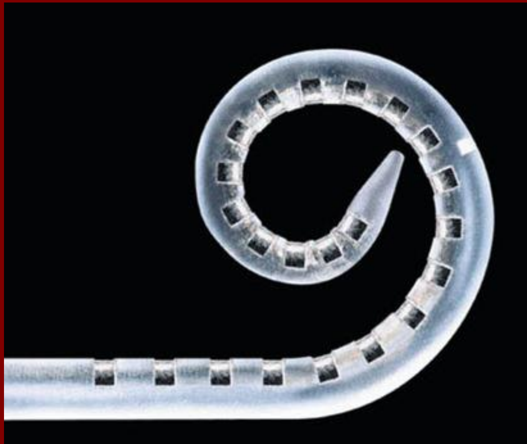
9

Hearing: Physiology and Psychoacoustics



- The Function of Hearing
- What Is Sound?
- Basic Structure of the Mammalian Auditory System
- Basic Operating Characteristics of the Auditory System
- Hearing Loss

The basics

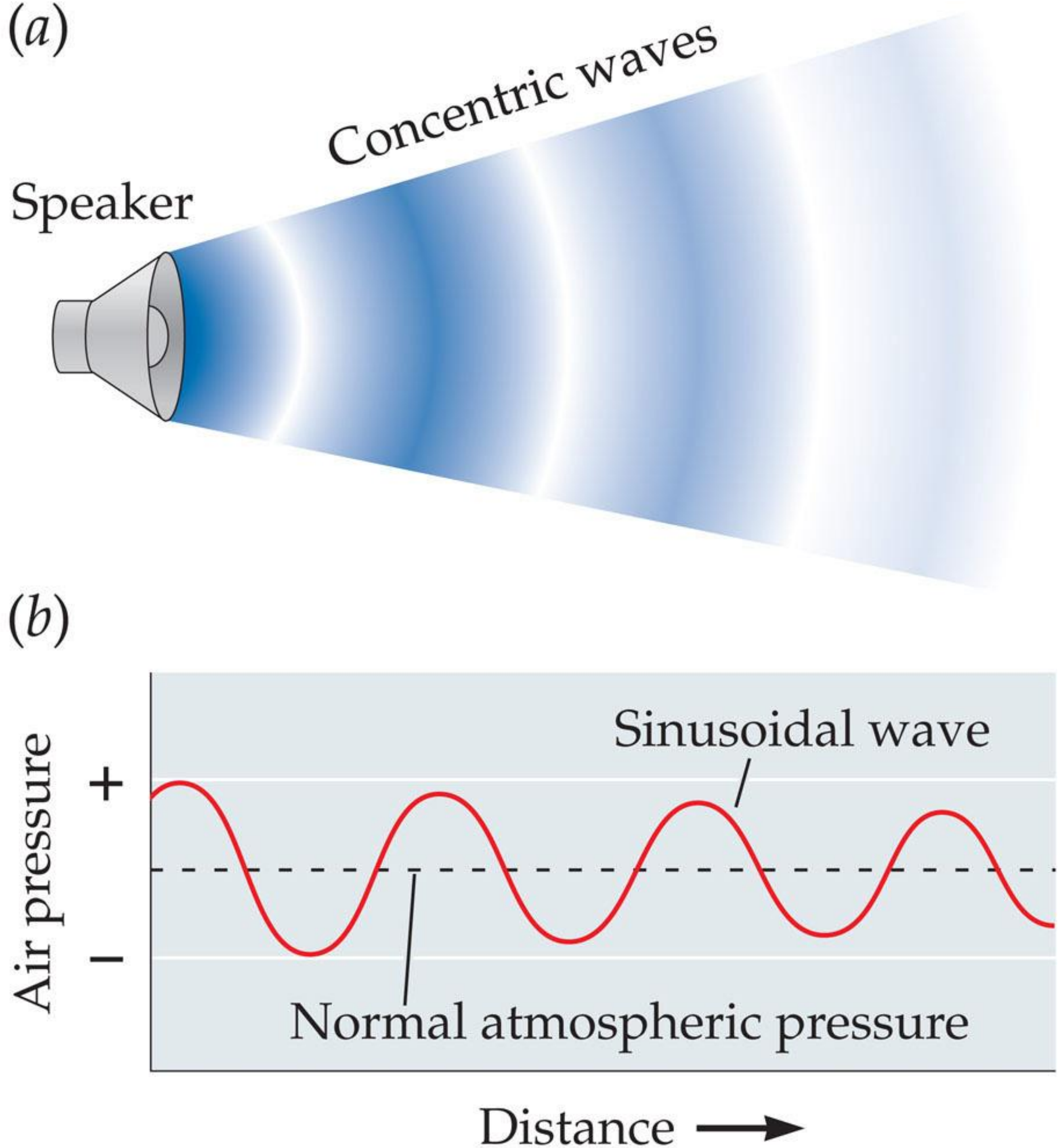
- Nature of sound
- Anatomy and physiology of the auditory system
- How we perceive loudness and pitch
- Impairments of hearing and how to ameliorate them

What Is Sound?

Sounds are created when objects vibrate.

- Object vibrations cause molecules in the surrounding medium to vibrate, creating pressure changes in the medium.

Figure 9.1 The pattern of pressure fluctuations of a sound



SENSATION & PERCEPTION 4e, Figure 9.1

What Is Sound?

Sound waves travel at a particular speed.

- Depends on the medium
- Example: Speed of sound through air is about 340 meters/second, but speed of sound through water is 1500 meters/second.

What Is Sound?

Physical qualities of sound waves

- Amplitude or Intensity: The magnitude of displacement (increase or decrease) of a sound pressure wave.
  - Perceived as *loudness*
- Frequency: For sound, the number of times per second that a pattern of pressure change repeats.

Units for measuring sound:

- Hertz (Hz): A unit of measure for frequency. One Hz equals one cycle per second.
- Decibel (dB): A unit of measure for the physical intensity of sound.
  - Decibels define the difference between two sounds as the ratio between two sound pressures.
  - Each 10:1 sound pressure ratio equals 20 dB, and a 100:1 ratio equals 40 dB.

What Is Sound?

Psychological qualities of sound waves

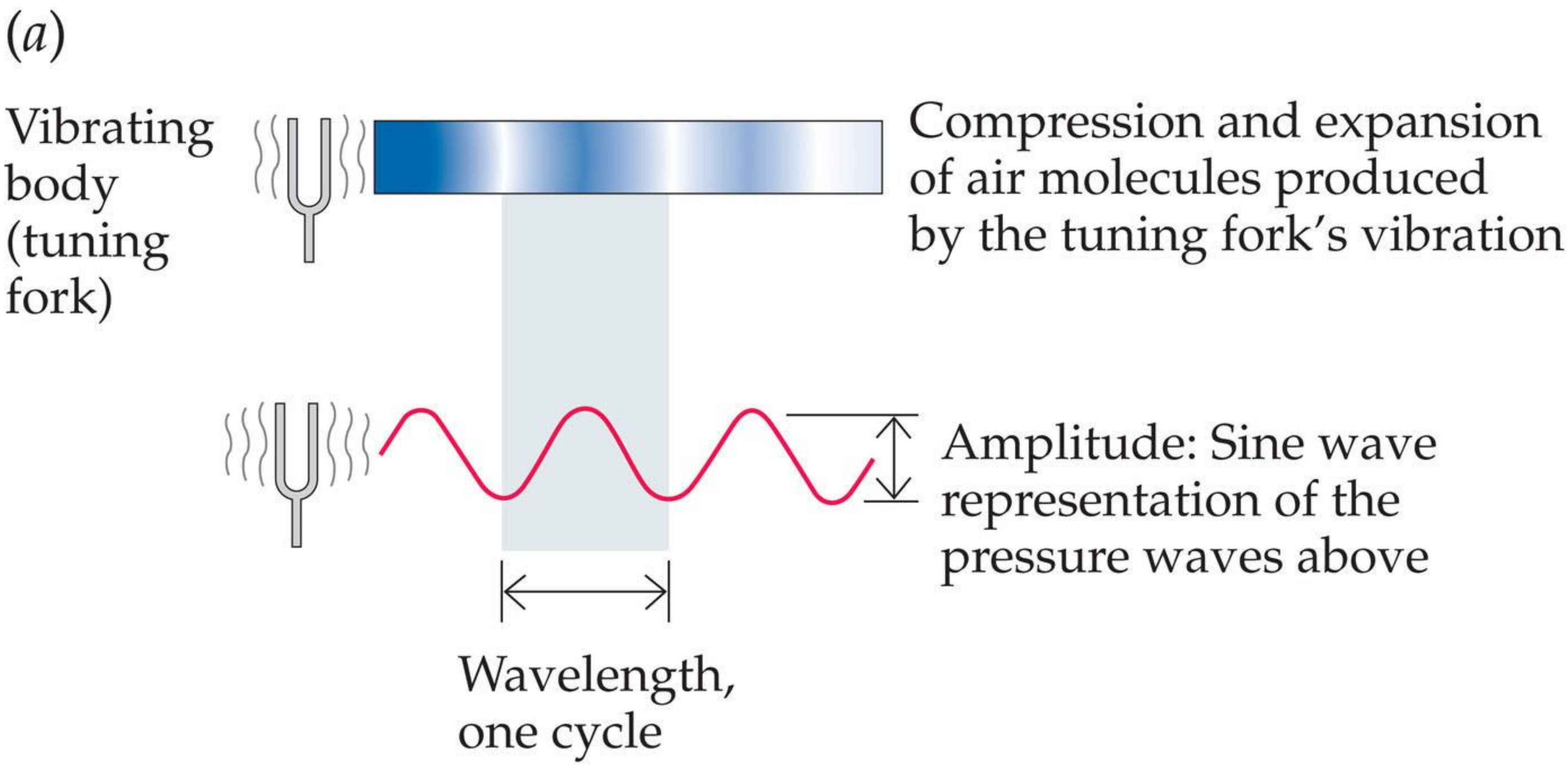
- Loudness: The psychological aspect of sound related to perceived intensity or amplitude.
- Pitch: The psychological aspect of sound related mainly to the fundamental frequency.

What Is Sound?

Frequency is associated with pitch.

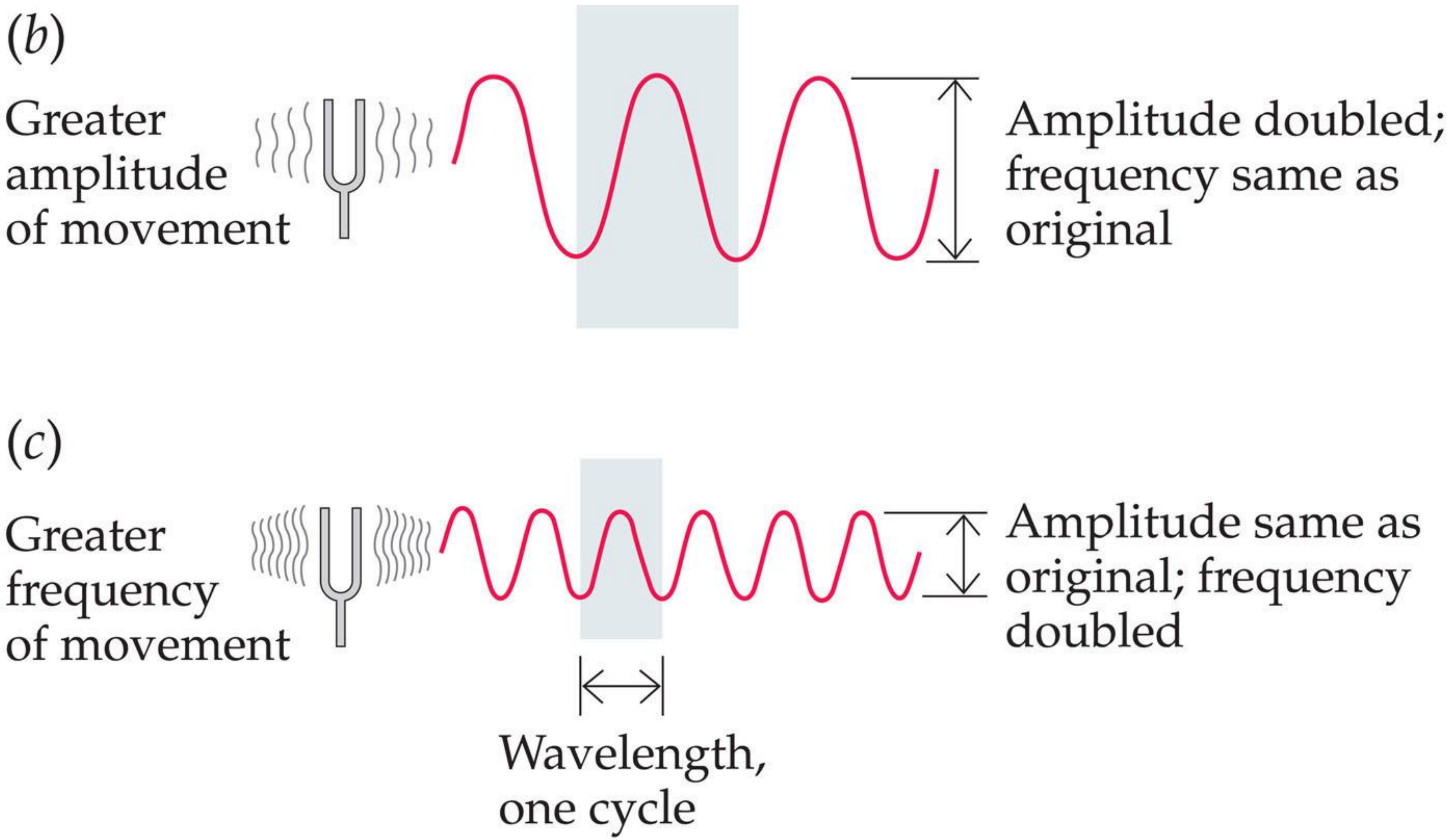
- Low-frequency sounds correspond to low pitches.
- High-frequency sounds correspond to high pitches.

Figure 9.2 Amplitude and frequency (Part 1)



SENSATION & PERCEPTION 4e, **Figure 9.2 (Part 1)**

Figure 9.2 Amplitude and frequency (Part 2)

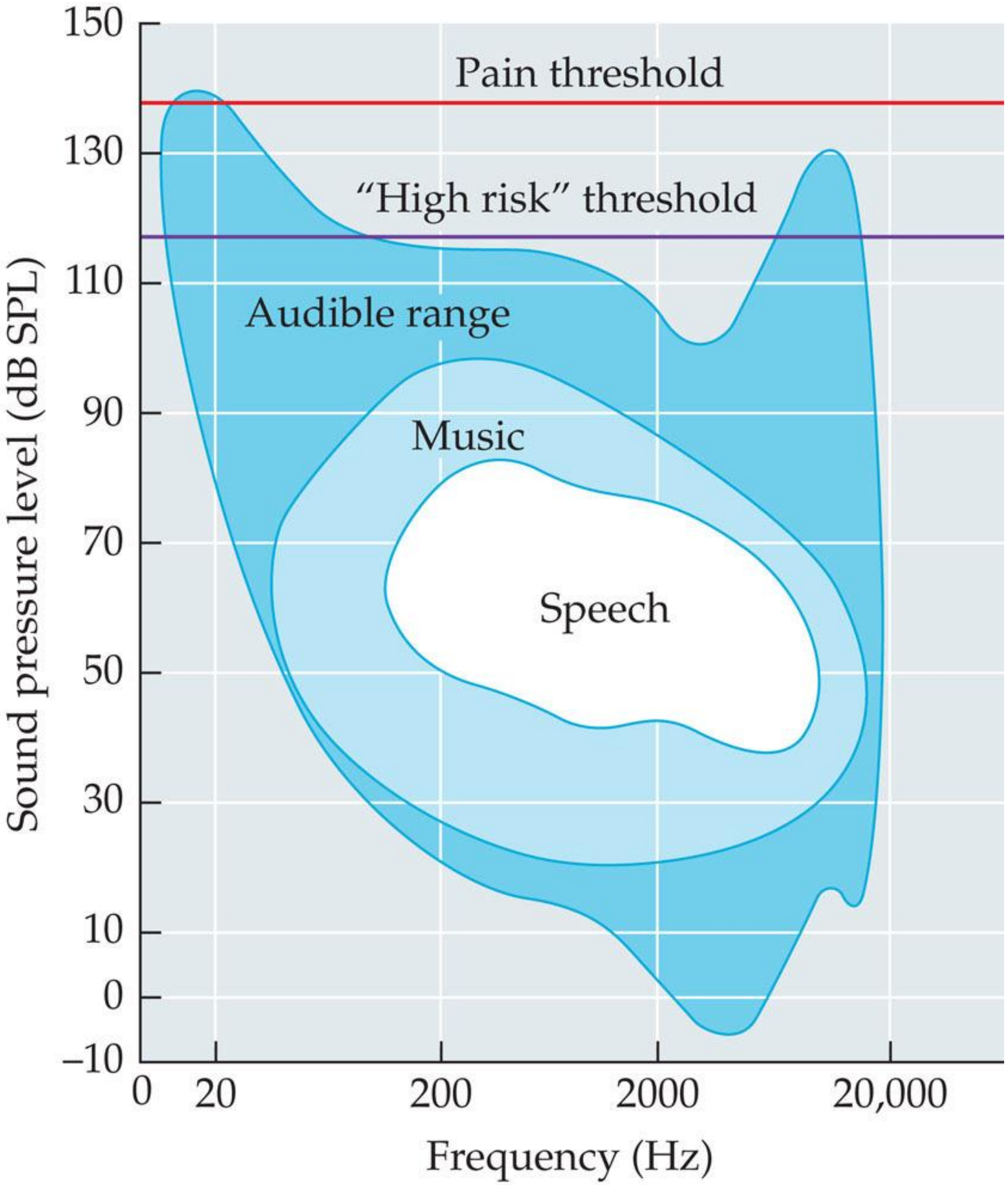


SENSATION & PERCEPTION 4e, Figure 9.2 (Part 2)

What Is Sound?

Human hearing uses a limited range of frequencies (Hz) and sound pressure levels (dB).

