Musical Acoustics

Lecture 15

Pitch & Frequency

(Psycho-Acoustics)

Pitch

- **Pitch is a subjective characteristic of sound**
  Some listeners even assign pitch differently depending upon whether the sound was presented to the right or left ear

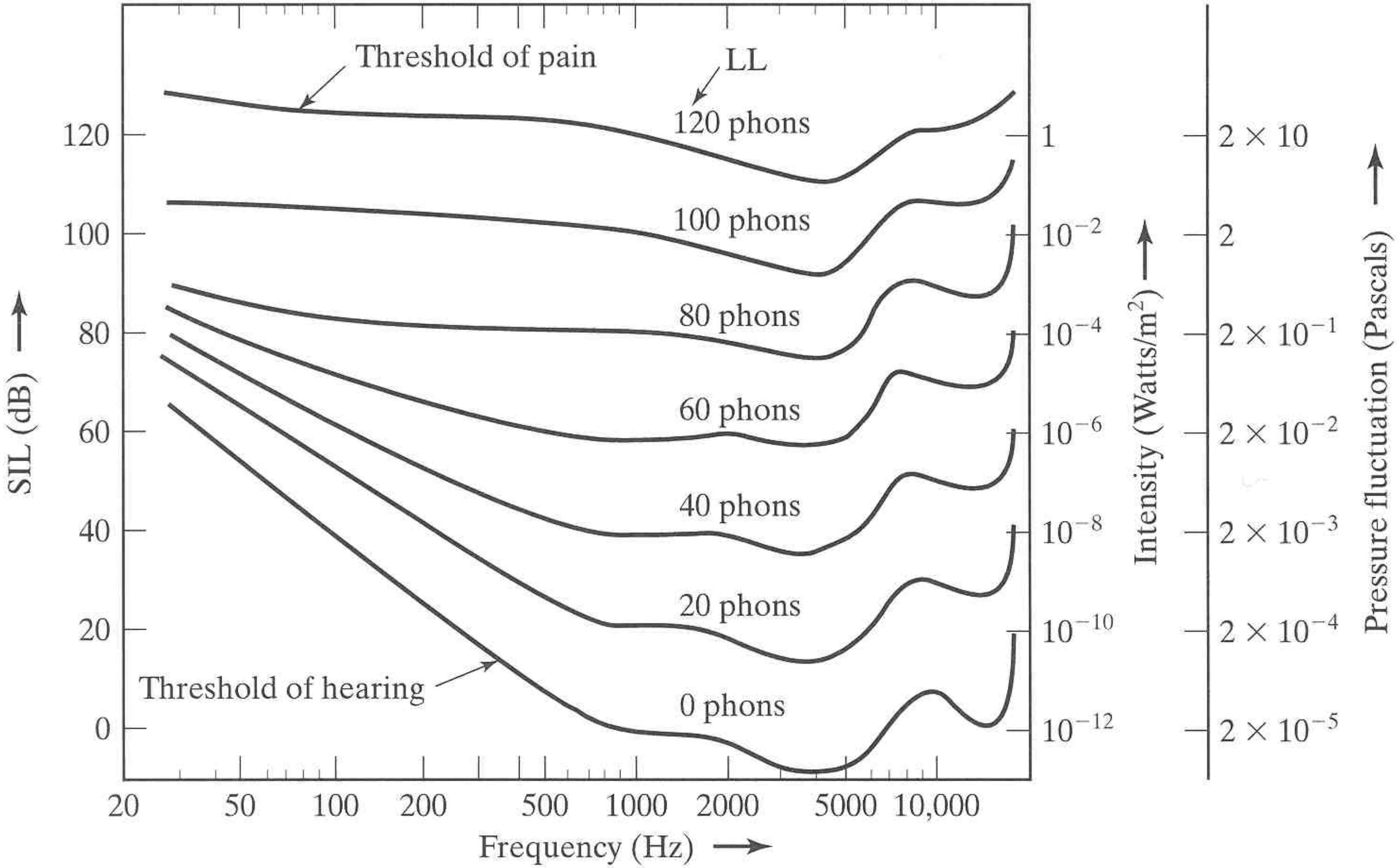
- Pitch characterizes how **high or low** is sound

- Pitch is mainly determined by the **fundamental frequency**

- Pitch is quantitative characteristic (it means we need a **scale**)

