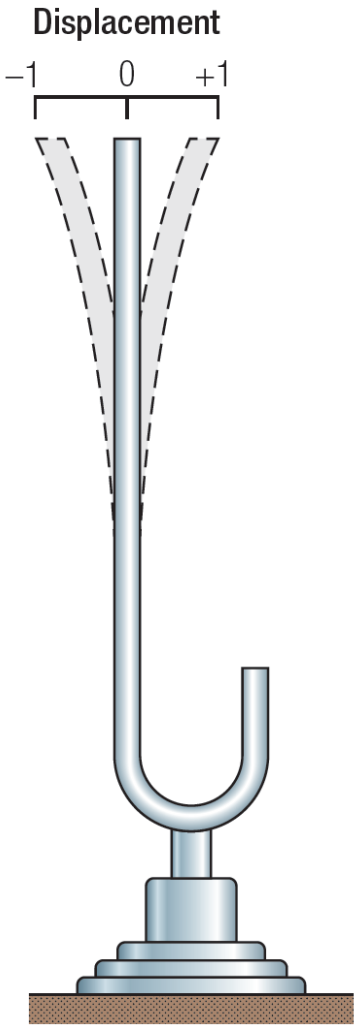
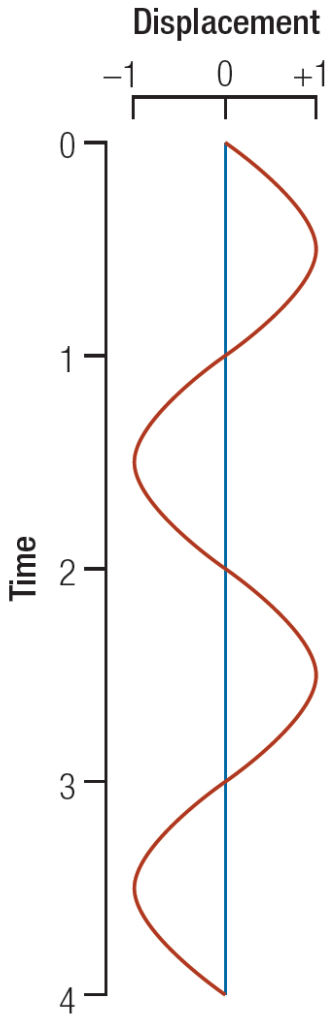
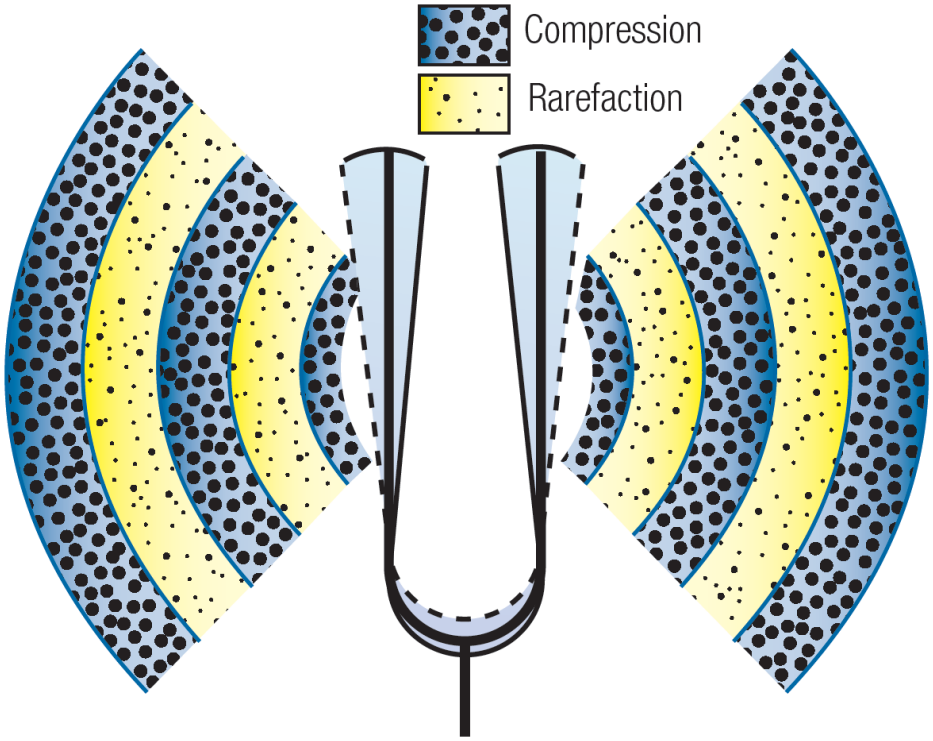
Sound and Hearing

Nature of the Sound Stimulus





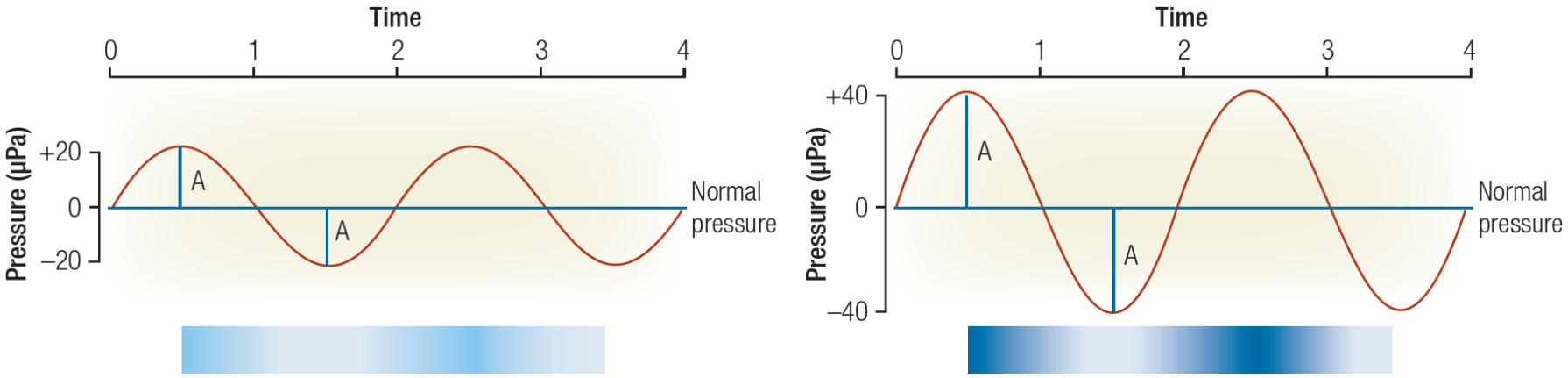


"Sound" is the rhythmic compression and decompression of the air around us caused by a vibrating object.

Applet

Applet2

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)

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

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:

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

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

-6 **dB_{SPL}** = ½ sound pressure

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

-20 **dB_{SPL}** = 1/10 pressure

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_{SPL} then how much sound amplitude would be expected from two machines side-by-side?

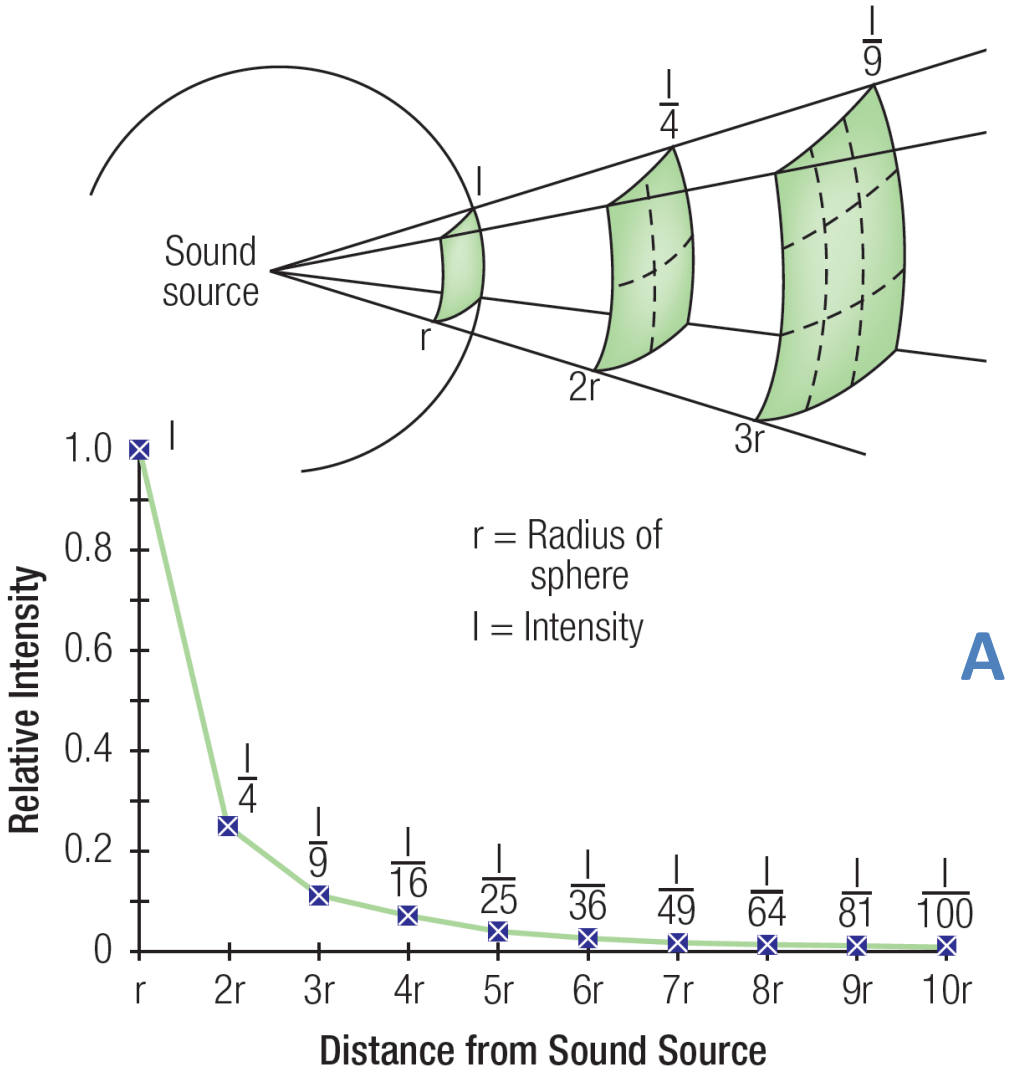
  2 x 80 = 160 dB_{SPL} ??? (That's pretty intense)

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

  80 dB_{SPL} → antiLog(80/20) → 10,000

  20 log (10,000+10,000) = 86 dB_{SPL} (approx.)

Inverse-Square Law

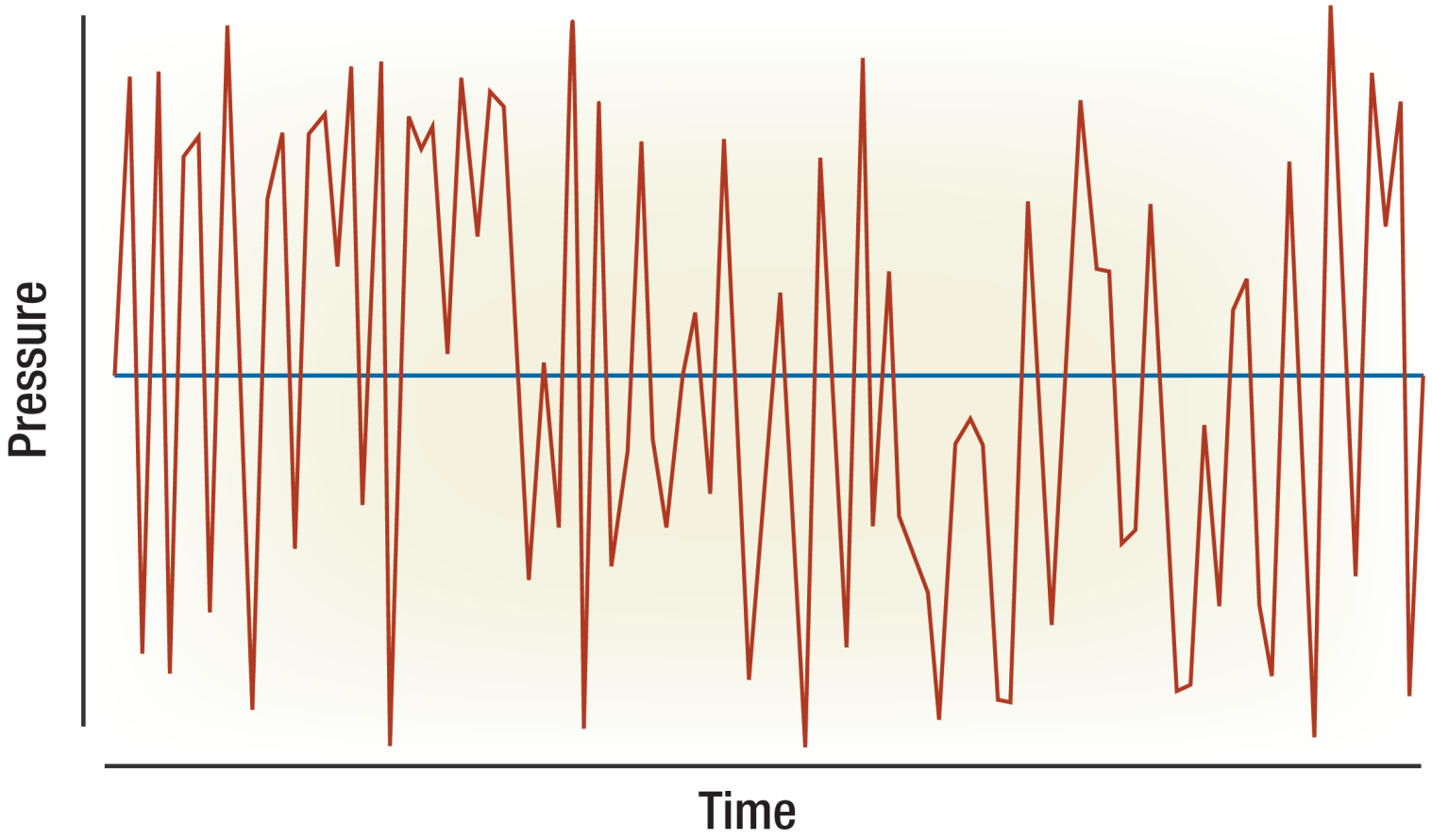


Area of sphere = $4\pi r^2$

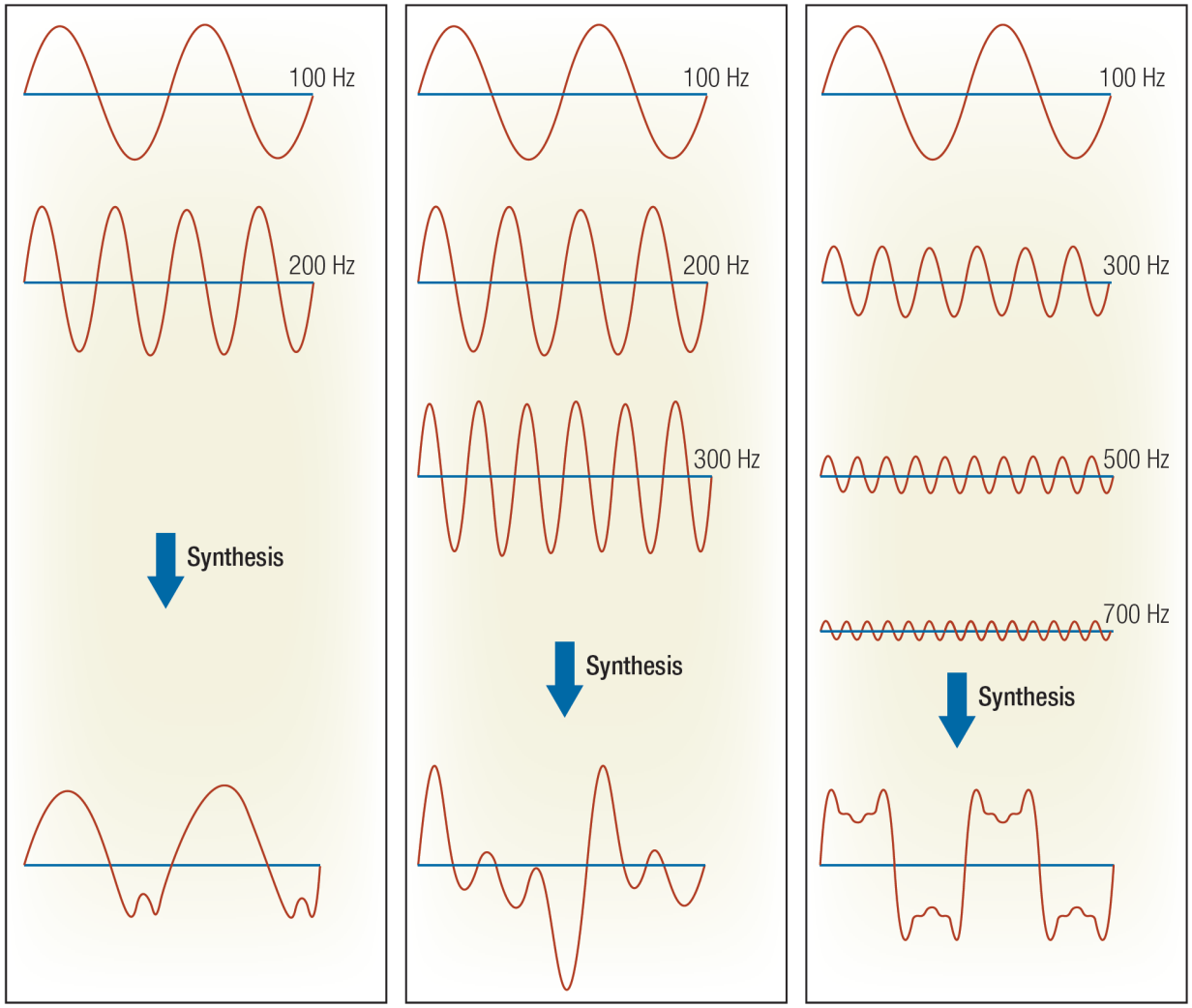
A “Better” Sound Amplitude Table?