Figure 9.3 Humans can hear frequencies that range from about 20 to 20,000 Hz across a very wide range of intensities, or sound pressure levels



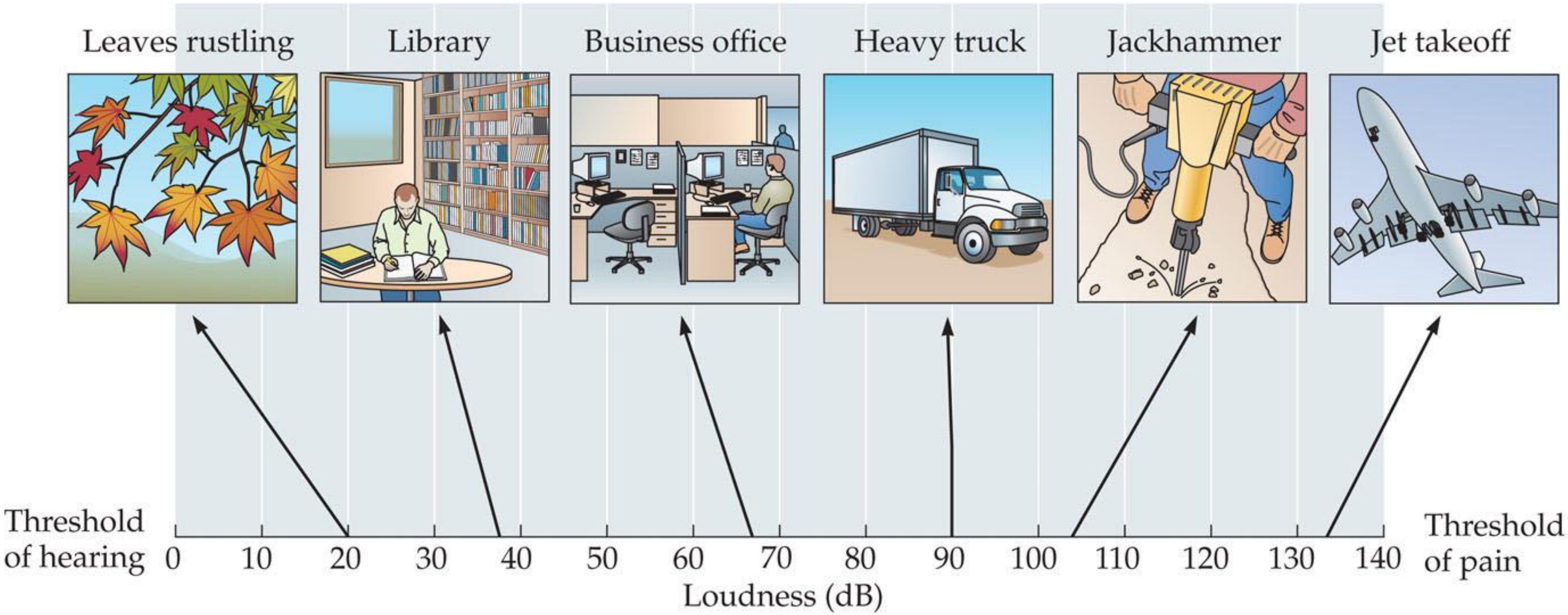
SENSATION & PERCEPTION 4e, Figure 9.3

What Is Sound?

Humans can hear across a wide range of sound intensities.

- Ratio between faintest and loudest sounds is more than 1:1,000,000.
- To describe differences in amplitude, sound levels are measured on a logarithmic scale, in decibels (dB).
- Relatively small decibel changes can correspond to large physical changes.
  - For example: An increase in 6 dB corresponds to a doubling of the amount of pressure.

Figure 9.4 Sounds that we hear in our daily environments vary greatly in intensity



SENSATION & PERCEPTION 4e, **Figure 9.4**

What Is Sound?

One of the simplest kinds of sounds: Sine waves, or pure tone

- Sine wave: The waveform for which variation as a function of time is a sine function.

Sine waves are not common in everyday sounds because not many vibrations in the world are so pure.

- Most sounds in the world are complex sounds.

What Is Sound?

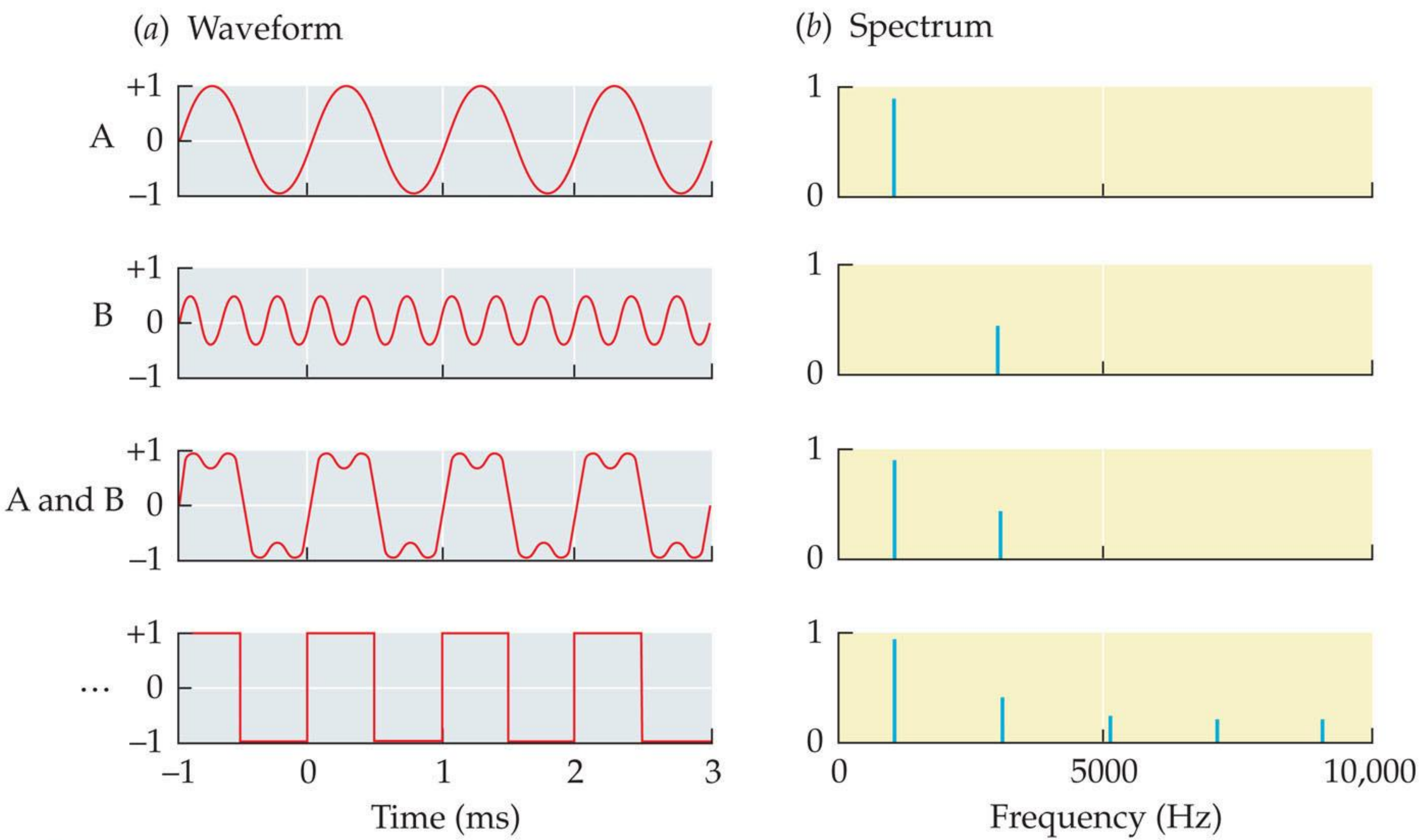
Nonetheless, all sound waves can be described as some combination of sine waves.

- Fourier Analysis

What Is Sound?

Complex sounds are best described as a spectrum that displays how much energy is present in each of the frequencies in the sound.

Figure 9.5 A spectrum displays the amplitude for each frequency present in a sound wave



SENSATION & PERCEPTION 4e, Figure 9.5

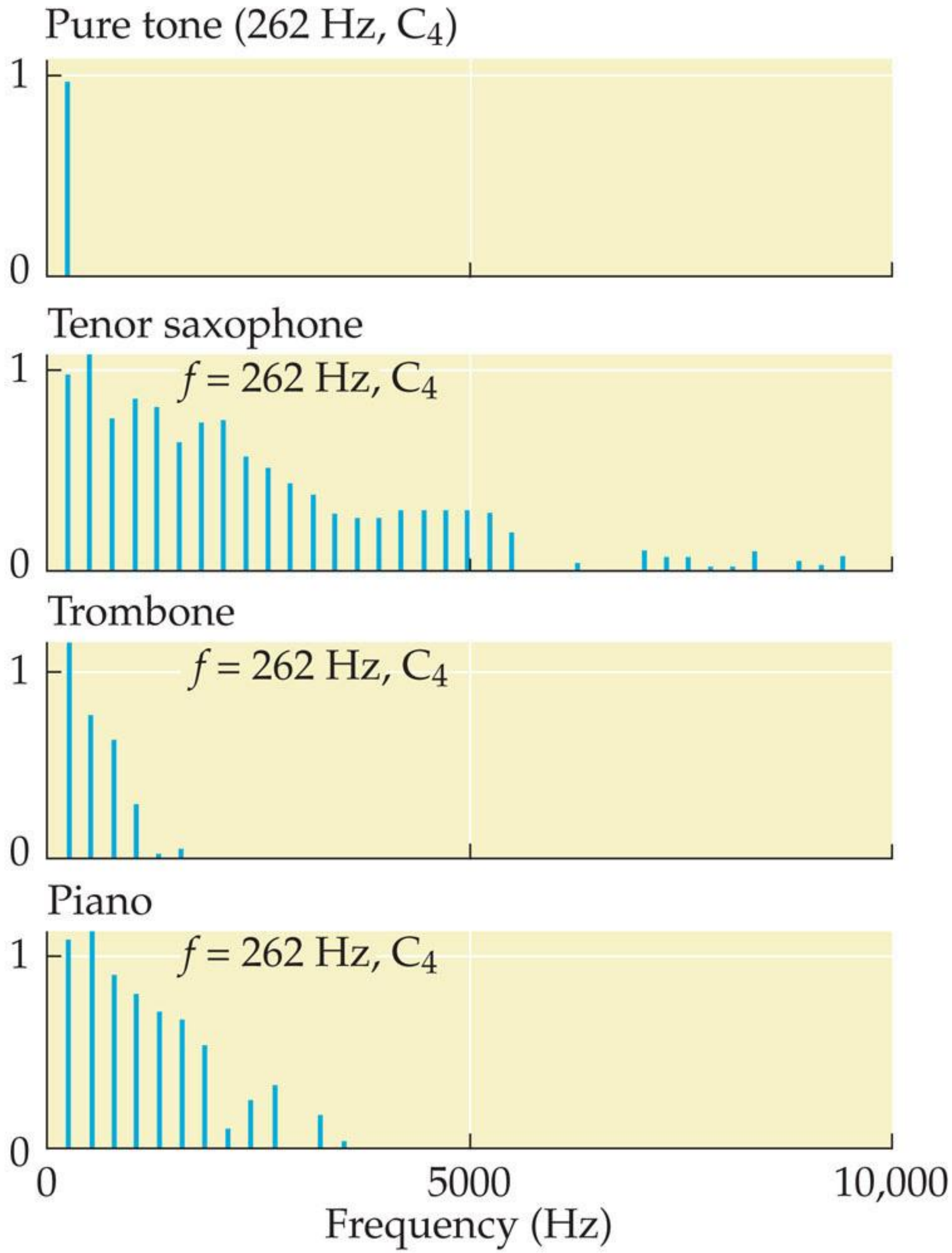
Harmonic spectrum: The spectrum of a complex sound in which energy is at integer multiples of the fundamental frequency.

- Typically caused by a simple vibrating source (e.g., string of a guitar, or reed of a saxophone)
- Fundamental frequency: The lowest-frequency component of a complex periodic sound.

What Is Sound?

- Timbre: The psychological sensation by which a listener can judge that two sounds with the same loudness and pitch are dissimilar.
  - Timbre quality is conveyed by harmonics and other high frequencies.

Figure 9.6 Harmonic sounds with the same fundamental frequency can sound different



SENSATION & PERCEPTION 4e, **Figure 9.6**

How are sounds detected and recognized by the auditory system?

- Sense of hearing evolved over millions of years.
- Many animals have very different hearing capabilities.
  - For instance, dogs can hear higher-frequency sounds and elephants can hear lower-frequency sounds than humans can.

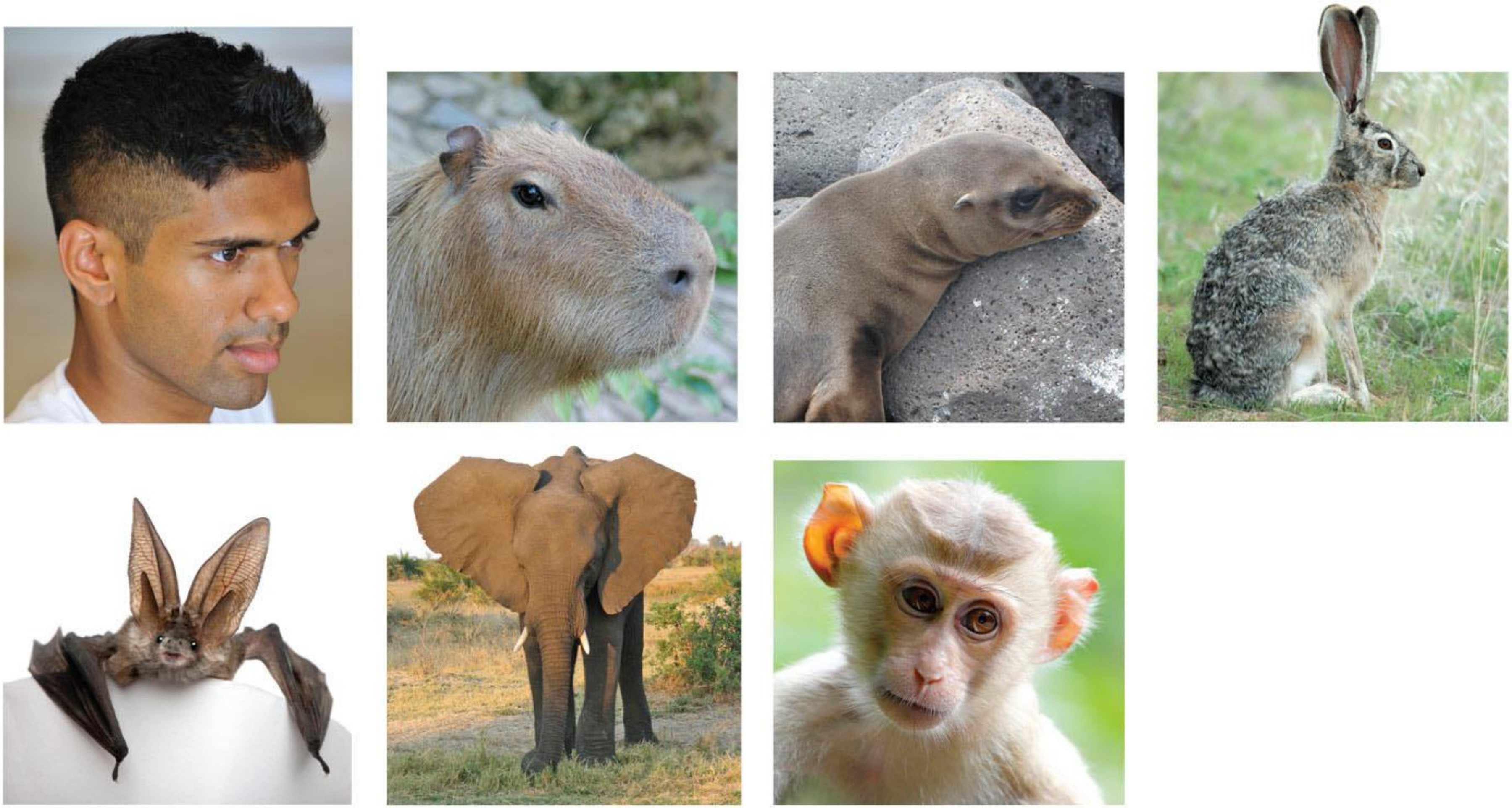
Outer ear

- Sounds are first collected from the environment by the pinnae.
- Sound waves are funneled by the pinnae into the ear canal.
- The length and shape of the ear canal enhances certain sound frequencies.

Outer ear (*continued*)

- Purpose of the ear canal:
  - To collect sound waves and funnel them to the tympanic membrane
  - To insulate and protect the tympanic membrane

Figure 9.7 The size and shape of pinnae vary greatly among mammals



***SENSATION & PERCEPTION* 4e, Figure 9.7**

Tympanic membrane: The eardrum. A thin sheet of skin at the end of the outer ear canal. Vibrates in response to sound.

Common myth: Puncturing your eardrum will leave you deaf.

