KTH ROYAL INSTITUTE
OF TECHNOLOGY

DT2212: Music Acoustics

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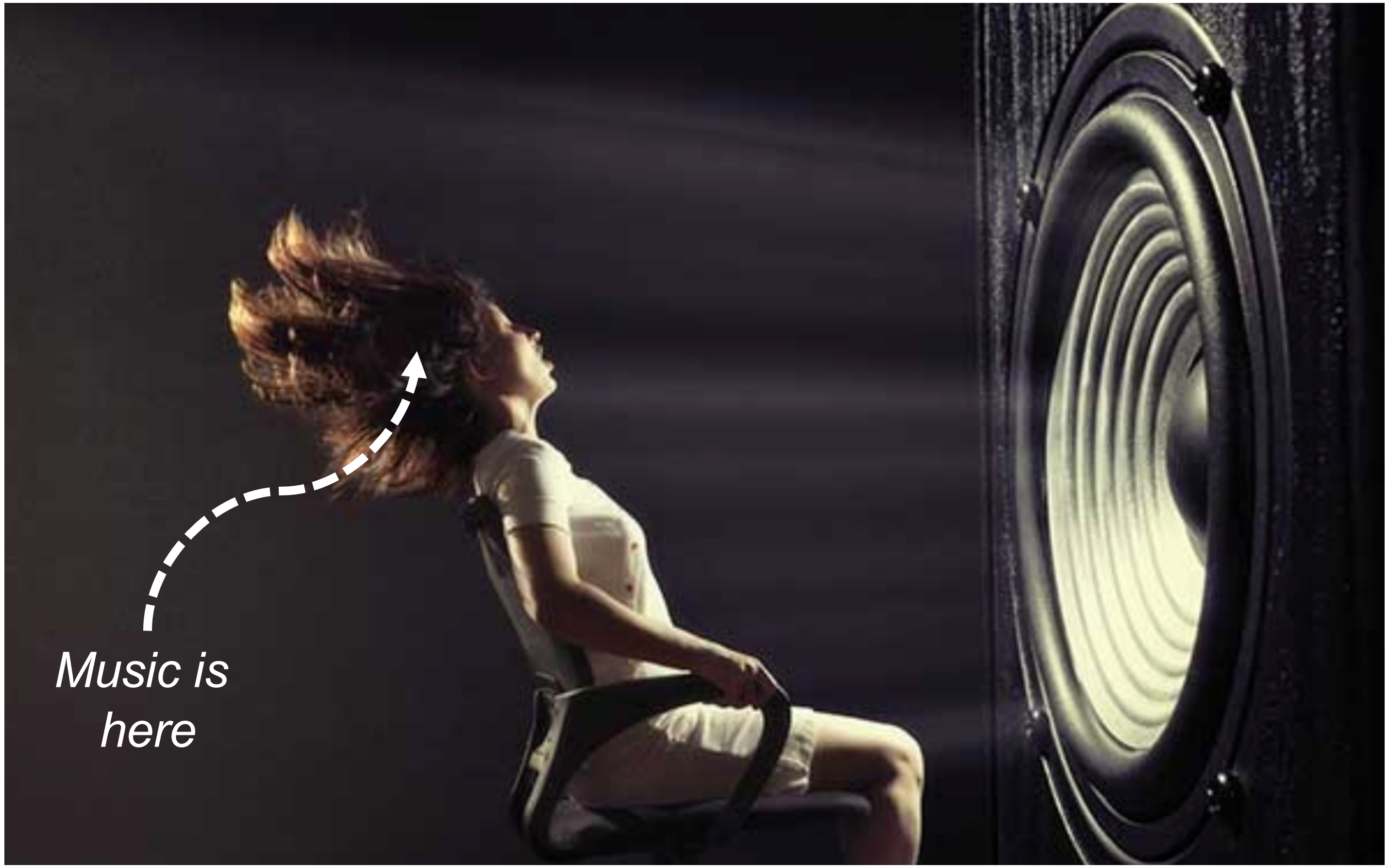
Lecture 3: Sound and music perception
Chapters 11–14 in Hartmann

Musical sound is all around us

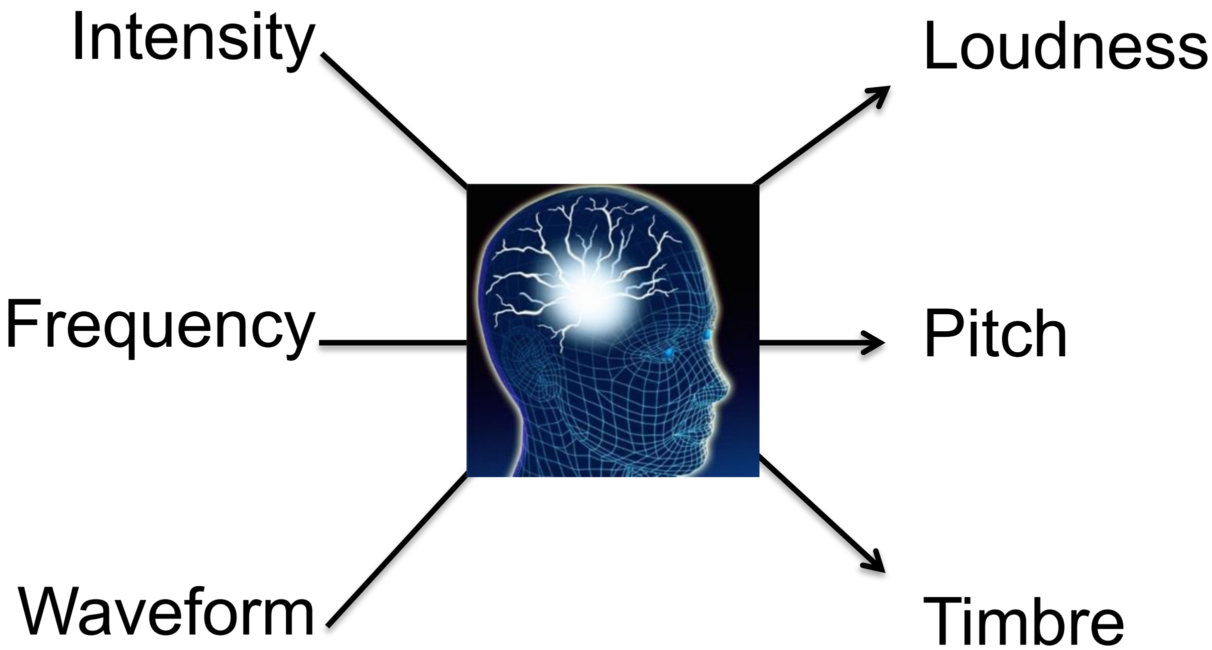


Question:

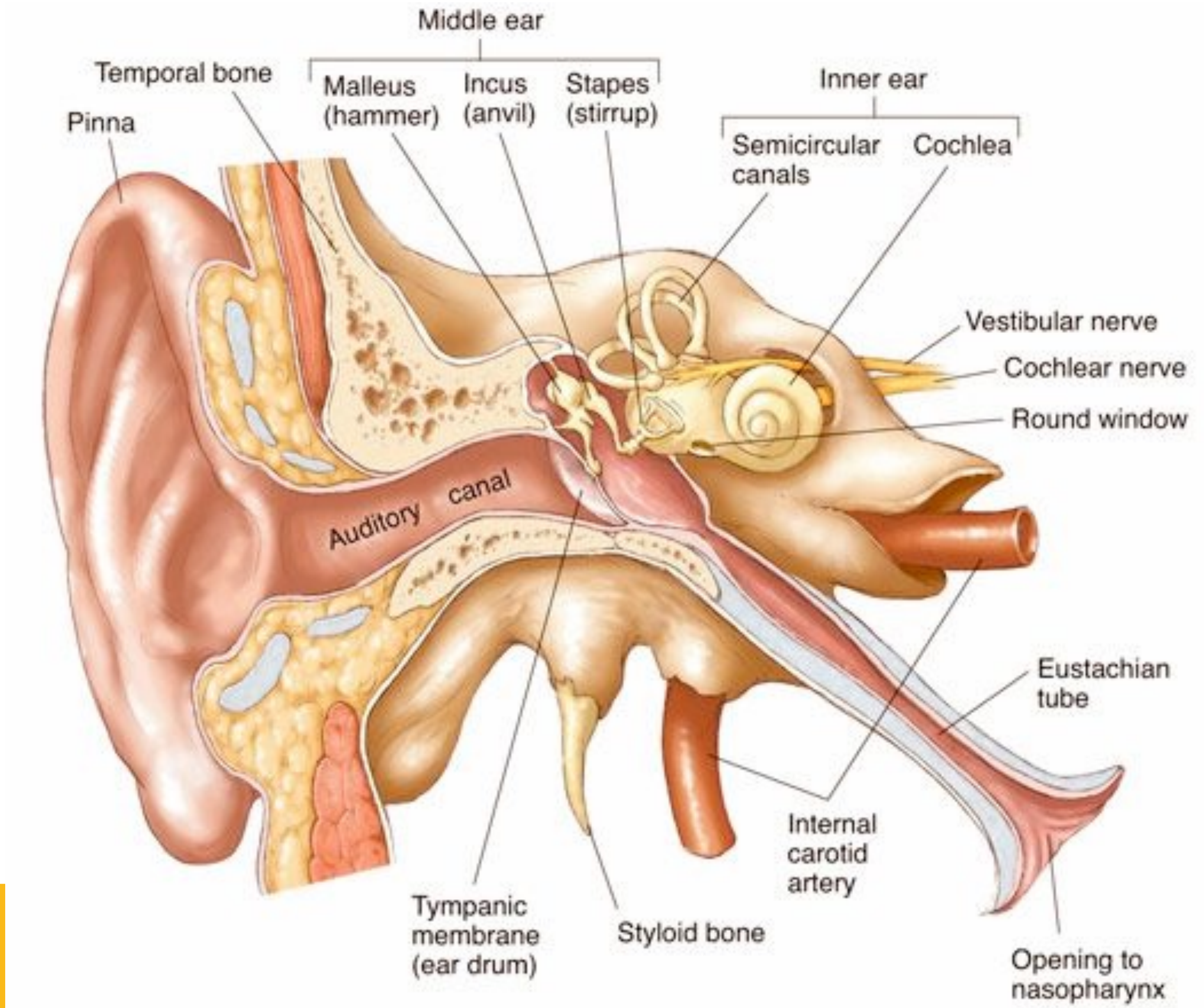
How do we know if a baby's hearing is functioning normally?

