Psychoacoustics

Fundamental Definitions

- **Acoustics**
  - branch of physics concerned with the study of sound/ science of sound
  - studies audibility and characteristics of sound propagation (typically in a closed space (room); reverberation, etc)
- **Psychoacoustics**
  - branch of science studying the psychological and physiological responses associated with sound (including noise, speech and music). It can be further categorized as a branch of psychophysics which aims at **linking perception of acoustical stimuli with auditory sensations**

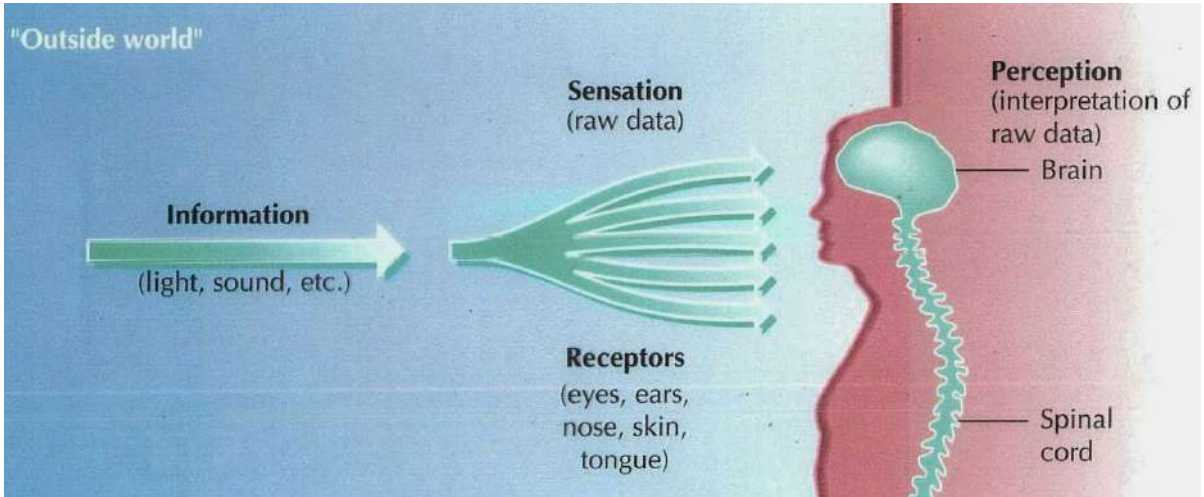
Fundamental Question of Psychoacoustics

- how do certain perceptual qualities of sound depend on the physical properties of sound?

SENSATION **?** PERCEPTION

SENSATION

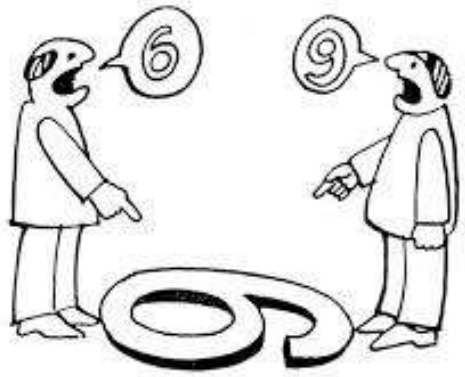
- gathering info from the environment via your senses (ex: visual, auditory, etc) and transmit them to the brain
- sensory information that has registered in the brain but has not been interpreted



PERCEPTION

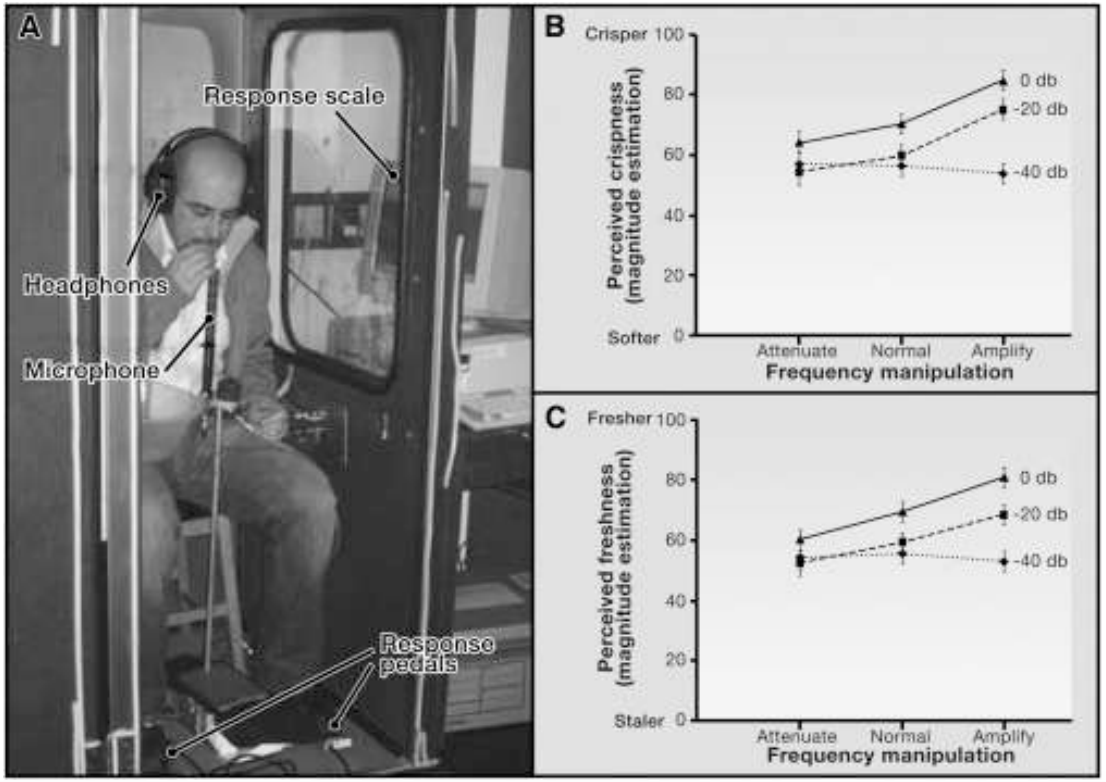
the ILLUSION *of* REALITY

- process by which sensory information is actively organized and interpreted by the brain
- understanding what is being sensed
- integration of multiple sensory streams (eg: audio + visual)



Example: Crossmodal Phenomena

The “Sonic Chip” Experiment



Zampini, M., & Spence, C. (2004). The role of auditory cues in modulating the perceived crispness and staleness of potato chips. Journal of Sensory Studies, 19, 347–363.

Example: Crossmodal Phenomena

http://www.sbs.com.au/food/4-heston-experiments-try-home

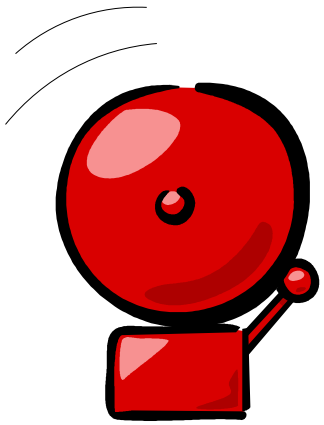
Digital Seasoning??!!!


SENSATION

What is sound?

- a vibration that typically propagates as a wave of pressure, through a transmission medium such as air, water or other materials.

Medium	Speed (m/s)
Air (+20°C)	343
Carbon dioxide 0°C	258
Helium	970
Water	1410
Steel	5100
Glass	3700-5000



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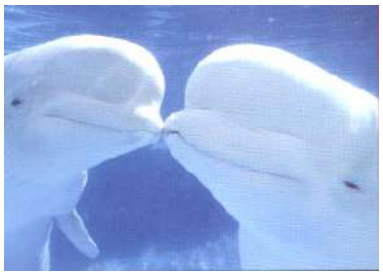

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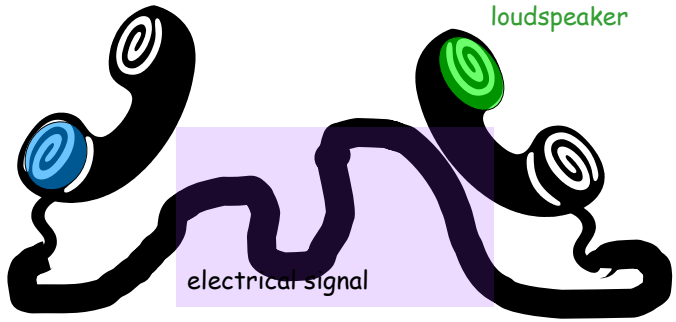
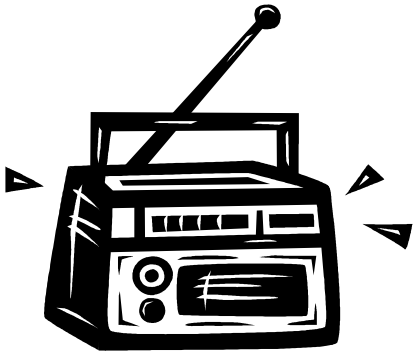
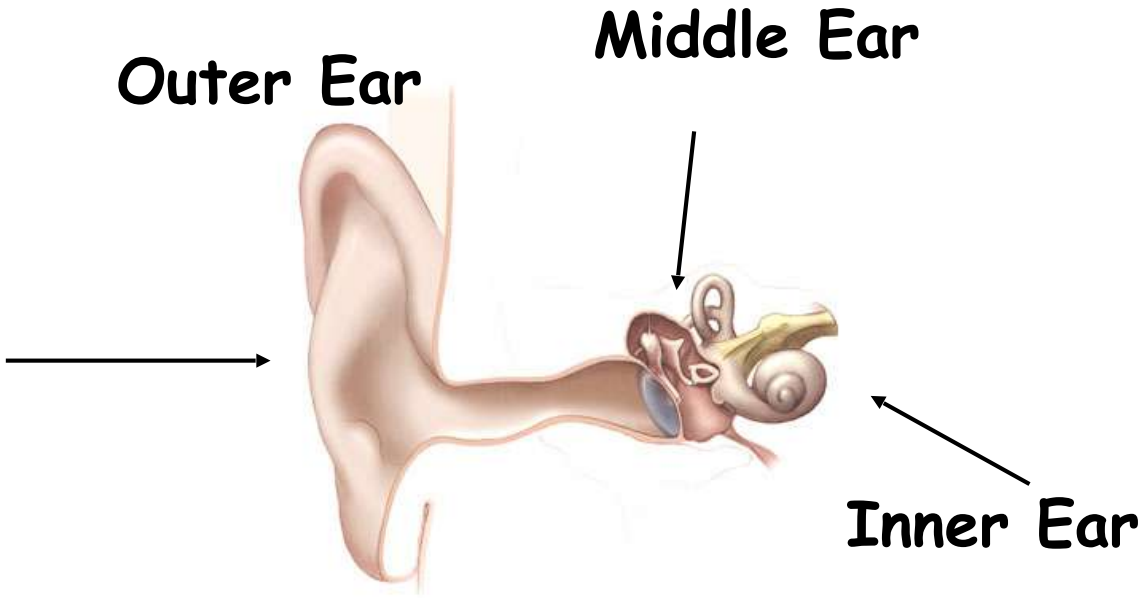
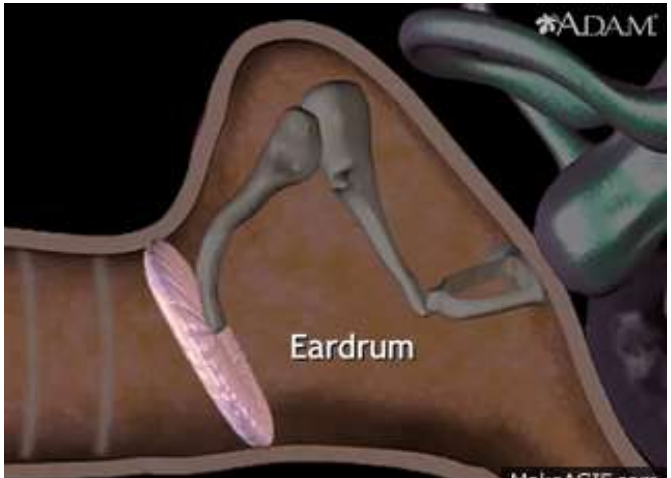


How do we sense sound?



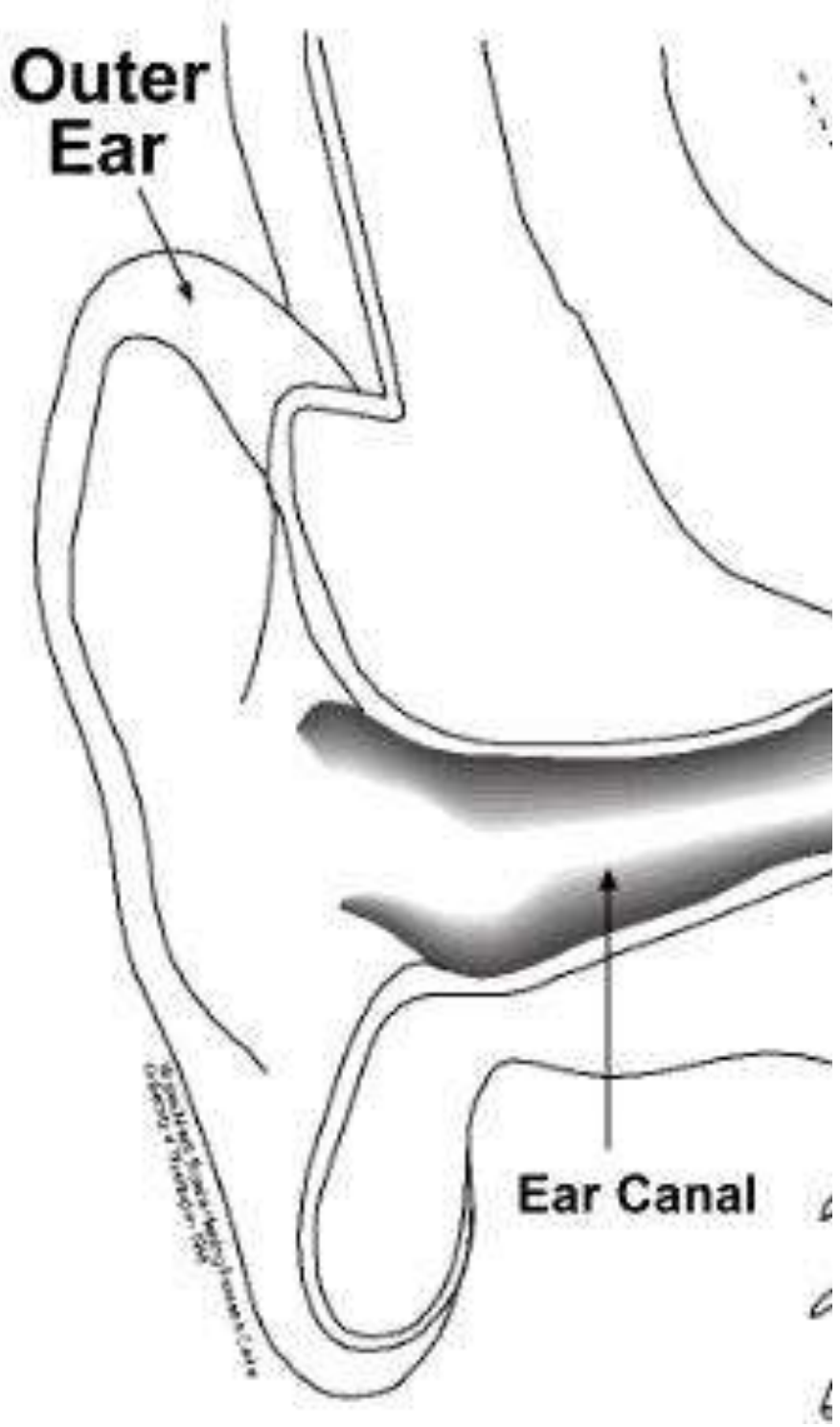
Sound Waves





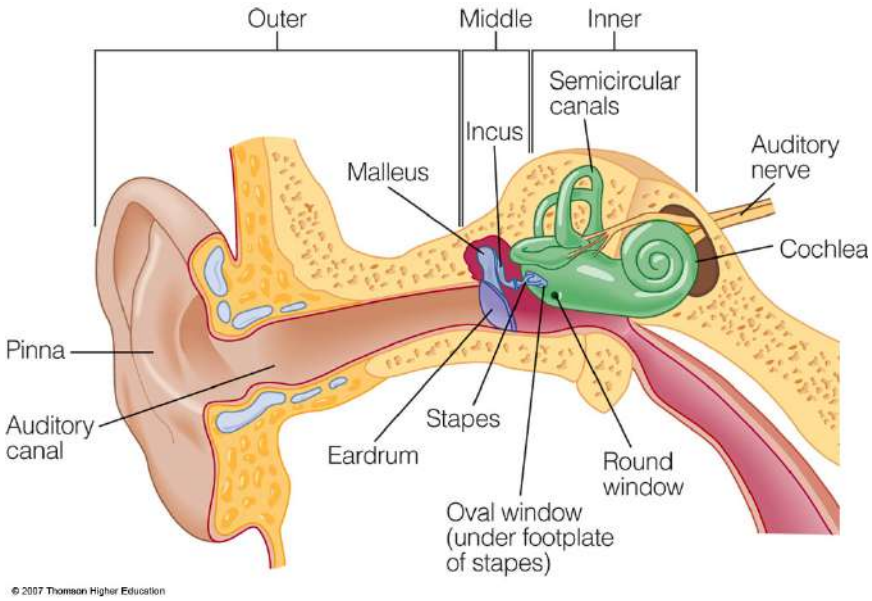
The Outer Ear

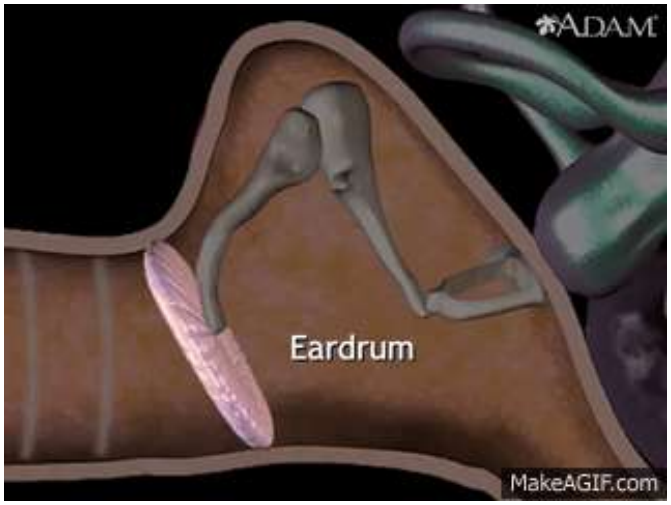
- The curved formation on the outside (the pinna) helps funnel sound down the ear canal to the eardrum



