PHY-2464
Physical Basis of Music

Presentation 6
Human Ear and Perception

Taken largely from Sam Matteson’s
Unit 2 Sessions 13 & 14:
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The Human Ear is a “non-linear Sensor”
Summary from Presentation 5:
Anatomy: Outer, Middle and Inner Ear.
Function:
- **Outer** – converts pressure fluctuations to displacement.
- **Middle** – amplifies displacement, protects against loud noise.
- **Inner** – converts displacement to neural impulses, sorted by frequency.

Summary from Presentation 5 (concluded):
- **Physiology** determines function.
- No phase detection mechanism.
- Large “non-linear” range of 12 orders of magnitude in intensity
- Three (3) orders of magnitude in frequency (20 Hz to 20 kHz).
- Trauma (due to loud sounds) is a cause of deafness.
Frequency Discrimination in Cochlea

- 20 Hz to 20 kHz (text book “typical in human beings” – reality is usually smaller range)
- Resonances in Basilar membrane and in Hair Cells (HC) cause spatial separation by frequency.
- Differential movement of membranes stimulate HC.
- Minimum stimulation required for response. Inhibition of neighbors causes non-linear response.

Neuronal Decoding of Sound (Schematic)
Neuronal Response to Sound (Place Theory)

- **Frequency → Where?** The location in the Cochlea at which the stereocilia (HC) are stimulated.
- **Intensity → How many?** The number of HC that are stimulated by the sound determines the perceived intensity (loudness).

Cilia Displacement vs Location on Basilar Membrane

*Position*  
At 2800 Hz
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**Cilia Displacement vs Location on Basilar Membrane**

- **Relative Response**
- **Position**
  - At 400 Hz

**Peak Frequency of Response vs Location on Basilar Membrane**

- **$f$ (Hz)**
- **Distance from Stapes (cm)**

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FACTS:
The frequency range of detectability for human beings is \( \approx 20 \, \text{Hz} \rightarrow 20 \, \text{kHz} \).
We are most sensitive in the freq. range \( 2 \rightarrow 5 \, \text{kHz} \).
The lowest humanly detectable intensity (the threshold of hearing, is about \( I_{\text{threshold}} = 1 \, \text{pW/m}^2 = 1 \times 10^{-12} \, \text{W/m}^2 \).
The intensity at which one experiences pain (the threshold of pain) is about \( 1 \, \text{W/m}^2 \).

Consequence: Threshold and Non-linear Response

Threshold of Hearing \( 10^{-12} \, \text{Watt/m}^2 \)
Desensitization with greater stimulus

Stimulus (Intensity)
Response (sensation)
Neuronal Response of Hair Cells

Hair Cells in the Basilar Membrane

Larger Stimulus

Neuron fires and neighbors are inhibited

No increased response

No response

No larger response because of inhibition

Attenuated response to much larger stimulus
**Consequence: Threshold and Non-linear Response**

**Threshold of Pain**

1 Watt/m²

**Logarithm of Stimulus vs Response**

\[ SIL = 10 \log \left( \frac{I}{I_{\text{threshold}}} \right) \]

\[ I_{\text{threshold}} = 10^{-12} \text{ W/m}^2 \]
The Fletcher-Munson Diagram is a plot of the SIL (in dB) versus frequency for the SIL required to produce the perception of loudness (sensation) equal to that produced at 1000 Hz.

The Fletcher-Munson contours are of equal loudness level for human beings therefore. (Surely the F-M contours for cats are different!)

The unit of loudness level is the phon. It is defined only relative to human beings!
**Fletcher- Munson Diagram**

Fletcher and Munson, J. Acoust. Soc. Am. 55, 82-108 (1933)

**Auditory Demonstration #6**

Houstma and Rossing
Institute for Perception Research (IPO) Eindhoven, The Netherlands &
Acoustical Society of America
Tracks 17, 18

Decreasing “staircase” of loudness - Count the number of steps you that can hear at each frequency:
125, 250, 500, 1000, 2000, 4000, 8000 Hz.
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Use the Fletcher-Munson Diagram to determine the SIL necessary to have a 70 phon Loudness Level at 200, 2000, and 10,000 Hz.

Fletcher-Munson Diagram

Frequency (Hz)

SIL (dB)

-10  10  100  1000  10000

200 Hz—70 dB
2 kHz—70 dB
10 kHz—75 dB
Equal Loudness (70 phon)
Use the Fletcher-Munson Diagram to determine the Loudness Level of an 80 dB tone at 100, 400, and 8000 Hz.
The Loudness Level for a given frequency can be approximated by a linear function of the Intensity Level:

\[ LL \approx A_f (SIL - SIL_{\text{threshold}}) \]

Thus, one of the standard settings of a Sound Level Meter (filter switch or scale “A”) modifies the calibration of the instrument to account for the frequency dependence of human hearing.

That Sound Level is reported as “dBA.”
You can remember this as “dB” “adjusted for humans”

Loudness

A subjective measure of the magnitude of auditory sensation is called Loudness. It is measured in sone. In this system, one listens to two sounds and judges how much louder or softer a test sound is compared to the reference.

Example: a tone of 2 sone sounds twice as loud as a tone of 1 sone.
Auditory Demonstration #7
Houstma and Rossing
Institute for Perception Research (IPO), Eindhoven, The Netherlands
& Acoustical Society of America
Tracks 19, 20

Estimate how loud each of the sound samples is as compared to the reference sound sample.

The reference is presented first along with the loudest and softest sounds.

Loudness Scaling

\[ \text{Loudness } L = \text{constant} \times I \]

Thus, an eight (8) singer ensemble sounds about twice (2x) as loud as a soloist: \( \sqrt[3]{8} = 2 \).
Likewise, a choir of sixty-four (64) sounds about four (4x) times louder than a soloist: \( \sqrt[3]{64} = 4 \).
Summary:
• Perception of loudness depends on frequency
• Frequency & loudness detection in the ear depend on location and area, respectively, of excitation of HCs
• Loudness is the magnitude of the sensation produced by a sound; measured in sone.
• Loudness Level (in phon) is equal to the SIL at 1000 Hz that produces the same magnitude of sensation.
• Loudness increases approximately with the cube root of intensity.