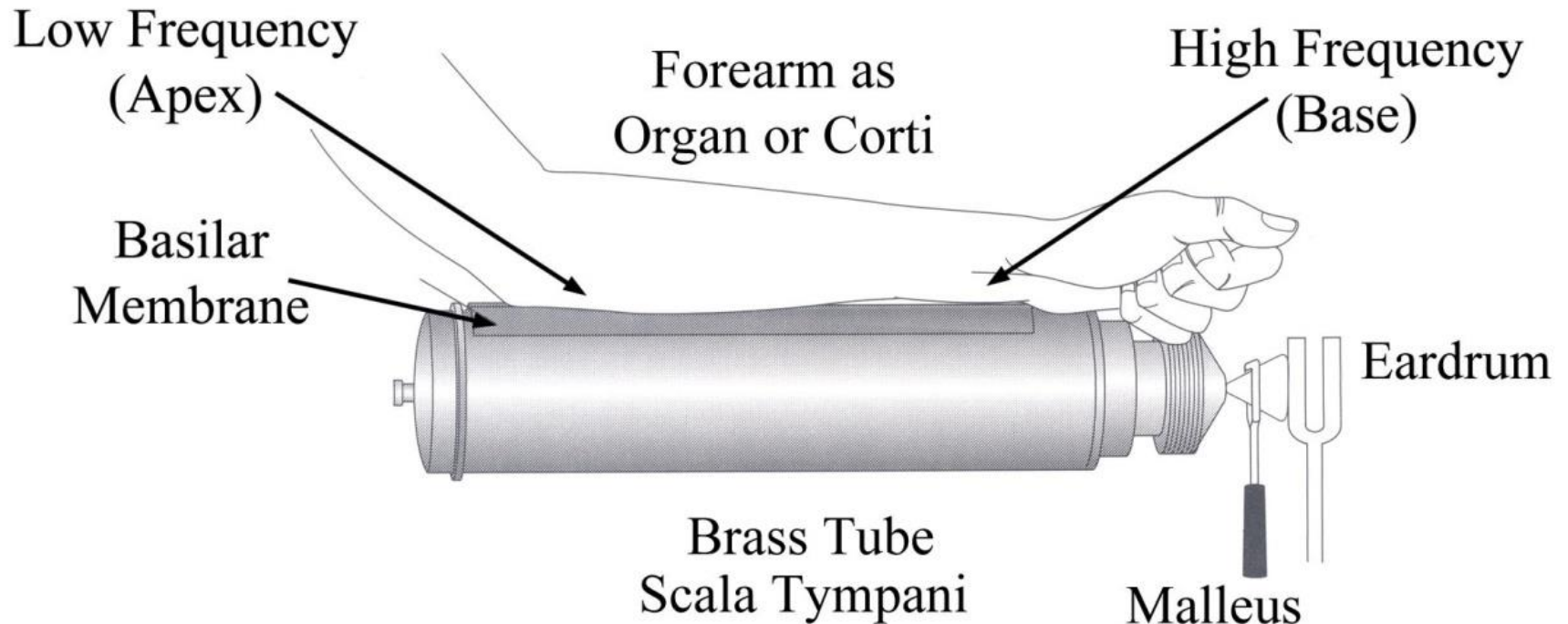
Frequency Theory (Rutherford)

- 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)

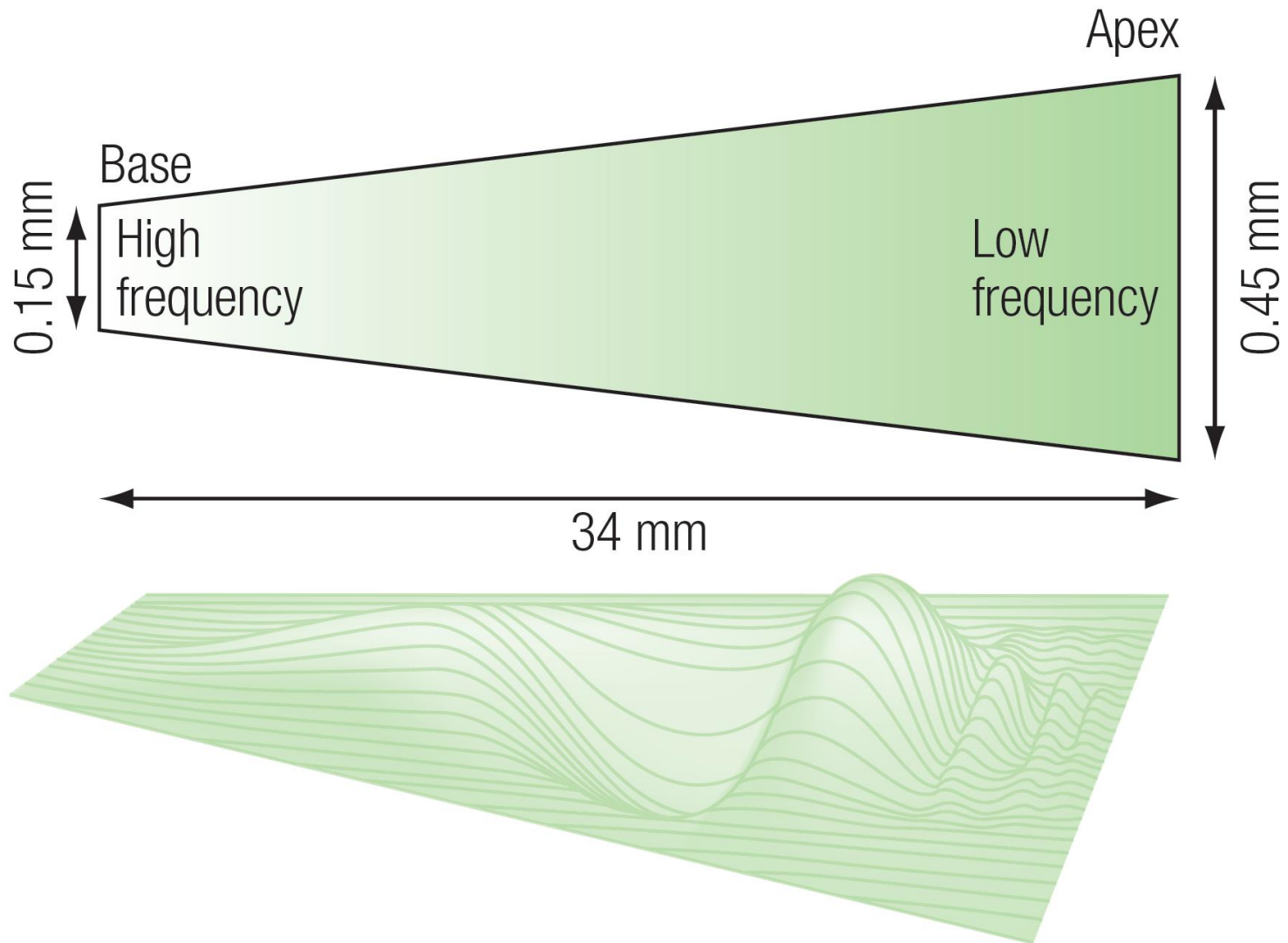
von Békésy Place Theory: Focus on Basilar Membrane Dynamics



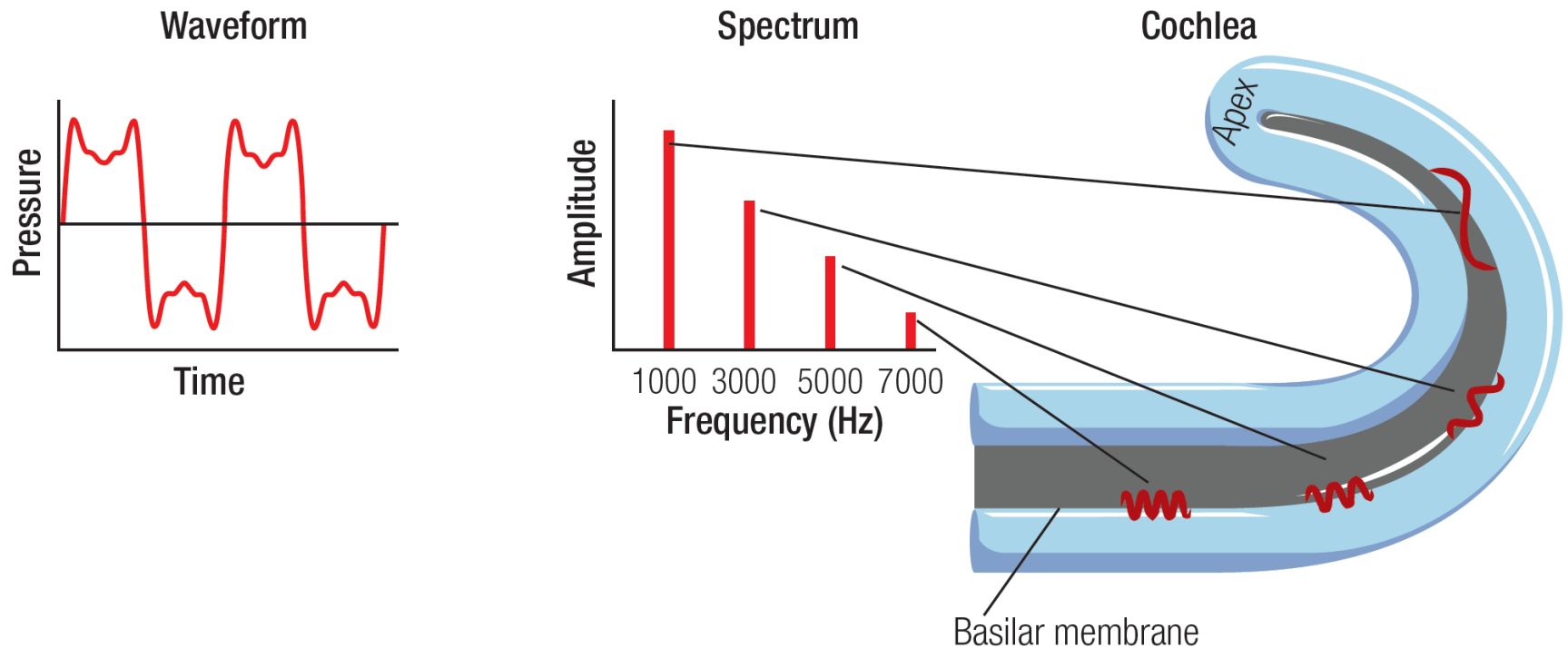
The Simple Beginnings for von Békésy's Nobel Prize



