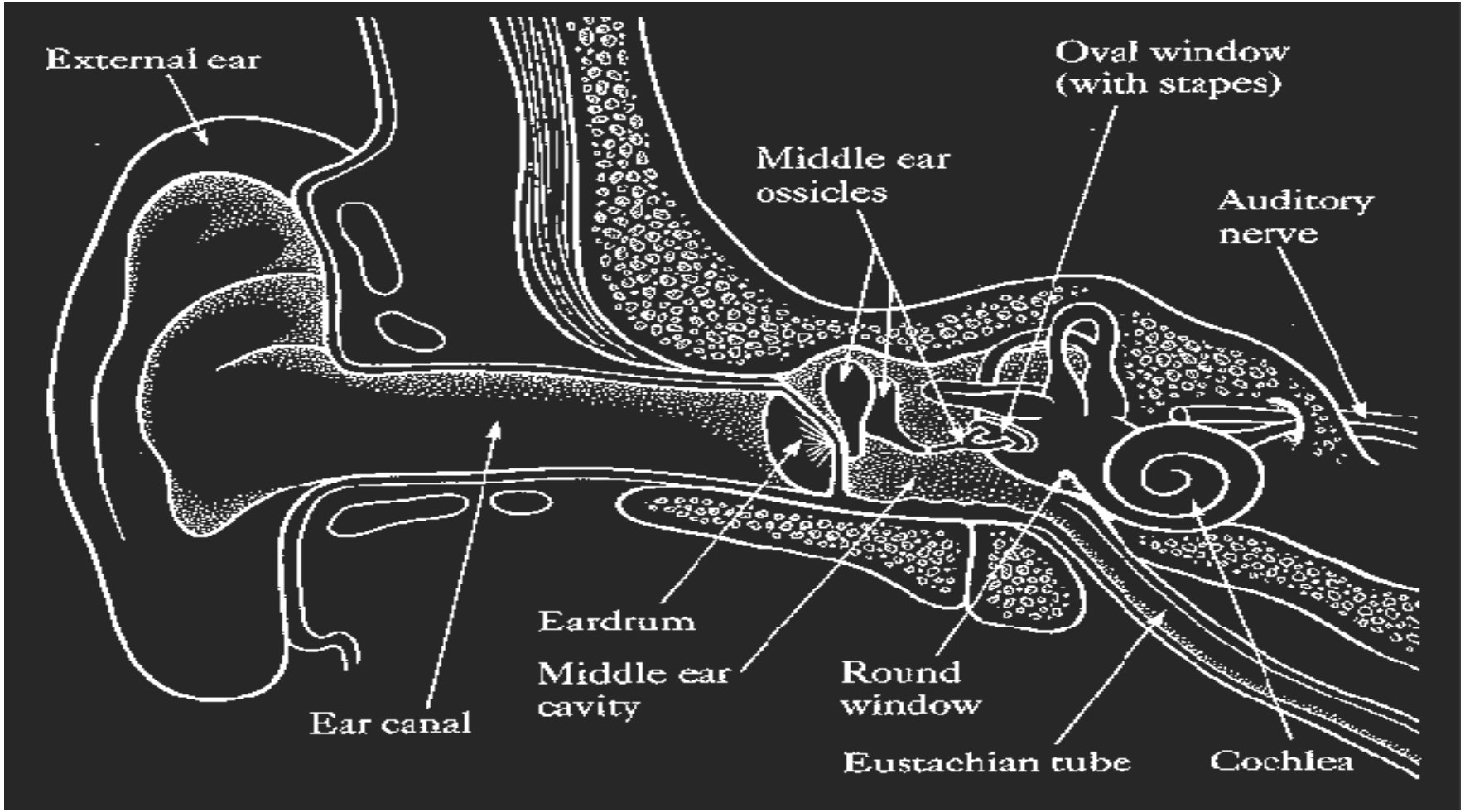
Chapter 5

HEARING

The mind is for seeing, the heart is for hearing.

- **Two aspects of hearing will be considered:**
  - » **Anatomy and physiology of the hearing organs, from the visible external organs of the ear, to the point where sound signals are transformed into neural activity**
    - ♦ **Outer ear, middle ear, inner ear**
  - » **Perception of sound -- the sensations we experience in response to the input of a variety of sound signals**
    - ♦ **Loudness level and loudness**
    - ♦ **Pitch (simple tone, complex tone)**
    - ♦ **Differential threshold**
    - ♦ **Masking**
    - ♦ **Localization and lateralization**

Hearing: The Hearing Organs



- **THE OUTER EAR**
  - » **Includes the AURICLE, or PINNA (the visible portion of the ear), and the EXTERNAL AUDITORY MEATUS (ear canal)**
  - » **The ear canal is an air-filled tube that is slightly more than 25 mm (2.5 cm; about 1 in.) long**
  - » **The canal is an acoustic tube that is open at outer end and closed at inner end by the TYMPANIC MEMBRANE (ear drum)**
  - » **Sound waves impinging on the external ear are transmitted through the ear canal to the tympanic membrane**
  - » **The tympanic membrane is set into forced vibration with a frequency equal to the frequency of the applied force**

- **Outer Ear (cont'd)**
  - » **The external ear and the ear canal form an ACOUSTICAL RESONATOR, an air-filled tube that is open at one end (outer) and closed at the other (inner)**
  - » **Sound waves with frequencies corresponding to the resonant frequency will have greater amplitudes of vibration**
  - » **The resonant frequency is approximately 3500 Hz, and pressure on the ear drum for frequencies of about 3500 Hz will be as much as 10 times greater than the pressure observed at entrance to the canal**

- **THE MIDDLE EAR**
  - » **Contains the AUDITORY OSSICLES, the three smallest bones of the body that compose the OSSICULAR CHAIN**
    - ◆ **MALLEUS (hammer)**
    - ◆ **INCUS (anvil)**
    - ◆ **STAPES (stirrup)**
- **Middle ear chamber is an air-filled cavity**
  - » **Malleus attached to tympanic membrane (ear drum)**
  - » **Vibratory motion of the ear drum is transmitted to the malleus, then to the incus (which acts as a fulcrum between the other two bones), and then to the stapes**

- **Why do we need a middle ear?**
  - » **99.9% of air-borne sound, upon encountering the oval window, would be reflected back. We would lose about 30 dB of sound energy**
  - » **The middle ear acts as a transformer, and increases sound pressure by slightly more than 30 dB (not 38 dB as stated in the text), essentially recovering nearly all that would have been lost with the air-fluid barrier**
- **How does the transformer work?**
  - » **AREAL mechanism**
  - » **OSSICULAR LEVER**
  - » **MEMBRANE BUCKLING**
  - » **Combined benefit from all three mechanisms**
    - ♦**17.7 x 1.3 x 2 = 46:1**
    - ♦**20 log 46 = 33 dB**

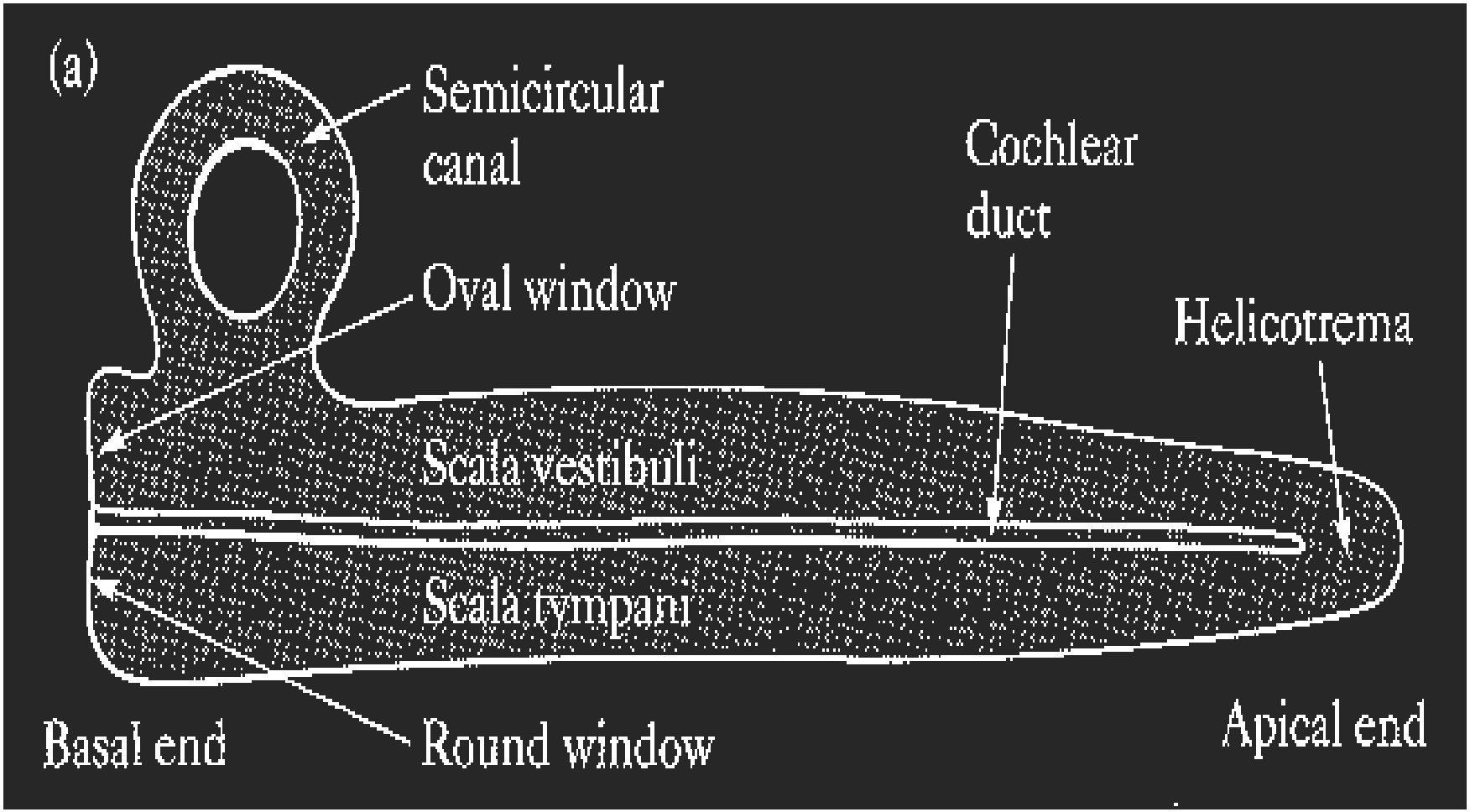
- **How does the transformer work?**
  - » **AREAL mechanism**
    - ♦**Area of footplate of stapes is much smaller than area of tympanic membrane --- thus, pressure on footplate is greater by a factor of 17.7:1, which increases the sound pressure**
  - » **OSSICULAR LEVER**
    - ♦**Lever action provides an additional advantage of 1.3:1 over a single straight bone**
  - » **MEMBRANE BUCKLING**
    - ♦**The curved membrane of the ear drum provides a lever-like advantage of 2:1**
  - » **Combined benefit from all three mechanisms**
    - ♦**17.7 x 1.3 x 2 = 46:1**
    - ♦ **Finally, 20 log 46 = 33 dB**