The Middle Ear

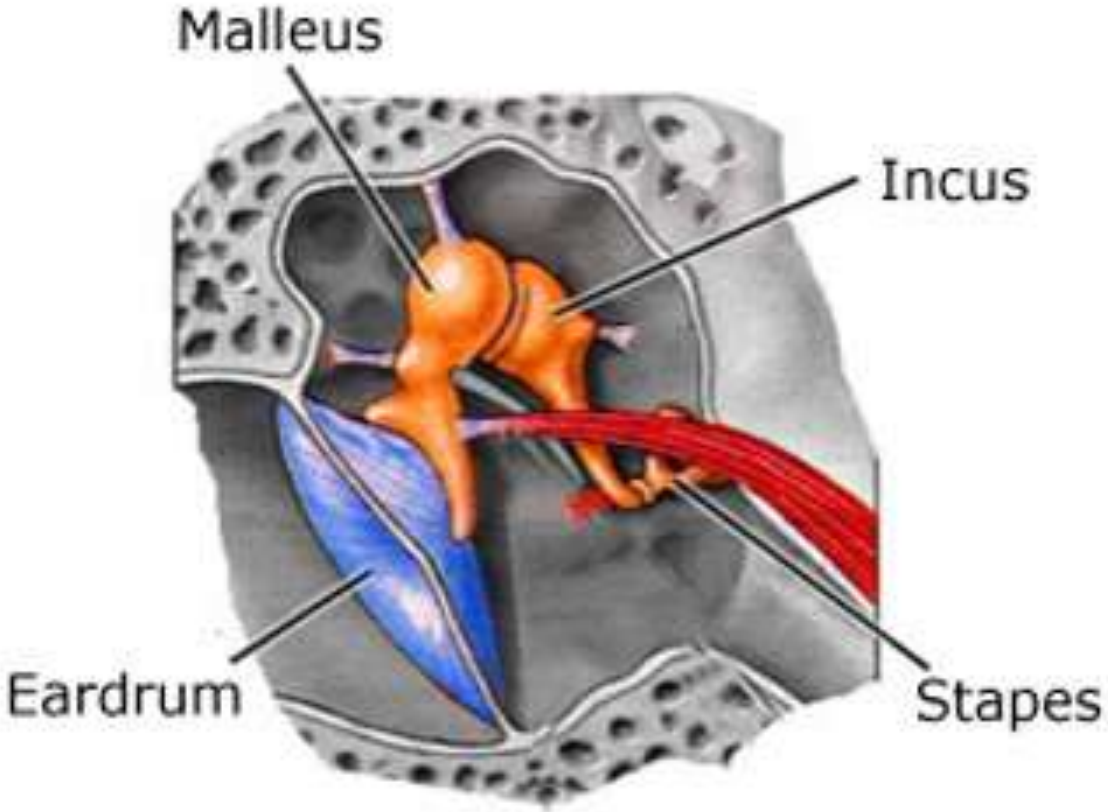
- transfers the energy of a sound wave by vibrating the three bones found there.
- ossicles are arranged and interact with each other as a lever system
- **amplifier** - without them, only about 0.1 percent of sound energy would make it into the inner ear.





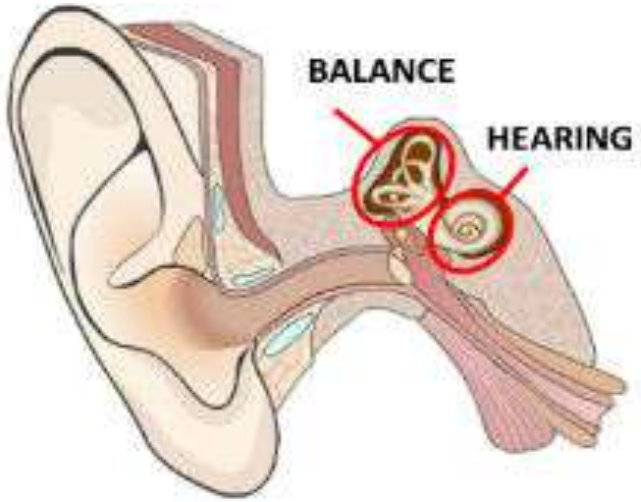
Bones of the Middle Ear

- These are the smallest bones in your body!



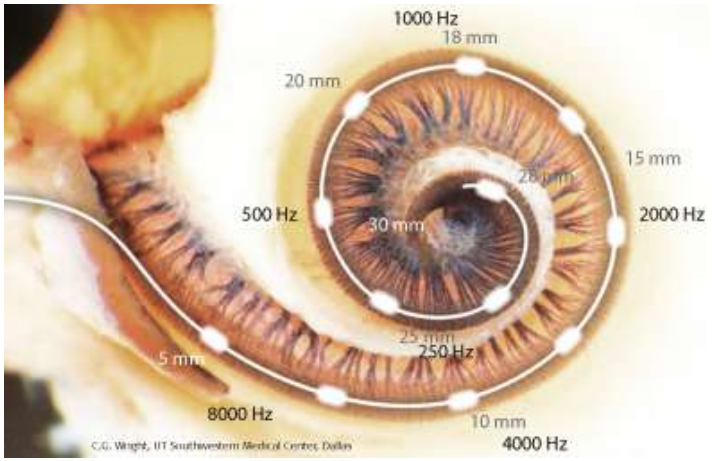
The Inner Ear

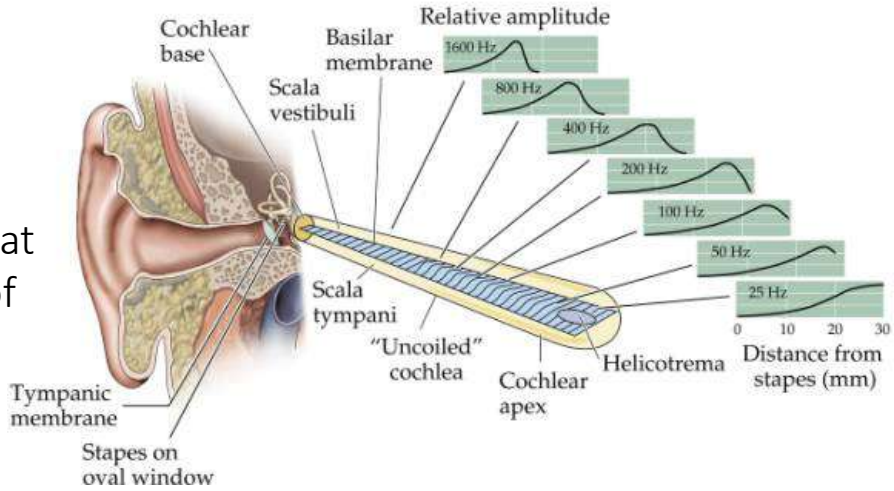
- Two main parts:
  - **Vestibular system** (**balance**) - Semicircular Canals- Fluid filled tubes attached to the cochlea that help us maintain our sense of balance
  - **Cochlea** (**hearing**) converting sound pressure patterns from the outer ear into electrochemical impulses which are passed on to the brain via the auditory nerve.



The Inner Ear

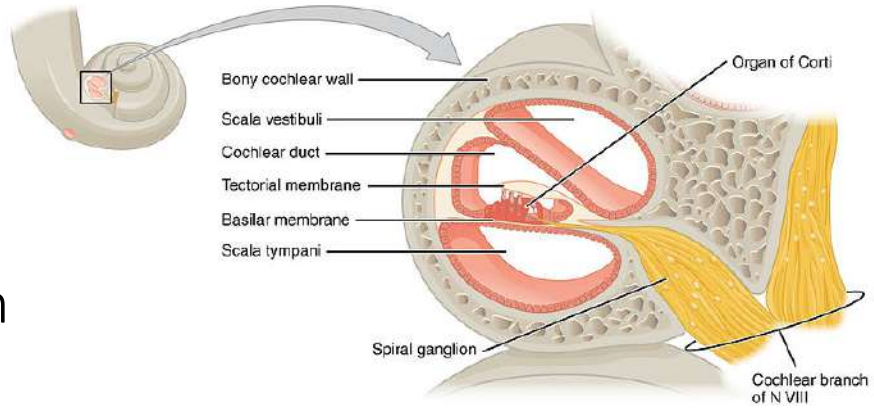
- **Cochlea**
  - Coiled like a snail shell, fluid-filled; it is lined with cilia (tiny hair) that move when vibrated and cause a nerve impulse to form.
  - tonotopic map - a location code formed on the cochlea
- **Basilar membrane**
  - stiff long structural element varying in width and stiffness and bends rows of hair cells beneath it based on incoming signal
  - base for the sensory cells of hearing & acts as a frequency analyser
  - the front end (base) of the membrane to resonate with higher frequencies, and its rear end (apex) with lower frequencies
  - bending of the hair cells gives rise to electric impulses that encode information about the periodicity and intensity of the sound.

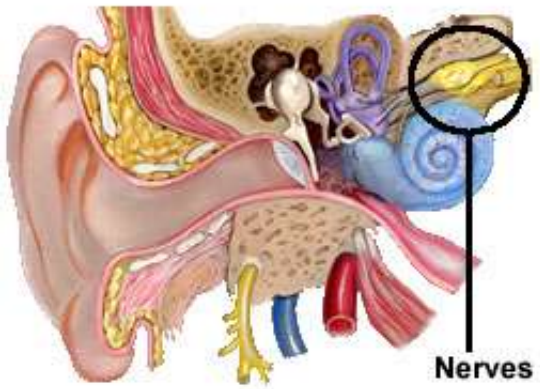




The Inner Ear

- **Organ of Corti**
  - contains auditory receptors that transduce auditory signals into nerve impulses' action potential
- **Auditory/Cochlear nerve**
  - these carry electro-chemical signals from the inner ear (the cochlea) to the brain.

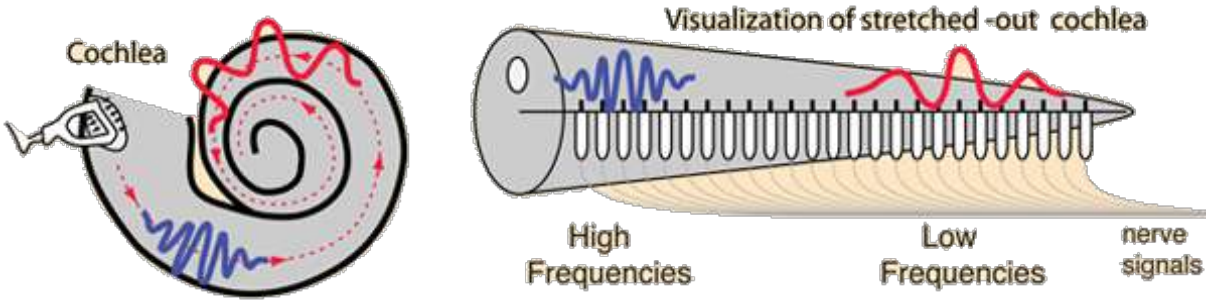


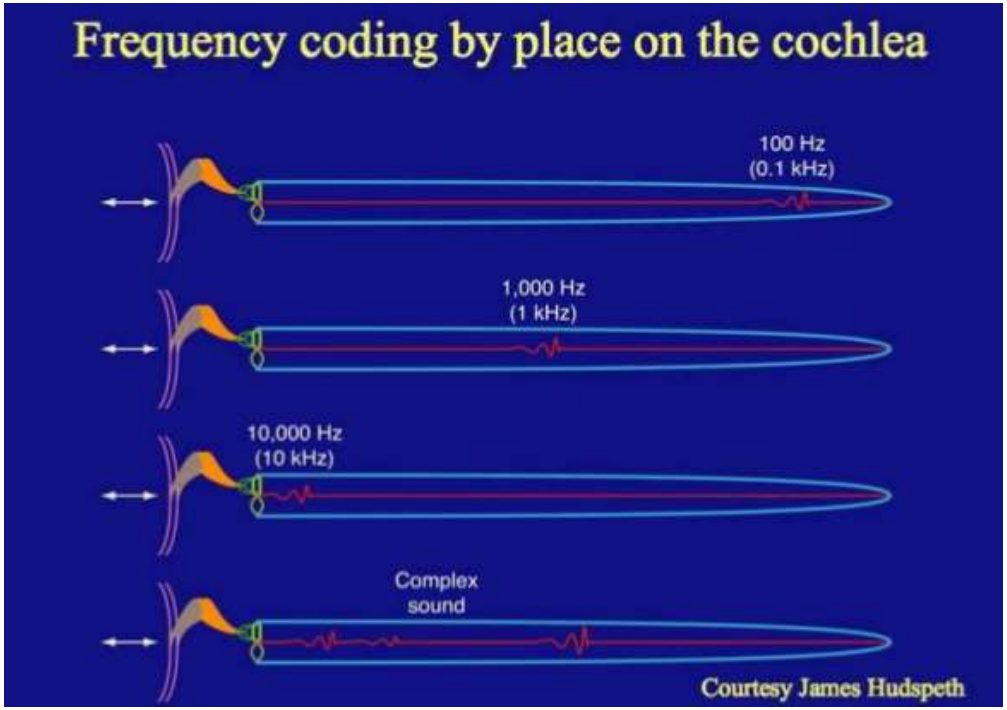


Theories of Hearing

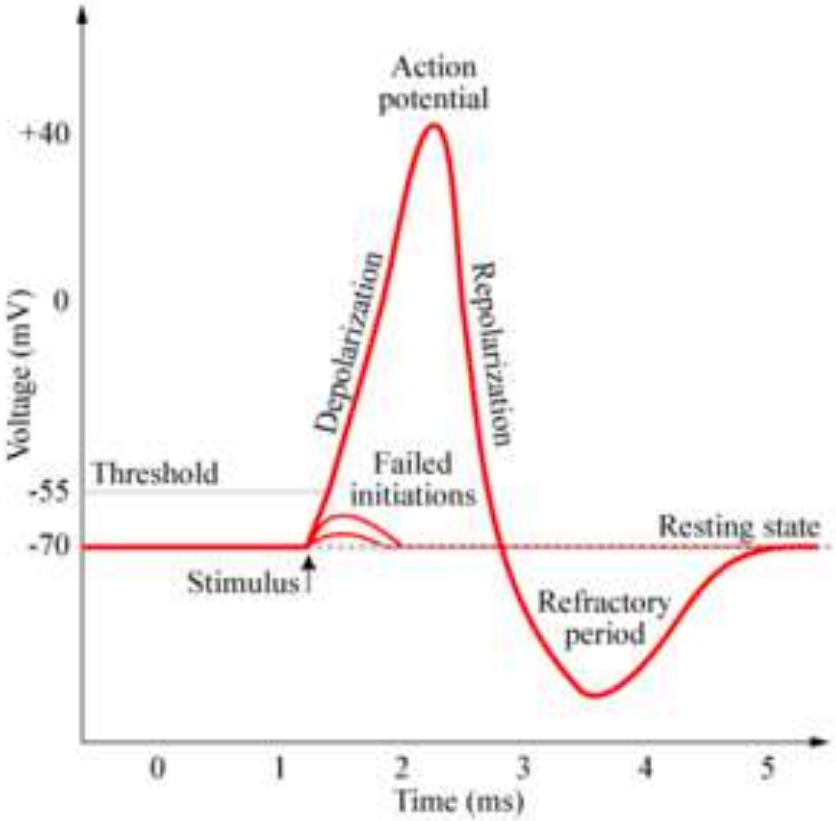
- **Place Theory**
  - encoded at different places on the basilar membrane
- **Temporal Theory**
- **Volley Theory**