- The basic unit in most scales is **octave**

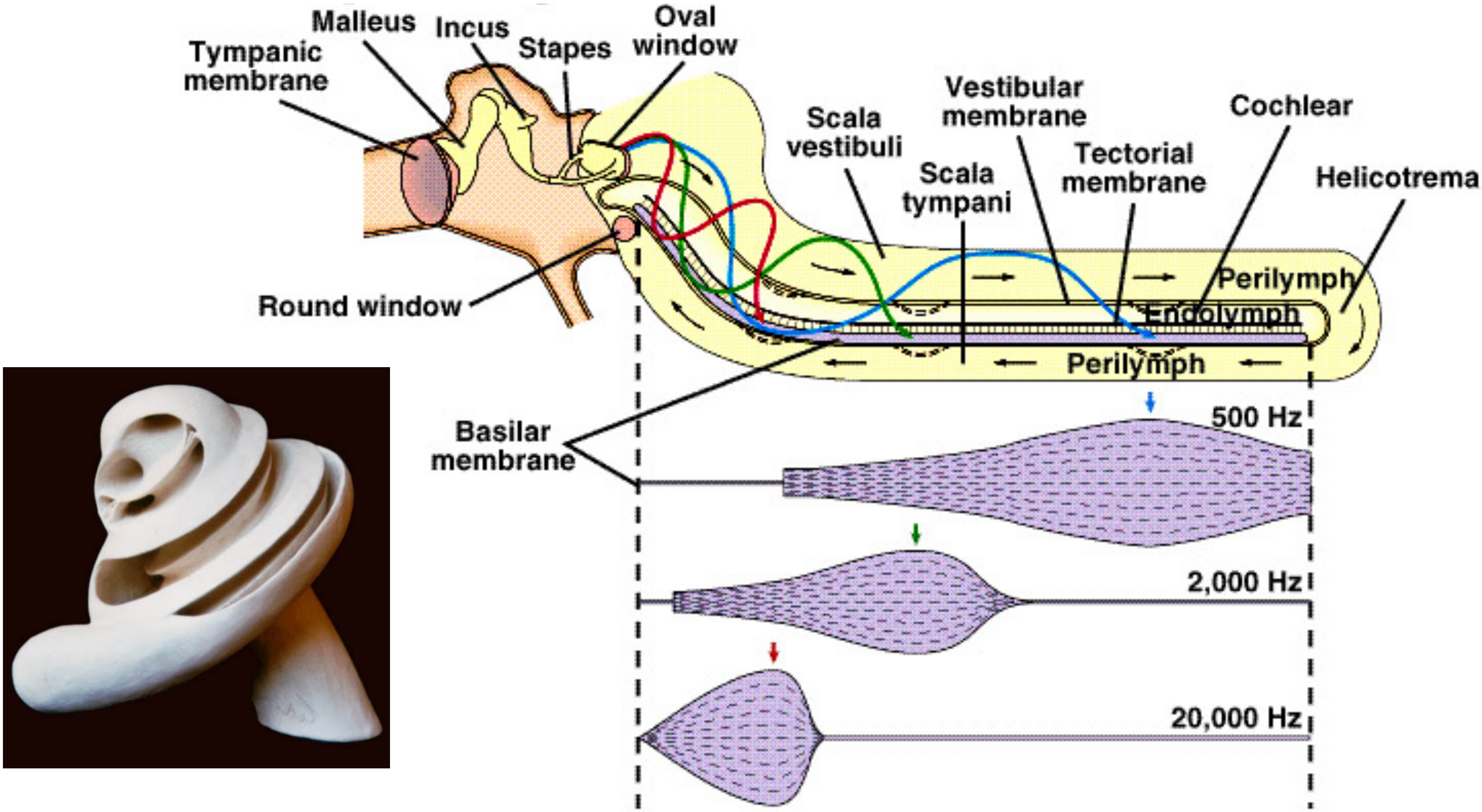
- Variations in pitch create a sense of **melody**



Pitch sensitivity of the human ear

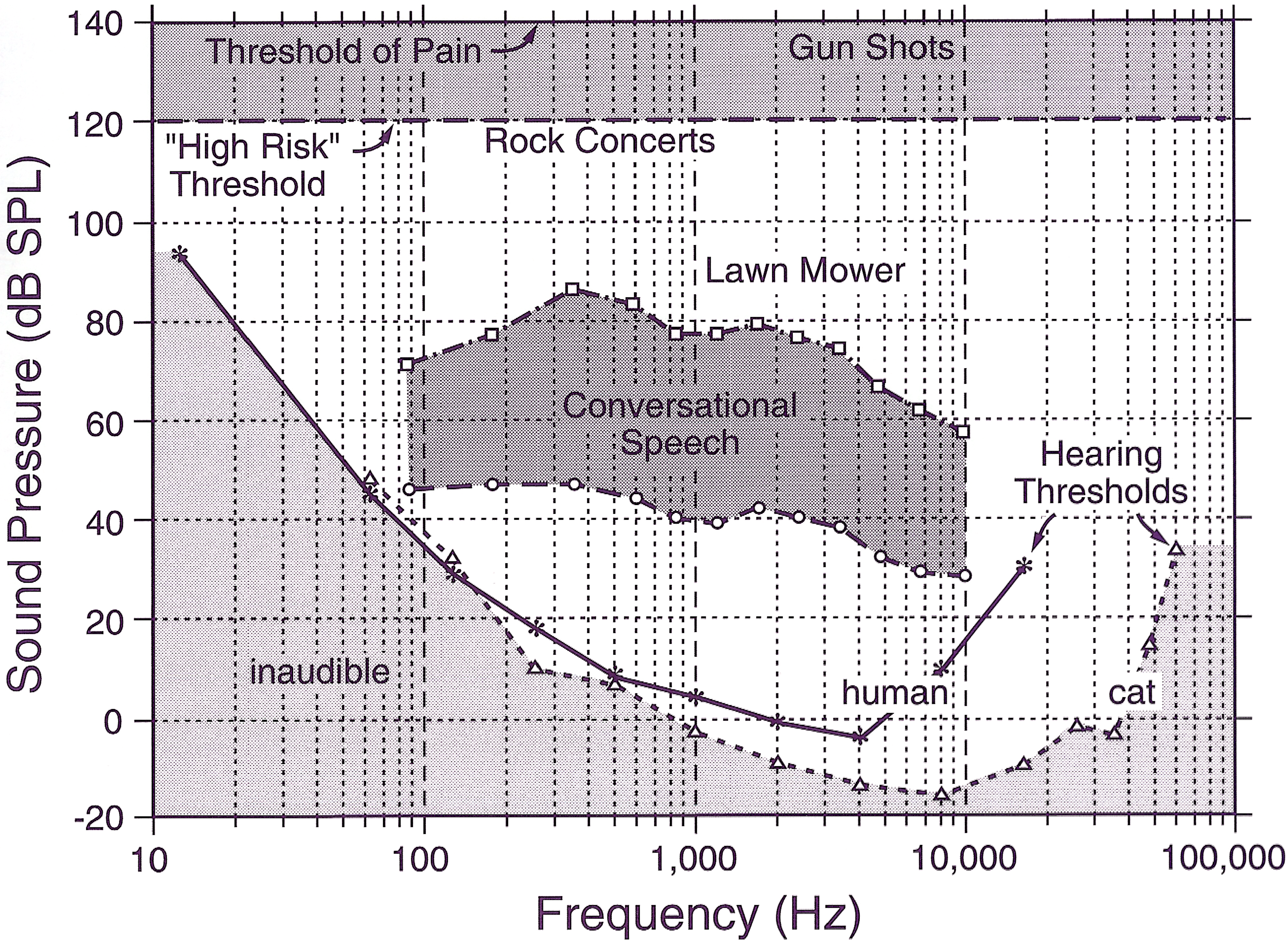
- varies with frequency
- varies with loudness

Pitch Discrimination



Audible range: 20 Hz – 20 kHz

Speech vs hearing



The ear gets old along with the body

- Age 40
  - Ear is only 10% of a young person.