- **THE INNER EAR**
  - » **System of fluid-filled cavities in temporal bones of skull**
- **Inner Ear comprises:**
  - » **semicircular canals (maintaining equilibrium and balance)**
  - » **COCHLEA (mechanical vibrations transformed to electrical signals to be transmitted to the central nervous system (CNS) for processing**
  - » **Total volume of inner ear: a small grape**

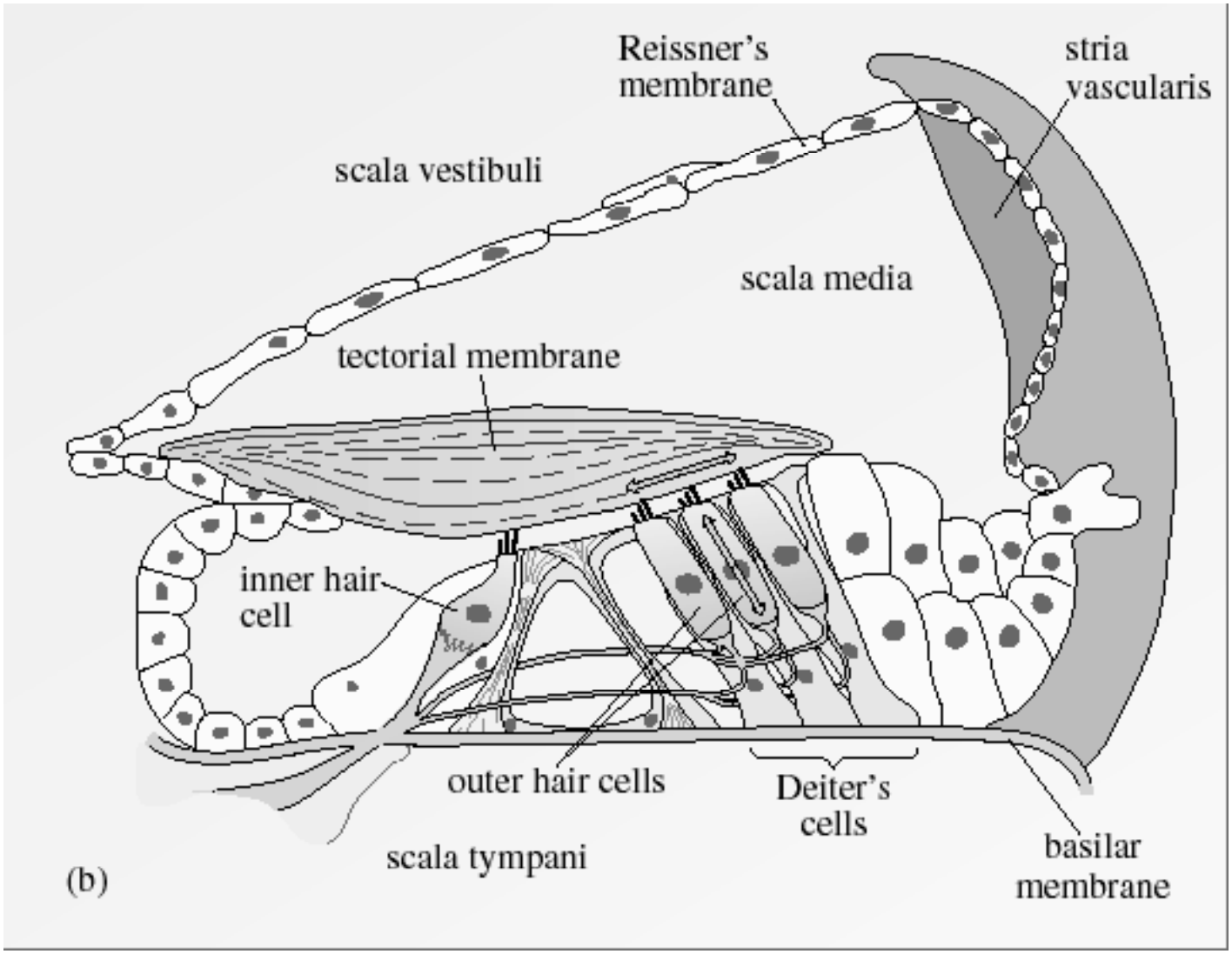
Cochlea. The bony labyrinth has been dissected out, showing the membranous labyrinth coils.

Source: Promenade 'round the Cochlea
Owner: Mireille Rebillard
(Unit 254 Inserm France)

- **The Cochlea**
  - » **Snail-like shape with length of 3.5 cm completes 2 3/4 turns**
- **Divided into three regions along <u>most</u> <u>of</u> <u>length</u> by the COCHLEAR PARTITION**
  - » **SCALA MEDIA (filled with endolymph)**
  - » **SCALA VESTIBULI (filled with perilymph)**
  - » **SCALA TYMPANI (filled with perilymph)**


(a)
Semicircular canal
Cochlear duct
Oval window
Helicotrema
Scala vestibuli
Scala tympani
Basal end
Round window
Apical end