Attributes of sound

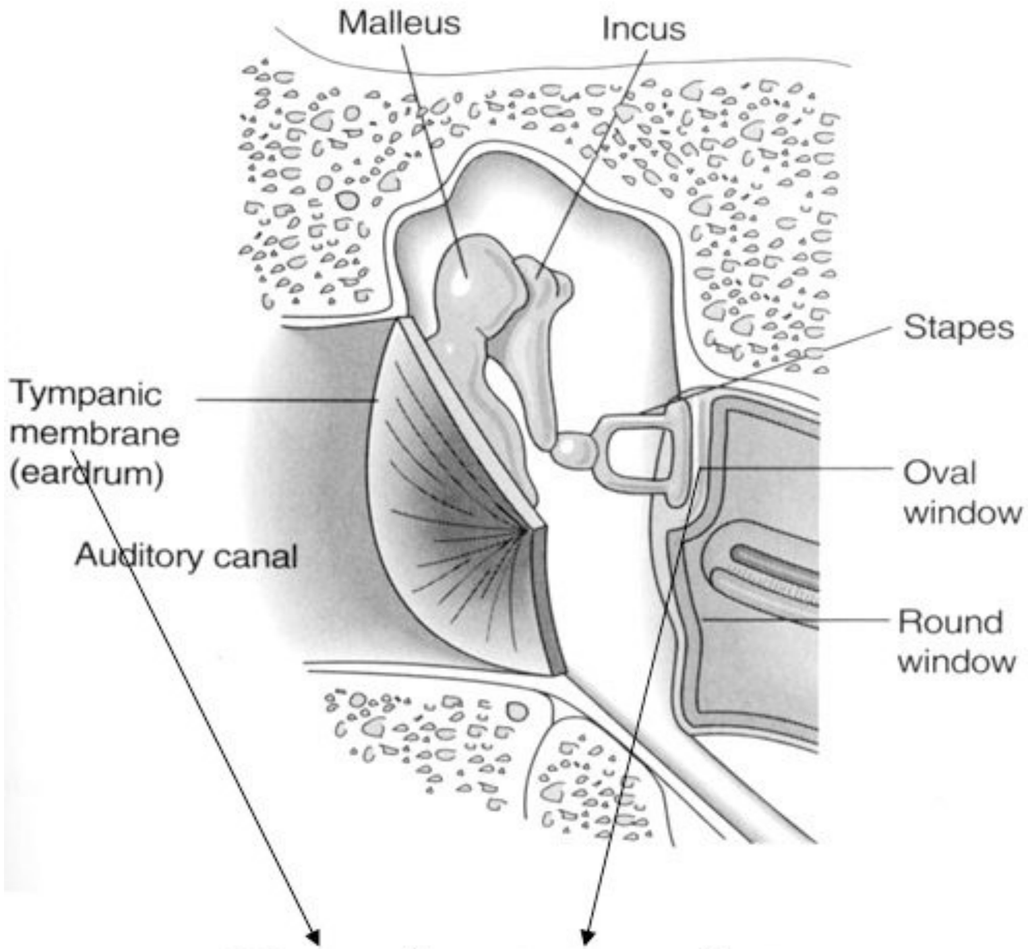
Physical *Perceptual*



The Ear Anatomy



Middle ear

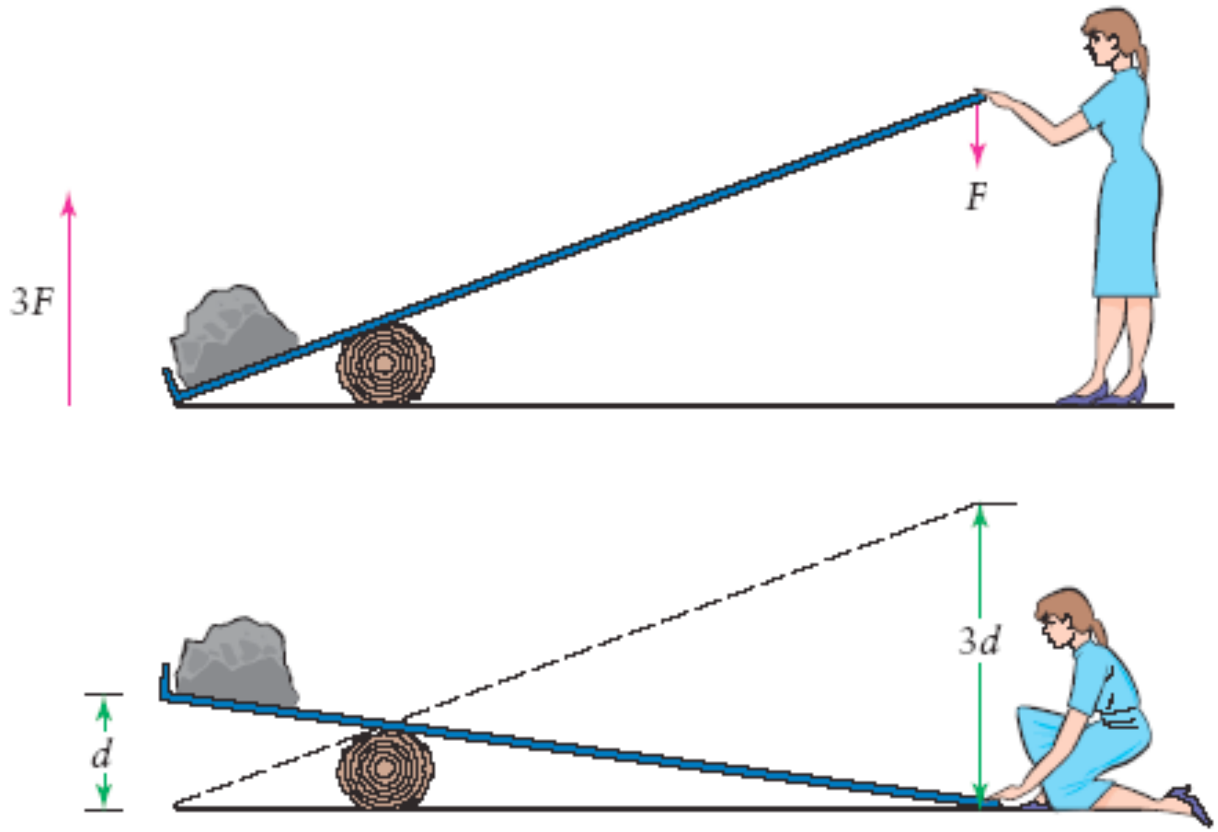


55 mm^2 3.2 mm^2

Ossicles amplify the vibrations in two ways:

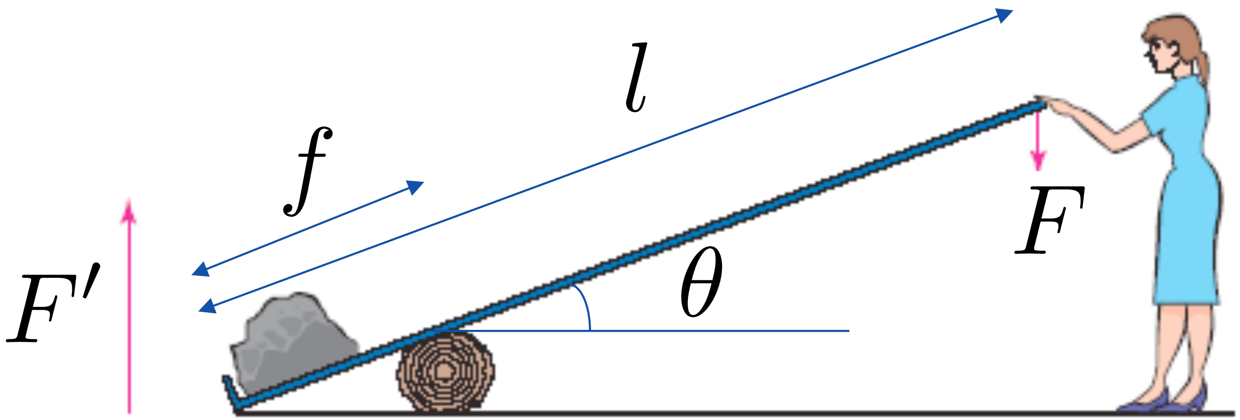
1. Concentrating the vibration of the large tympanic membrane onto the much smaller stapes
2. Create a lever action

The lever

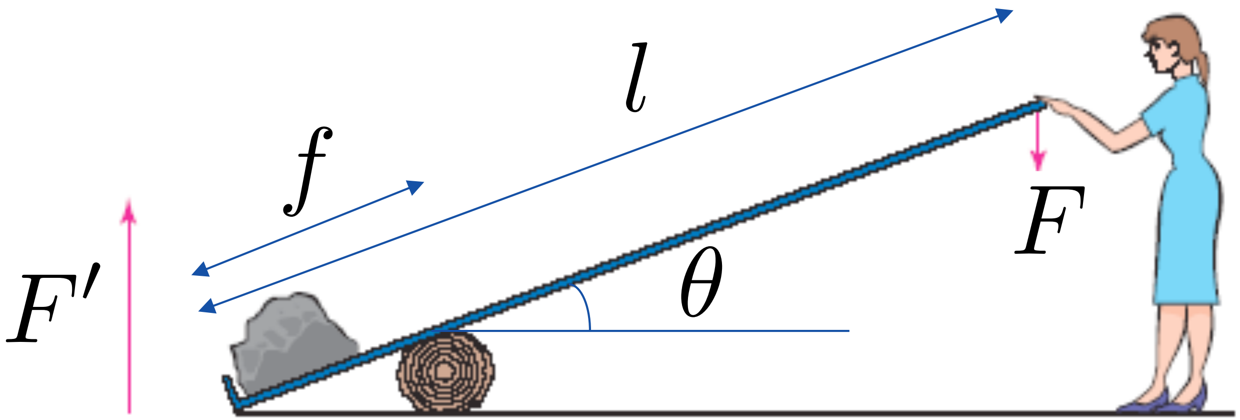


Archimedes: “Give me a lever and a place to stand, and I will move the earth.”

The physics of the lever



The physics of the lever



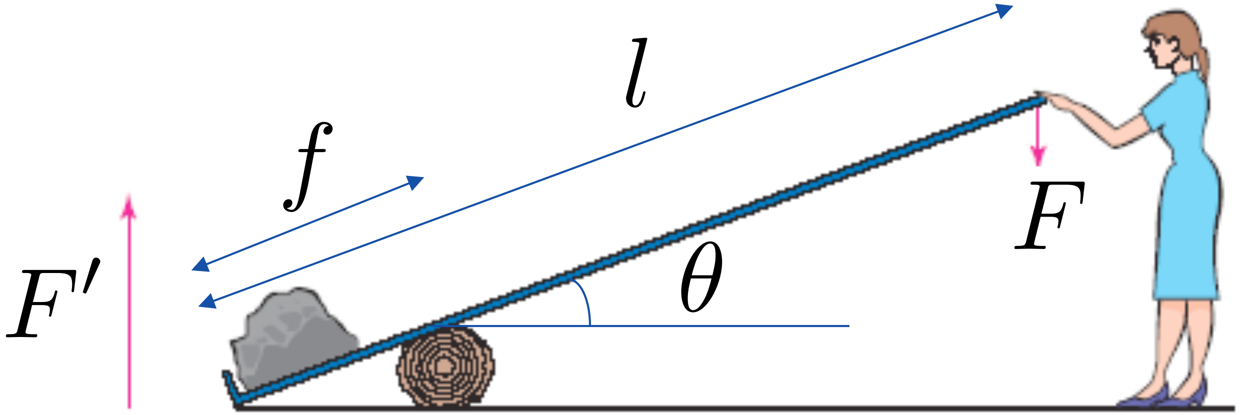
Work done moving right hand side by θ

$$W = F(l - f)\sin\theta$$

This is equal to the work done on the left hand side

$$W = F' f \sin\theta$$

The physics of the lever

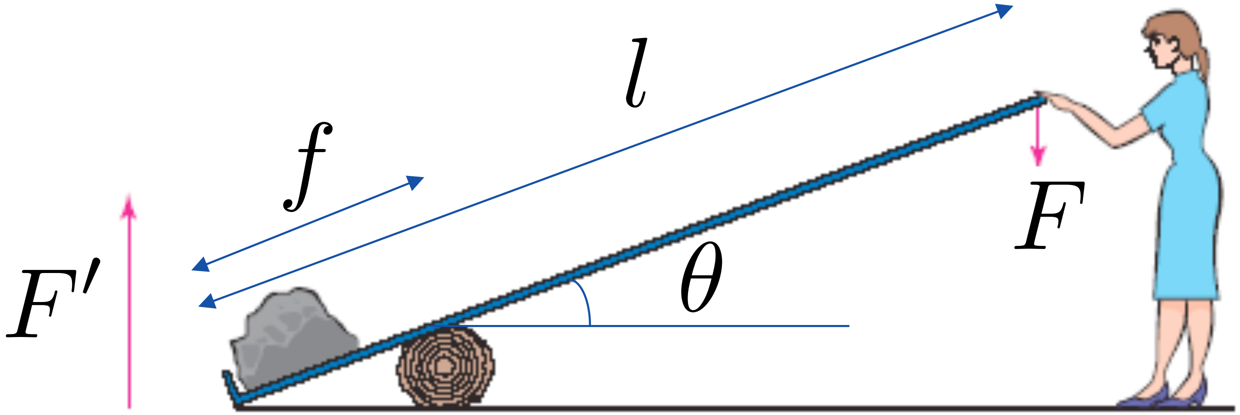


$$F' f \sin\theta = F(l - f)\sin\theta$$

$$F' = \frac{l - f}{f} F, l > f > 0$$

Amplification!

The physics of the lever



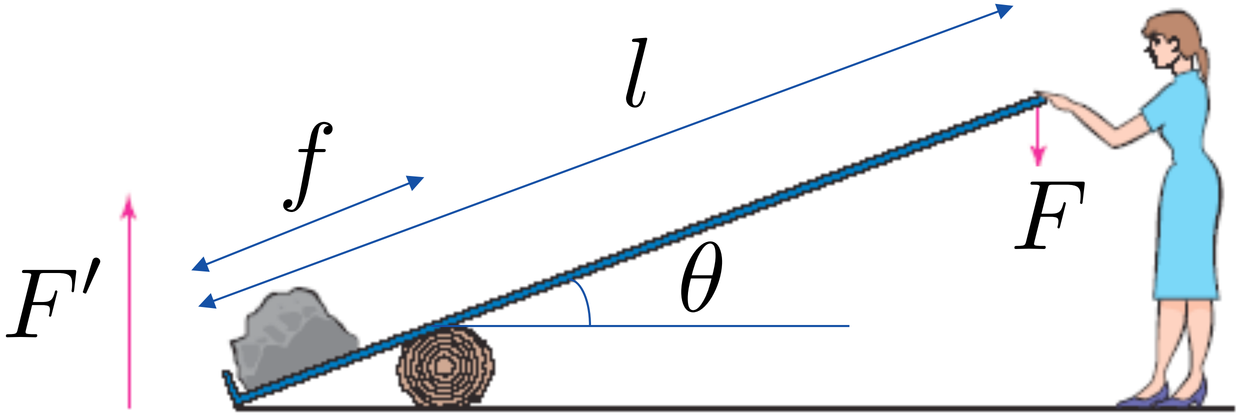
How does this relate to pressure? $P = F/A$