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)

Beats Applet

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

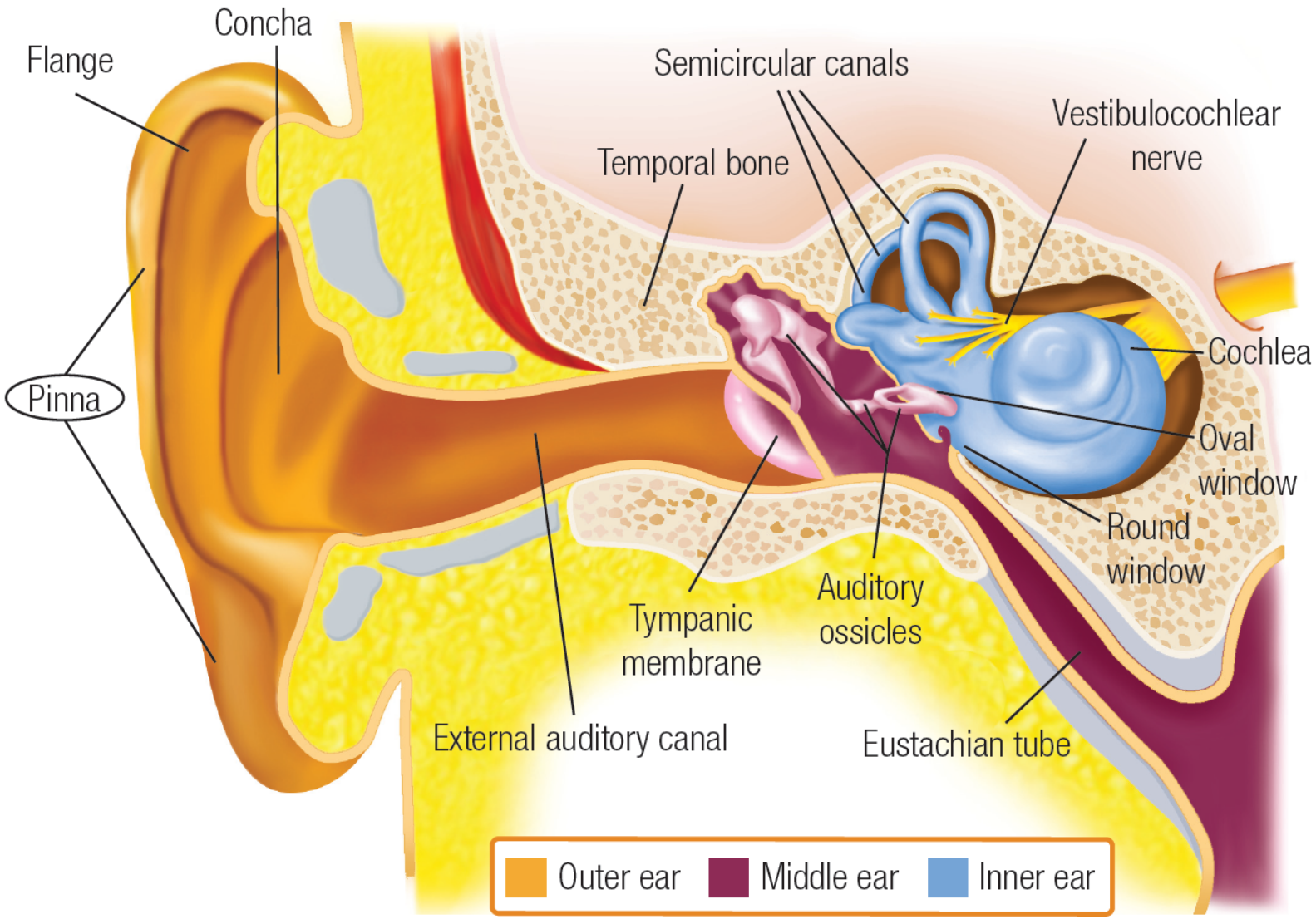
Acoustic energy results from a traveling wave of rhythmic "compression" through a physical medium (e.g., air; water; steel).

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).

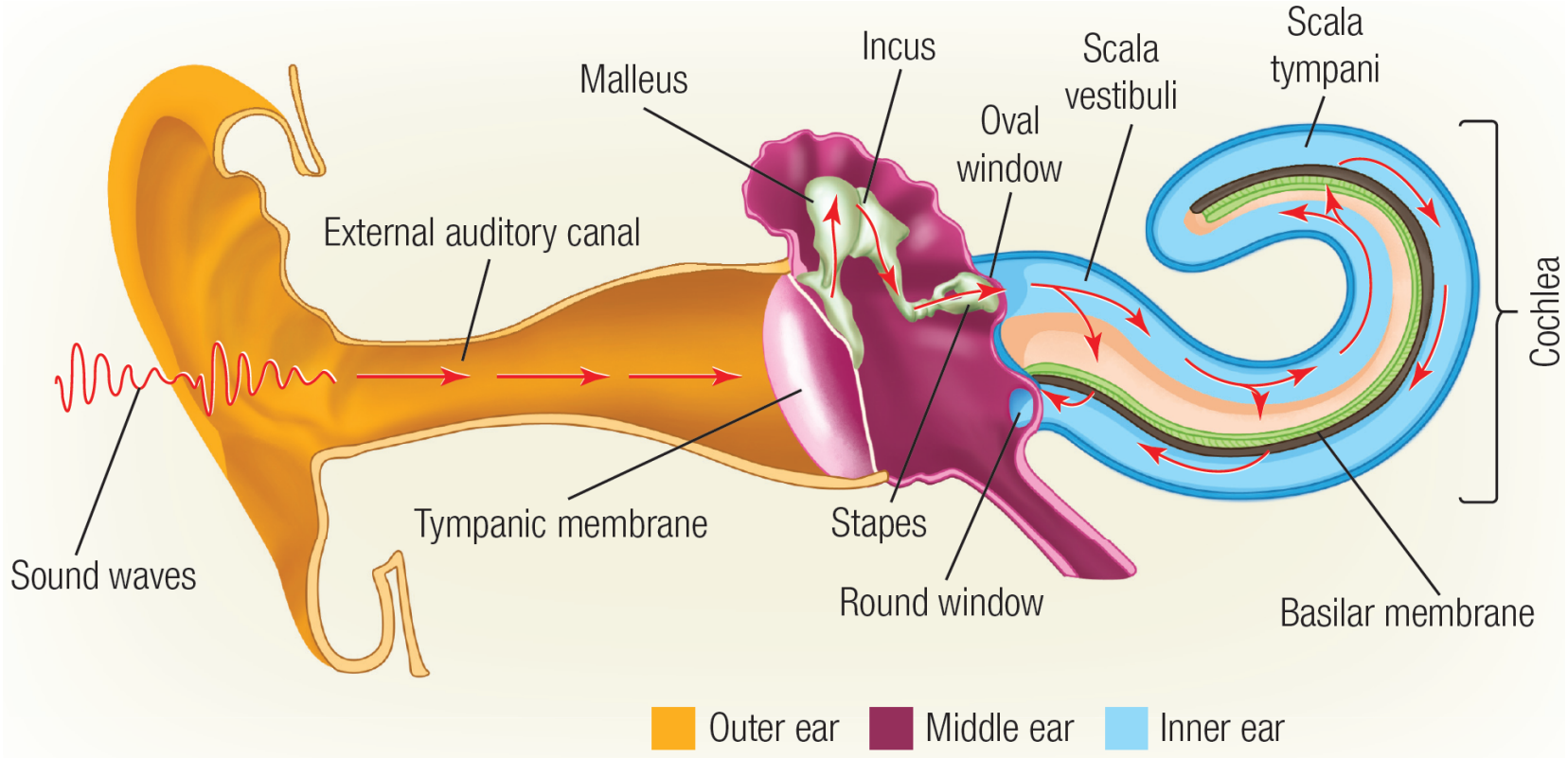
The speed of acoustic energy through the air (aka "sound") is 331 m/sec (or **742 MPH**) at 0-deg C (Faster at higher temperatures).

Gross Anatomy of the Ear

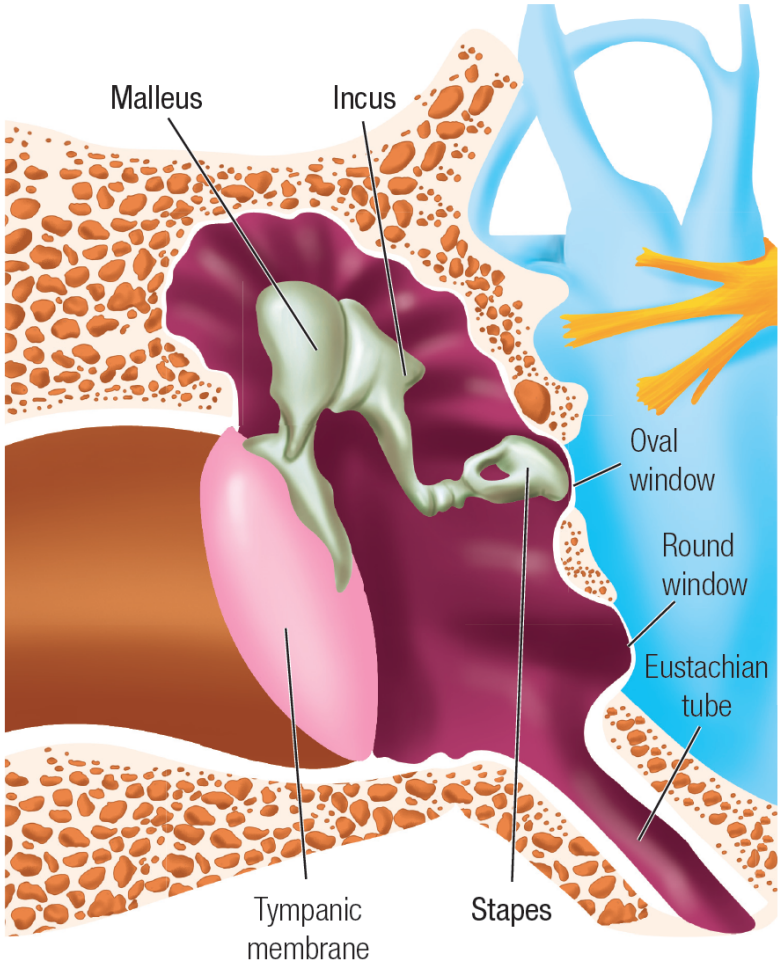


Flow of Acoustic Energy

(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)

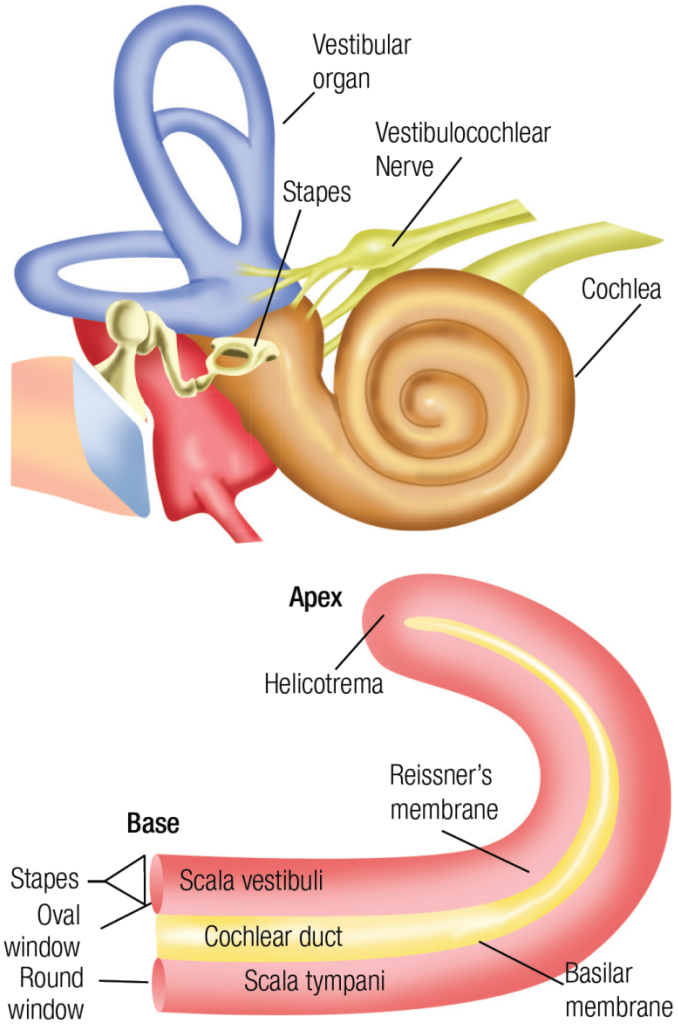
How does the ear compensate for this loss as sound energy is transmitted from the air to the fluid that filled the cochlea?

2 dB gain via ossicular leverage (1.6x)

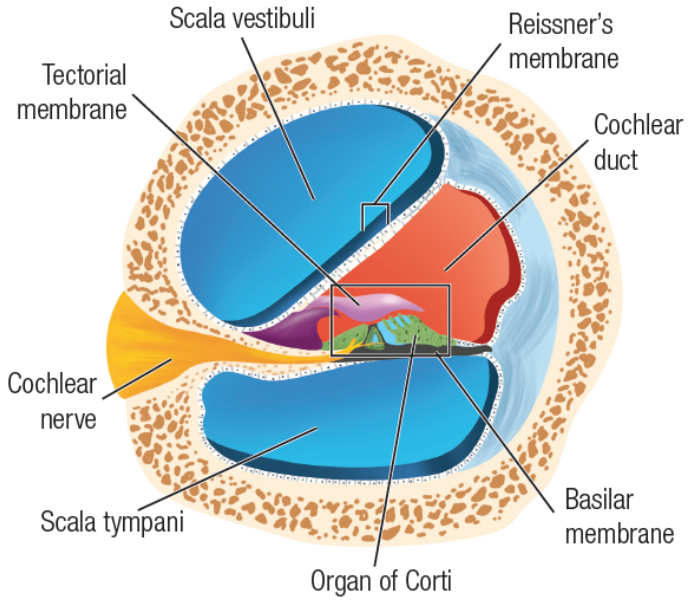
25 dB gain via surface area condensation (eardrum → stapes) (316x)

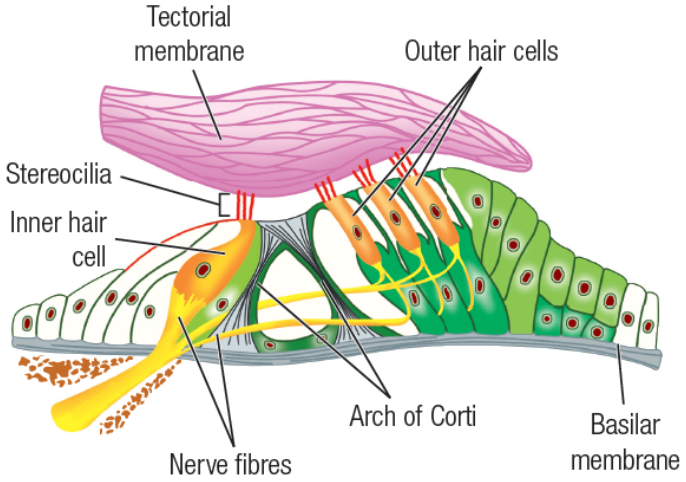
~5 dB gain at mid-frequencies (3x) due to pinna and auditory canal resonance

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)