Organ of Corti

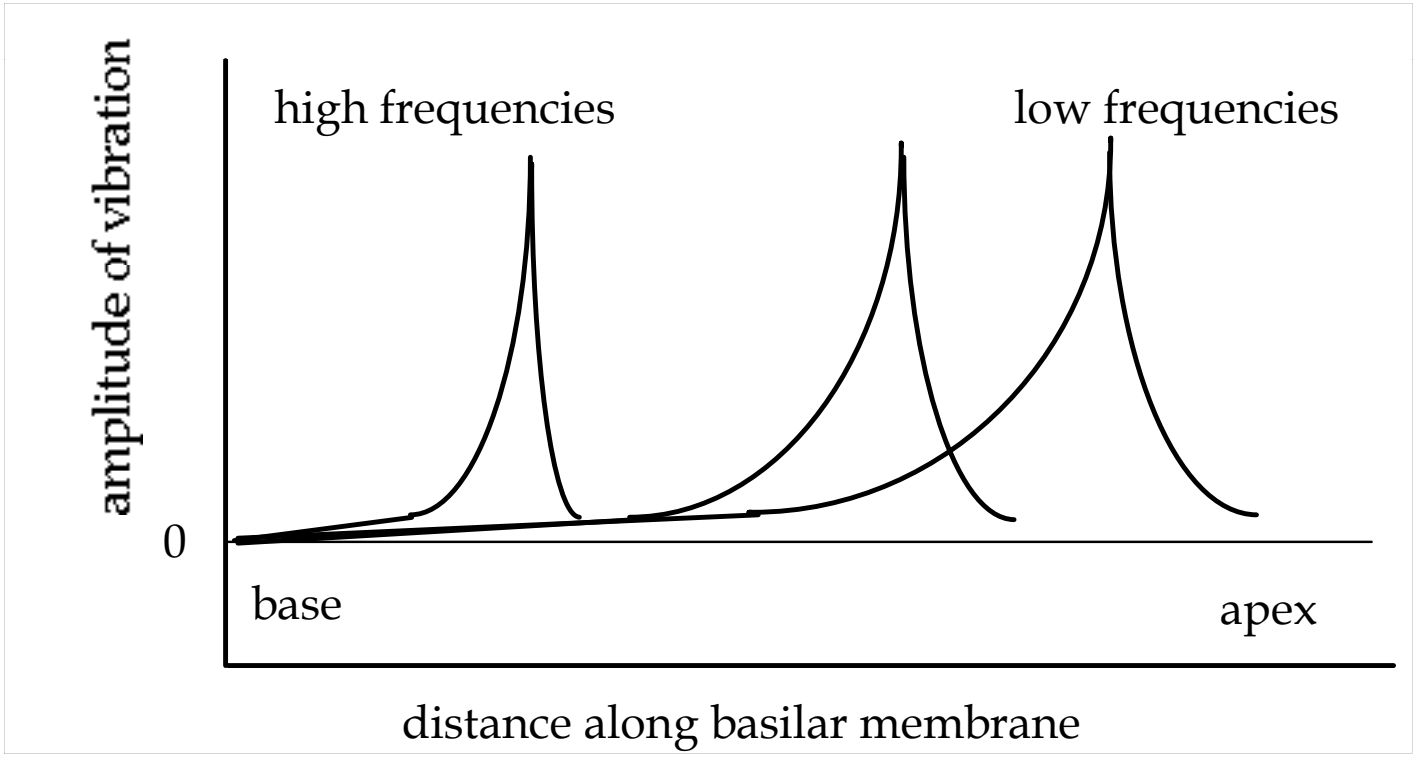


- **ORGAN OF CORTI comprises a large number of cells lying on the basilar membrane**
  - » **Contains HAIR CELLS, which are sensory receptors that accomplish the mechanical to electrical conversion**
  - » **Auditory nerve enters through modiolus**
- **The organ is divided into two parts by the PILLARS, or RODS OF CORTI**
  - » **On inner side is single row of INNER HAIR CELLS (about 3,500)**
  - » **On outer side are three or four rows of OUTER HAIR CELLS (about 12,500)**

- **Organ of Corti (cont'd)**
  - » **Organ of Corti is covered by the TECTORIAL MEMBRANE -- the tips of the tallest row of cilia from each of the outer hair cells are in contact with tectorial membrane**
  - » **Basilar membrane is displaced by vibration of fluids**
  - » **Cilia from hair cells are stimulated to move by shearing forces**
  - » **The nerve at the base of the hair cell initiates a neural potential, and that electrical signal is transmitted by the auditory nerve**

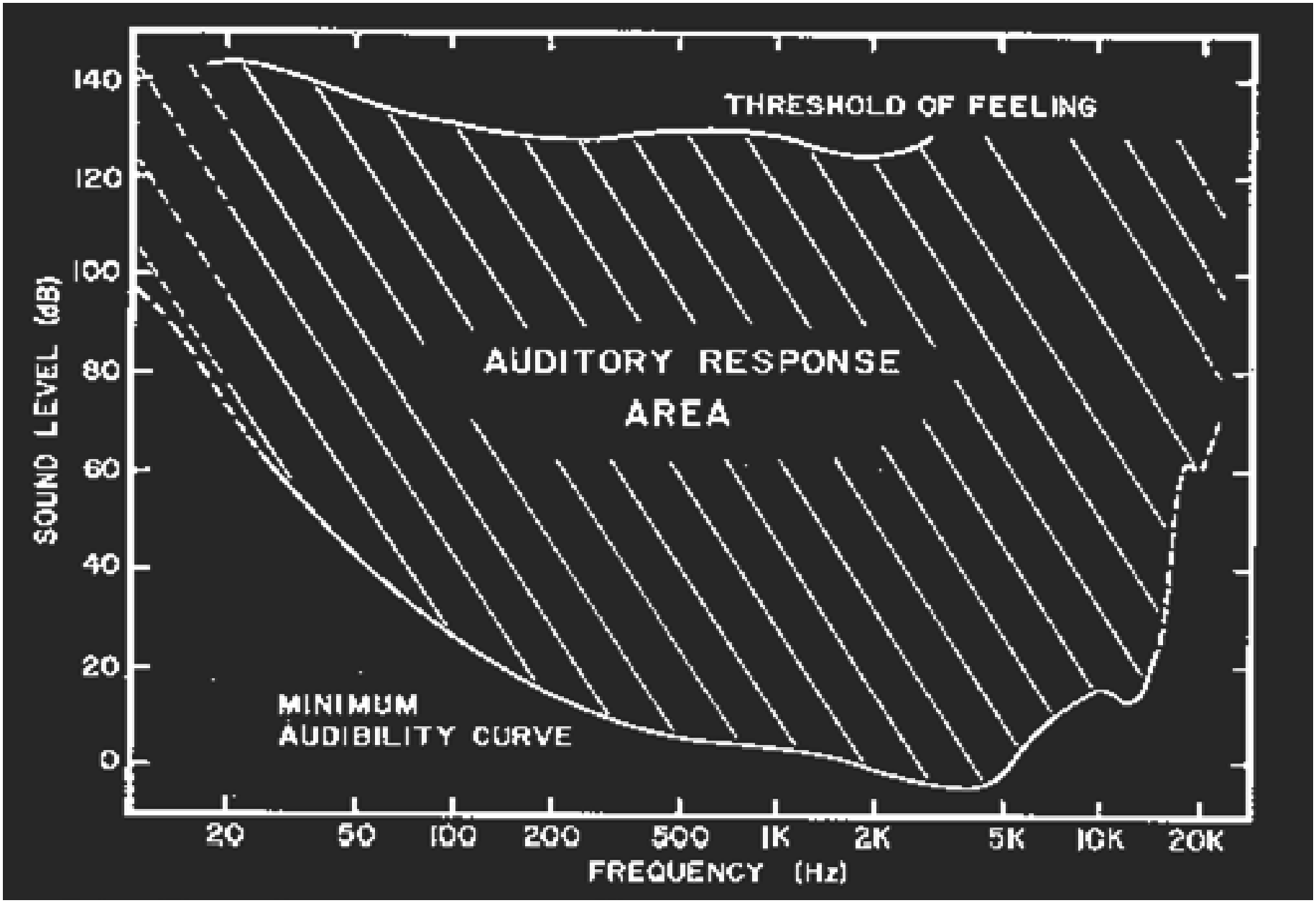
- **The shearing forces on cilia stimulate nerve fibers at base of <u>outer hair cells</u>, and mechanical energy is converted (transduced) into electrochemical activity by hair cells**
- **Comprises on the order of 30,000 nerve fibers**
  - » **Each fiber arises from a few hair cells**
  - » **Each hair cell excites several nerve fibers**
- **Nerve fibers excited by stimulation of hair cells**
- **Signals arrive at auditory cortex located in the temporal lobe -- a PLACE-FREQUENCY arrangement of the basilar membrane is preserved**
  - » **What is meant by place-frequency arrangement?**

Travelling wave on basilar membrane sorts sounds by frequency



The Perception of Sound

- **The discipline of psychoacoustics is a branch of psychophysics**
  - » **Quantification of sensations of listeners to physical, acoustic events (signals) -- measurement of psychological correlates of physical signals**


THRESHOLD OF FEELING
AUDITORY RESPONSE
AREA
MINIMUM
AUDIBILITY CURVE
SOUND LEVEL (dB)
140
120
100
80
60
40
20
0
20
50
100
200
500
1K
2K
5K
10K
20K
FREQUENCY (Hz)

Symptoms of SNHL

- Raised thresholds:

  helped by amplification

- Wider bandwidths:

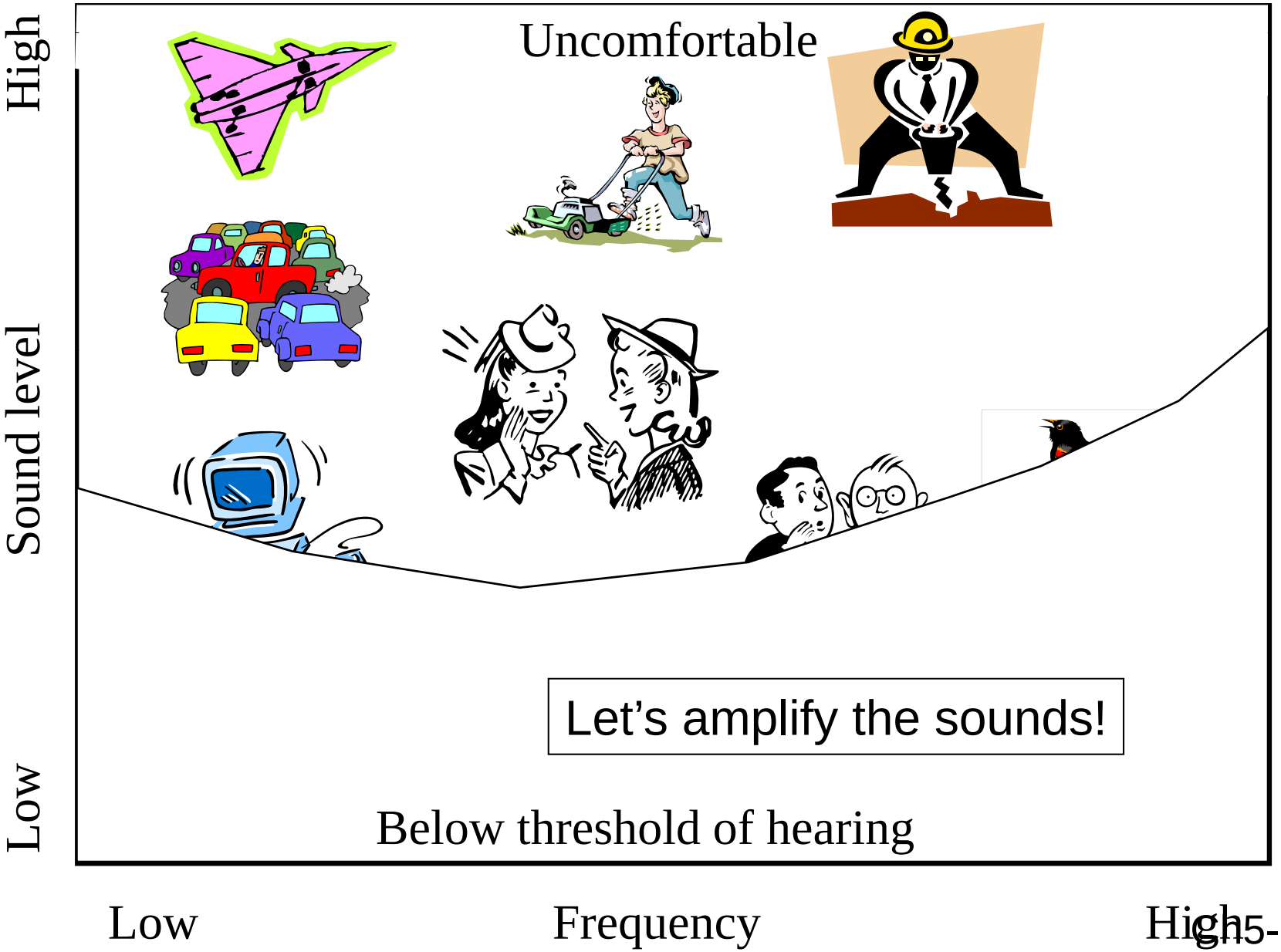
  no help possible

- Recruitment (restricted dynamic range):

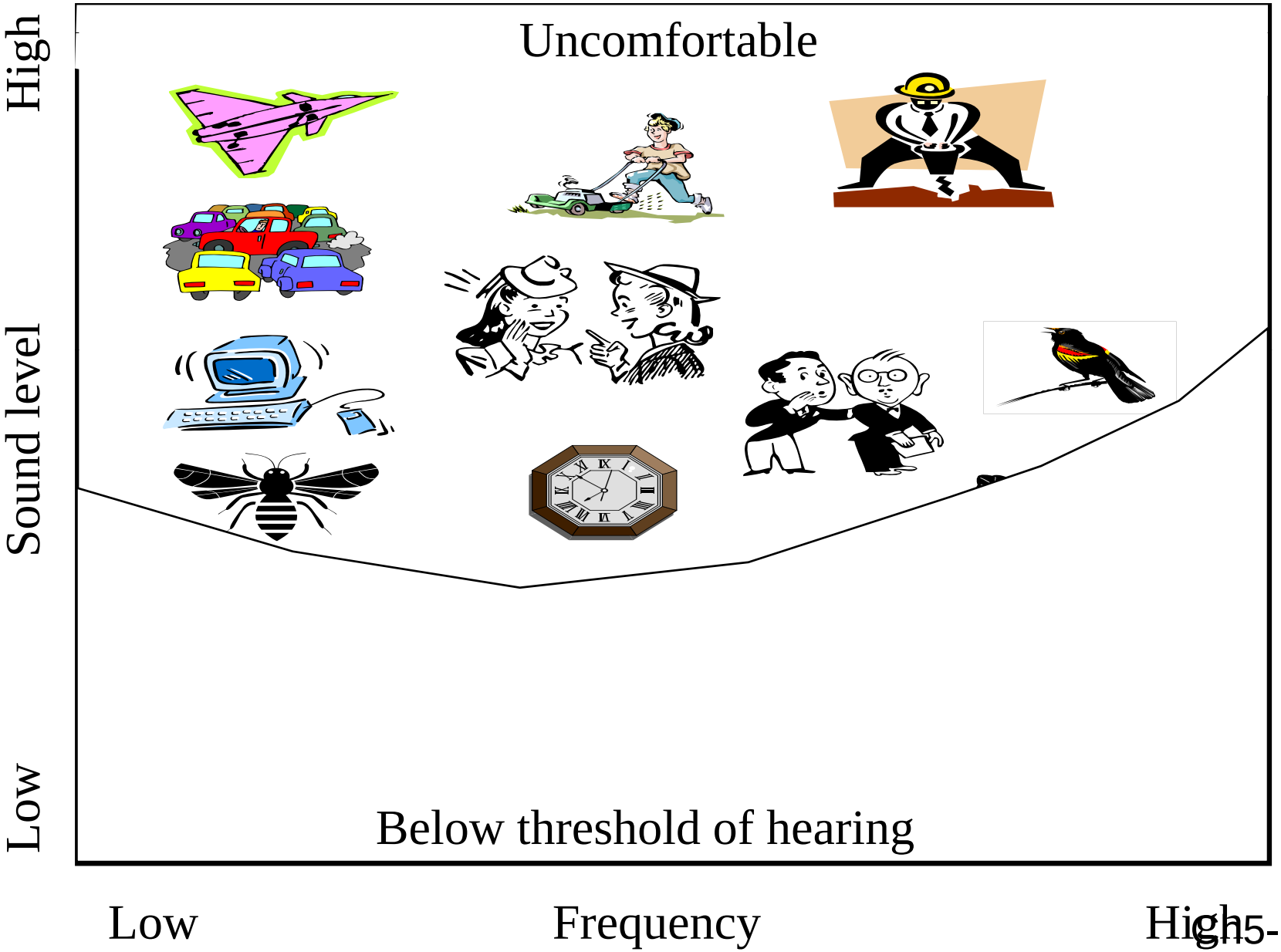
  partly helped by automatic gain controls in modern digital aids