$$P'A' = \frac{l-f}{f}PA, l > f > 0$$

At oval window

At eardrum

The physics of the lever



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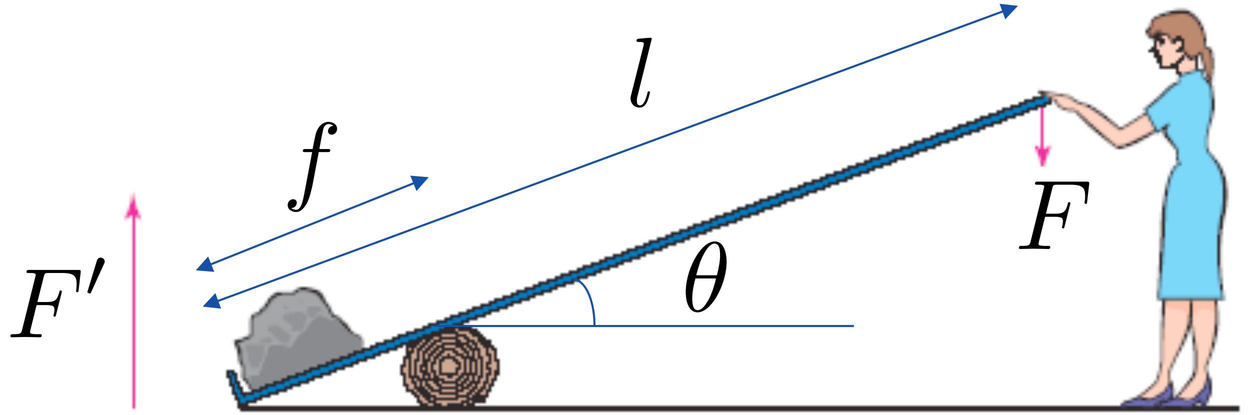
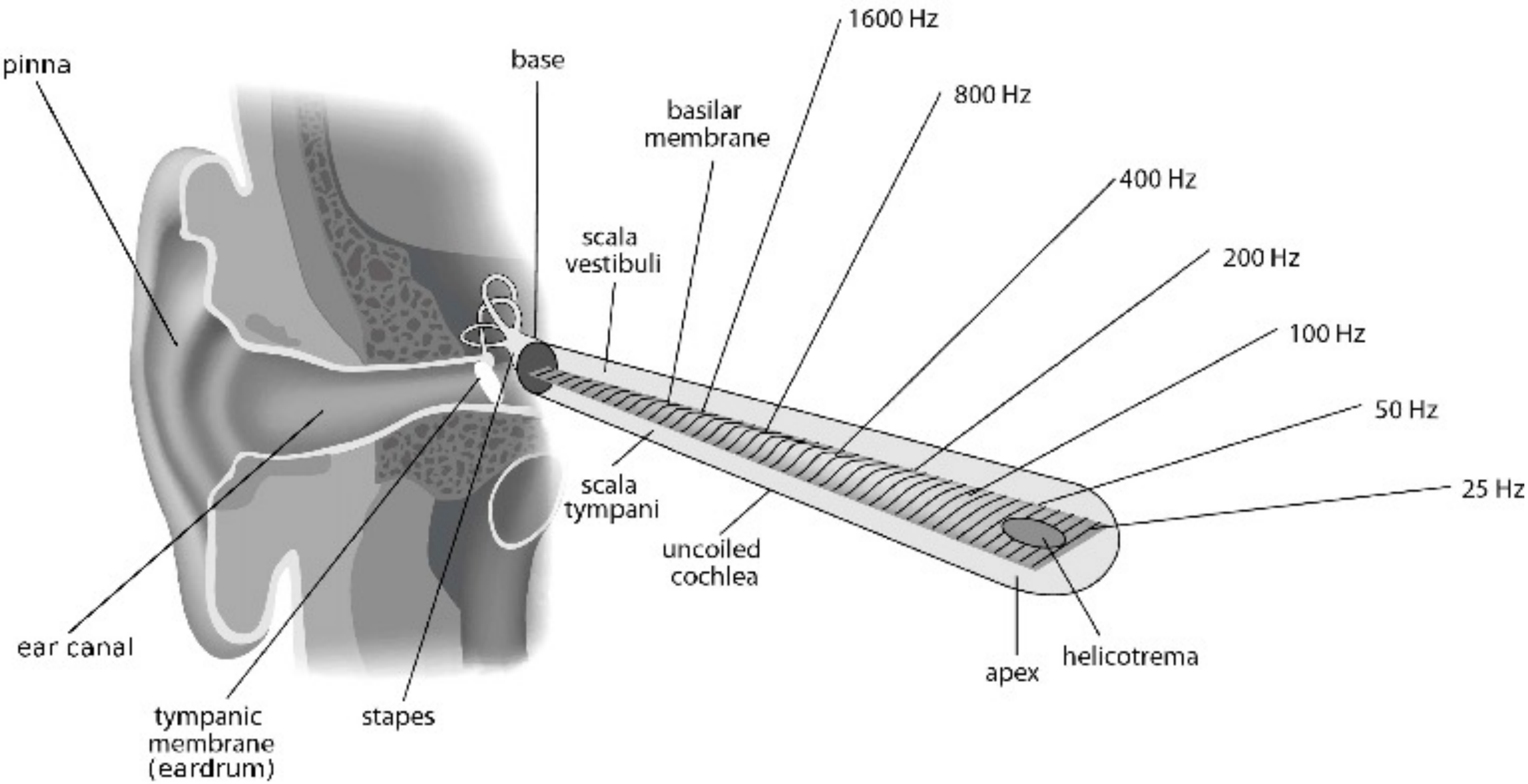


How does this relate to pressure? $P = F/A$

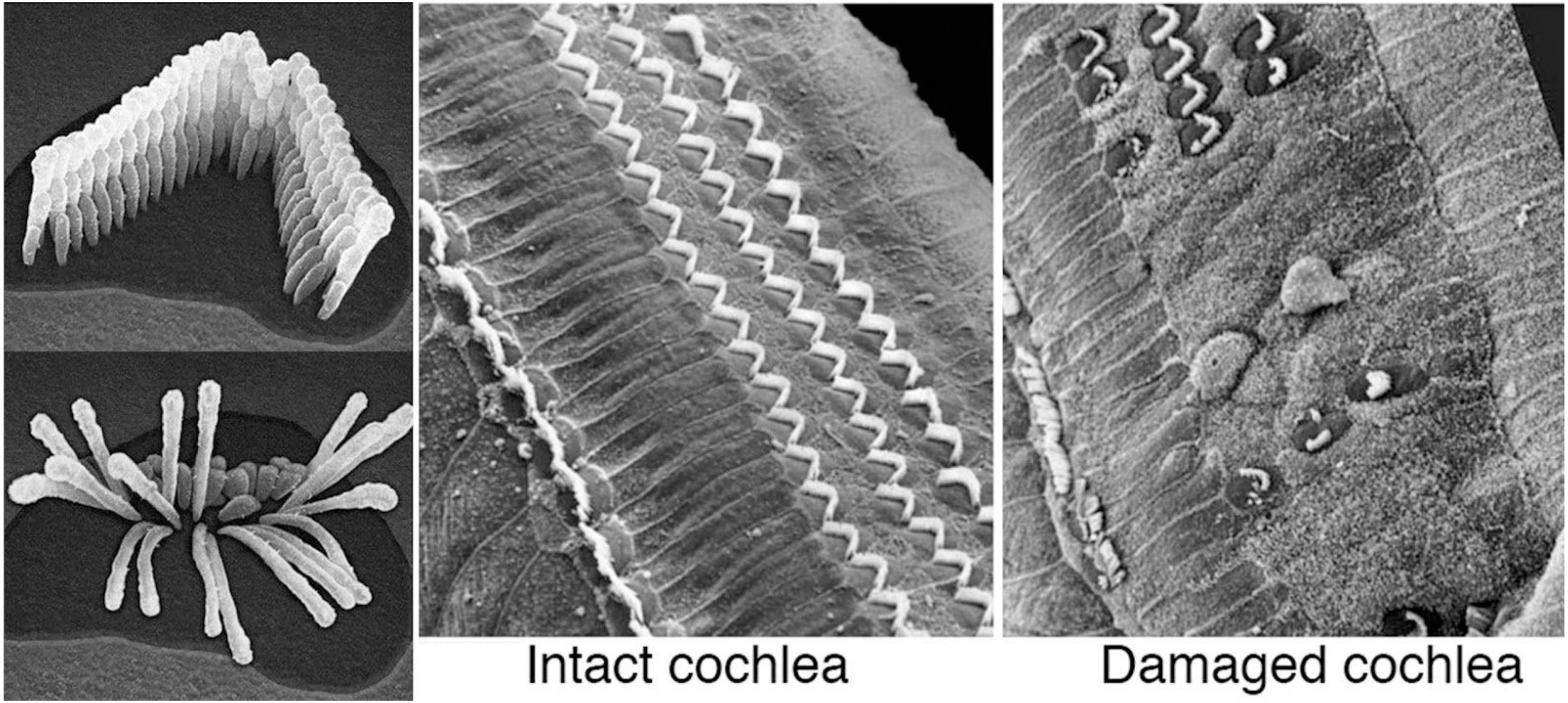
$$P' = P\frac{l-f}{f}\frac{A}{A'}, l > f > 0$$