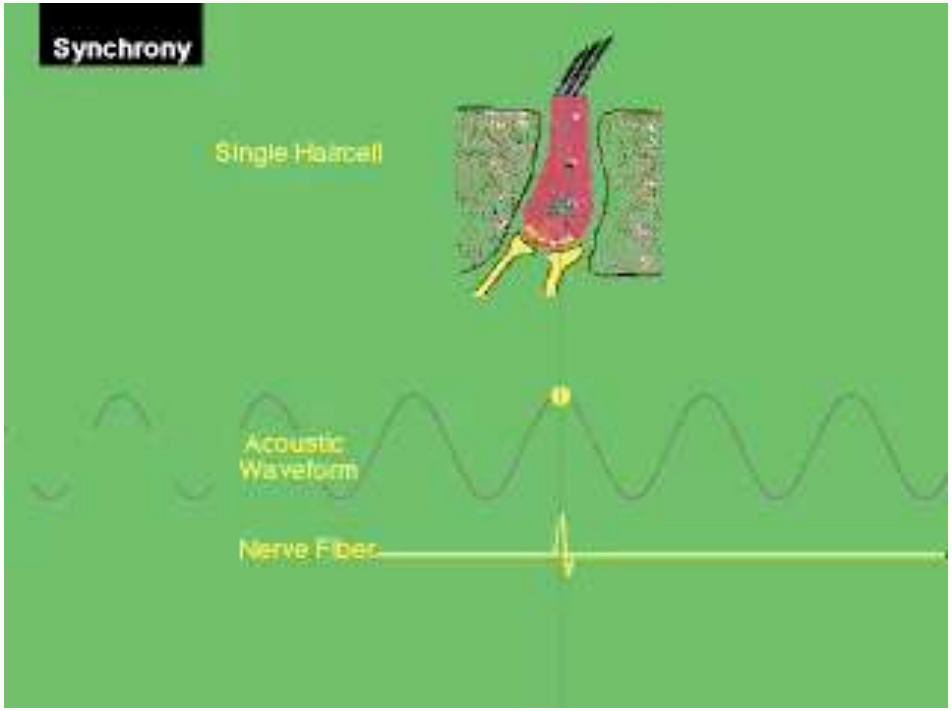
Frequency Coding by place on Cochlea
Place Theory





But: neurons are slow

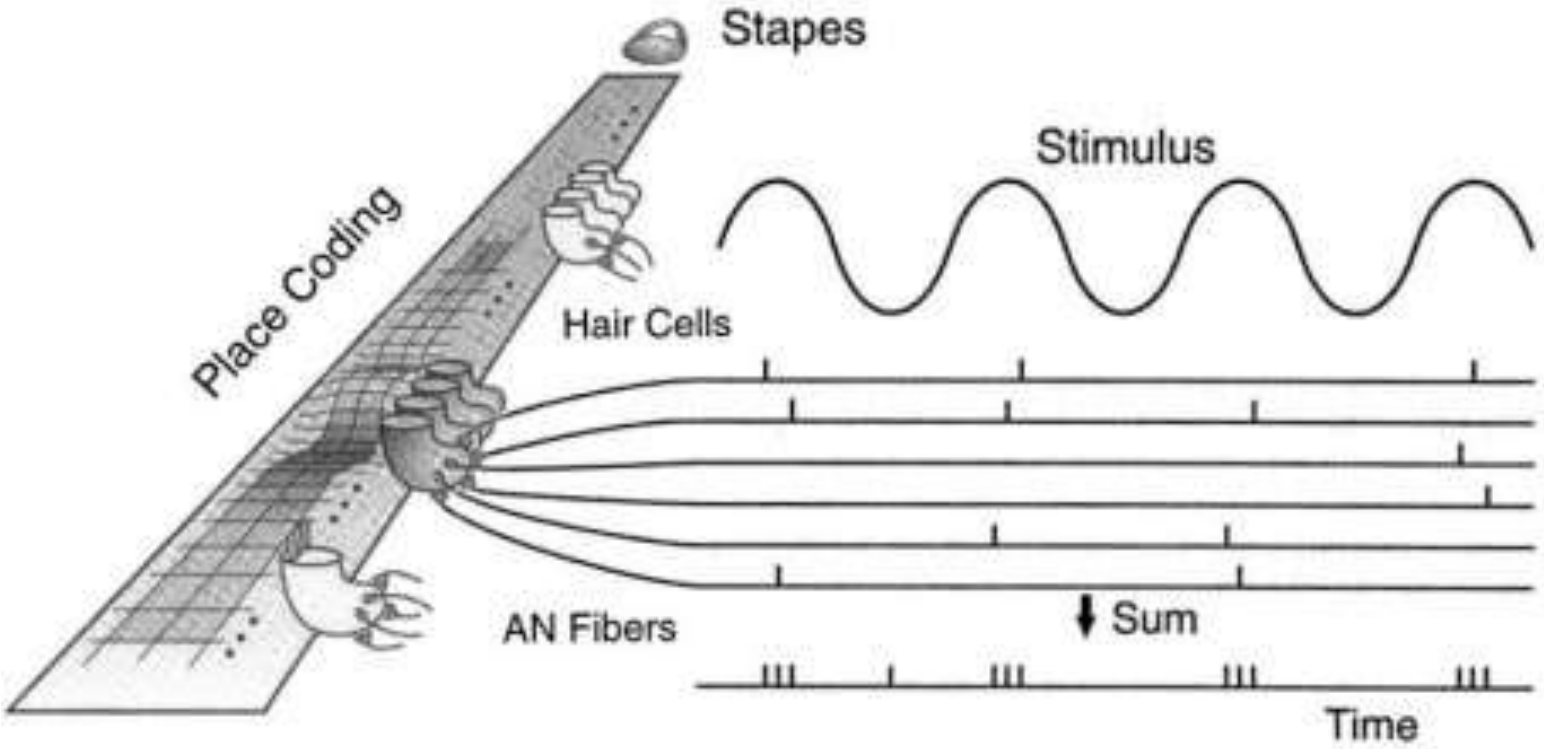




Each neuron can send at most ~1000 impulses/sec

How are frequencies > 1000 Hz encoded?

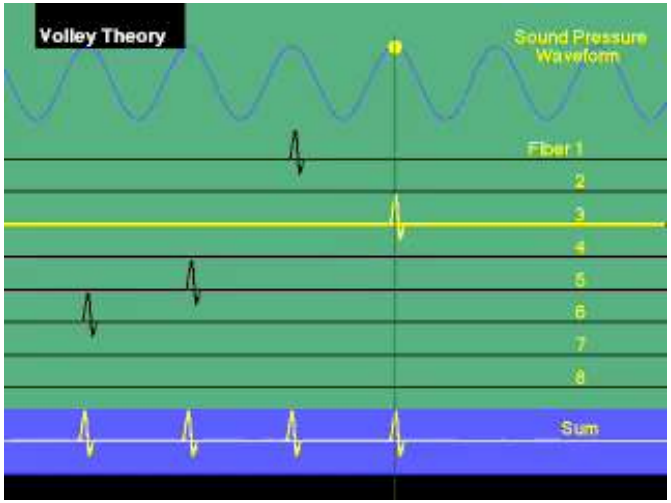
Temporal Coding



Temporal Coding

Volley Theory

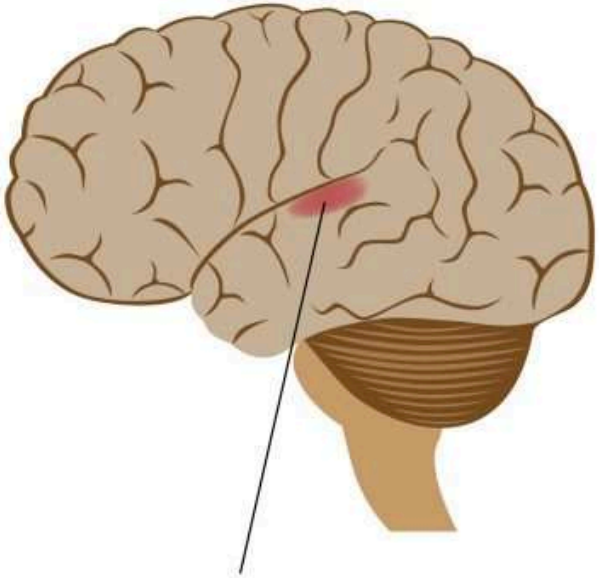
- synchronization of several adjacent neurons encodes periodicity information
- groups of auditory neurons use phase-locking to represent subharmonic frequencies of one harmonic sound



Theories of Hearing

- **Place Theory**
  - encoded at different places on the basilar membrane
- **Temporal Theory**
  - pitch encoded in timing of neural firings along the basilar membrane
  - nerve firings occur at particular phases of the waveform
- **Volley Theory**
  - synchronization of several adjacent neurons encodes periodicity information
  - groups of auditory neurons use phase-locking to represent subharmonic frequencies of one harmonic sound

Auditory pathway



Primary auditory cortex

relay station - hypothesised to be the root of **auditory fear conditioning**

responsive to specific **amplitude modulation** frequencies

time difference of sound arrival
sound intensity difference

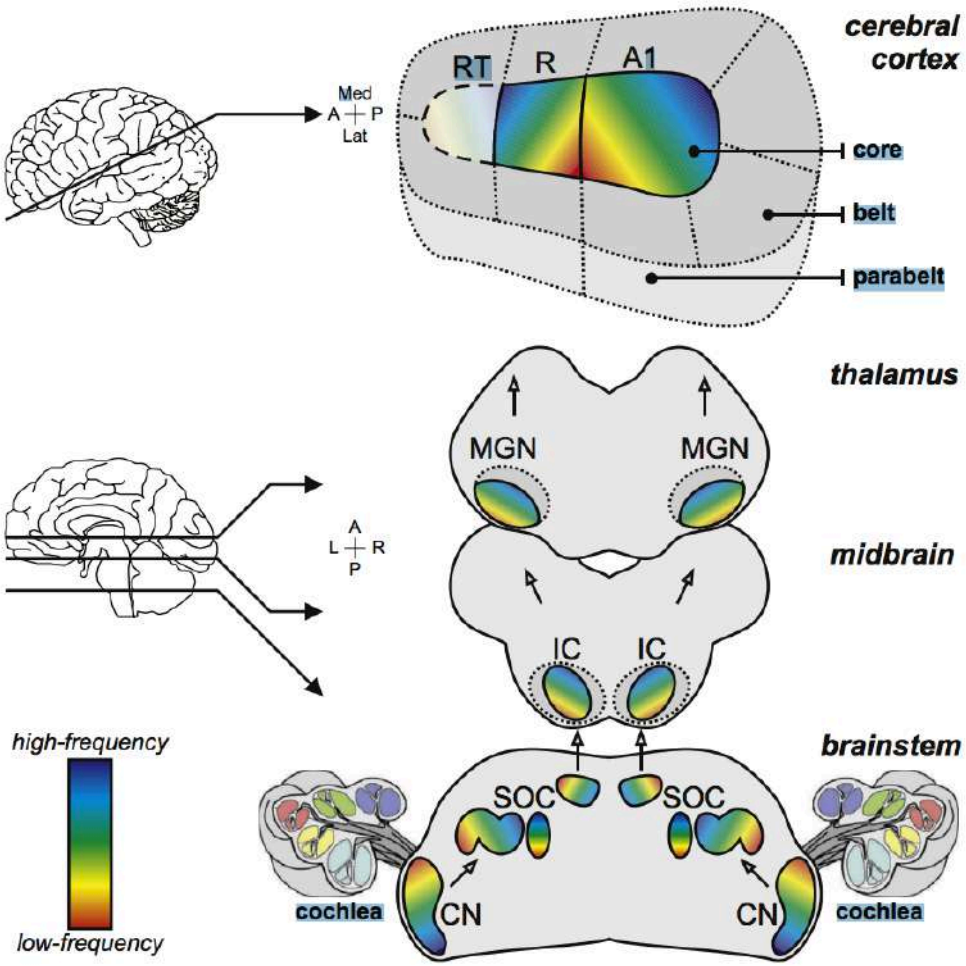
Medial geniculate

Inferior colliculus

Superior olive

Cochlear nucleus

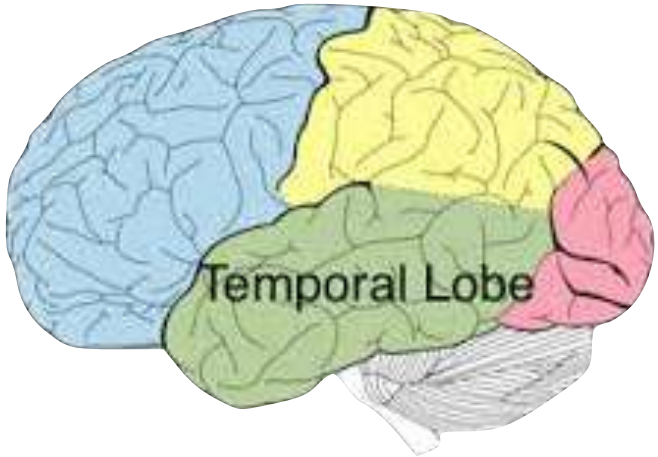
Frequency Encoding



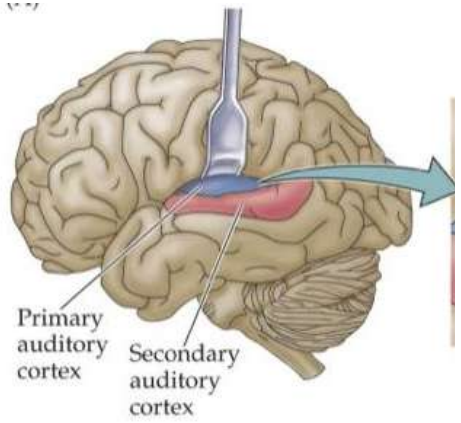
Saenz & Langers (2013) Tonotopic mapping of human auditory cortex. Hearing Research.

Auditory cortex

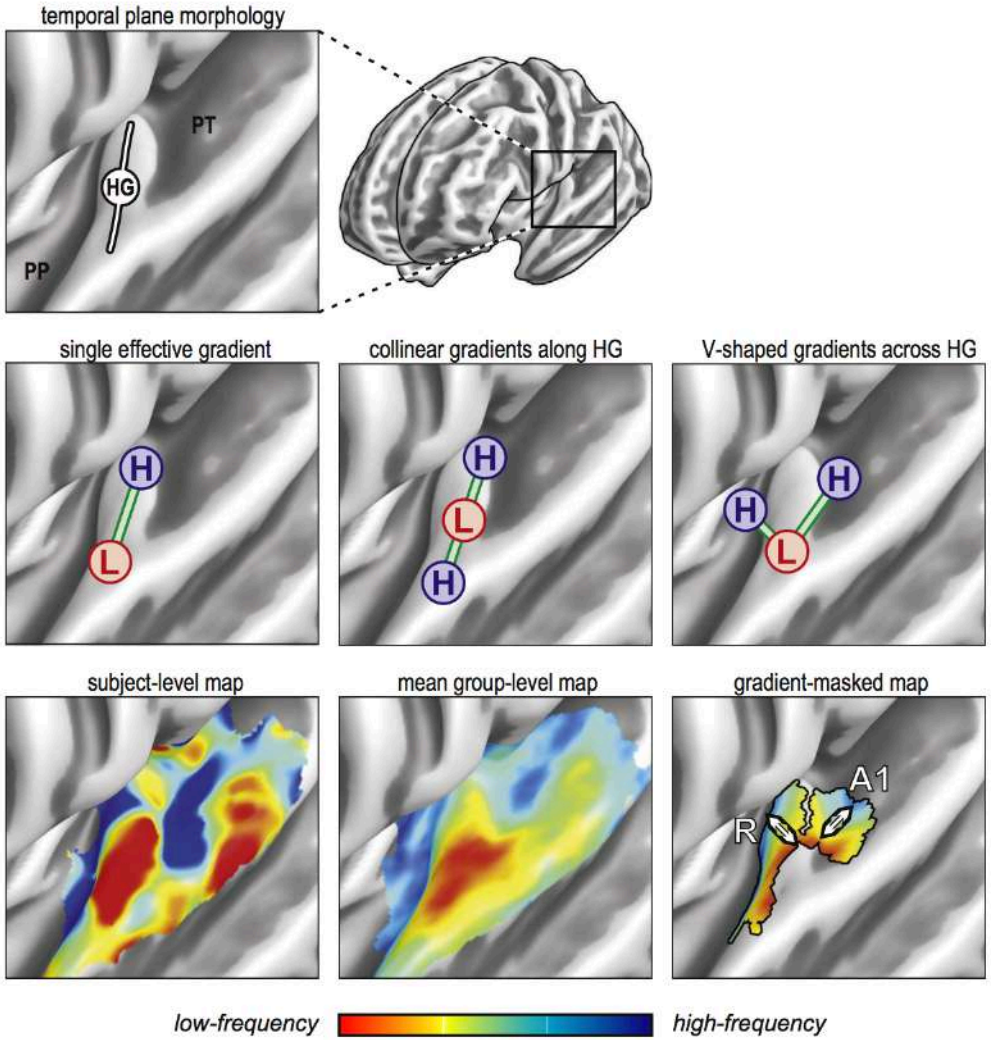
- **primary auditory cortex (PAC)**
  - BA 41 (42) - Heschl's gyrus
  - in the temporal lobe - involved with sense of hearing
  - tonotopic organisation



  - projects to numerous secondary cortical areas including multisensory areas (allow us to recognise animals or humans by both sound and sight) and to regions specifically involved in communication



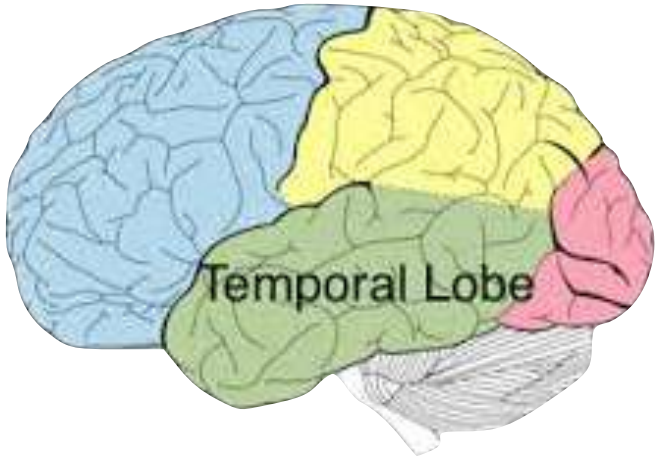
Evolution of Frequency Encoding Evidence in PAC

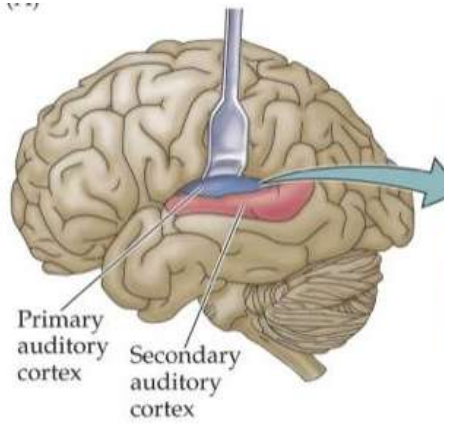


Saenz & Langers (2013) Tonotopic mapping of human auditory cortex. Hearing Research.