Basilar Membrane Response to Pure Tone Stimulus



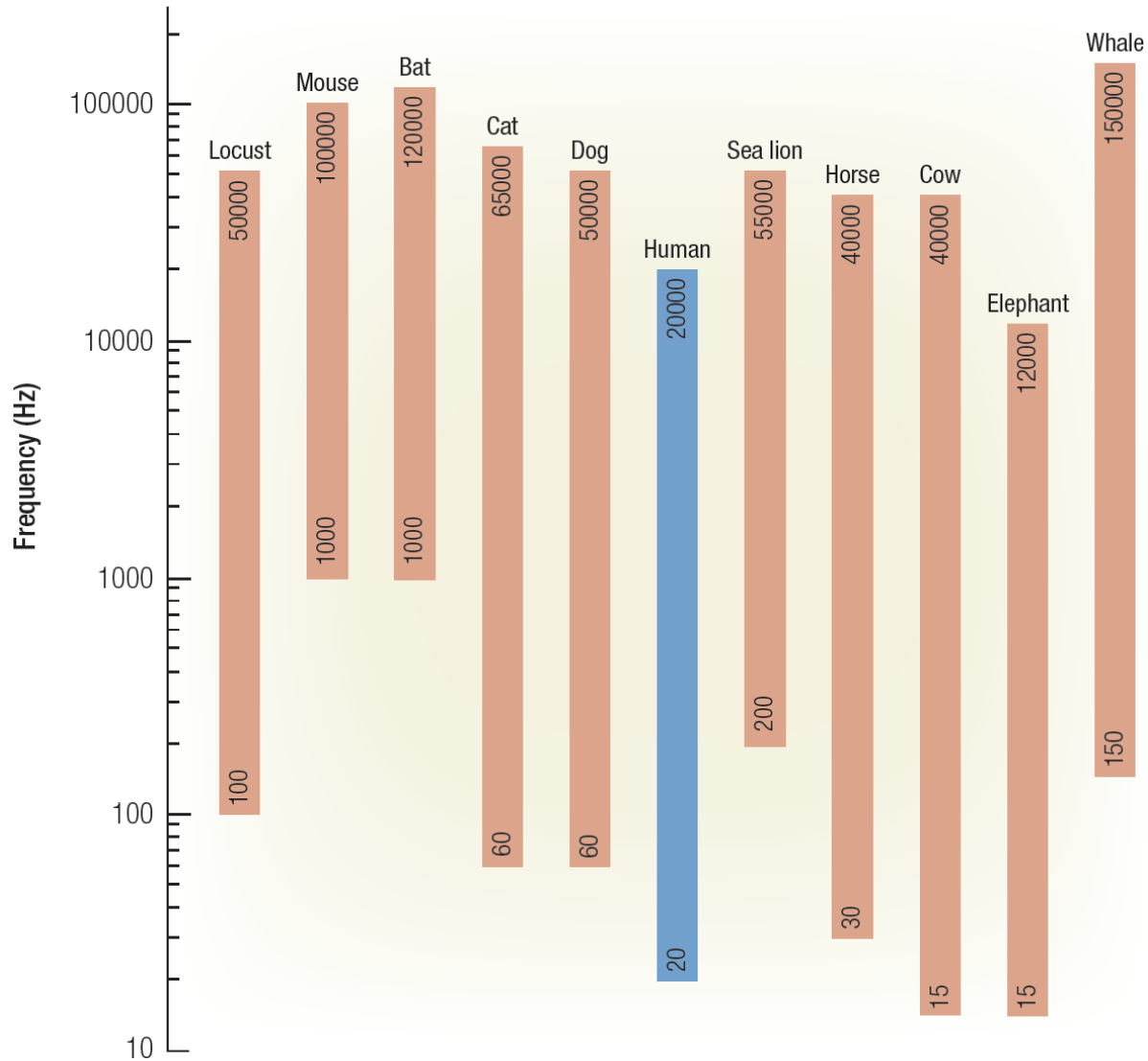
Von Békésy's "Place Mechanism" as Biological Fourier Analyzer



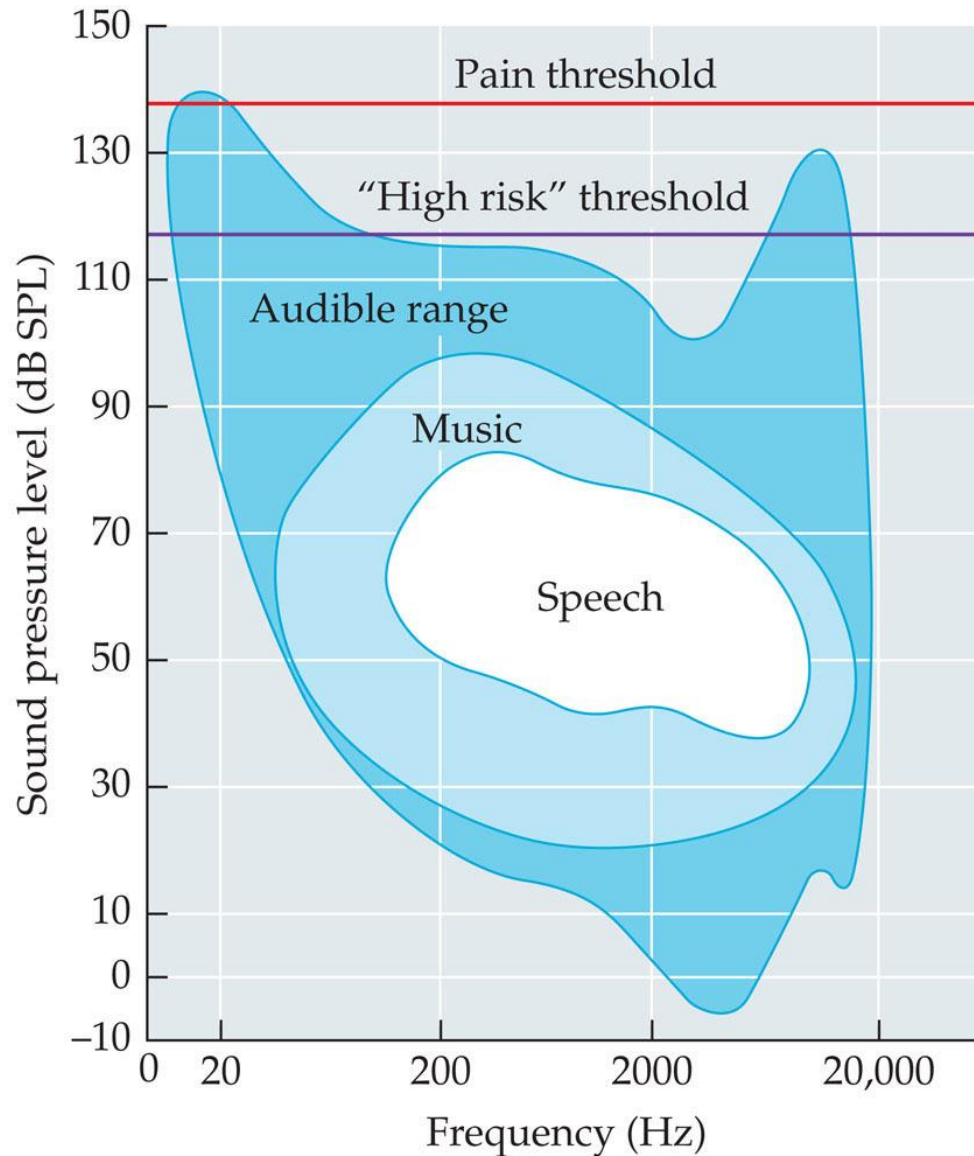
[Basilar Membrane Dynamic Simulation](#)
(animation)

Functional Aspects of Hearing

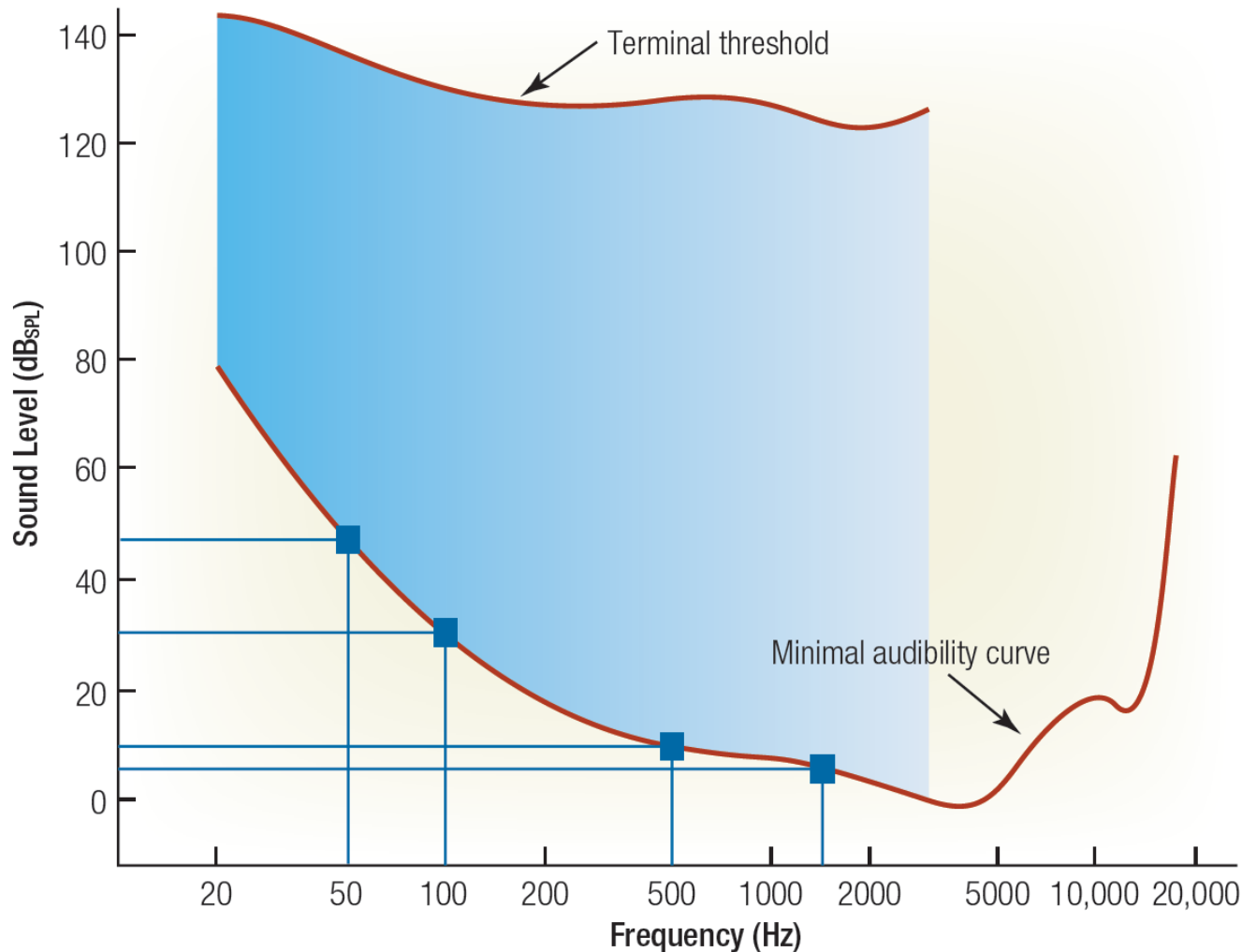
Species-Specific Frequency Range



Human “Earscape”