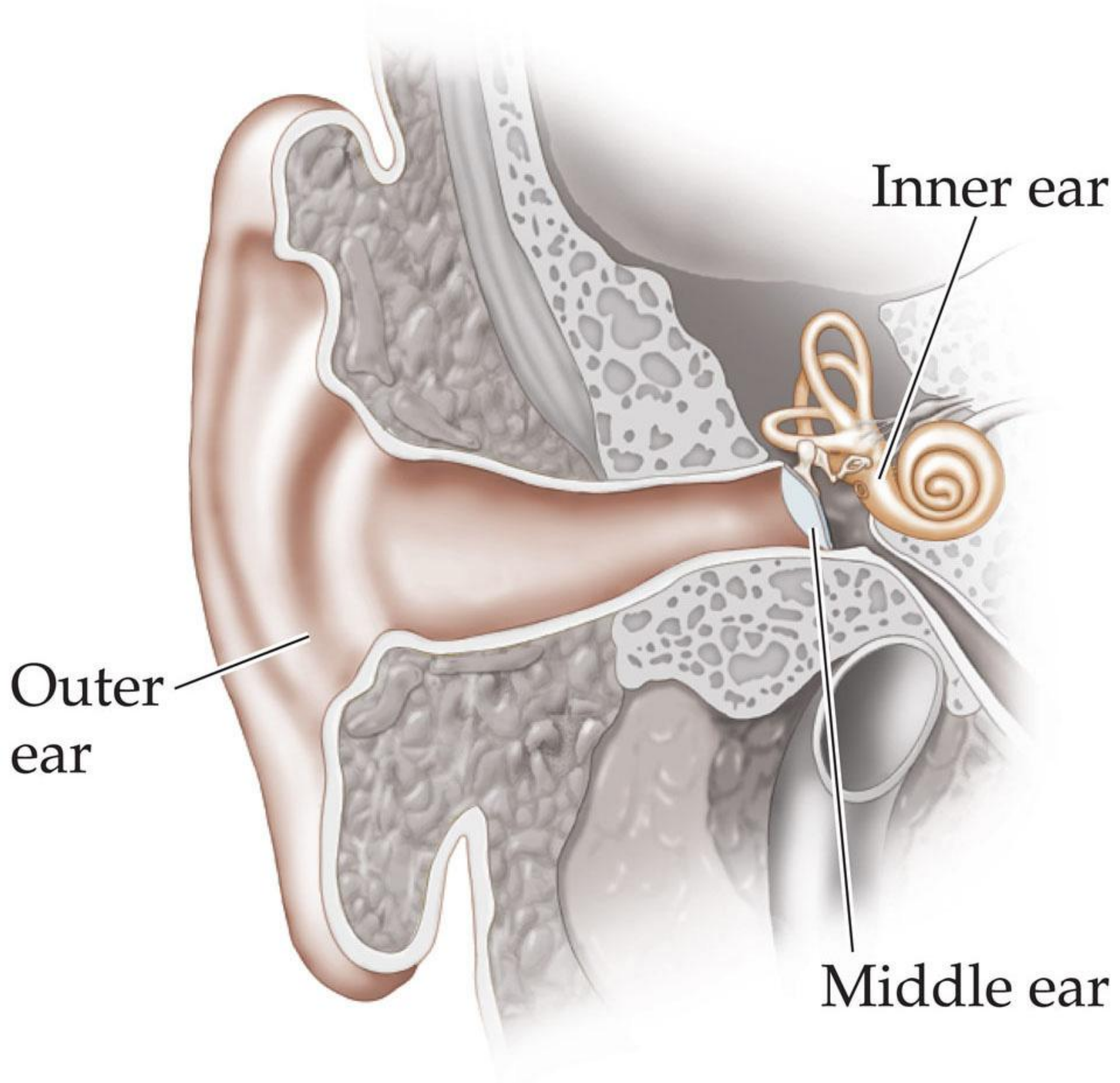
- In most cases it will heal itself.
- However, it is still possible to damage it beyond repair.

Middle ear

- Pinnae and ear canal make up the outer ear.
- Tympanic membrane is border between outer and middle ear.
- Middle ear consists of three tiny bones—ossicles—that amplify and transmit sounds to the inner ear.

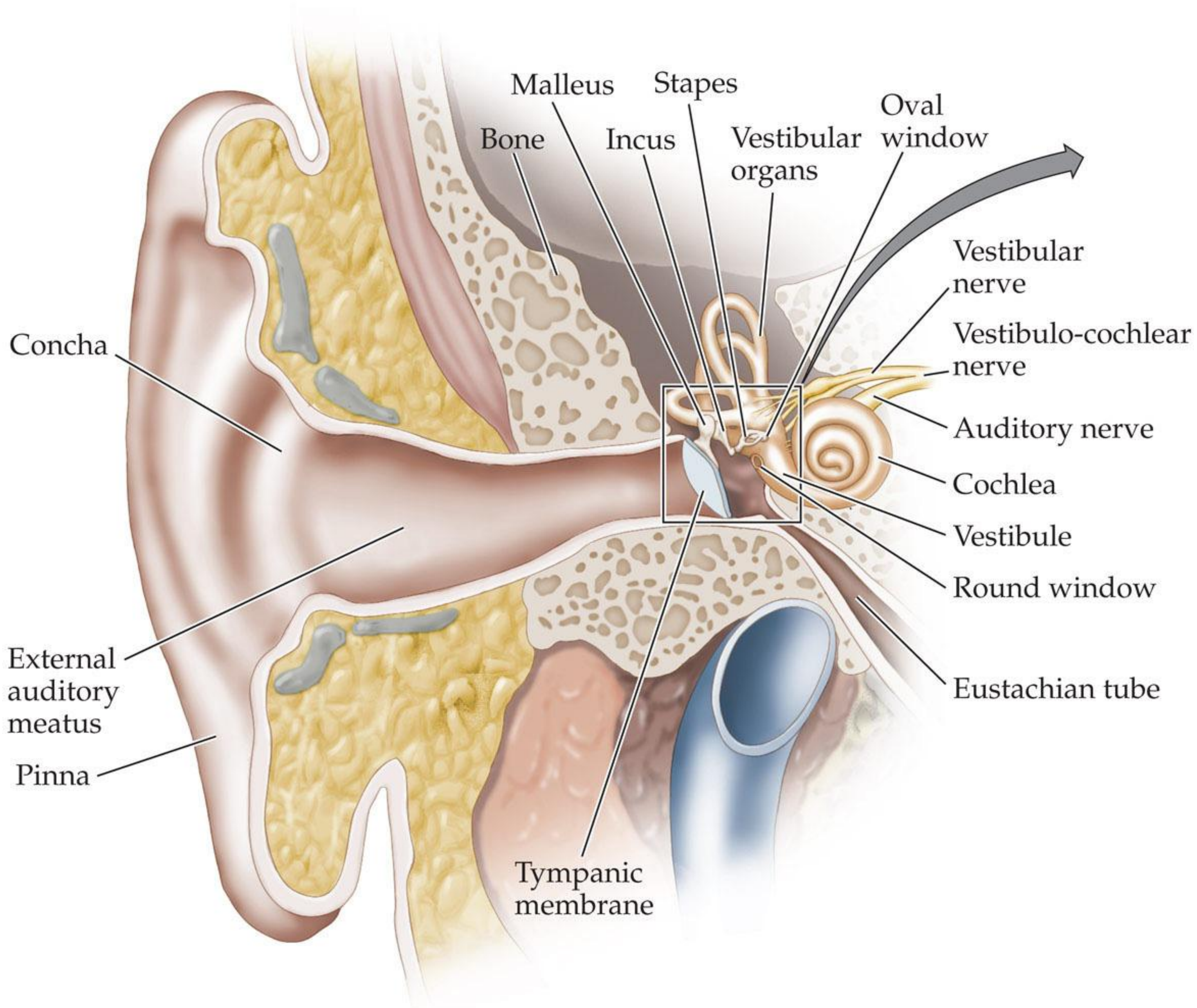
Ossicles: The smallest bones in the body.

- Malleus: Receives vibrations from the tympanic membrane and is attached to the incus.
- Incus: The middle ossicle.
- Stapes: Connected to the incus on one end and the oval window of the cochlea on the other.
  - Oval window is border between middle and inner ear.



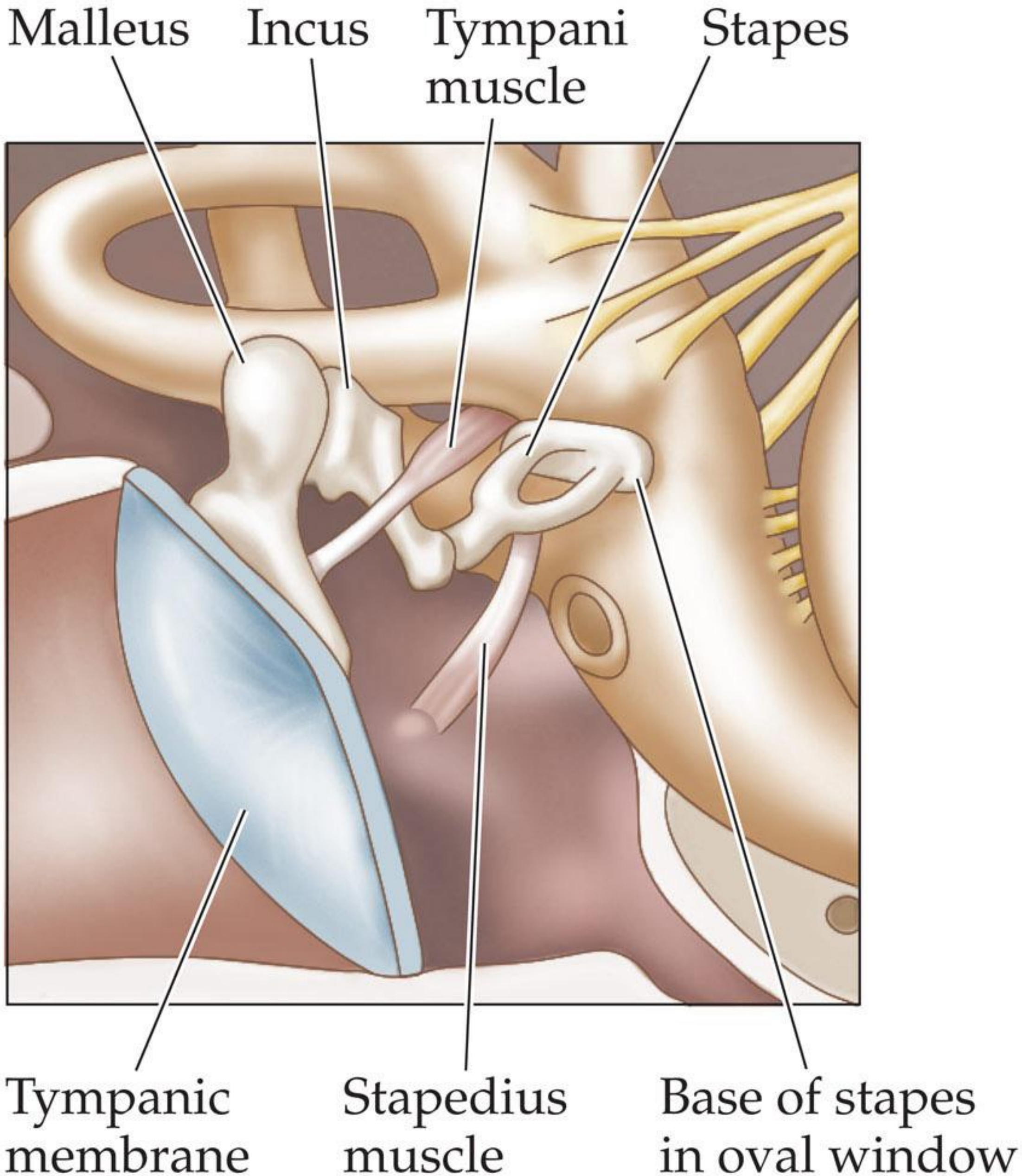
SENSATION & PERCEPTION 4e, Figure 9.8 (Part 3)

Figure 9.8 Structures of the human ear (Part 1)



SENSATION & PERCEPTION 4e, **Figure 9.8 (Part 1)**

Figure 9.8 Structures of the human ear (Part 2)



SENSATION & PERCEPTION 4e, Figure 9.8 (Part 2)

Basic Structure of the Mammalian Auditory System

Amplification provided by the ossicles is essential to our ability to hear faint sounds.

- Ossicles have hinged joints that work like levers to amplify sounds.
- The stapes has a smaller surface than the malleus, so sound energy is concentrated.
- The inner ear consists of fluid-filled chambers.
  - It takes more energy to move liquid than air.

Basic Structure of the Mammalian Auditory System

The ossicles are also important for loud sounds.

- Tensor tympani and stapedius:
  - Two muscles in the middle ear that decrease ossicle vibrations when tensed
  - Muffle loud sounds and protect the inner ear

However, acoustic reflex follows onset of loud sounds by 200 ms, so it cannot protect against abrupt sounds (e.g., gun shot).

Basic Structure of the Mammalian Auditory System

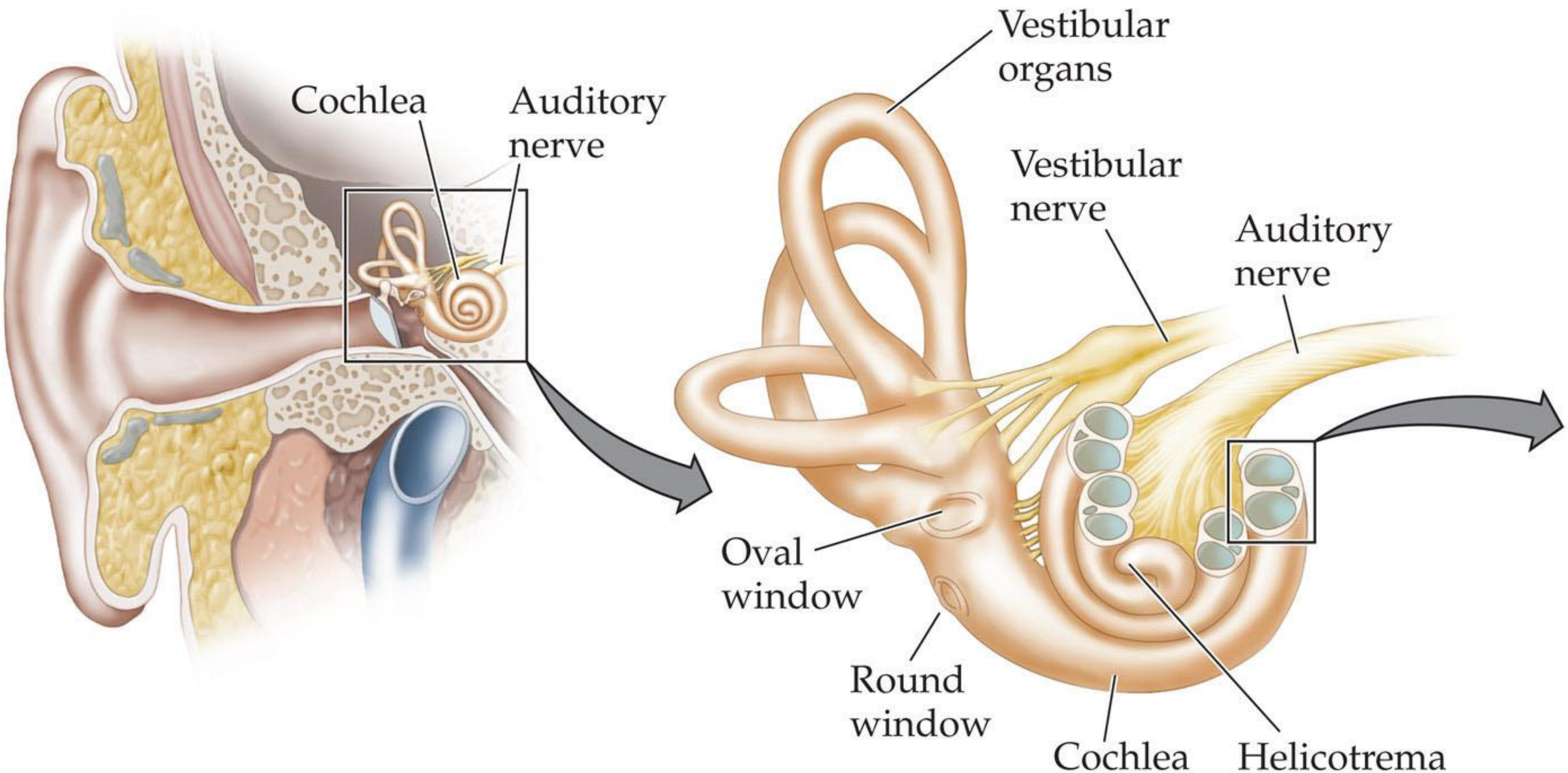
Inner ear

- Fine changes in sound pressure are transduced into neural signals.
- Function is roughly analogous to that of the retina.

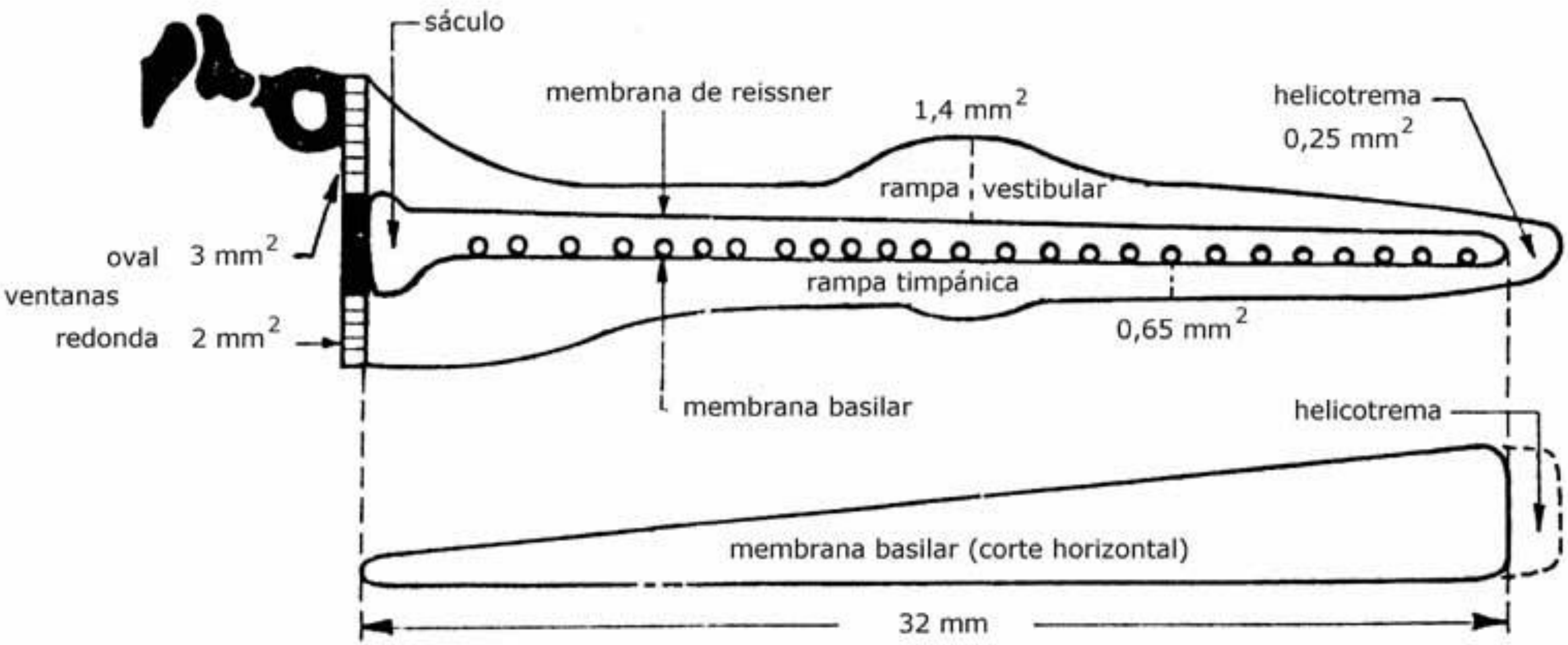
Cochlear canals and membranes

- Cochlea: Spiral structure of the inner ear containing the organ of Corti.
- Cochlea is filled with watery fluids in three parallel canals.