Auditory Transduction

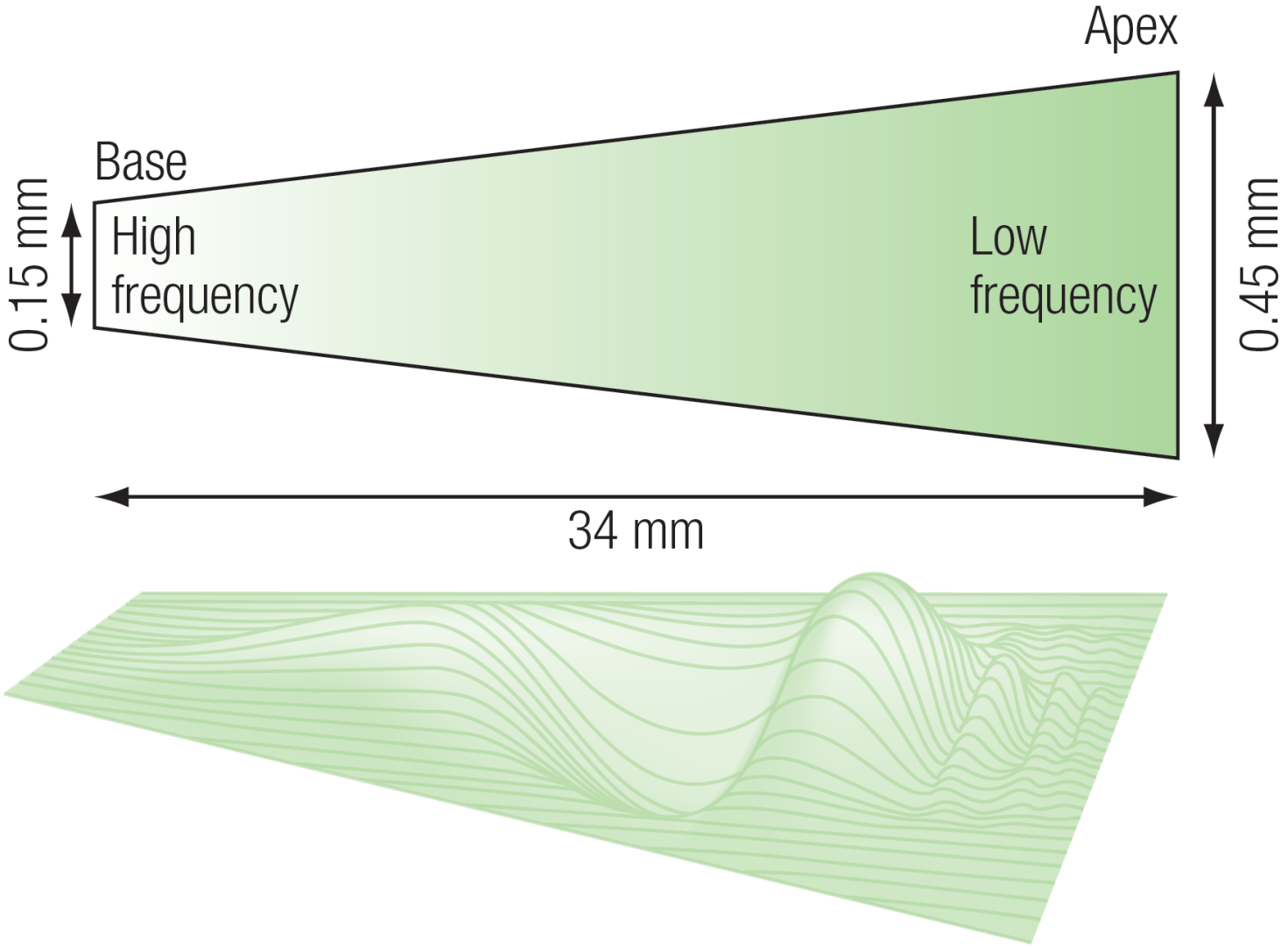
Photomicrograph: Sensory Hair Cells



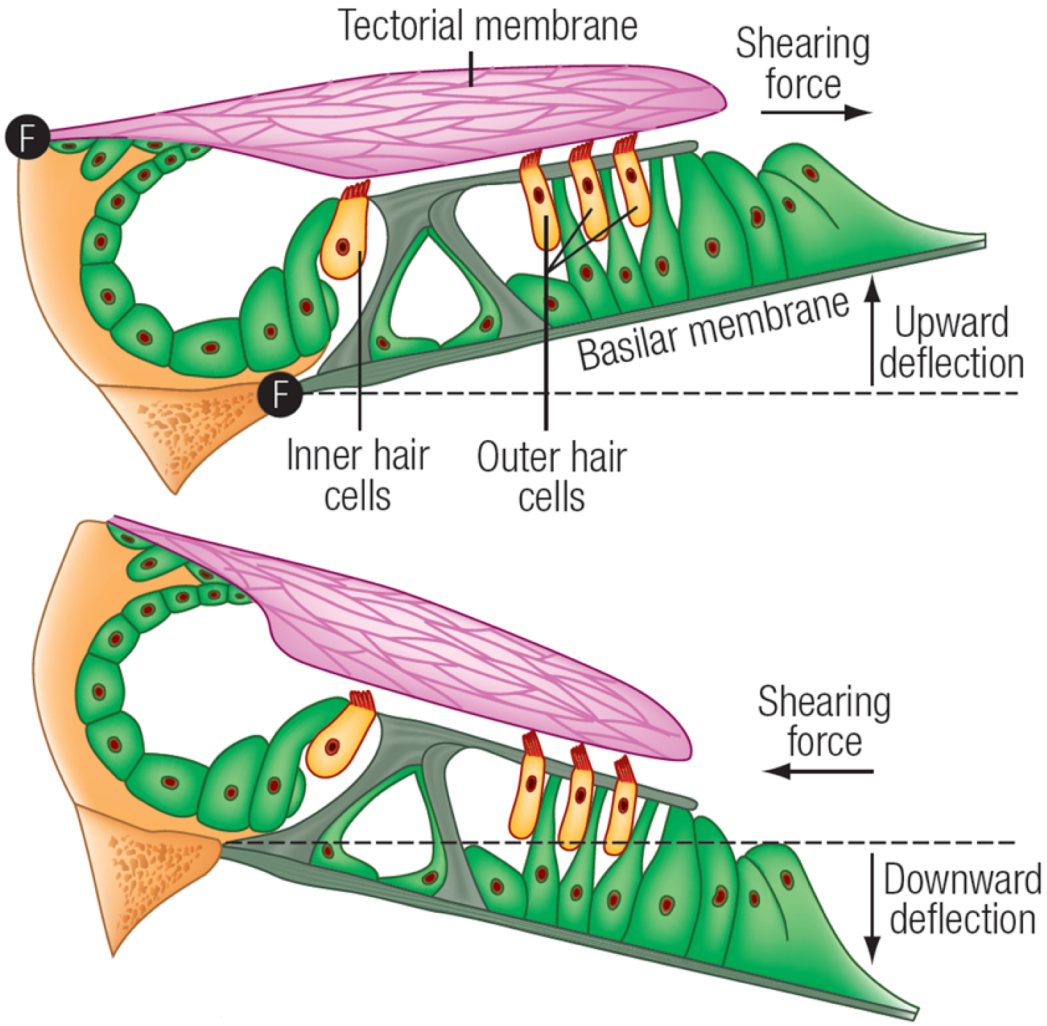
Three rows of
Outer Hair Cells

One Row of
Inner Hair Cells

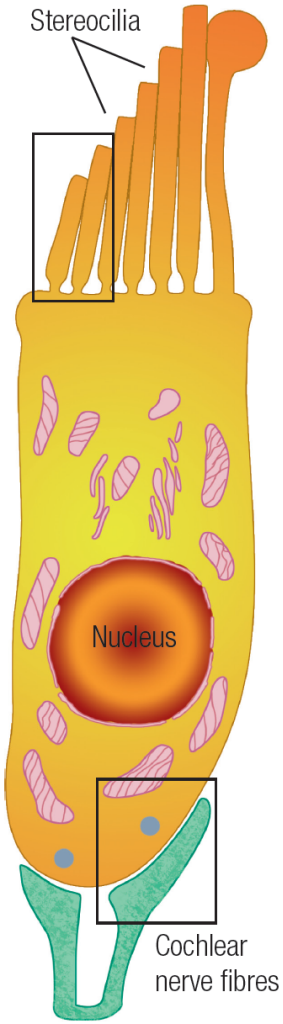
Basilar Membrane Response to Pure Tone Stimulus

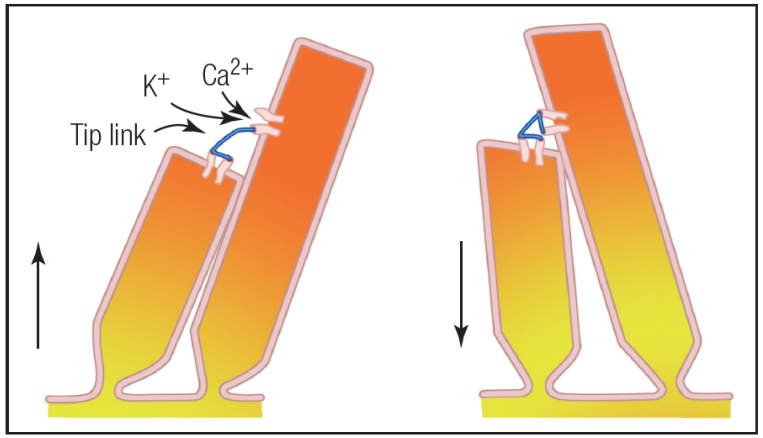


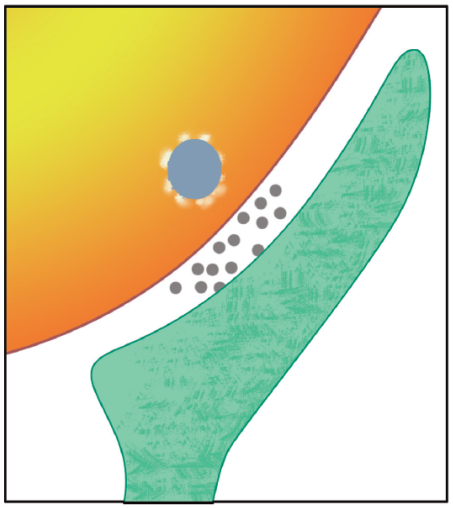
Basilar Membrane Modulation Effects upon Sensory Hair Cells



IHC Stereocilia "Tip Links"







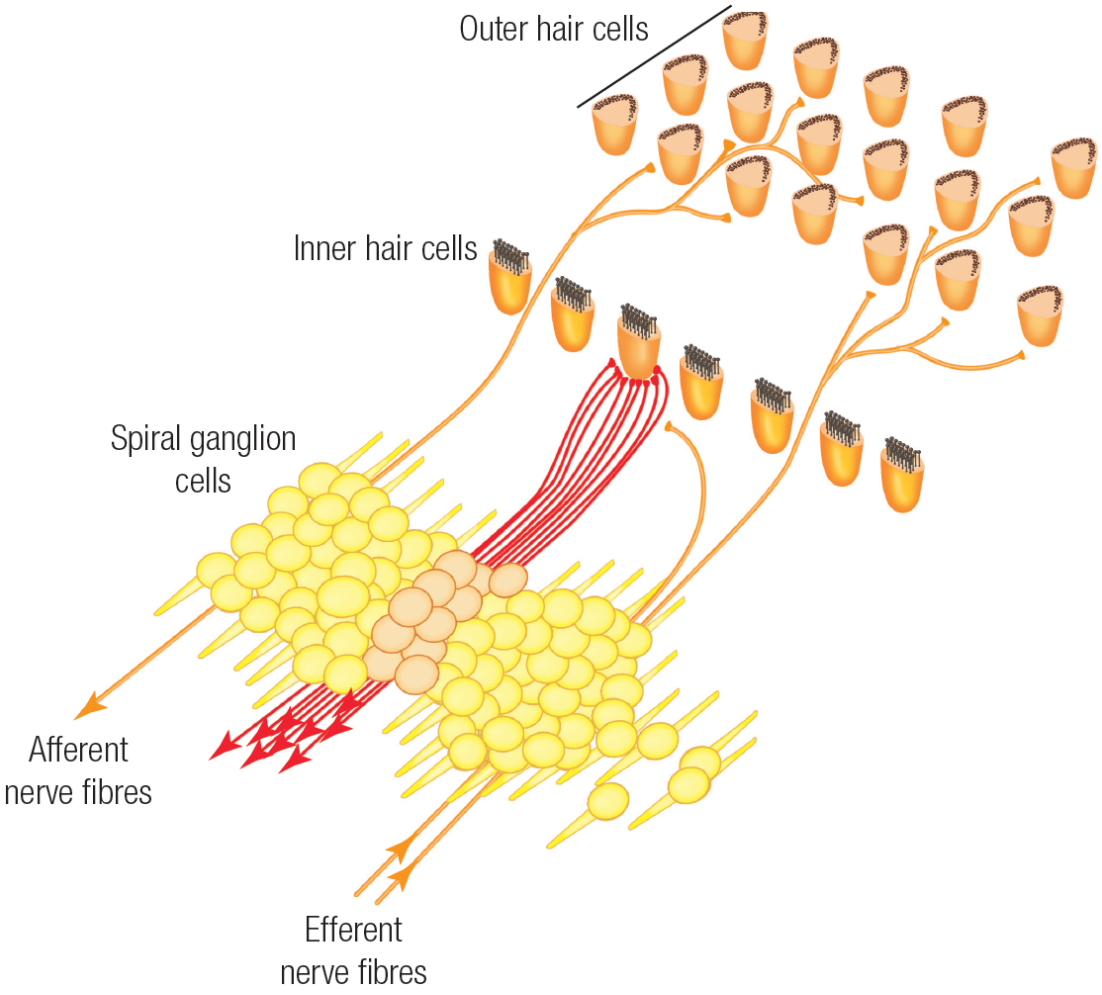
"tip link" connects gate to adjacent cilia.

Shearing motion forces gate to open.

Mechanical open-and-close of gate modulates influx of potassium ions (FAST).

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

Innervation of IHCs/OHCs



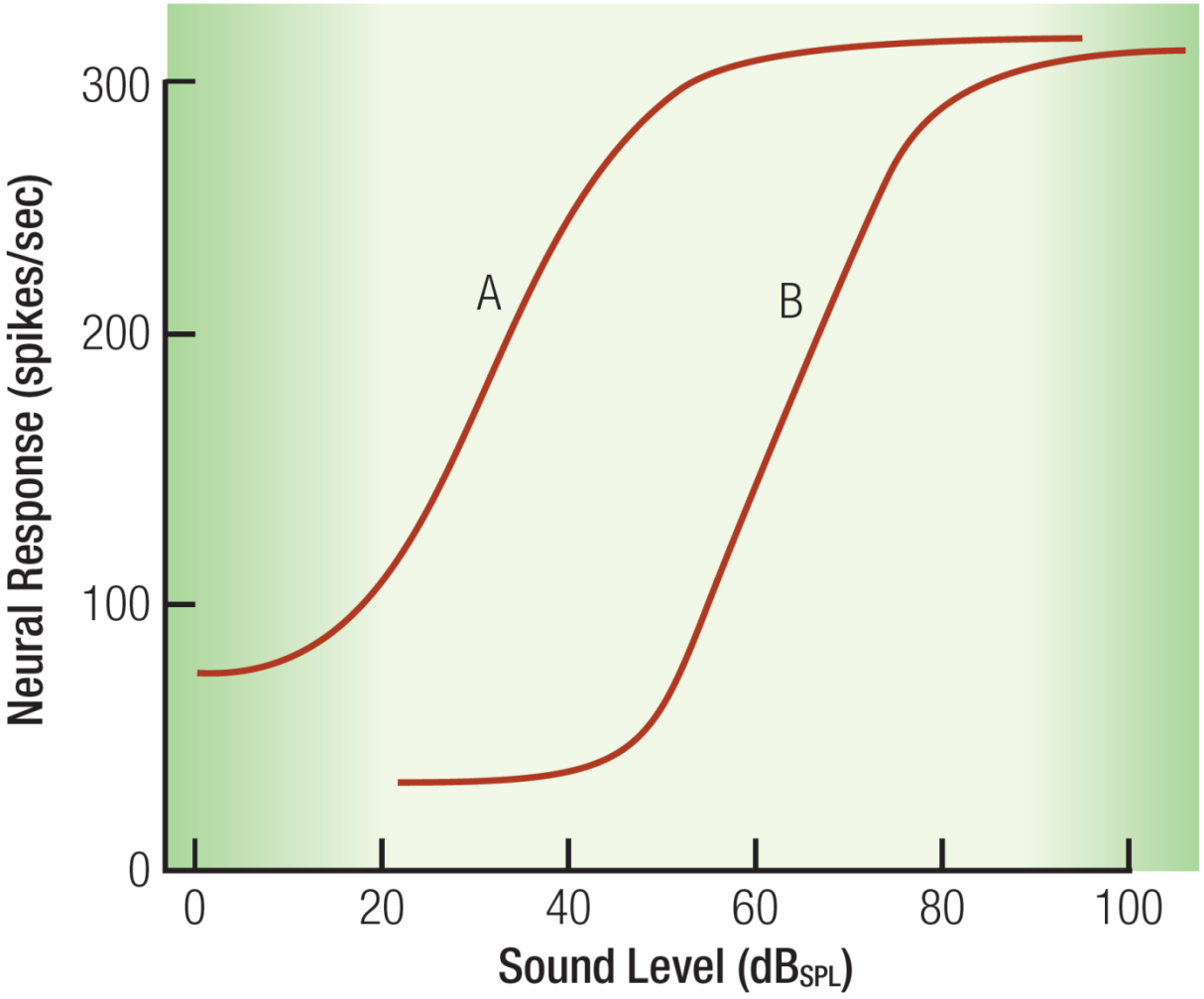
30K+ fibers in cochlear nerve. Nearly 10:1 fiber-to-IHC innervation ratio.

Sparse number of fibers carry info from OHC to brain.

Small number of fibers descend from brain to OHCs.

Role of OHC's?

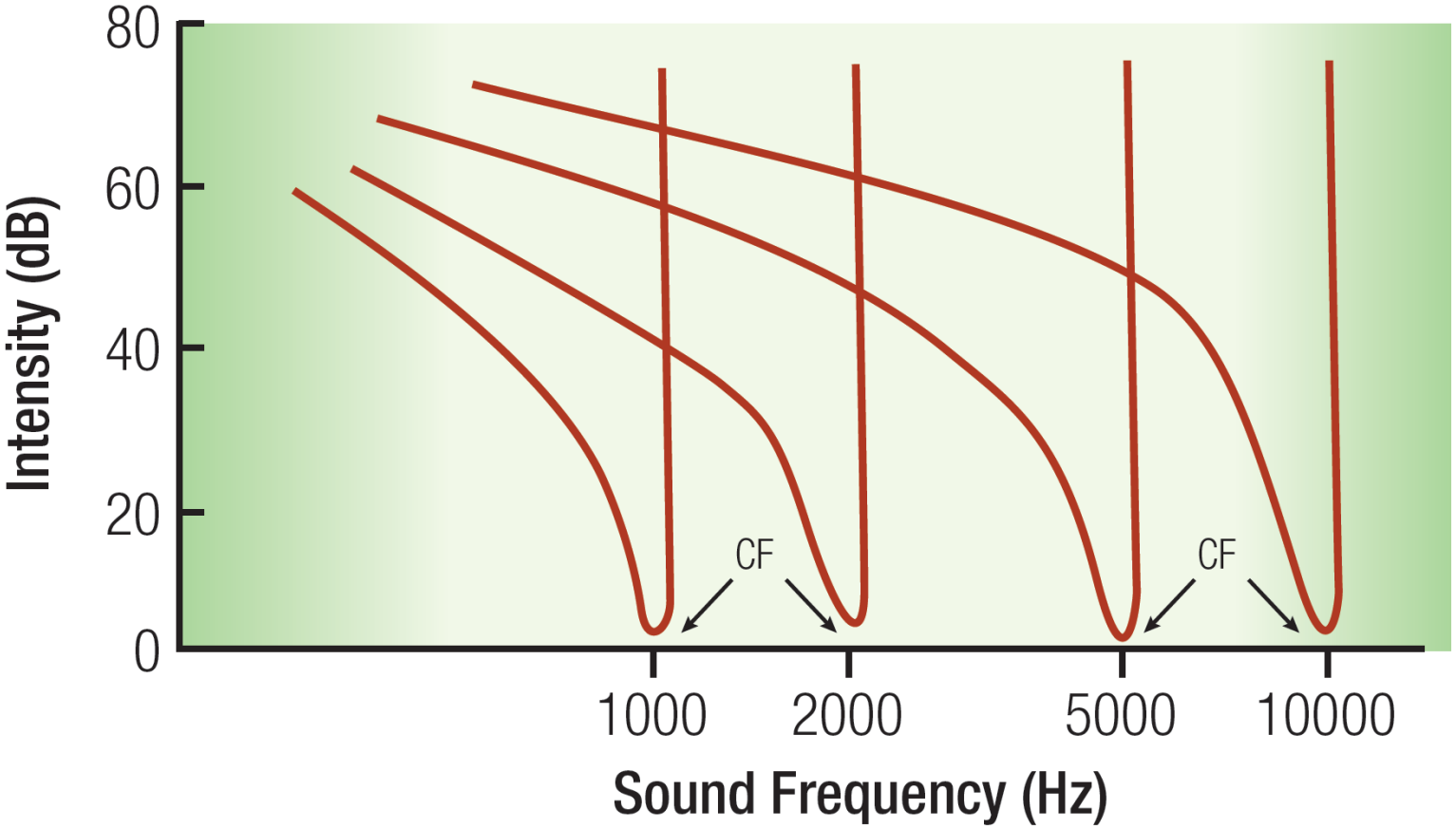
Amplitude Coding ("Divide and Conquer")



Multiple nerve fibers for each IHC.