- Age 80
  - Lost most of high frequency hearing so the "quality" of hearing changes significantly.
  - Consonants sound in the high frequency region which explains why older people have difficulties hearing (without any pathology).

- You lose $\frac{1}{2}$ Hz. per day in high frequency hearing:

Born → 20,000 Hz → 10,000 Hz → 7000 Hz → ***Dead***

Pitch Discrimination

- Practical audible range: 15 to 15,000 Hz (sensitivity of 1000/1)
- Pressure audible range: 1,000,000/1
- Frequency range of ***musical instruments: 27 – 4200 Hz***
- **Piano:** lowest tone, 27.5 Hz, highest tone, 4186 Hz
- Very hard to distinguish pitch at high frequencies.
- **Sounds above 7-8 kHz have no definite pitch.**

Perception of pitch

- The **just-noticeable difference** **(jnd)** - threshold at which a change is perceived
  - Two sounds are judged the same if they differ by less than a difference limen or just- noticeable difference **(jnd)**. A **limen** or a liminal point is a threshold of a physiological or psychological response.

- The jnd is typically tested by playing two tones in quick succession with the listener asked if there was a difference in their pitches

- It depends on the training of the listener and the method of measurement

- The jnd for pitch depends on the frequency, sound level, duration and the suddenness of the frequency change

Perception of pitch

Example:

$$1\,jnd \approx 4.3cents \approx 0.36Hz \text{ within the octave of 1000 - 2000Hz}$$

$$1\,jnd \approx 40cents \approx 2Hz \text{ within the octave of 62 - 125Hz}$$

Definition: 1 cent = 1% of a semitone
1 semitone = 1/12 of octave
→ 1200 cents in an octave

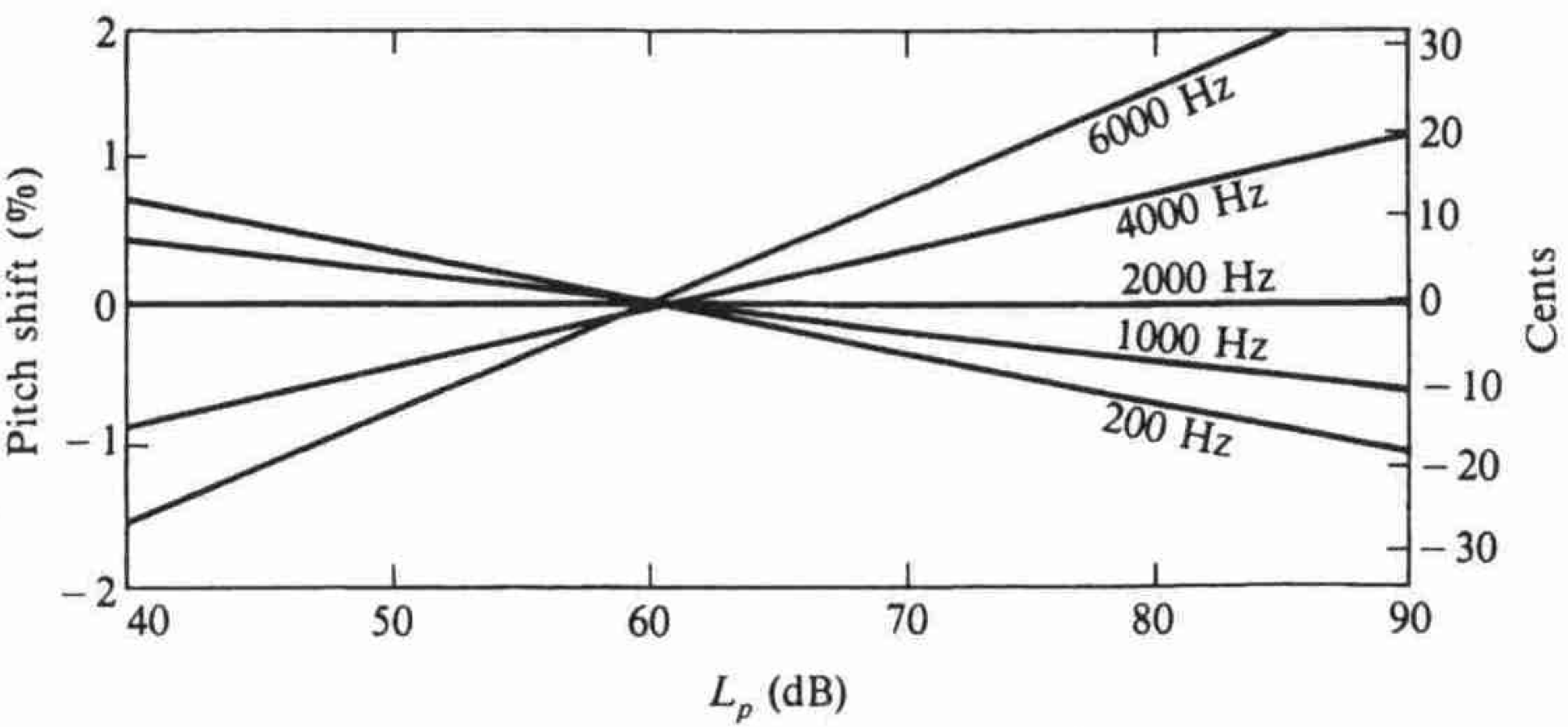
• The jnd becomes smaller if the two tones are played simultaneously as the listener is then able to discern beat frequencies.

• The total number of perceptible pitch steps in the range of human hearing is about 1,400; the total number of notes in the ***equal-tempered scale*** is 120.