- Often accompanied by tinnitus

Impaired hearing



Compression amplification

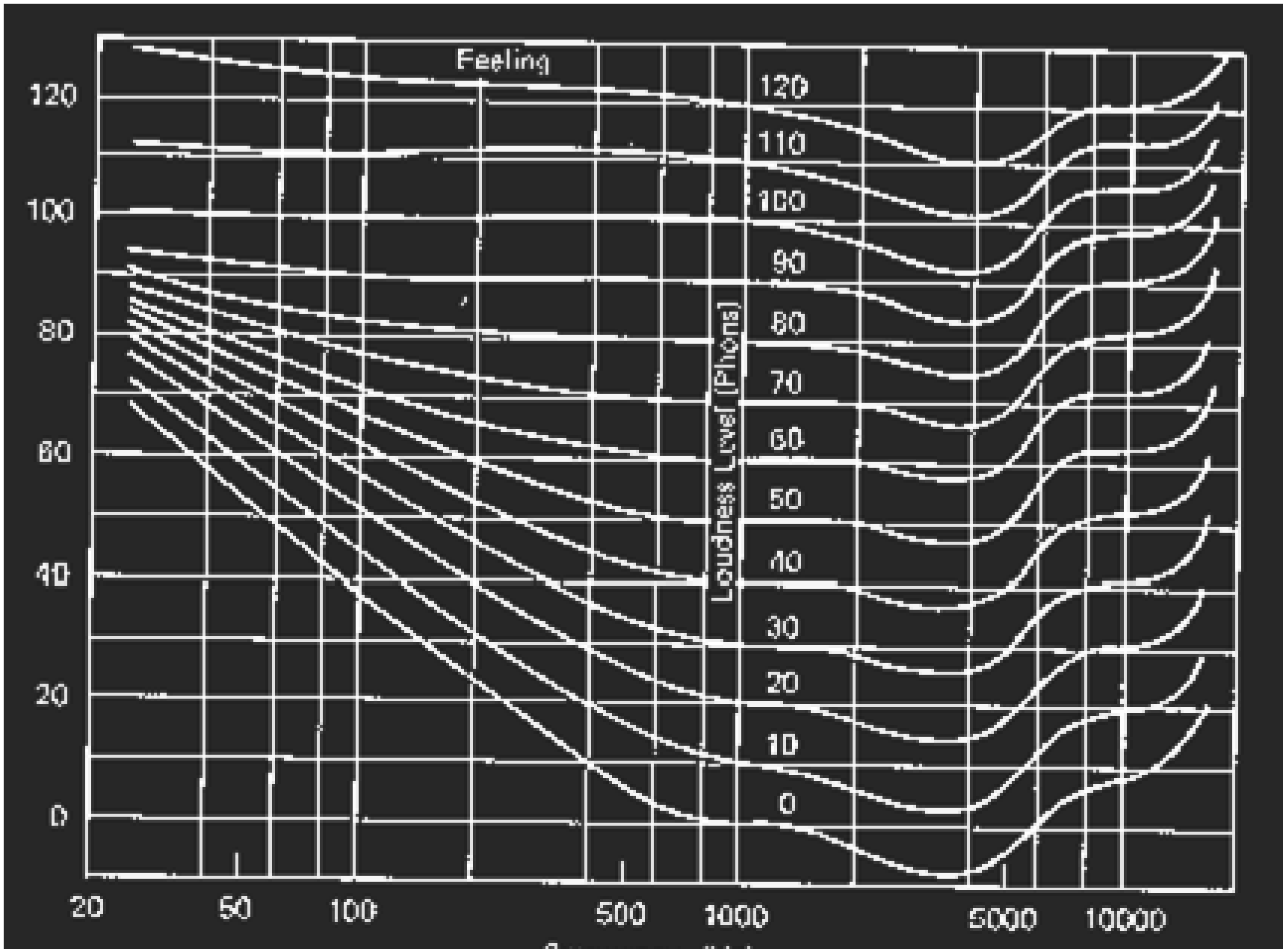


Physical Versus Subjective

- **When we refer to the <u>intensity</u> or <u>frequency</u> of a sound wave, we focus on PHYSICAL ATTRIBUTES of sound**
- **<u>Loudness</u> and <u>pitch</u>, on the other hand, are SUBJECTIVE ATTRIBUTES**
- **The subjective attributes are the psychological correlates of the physical characteristics, but they are distinctly different from one another**

LOUDNESS LEVEL

- » **LOUDNESS LEVEL of <u>comparison signal</u> "is defined as the intensity (measured in decibels) of a 1000 Hz tone that sounds equal in loudness (Denes and Pinson, 1993) to the <u>reference signal</u>" (1000 Hz).**
- » **The unit of measurement of LOUDNESS LEVEL is the PHON**

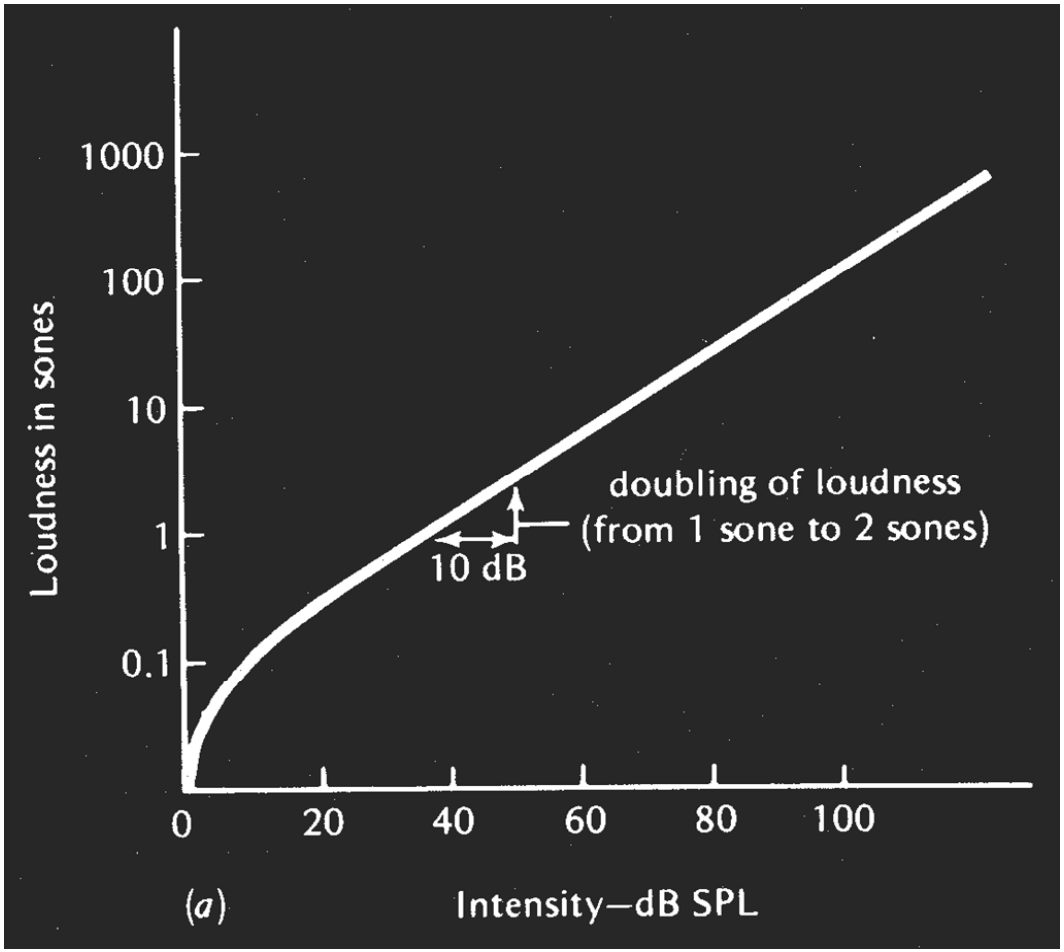

Feeling
120
110
100
90
80
70
60
50
40
30
20
10
0
Loudness Level [Phons]
120
100
80
60
40
20
0
20
50
100
500
1000
5000
10000

Loudness

- **S.S. Stevens (Harvard Psychoacoustic Laboratory) in 1930's attempted to define relation between LOUDNESS LEVEL (in phons) and LOUDNESS (expressed in sones)**

- **An experimental method (MAGNITUDE ESTIMATION)**
  - » **First, loudness of a 1000 Hz sinusoid at 40 dB SPL is defined as 1 SONE: 1 SONE = 40 PHONS**

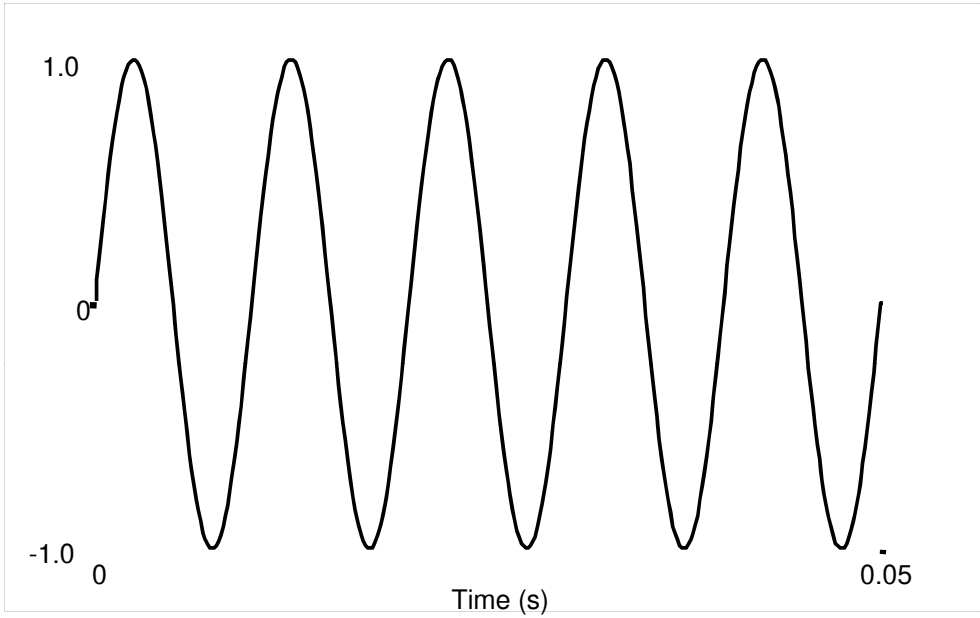
- **Magnitude Estimation cont'd**
  - » **Present L with two sinusoids of same frequency**
  - » **L adjusts intensity of one until it is just, for example, twice as loud as the other. That defines 2 sones.**



Pitch and Frequency

- **PITCH is the subjective attribute most closely related to frequency**
- **Just as loudness is not governed exclusively by intensity, pitch is not governed exclusively by frequency**
  - » **For sinusoids, pitch can be altered by changing intensity**
  - » **For complex waves, the piano for example, pitch is affected little by changes in intensity**