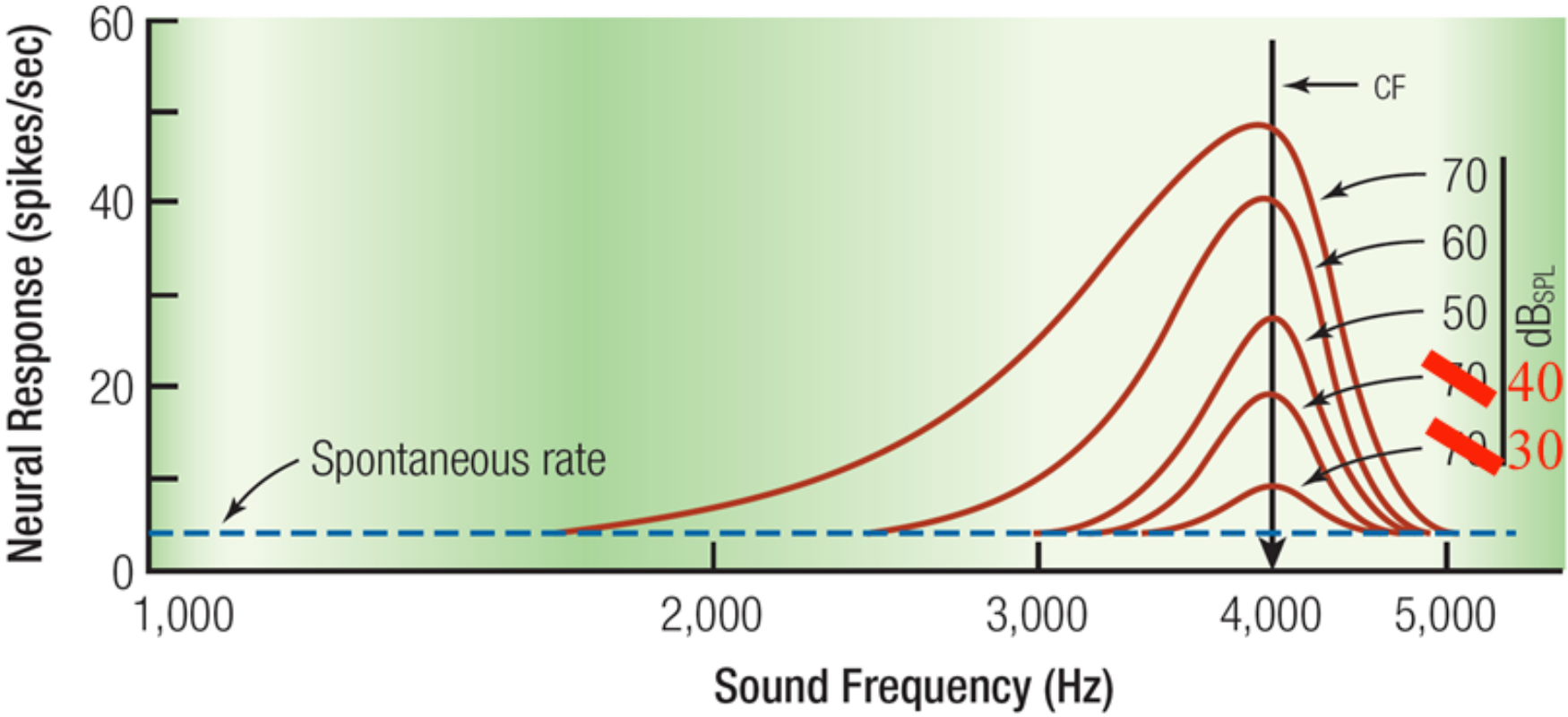
Each nerve fiber tuned to a different 40 dB "range" of stimulus intensity.

Asymmetrical Frequency Tuning of Cochlear Nerve Fiber "Thresholds"



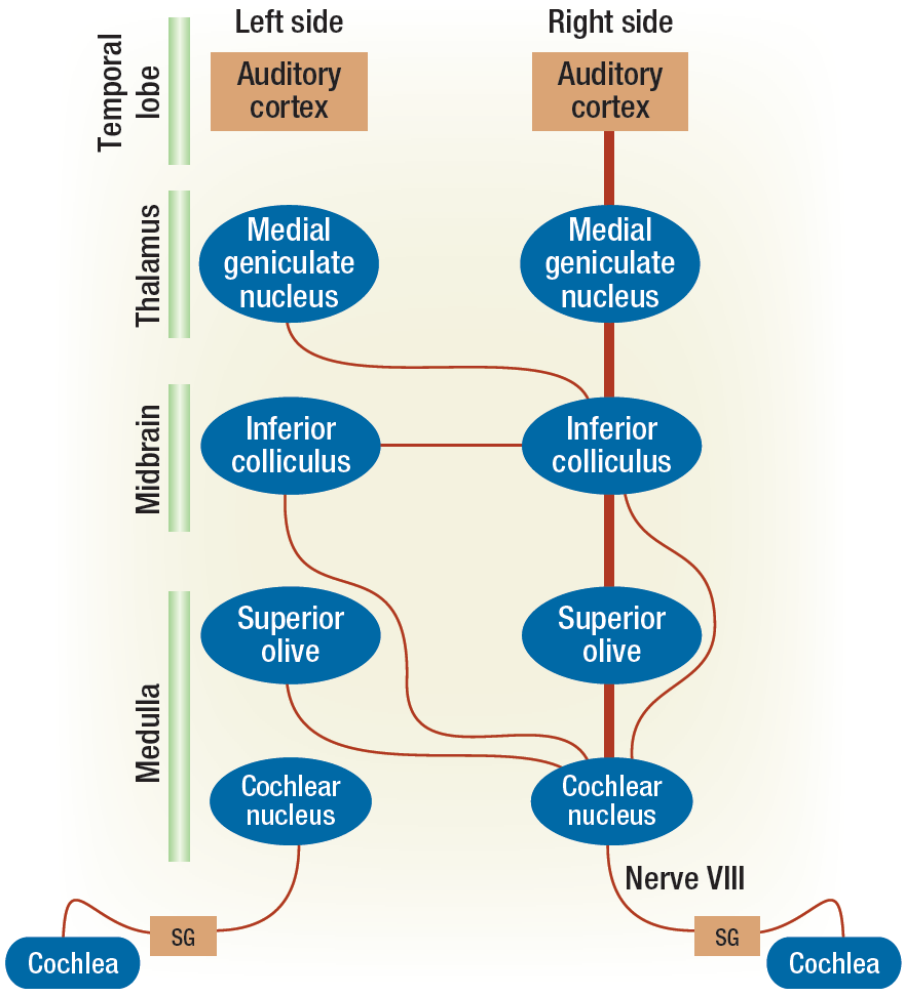
(Physiological basis for frequency-specific response explained below)

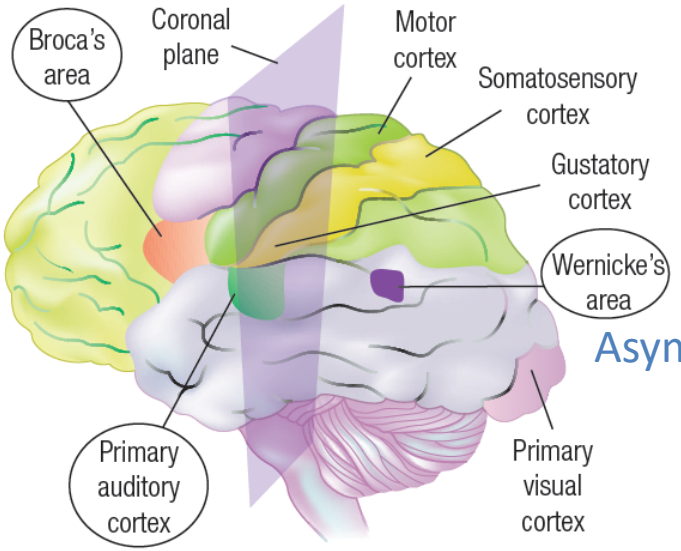
Tuning Specificity of Cochlear Nerve Fibers "Broadens" with Increased Intensity



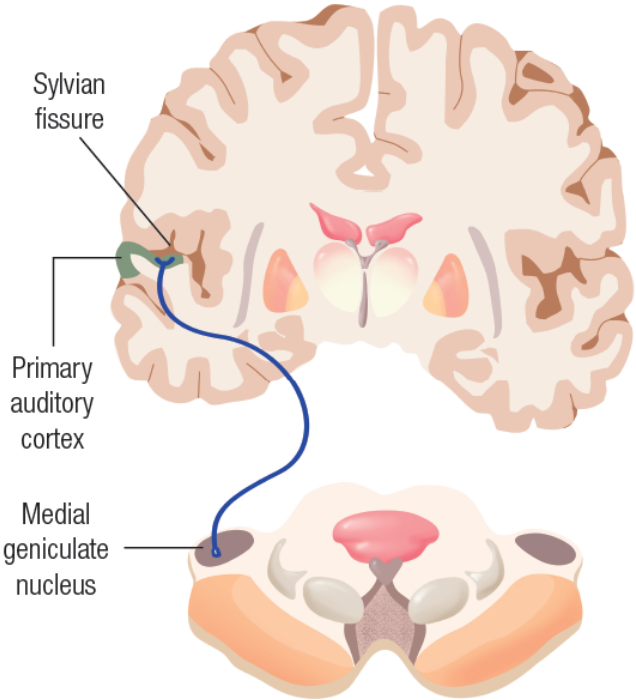
Q: Why the broadening and asymmetry? ~A: Look to the Basilar membrane

Ascending Pathways

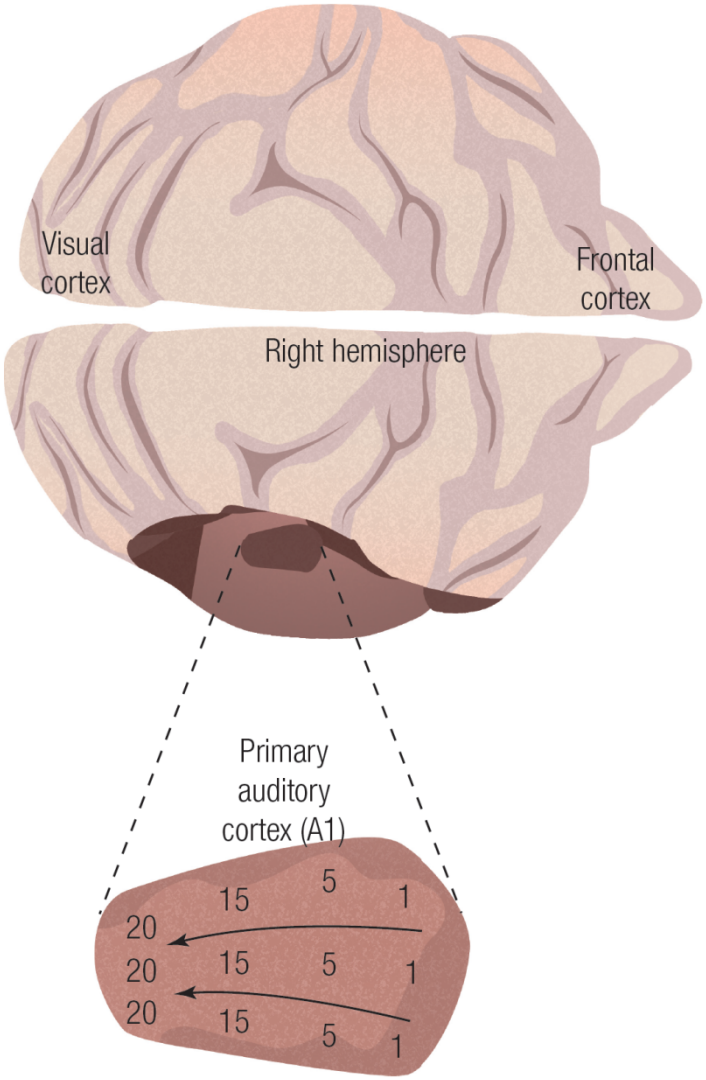




Asymmetry



Tonotopic Organization of Primary Auditory Cortex (A1)



Also note:

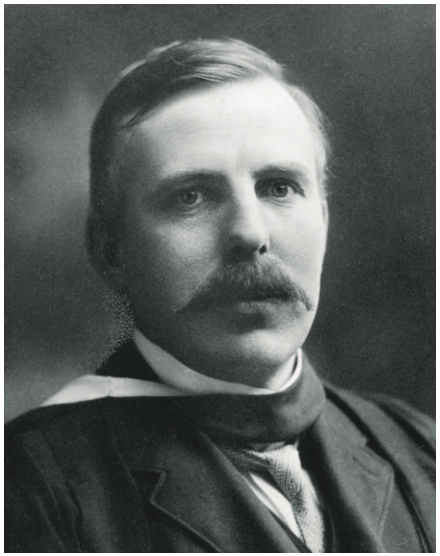
Segregation of monaural versus binaural cells is maintained.

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

Auditory Frequency Coding

Frequency Mechanism versus Place Mechanism

Frequency Theory



Ernest Rutherford
(1871-1937)

Place Theory

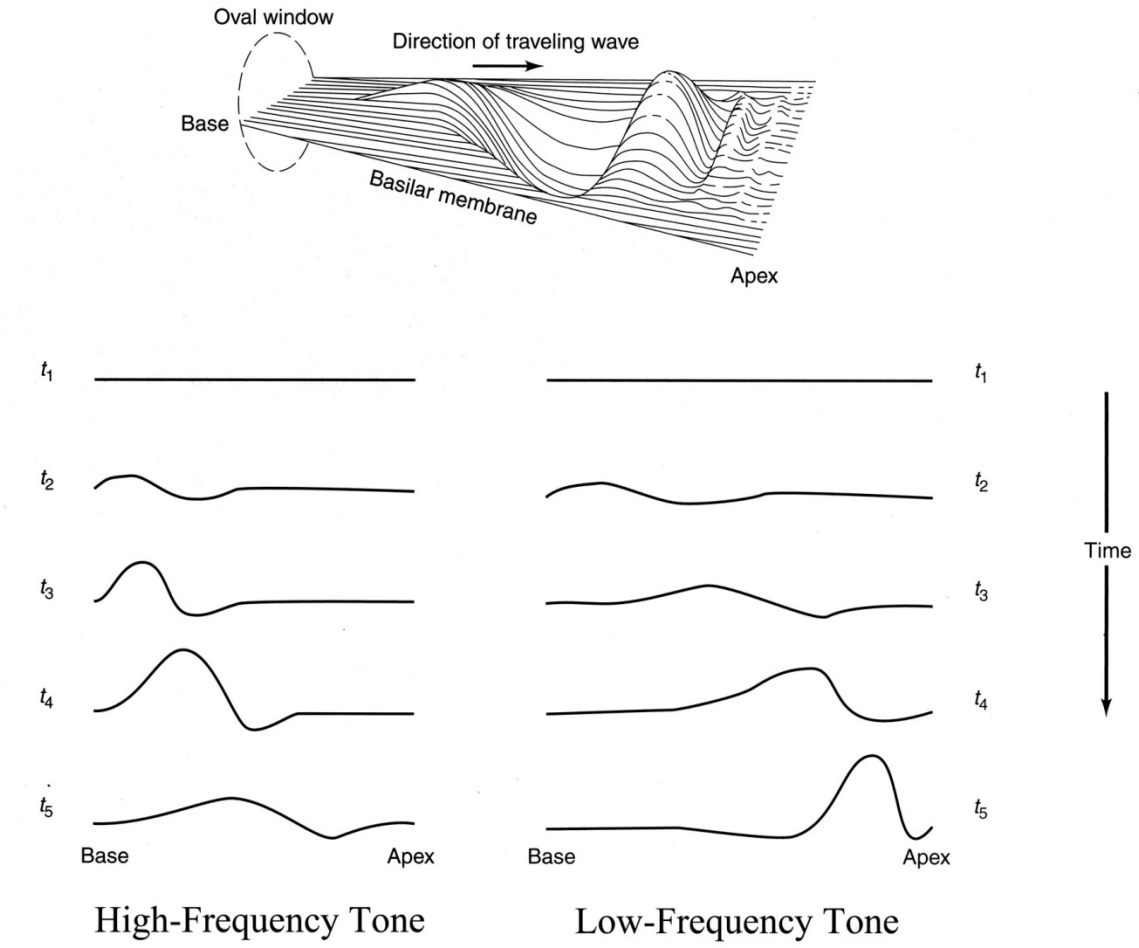


Georg von Békésy
(1899-1972)