Figure 9.9 The cochlea (Part 1)

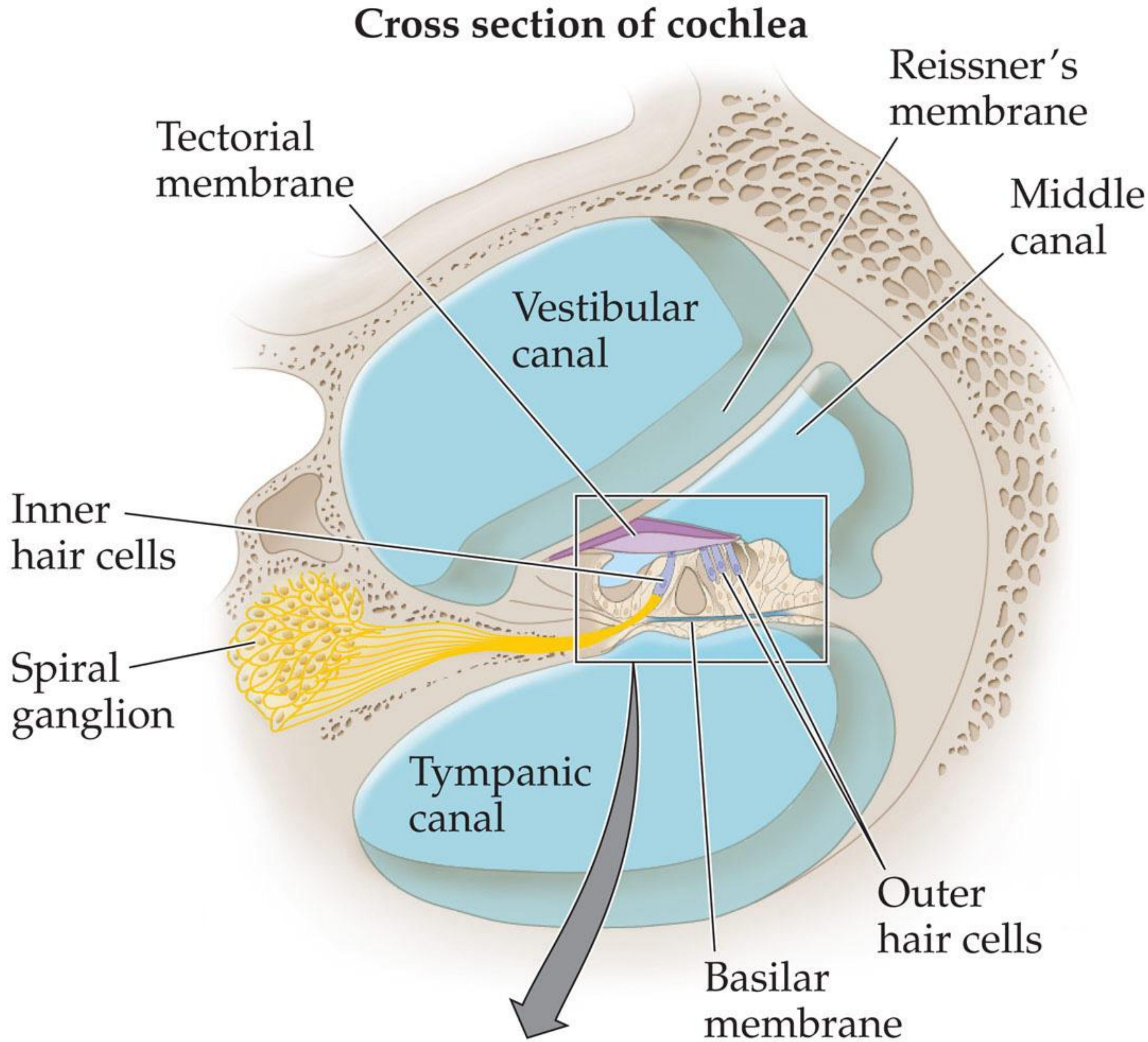


SENSATION & PERCEPTION 4e, Figure 9.9 (Part 1)



sáculo
membrana de reissner
1,4 mm2
helicotrema
0,25 mm2
rampa vestibular
oval 3 mm2
ventanas
redonda 2 mm2
rampa timpánica
0,65 mm2
membrana basilar
helicotrema
membrana basilar (corte horizontal)
32 mm

Figure 9.9 The cochlea (Part 2)

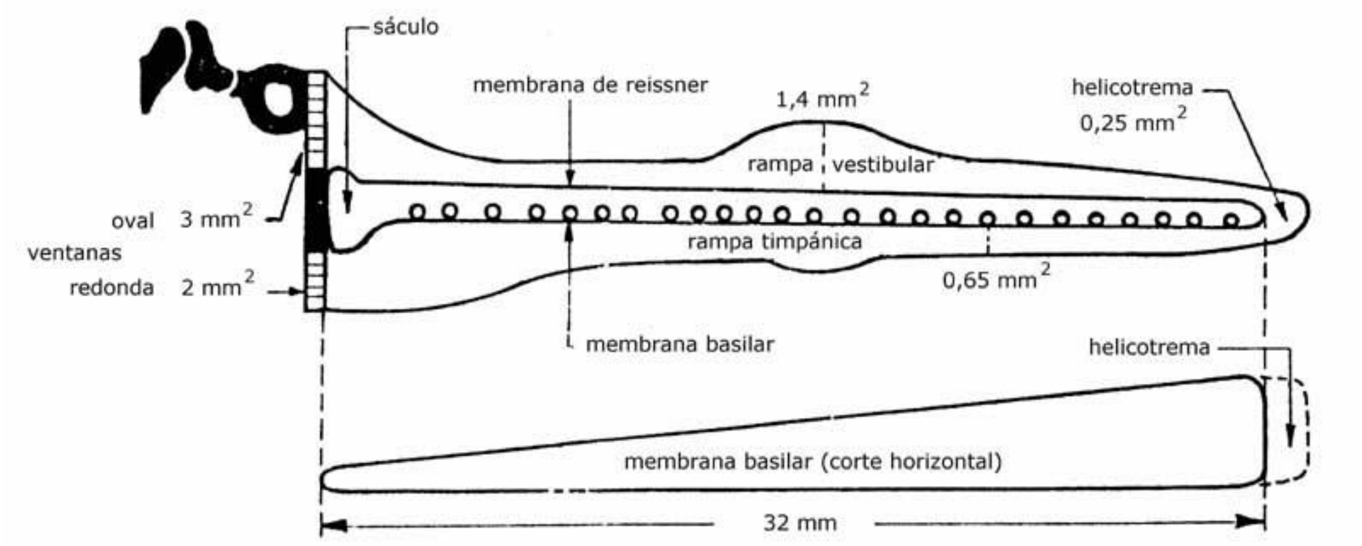


SENSATION & PERCEPTION 4e, Figure 9.9 (Part 2)

Basic Structure of the Mammalian Auditory System

The three canals of the cochlea

- Vestibular canal: Extends from oval window at base of cochlea to helicotrema at the apex. Canal closest to ossicles and through which pressure waves move first.
- Tympanic canal: Extends from the helicotrema at the apex to the round window at the base of the cochlea.
- Middle canal: Sandwiched between the vestibular and tympanic canals and contains the cochlear partition.



Three cochlear canals are separated by membranes.

- Reissner’s membrane: Thin sheath of tissue separating the vestibular and middle canals in the cochlea
- Basilar membrane: Plate of fibers that forms the base of the cochlear partition and separates the middle and tympanic canals in the cochlea

Basic Structure of the Mammalian Auditory System

Vibrations transmitted through tympanic membranes and middle-ear bones cause the stapes to push and pull the flexible oval window in and out of the vestibular canal at the base of the cochlea.

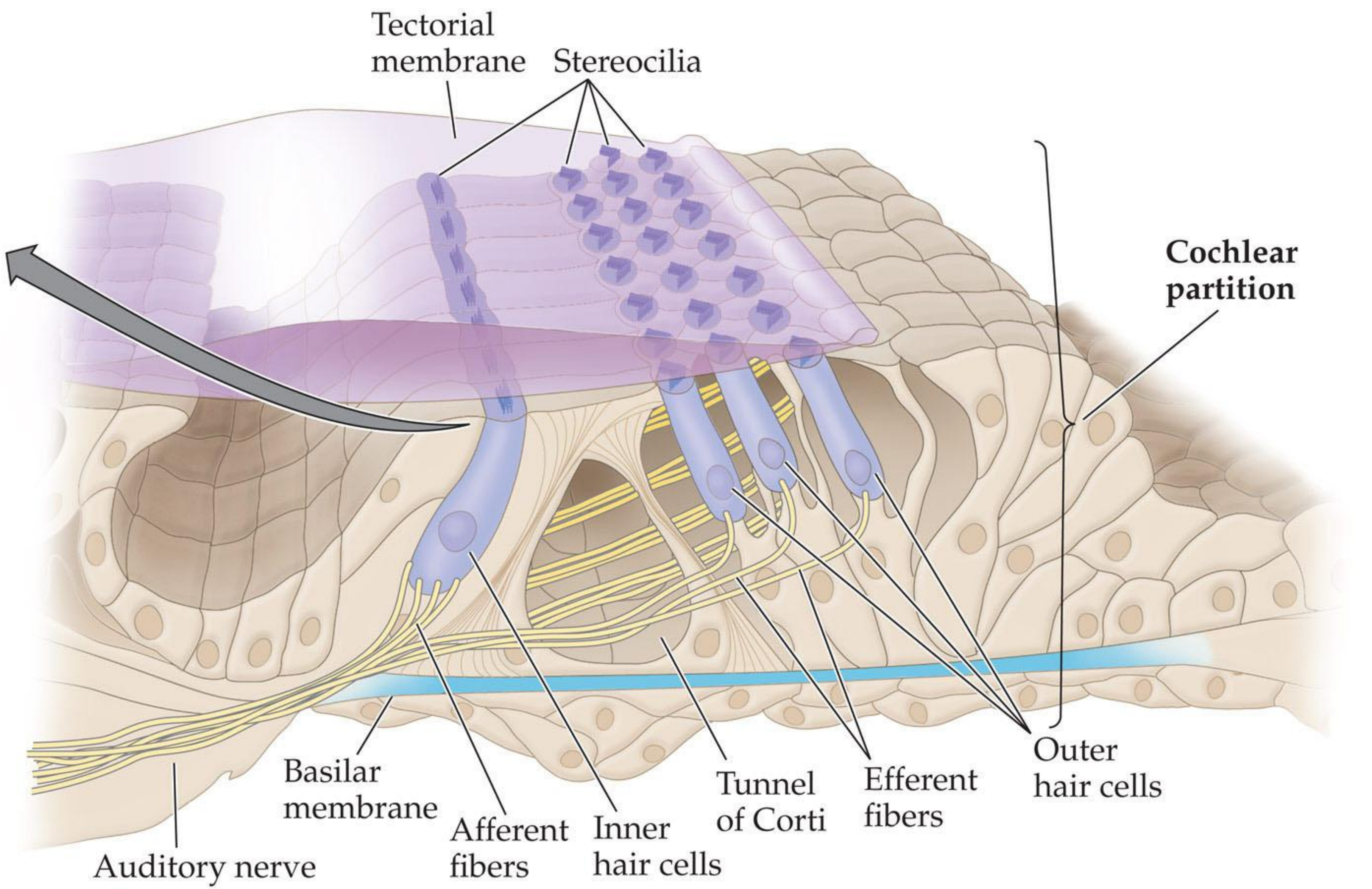
Any remaining pressure from extremely intense sounds is transmitted through the helicotrema and back to the cochlear base through the tympanic canal, where it is absorbed by another membrane—the round window.

Basic Structure of the Mammalian Auditory System

Organ of Corti: A structure on the basilar membrane of the cochlea that is composed of hair cells and dendrites of auditory nerve fibers.

Movements of the cochlear partition are translated into neural signals by structures in the organ of Corti.

Figure 9.9 The cochlea (Part 3)

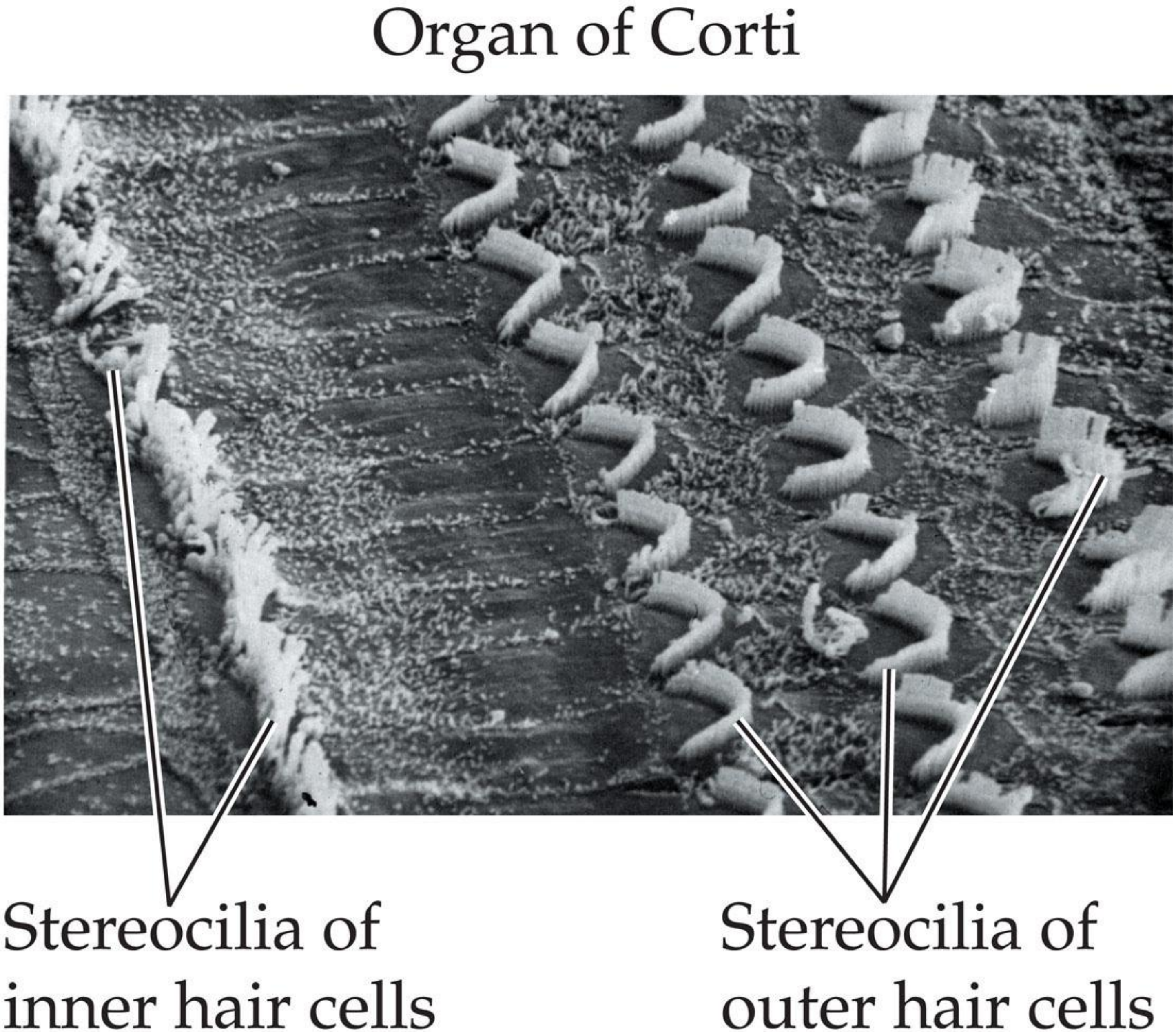


SENSATION & PERCEPTION 4e, Figure 9.9 (Part 3)

Basic Structure of the Mammalian Auditory System

Hair cells: Cells that support the stereocilia, which transduce mechanical movement in the cochlea into neural activity sent to the brain stem. Some hair cells also receive input from the brain.

- Arranged in four rows that run down length of basilar membrane

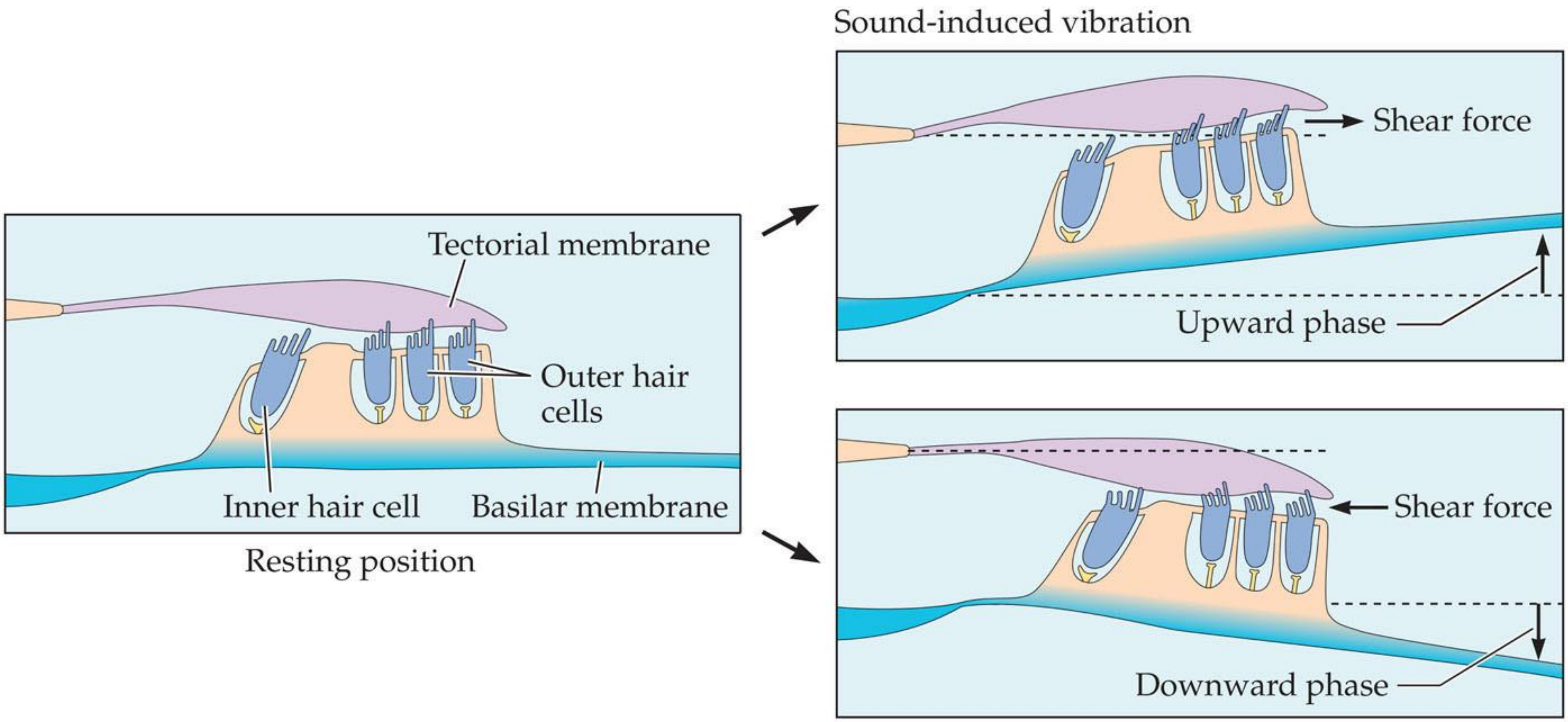


SENSATION & PERCEPTION 4e, Figure 9.9 (Part 4)

Tectorial membrane: A gelatinous structure, attached on one end, that extends into the middle canal of the ear, floating above inner hair cells and touching outer hair cells.