Frequency: 100-Hz Sine Wave

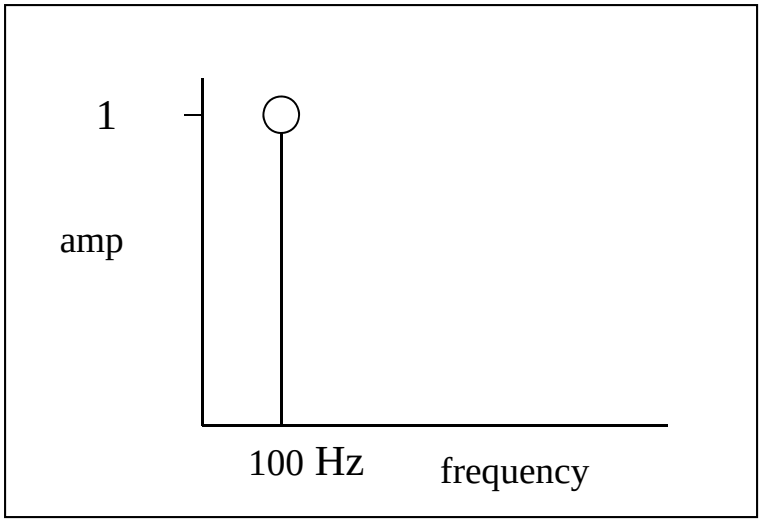


Waveform

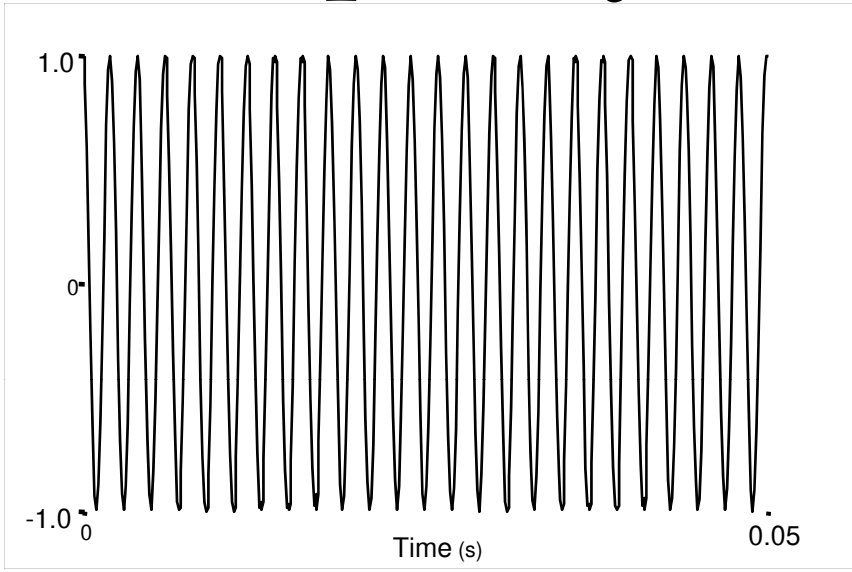
Amplitude against time

Spectrum

Amplitude against frequency



Frequency: 500-Hz Sine Wave

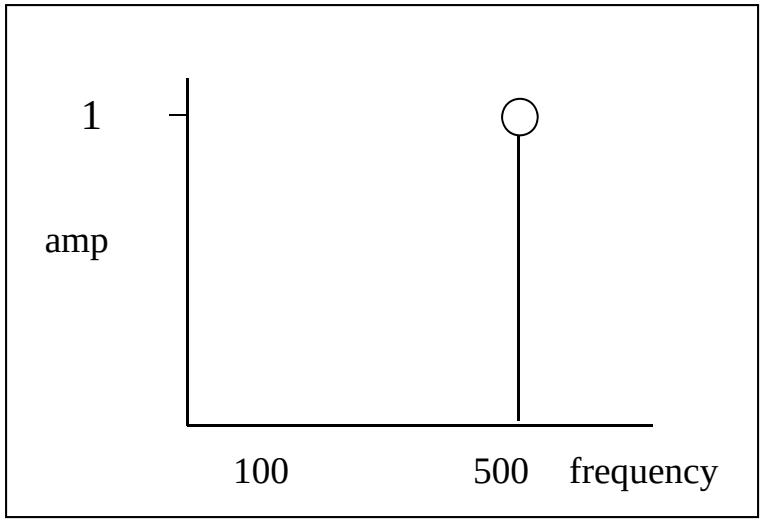


Waveform

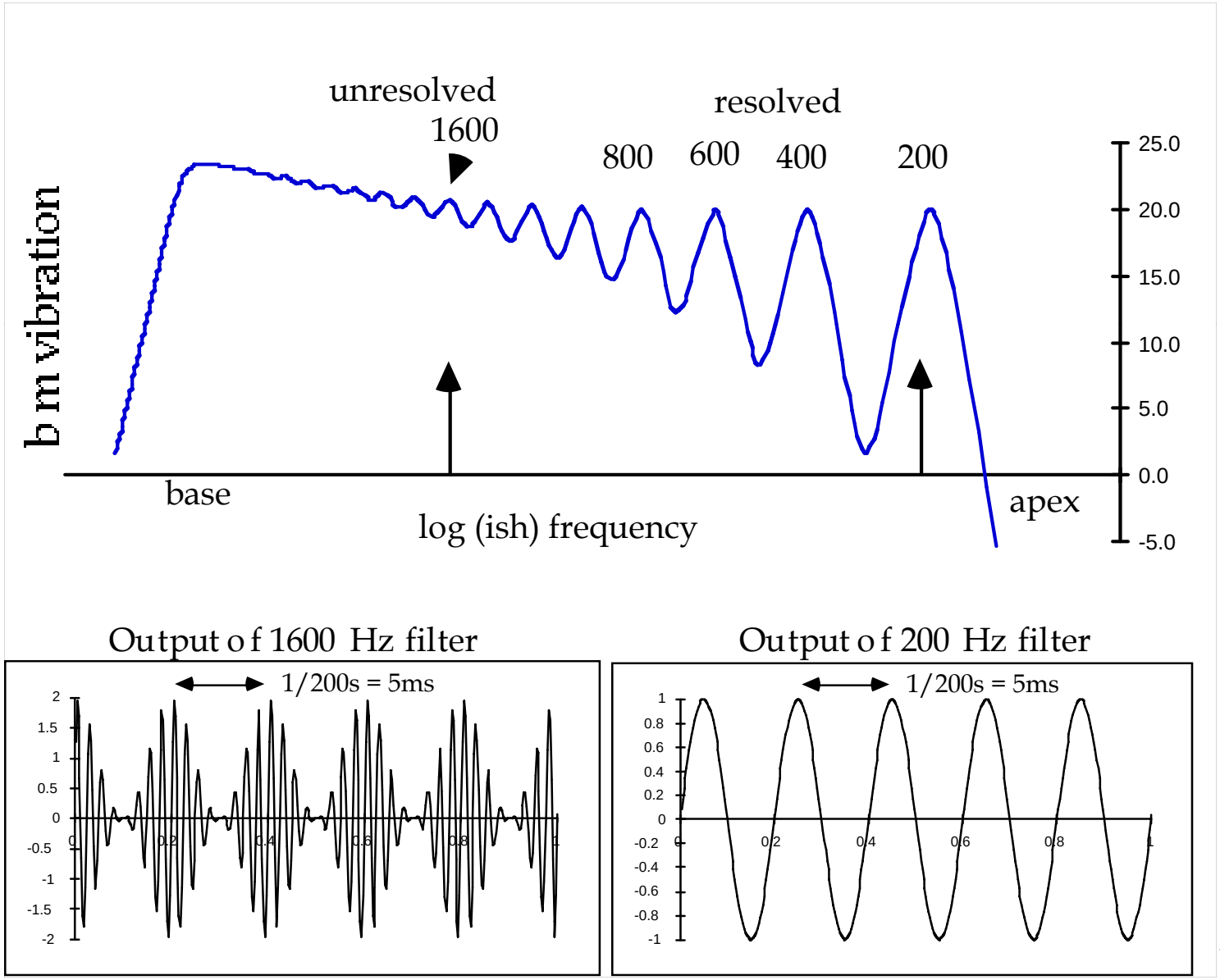
Amplitude against time

Spectrum

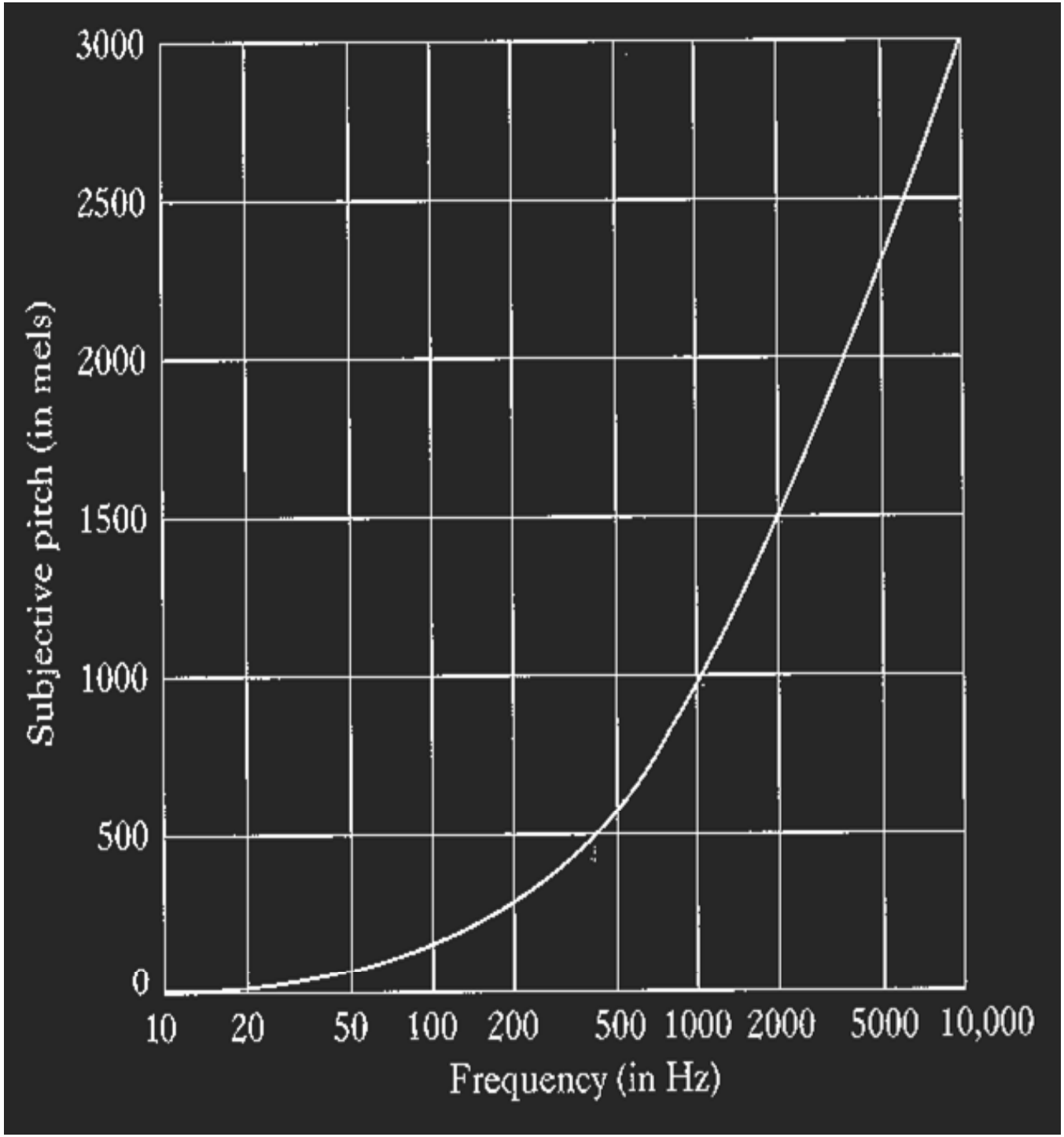
Amplitude against frequency



Excitation pattern of complex tone on bm



- **The unit of pitch is the MEL -- 1000 mels are defined as the pitch of a 1000 Hz tone (at 40 phons) -- Therefore,**
  - » **500 mels is pitch of some tone that sounds half as high**
  - » **2000 mels is pitch of some tone that sounds twice as high**


3000
2500
2000
1500
1000
500
0
Subjective pitch (in mels)
10
20
50
100
200
500
1000
2000
5000
10,000
Frequency (in Hz)

The Pitch of Complex Tones

- **Complex tones such as music, spoken words, etc. also evoke the sensation of pitch**
- **For many complex, periodic sounds, the pitch is associated primarily with the fundamental frequency, f_o**
- **Earl Stanley Gardner and "the case of the missing fundamental frequency"**
  - » **Combine 700, 800, 900, and 1000 Hz**
  - » **Pitch corresponds to a frequency of about 100 Hz -- the common difference frequency -- <u>the missing fundamental frequency</u>**

- **The missing fundamental frequency (cont'd)**
  - » **Combine 400, 600, 800, and 1000 Hz -- to what frequency does the pitch correspond?**
    - ♦**200 Hz (the missing fundamental, the periodicity pitch, or the residue pitch)**
  - » **Add 500, 700, and 900 Hz to that series above -- to what frequency does the pitch correspond?**
    - ♦**100 Hz**

Hearing: Differential Thresholds

- **ABSOLUTE THRESHOLD -- minimum intensity required to detect a signal**
- **DIFFERENTIAL THRESHOLD -- how small a <u>difference</u> can L detect?**
  - » **Called a DIFFERENCE LIMEN (DL), or a JUST NOTICEABLE DIFFERENCE (jnd) -- "limen" is the German word for threshold**