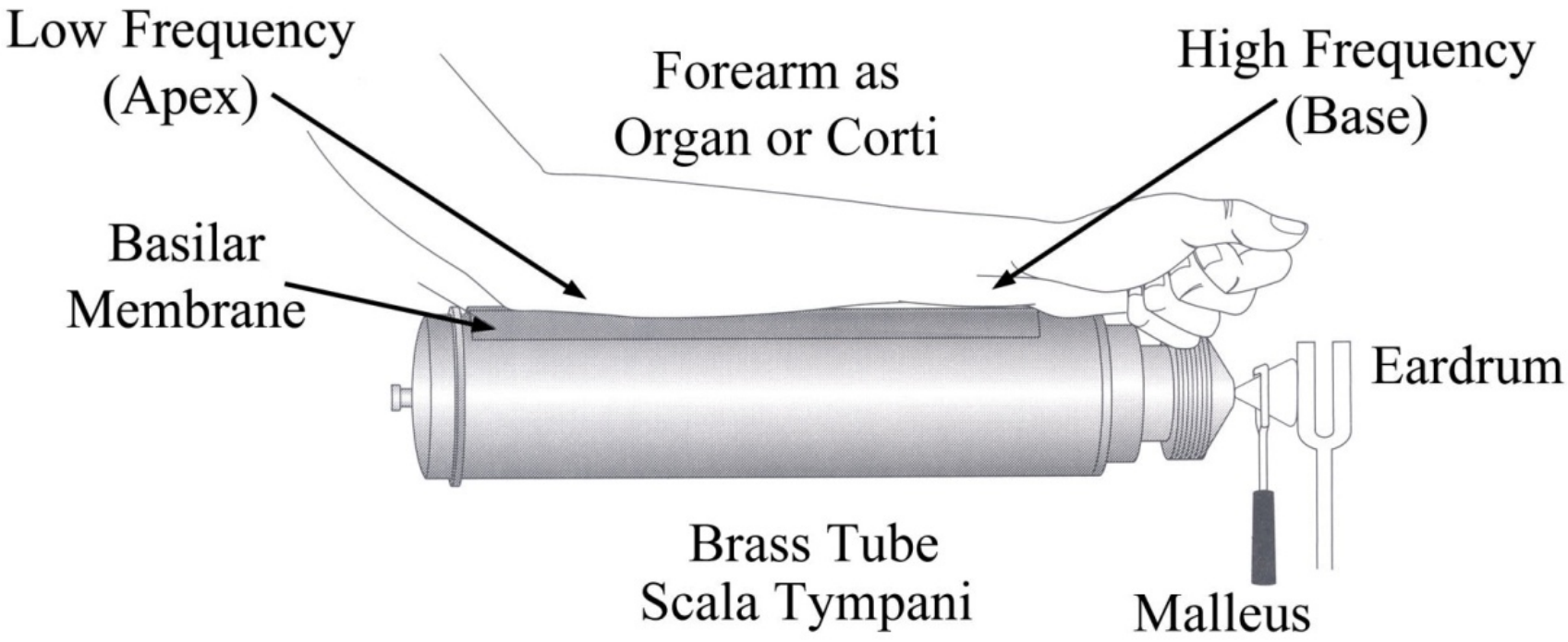
Frequency Theory (Rutherford)

- 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)

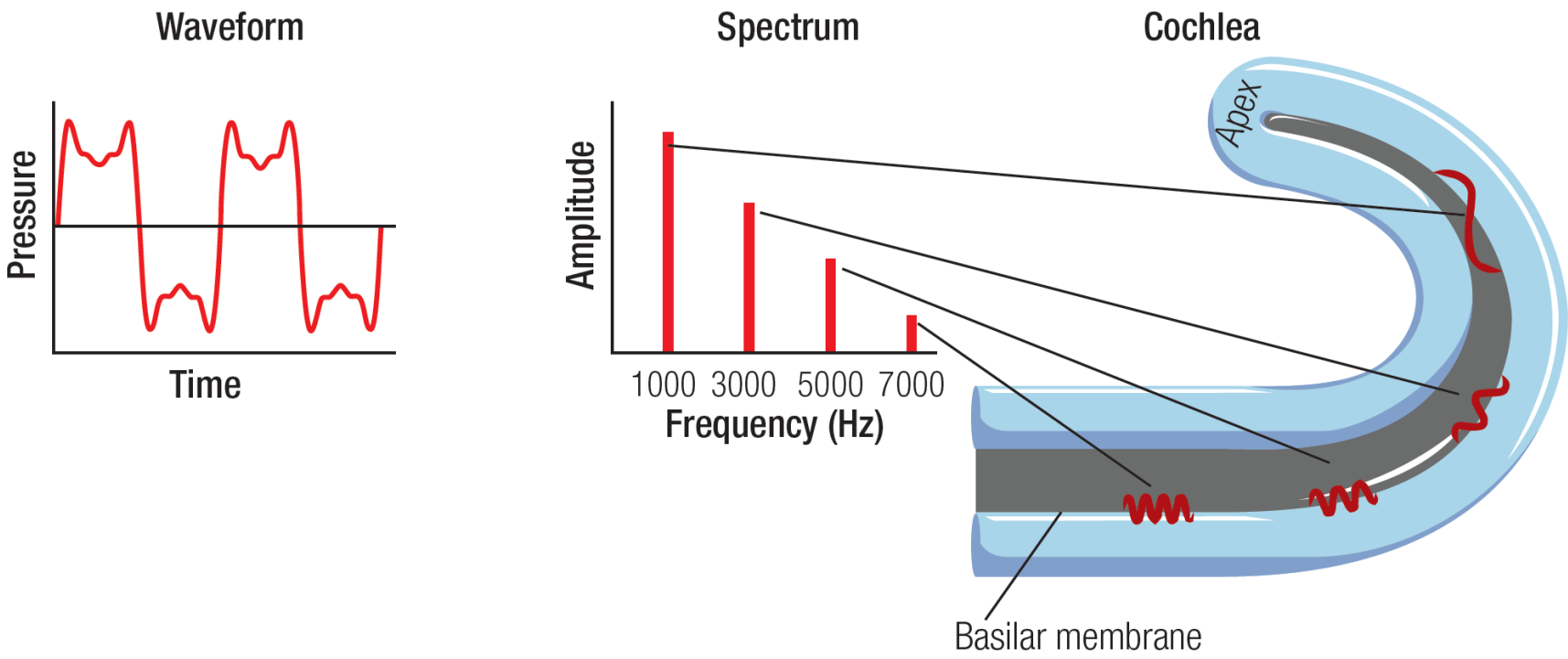
von Békésy Place Theory: Focus on Basilar Membrane Dynamics



The Simple Beginnings for von Békésy's Nobel Prize



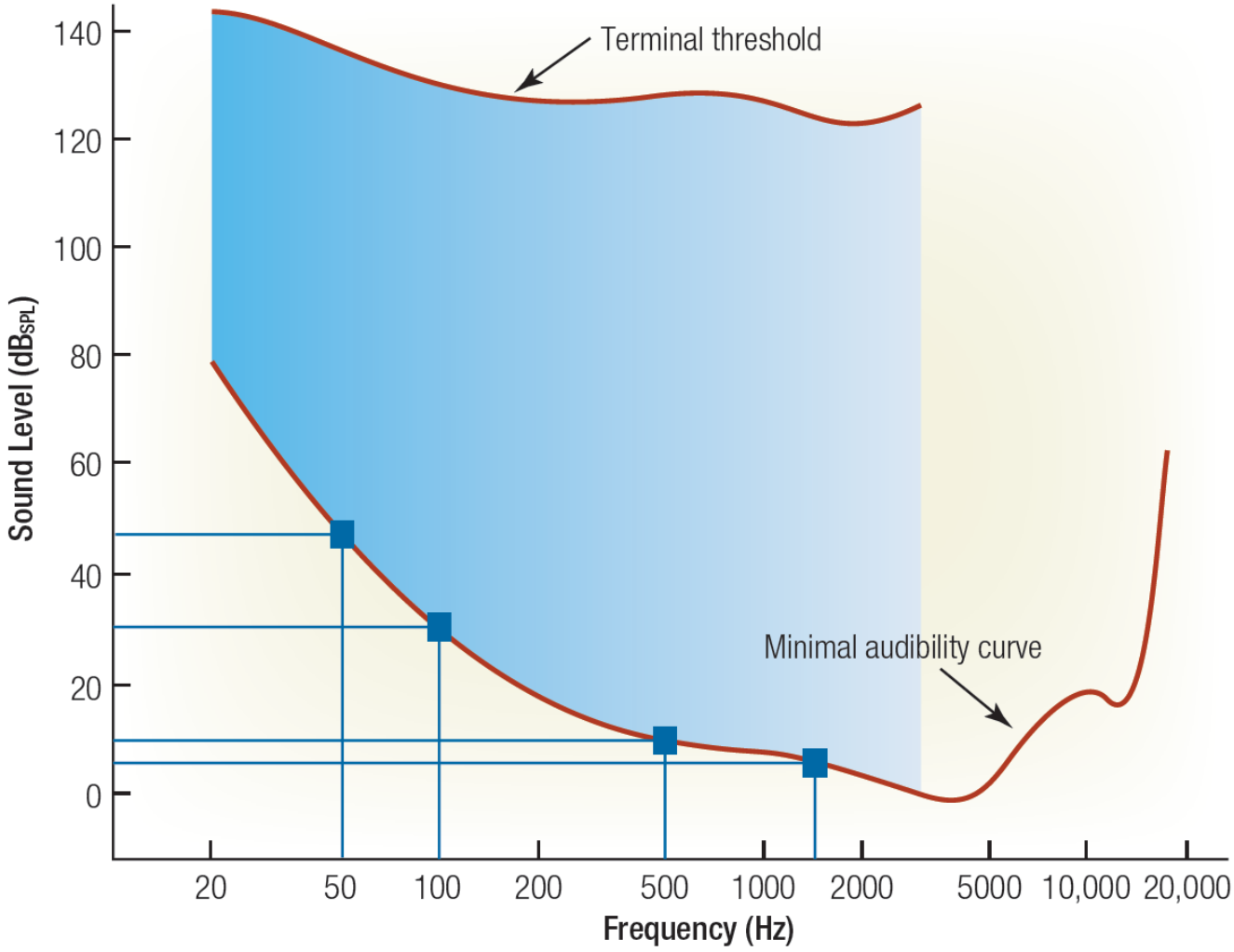
Von Békésy's "Place Mechanism" as Biological Fourier Analyzer



Basilar Membrane Dynamic Simulation
(animation)

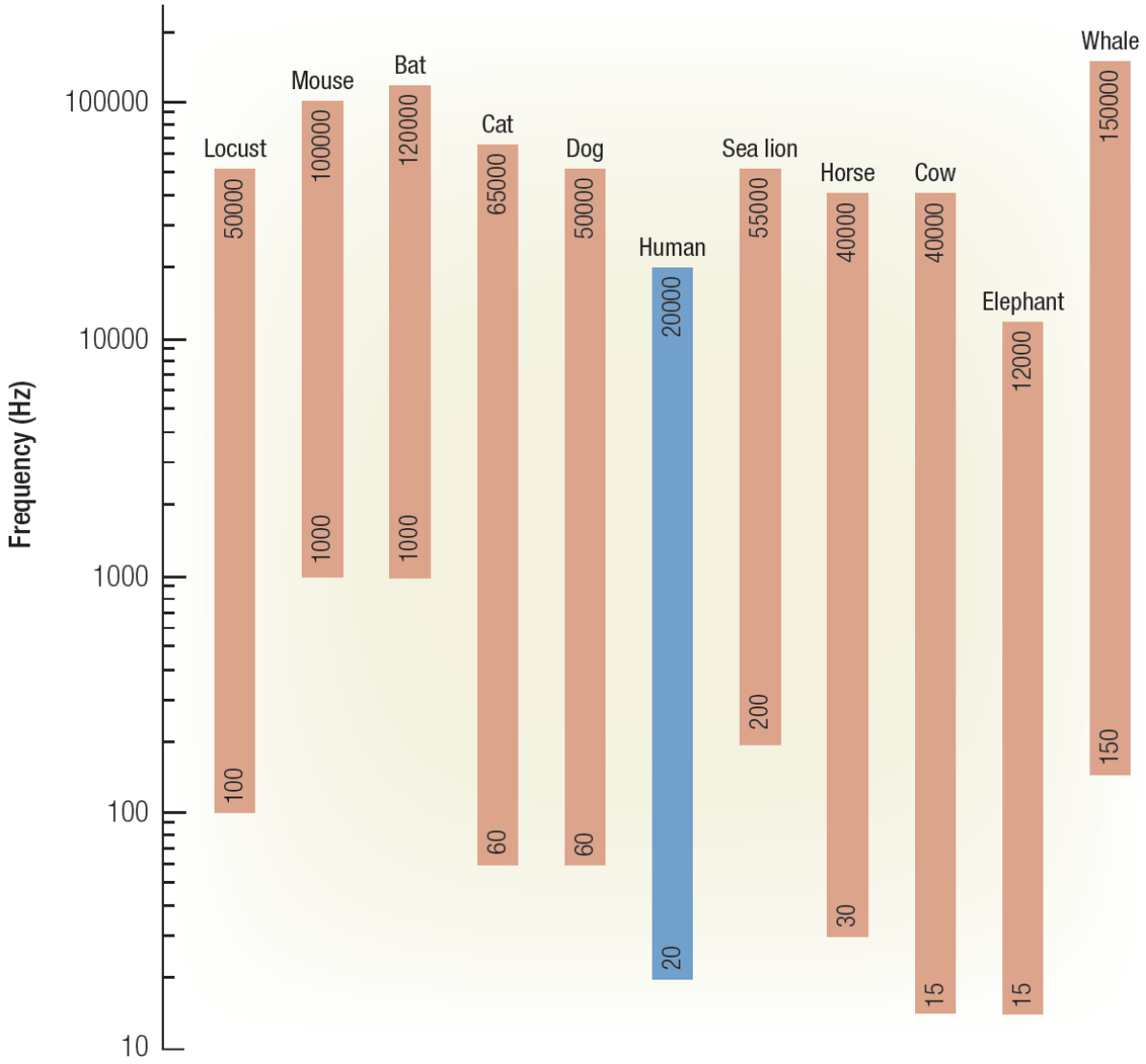
Functional Aspects of Hearing

Minimum Audibility Curve

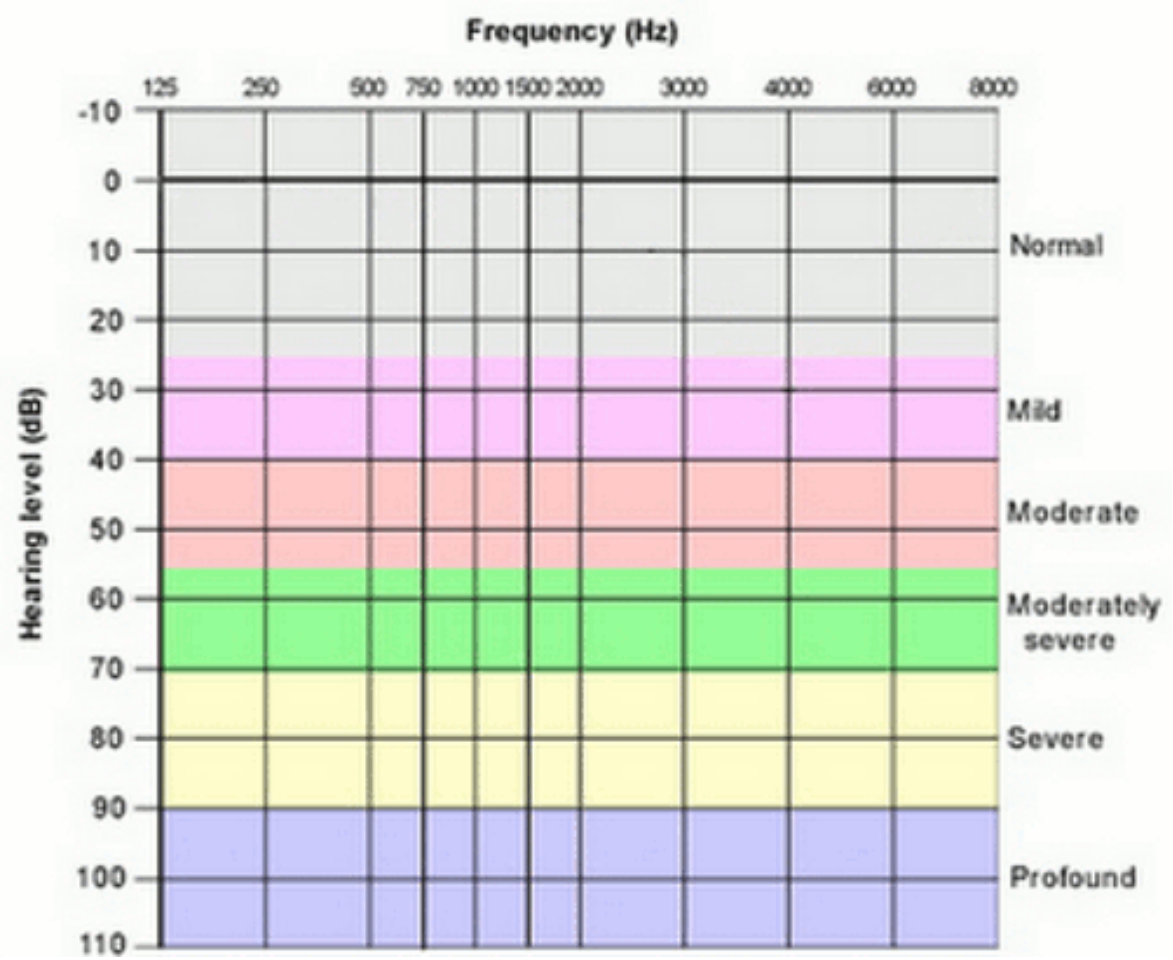


Average detection threshold for 18-yr-olds for 1KHz tone at sea level is **20 microPa (µPa)**

Species-Specific Frequency Range



Clinical Audiogram (dB_{HL})

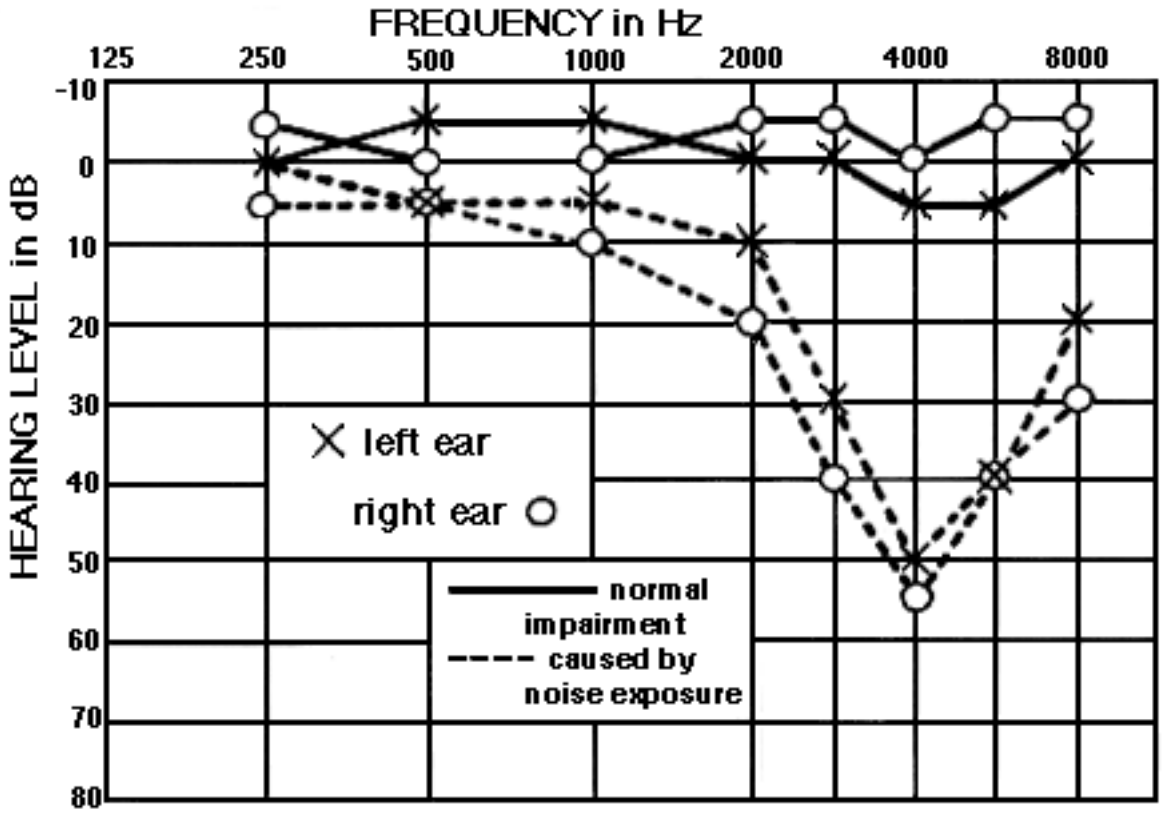


dB-HL (Hearing Level) uses a different reference level for each test frequency.