Pitch of pure tone

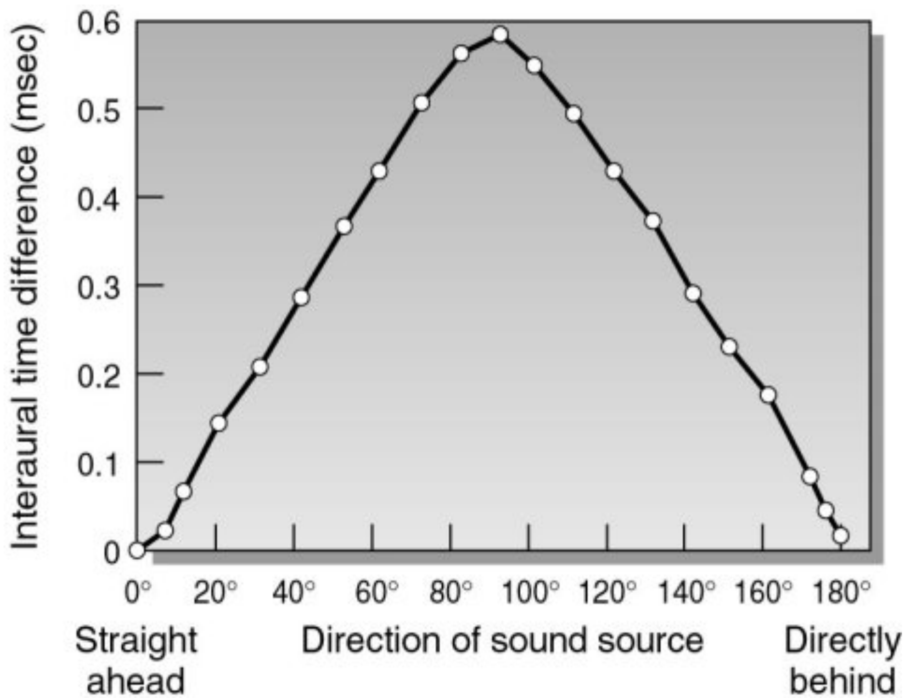
- Pitch increases with sound level for high frequencies
  - The largest upward shift occurs at 8000 Hz
- Pitch decreases with sound level for low frequencies
  - The maximum downward shift occurs at 150 Hz
- Pitch shows little changes for middle frequencies (~ 2000 Hz)
- This change is very subjective

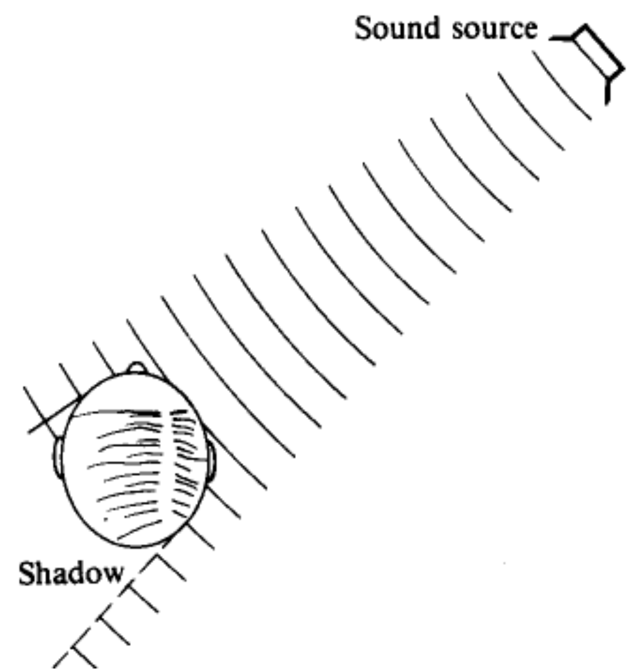
Example: The shift is between 10 and - 15 cents when a 250 Hz tone is increased from 40 to 90 dB



Perception of Localization of Sound

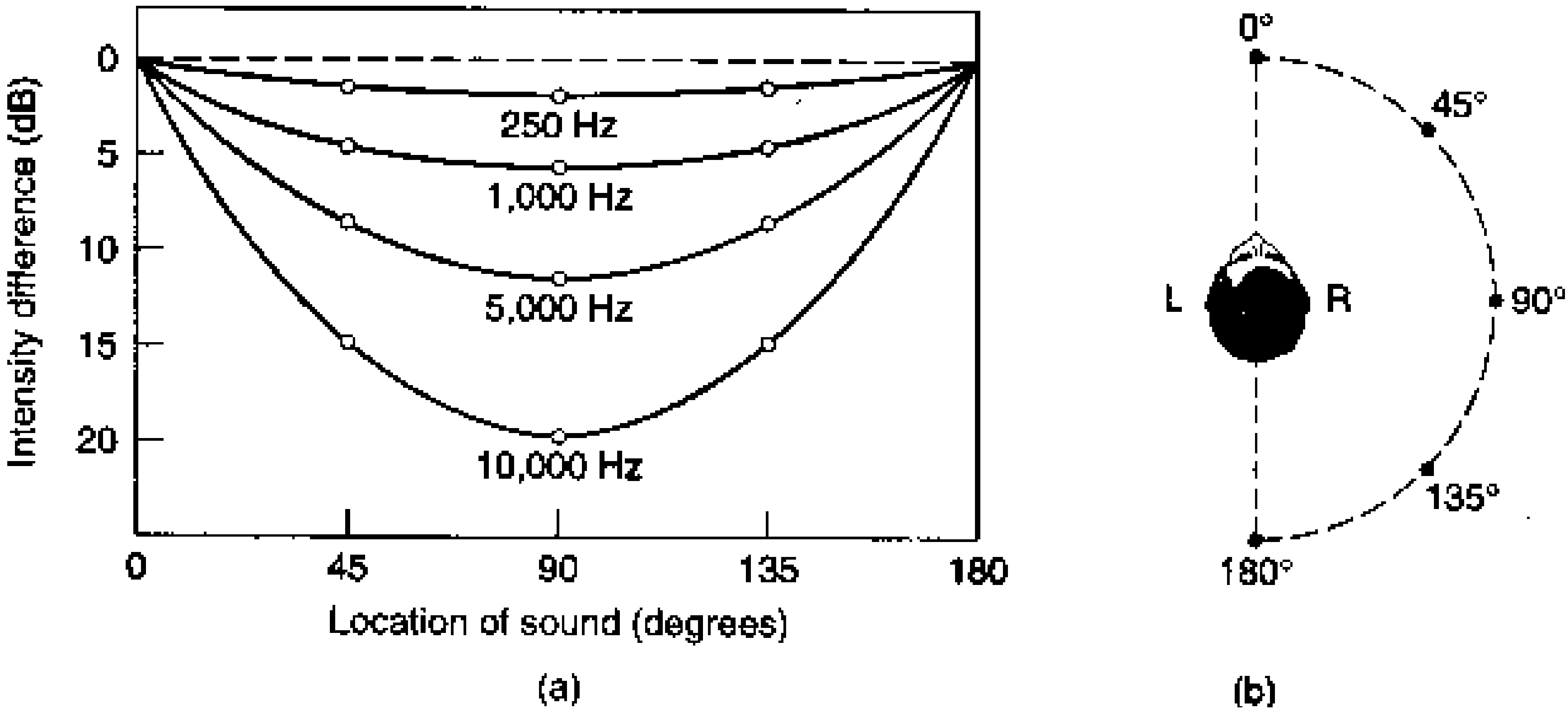
- At low frequencies (< 1000 Hz), ear detects phase difference
  - wave crest hits one ear before the other
  - "shadowing" not very effective because of **diffraction**
- At high frequencies (> 4000 Hz), use relative intensity in both ears
  - one ear is in sound shadow
  - even with one ear, can tell front vs. back at high freq.