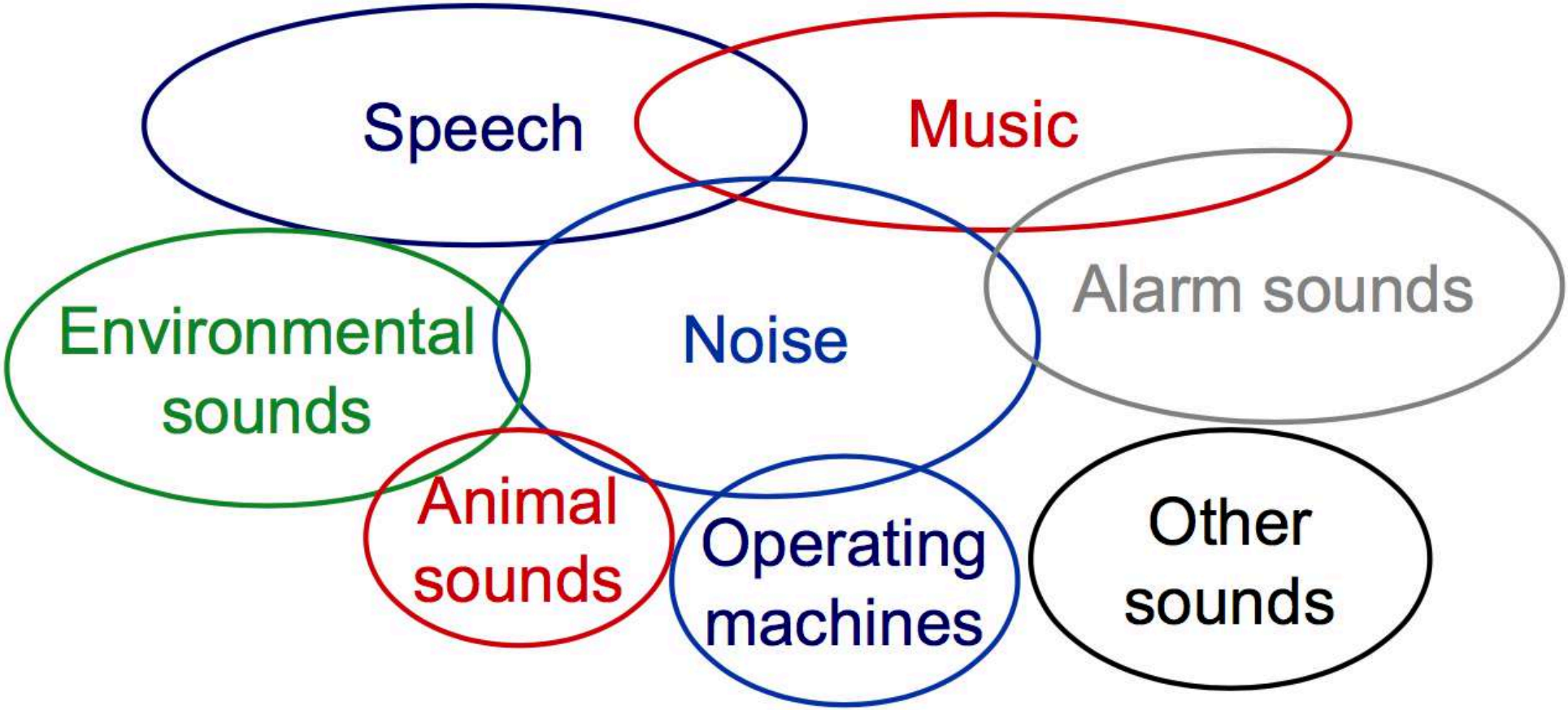
Auditory cortex

- **secondary auditory cortex**
  - BA 22 - Superior temporal gyrus
  - home to Wernicke's area (association)
  - left possesses greater temporal resolution
  - right associated with greater spatial resolution



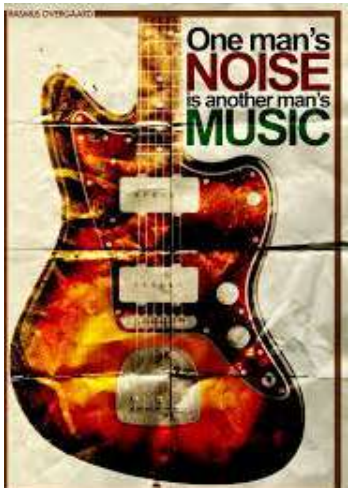


Types of sounds

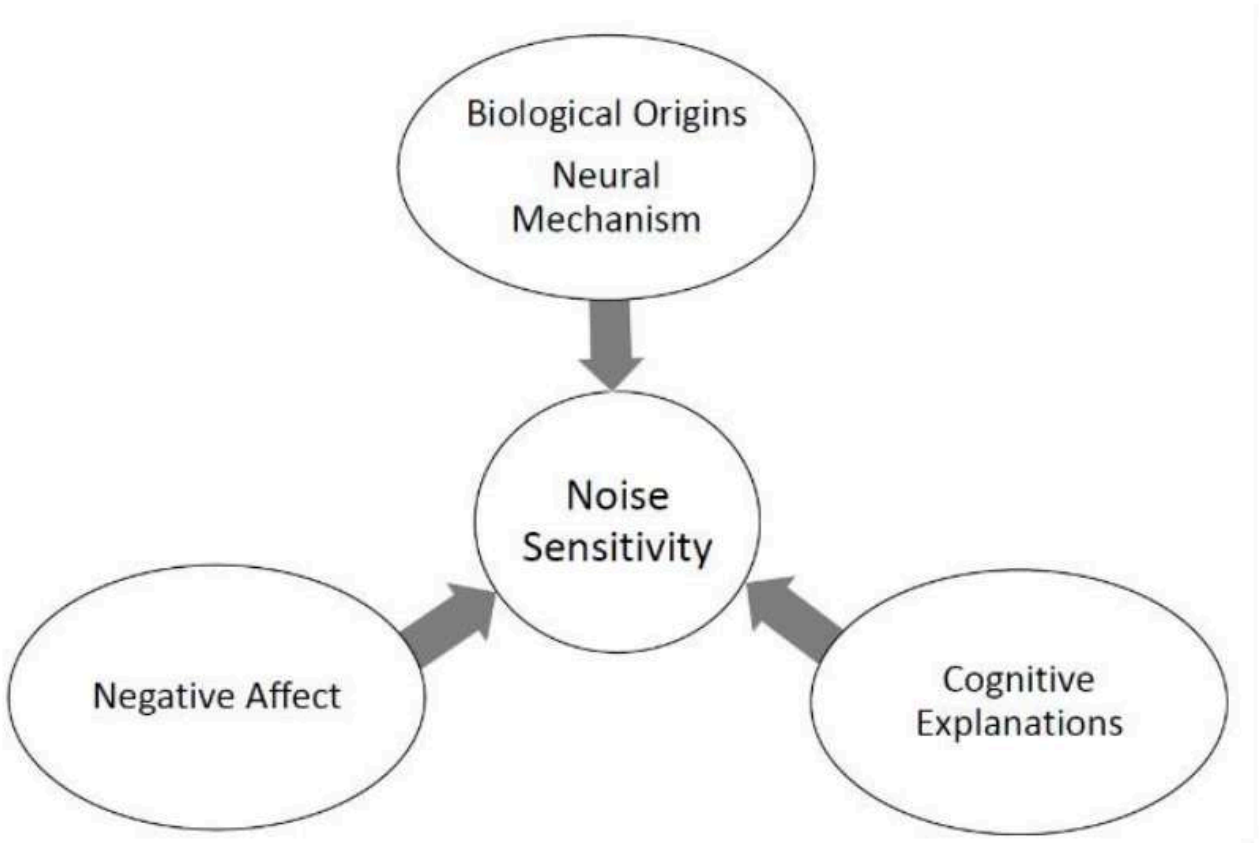


Noise

- disturbing sound
- typically an environmental problem
- can cause unwanted physiological and psychological effects
- sometimes it is a matter of taste
  - E.g. an outdoor concert,



Noise Sensitivity



Heinonen-Guzejev et al. (2018) Studying the origins of noise sensitivity–negative affect or biological factors

Noise Sensitivity

- **Negative Affect:** NS a dispositional tendency to negatively evaluate situations and the self
  - sound only has to be audible to be annoying
  - Shepherd et al. (2015) failed to support this notion
  - instead - “noise vulnerability hypothesis”, which asserts that noise has its greatest impact on vulnerable (i.e., noise-sensitive) individuals
- **Biological origins:**
  - NS only to noise and not to other sound features such as pitch, location or intensity
  - independent of loudness levels
  - potential heritability (36%)
  - appears to be a more acceptable theory for NS

Noise Sensitivity

- **Cognitive Explanations:**
  - noise-induced memory and attentional deficits lead to annoyance or distress
  - Noise-induced interference of cognitive processes
  - has been well described (auditory distractors)
  - NS exerts a negative effect on cognitive functions, such as attention, working memory and episodic recall

Noise Sensitivity

- Weinstein Noise Sensitivity Scale (1978)

Table 2. Weinstein Noise Sensitivity Scale.

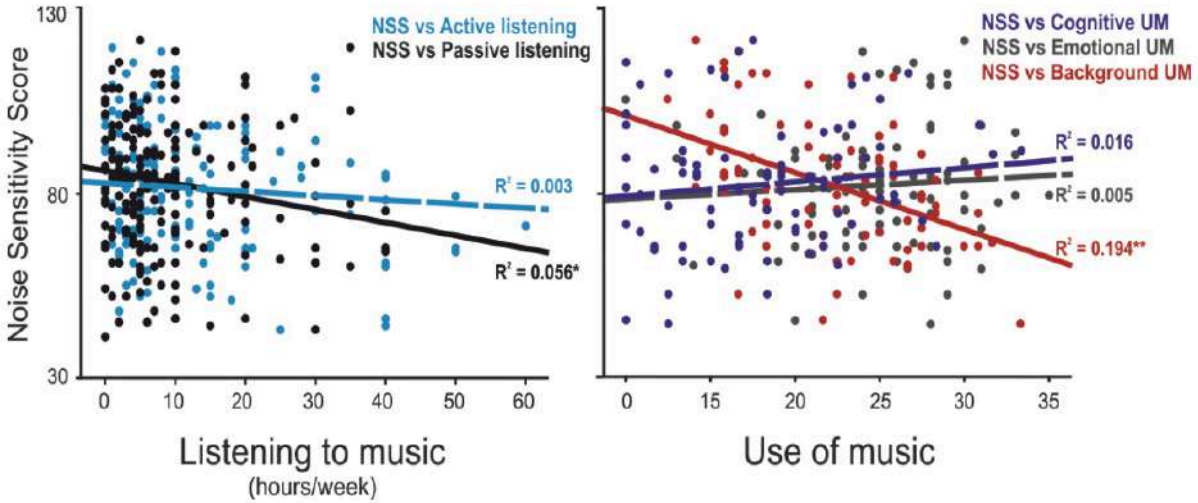
Instructions – Circle the number corresponding to how well you agree or disagree. Don't be disturbed by the reversals of order from one line to another. At the end, add up the numbers for your score.

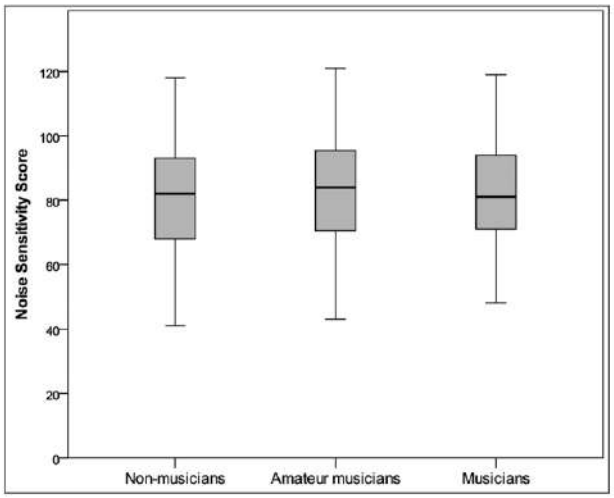
1.	I wouldn't mind living on a noisy street if the apartment I had was nice.	AGREE 1 2 3 4 5 6 DISAGREE
2.	I am more aware of noise than I used to be.	AGREE 6 5 4 3 2 1 DISAGREE
3.	No one should mind much if someone turns up his stereo full blast once in a while.	AGREE 1 2 3 4 5 6 DISAGREE.
4.	At movies, whispering and crinkling candy wrappers disturb me.	AGREE 6 5 4 3 2 1 DISAGREE
5.	I am easily awakened by noise.	AGREE 6 5 4 3 2 1 DISAGREE
6.	If it's noisy where I'm studying, I try to close the door or window or move someplace else.	AGREE 6 5 4 3 2 1 DISAGREE
7.	I get annoyed when my neighbors are noisy.	AGREE 6 5 4 3 2 1 DISAGREE
8.	I get used to most noises without much difficulty.	AGREE 1 2 3 4 5 6 DISAGREE
9.	How much would it matter to you if an apartment you were interested in renting was located across from a fire station.	A LOT 6 5 4 3 2 1 NOT MUCH
10.	Sometimes noises get on my nerves and get me irritated.	AGREE 6 5 4 3 2 1 DISAGREE
11.	Even music I normally like will bother me if I'm trying to concentrate.	AGREE 6 5 4 3 2 1 DISAGREE
12.	It wouldn't bother me to hear the sounds of everyday living from my neighbors (footsteps, running water, etc).	AGREE 1 2 3 4 5 6 DISAGREE
13.	When I want to be alone, it disturbs me to hear outside noises.	AGREE 6 5 4 3 2 1 DISAGREE
14.	I'm good at concentrating no matter what is going on around me.	AGREE 1 2 3 4 5 6 DISAGREE
15.	In a library, I don't mind if people carry on a conversation if they do it quietly.	AGREE 1 2 3 4 5 6 DISAGREE
16.	There are often times when I want complete silence.	AGREE 6 5 4 3 2 1 DISAGREE
17.	Motorcycles ought to be required to have bigger mufflers.	AGREE 6 5 4 3 2 1 DISAGREE
18.	I find it hard to relax in a place that's noisy.	AGREE 6 5 4 3 2 1 DISAGREE
19.	I get mad at people who make noise that keeps me from falling asleep or getting work done.	AGREE 6 5 4 3 2 1 DISAGREE
20.	I wouldn't mind living in an apartment with thin walls.	AGREE 1 2 3 4 5 6 DISAGREE
21.	I am sensitive to noise.	AGREE 6 5 4 3 2 1 DISAGREE

TOTAL SCORE _____

Noise

- NS moderates how and why individuals listen to music





while NS individuals seem to be able to enjoy the sound of music, use it for mood regulation, and they attentively (actively) listen to music like non-sensitive individuals, they prefer not having it in the background.