Minimum Audibility Curve

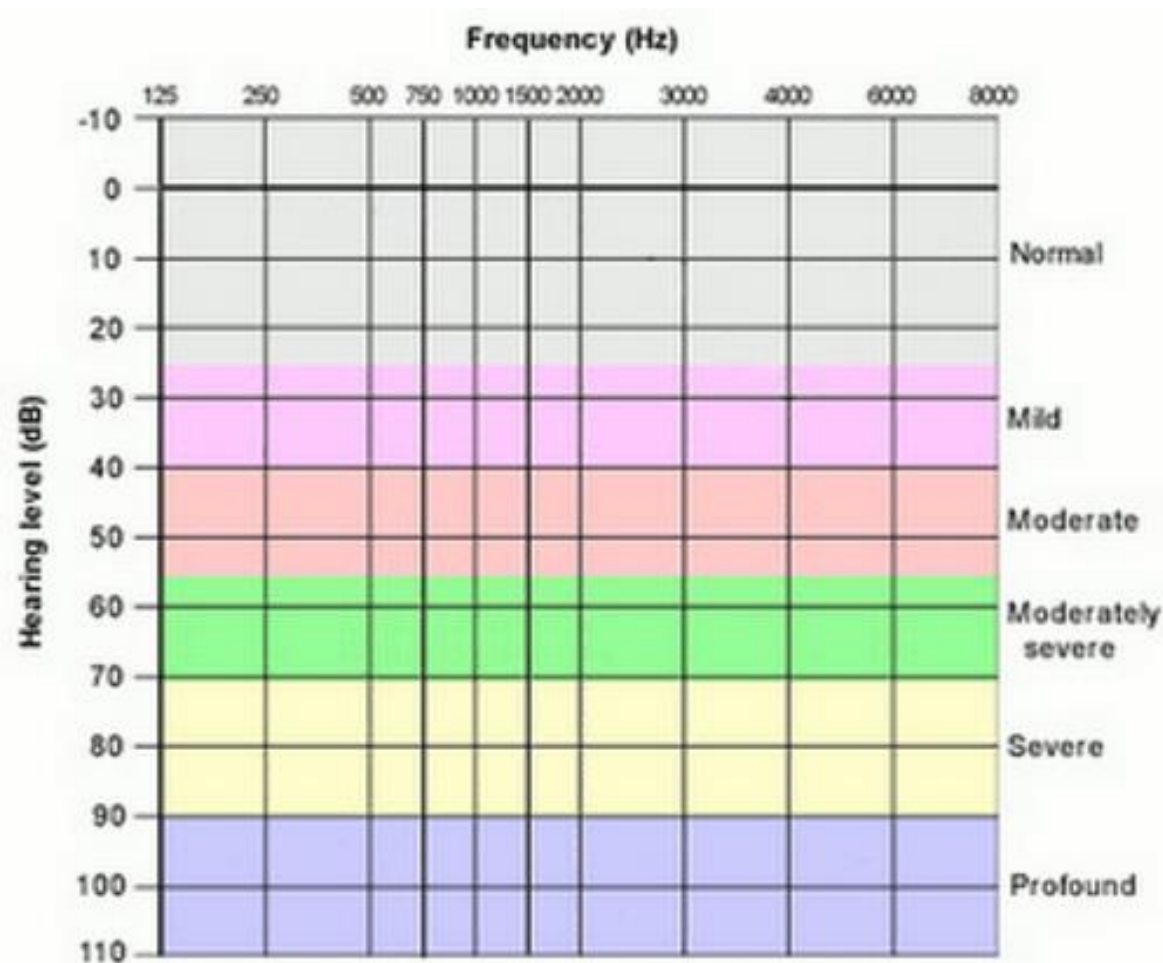


Average detection threshold for 18-yr-olds for 1KHz tone at sea level is **20 microPa (μPa)**

Minimum occurs at approx. 3 KHz

Binaural intensity thresholds are 3 dB lower than mono

Clinical Audiogram (dB_{HL})

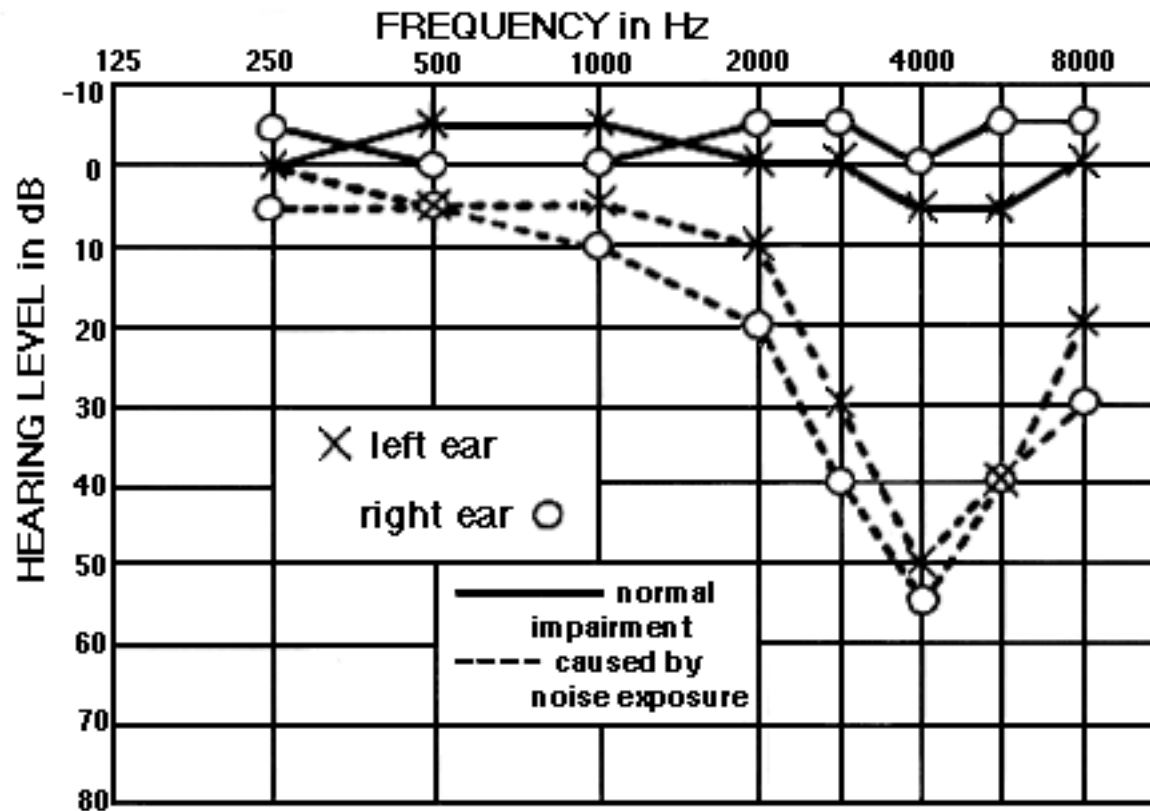


dB-HL (Hearing Level) uses a different reference level for each test frequency.

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.