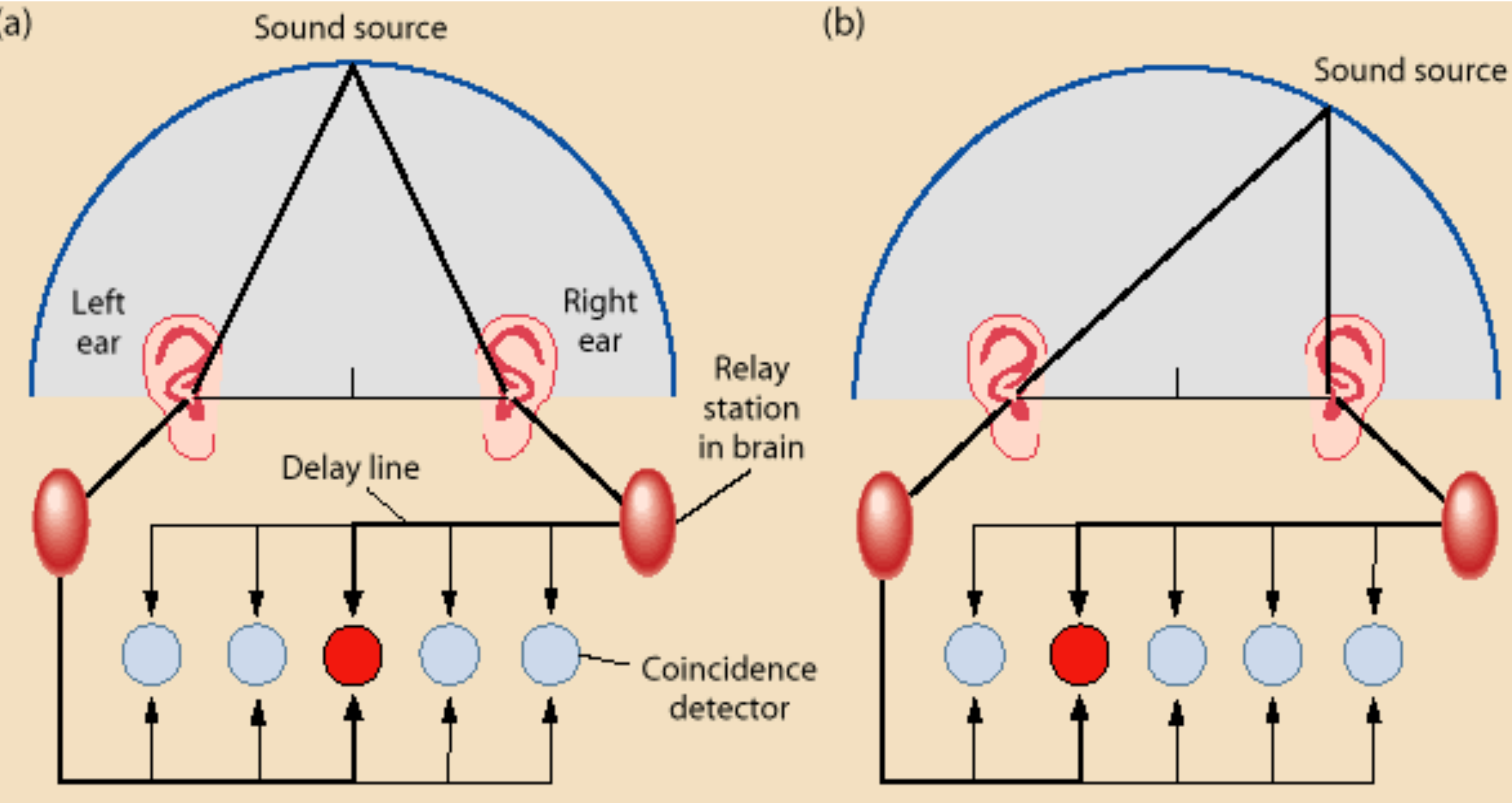
Perception of Localization of Sound

because of **diffraction**



Perception of Spatial Location

- Arrival time difference for high frequency sound used by the ear to tell direction of sound (**localization, stereophonic effect)**



Binaural beats

- Binaural beats may be heard when a pair of tones of slightly different frequencies are presented one to each ear via headphones.