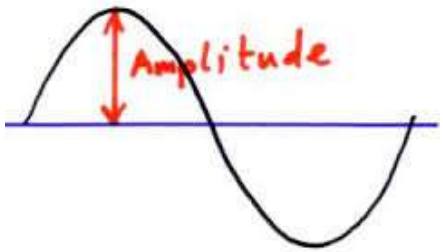
Noise

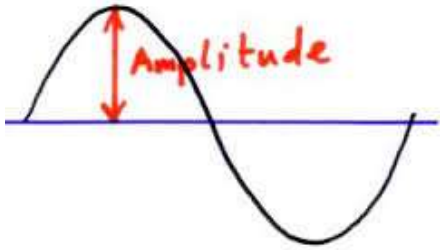
- higher NS
  - rated music as less important in their life than did individuals with lower sensitivity to noise
  - not associated with musical training
  - spend less time in passive (background) listening to music than those with lower sensitivity to noise

Thesis: https://helda.helsinki.fi/bitstream/handle/10138/217878/NOISESEN.pdf?sequence=1

Physical

Perceptual



Physical	Perceptual
	
	
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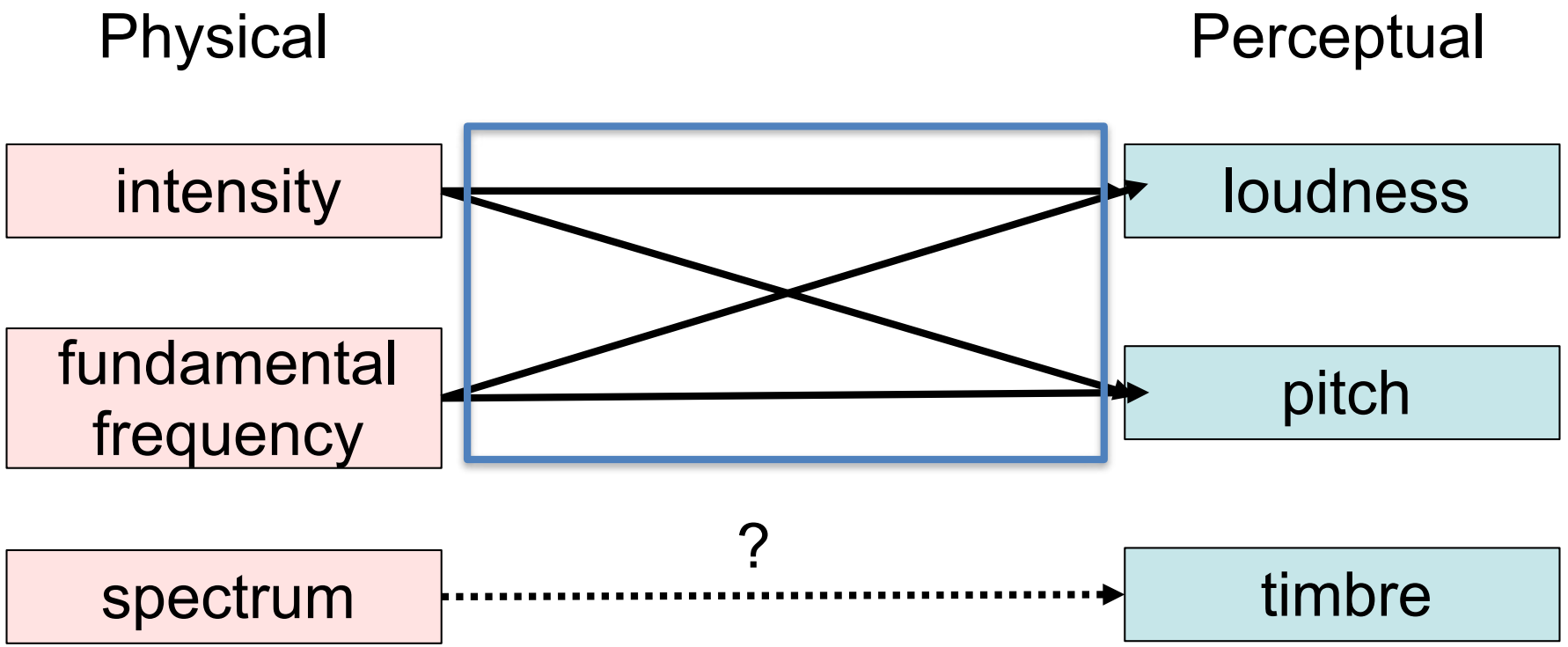
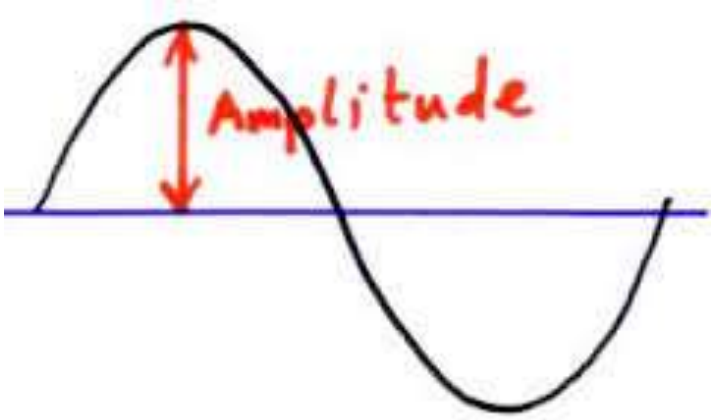
Fundamental Question of Psychoacoustics



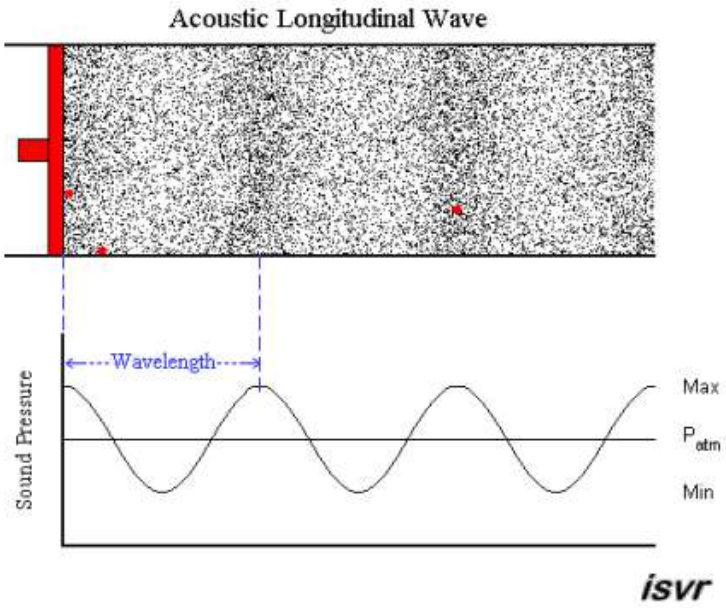


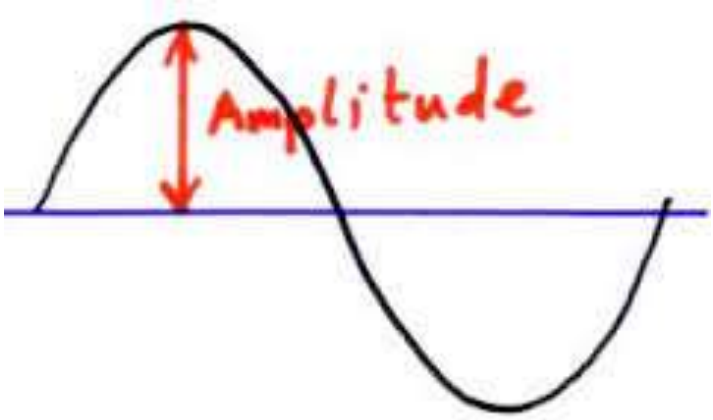
amplitude - the objective measurement of the degree of change in atmospheric pressure

- directly related to the acoustic energy or intensity of a sound

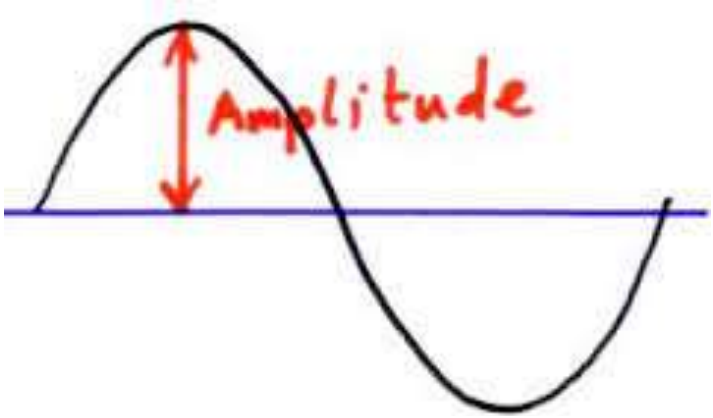
loudness - psycho-physiological correlate of amplitude

- physical measure of sound strength typically sound pressure, sound pressure level (in decibels), sound intensity or sound power



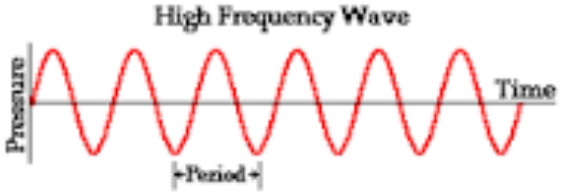


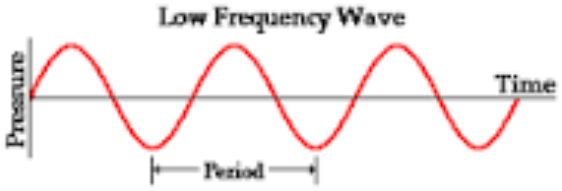
- ear can respond to various levels of sound intensities
  - Ratio of the smallest and largest air pressure = 10,00,000 : 1 = 10^6 : 1
- **decibel** - unit used to measure the intensity of a sound (logarithmic) (130 dB and 0dB)



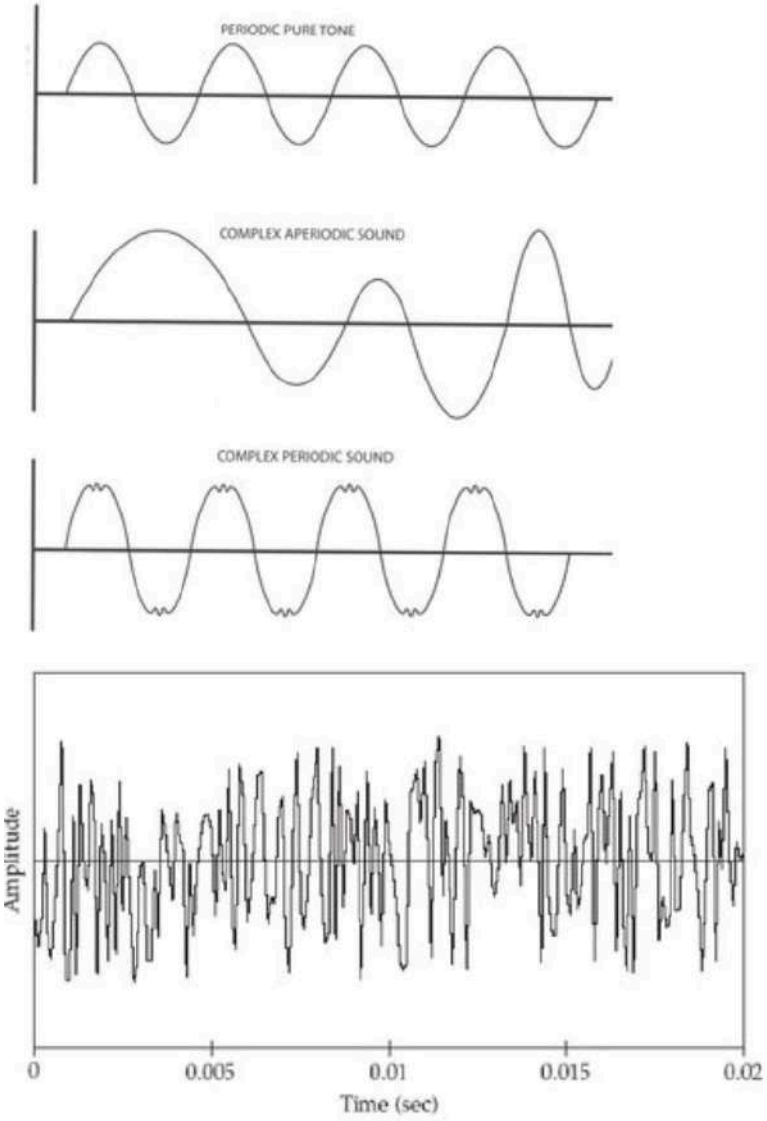
Sound sources (noise) Examples with distance	Sound pressure Level L_p dB SPL
Jet aircraft, 50 m away	140
Threshold of pain	130
Threshold of discomfort	120
Chainsaw, 1 m distance	110
Disco, 1 m from speaker	100
Diesel truck, 10 m away	90
Kerbside of busy road, 5 m	80
Vacuum cleaner, distance 1 m	70
Conversational speech, 1 m	60
Average home	50
Quiet library	40
Quiet bedroom at night	30
Background in TV studio	20
Rustling leaves in the distance	10
Hearing threshold	0

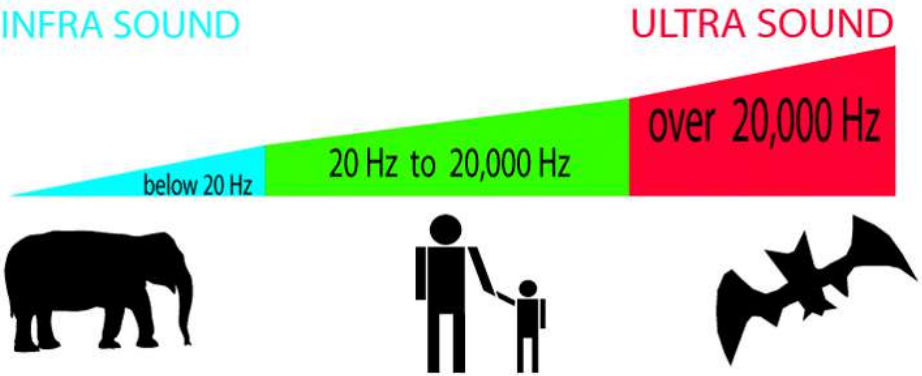
- **frequency** - number of sound wave cycles per second
  - measured in hertz (Hz)
  - wide audible frequency range: 20 — 20 000 Hz
  - varies according to age and exposure to noise
- **pitch** - psycho-physiological correlate of frequency






Frequency


PERIODIC PURE TONE
COMPLEX APERIODIC SOUND
COMPLEX PERIODIC SOUND
Amplitude
0
0.005
0.01
0.015
0.02
Time (sec)

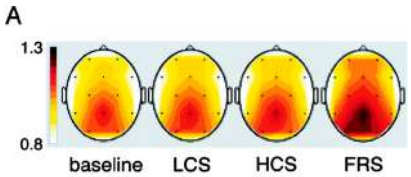

INFRA SOUND
ULTRA SOUND
below 20 Hz
20 Hz to 20,000 Hz
over 20,000 Hz

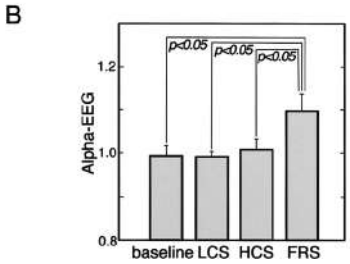
- can cause various unwanted physiological and psychological reactions as well as hearing damage at very high levels
- caused for example by machines or structural vibrations

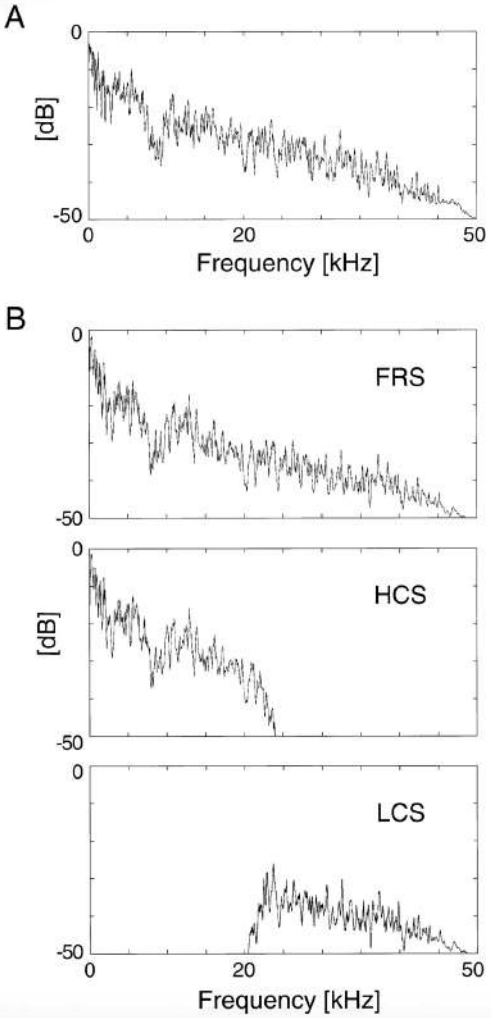
Frequency

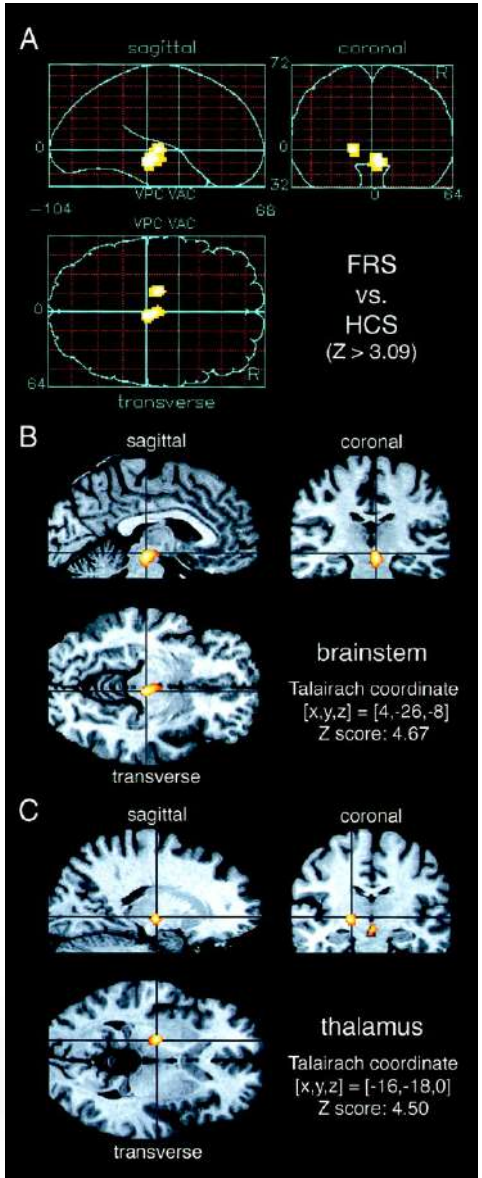
Inaudible High-Frequency Sounds Affect Brain Activity: Hypersonic Effect
Oohashi et al. (2000). Journal of Neurophysiology, 83 (6) 3548-3558;