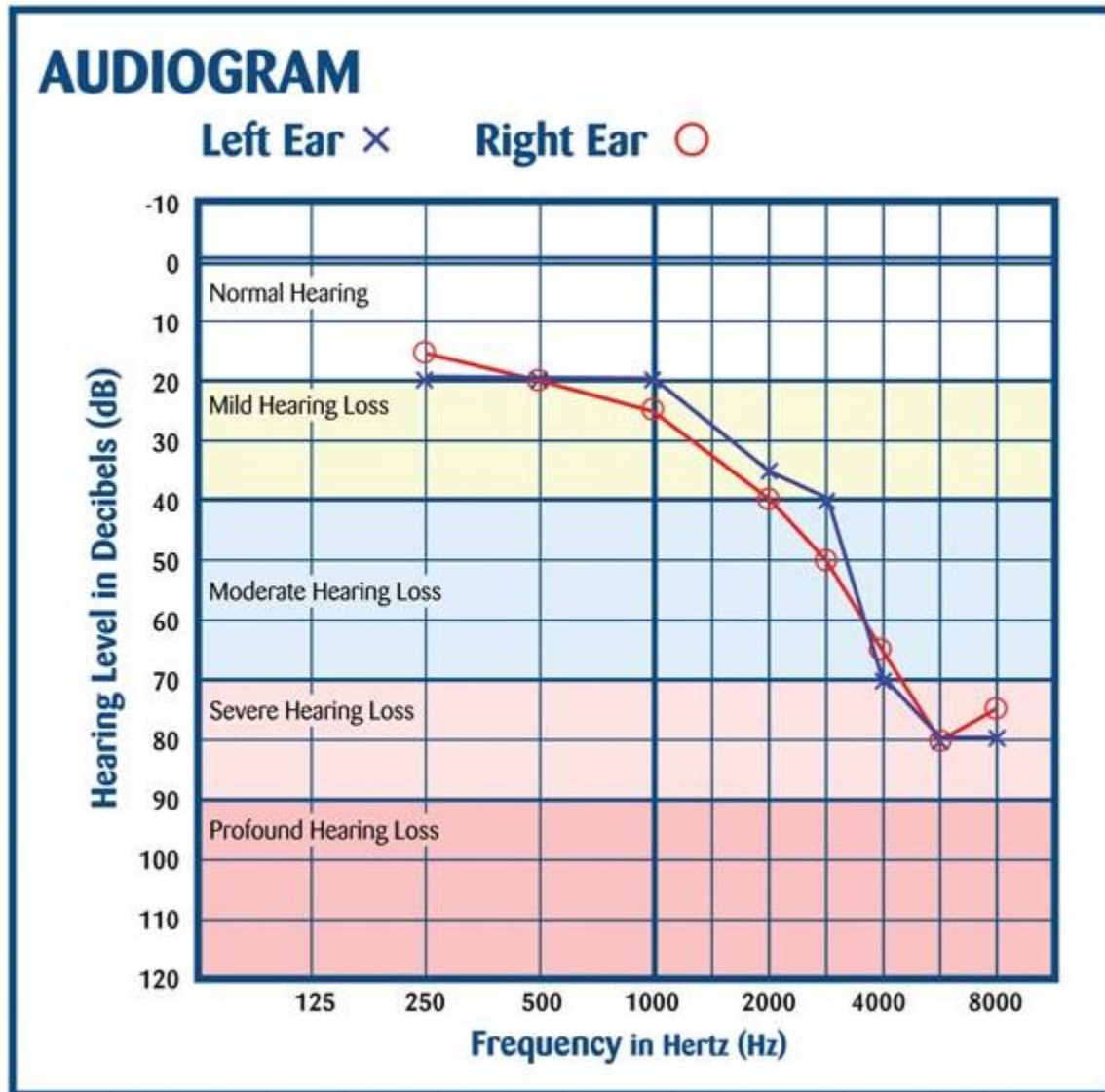
Normal vs. Noise-Induced Hearing Loss



**Note “notch”
At 4 KHz.**

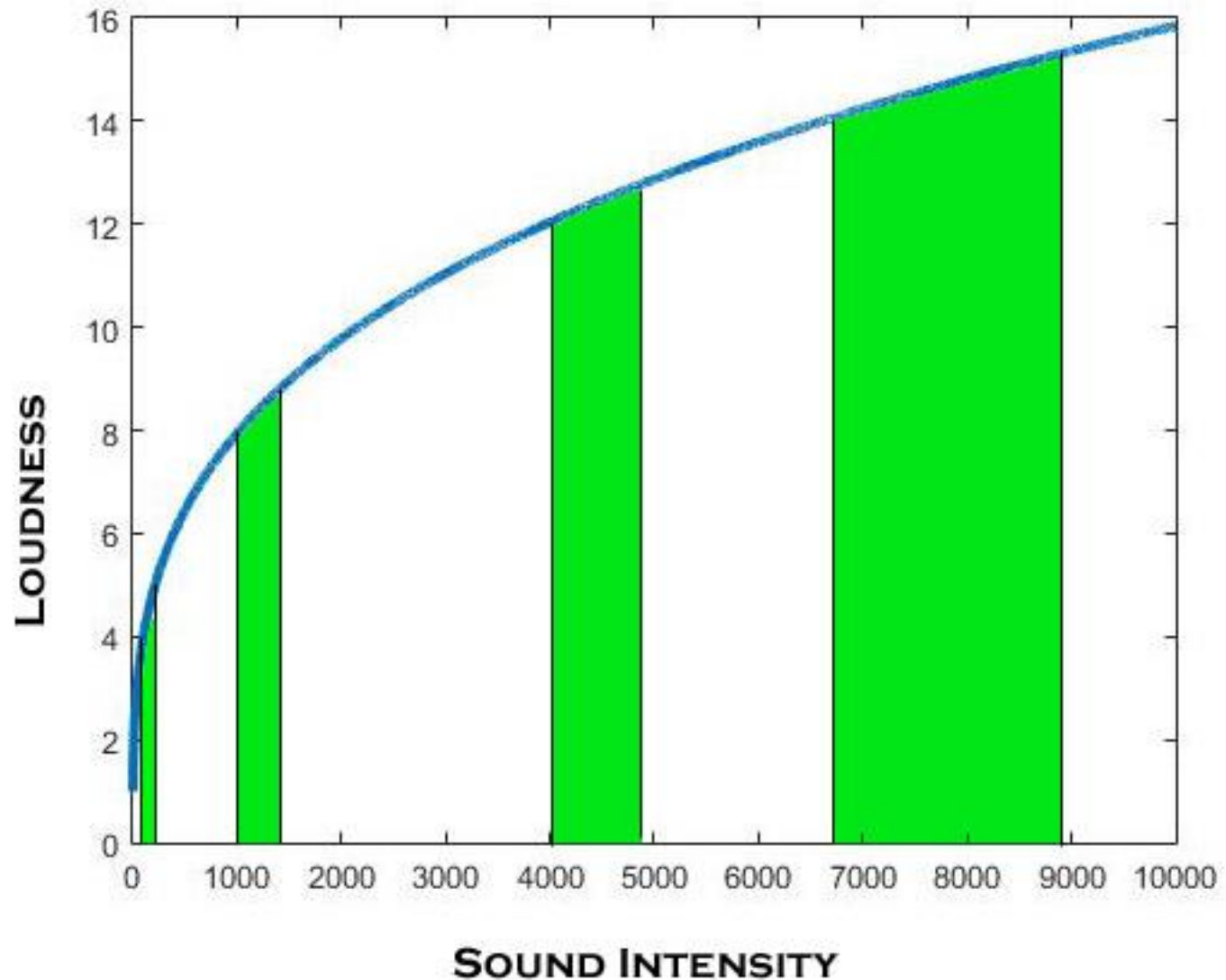
Source: http://mustelid.physiol.ox.ac.uk/drupal/?q=acoustics/clinical_audiograms

Age-related Hearing Loss (Presbycusis)

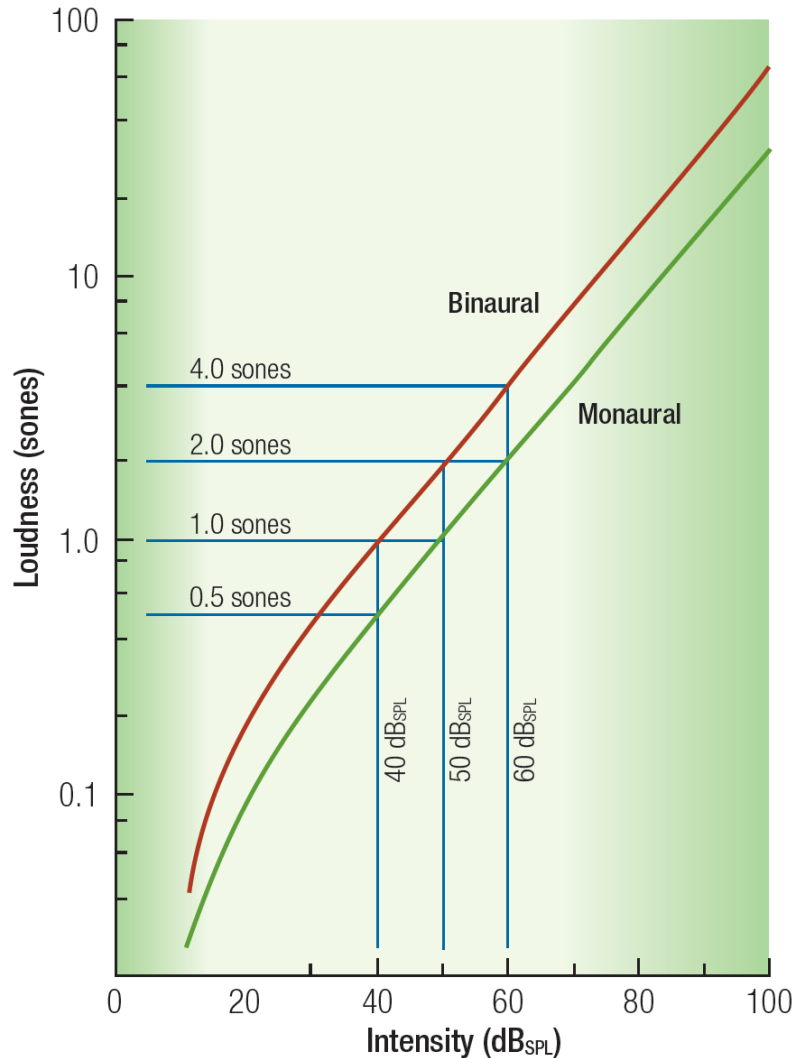


Inevitable or preventable?

Loudness is non-linear



Loudness



Stevens' **SONE SCALE** of Loudness Perception

Perceptual Anchor:

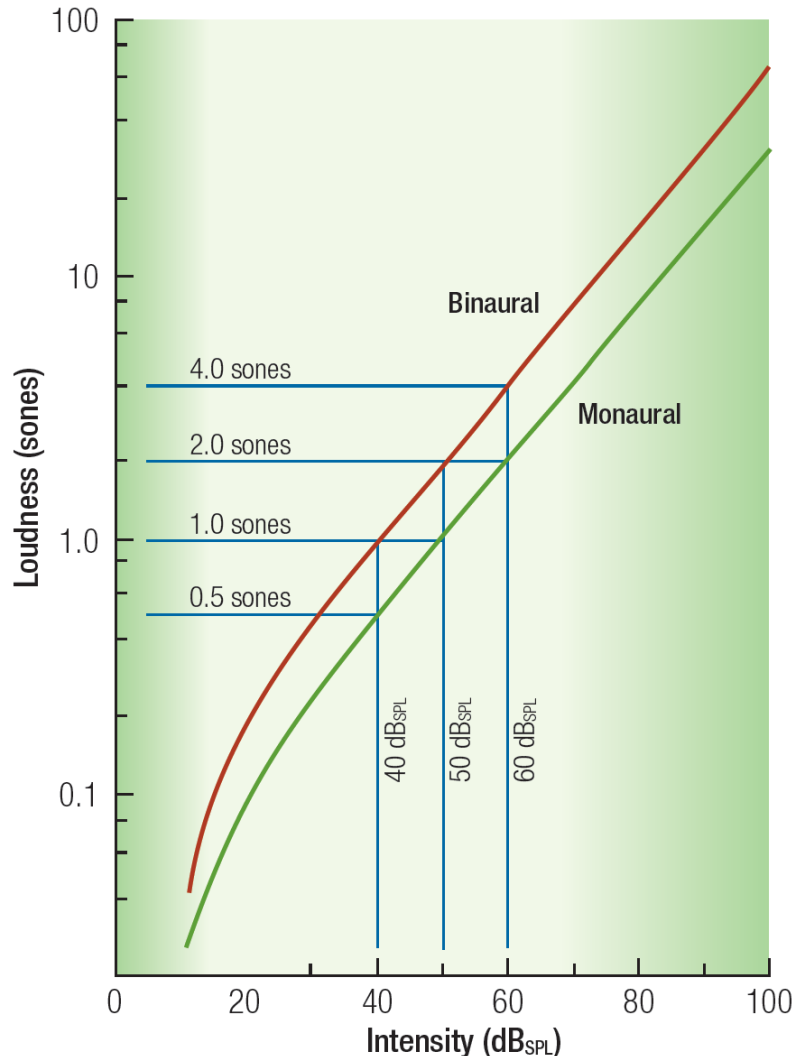
1 sone = loudness of 1 KHz
at 40 dB (40 phons)

Find the dB level that is twice as loud (2 sones) or half as loud (0.5 sones), etc. and construct a scale.

[i.e., **Magnitude Estimation**]

The psychological magnitude of sound (i.e., “Loudness”) grows at a slower rate than the physical magnitude of the sound stimulus.

Loudness



Using magnitude estimation techniques, S.S. Stevens has quantified this nonlinear relationship as:

$$L = k * P^{0.6}$$
$$= k * I^{0.3}$$

L=loudness; P=sound pressure (μPa)
I=sound intensity (pW/m^2)

Stevens' Power Law; Linear in log-log plot; slope $\approx$ exponent

$$\log(L) = \log(k) + 0.3 \log(I) \text{ straight line}$$

$$\log(L) \approx 0.3 \log(I)$$

Hence, a log unit increase (10dB) of intensity yields $0.3 \log(10^{0.3})$ or 2-fold increase in loudness.