Vibrations cause displacement of the tectorial membrane, which bends stereocilia attached to hair cells and causes the release of neurotransmitters.

Figure 9.10 Vibration causes a displacement along the cochlear partition and leads to the release of neurotransmitters

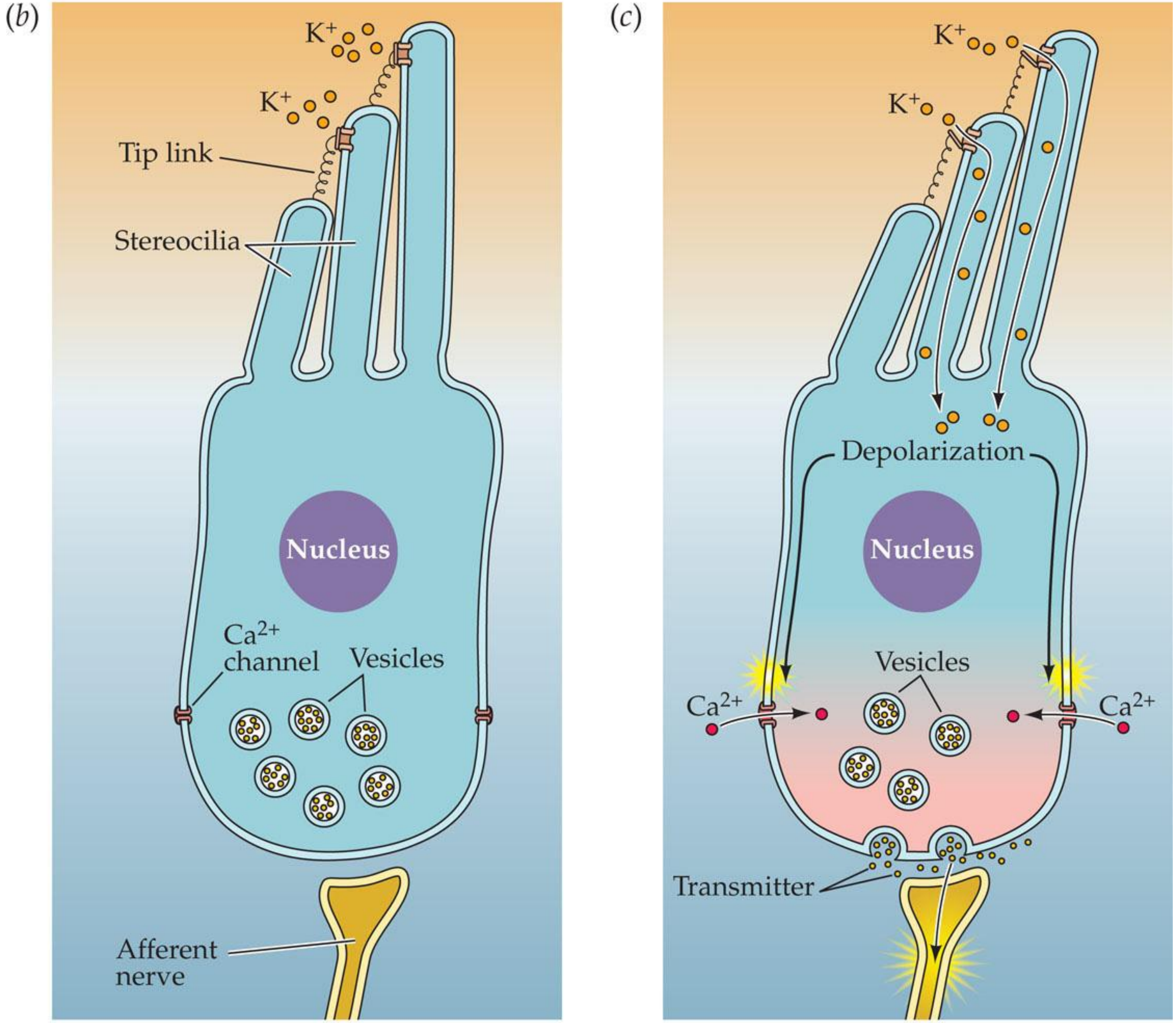


SENSATION & PERCEPTION 4e, Figure 9.10

Stereocilia: Hairlike extensions on the tips of hair cells in the cochlea that initiate the release of neurotransmitters when they are flexed.

The tip of each stereocilium is connected to the side of its neighbor by a tiny filament called a tip link.

Figure 9.11 Stereocilia regulate the flow of ions into and out of hair cells (Part 2)

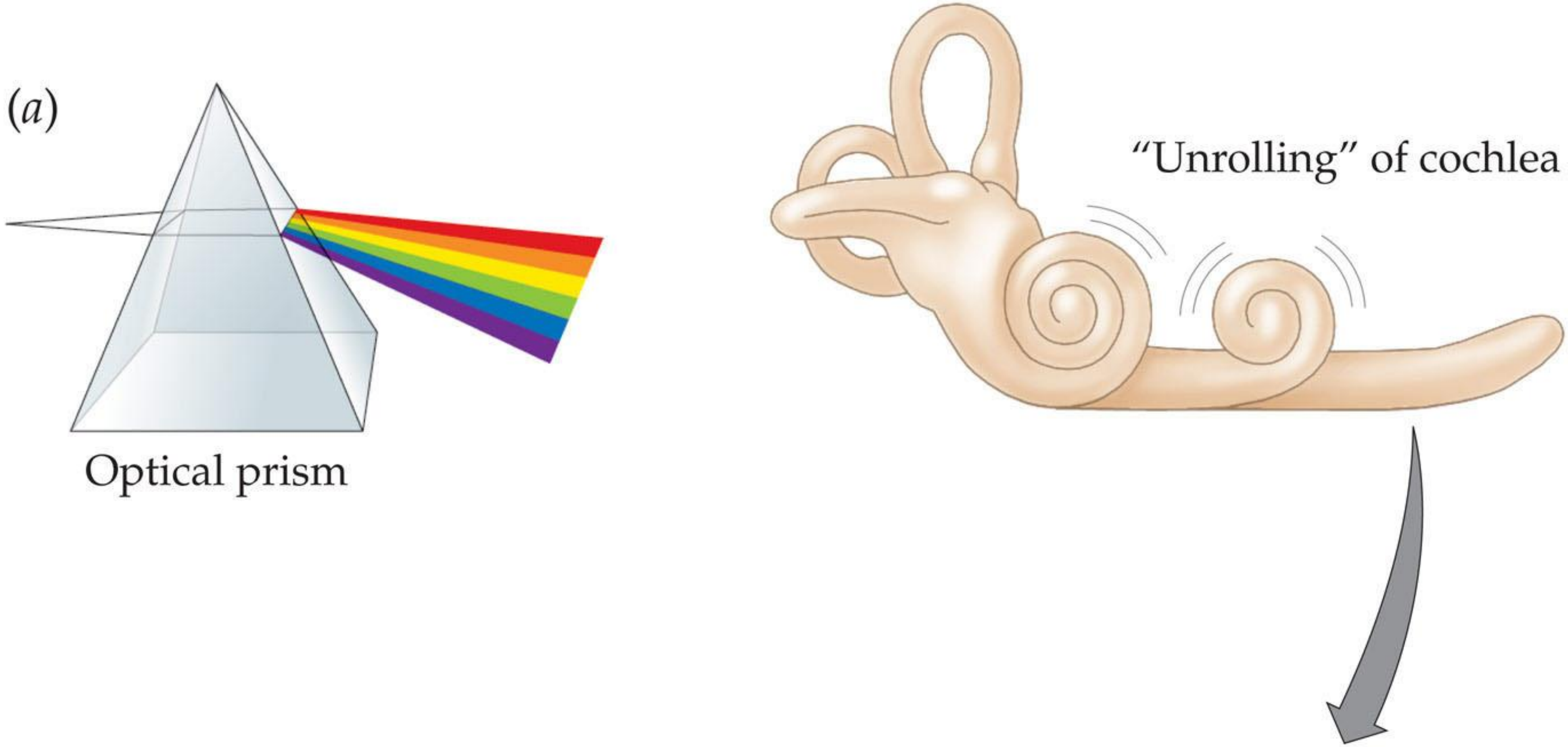


***SENSATION & PERCEPTION 4e*, Figure 9.11 (Part 2)**

Coding of amplitude and frequency in the cochlea

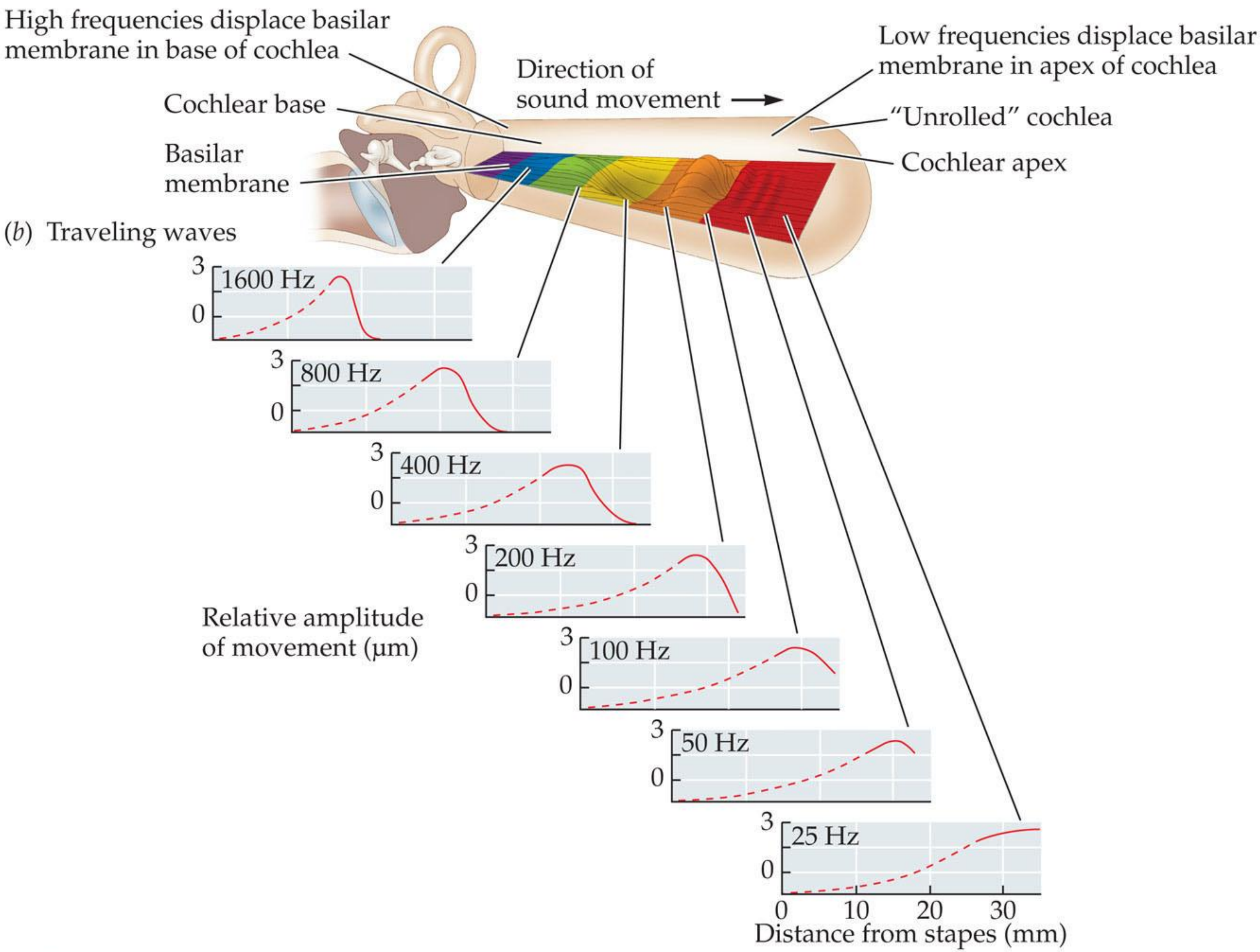
- Place code: Tuning of different parts of the cochlea to different frequencies, in which information about the particular frequency of an incoming sound wave is coded by the place along the cochlear partition with the greatest mechanical displacement.

Figure 9.12 The cochlea is like an acoustic prism in that its sensitivity spreads across different sound frequencies along its length (Part 1)



SENSATION & PERCEPTION 4e, Figure 9.12 (Part 1)

Figure 9.12 The cochlea is like an acoustic prism in that its sensitivity spreads across different sound frequencies along its length (Part 2)



SENSATION & PERCEPTION 4e, Figure 9.12 (Part 2)

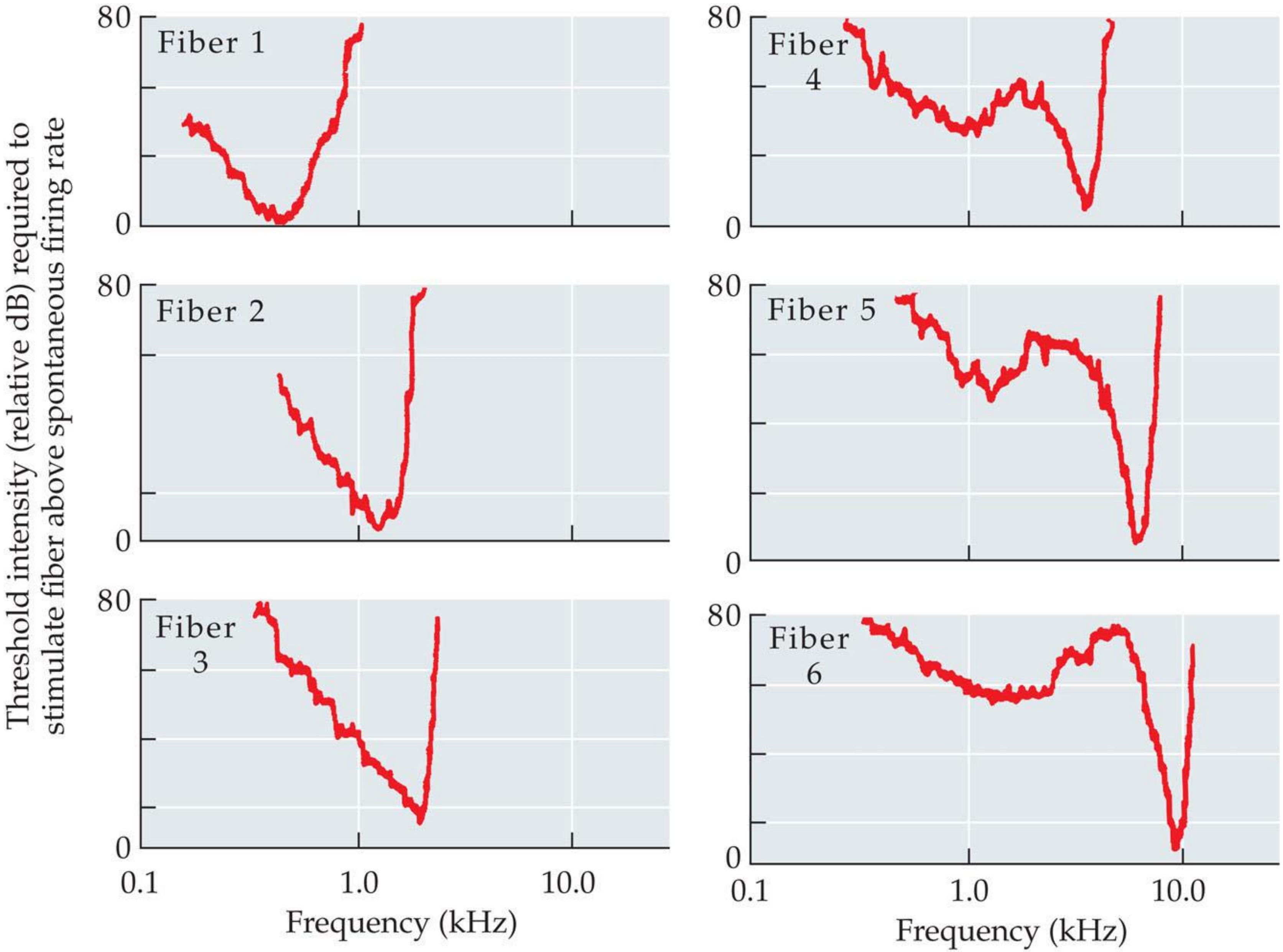
Inner and outer hair cells

- Inner hair cells: Convey almost all information about sound waves to the brain (using afferent fibers).
- Outer hair cells: Receive information from the brain (using efferent fibers). They are involved in an elaborate feedback system.