For the human ear ≈ 1.3 ≈ 20 Therefore $P' \approx 26P$

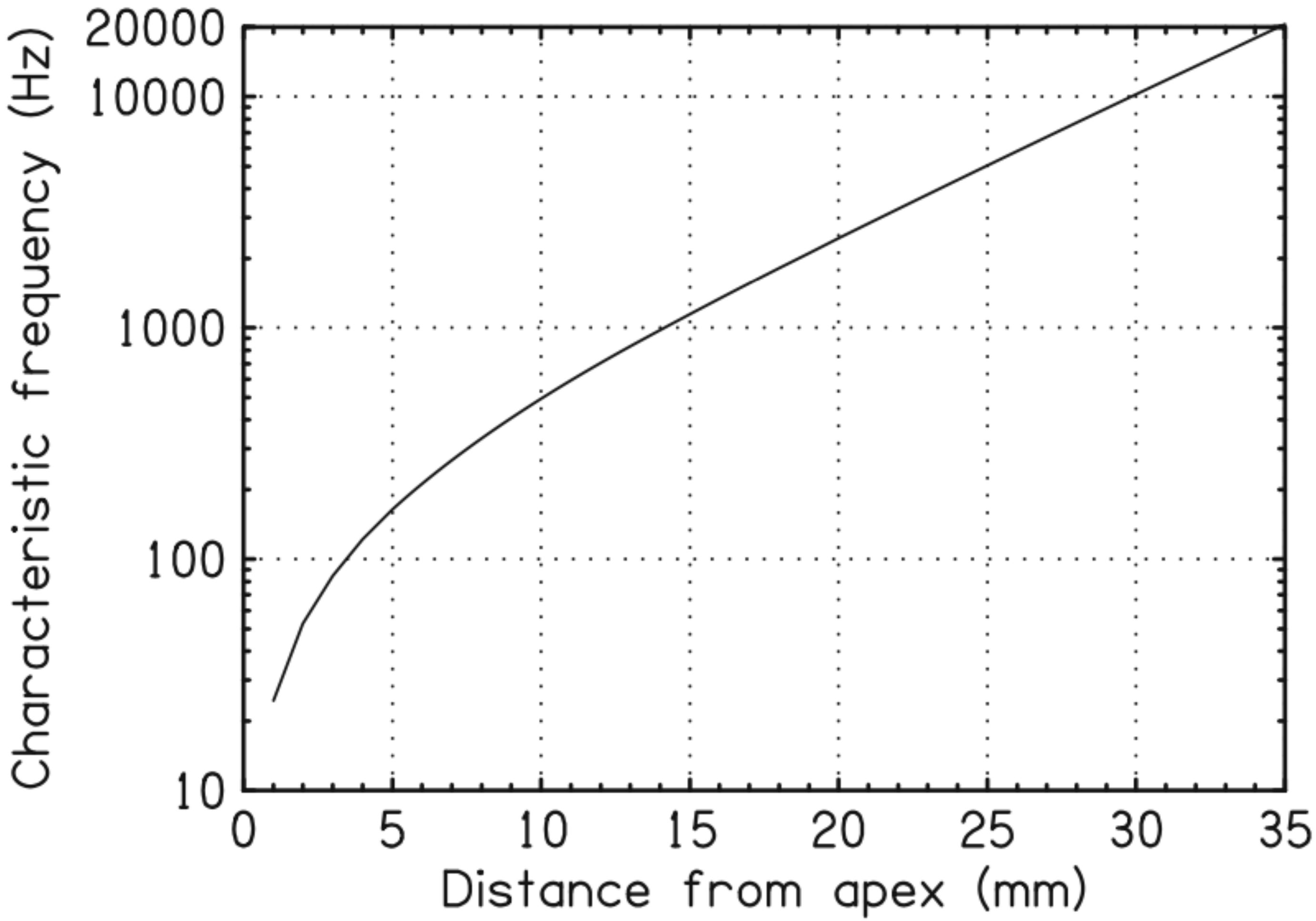
The Cochlea, unrolled



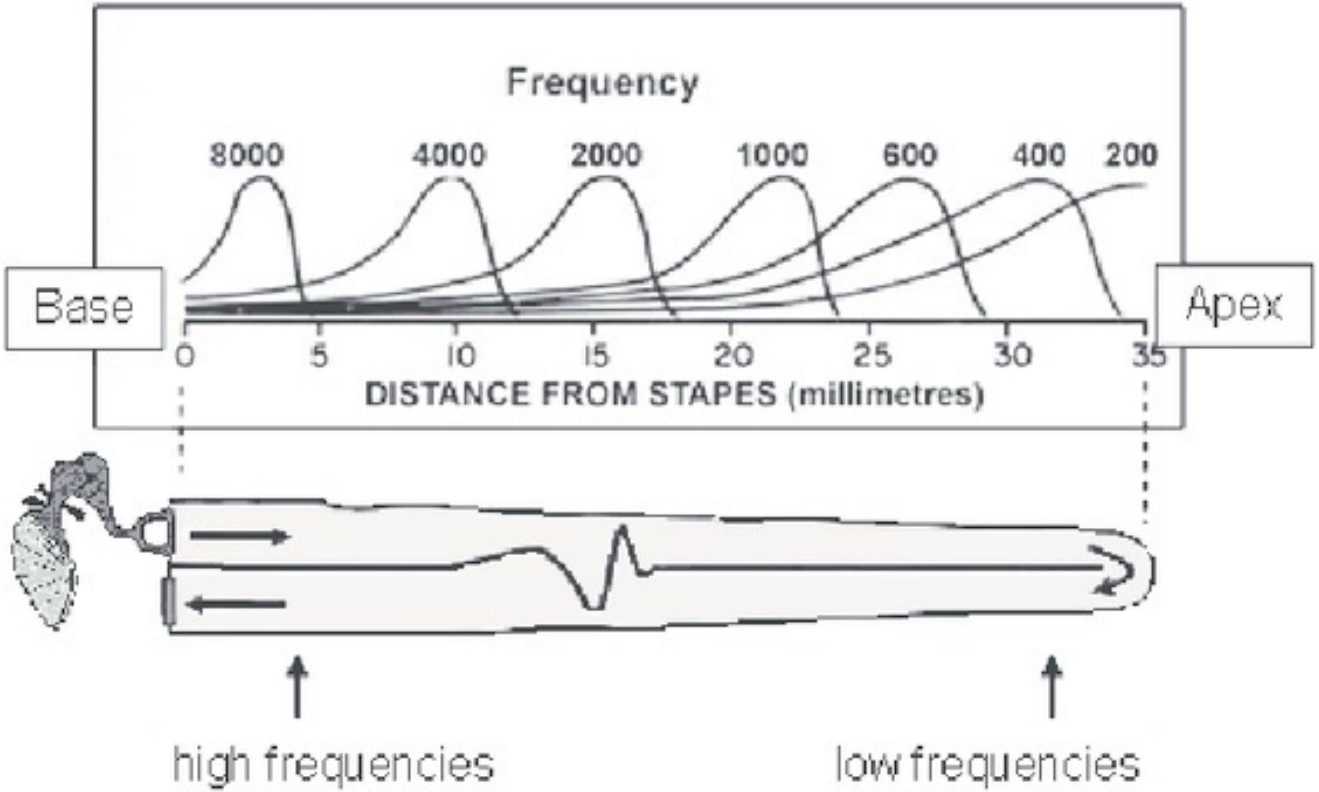
Hair cells on the basilar membrane



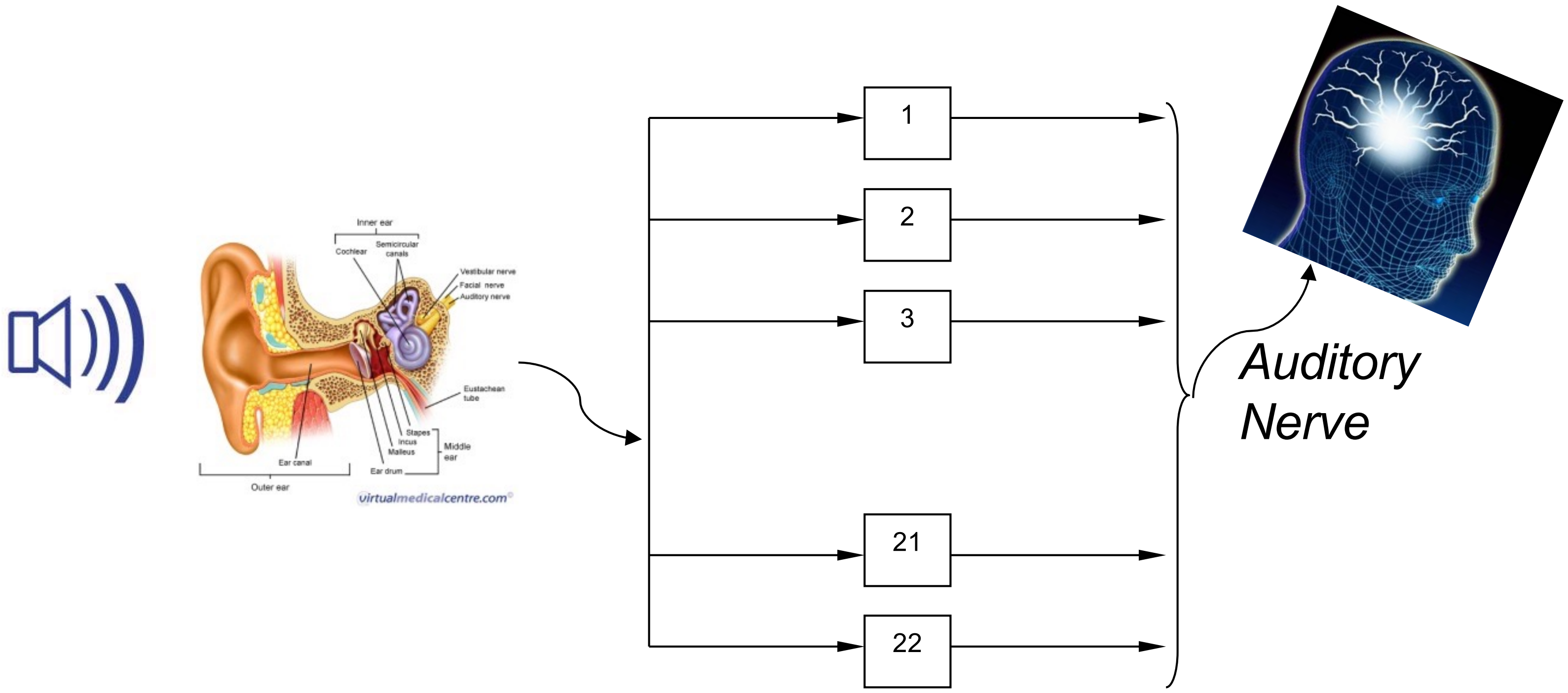
Characteristic frequencies along basilar membrane



Frequency response of hair cells



Simple model of auditory system



Filterbank
"frequency bands"

Critical bandwidth (CB)

- Range of frequencies that overlap on the basilar membrane
  - Gives an idea of how much of the basilar membrane reacts to a stimulus of a given frequency
- Below 500 Hz, CB is about 90 Hz
- Above 500 Hz, about 19% of the center frequency
- Ex: @1000 Hz: CB is 190 Hz, so the portion of the basilar membrane "tuned" to [905, 1095] Hz will "fire" when a sound has energy in that band

Critical bandwidth (CB)

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membrane
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membrane “tur
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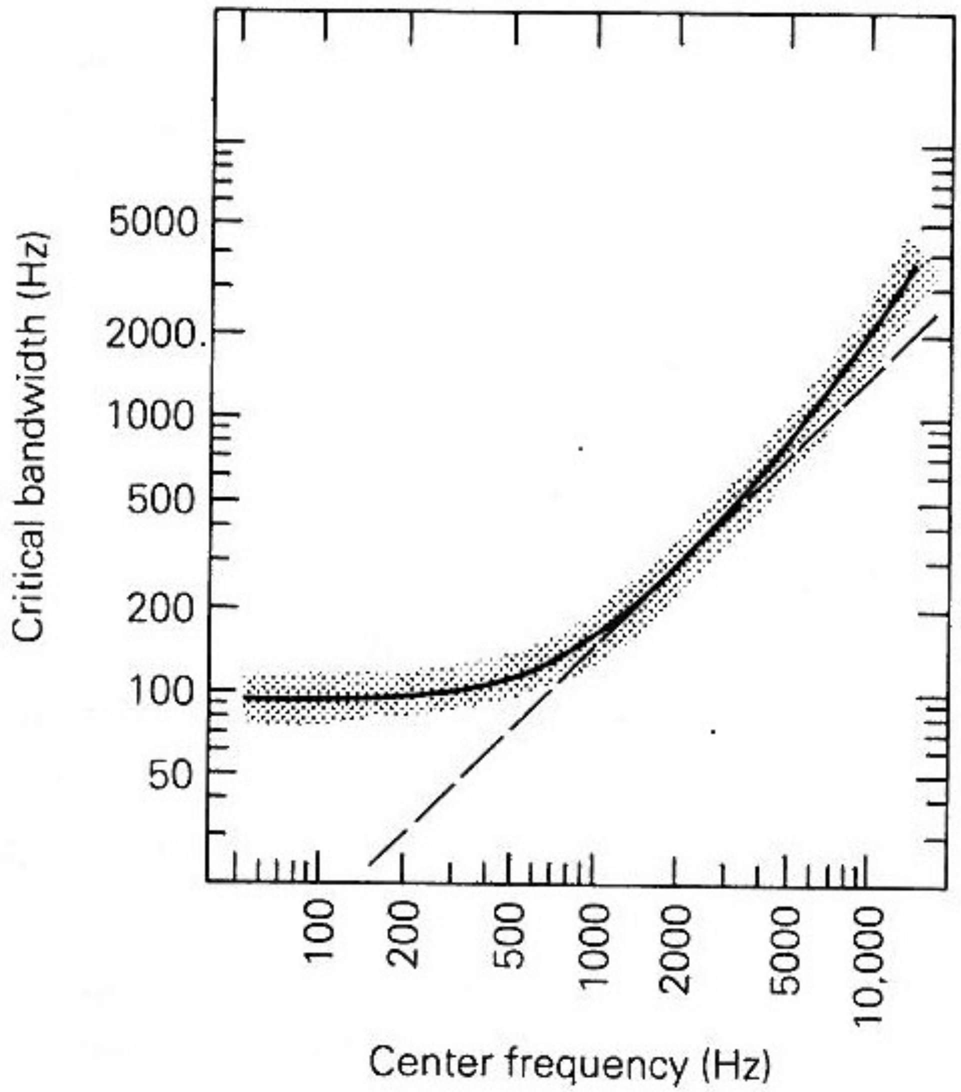
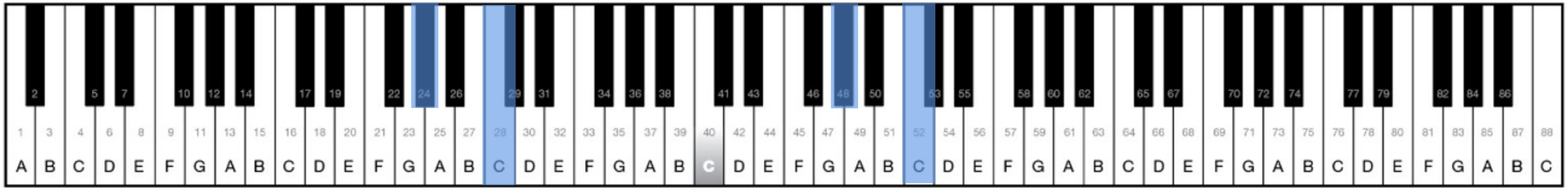
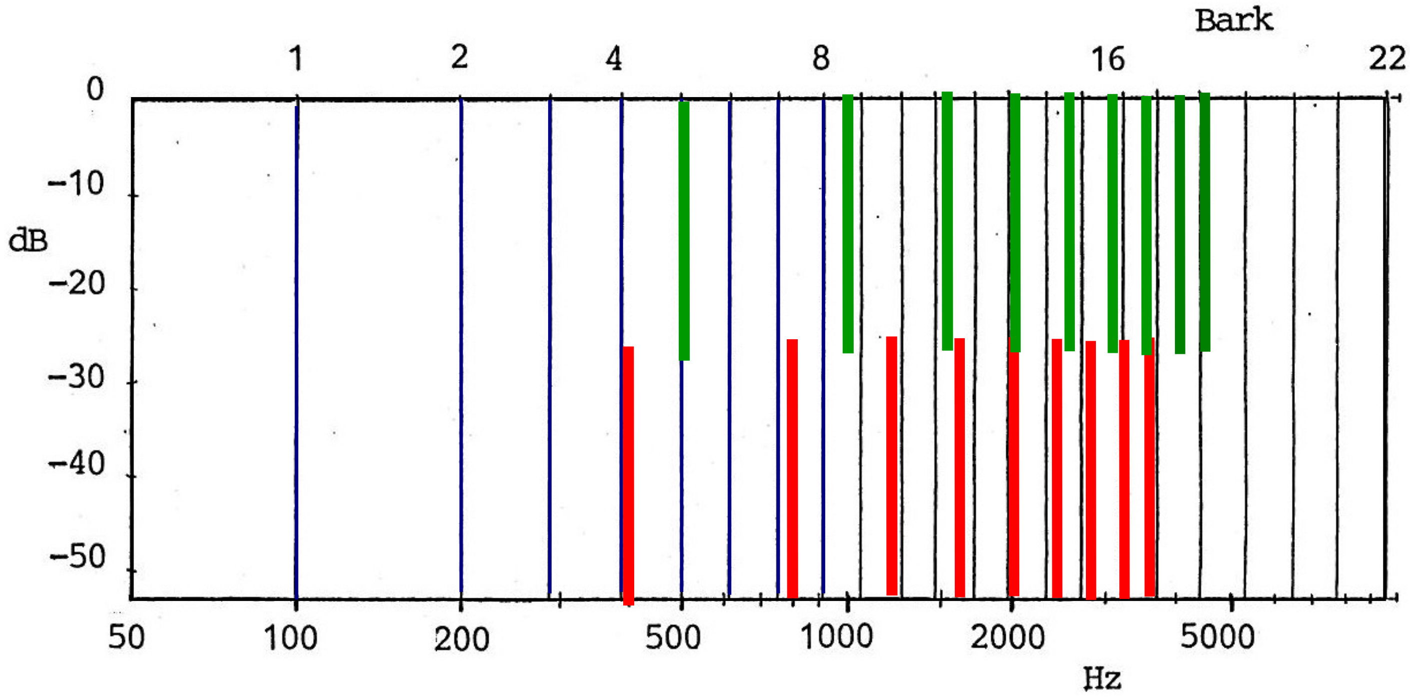


Consider two simple chords on the piano

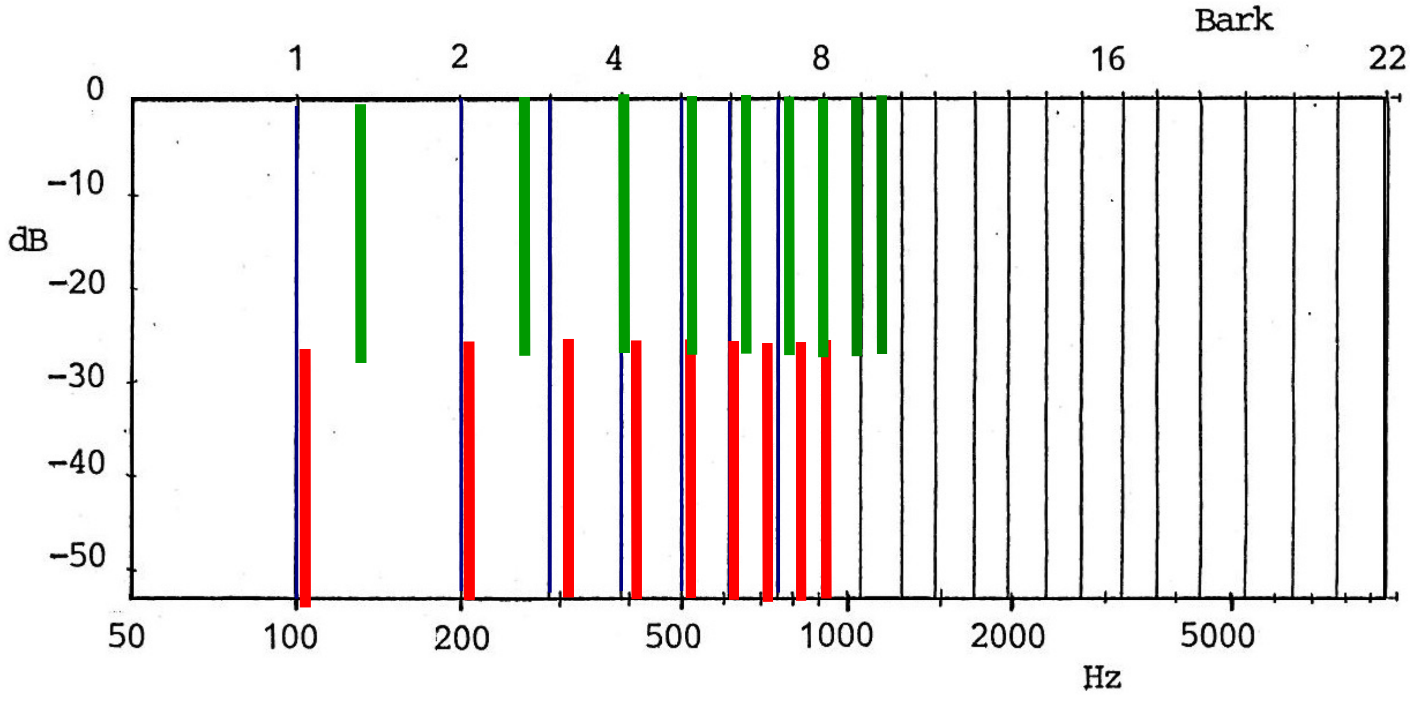


Perceptual roughness



If we play on a piano the pitches G#4 & C5 simultaneously, the harmonics (red and green bars, respectively) coincide (harmonious) and there is about one harmonic per critical band.