ULTRA SOUND
over 20,000 Hz







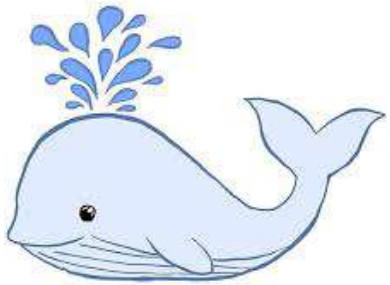


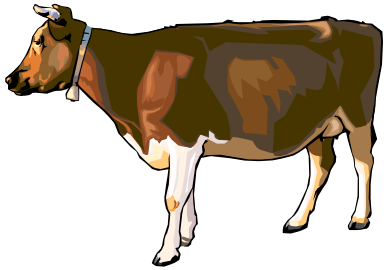
sound containing HFC to be more pleasant
than the same sound lacking an HFC

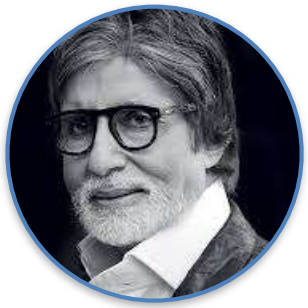
- Pitch is that auditory attribute of sound according to which sounds can be ordered on a scale from low to high

- The property of a sound and especially a musical tone that is determined by the frequency of the waves producing it: highness or lowness of sound

pitch



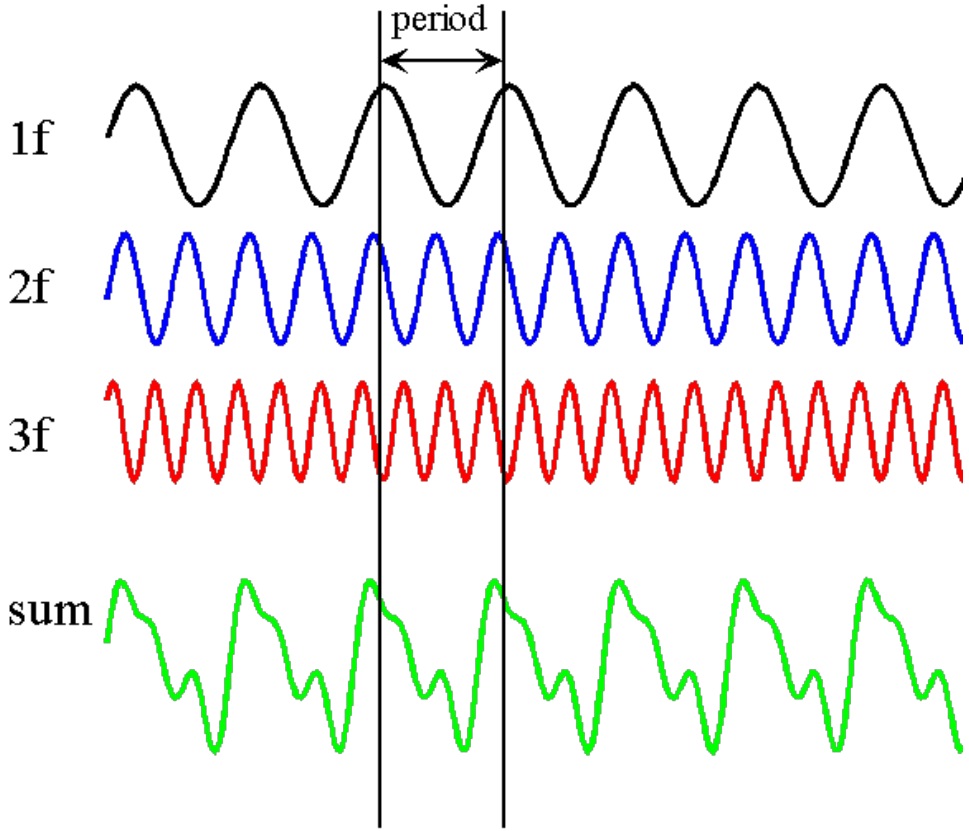




low

high

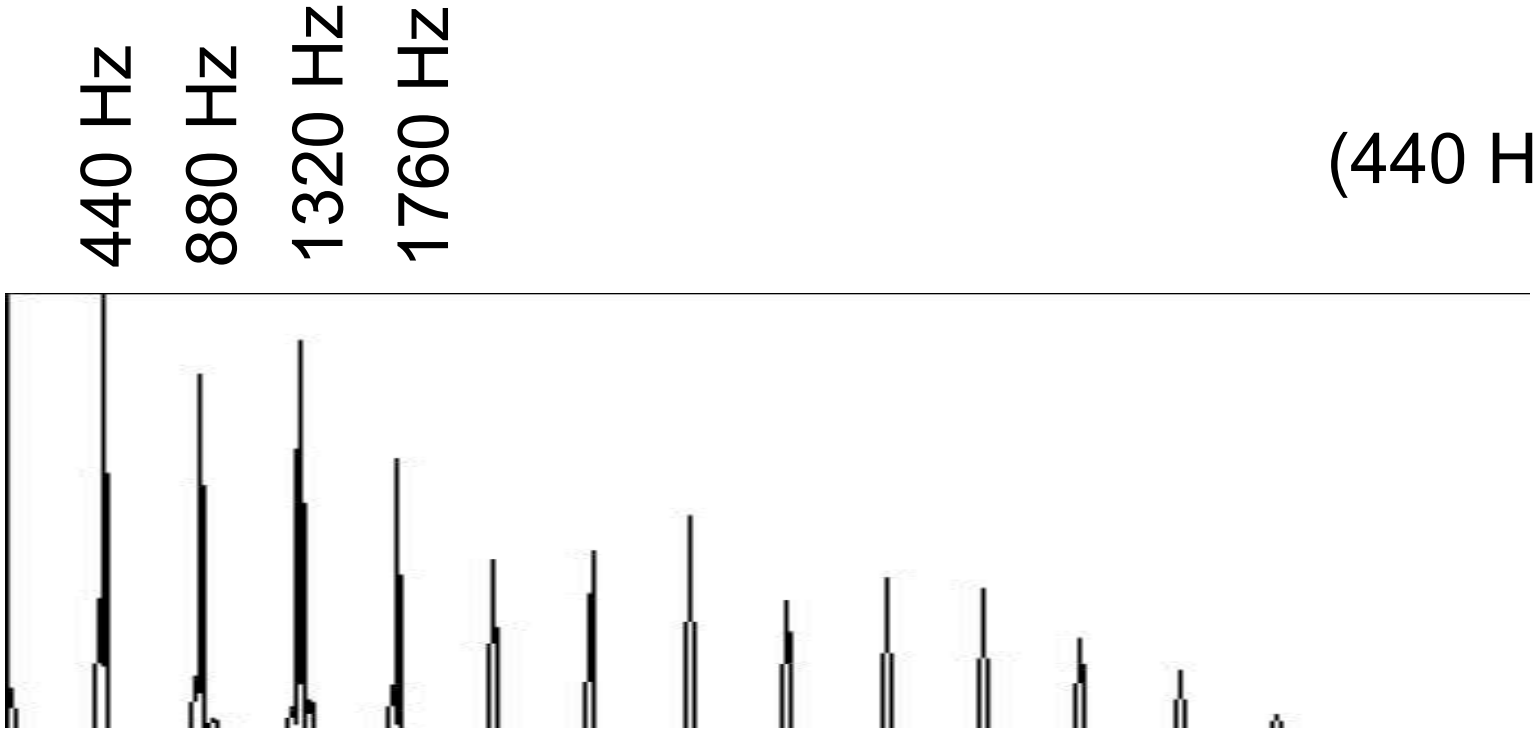
Klofstad, C.A., Anderson, R.C., Peters, S., 2012.**Sounds like a winner**: voice pitch influences perception of leadership capacity in both men and women. Proc. R. Soc. B: Biol.Sci. 279, 2698–2704.



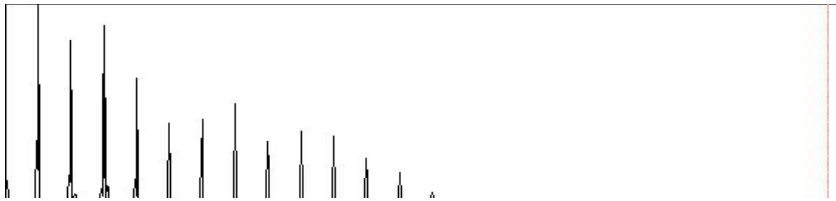
MATLAB: ADDITIVE SYNTHESIS

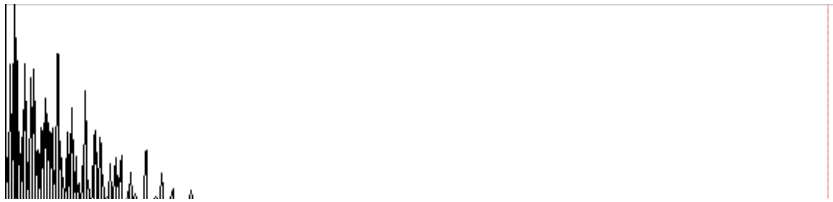
Pitch of periodic tones

≈ pitch of the sine tone with frequency equal to the frequency of the first partial

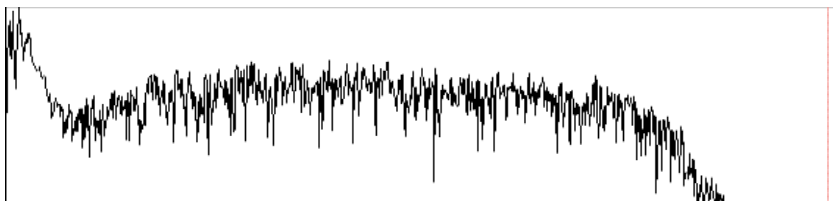


(440 Hz sine tone)



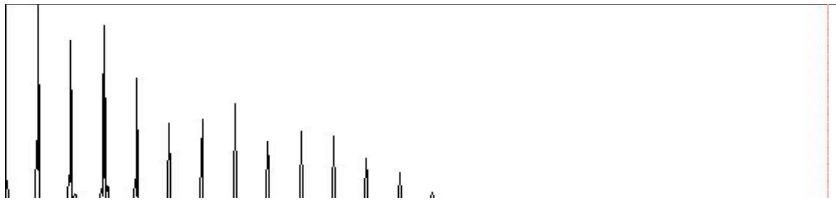


periodic tones
(harmonic spectrum)

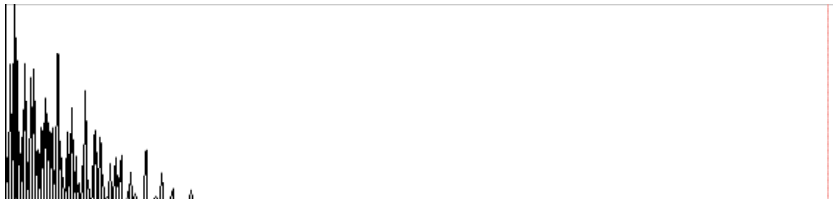


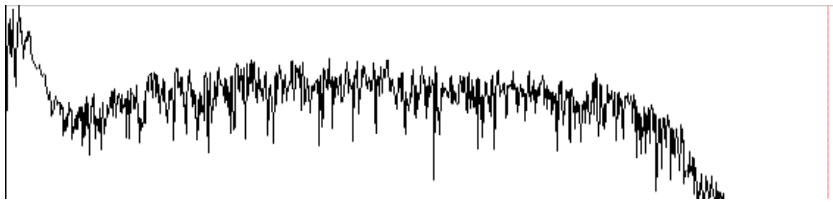
aperiodic tones
(non-harmonic spectrum)

Which one sounds higher?



periodic tones
(harmonic spectrum)





aperiodic tones
(non-harmonic spectrum)

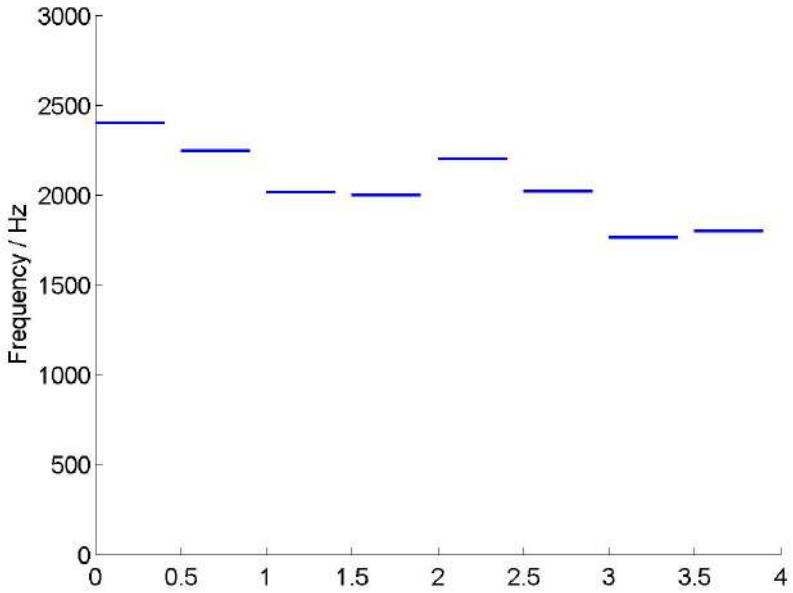
Pitch of aperiodic tones

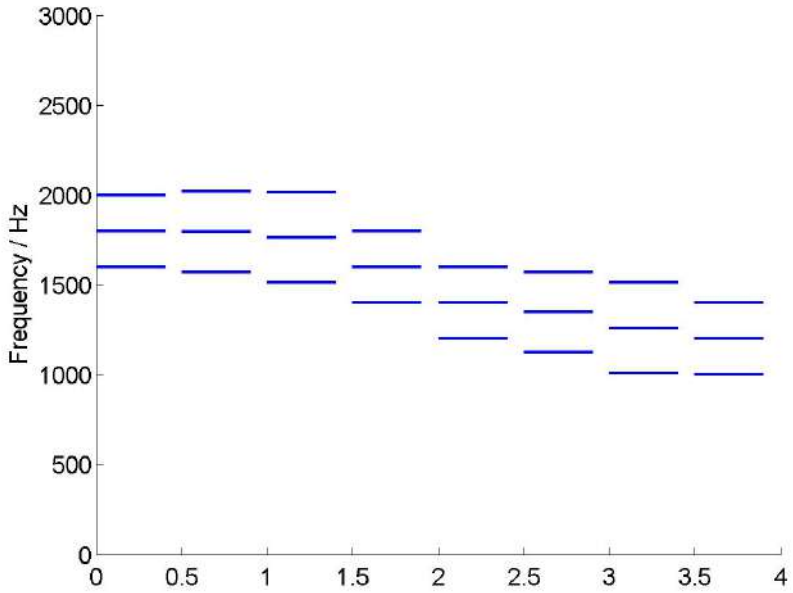
- difficult to define generally
- pitch salience
  - depends on the degree of harmonicity of the tone (degree of coincidence of subharmonics of partials) (Terhardt, E., Stoll, G., Seewann, M.1982)

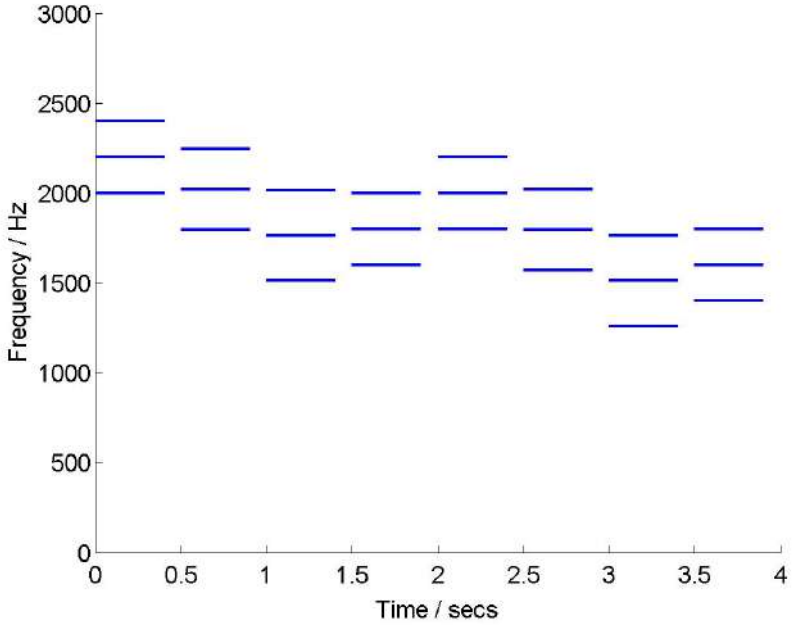
What would be the fundamental pitch?