The auditory nerve (AN)

- Responses of individual AN fibers to different frequencies are related to their place along the cochlear partition.
- Frequency selectivity: Clearest when sounds are very faint.
- **Threshold tuning curve:** A graph plotting thresholds of a neuron or fiber in response to sine waves with varying frequencies at the lowest intensity that will give rise to a response.

Figure 9.13 Threshold tuning curves for six auditory nerve fibers, each tuned to a different frequency



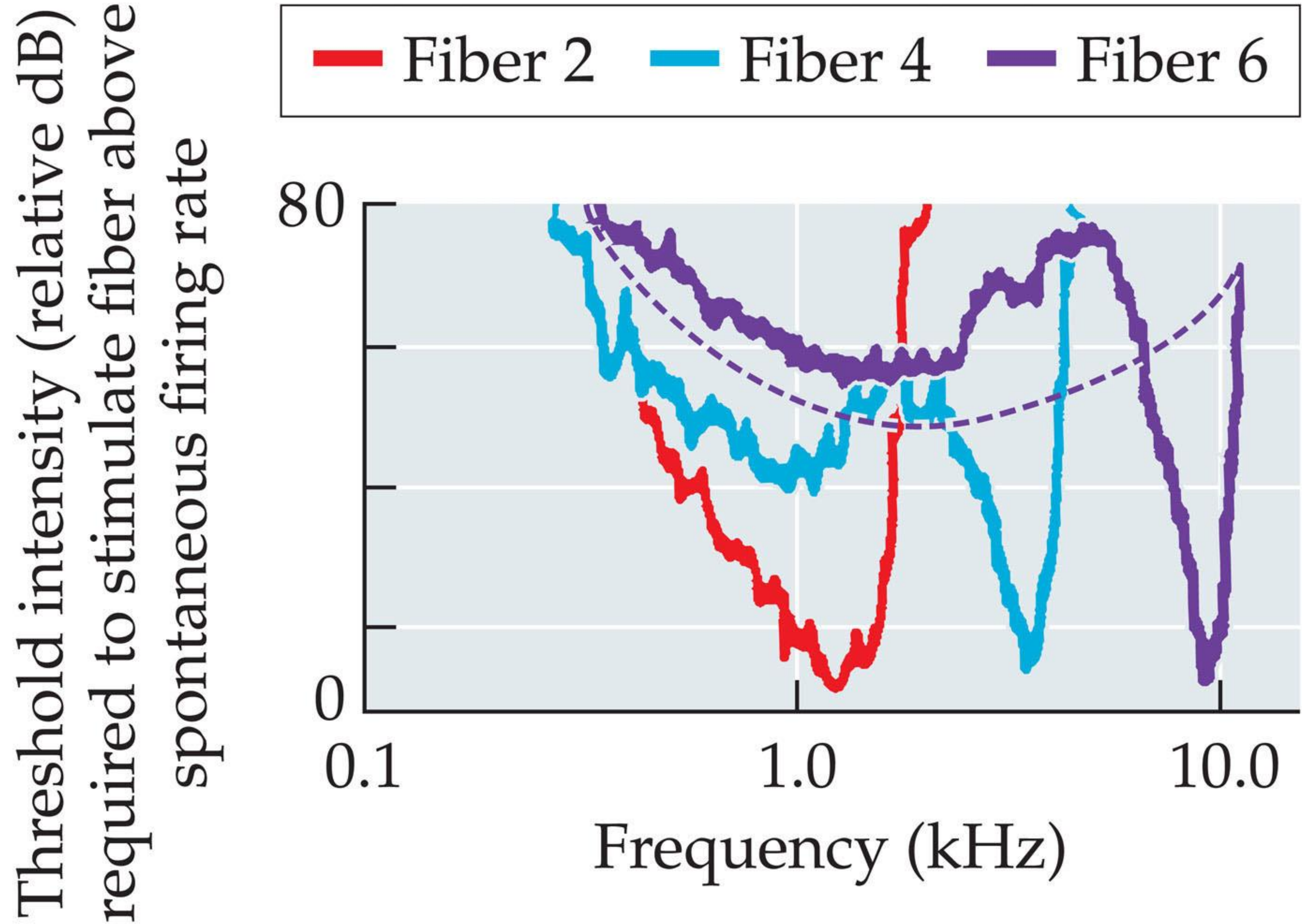
SENSATION & PERCEPTION 4e, Figure 9.13

Basic Structure of the Mammalian Auditory System

Outer hair cells receive feedback from the brain and can make parts of the cochlear partition stiffer.

This makes the responses of inner hair cells more sensitive and more sharply tuned to specific frequencies.

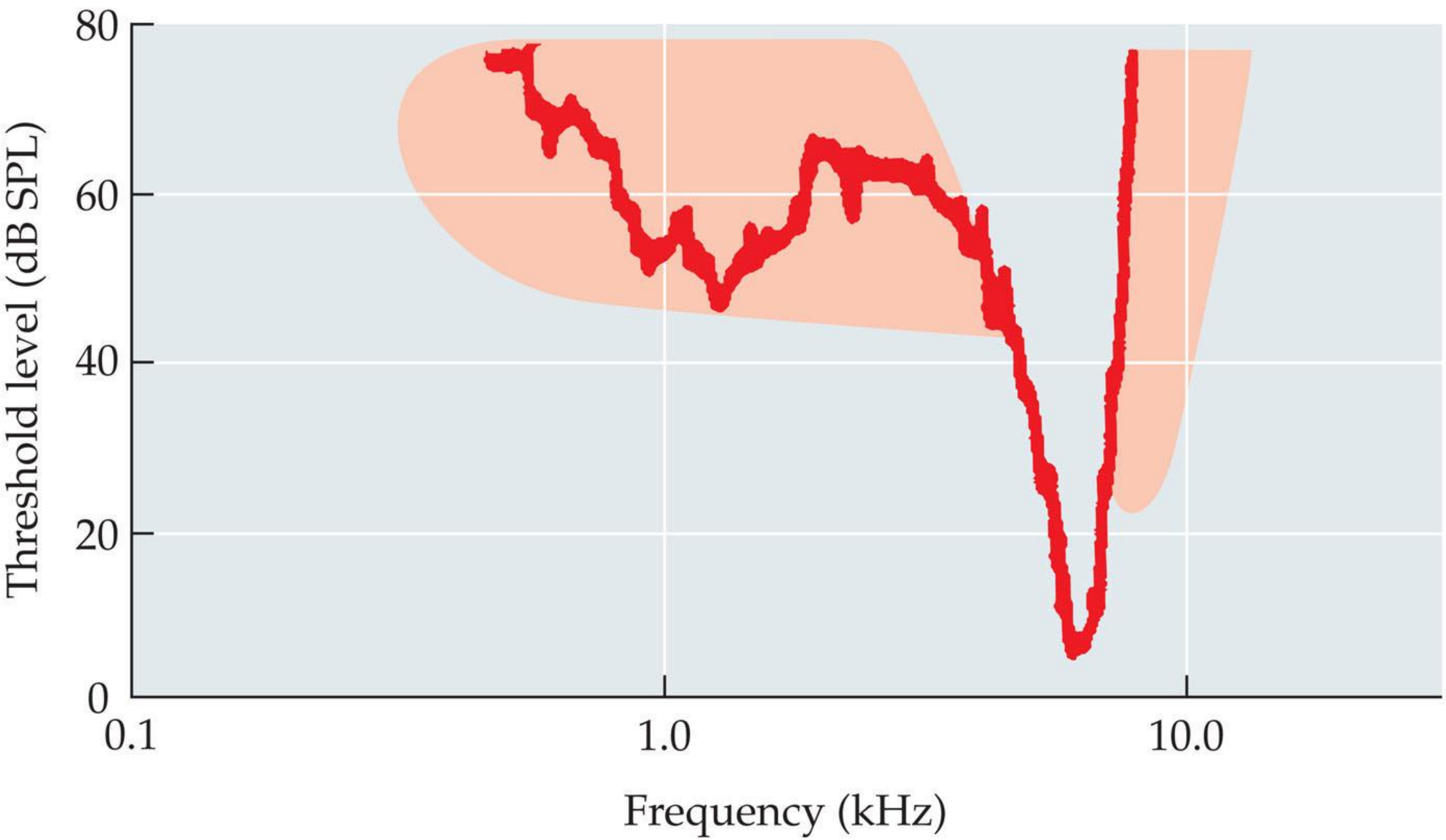
Figure 9.14 Outer hair cells improve both sensitivity and frequency selectivity



SENSATION & PERCEPTION 4e, **Figure 9.14**

Two-tone suppression: Decrease in firing rate of one auditory nerve fiber due to one tone, when a second tone is presented at the same time.

Figure 9.15 Two-tone suppression



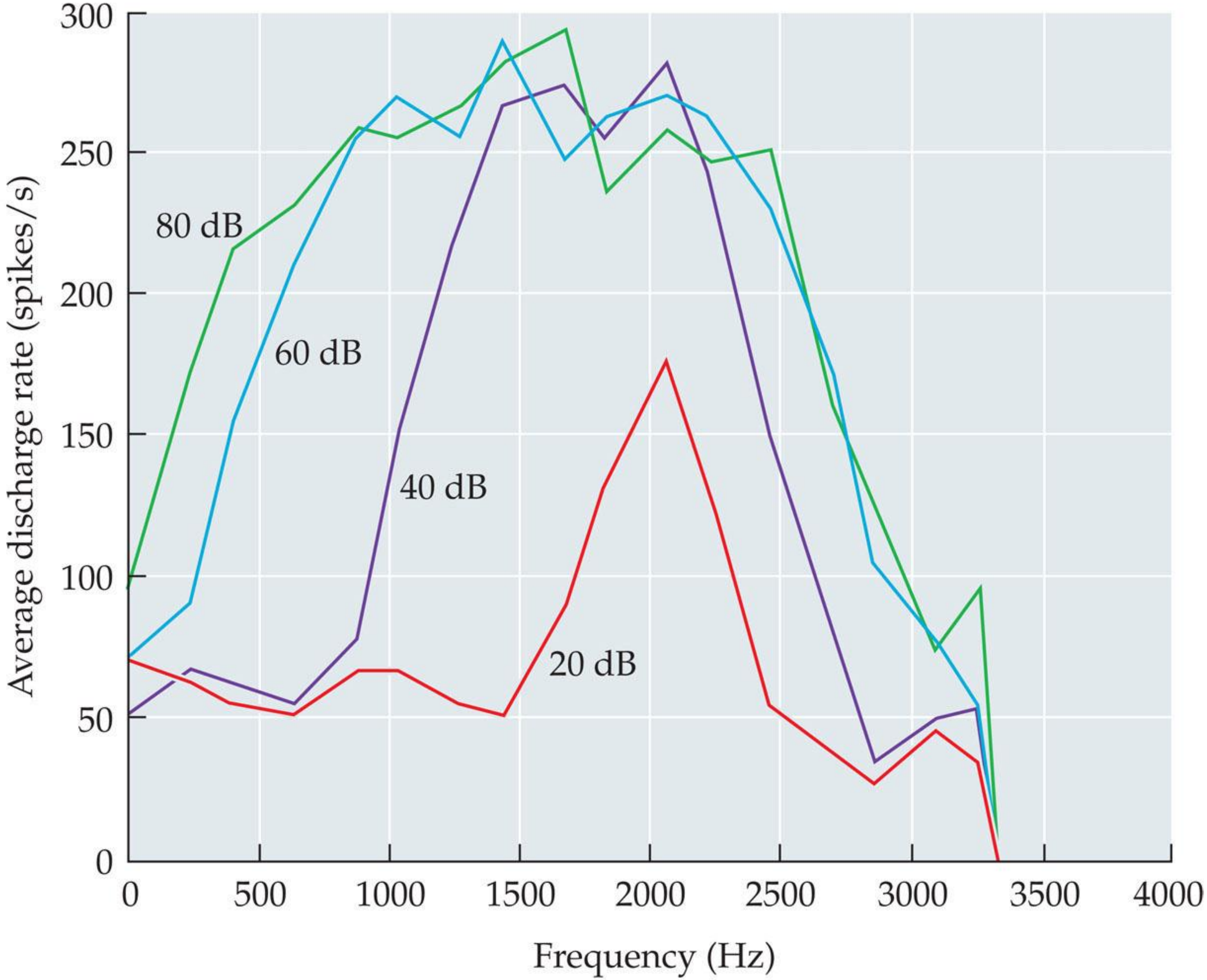
SENSATION & PERCEPTION 4e, Figure 9.15

Rate saturation

- Are AN fibers as selective for their characteristic frequencies at levels well above threshold as they are for barely audible sounds?
- To answer this, look at **isointensity curves**: A chart measuring an AN fiber’s firing rate to a **wide range of frequencies, all presented at the same intensity level.**

- **Rate saturation:** The point at which a nerve fiber is firing as rapidly as possible and further stimulation is incapable of increasing the firing rate.

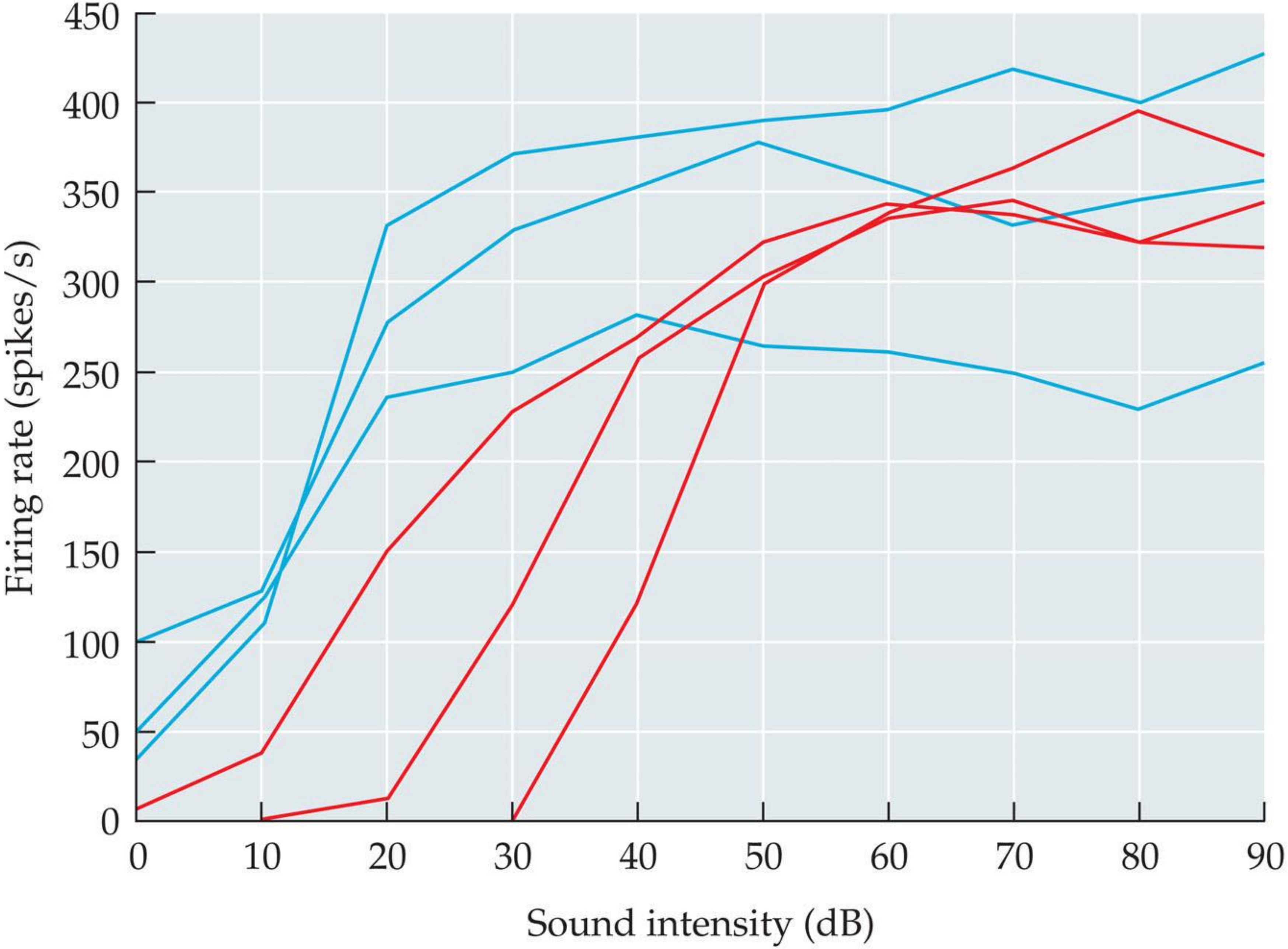
Figure 9.16 Isointensity functions for one AN fiber with a characteristic frequency of 2000 Hz



SENSATION & PERCEPTION 4e, Figure 9.16

Rate-intensity function: A map plotting firing rate of an auditory nerve fiber in response to a sound of constant frequency at increasing intensities.