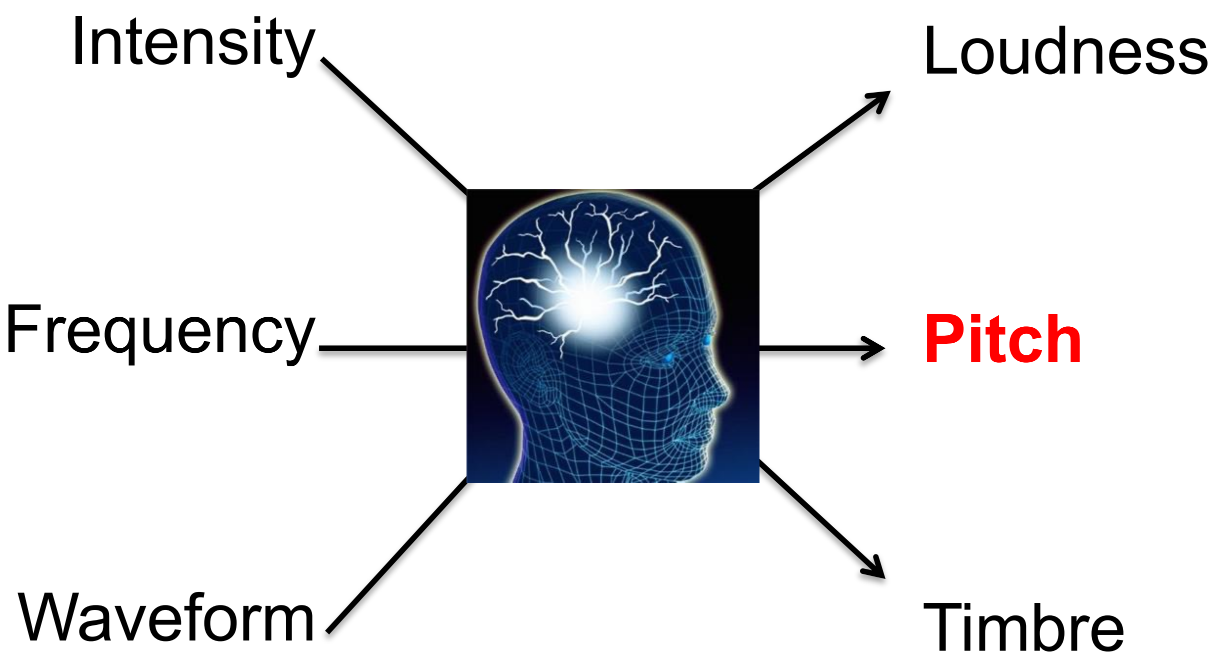
Perceptual roughness



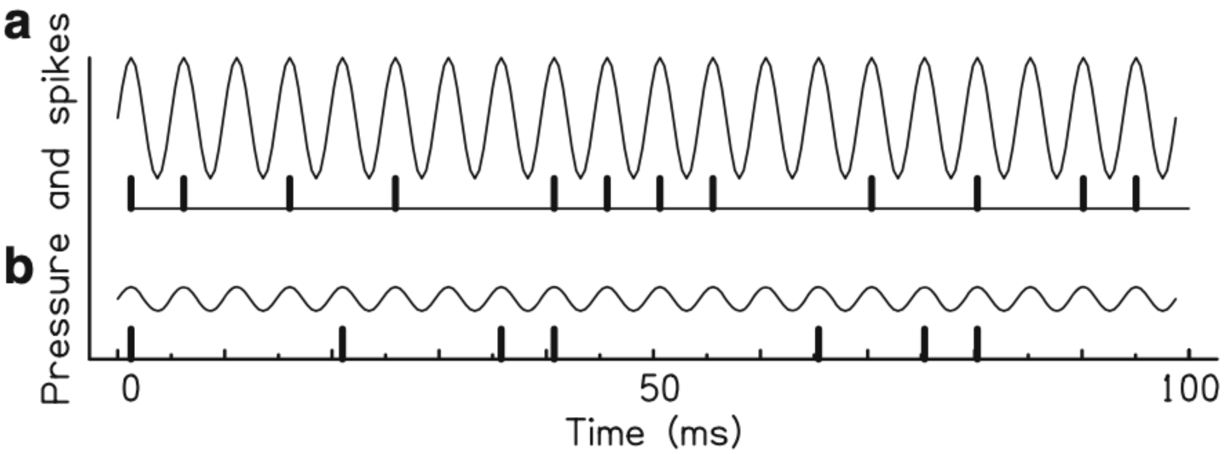
If we play on a piano the pitches G#2 and C3 simultaneously, the harmonics (red and green bars, respectively) coincide (harmonious) and there is two or more harmonics per critical band.

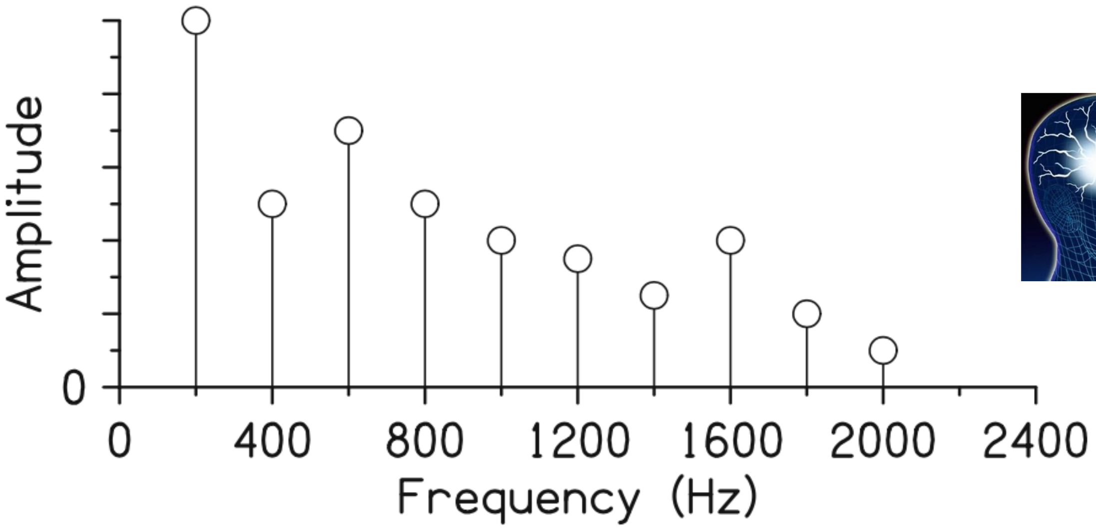
Attributes of sound

Physical *Perceptual*



Hair cells fire in synchronous ways

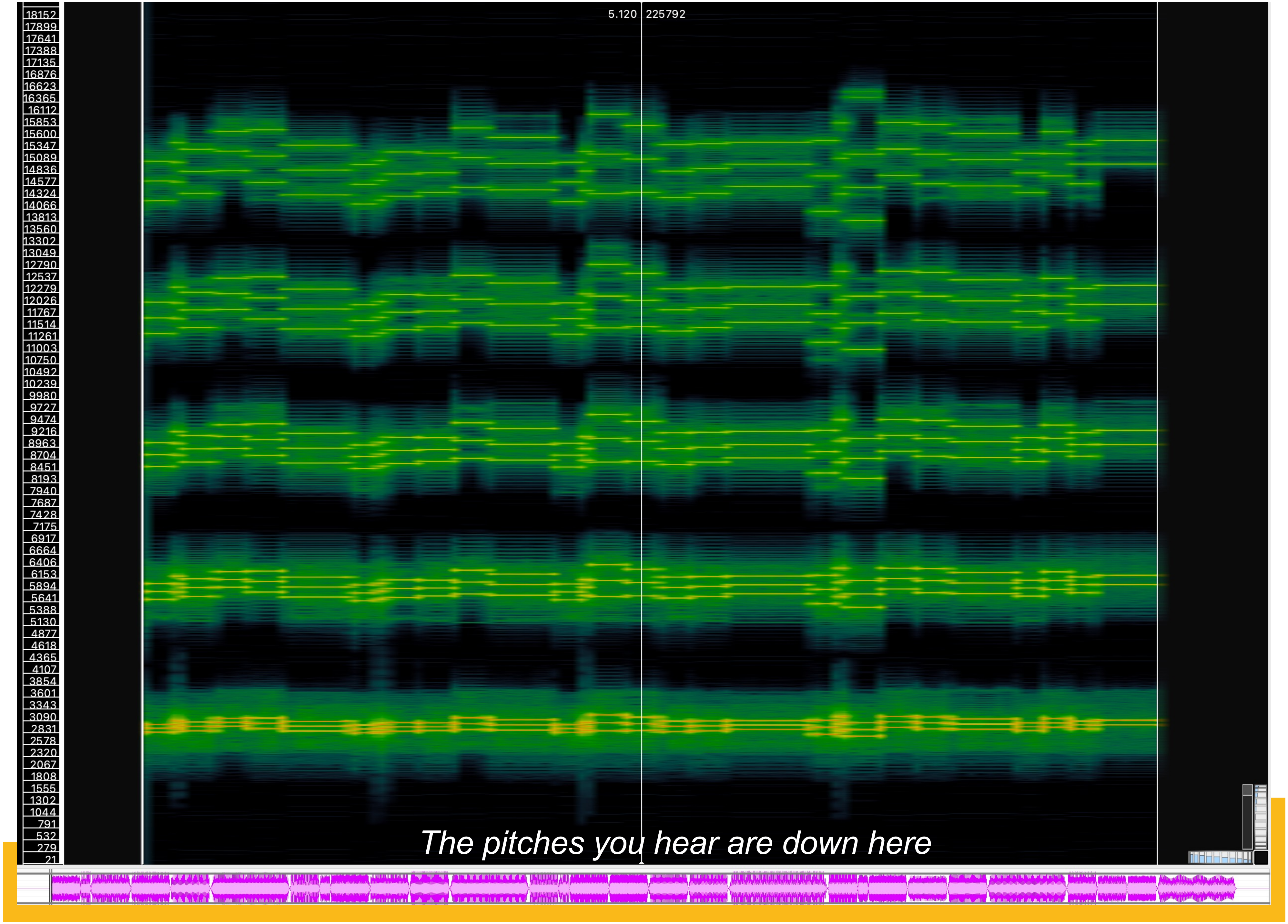




Pitch perceived has fundamental 200 Hz ≈ G3

https://pages.mtu.edu/~suits/notefreqs.html

An auditory illusion



18152
17899
17641
17388
17135
16876
16623
16365
16112
15853
15600
15347
15089
14836
14577
14324
14066
13813
13560
13302
13049
12790
12537
12279
12026
11767
11514
11261
11003
10750
10492
10239
9980
9727
9474
9216
8963
8704
8451
8193
7940
7687
7428
7175
6917
6664
6406
6153
5894
5641
5388
5130
4877
4618
4365
4107
3854
3601
3343
3090
2831
2578
2320
2067
1808
1555
1302
1044
791
532
279
21
5.120
225792
The pitches you hear are down here

Florian Hecker

”Hallucination, Perspective, Synthesis” (2017)

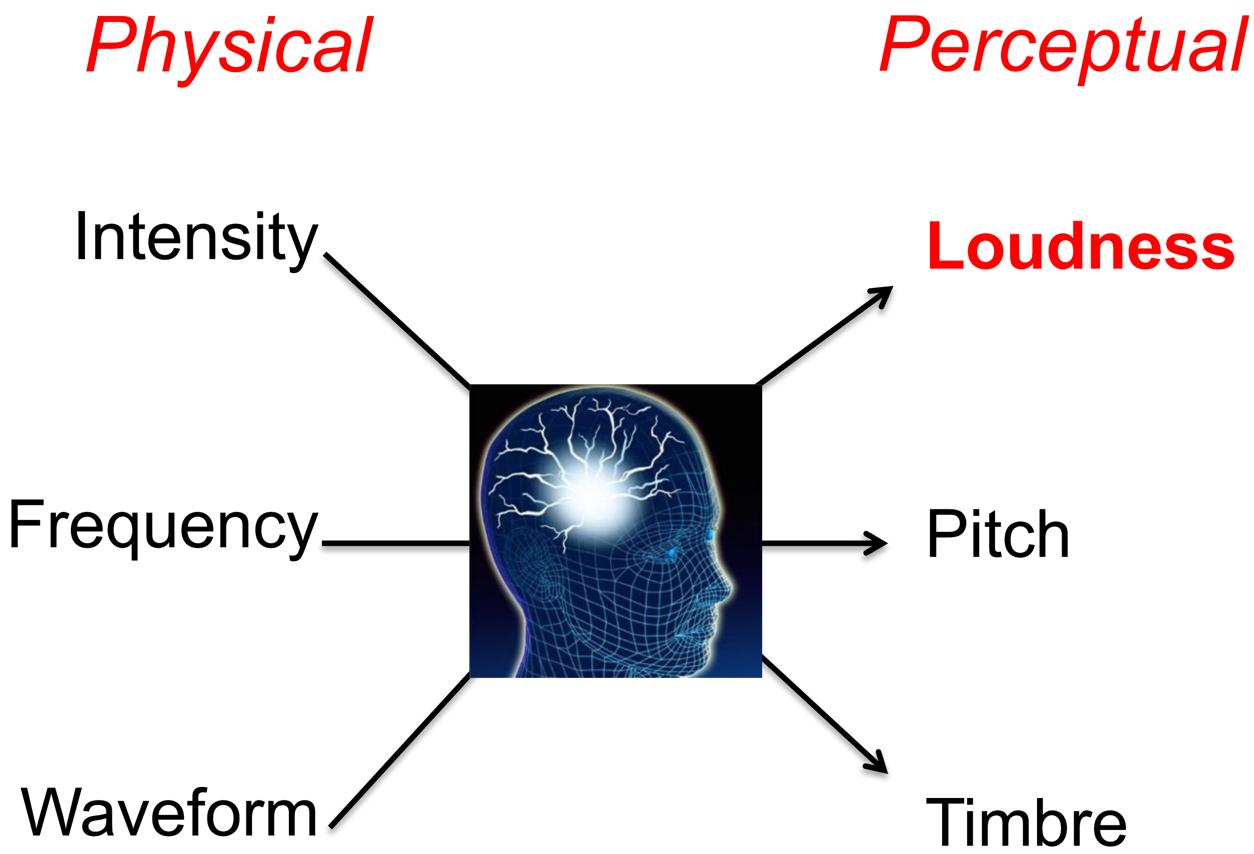
https://youtu.be/-5TUQy3AjCs

Maryanne Amacher

Chorale (1999)