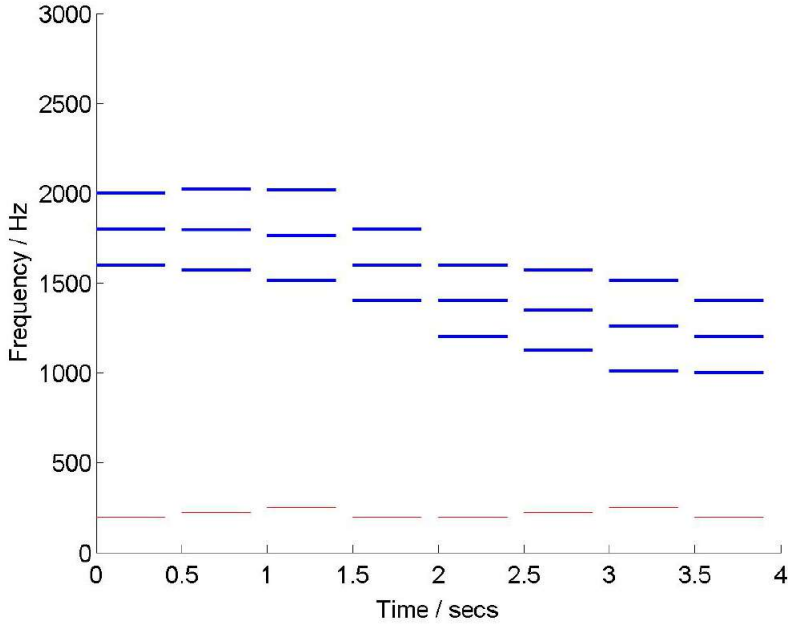
MATLAB DEMO

Do you hear a familiar melody?





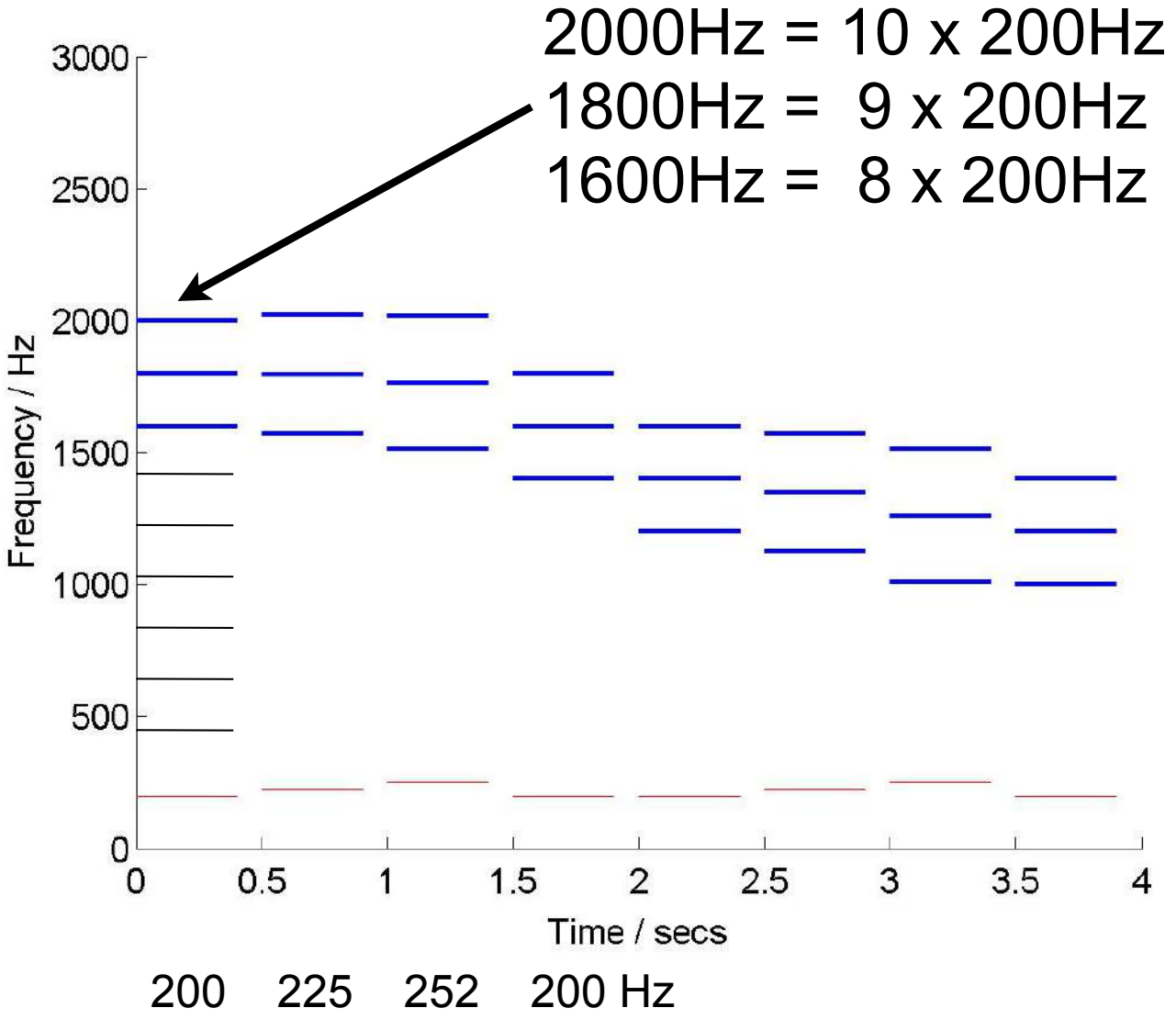




Two kinds of pitch

spectral pitch

virtual pitch



200 225 252 200 Hz

Spectral vs. virtual pitch

- spectral pitch
  - corresponds to frequencies present in the tone
- virtual pitch
  - corresponds to frequencies not necessarily present in the tone

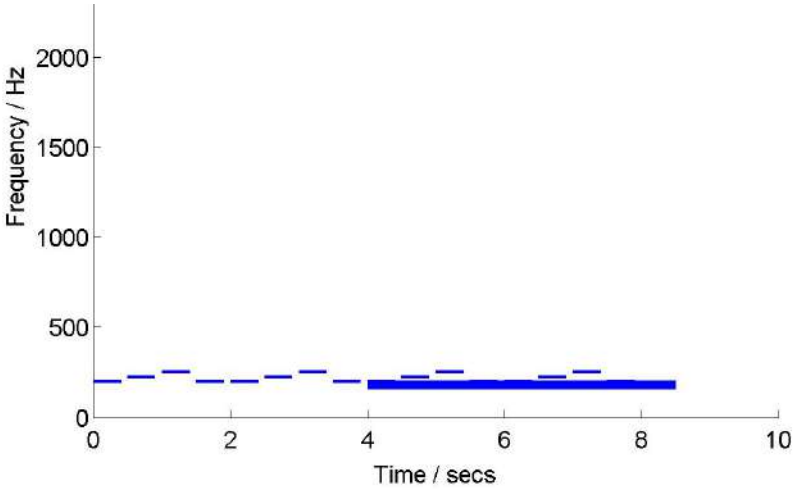
Virtual pitch in everyday life

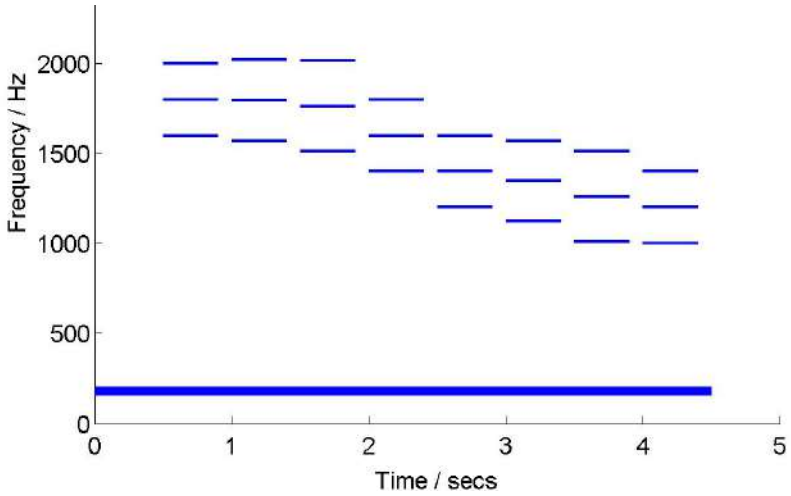
- mobile phone
  - bandwidth 500-3000 Hz
  - male voice 100-200 Hz
- small multimedia speakers
  - music 50- Hz

Explanation of virtual pitch

- Rate theory of pitch perception (volley theory)
  - pitch is encoded in the periodicity pattern of neural firings

Evidence for rate/temporal coding





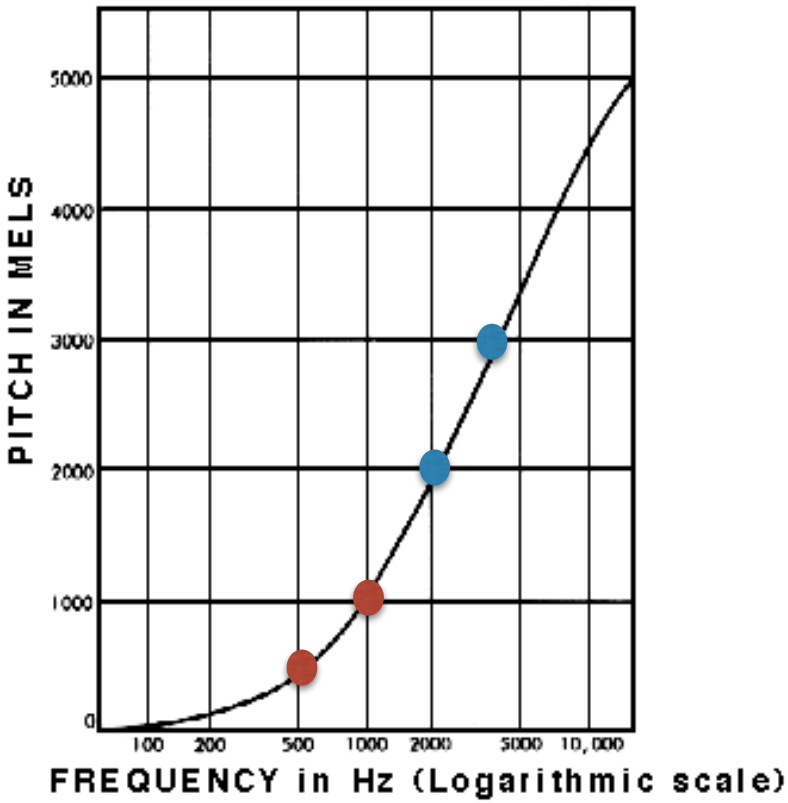
- virtual pitch is not masked
- thus: it is perceived in cochlea at a location different from that of corresponding spectral pitch

What is twice as high?

MATLAB DEMO

What is twice as high?

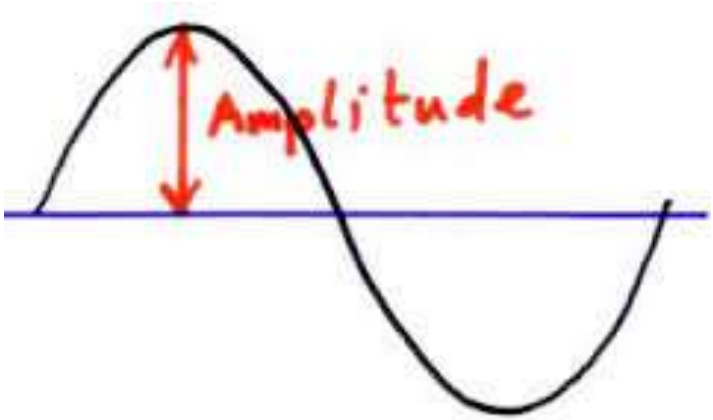
- **mel scale** is a scale of pitches judged by listeners to be equal in distance one from another
  - 1000 Hz, 40 dB sine tone = 1000 mels
- at high frequencies, larger and larger intervals are needed to produce equal pitch increments



$$m = 2595 \log_{10}\left(\frac{f}{700} + 1\right) = 1127 \log_{e}\left(\frac{f}{700} + 1\right)$$

Summarizing Pitch

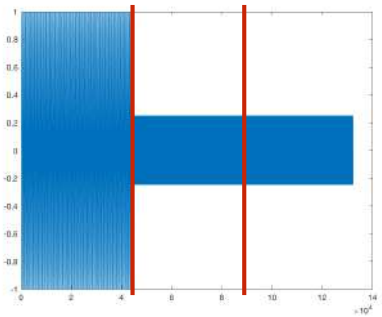
- pitch of harmonic tones ≈ fundamental frequency
- pitch depends slightly on intensity
- two kinds of pitch
  - spectral
  - virtual
- pitch perception occurs as a combination of
  - place coding: location of maximal oscillation along basilar membrane
  - frequency coding: periodicity information encoded in neural firing patterns of groups of neurons
  - volley theory: periodicity information encoded in neural firing clustered at certain places

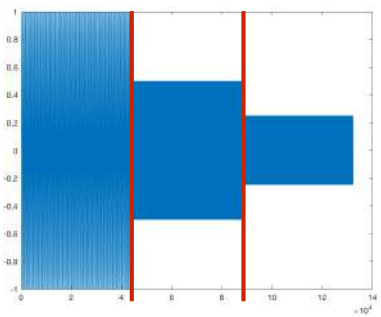


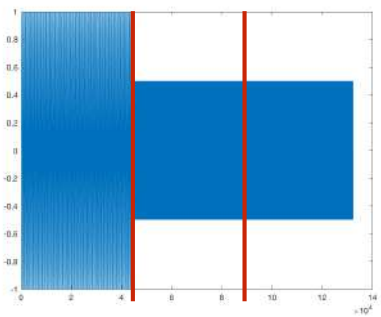
interaction

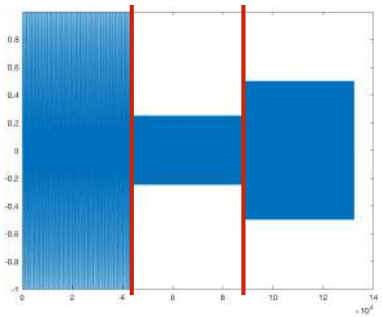
150 Hz **1000 Hz** **5000 Hz**

Which sine wave sounds louder?