Figure 9.17 Firing rate plotted against sound intensity for six auditory nerve fibers

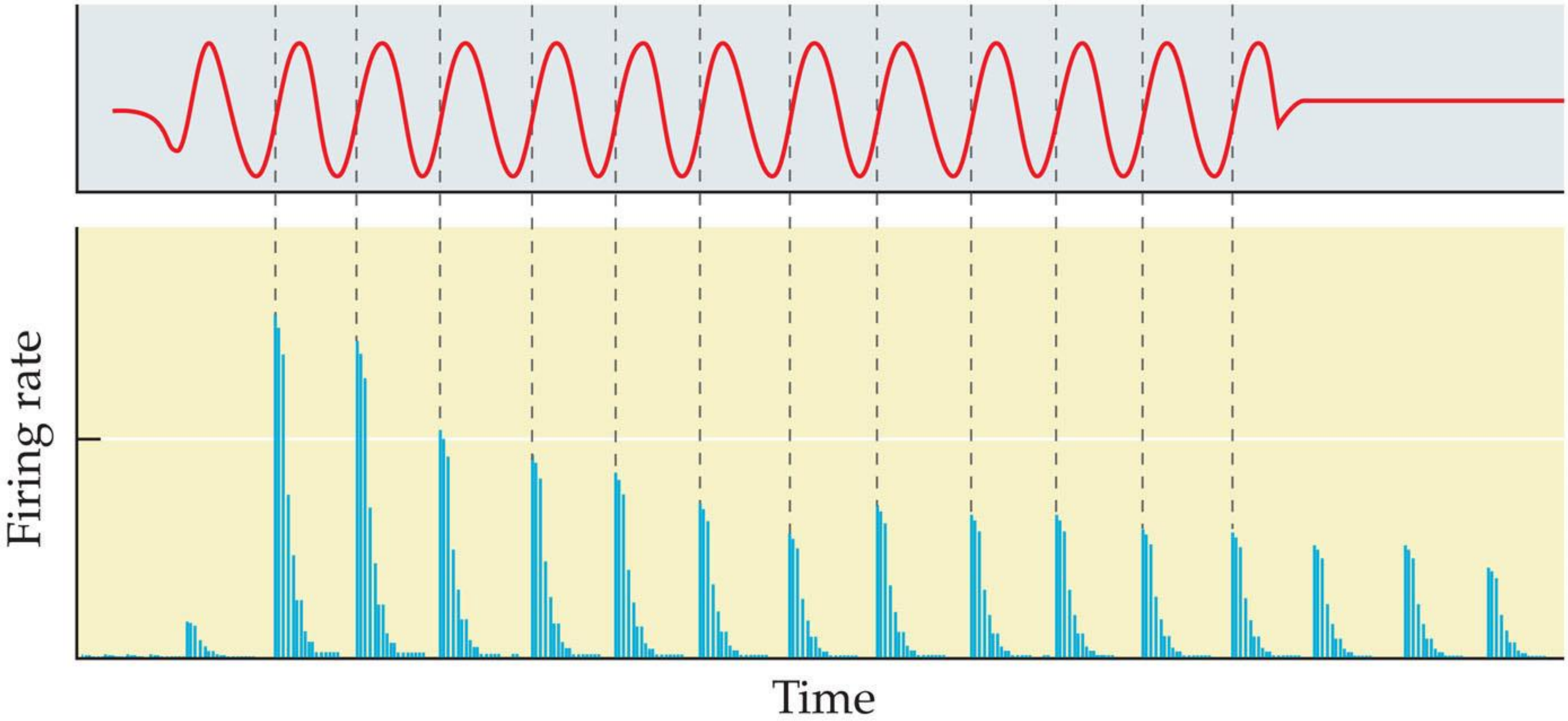


SENSATION & PERCEPTION 4e, **Figure 9.17**

Temporal code for sound frequency

- The auditory system has another way to encode frequency aside from the cochlear place code.
- Phase locking: Firing of a single neuron at one distinct point in the period (cycle) of a sound wave at a given frequency.
- The existence of phase locking means that the firing pattern of an AN fiber carries a temporal code.

Figure 9.18 Phase locking

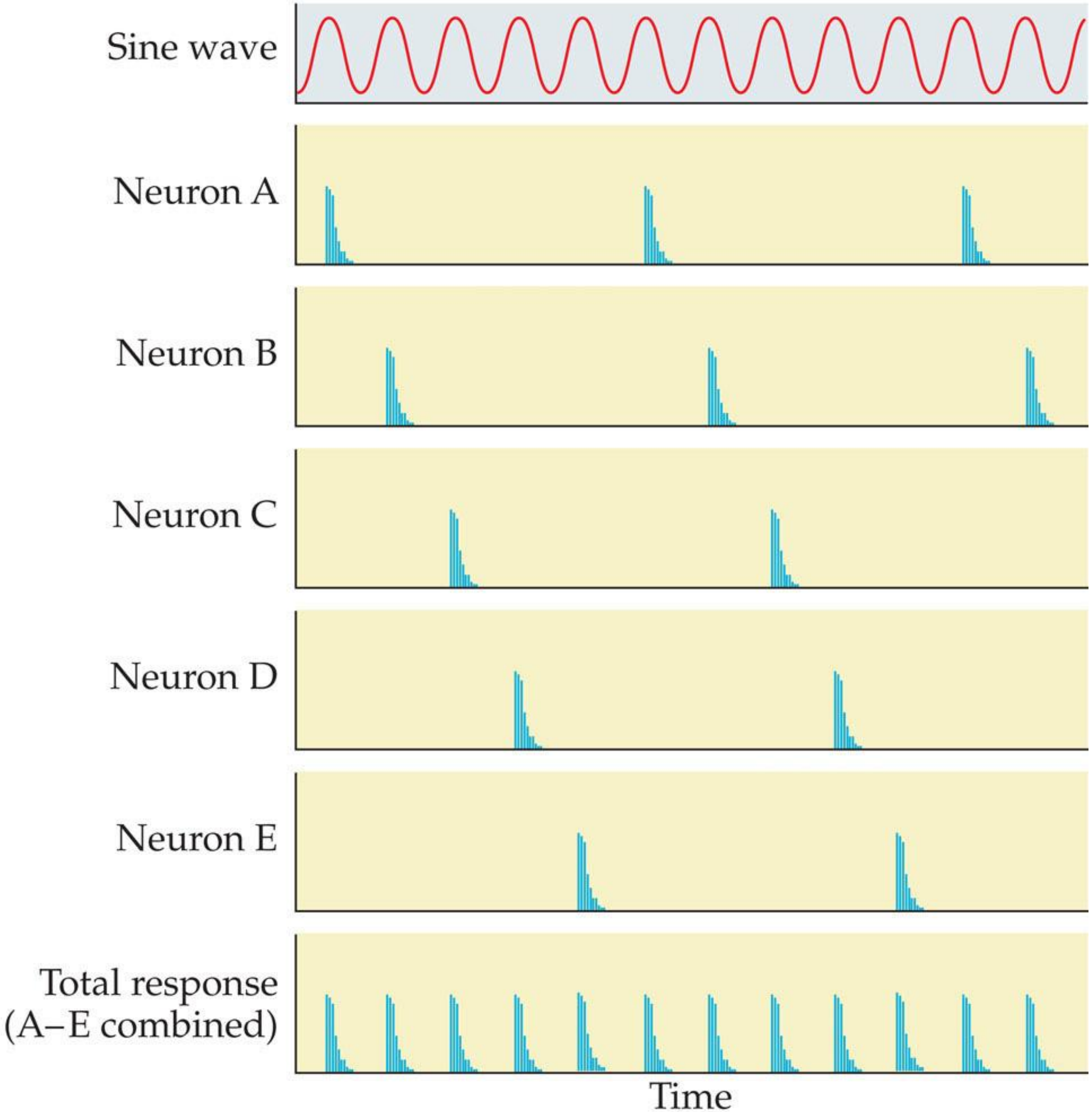


SENSATION & PERCEPTION 4e, Figure 9.18

Temporal code: Tuning of different parts of the cochlea to different frequencies, in which information about the particular frequency of an incoming sound wave is coded by the *timing* of neural firing as it relates to the period of the sound.

The volley principle: An idea stating that multiple neurons can provide a temporal code for frequency if each neuron fires at a distinct point in the period of a sound wave but does not fire on every period.

Figure 9.19 The volley principle



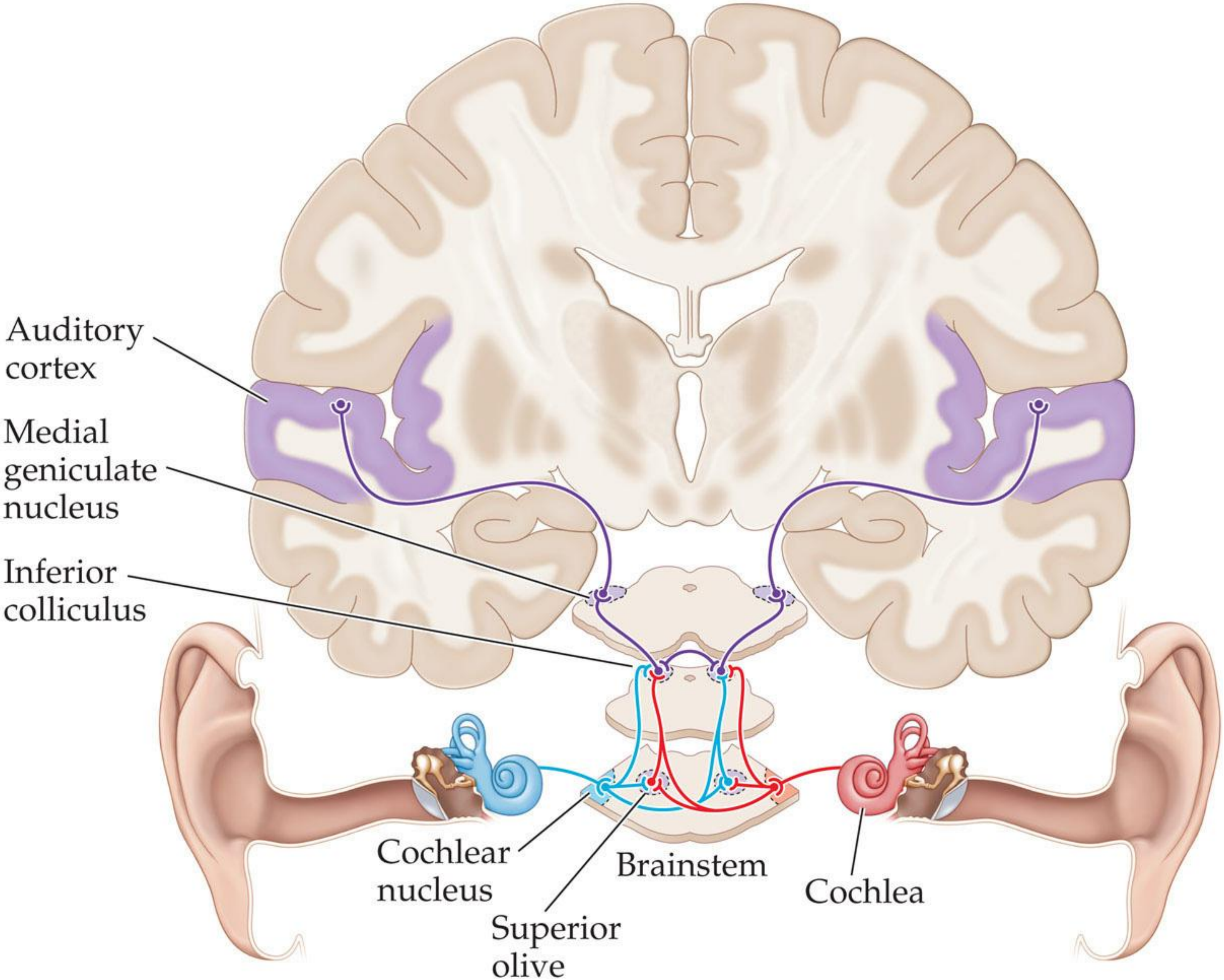
Auditory brain structures

- Cochlear nucleus: The first brain stem nucleus at which afferent auditory nerve fibers synapse.
- Superior olive: An early brain stem region in the auditory pathway where inputs from both ears converge.

Auditory brain structures (*continued*)

- Inferior colliculus: A midbrain nucleus in the auditory pathway.
- Medial geniculate nucleus: The part of the thalamus that relays auditory signals to the temporal cortex and receives input from the auditory cortex.

Figure 9.20 Pathways in the auditory system



SENSATION & PERCEPTION 4e, **Figure 9.20**

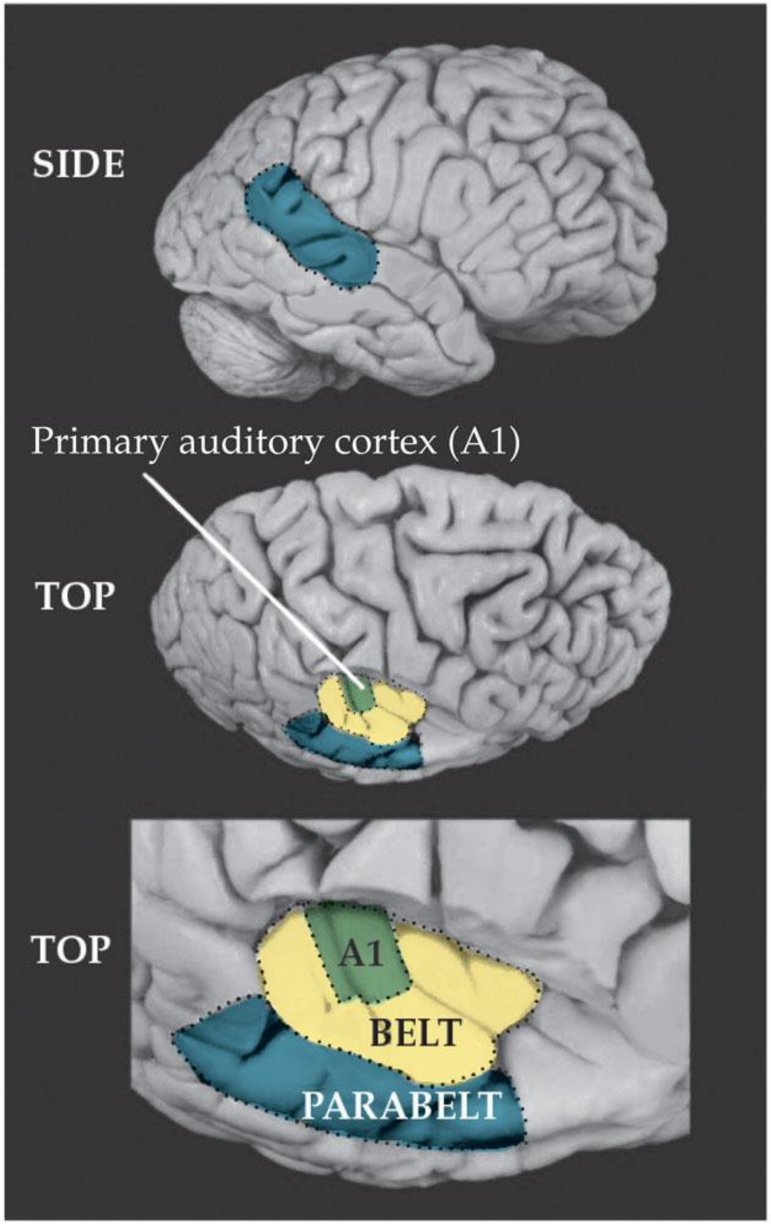
Auditory brain structures (*continued*)

- Primary auditory cortex (A1): The first area within the temporal lobes of the brain responsible for processing acoustic organization.
- Belt area: A region of cortex, directly adjacent to A1, with inputs from A1, where neurons respond to more complex characteristics of sounds.

Auditory brain structures (*continued*)

- Parabelt area: A region of cortex, lateral and adjacent to the belt area, where neurons respond to more complex characteristics of sounds, as well as to input from other senses.

Figure 9.21 The first stages of auditory processing begin in the temporal lobe in areas within the Sylvian fissure



SENSATION & PERCEPTION 4e, Figure 9.21

Basic Structure of the Mammalian Auditory System

Tonotopic organization: An arrangement in which neurons that respond to different frequencies are organized anatomically in order of frequency.

- Starts in the cochlea
- Maintained all the way through primary auditory cortex (A1)

Comparing overall structure of auditory and visual systems

- Auditory system—Large proportion of processing is done *before A1*
- Visual system—Large proportion of processing occurs *beyond V1*
- Differences may be due to evolutionary reasons

Basic Operating Characteristics of the Auditory System

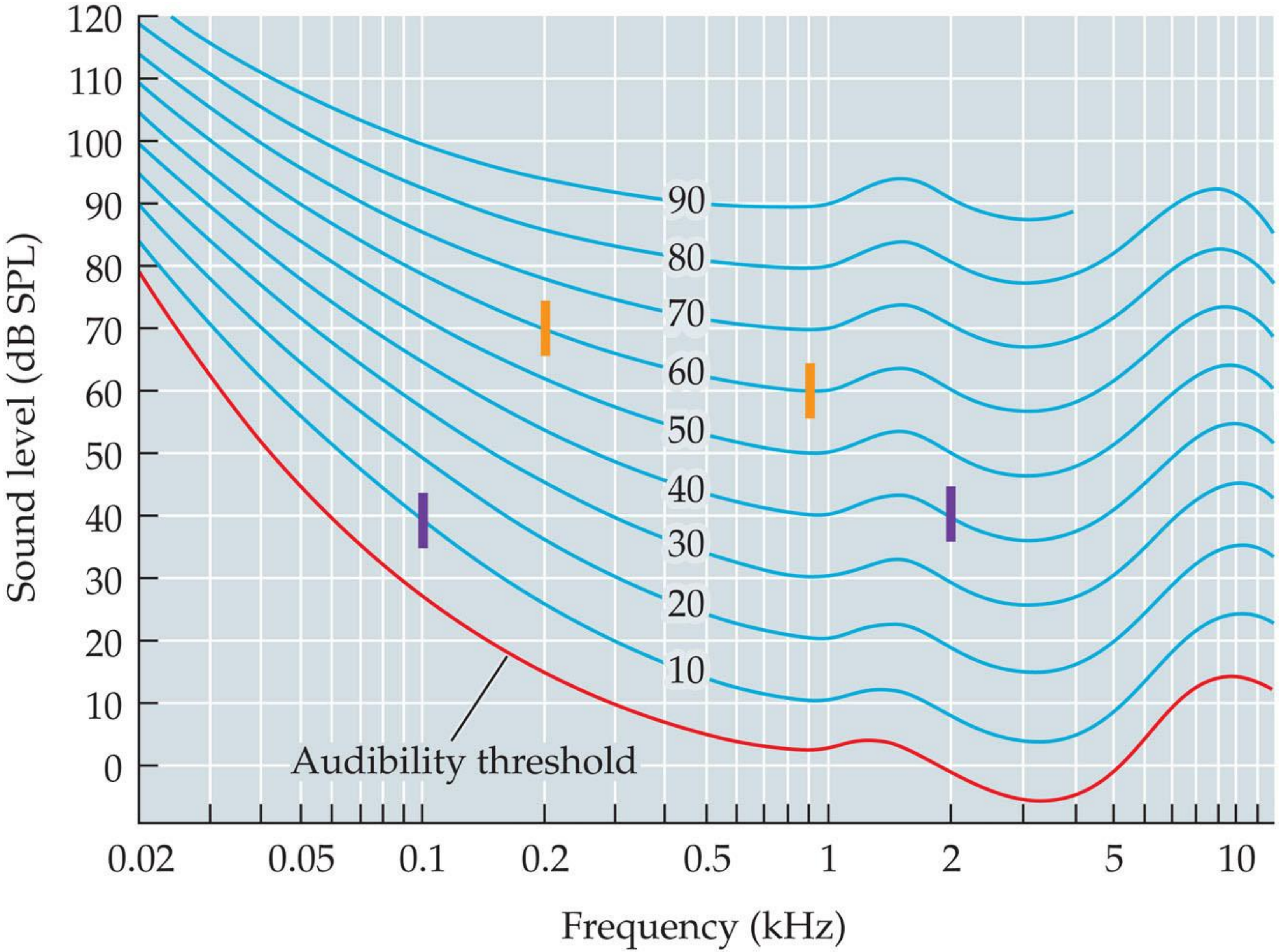
Psychoacoustics: The study of the psychological correlates of the physical dimensions of acoustics.