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

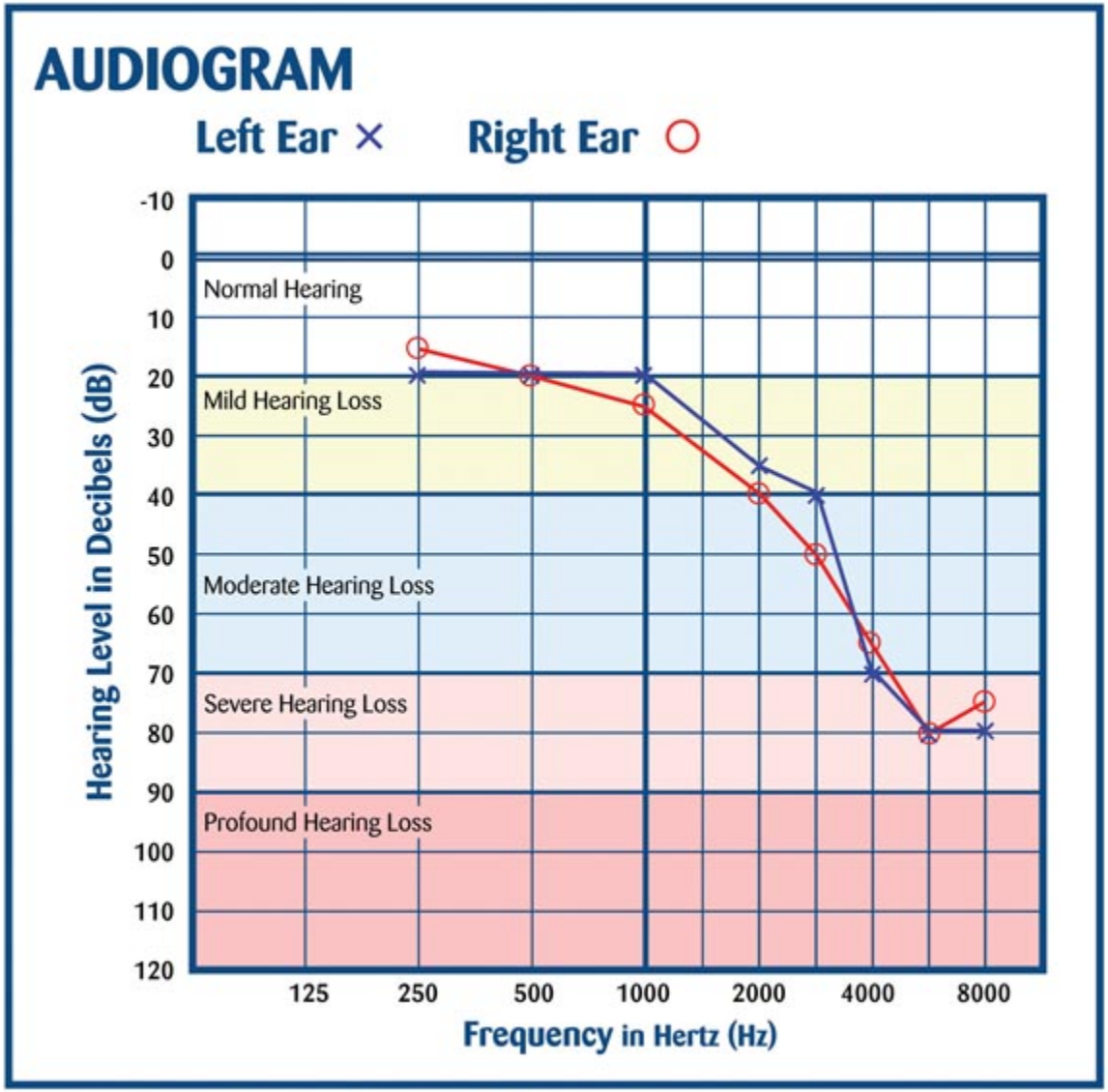
Hence, a value of **0 dB-HL** means "average" hearing level at the frequency under test.

Normal vs. Noise-Induced Hearing Loss

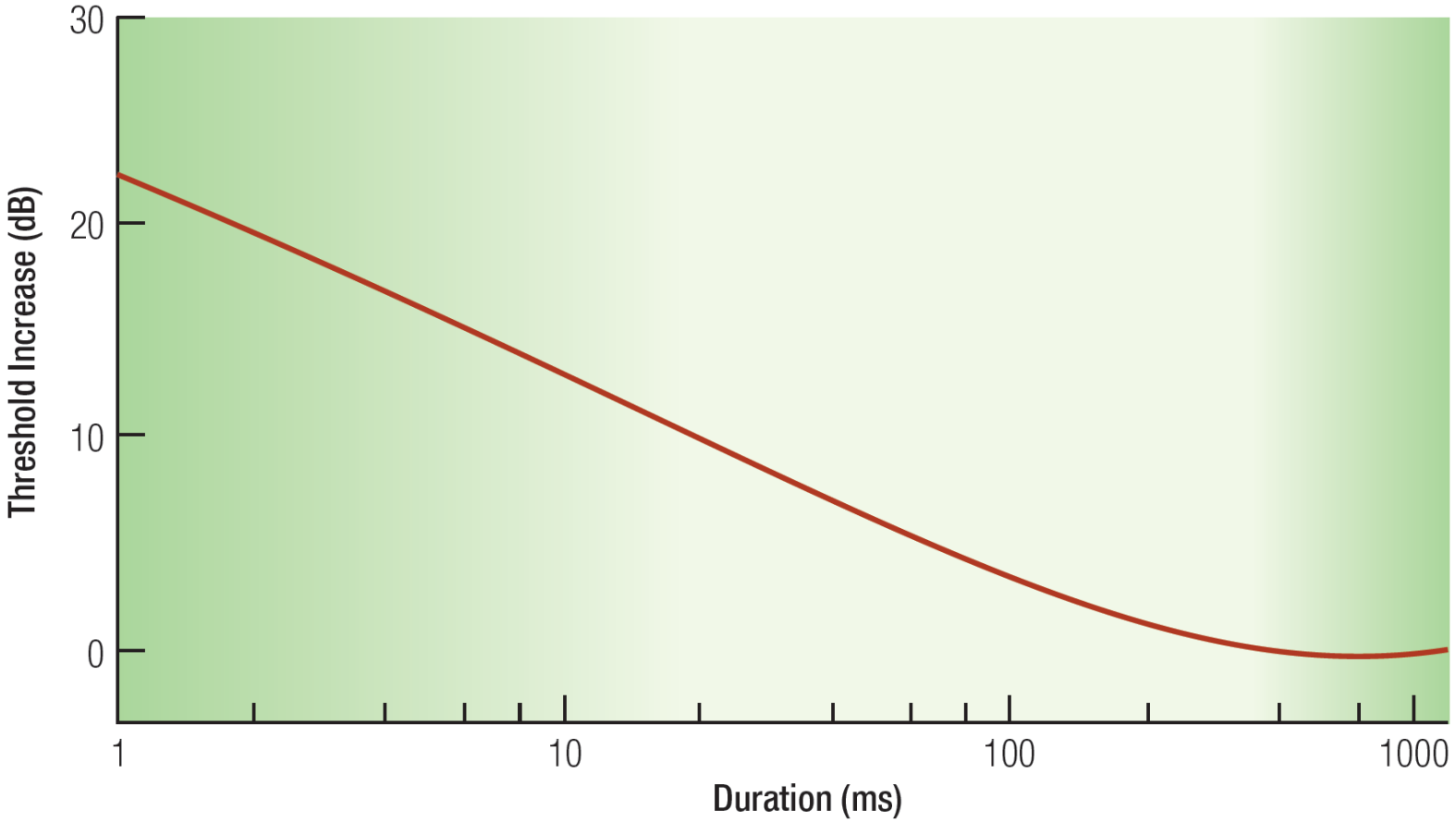


Source: http://mustelid.physiol.ox.ac.uk/drupal/?q=acoustics/clinical_audiograms

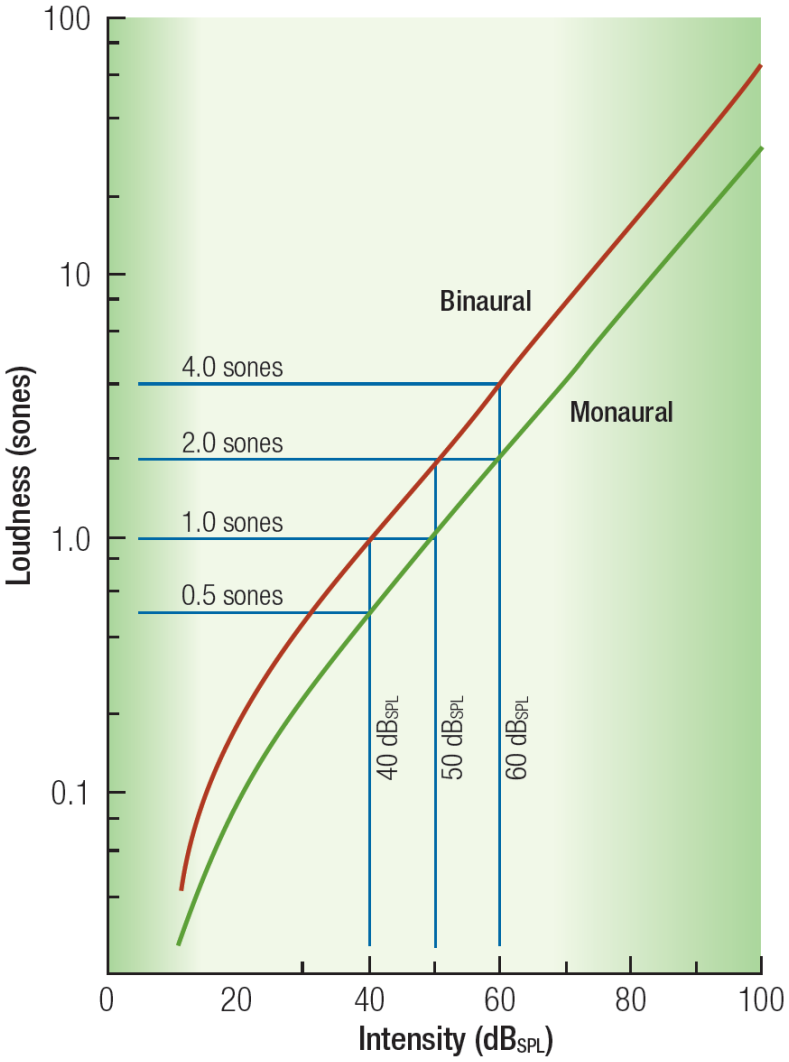
Age-related Hearing Loss (Presbycusis)



Auditory Summation Effect



Loudness



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

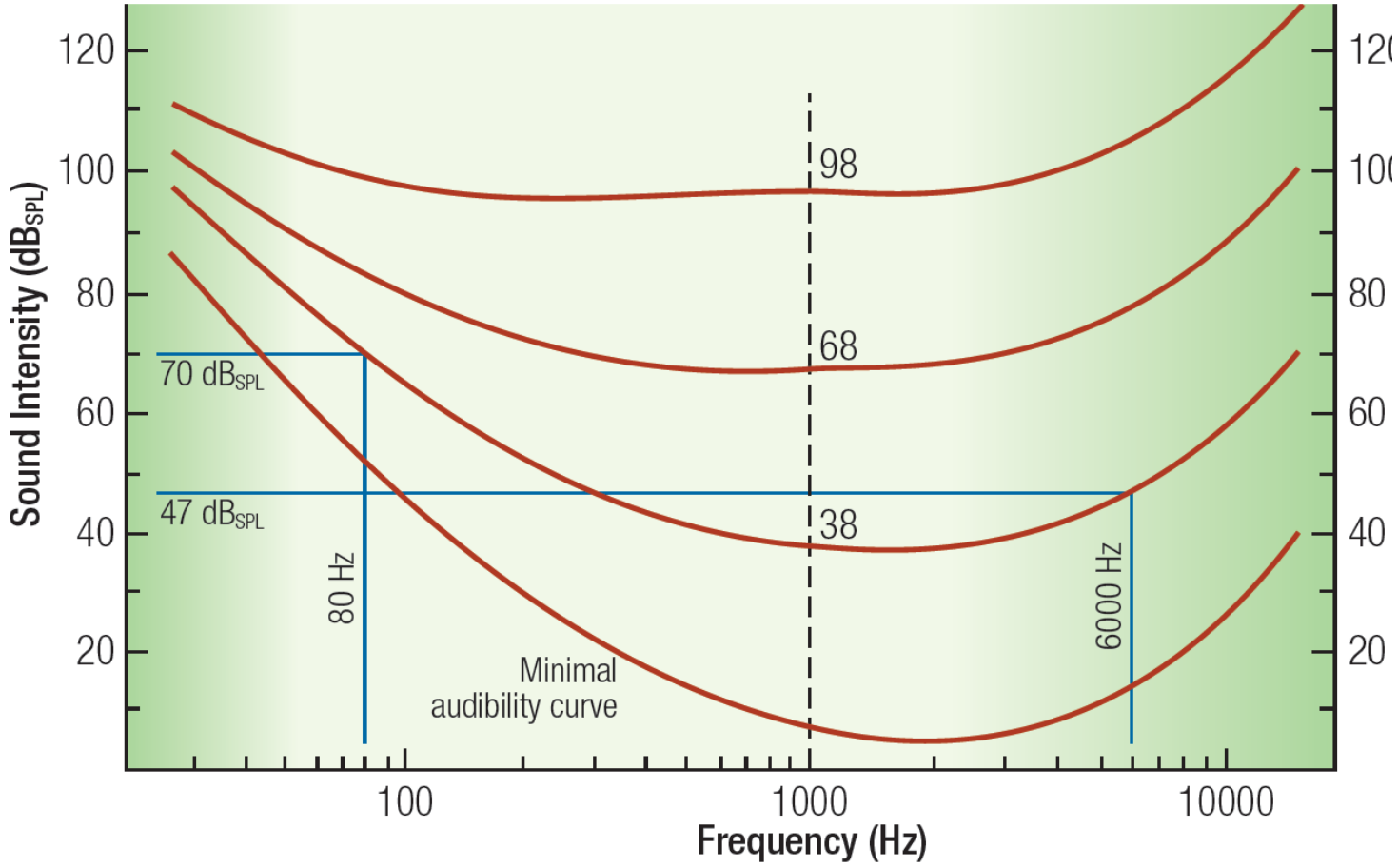
Using magnitude estimation techniques, S.S. Stevens has quantified this nonlinear relationship as:

$$L = K * P^{0.67}$$

L=loudness; P=sound pressure
Stevens' Power Law; Linear in log-log plot; slope ≈ exponent

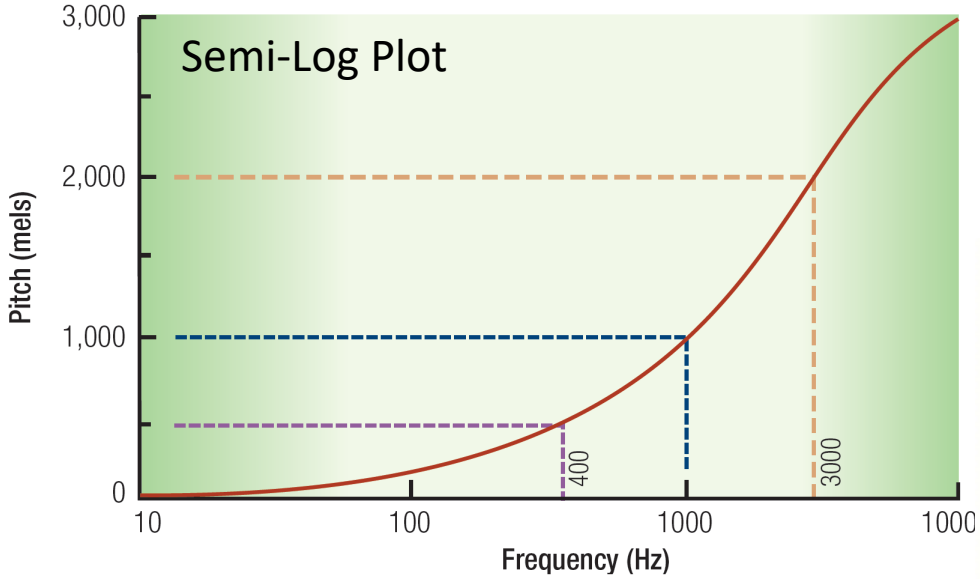
Doubling SP yields 60% ↑ loudness
3-fold increase in SP → 2X loudness

Equal Loudness Contours



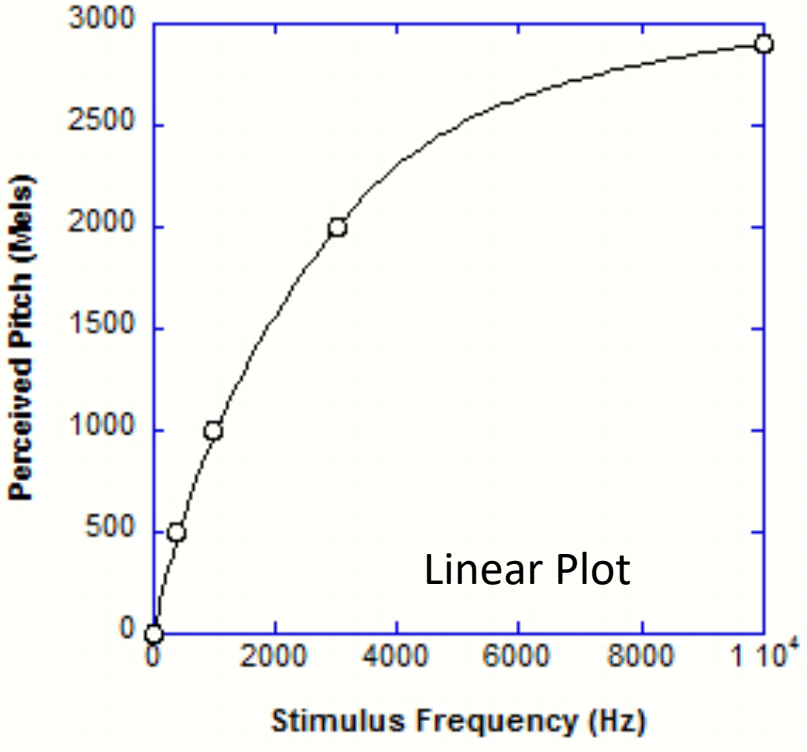
Frequency differentiation is flattened at high amplitudes; Speech and music sounds “tinny” at high loudness levels; Remember change in cochlear nerve tuning at higher intensity levels.