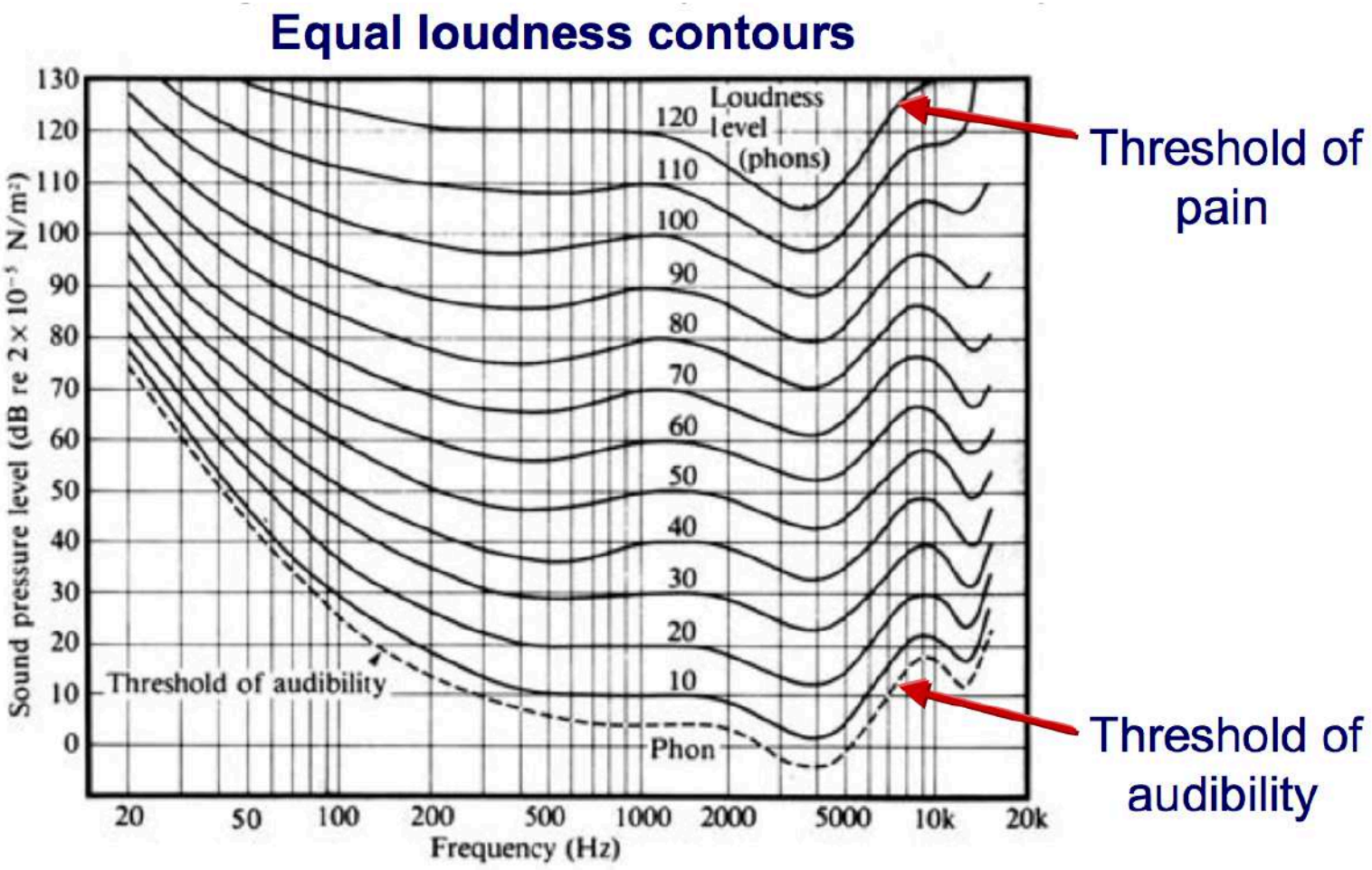






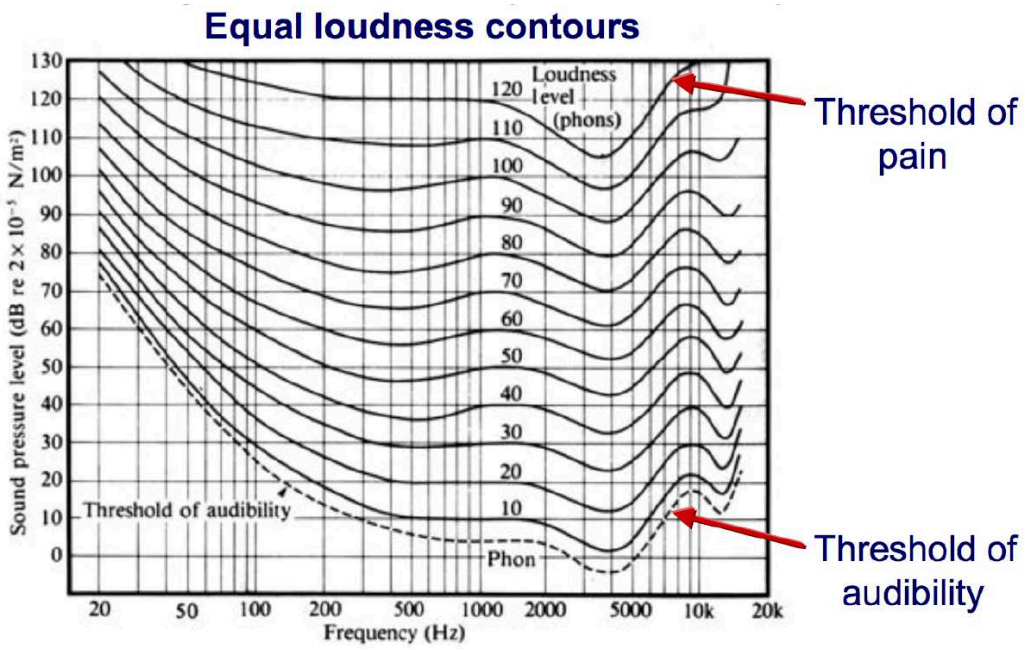
Hearing Sensitivity

- sensitivity of hearing depends heavily in frequency



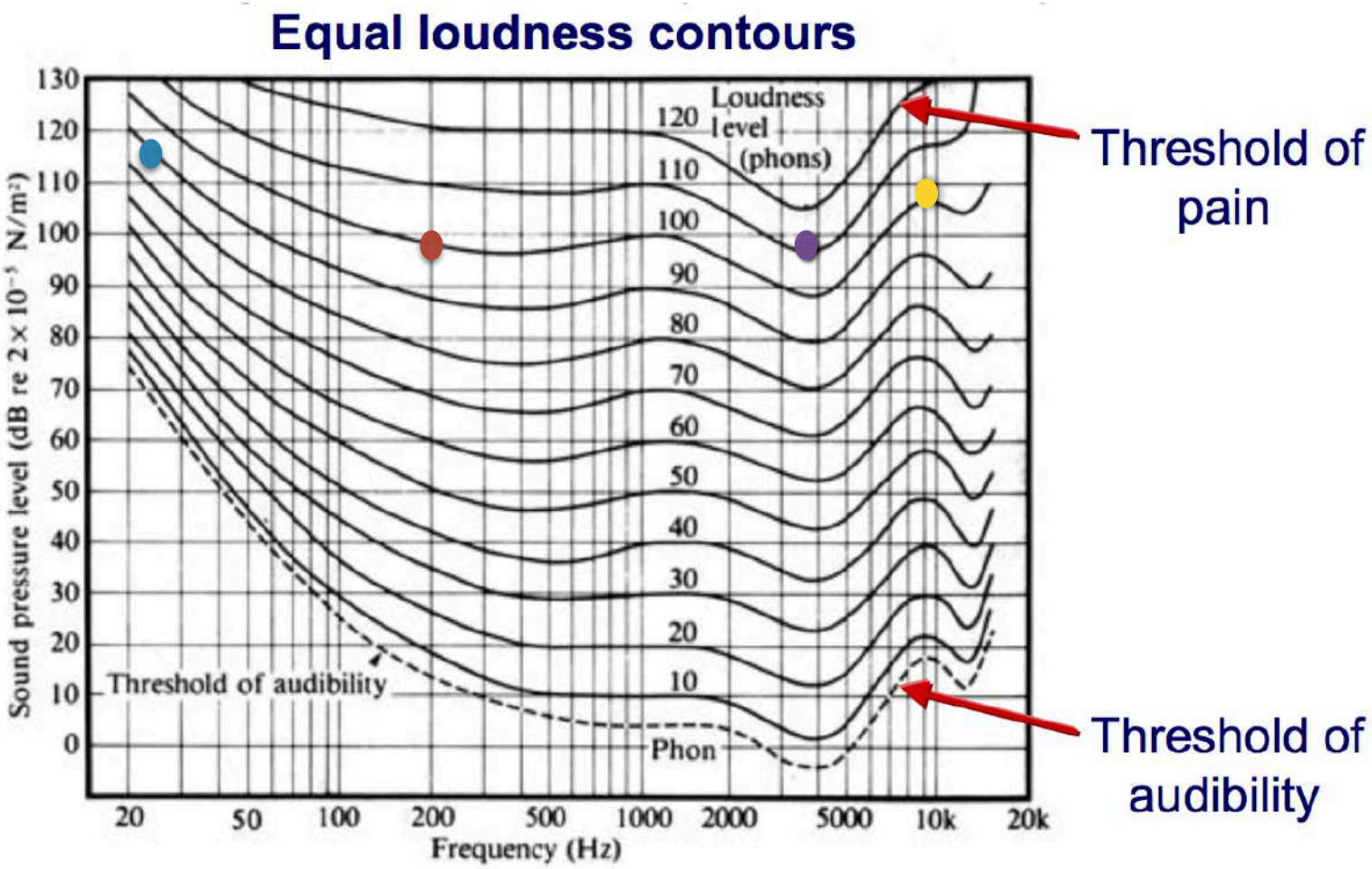
Hearing Sensitivity

- ear most sensitive in the 1kHz-5kHz range
- absolute threshold of human hearing determined by human testing (describes energy in a pure tone needed for audibility in a noiseless environment)



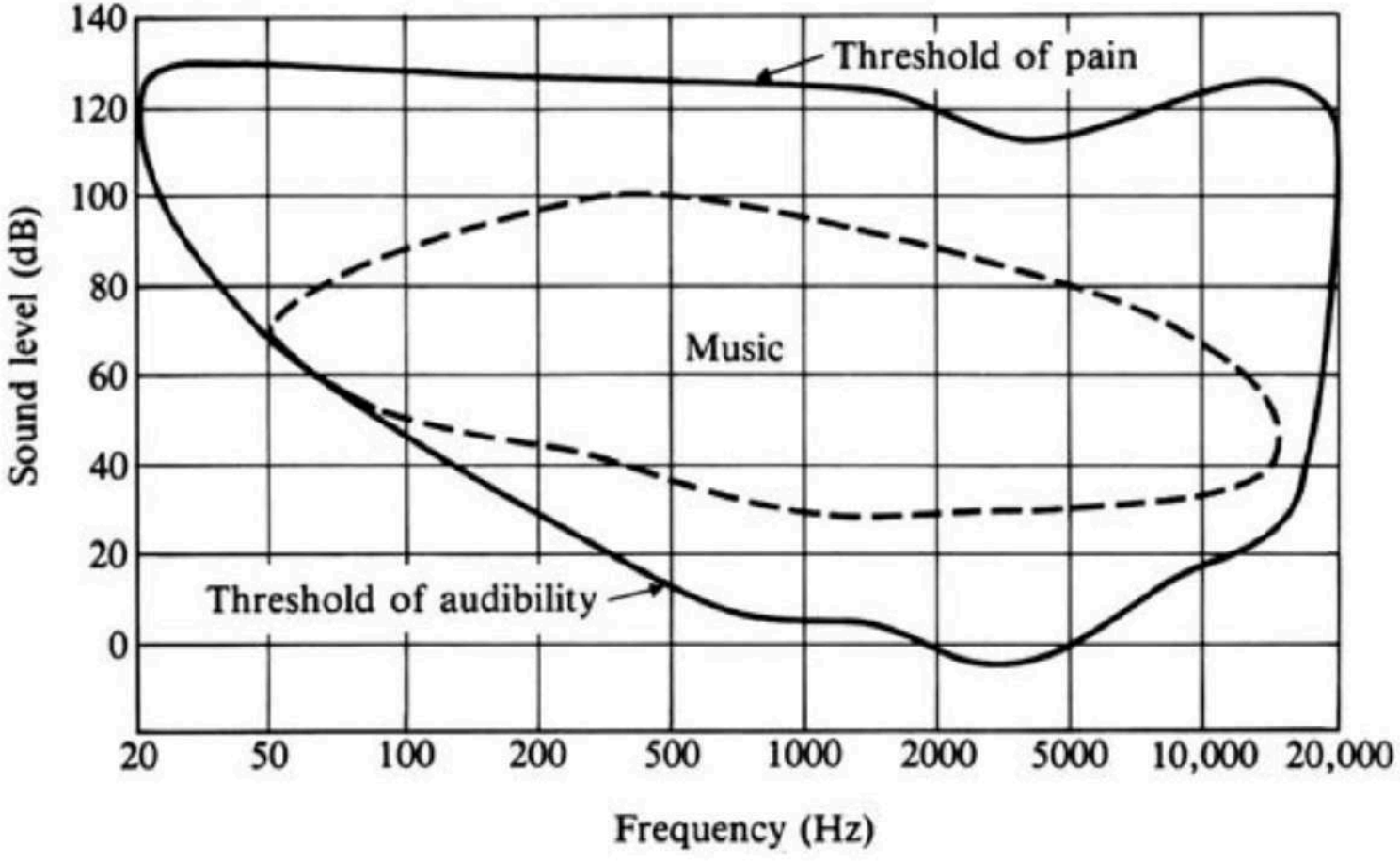
Hearing Sensitivity

- phons = units of perceptual amplitude



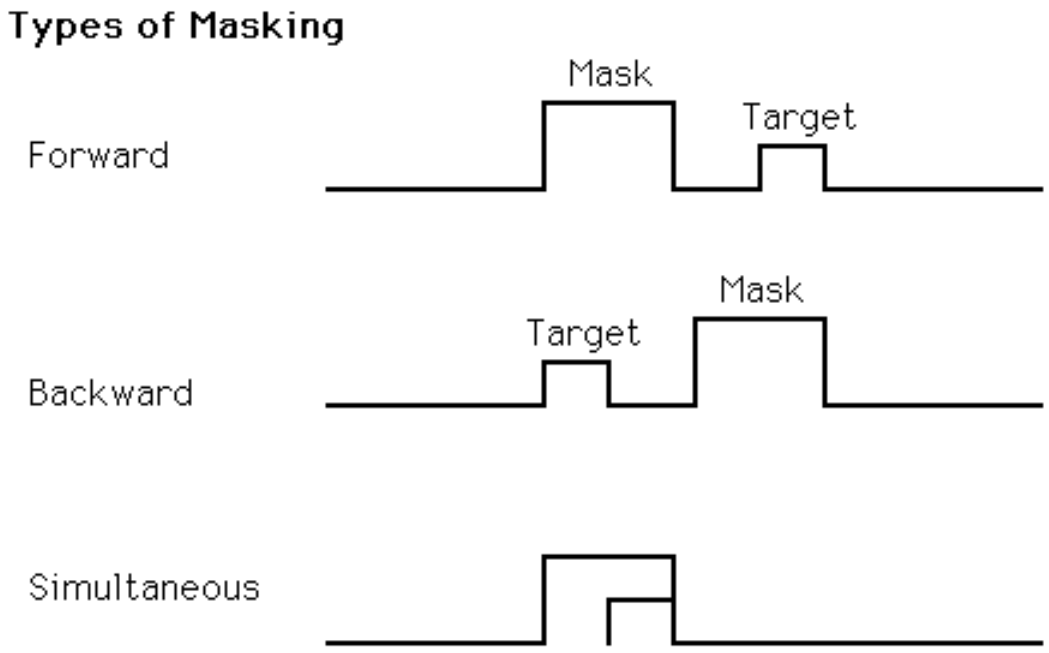
Hearing Sensitivity

- sounds targeted to humans go well with the properties of hearing



Audio Masking

- **Simultaneous masking vs temporal masking**



Audio Masking

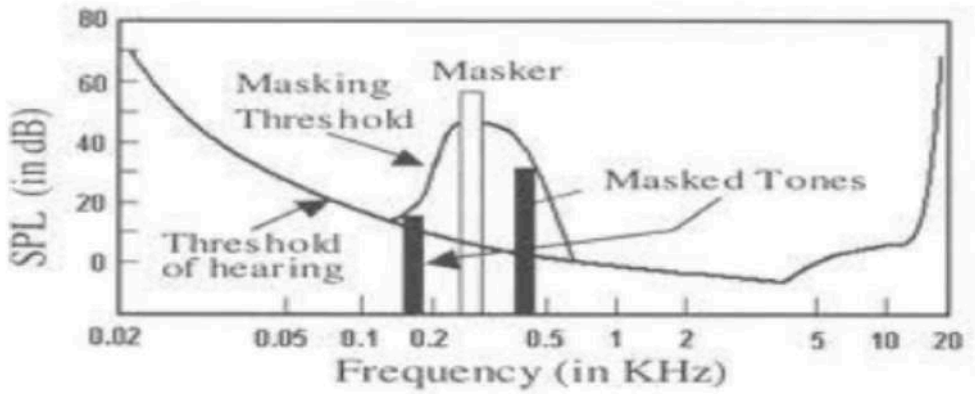
- **Non-Simultaneous masking/temporal masking**
  - when both **do not** occur at same time

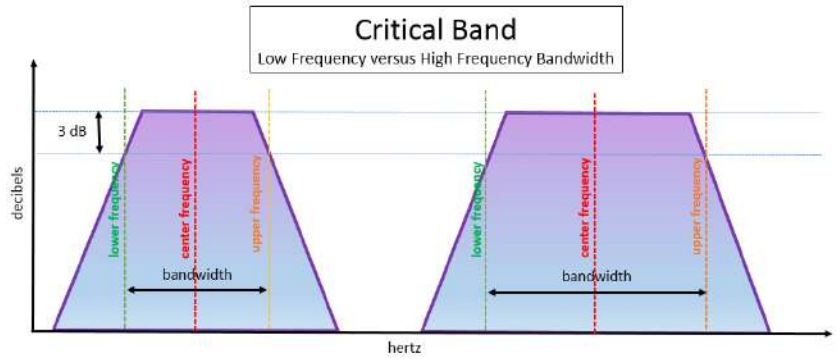
Audio Masking

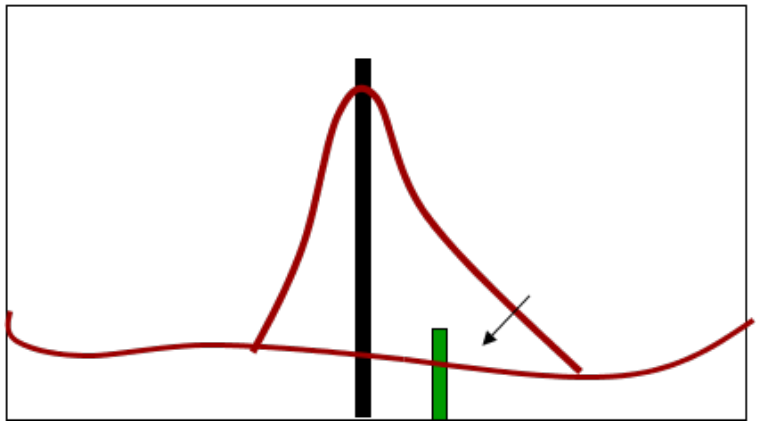
- **Simultaneous masking/frequency masking**
  - when both occur at same time and close in frequency

Audio Masking

- **Simultaneous masking/frequency masking**
  - when both occur at same time and close in frequency







Audio Masking

lossless ———> lossy

Audio Masking