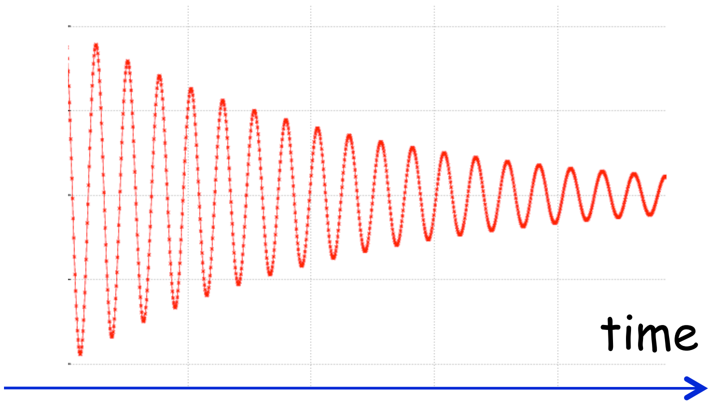
- Frequency difference < 2 Hz the sound appears to move right and left across the head.

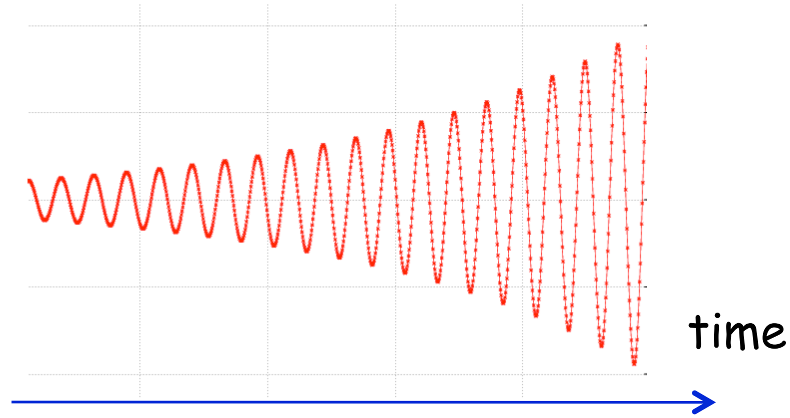
- Larger frequency difference the sound no longer appears to move but is rough with a fixed location.

- Provide evidence that phase information is preserved in the discharges of the neurons in the auditory nerve and that the auditory system can detect the phase difference at the two ears.

Pitch depends on duration & envelope of sound

- Sound must **last 0.04 s at 100 Hz** to be perceived as pitch
- and at least **0.013 s above 1000 Hz**





- The perceived pitch of a short exponentially decaying sinusoidal tone is found to be higher than a simple sine tone with the same frequency and energy

- The same is true for sinusoidal tones rising exponentially

Pitch is affected by interfering sounds

- The ear is extremely sensitive to frequency changes in **pure tones**
  - The jnd for frequency changes in pure tones is less than for noise, provided that the amplitude of the pure tone remains constant
  - The jnd for a narrow band noise (10 Hz with center frequency of 1500 Hz) is 6 times greater than that of a pure tone
- For a **pure tone** in the presence of an interfering tone/noise the following applies:
  - If the interfering tone has a lower frequency, there is an upward shift
  - If the interfering tone is above, a downward shift is observed at low frequencies

Diaplacusis

- People with unilateral **cochlear hearing losses** or asymmetrical hearing losses:
  - same tone presented alternately to the two ears may be perceived as having different pitches in the two ears.

Normal Hearing: **frequency** and **pitch** are **synonymous**.

Pitch discrimination as a function of frequency:

- a 3 Hz change at 30 Hz (only 10% discrimination: two semitones)
- 4 Hz at 400 Hz (~ 1%)
- 5 Hz at f > 1000 Hz (< 0.5 %,   0.08 semitones)
- If pitch change is very abrupt, ear can notice with better discrimination

- Psychologists often use definition: 1000 Hz = 1000 **mels**
  - sound twice as high (2 mels), twice as low (1/2 mels)

Absolute pitch

The ability to recognize and define the pitch of a tone without the use of a reference tone.

(Less the 0.01% of population have it)

Relative pitch

The ability to tell whether one tone is higher than another, and with some musical training can recognize intervals

Absolute pitch theories

- **Heredity theory** – it is an inherited trait
- **Learning theory** – it can be acquired by almost anyone with diligent and constant practice (not too widely believed)
- **Unlearning theory** – can be perfected if learned at an early age (relative pitch) !!!
- **Imprinting theory** – irreversible learning that takes place at a specific developmental stage !!!

Pitch standards (A4)

- Old organs (Helmholtz 1877): 374-567 Hz
- Praetorius, 1619: 424 Hz
- Handel's tuning fork: 422.5 Hz
- French commission 1859: 435 Hz
- Early 20th century: 431 Hz
- International conference 1939: 440 Hz

Pitch of complex tone: virtual pitch

If tone is composed of exact harmonics then pitch is the **fundamental:** One hears the **fundamental tone + a particular tone quality**.

Virtual pitch: missing fundamental

Example: a) f = 600, 800, 1000, 1200 Hz;
Fundamental and pitch = 200 Hz (difference tone)
b) f = 200, 300, 400 Hz;
Fundamental and pitch = 100 Hz (difference tone)

This is used in small loudspeakers to produce bass tone

BUT NOTICE: Example c) f = 300, 500, 700 Hz;
Fundamental and pitch still 100 Hz
(not a difference tone) – *Always occurs with odd harmonics*

Pitch of complex tone: virtual pitch

Which harmonics are most important?

- For fundamental ~200 Hz important are 4th and 5th harmonics
- As fundamental frequency increases, the number of the dominant harmonics decreases, reaching the fundamental itself at 1500 Hz and above

If partials are not harmonic: pitch is picked up from the nearly harmonic partials near the center of audible range

Examples: bells and chimes. Partials have ratio almost 2:3:4.