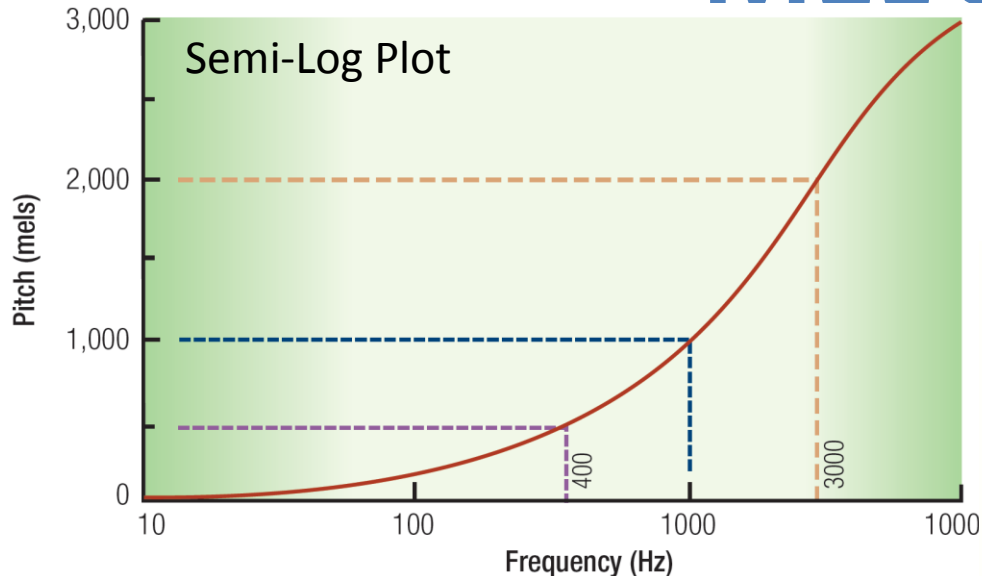
Note: Binaural presentation perceived as approx. 2x more loud than monaural equivalent.

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

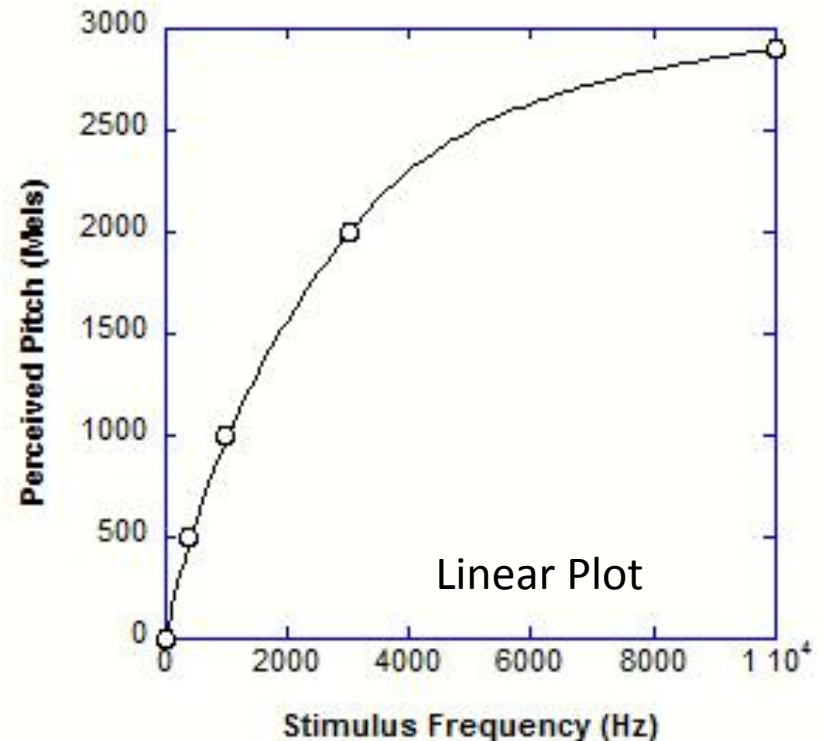
Pitch = f(Frequency)

MEL Scale



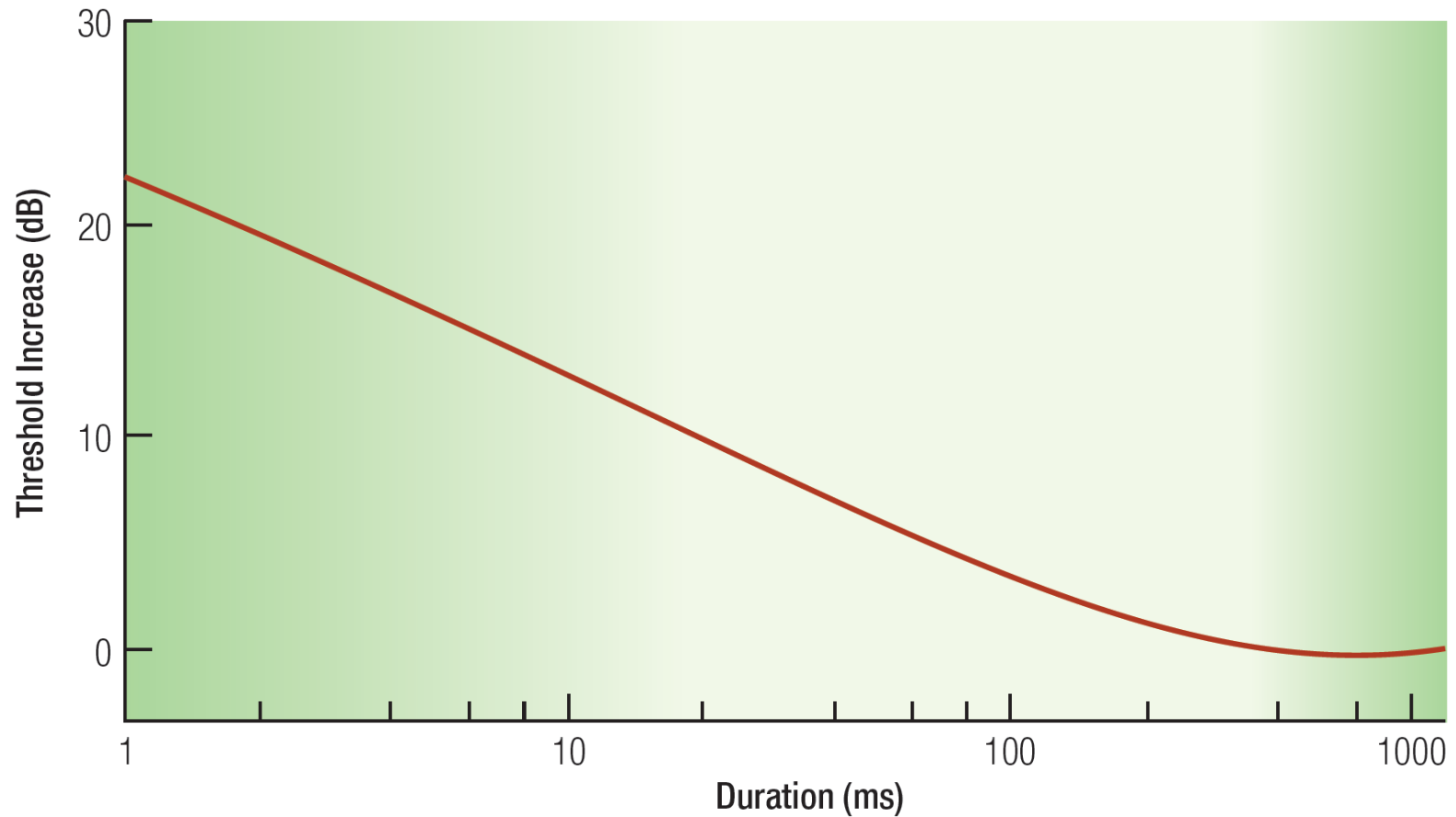
Reference unit of perceived PITCH:
1000 Hz = 1000 Mels

Perceived pitch increases “linearly” with stimulus frequency below 4KHz; but grows at a much slower rate at 4KHz and above.

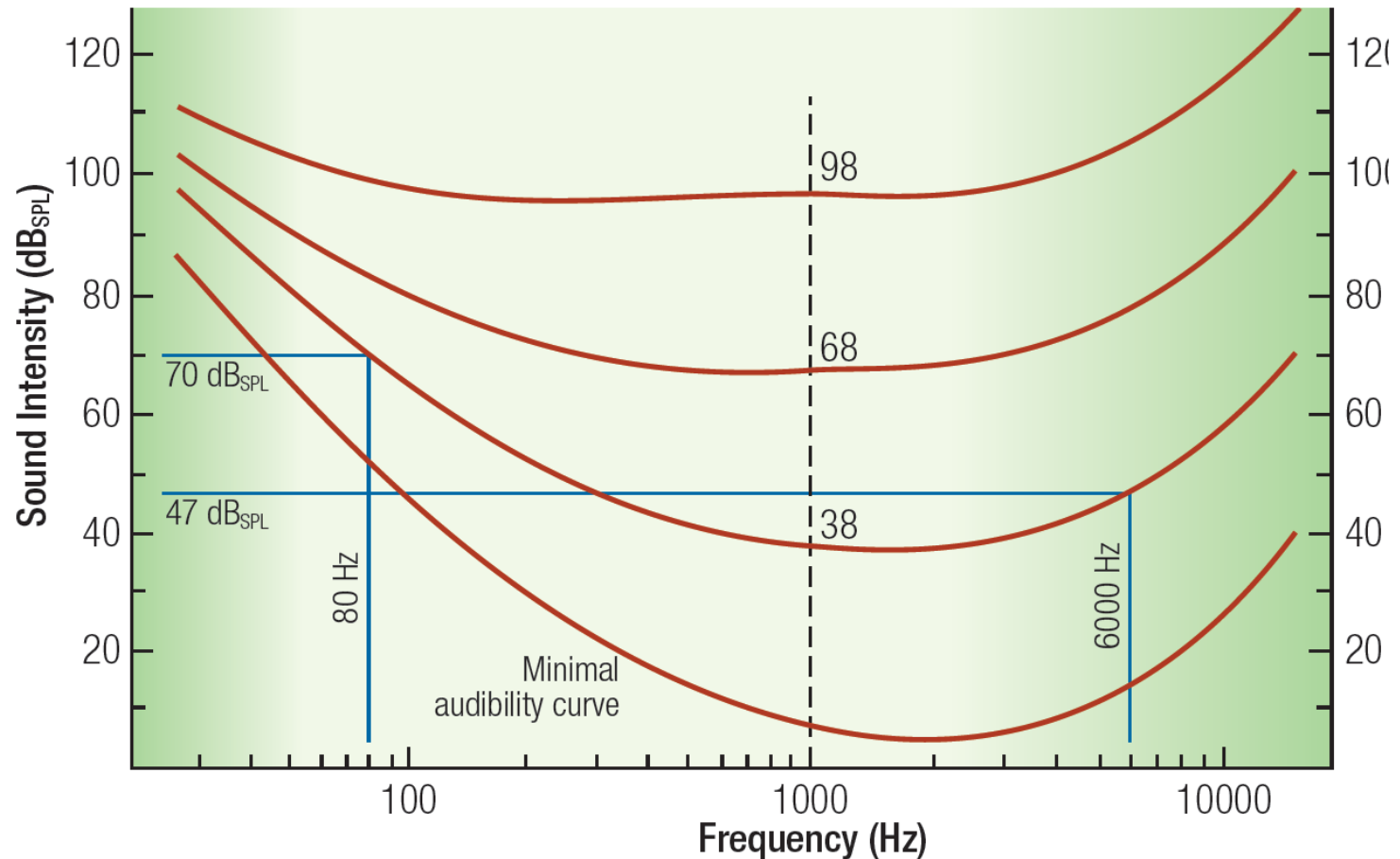


Temporal Summation (< 200 msec)