Pitch = f(Frequency)
MEL Scale

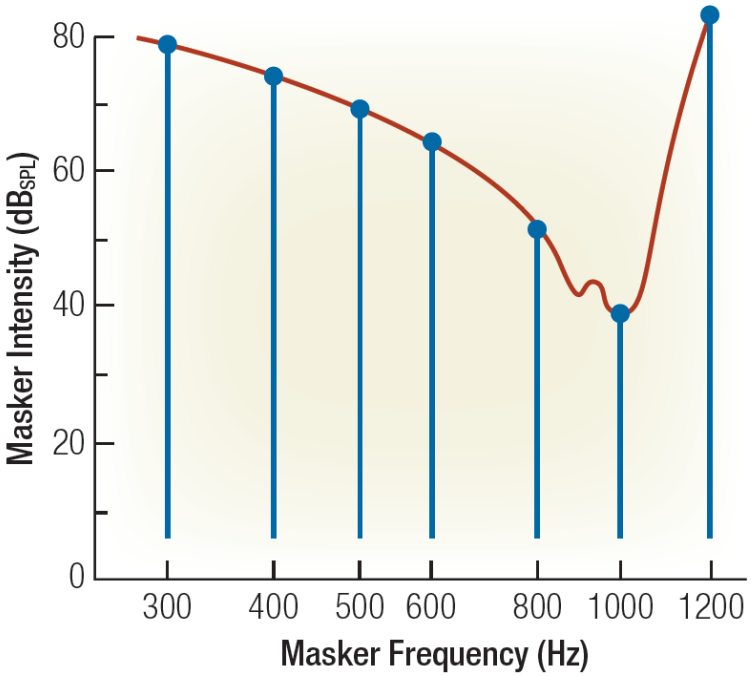


Reference unit of perceived PITCH:
1000 Hz = 1000 Mels

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



Tonal Masking: Psychophysical Tuning Curves



Fixed **test tone** (e.g., 1KHz @ +10 dB)

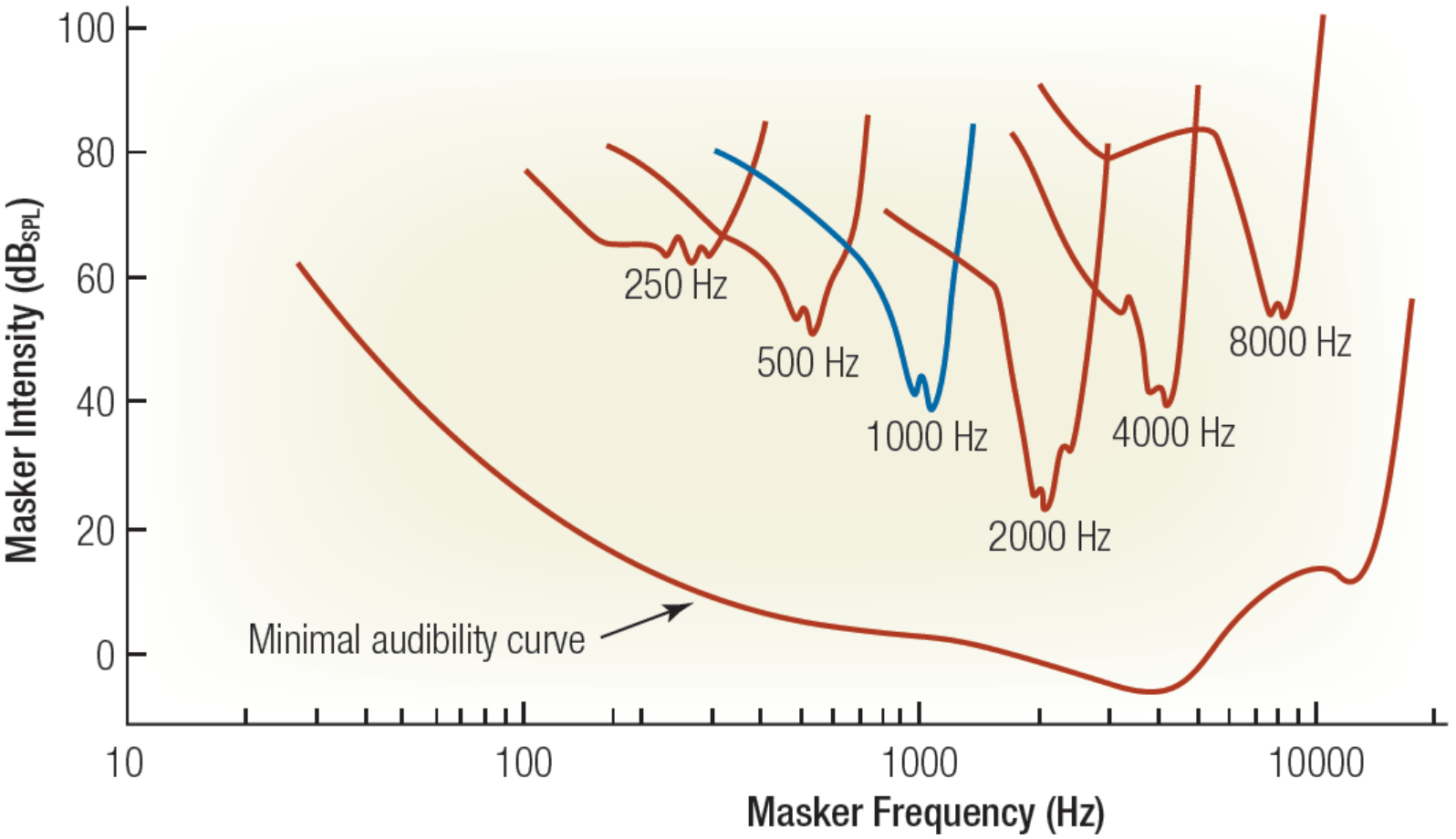
Frequency of **masking tone** varied

How intense must masking tone be in order to make the test tone indiscriminable?

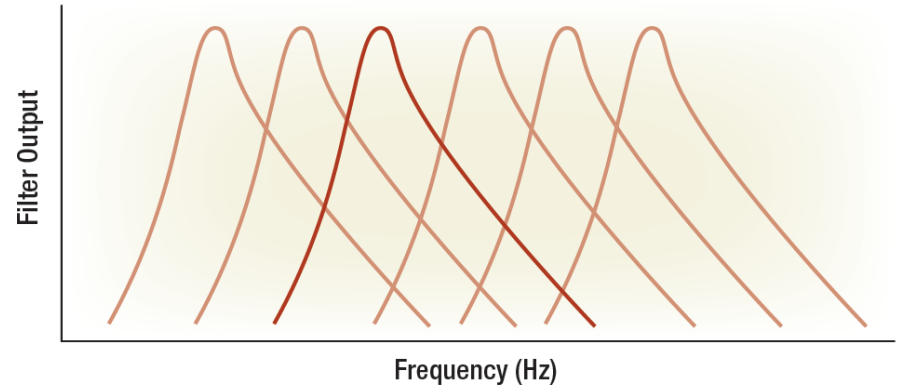
Plot of masking intensity thresholds reveals **frequency tuning** of underlying auditory processing channel(s)

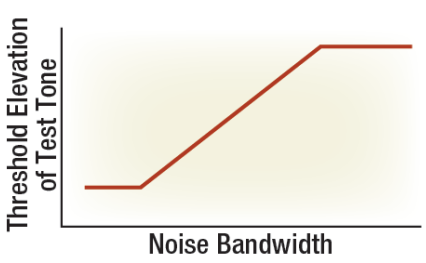
Masking Demo

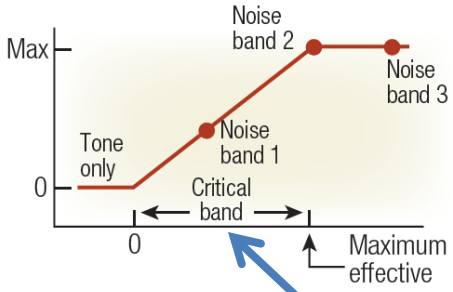
Multiple "Frequency Channels" Revealed by Masking Curves

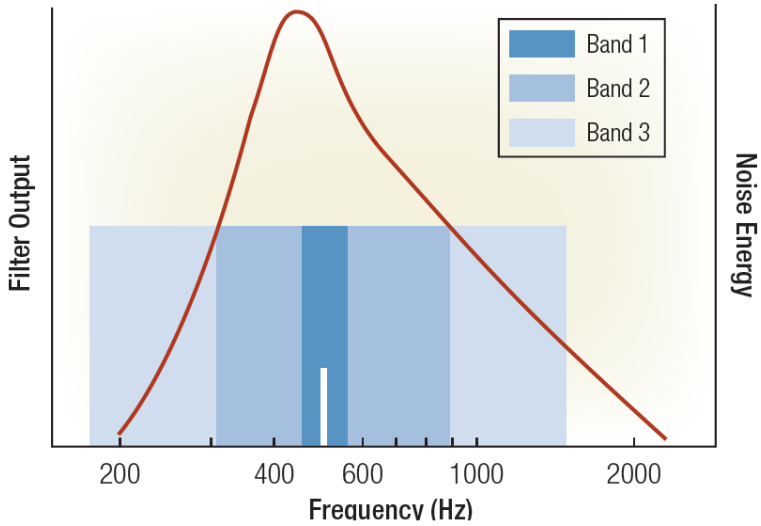


Noise Masking Curves Reveal Channel "Bandwidth"





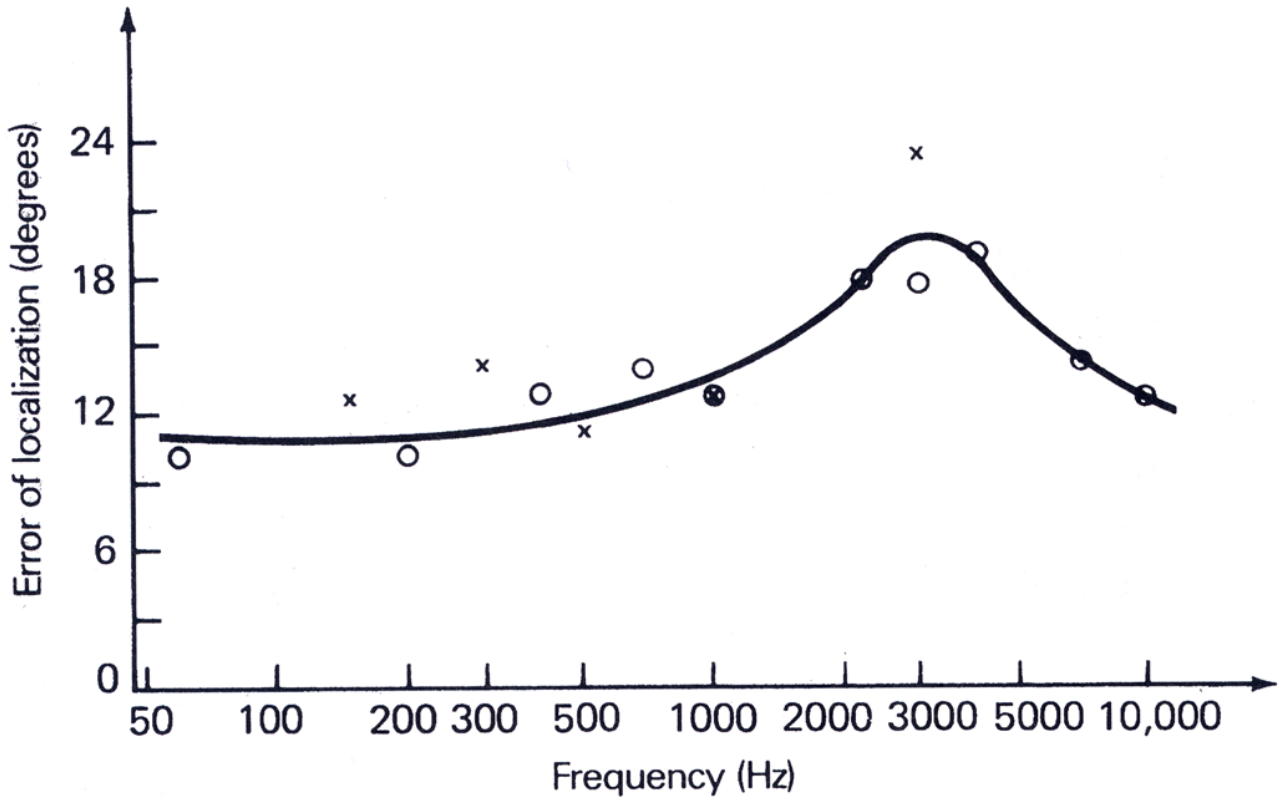




"Critical Band" of Noise Masking

Sound Localization

Localization Accuracy vs. Frequency

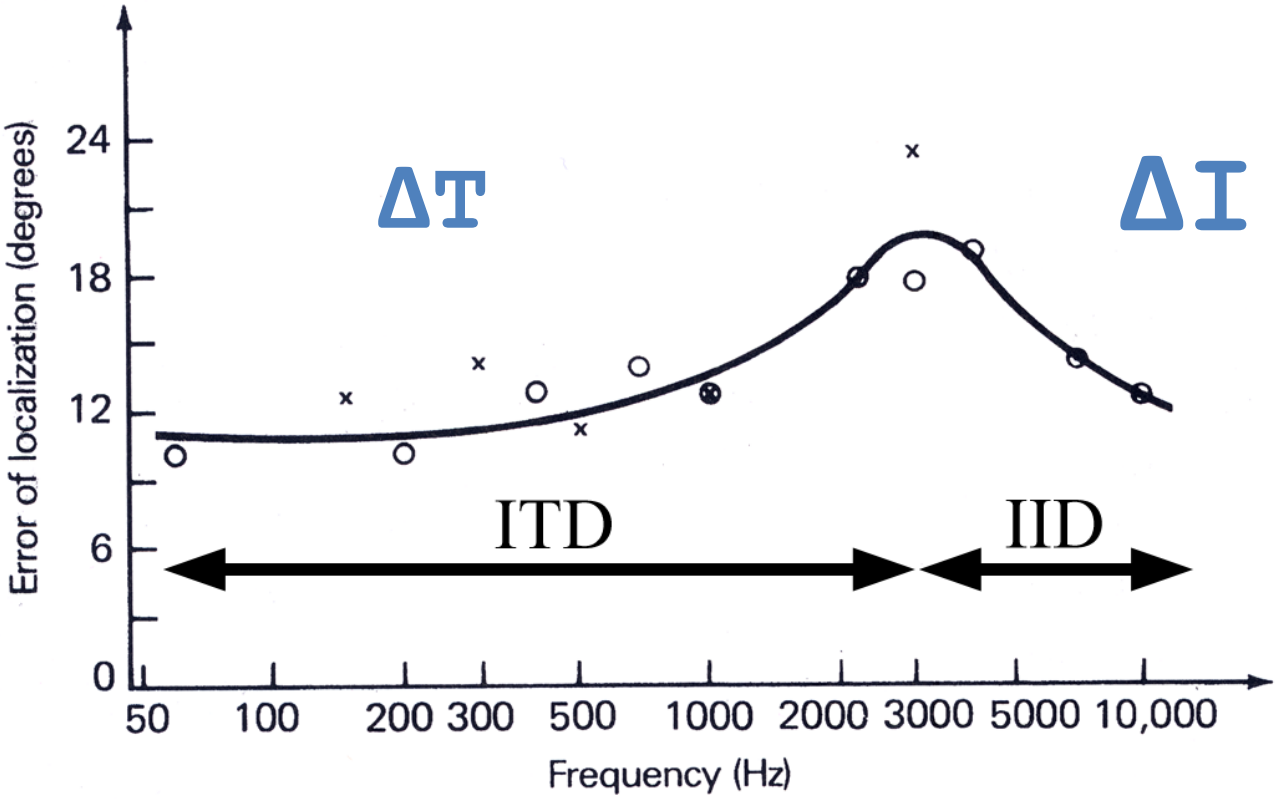


Signature of a dual-mechanism process?