https://youtu.be/nAXlF0n5XAg

Attributes of sound

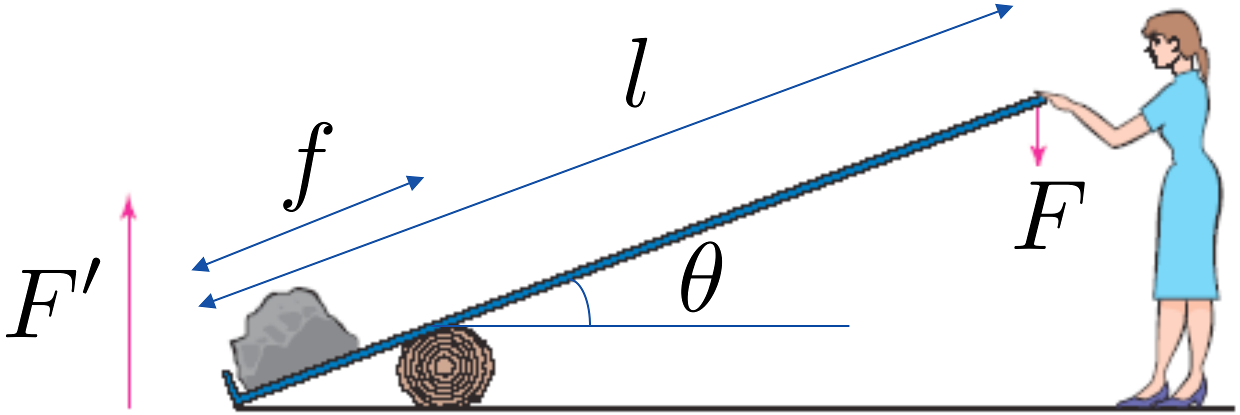


Sound intensity

$$dB = 20 \log_{10}(p/p_0)$$
$$dB = 10 \log_{10}(I/I_0)$$

Sound Sources Examples with distance	Sound Pressure Level L_p dBSPL	Sound Pressure p N/m^2 = Pa	Sound Intensity I W/m^2
Jet aircraft, 50 m away	140	200	100
Threshold of pain	130	63.2	10
Threshold of discomfort	120	20	1
Chainsaw, 1 m distance	110	6.3	0.1
Disco, 1 m from speaker	100	2	0.01
Diesel truck, 10 m away	90	0.63	0.001
Kerbside of busy road, 5 m	80	0.2	0.0001
Vacuum cleaner, distance 1 m	70	0.063	0.00001
Conversational speech, 1 m	60	0.02	0.000001
Average home	50	0.0063	0.0000001
Quiet library	40	0.002	0.00000001
Quiet bedroom at night	30	0.00063	0.000000001
Background in TV studio	20	0.0002	0.0000000001
Rustling leaves in the distance	10	0.000063	0.00000000001
Threshold of hearing	0	0.00002	0.000000000001

The physics of the lever



Recall:

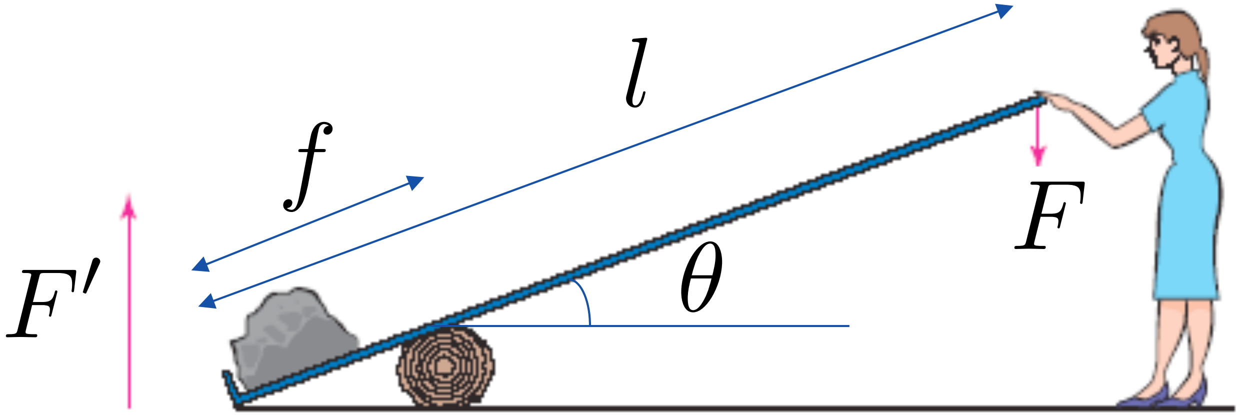
$$P' = P\frac{l-f}{f}\frac{A}{A'}, l > f > 0$$

For the human ear ≈ 1.3 ≈ 20

Therefore $P' \approx 26P$

How does this relate to dB?

The physics of the lever (in dB)



$$dB = 20\log_{10}(p/p_0) = 20\log_{10}(26) \approx 30$$

$$10\log_{10}(I/I_0) = 30$$

$$\log_{10}(I/I_0) = 3$$

$$I/I_0 = 10^3 = 1000$$

1 unit change to I_0 creates 1000 unit change in I

Sones and Phones: Units of loudness

Loudness of 1 **sone** defined as perceived loudness of 1 kHz sine wave at 40 dB sound level

- Doubling perceived loudness of a sound doubles its **sones**

The loudness of a sound in **phons** is the dB SPL of a 1 kHz sound that is just as loud

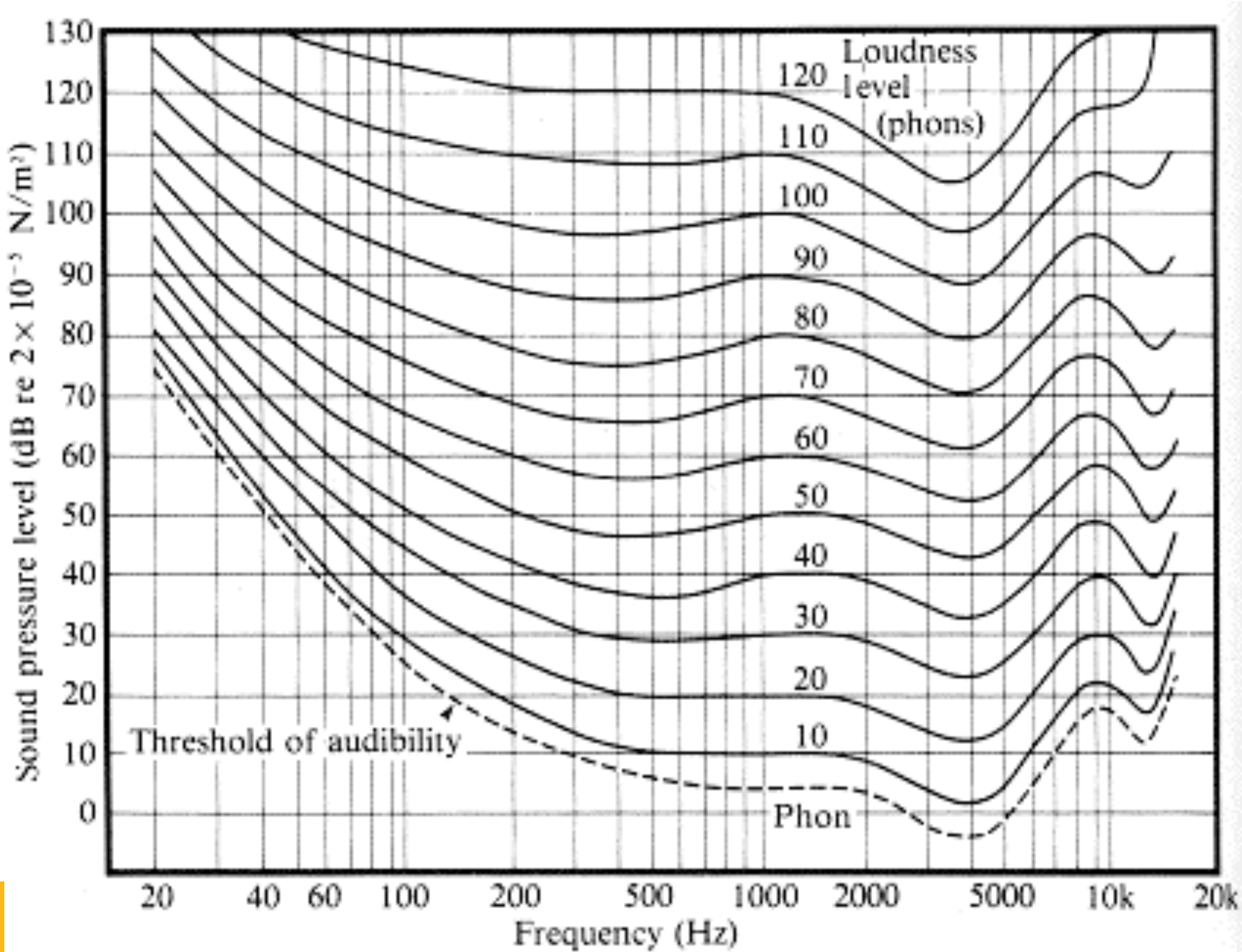
- Relative to pure tones

sone	1	2	4	8	16	32	64	128	256	512	1024
phon	40	50	60	70	80	90	100	110	120	130	140

Table of sones and relative SPLs

Description	Sound pressure	Sound pressure level	Loudness
	pascal	dB re 20 μPa	sone
Threshold of pain	~ 100	~ 134	**~ 676**
Hearing damage during short-term effect	~ 20	~ 120	**~ 256**
Jet, 100 m away	6 ... 200	110 ... 140	**128 ... 1024**
Jack hammer, 1 m away / nightclub	~ 2	~ 100	**~ 64**
Hearing damage during long-term effect	~ 6×10^{-1}	~ 90	**~ 32**
Major road, 10 m away	2×10^{-1} ... 6×10^{-1}	80 ... 90	**16 ... 32**
Passenger car, 10 m away	2×10^{-2} ... 2×10^{-1}	60 ... 80	**4 ... 16**
TV set at home level, 1 m away	~ 2×10^{-2}	~ 60	**~ 4**
Normal talking, 1 m away	2×10^{-3} ... 2×10^{-2}	40 ... 60	**1 ... 4**
Very calm room	2×10^{-4} ... 6×10^{-4}	20 ... 30	**0.15 ... 0.4**
Rustling leaves, calm breathing	~ 6×10^{-5}	~ 10	**~ 0.02**
Auditory threshold at 1 kHz	2×10^{-5}	0	**0**

Fletcher Munson Curves



Just noticeable differences (JND)

Consider the following experiment:

For i=1:100+

- Present two stimuli to a subject, where difference between them is a Δ change of an independent variable (e.g., frequency, intensity)
- Ask subject whether stimuli are different or not in that variable

The Δ such that subject is correct half of the time is *the just noticeable difference*

JND for human auditory system

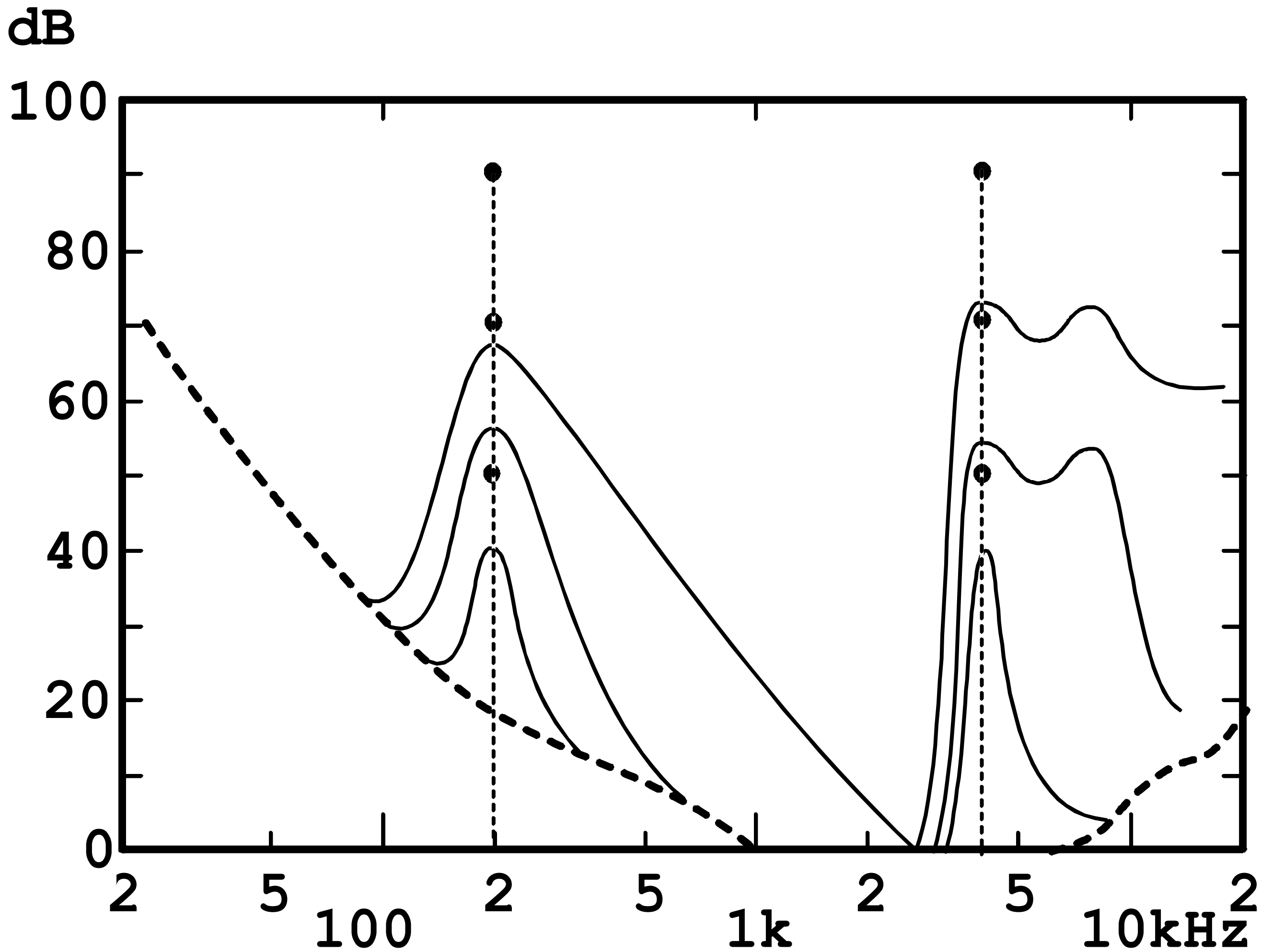
JND for Frequency:

- About 1 Hz for frequencies below 1 kHz
- Greater than f/500 Hz (4 Hz) for frequencies above 2 kHz

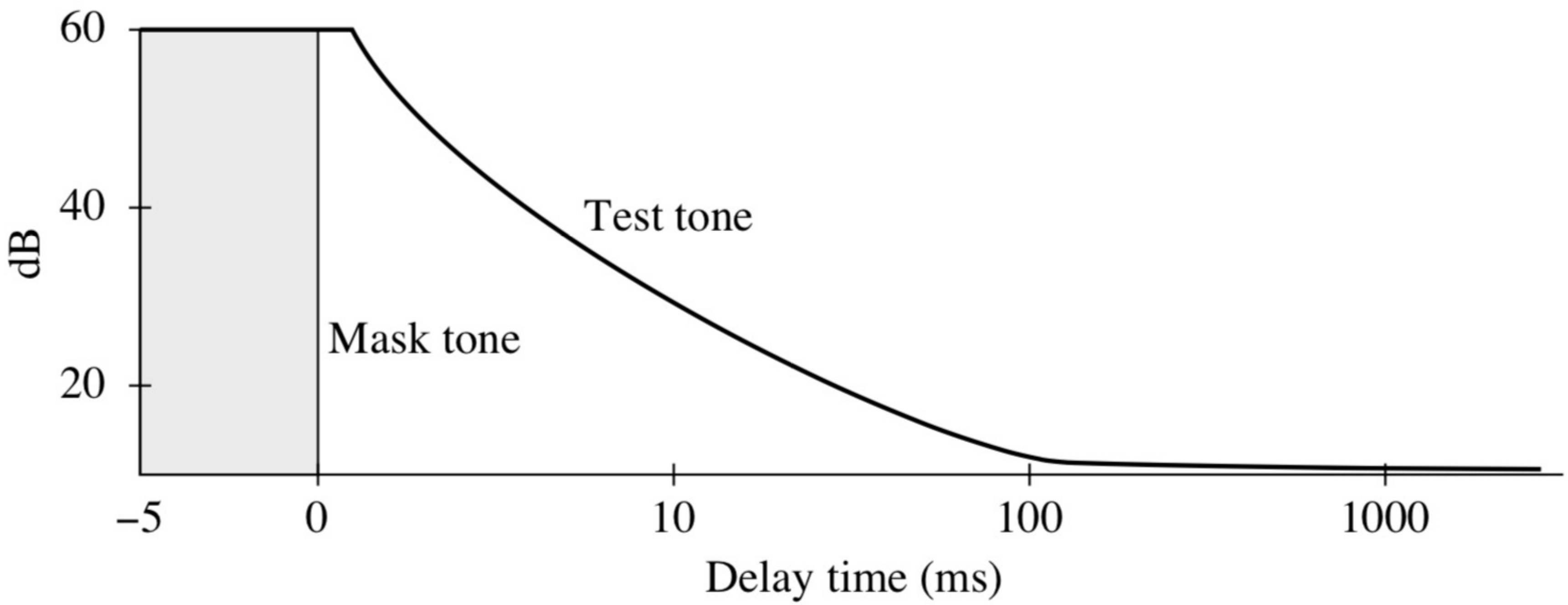
JND for Intensity:

- About 1 dB for intensities between 40–60 dB

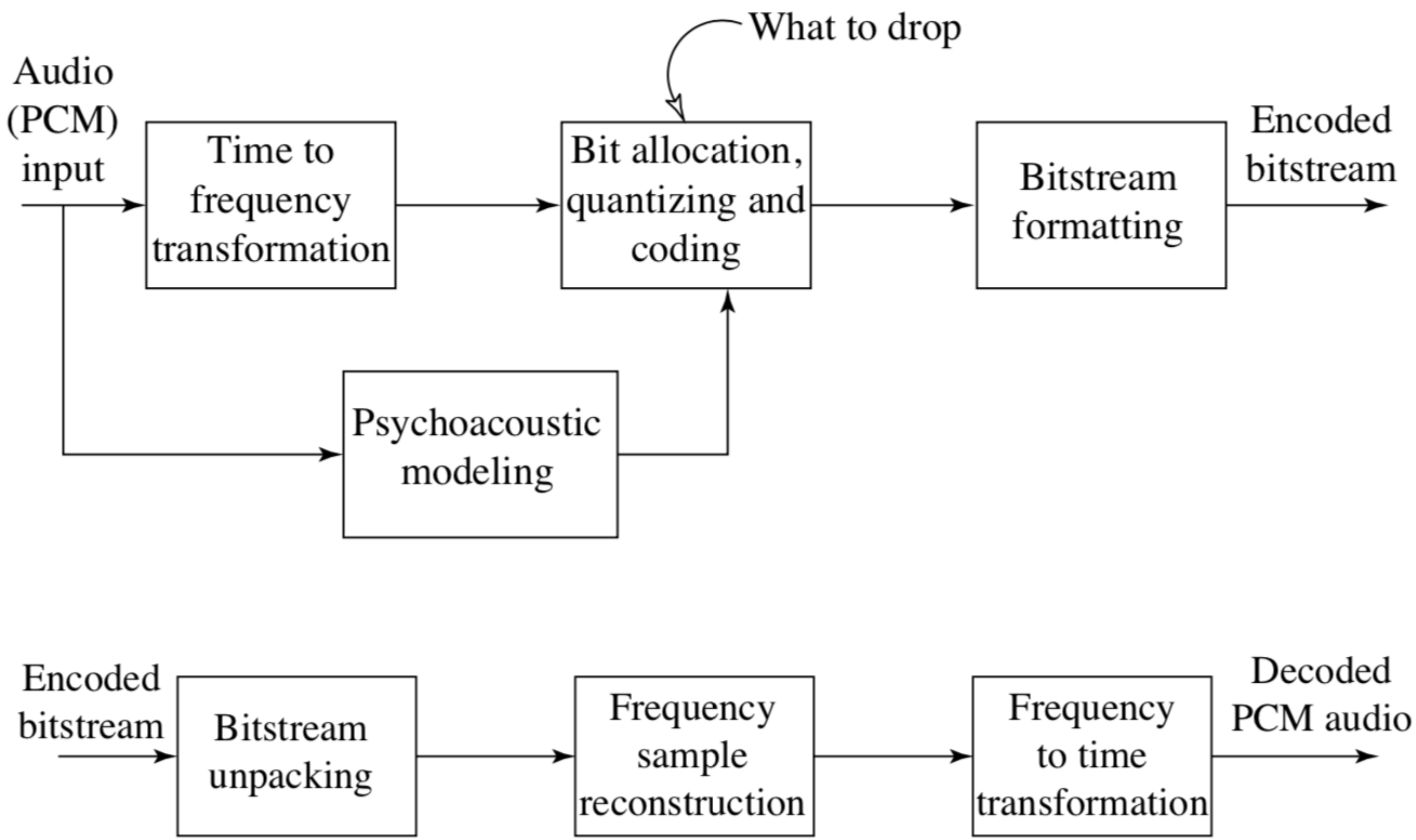
Frequency masking phenomenon



Temporal masking phenomenon



MP3 Perceptual Audio Encoding!



Attributes of sound

Physical | *Perceptual*

Intensity → Loudness

Frequency → Pitch

Waveform → **Timbre**

Timbre

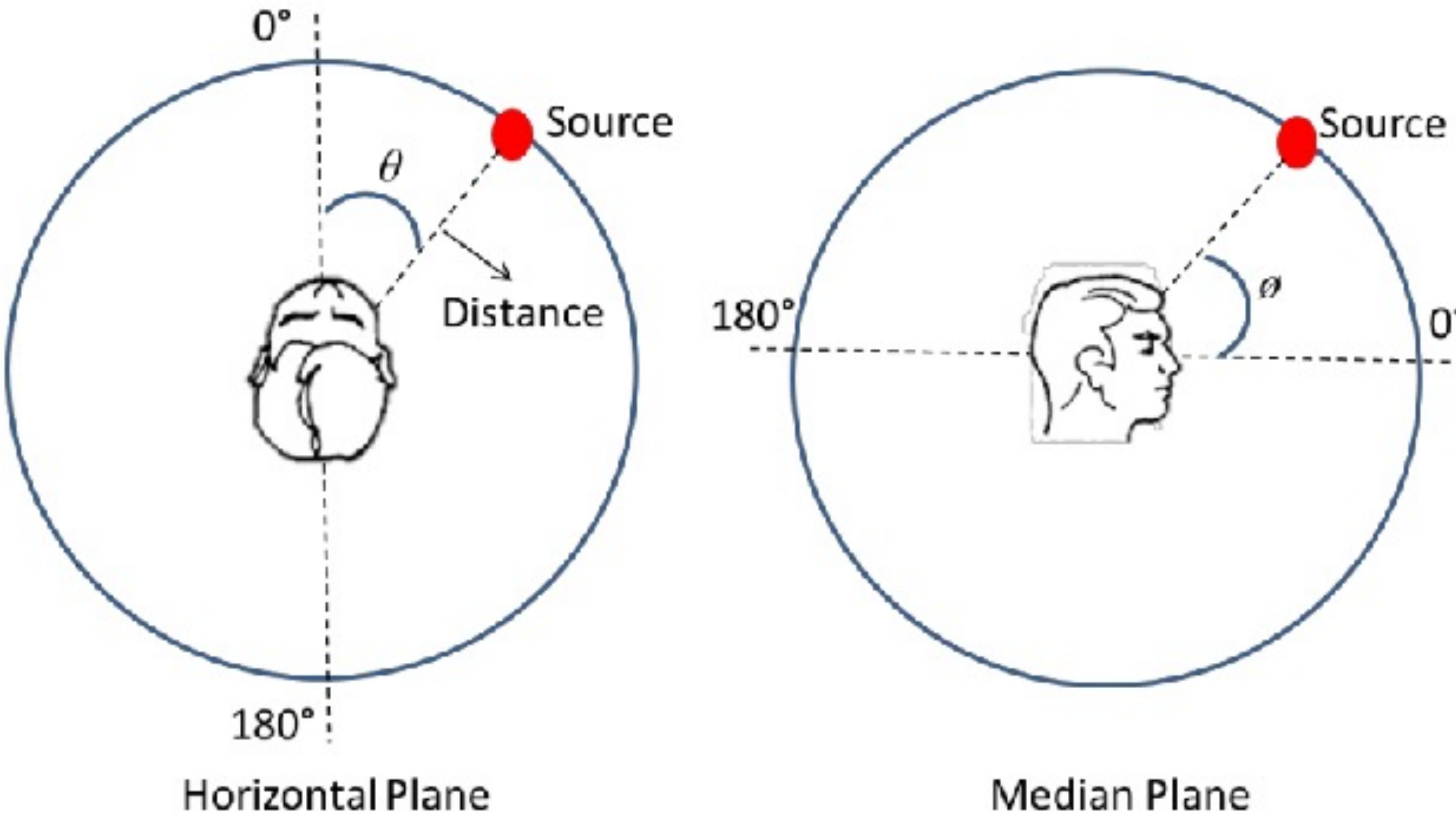
Tone color, tone quality -> *instrument recognition*

Acoustical Terminology definition 12.09 of Acoustical Society of America defines **timbre**:

- “That attribute of auditory sensation which enables a listener to judge that two nonidentical sounds, similarly presented and having the same loudness and pitch, are dissimilar”
- "Timbre depends primarily upon the frequency spectrum, although it also depends upon the sound pressure and the temporal characteristics of the sound"

Examples of different timbres

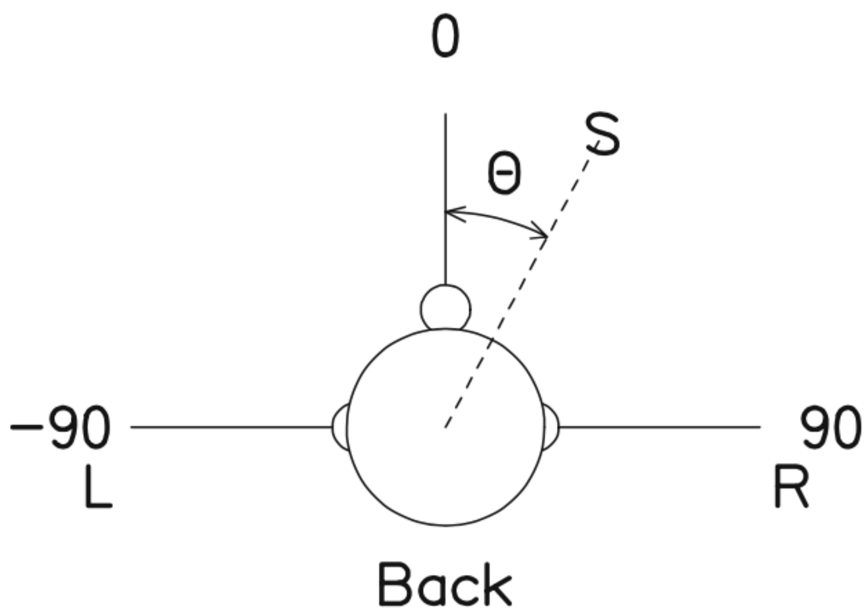
Localization



How do we localize sound horizontally?