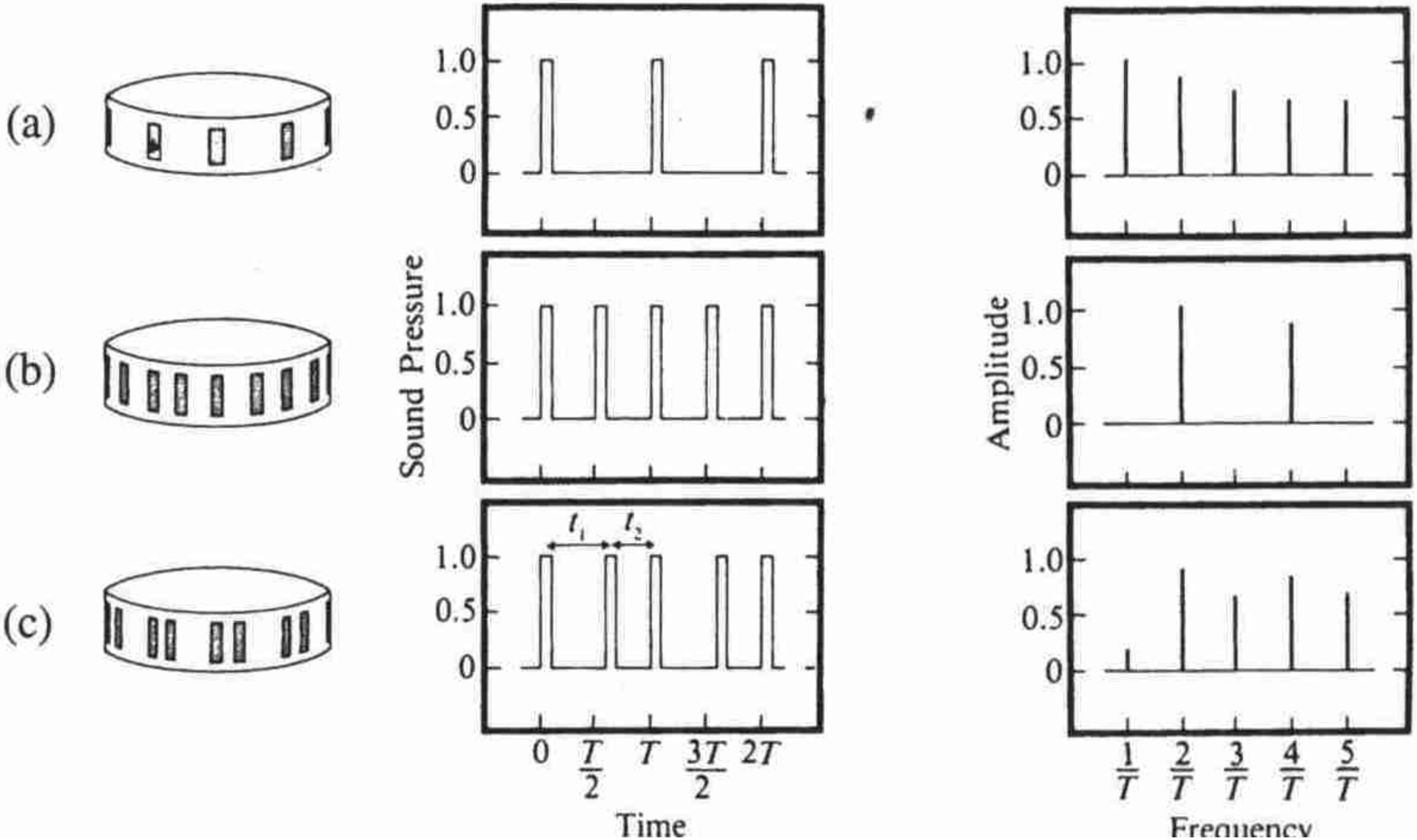
- Chimes do not have partials near the fundamental – pitch is purely subjective.
- Chimes partials: $9^2:11^2:13^2 = 81:121:169 \sim 2:3:4$

Definition (ANSI): "**Timbre** is that attribute of auditory sensation in terms of which a listener can judge two sounds…having the same loudness and pitch as dissimilar." !!!

Seebeck's siren

Seebeck performed a series of experiments on pitch perception that produced some significant but "surprising" results.

The siren consisted of a rotating disc with periodically spaced holes that created puffs of compressed air at regular intervals



Seebeck's siren

- Pitch of siren corresponds to the time between puffs of air
- Doubling the number of holes raised the pitch by exactly an octave
- Using a disk with unequal spacing of holes produced an "unexpected" result
  - As shown in (c) on the figure, the pitch matched that
  - shown in (a)
  - By looking on the spectrum, it is clear that they have the same harmonics, with different amplitudes
  - The period in (c) is $T = T_1 + T_2$
  - The harmonics are therefore the same, however, the fundamental is weaker