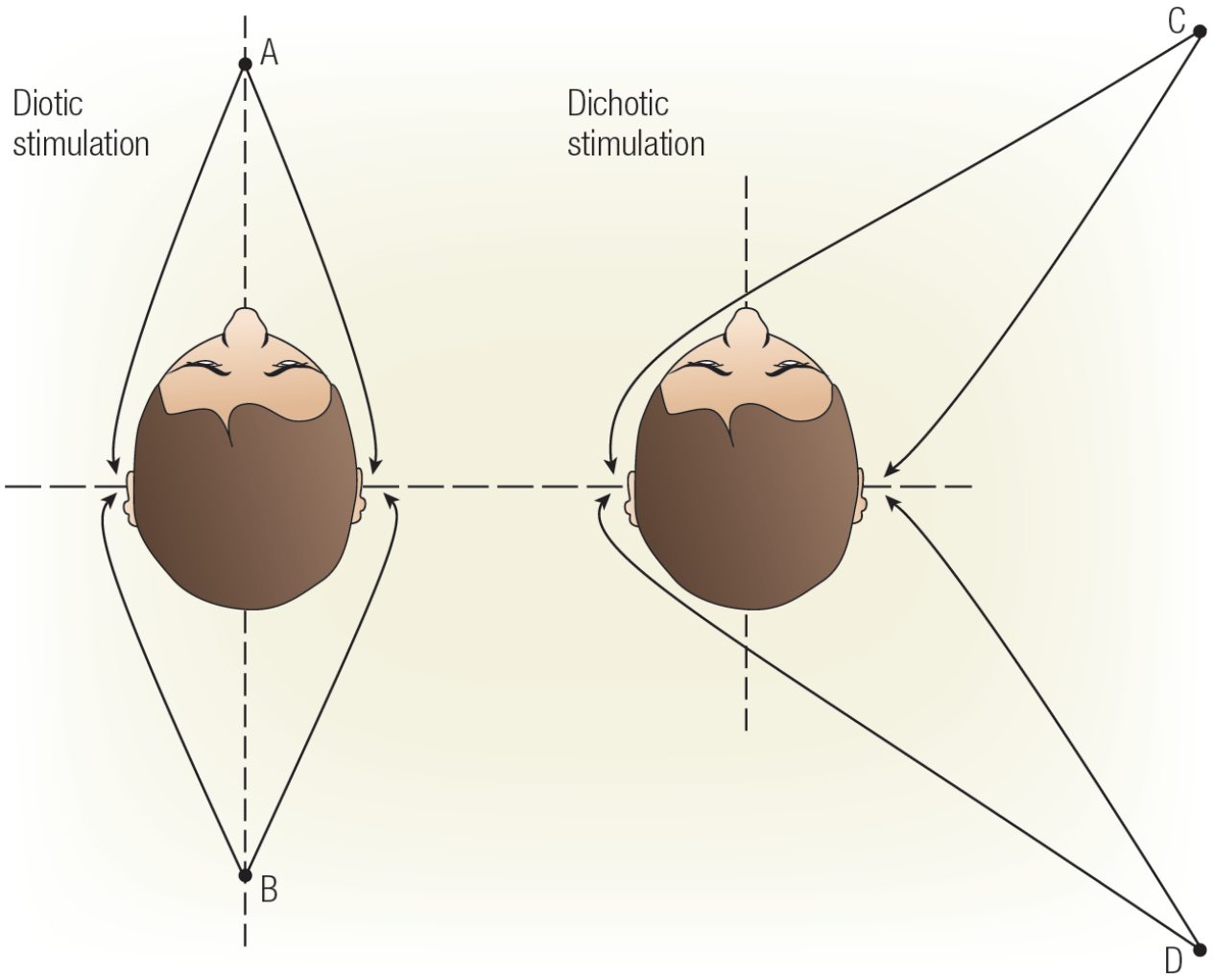
Localization Accuracy vs. Frequency:

Low Freq – Interaural Time Difference

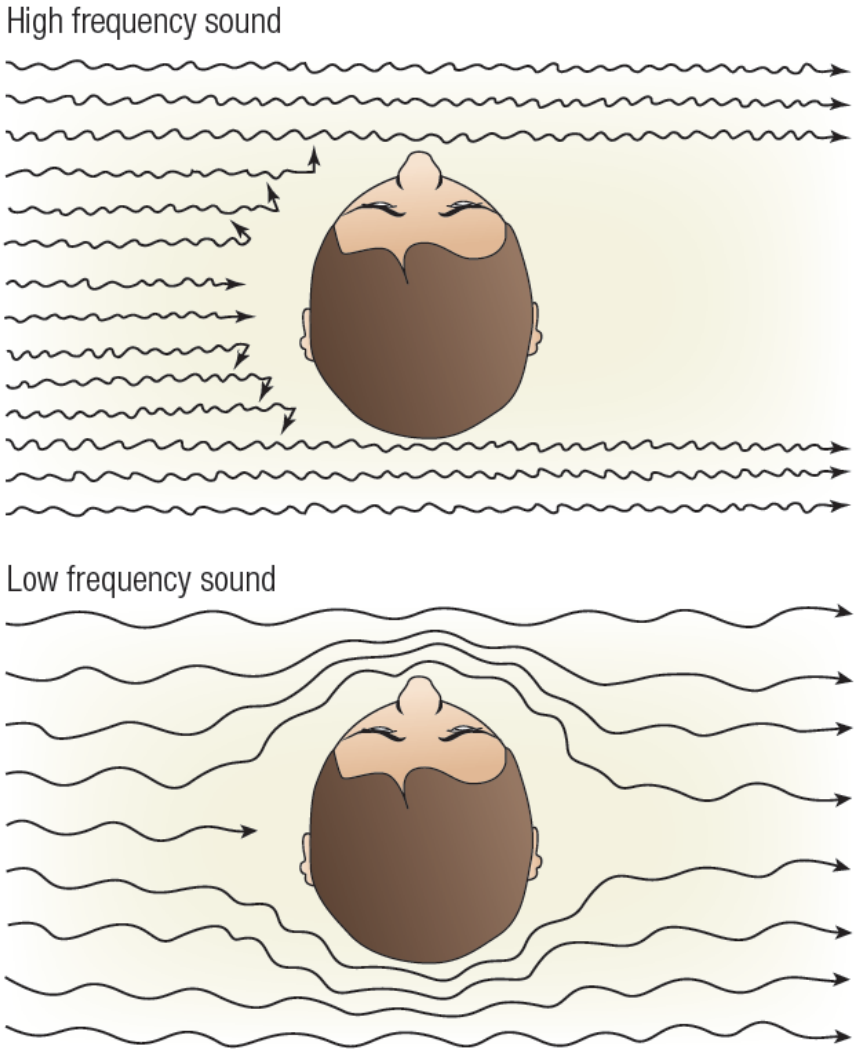
High Freq – Interaural Intensity Difference



“Diotic” vs. “Dichotic” Stimulation



Sound Shadowing
(Interaural Intensity Difference –IID)



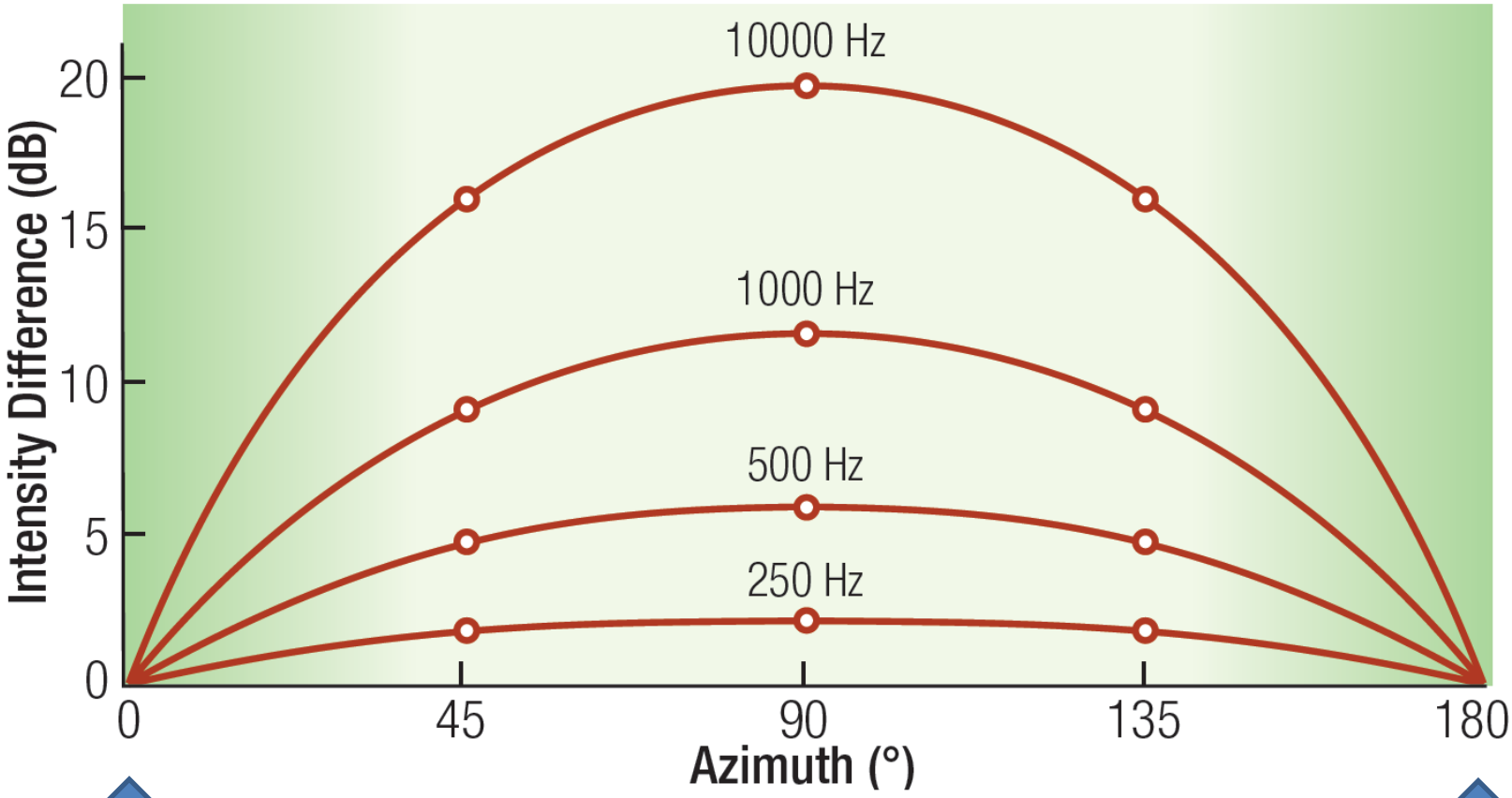
High-frequency sound waves are “blocked” by the human head and cast a “shadow” at the far ear **(Strong IID cue)**

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



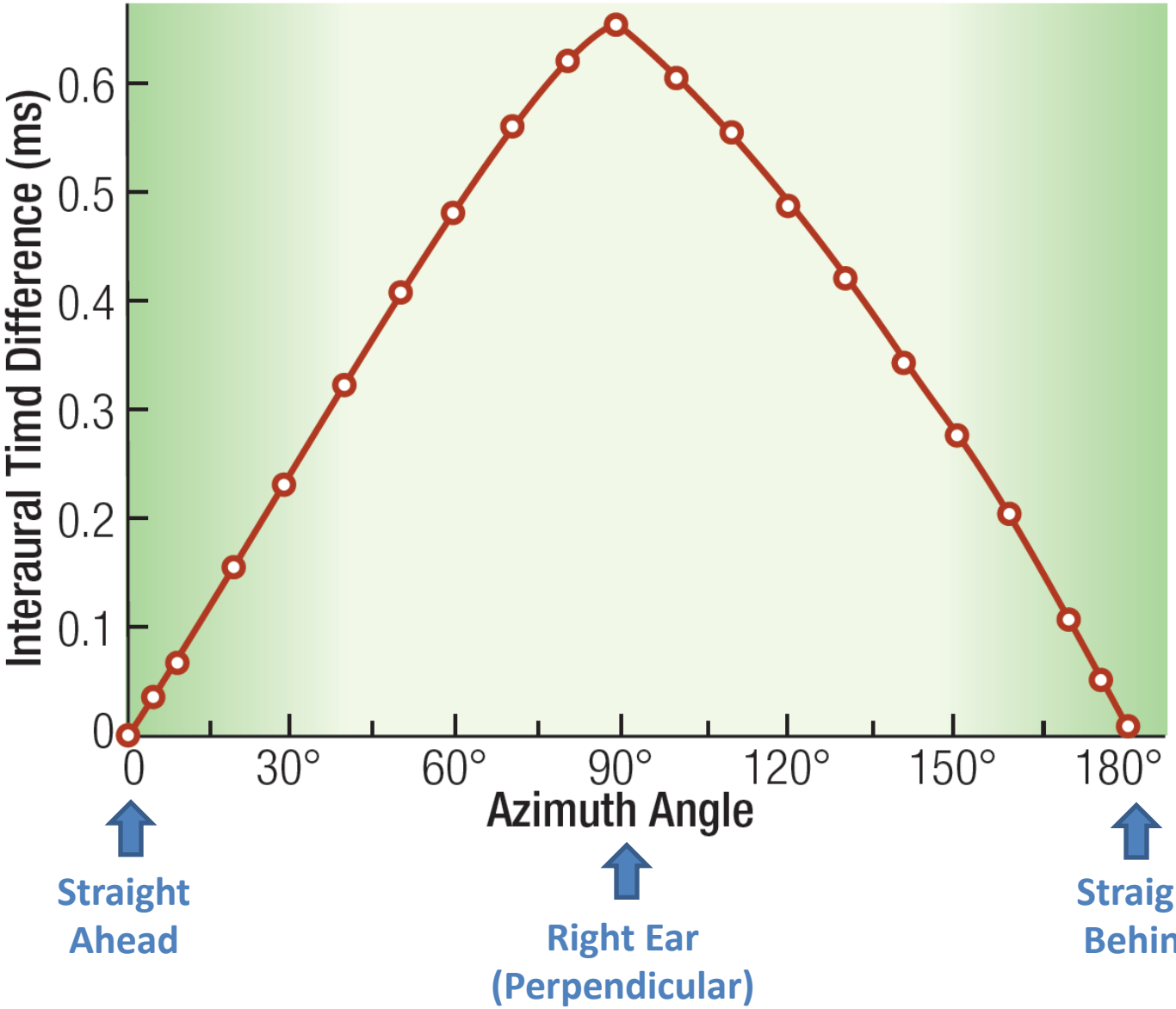
Straight Ahead

Right Ear (Perpendicular)

Straight Behind

ITD versus Location

ΔT



Straight Ahead 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

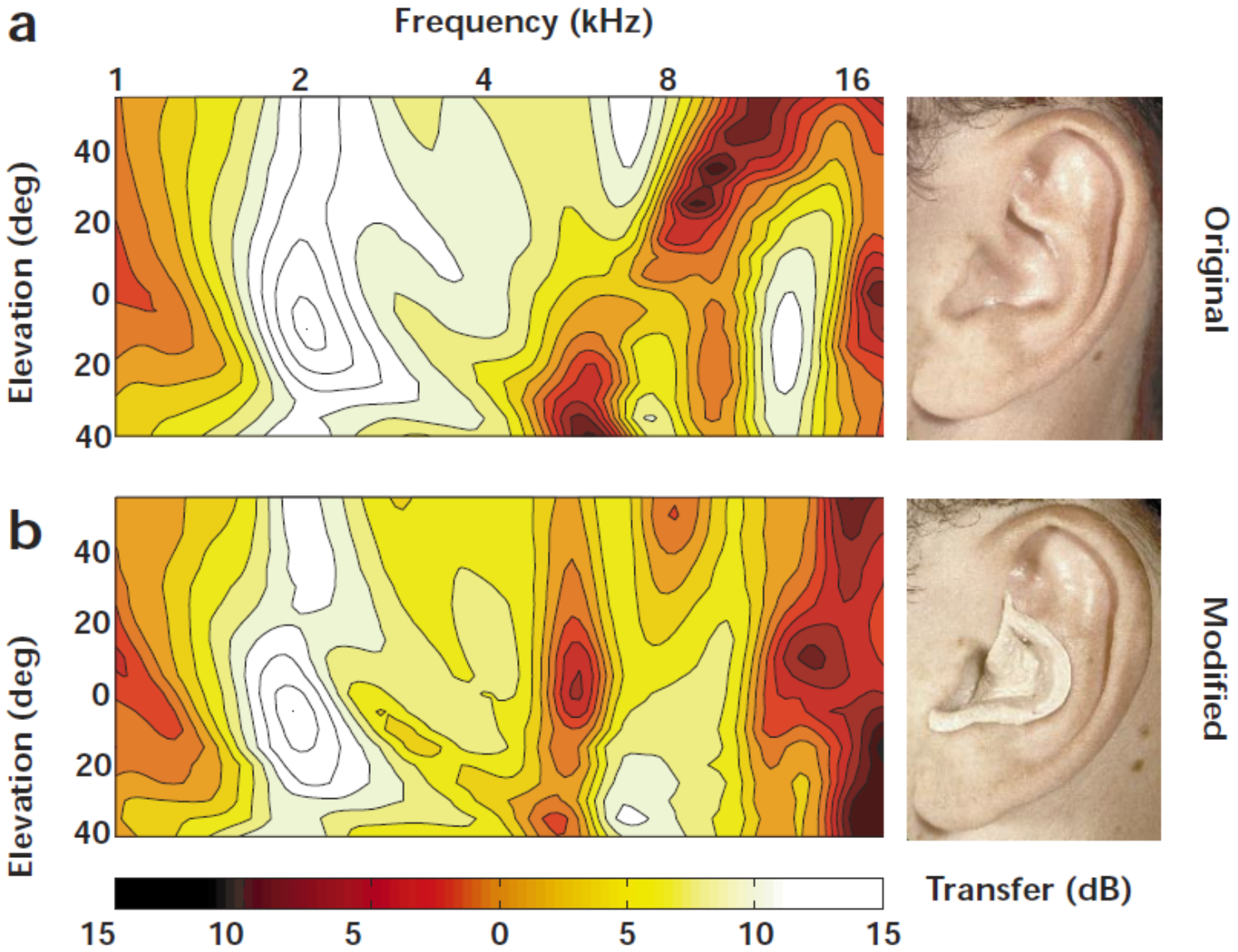
Modifying shape of pinna causes immediate reduction in localization accuracy (Hoffman, et al., 1998)

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)