  - » **DL is not a constant -- varies with both intensity and frequency**

- **How many different pure tones can an ordinary listener detect?**
  - » **Hold loudness level constant at 40 phons**
    - ♦**About 1,400 distinguishable frequencies**
  - » **Hold frequency constant at 1000 Hz**
    - ♦**About 280 distinguishable intensities**
  - » **Co-vary frequency and intensity -- nearly 400,000**

Hearing: Masking Effects

- **The interest is in how the presence of a certain sound "drowns out" -- makes it difficult to hear -- other sounds**
  - » **Listening to car radio with windows open in traffic**
  - » **Talking to a partner in a crowded, noisy room**
- **The noise that makes it difficult to hear the intended signal is called a MASKER, or MASKING NOISE**

- **How are masking experiments conducted?**
  - » **Measure two thresholds:**
    - ♦**Threshold for signal (dB S)**
    - ♦**Threshold for signal + masker (dB S + N)**
    - ♦**Measure of masking?**
      - **dB masking = (dB S + N) – (dB S)**
      - **If measure of masking is a ratio, why can we simply subtract: (dB S + N) – (dB S) ?**

- **In the experiment, we can hold S intensity constant and vary N, or we can hold N constant and vary S**
- **Importantly, the amount of masking depends not only on the intensities of the masker and the signal, <u>but on the spectrum and temporal characteristics of the masker</u> and, in the case of speech as a masker, on the linguistic complexity of the signal**

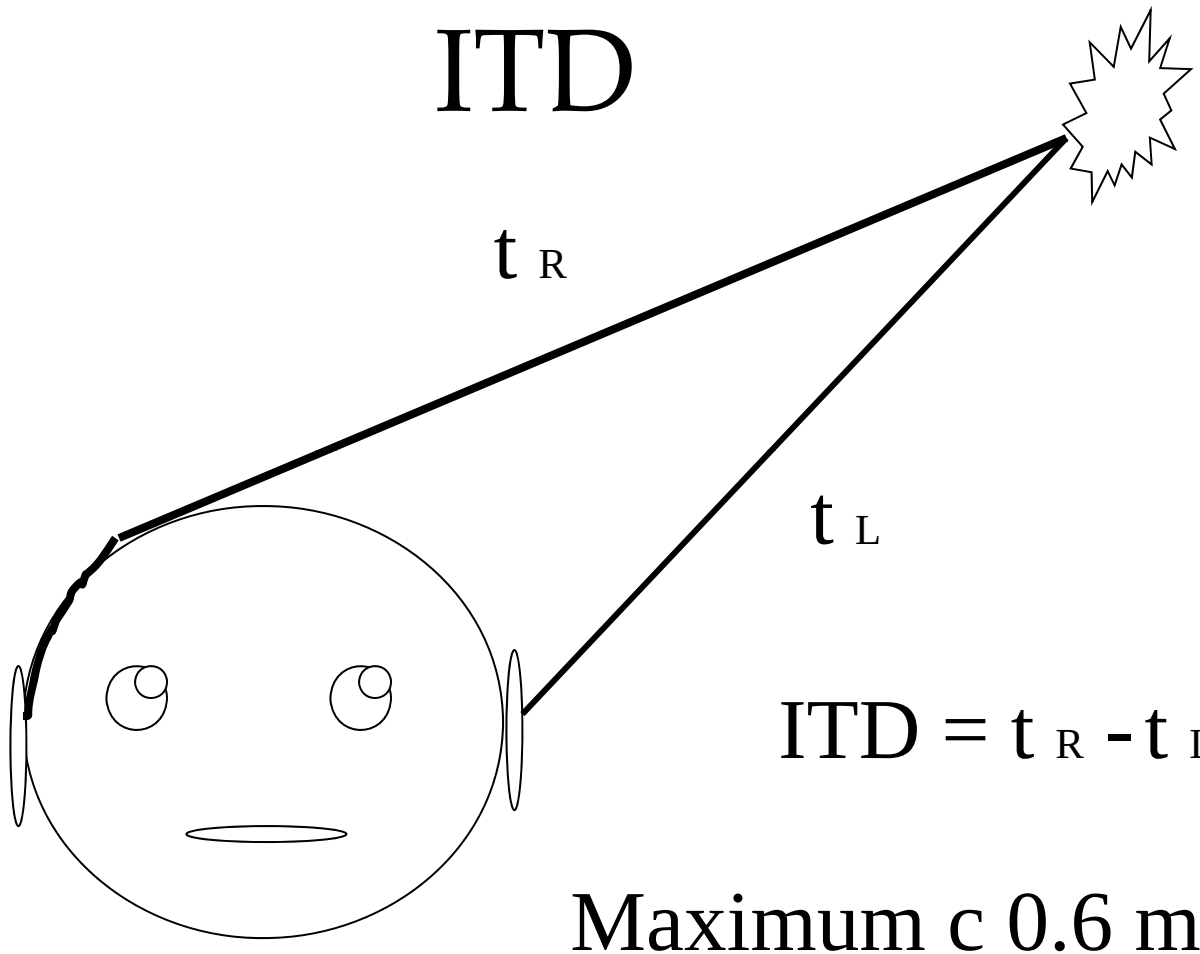
- **Pure tones as maskers: two important findings:**
  - » **At moderate intensities, tones provide greater masking for sinusoids of similar frequency rather than sinusoids at remote frequencies**
  - » **Upward spread of masking:**
    - ♦**Low-frequency tones can mask high-frequency tones**
    - ♦**High-frequency tones produce less masking of low-frequency tones**