Complements Binaural (i.e., Spatial) Summation



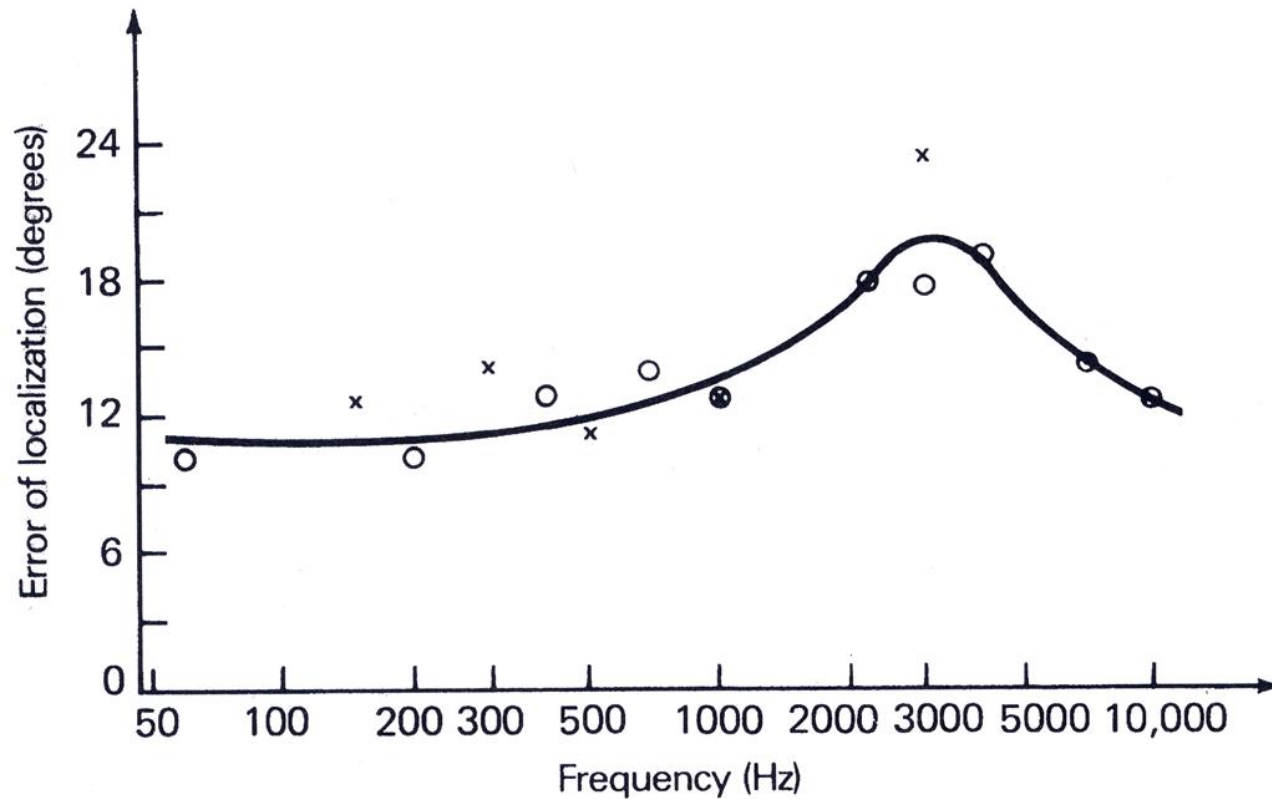
Equal Loudness Contours



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.

Sound Localization

Localization Accuracy vs. Frequency

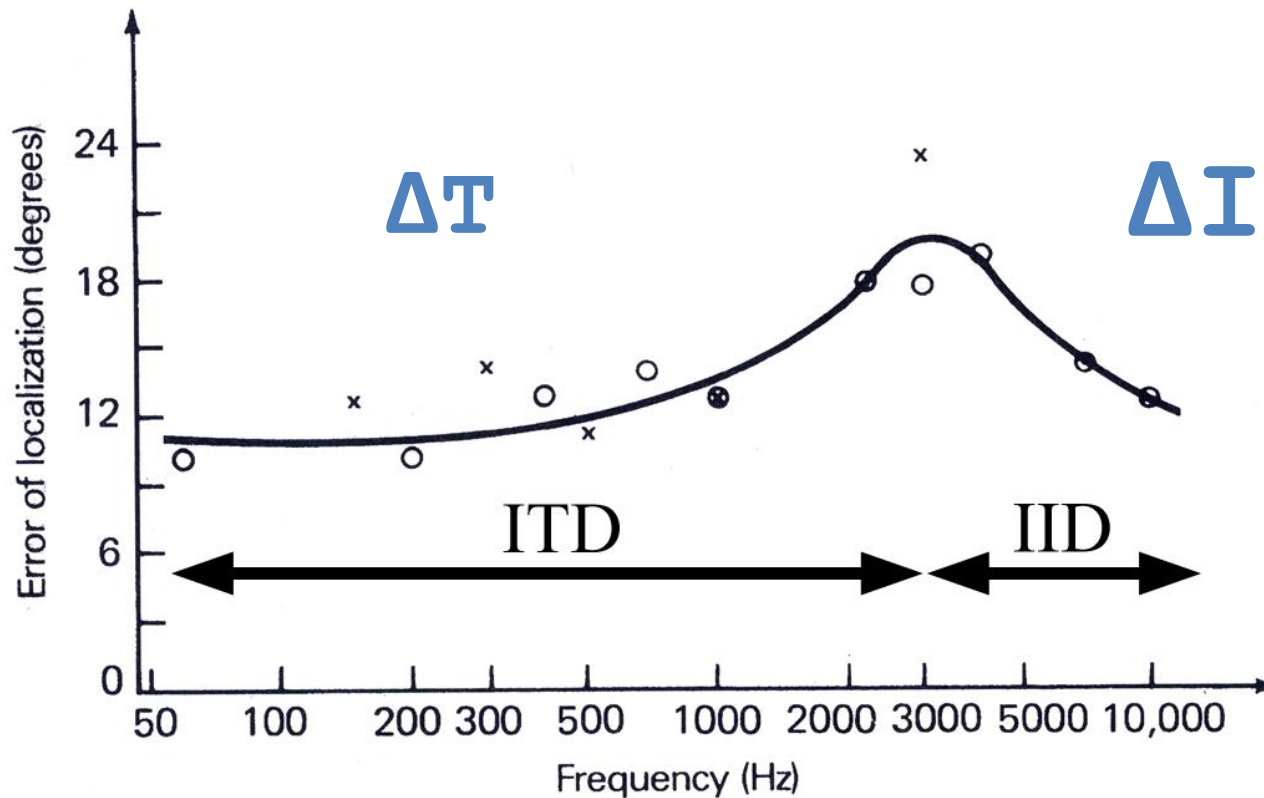


Signature of a dual-mechanism process?

Localization Accuracy vs. Frequency:

Low Freq – Interaural Time Difference

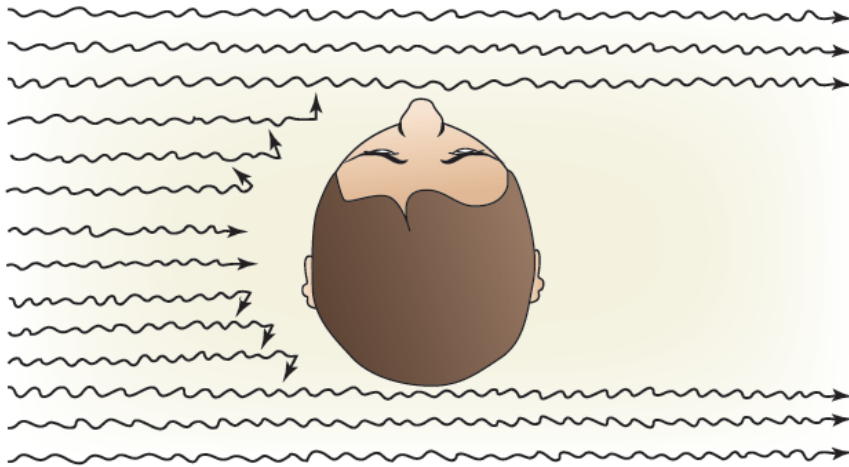
High Freq – Interaural Intensity Difference



Sound Shadowing

(Interaural Intensity Difference –IID)

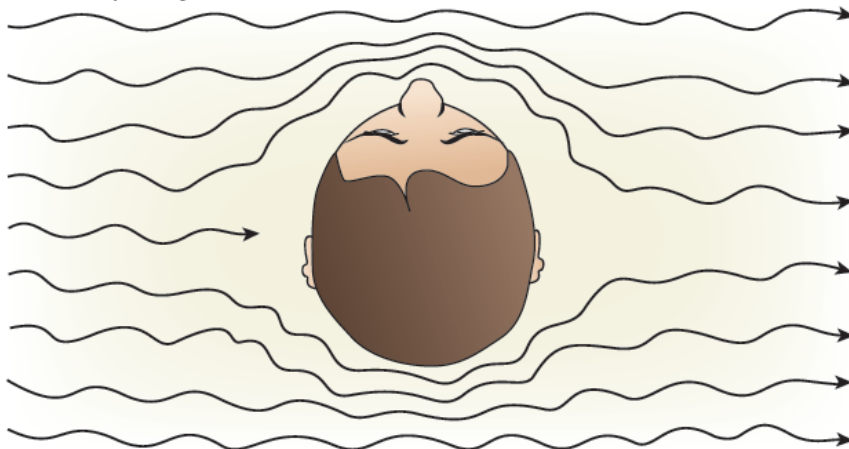
High frequency sound



High-frequency sound waves are “blocked” by the human head and cast a “shadow” at the far ear

(Strong IID cue)