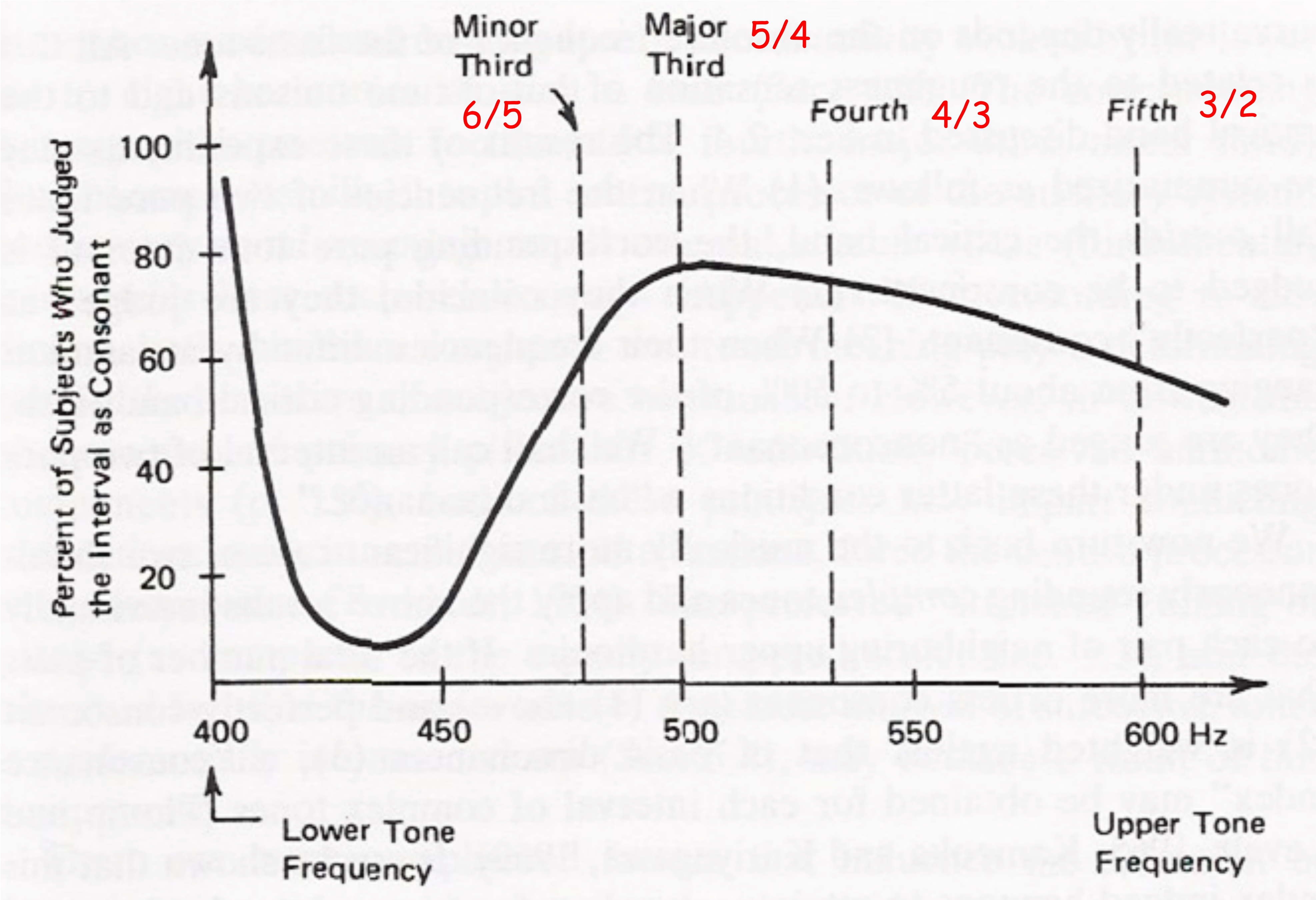
Perception of multiple tones, related to "consonance"

Assume two pure tones are heard, one stays the same and the second one can be varied in pitch.

1. When second pitch is close, most people think the resultant sound is ***"consonant"***

2. As second sound gets farther away, very few people think sound is consonant

3. After two sounds get to around the distance of a minor third (6/5), most people again think the resultant sound is consonant



Consonance "index" for the superposition of two pure tones.

Perception of two pure tones

Again, two pure tones are heard, one stays the same and the second one can be varied in pitch.

1. Very close → sounds like one tone, with **beats**

•

2. After passing "limit of frequency discrimination" → sounds like two tones with **"roughness"**

•

3. After passing **"critical band"** → sounds like two tones sounding **smooth**

- These effects depend on how high the tones are
- Phenomenon is true for both tones heard by one or two ears
- When 2 tones are separated and fed into different ears, *roughness disappears*

- We infer that effect comes from each tone exciting a "range" on the basilar membrane (not one single point), and that the two tones interfere with each other

- This supports the ***"place" theory*** of response of the basilar membrane

Theories of Pitch

Place theory: Vibrations of different frequencies excite resonant areas on the basilar membrane

Periodicity theory: The ear performs a time analysis of the sound.

Place theory of pitch perception

- The pitch of the sound is assumed to be related to the excitation pattern it produces on the basilar membrane.
- The pitch of a pure tone may be explained by the position of maximum excitation.
- For a sound made up of many frequency components, many different maxima occur along the basilar membrane at places corresponding to the frequencies of the components.
- The position of the overall maximum, or the position of the maximum due to the lowest frequency component may not correspond to the perceived pitch of the sound.
- It is known that the pitch of a harmonic sound can remain the same even when energy at its fundamental frequency has been removed.
- This cannot be explained by the place theory

Temporal theory of pitch perception

- The waveform of a sound with a strong unambiguous pitch is periodic.
- The basis for the ***temporal theory*** of pitch perception is the ***timing of neural firings***, which occur in response to vibrations on the basilar membrane.
- Nerve firings occur at particular phases of the waveform; a process called **phase locking**.
- Due to phase locking the time intervals between the successive firings occur at approximately integer multiples of the period of the waveform.
- In this way the waveform periodicity that occurs at each place on the basilar membrane is coded.
- *At some point in the auditory system these time intervals have to be measured.*

Temporal theory

- The precision with which the nerve firings are linked to a particular phase in the waveform declines at high frequencies: upper limit of ~ 4-5 kHz.
- the ability to perceive pitches of sounds with fundamental frequencies greater than 5 kHz cannot be explained by this theory.
- It has been found that musical interval and melody perception decreases for sounds with fundamental frequencies greater than 5 kHz, although differences in frequency can still be heard.
- The pitches of notes are most often tuned according to the system of ***equal temperament.***
- Equal tempered tuning was formed out of a requirement for equally spaced intervals in terms of frequency ratio regardless of tonality (the musical key).
- In equal tempered tuning the **octave is divided into twelve equal steps** called ***semitones.***

Pitch in two dimensions

- Pitch perception in music is often thought of in two dimensions, pitch ***height*** and pitch ***chroma***

- This is to account for the perceived similarity of pitches that are separated by octaves.

- Pitch height is the low / high dimension of pitch. It is how high or low a note sounds.

- The relative position of a pitch within a given octave is referred to as its chroma.