In the horizontal plane:

- Interaural level differences
- Interaural time differences



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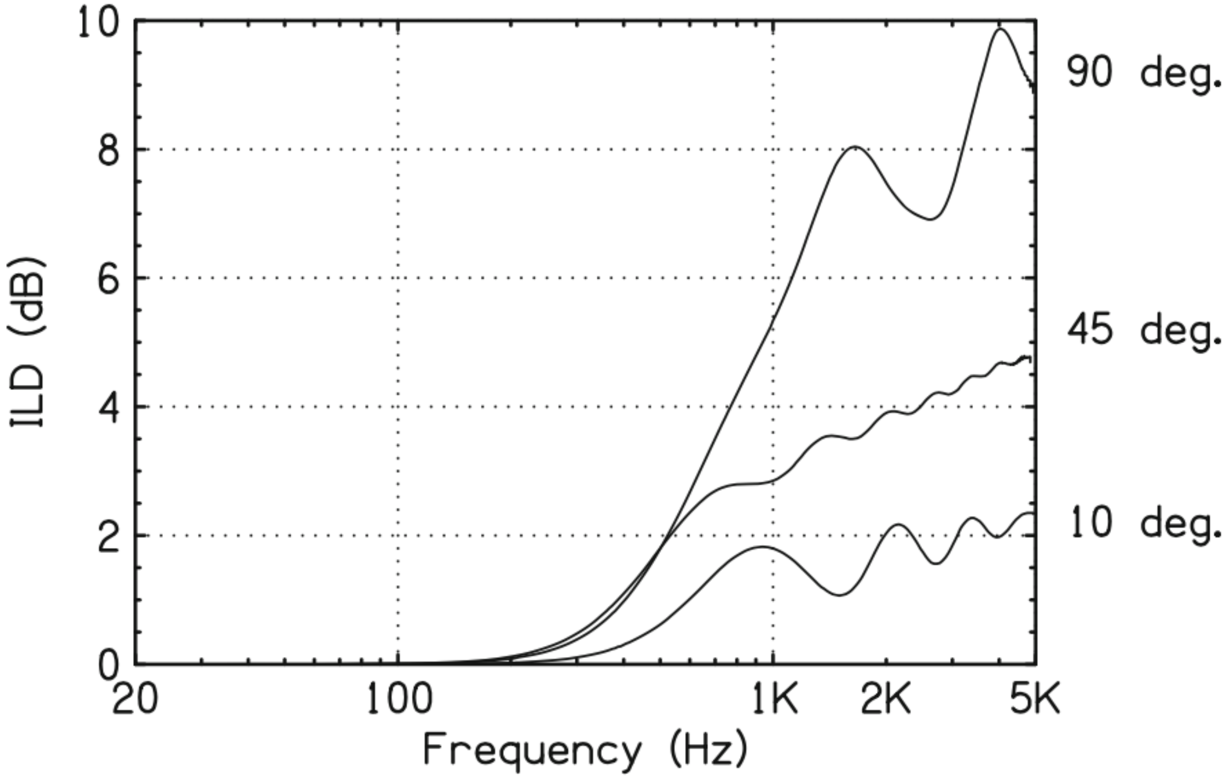

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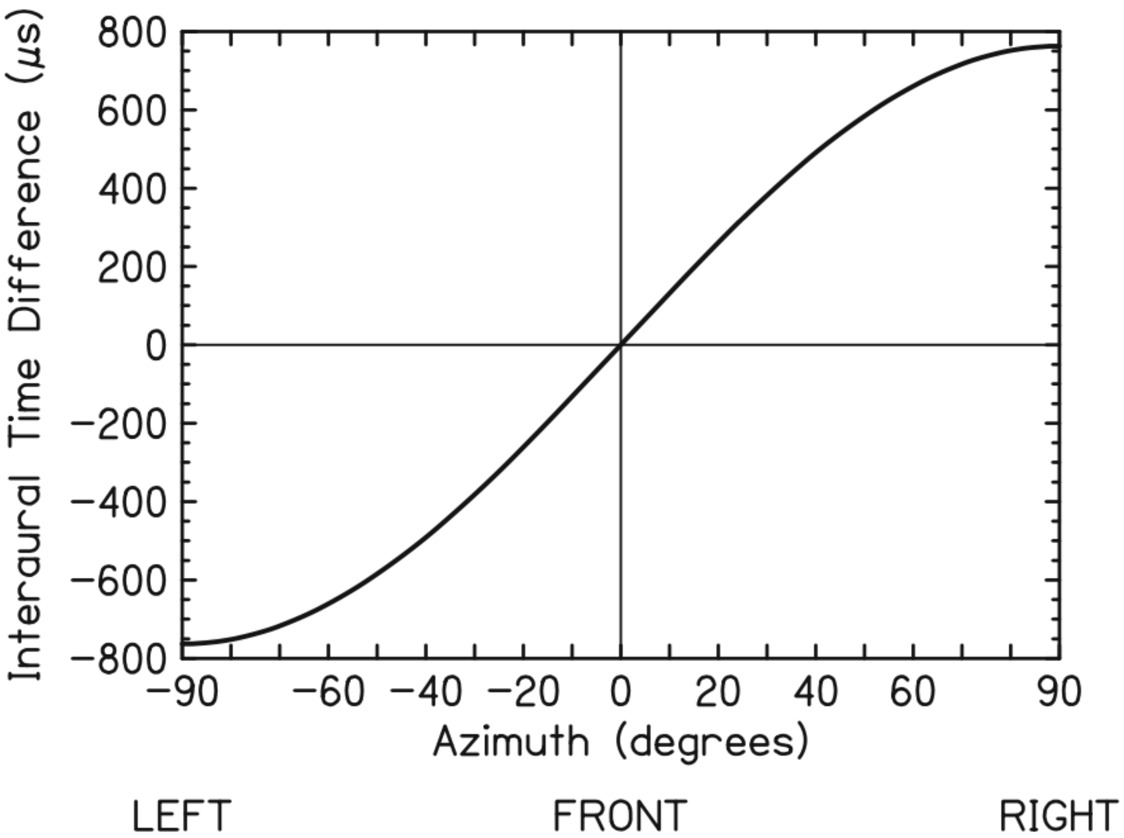
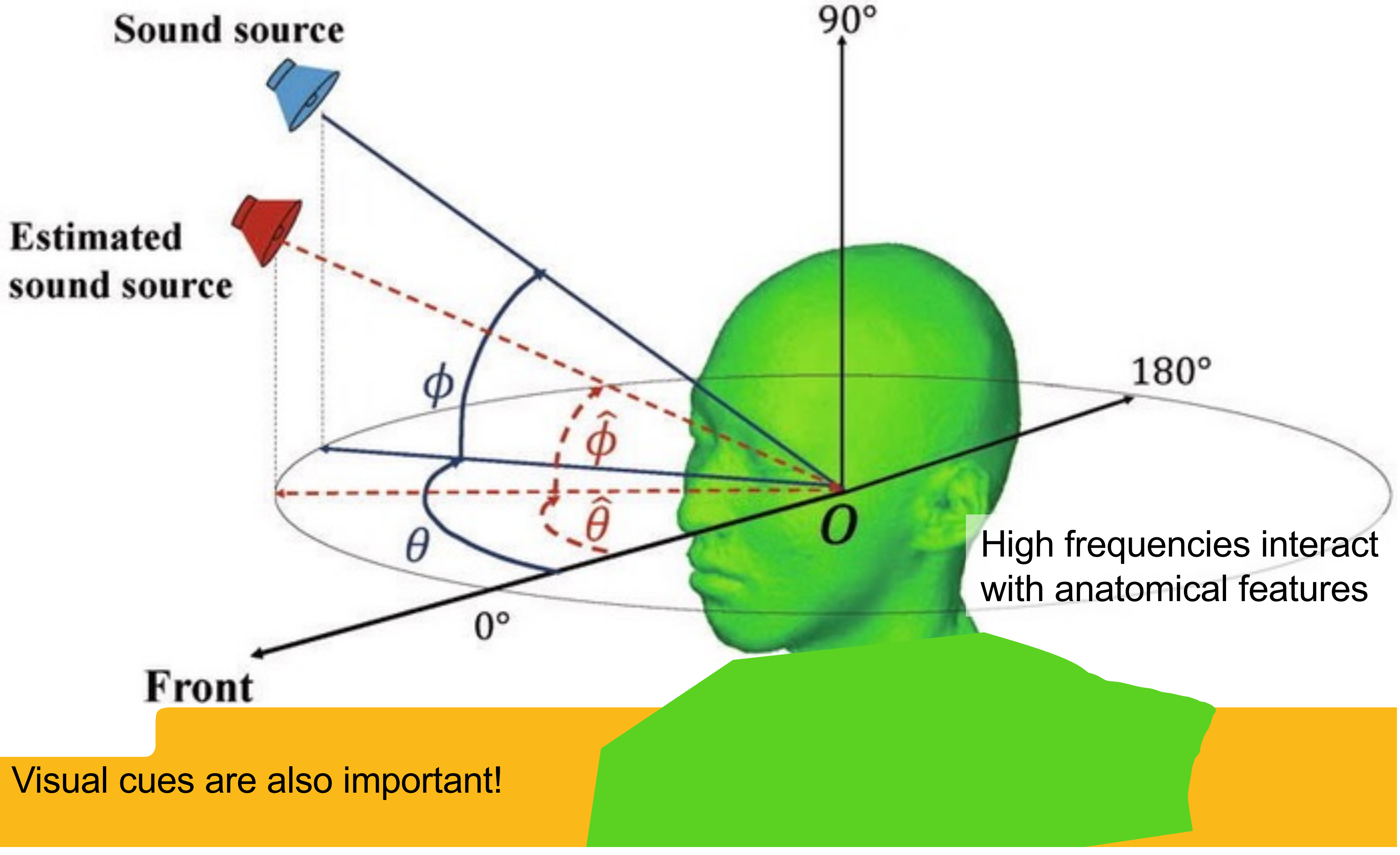


How do we localize sound vertically?



High frequencies interact with anatomical features

Visual cues are also important!

Question:

How do we know if a baby's hearing is functioning normally?

The ear is not passive!

Otoacoustic emissions (OAE)

- Sound generated from within inner ear!
- Between 500 – 4500 Hz at -30–+10 dB SPL

Healthy ears produce OAE, spontaneously or by external stimulation

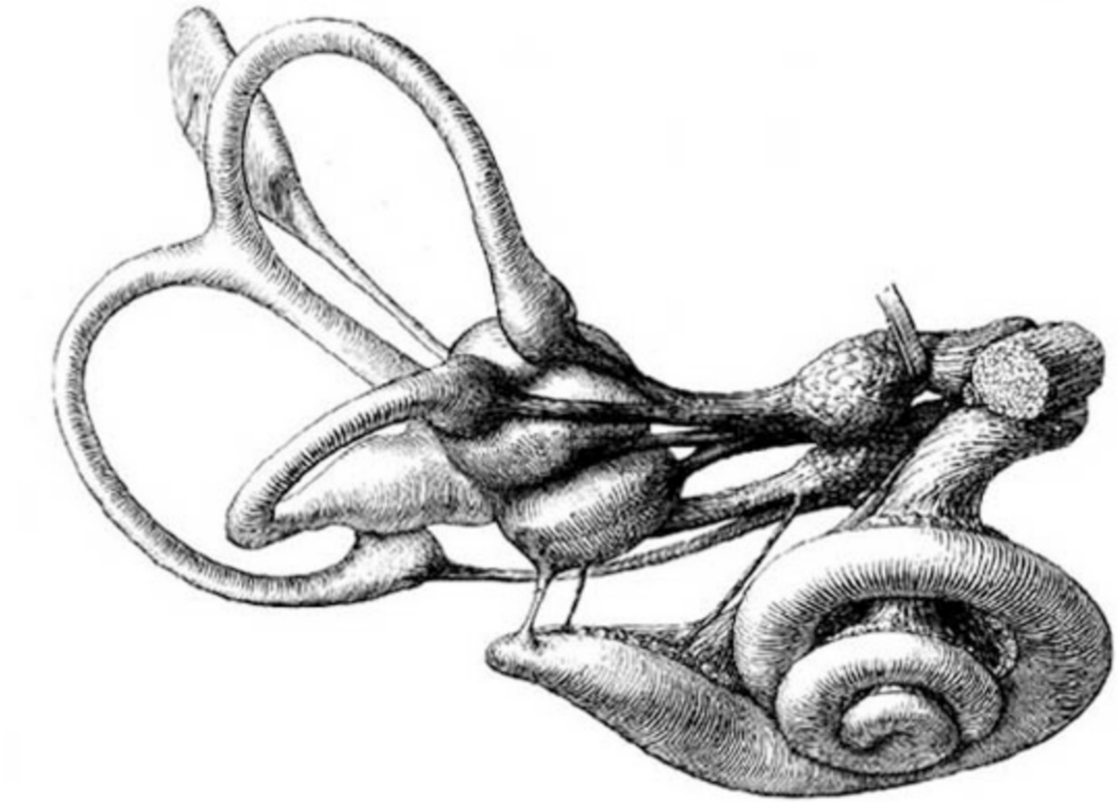
Otoacoustic emissions music

LABYRINTHITIS

4- or 16-channel composition / sound installation (2007) 40-minutes. Commissioned by- and first performed at the Medical Museion, Copenhagen, Denmark. Limited release of the composition on Touch (2008)

Labyrinthitis works with otoacoustic emissions generated by the artist's ears to produce otoacoustic emissions in the ears of the listeners

The 16 speakers were installed on metal rods of varying lengths to create a 3-dimensional ascending spiral hanging from the dome ceiling of a former operating theatre in the museum



Jacob Kirkegaard, http://www.fonik.dk/works/labyrinthitis.html

https://youtu.be/c1w8Y9XXF5E