VS265 Lecture Notes

Sound and the ear

The nature of sound

- The perceptual phenomenon we call "sound" is created by *variations in air pressure*. When an object in the environment moves or deforms its shape, it will displace the air molecules around it. This temporary displacement is propagated through space by air molecules bumping into each other, creating a *sound wave*.

- These variations in air pressure provide information about the environment, so many organisms have evolved specialized organs - hearing organs - that allow these variations to be detected.

- Both vision and sound acquire information about the environment by detecting forms of energy that propagate in the form of *waves*. An important *distinction* between vision and hearing is that in the former case we rely mainly on *reflections* of light waves off of objects, whereas in the latter case we rely on mainly on waves *emanating directly from the objects themselves*.

- The intensity of sound, or *sound level*, is measured in *decibels* (dB). This scale is so named for Alexander Graham Bell, who first observed that the discriminability between sound levels depends on the ratio of their amplitudes, not on the absolute difference. Thus, the decibel scale measures the difference between two sound levels by the logarithm of the ratio between the two. Mathematically, this is expressed as

  $$\text{sound level in dB} = 20 \log_{10} \frac{a_1}{a_2}$$

  where a_1 is the amplitude of one sound and a_2 is the amplitude of the other. Thus, decibels are a *relative* measure. If you want to compute the absolute sound level, then you set $a_2 = 20$ micropascals, which is the threshold amplitude for human hearing (the average air pressure at sea level is approximately 100,000 pascals).

- Because many air pressure variations reaching the ear are the result of vibrating membranes, sound is often characterized by the *frequency* of vibration, or how many cycles per second (measured in Hz) the air pressure is changing. A sound that consists of a single sinusoidal oscillation of air pressure, $s(t) = \sin 2\pi f t$, is referred to as a *pure tone* (bear in mind though that there is nothing intrinsically "pure" about a pure tone - it is just a man-made term for a particular type of waveform that can be described in a simple mathematical form). Most physical objects have many resonant modes of vibration, and so give off sound waves that can be characterized as a mixture of pure tones at different frequencies, or *harmonics.*

- *Loudness, pitch*, and *timbre* are the subjective percepts we usually attach to the physical aspects of *intensity*, *frequency*, and *harmonic content*, respectively.

The ear

- The ear is subdivided into *outer*, *middle*, and *inner* portions, each playing a different role in transducing sound waves into the eventual electrical impulses that send information to the brain.

- The outer ear consists of the pinna and auditory canal, and is responsible for collecting sound and *funneling* it into the tympanic membrane. The shape of the pinna *filters* sound in such a way that can provide cues to the direction of the sound.

- The middle ear is responsible for impedance matching between the tympanic membrane and oval window of the cochlea, and consists of a number of small bones and muscles that transform mechanical displacements of the tympanic membrane into displacements of the oval window. The large ratio between the area of these two interfaces provides a huge source of leverage and *amplification* for overcoming the loss that would normally accompany an air/water interface.

- The inner ear consists of the liquid-filled *cochlea*, a snail-like structure containing the *organ of Corti.* Mechanical displacements at the oval window cause the fluid within the cochlea to move accordingly.

- As the fluid in the cochlea moves back and forth, it causes motions in the *basilar membrane,* which is the principal structure of the organ of Corti. The basilar membrane is narrow and stiff at the base of the cochlea and wide and floppy at the apex of the cochlea. These differences in width and stiffness cause each portion of the basilar membrane to have a different *resonant frequency*.

- *Hair cells* along the basilar membrane move back and forth as the basilar membrane moves. It is these back and forth motions of the hair cells that finally transduce mechanical movement into electrochemical signals.

- The different resonant frequencies at each portion of the basilar membrane give rise to a *frequency tuning* for each hair cell along the membrane. i.e., any given hair cell will become electrically excited only to a limited range of frequencies.

- Thus, the cochlea performs a *frequency analysis* of sound, and forms a *tonotopic representation* of sound by the fact that neighboring hair cells will have similar frequency tuning.