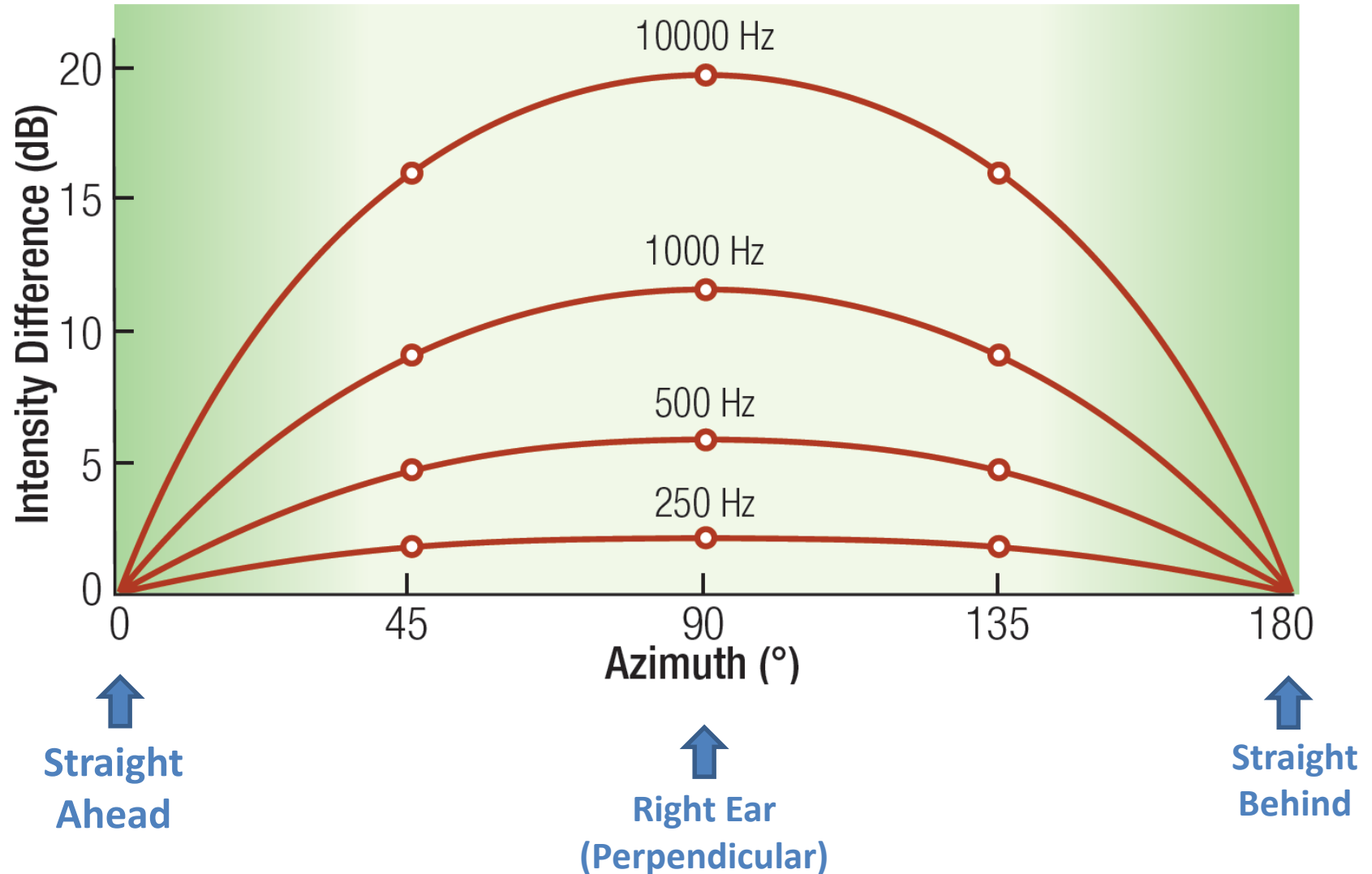
Low frequency sound



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

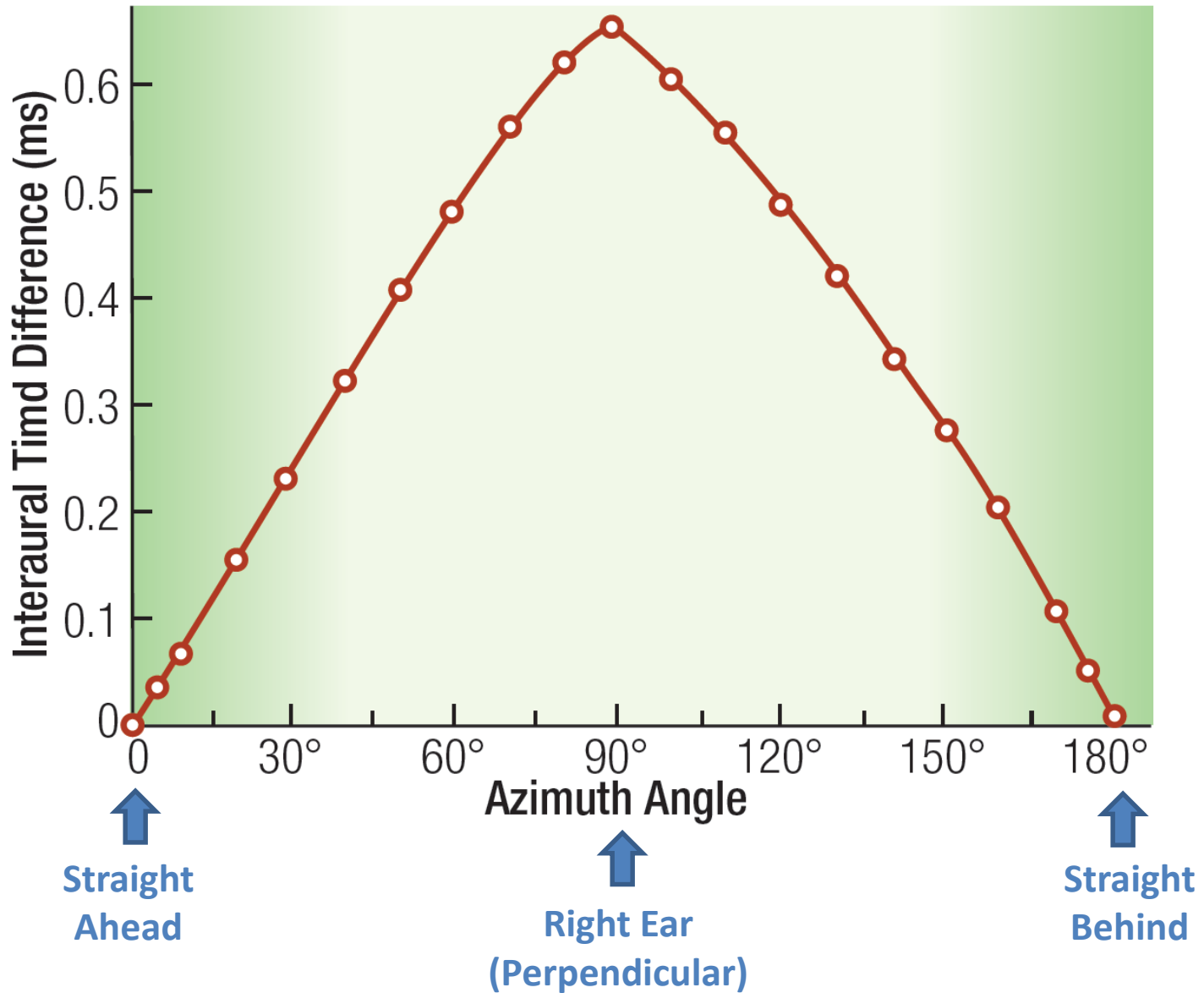
ΔI

IID = f(Location, Frequency)



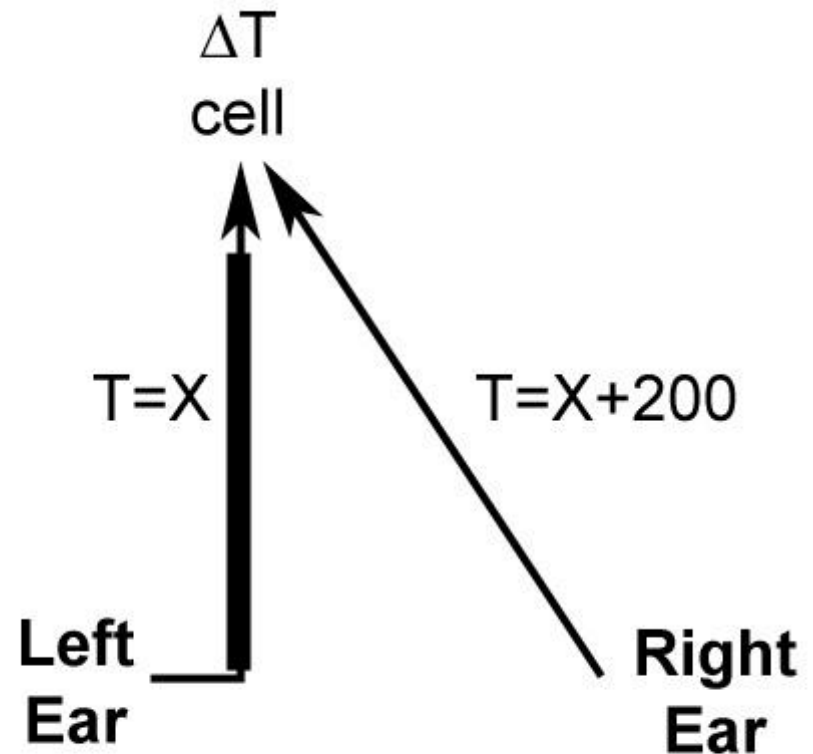
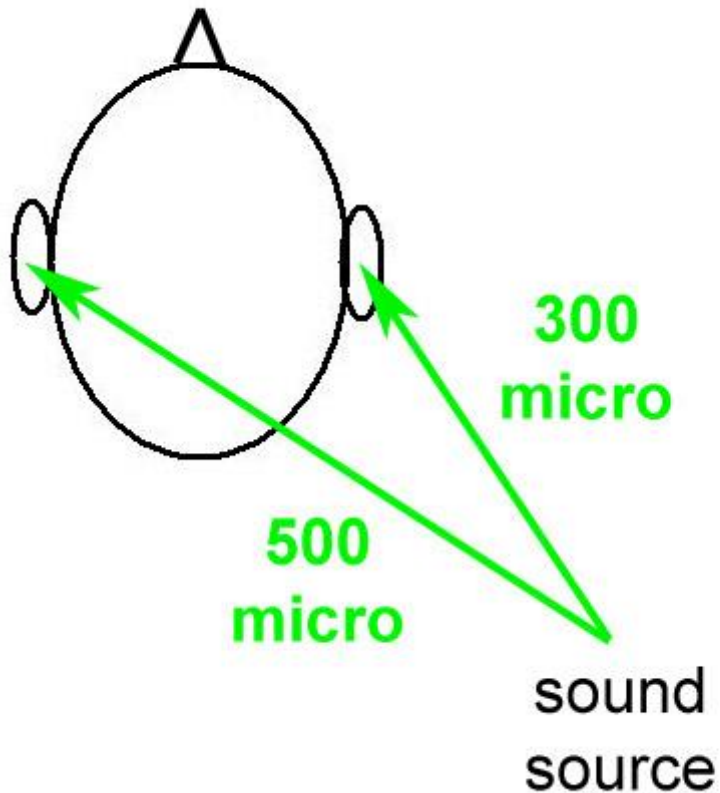
ITD versus Location