- A branch of psychophysics

Intensity and loudness

- Audibility threshold: A map of just barely audible tones of varying frequencies.
- Equal-loudness curve: A graph plotting sound pressure level (dB SPL) against the frequency for which a listener perceives constant loudness.
- The tonotopic organization of the auditory system suggests that frequency composition is the determinant of how we hear sounds.

Figure 9.22 The lowest curve (red) illustrates the threshold for hearing sounds at varying frequencies



SENSATION & PERCEPTION 4e, Figure 9.22

Temporal integration: The process by which a sound at a constant level is perceived as being louder when it is of greater duration.

- The term also applies to perceived brightness, which depends on the duration of the light.

Basic Operating Characteristics of the Auditory System

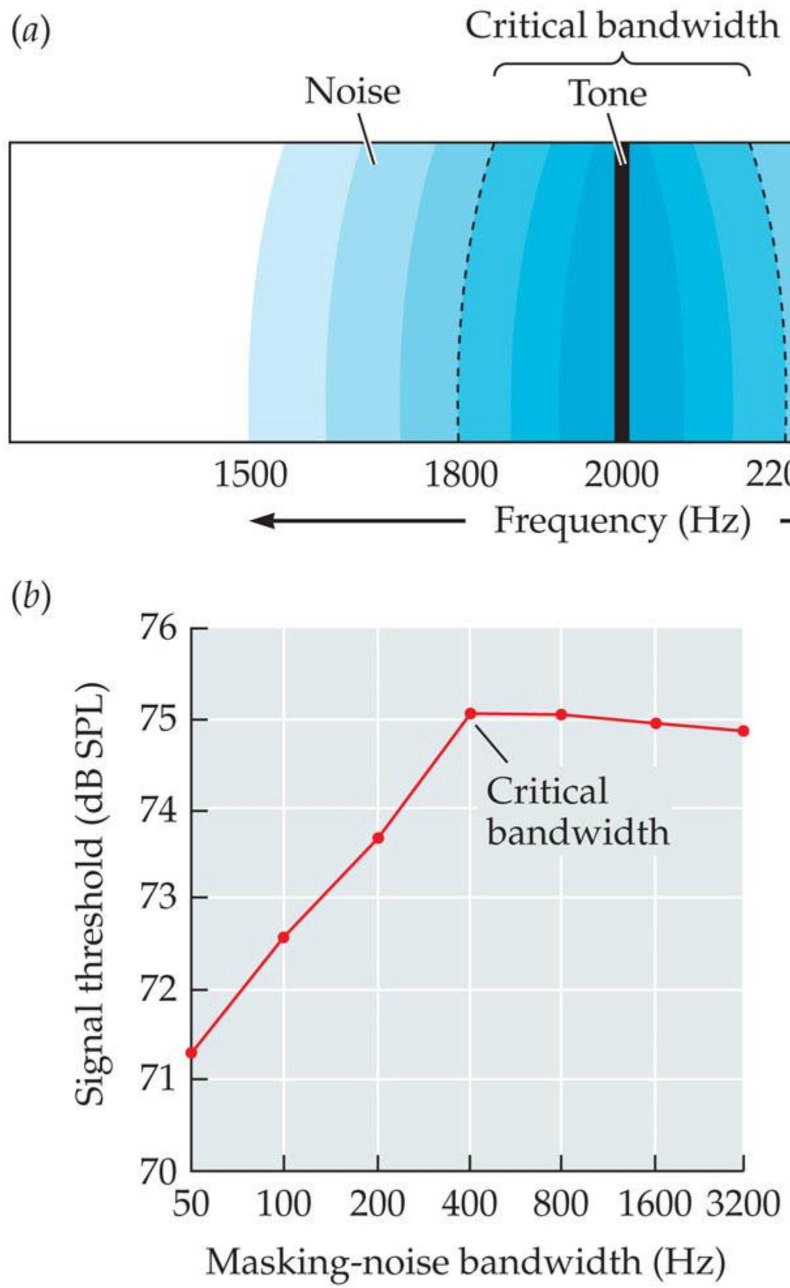
Psychoacousticians study how listeners perceive pitch.

- Research done using pure tones suggests that humans are good at detecting small differences in frequency.
- Masking: Using a secondary sound, frequently noise, to make the detection of a primary sound more difficult; used to investigate frequency selectivity.

Basic Operating Characteristics of the Auditory System

- White noise: Consists of all audible frequencies in equal amounts; used in masking.
- Critical bandwidth: The range of frequencies conveyed within a channel in the auditory system.

Figure 9.23 Critical bandwidth and masking



SENSATION & PERCEPTION 4e, Figure 9.23

Hearing Loss

Hearing can be impaired by blockage or damage to any of the structures along the chain of auditory processing.

- Obstruction of the ear canal (e.g., earplugs)
- Excessive buildup of ear wax (cerumen) in ear canal
- Conductive hearing loss: Caused by problems with the bones of the middle ear (e.g., during ear infections, otitis media).

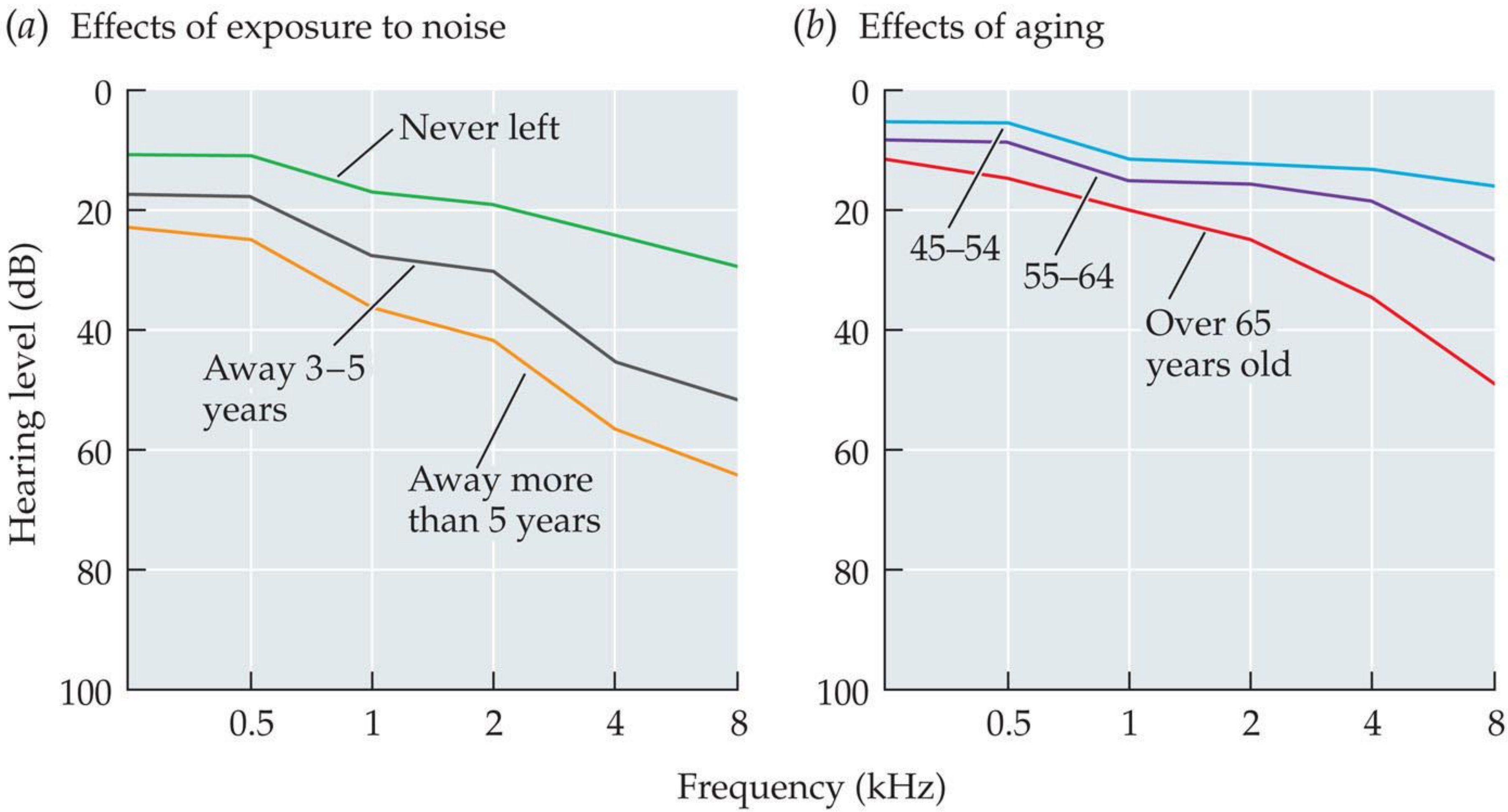
Hearing Loss

- More serious type of conductive loss—otosclerosis
  - Caused by abnormal growth of middle ear bones; can be remedied by surgery
- Most common, most serious auditory impairment—sensorineural hearing loss
  - Due to defects in cochlea or auditory nerve; when hair cells are injured (e.g., as a result of antibiotics or cancer drugs, ototoxic)

Hearing Loss

- Common hearing loss—damage to hair cells due to excessive exposure to noise

Figure 9.24 Environmental noise affects hearing



SENSATION & PERCEPTION 4e, Figure 9.24

Hearing loss is a natural consequence of aging.

- Young people: Range of 20–20,000 Hz
- By college age: 20–15,000 Hz

Hearing aids

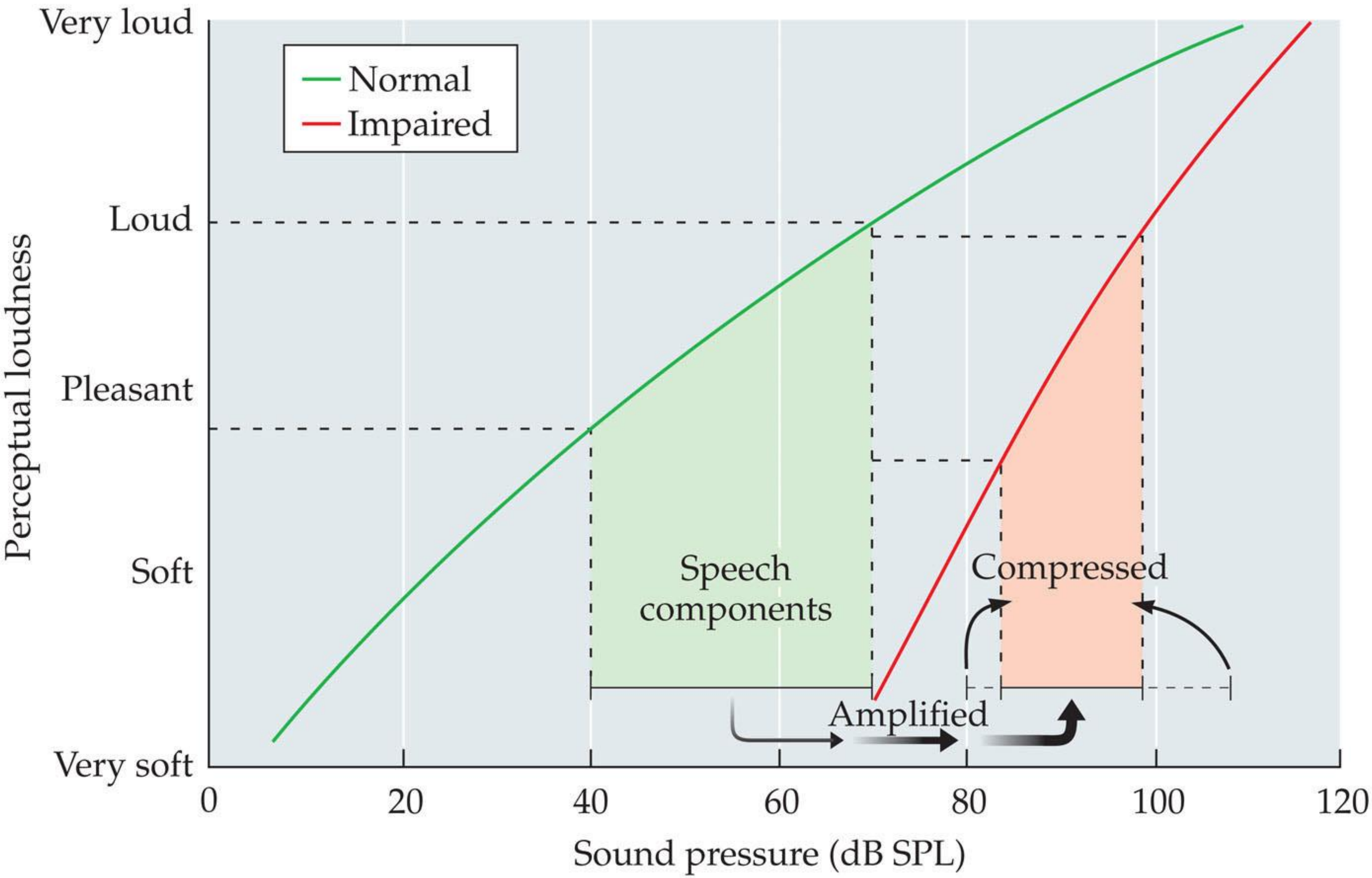
- Earliest devices were horns
- Today, electronic aids

Electronic hearing aids do more than just amplify sounds.

- Can’t amplify all sounds across the range because it would be painful and damaging to the listener.

Hearing aids compress sound intensities into a range the user can hear.

Figure 9.25 When hearing thresholds are increased by impairment, a sound must have more energy to be heard, but loudness increases faster than it does with healthy ears



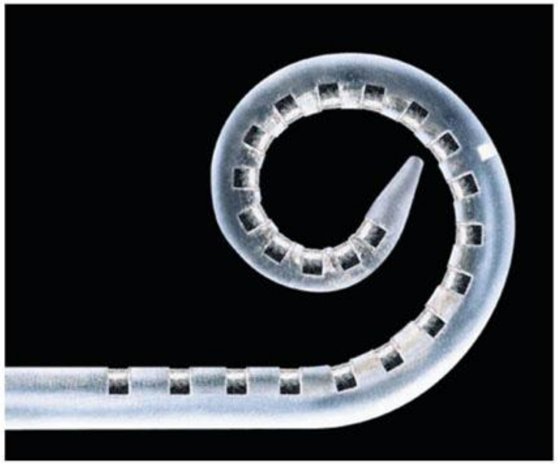
SENSATION & PERCEPTION 4e, **Figure 9.25**

Cochlear implants

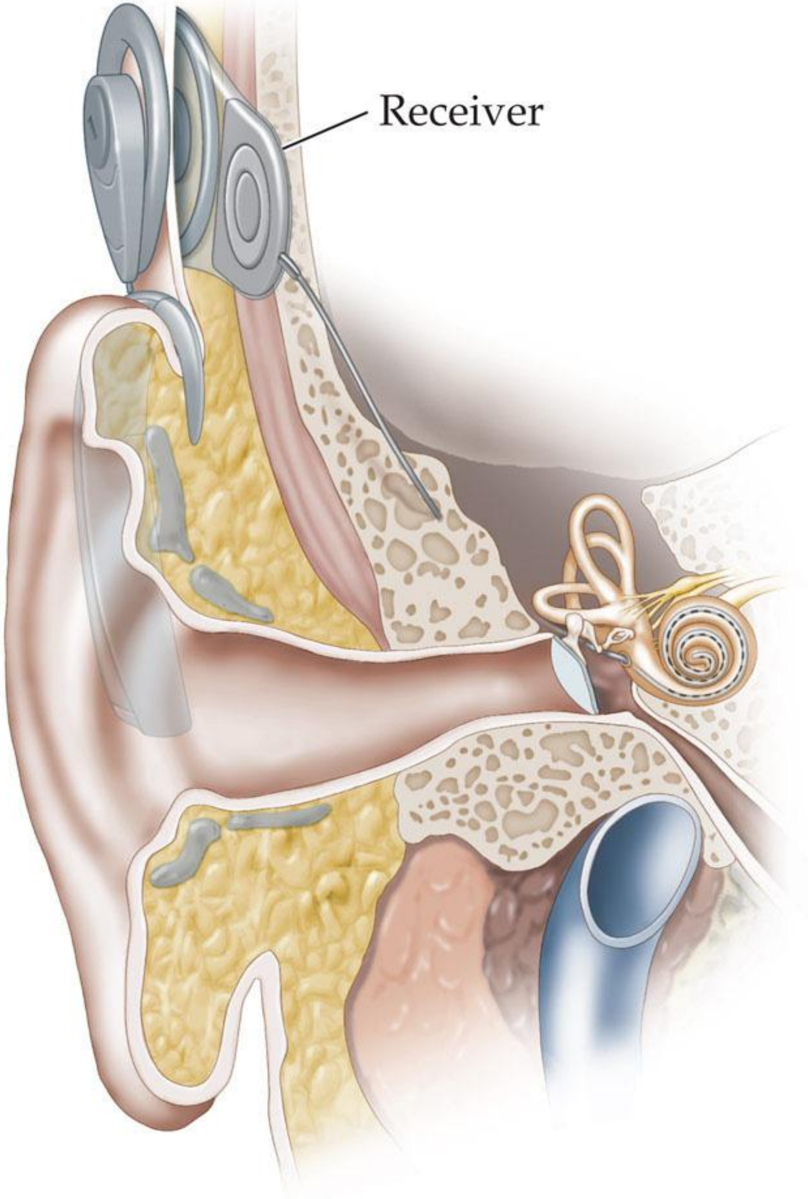
- Tiny flexible coils with miniature electrode contacts
- Surgeons thread implants through round window toward cochlea apex.
- Tiny microphone transmits radio signals to a receiver in the scalp.
- Signals activate miniature electrodes at appropriate positions along the cochlear implant.

Figure 9.26 Cochlear implants give some people who are deaf the ability to hear

(a)



(b)



SENSATION & PERCEPTION 4e, Figure 9.26