- **Noise as a masker**
  - » **Noise is the summed result of many sinusoids in combination**
  - » **With noise as the masker and a sinusoid as the signal, the most important sinusoidal components of the masker are those frequencies that lie closest in frequency to the signal**

Hearing: Binaural Effects

- **The experiments discussed to this point have involved MONAURAL, or MONOTIC, presentation of a signal -- the signal is delivered to only one ear**
- **In ordinary listening, however, a single sound wave reaches both ears, but not necessarily in identical ways (BINAURAL EFFECTS)**
  - » **Signal intensity may not be the same for both ears**
  - » **Time-of-arrival at the two ears may not be the same**

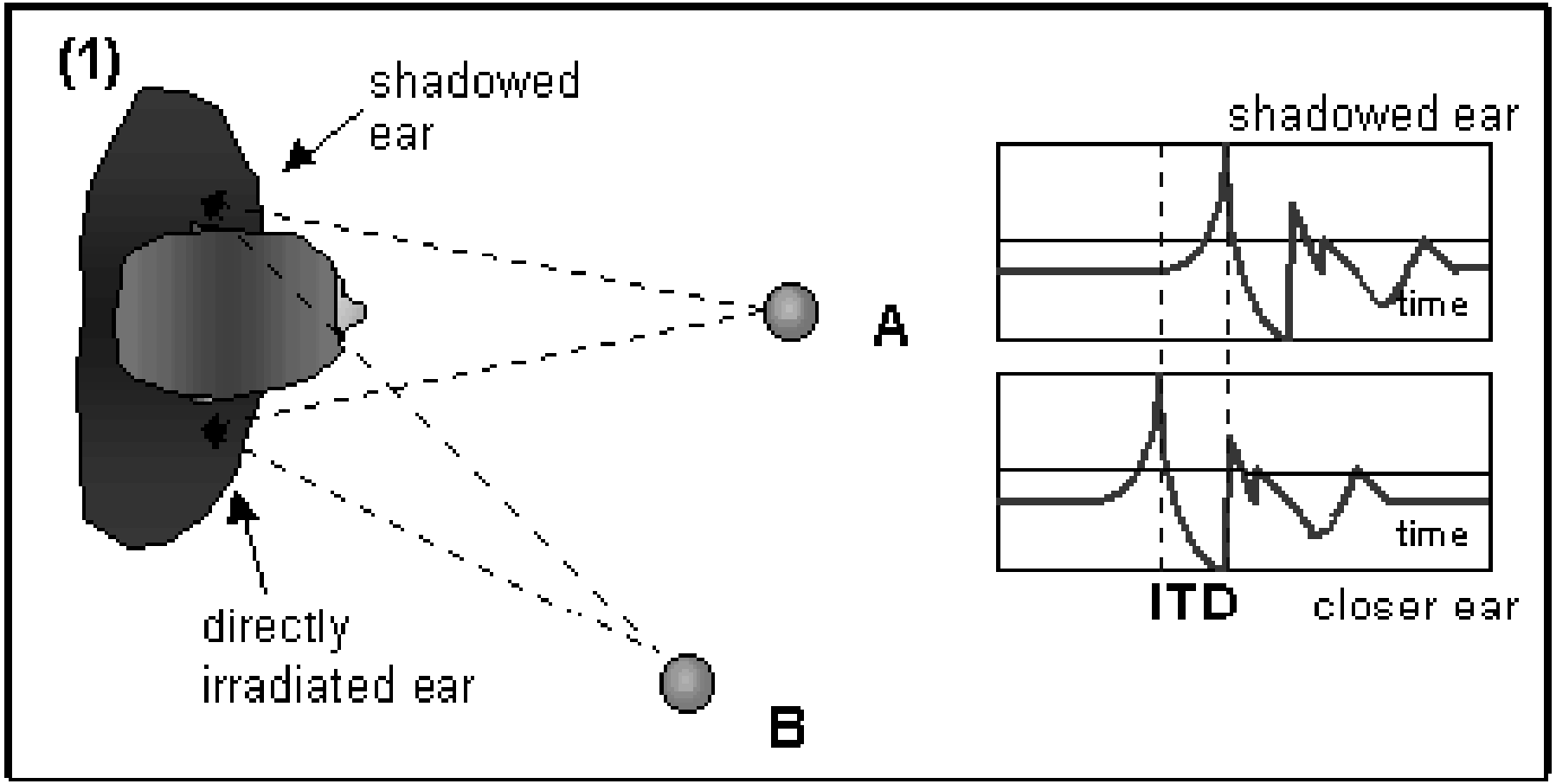
Interaural time-difference - ITD



$$ITD = t_R - t_L$$

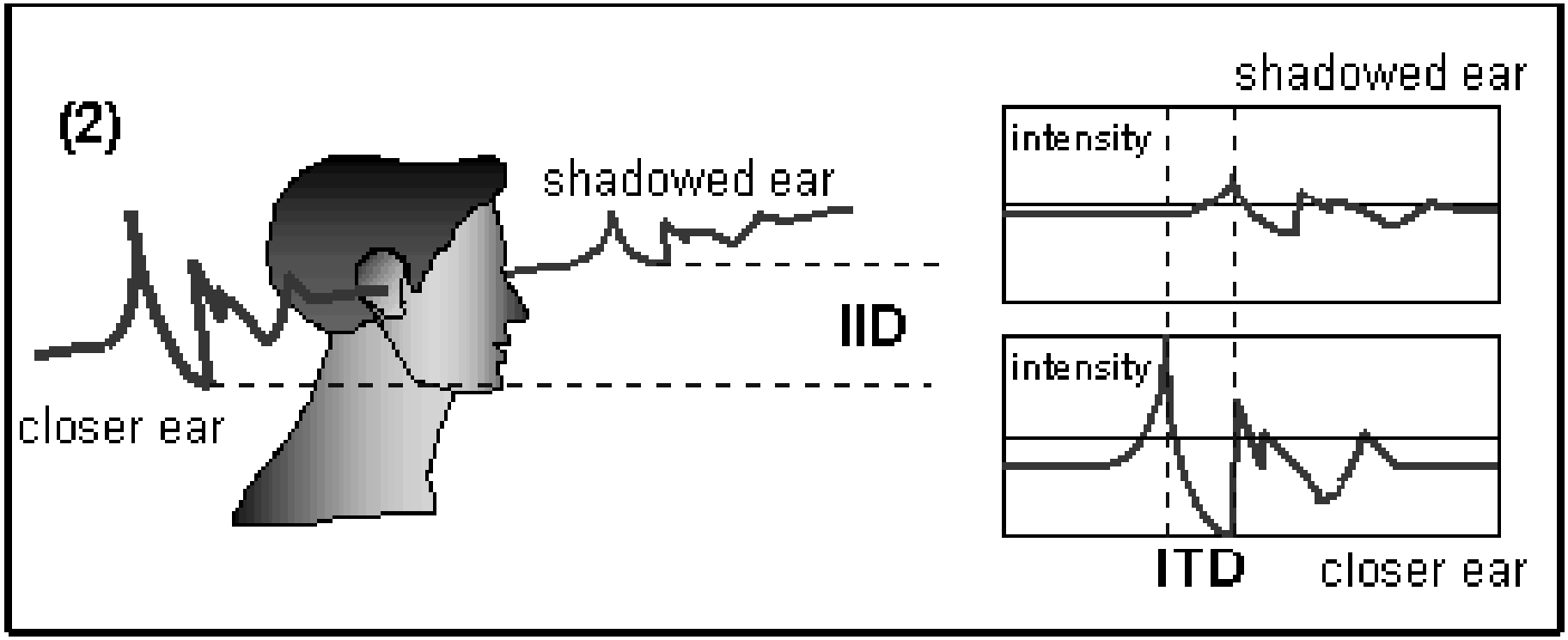
Maximum c 0.6 ms

Localization: Interaural Time Difference



Processed in Medial Superior Olive

Localization: Interaural Level Difference



Processed in Lateral Superior Olive

- **A second binaural effect concerns INTRACRANIAL LATERALIZATION, which the textbook incorrectly calls LOCALIZATION**
- **An experiment:**
  - » **Two identical sine waves are presented binaurally to L through earphones**
  - » **L hears a single, fused image arising from within the cranium close to median plane (in line with L's nose)**

- **Experiment (cont'd)**
  - » **Now, introduce some differences for the two ears**
  - » **Time-of-arrival is under control of the experimenter**
    - ♦ **RE signal, for example, can be made to lead LE signal, or**
    - ♦ **RE signal can be made to lag LE signal**
  - » **Listener attempts to identify the direction from which the sound arrives**
    - ♦ **If LE signal lags, the origin moves toward the RE: origin moves toward <u>leading</u> ear**
    - ♦ **If time-of-arrival is equal but intensity is decreased for RE, the origin moves toward LE:**

      origin moves toward ear with <u>greater</u> intensity