ΔT



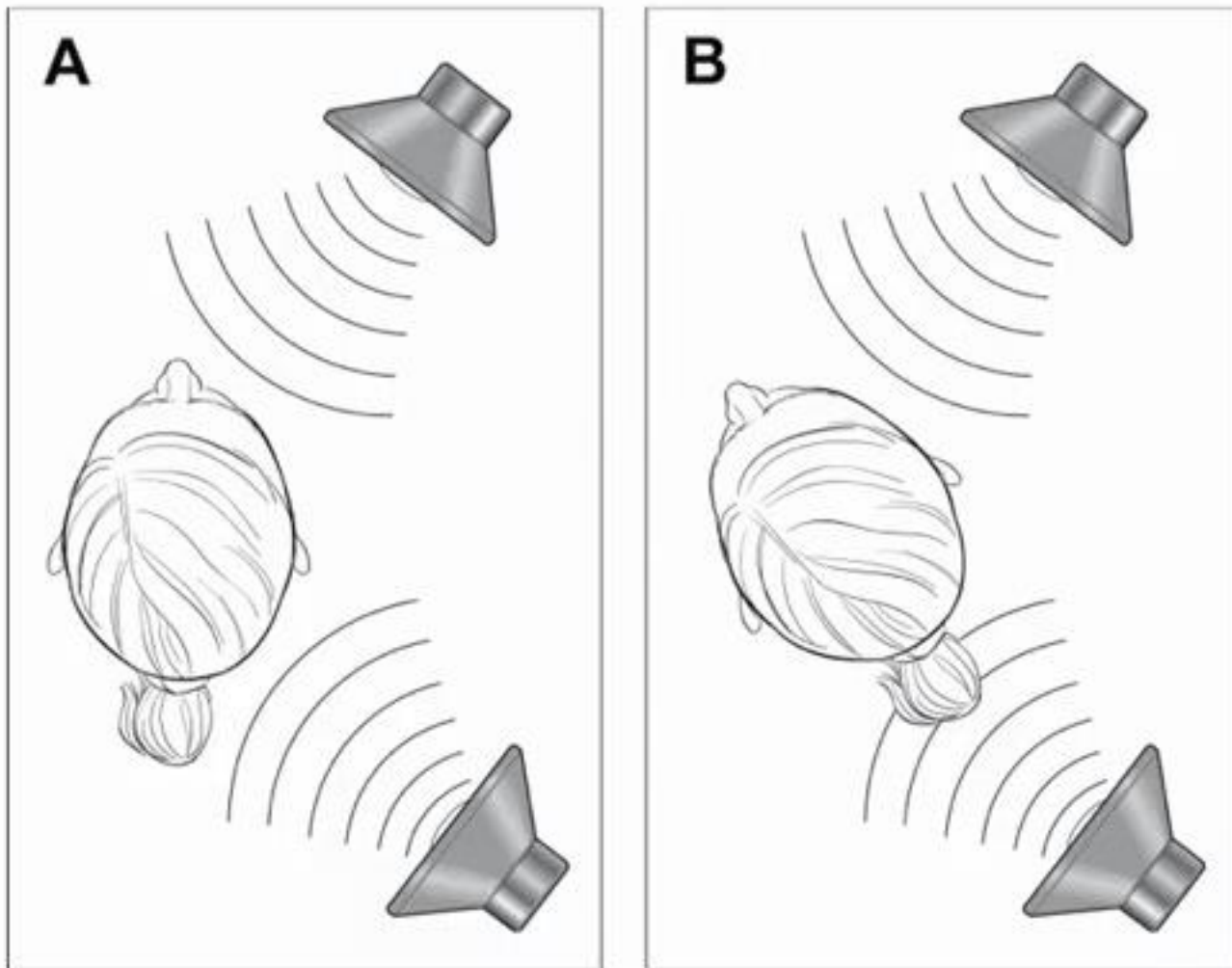
Delay Line Theory

(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

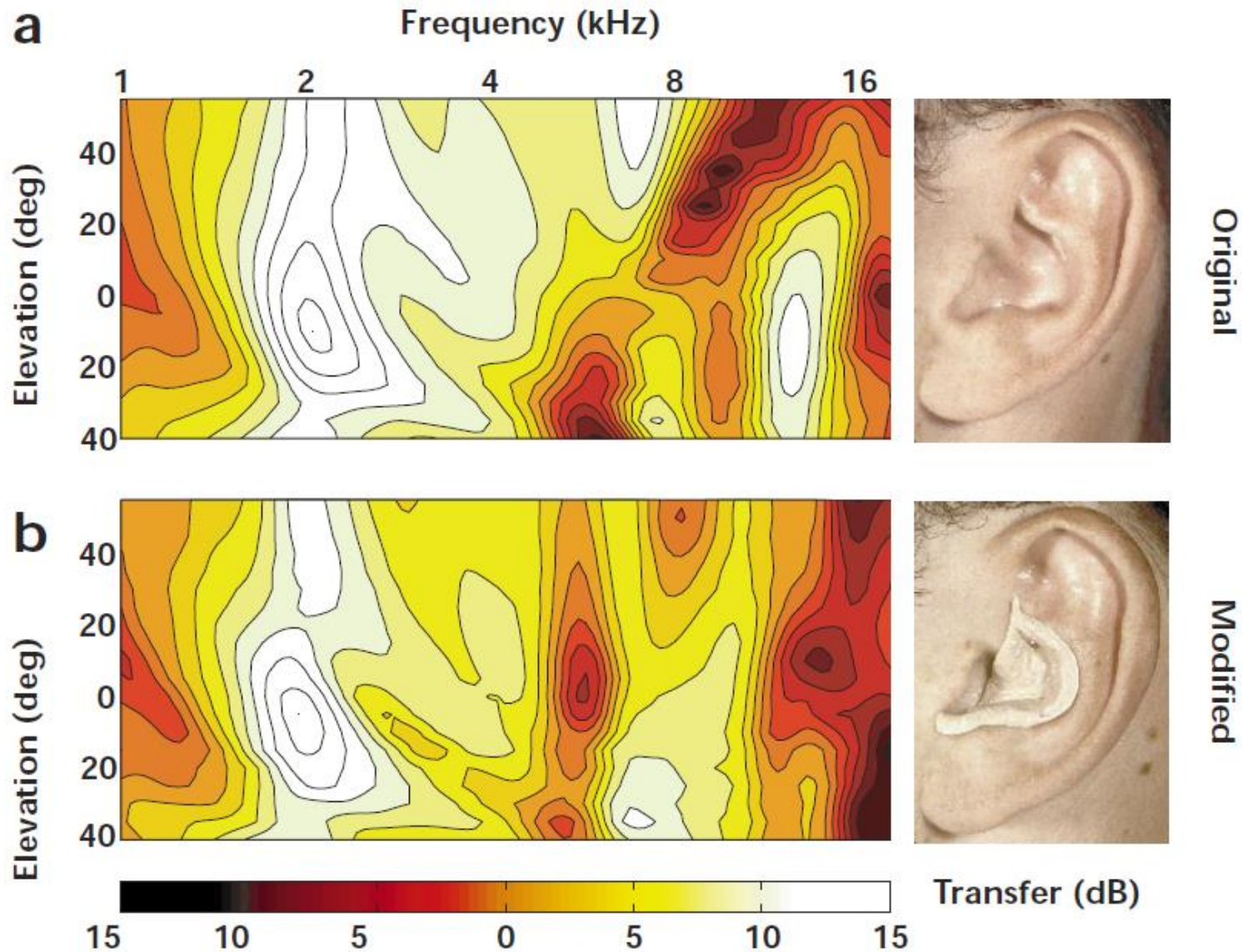
Modifying shape of pinna causes immediate reduction in localization accuracy (Hoffman, et al., 1998)

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

Modifying the Pinna Transfer Function

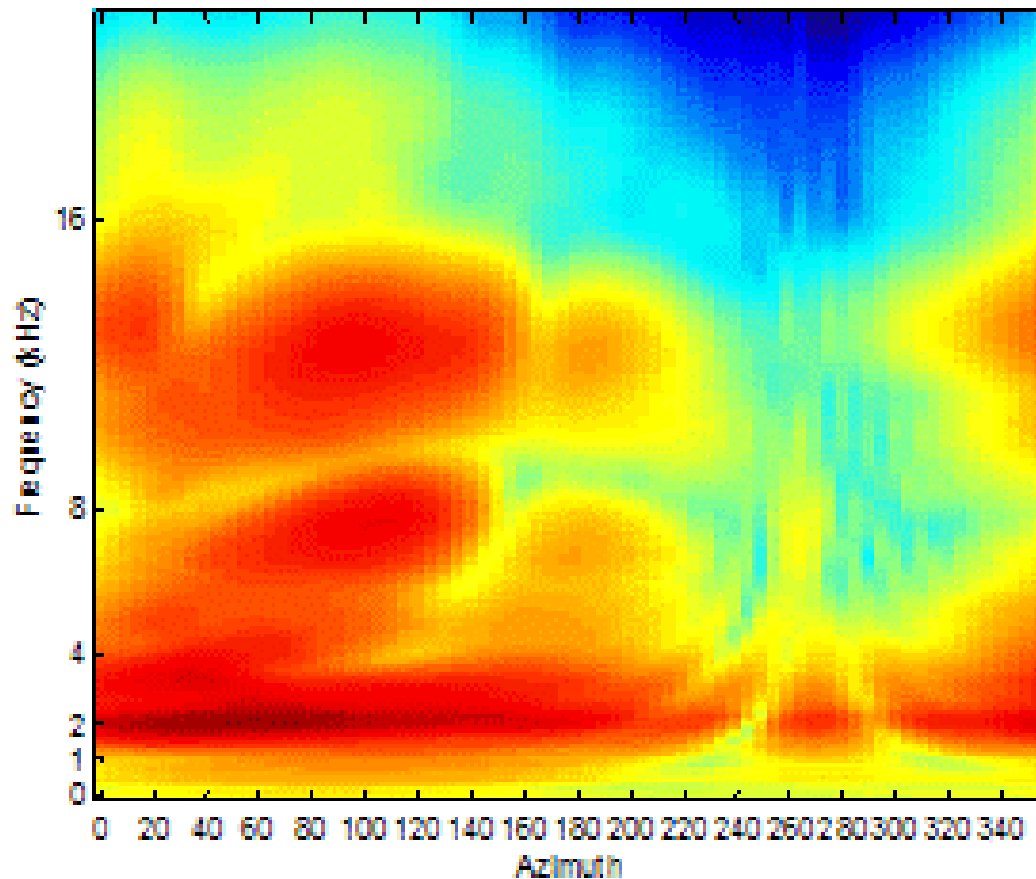
(Hoffman, et al., 1998)

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