LING 576 Acoustic Phonetics
Spring 2009
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Topic number 3: Sound Waves & Speech Transmission
1/13/09

Reading:

Backus, John. 1969. The acoustical foundations of music. New York: W. W. Norton. Read pp. 32-44.

Denes, P.B. & Pinson, E.N. 1993. The speech chain. 2nd edition. New York: W.H. Freeman. Read pp 17-29, 39-45.

Borden, Gloria J., Katherine S. Harris & Lawrence J. Raphael. 1994. Speech science primer: Physiology, acoustics, and perception of speech. Baltimore: Williams & Wilkins. Read pp. 37-39.

1. Speech transmission

The "speech chain":

- Mental representation of speech is converted to a series of *articulatory instructions* to vocal organs (planning phase).
- Articulatory instructions are executed as movements of articulatory organs (articulatory phase).
- These movements result in rapid fluctuations in air pressure which propagate away from the speaker (acoustic phase).
- The fluctuations in air pressure gives rise in turn to different vibration patterns in the ear.
- These patterns are processed by the brain in determining what was said (perception phase).

Note: This information is only *one type* of information used by the brain in speech recognition & processing.

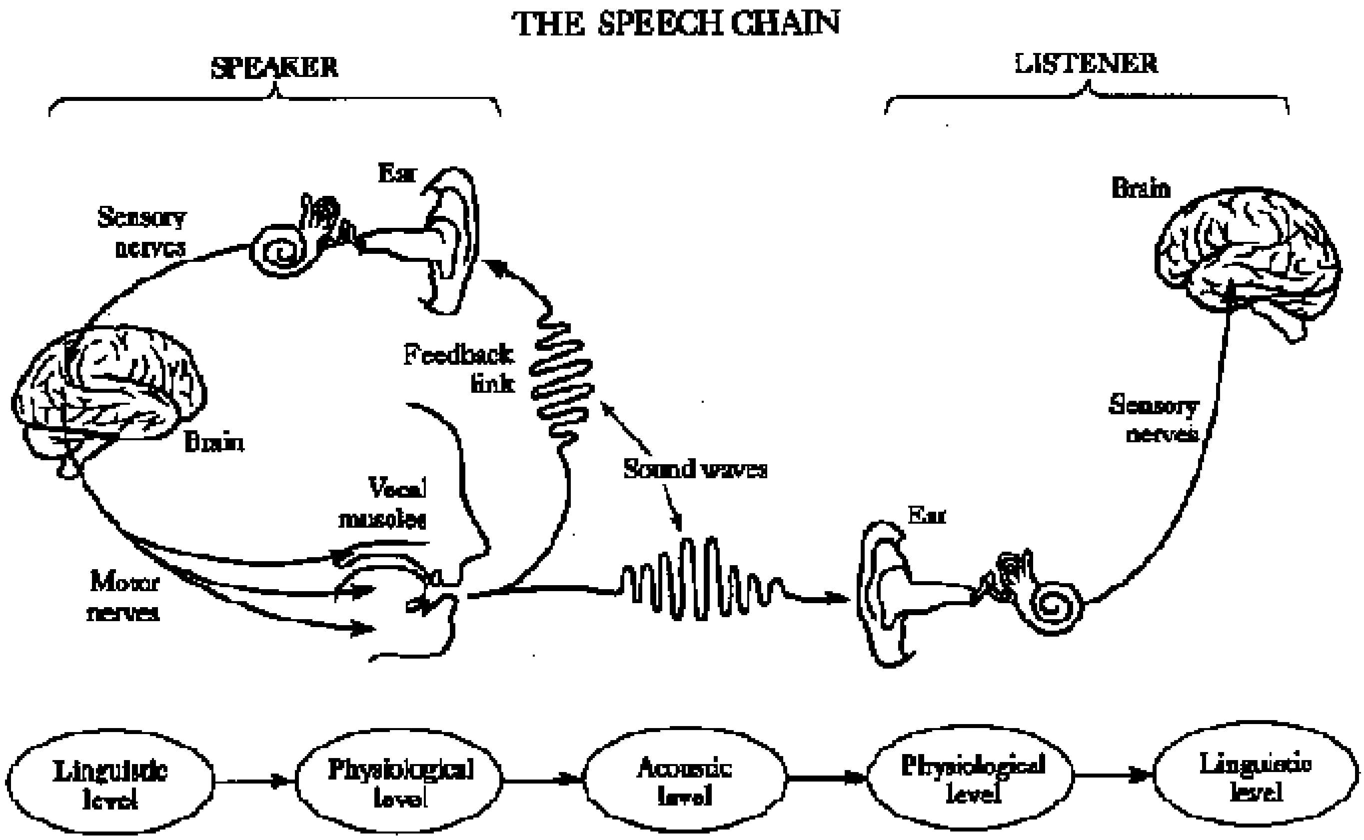


FIGURE 1.1 The speech chain: the different forms of a spoken message in its progress from the brain of the speaker to the brain of the listener.

-- From Denes & Pinson (1993:5)

Linguists generally assume that:

- Both speech production and speech perception operate on mental representations of speech consisting of abstract segments.
- The phonetic representation intended by the speaker is (generally) transferred reliably to the hearer.

Most of the time, linguists are not concerned with the details of *how* the phonetic representations are transmitted.

In practice, most work in linguistics proceeds as though the speaker's mental representation were *directly accessible* to the listener.

It is perhaps not very surprising that speakers' and listeners' brains should be capable of constructing the same mental representation of an utterance.

What is remarkable however is that during part of the transmission process all of the information needed to construct the phonetic representation must exist entirely in the form of vibration patterns of a very large number of air molecules.

2. Waves

Examples of waves:

A wave is the propagation of a disturbance through a medium, involving:

- A repeated pattern of movement of particles about some equilibrium position
- Transfer of energy among adjacent particles

In contrast to some other types of motion, waves do not involve the movement of individual particles of matter over long distances.

Note however that energy can sometimes be transmitted over very large distances by waves.

Some definitions:

- A *transverse* wave is one in which the vibration of particles is *perpendicular* to the direction in which the disturbance proceeds.
- A *longitudinal* wave is one in which the vibration of particles lies *in the same direction* as the disturbance.

Some examples in detail (http://physics-animations.com/Physics/English/waves.htm):

- Water waves
- Metal spheres connected by springs (transverse)
- Metal spheres connected by springs (longitudinal)

For additional illustrations, see Backus (1969:32-40) and Denes & Pinson (1993:25-29).

3. Fundamental wave quantities

Waves are typically described in terms of their amplitude, period, frequency, wavelength and velocity.

- The *amplitude* of a wave (measured in meters or other length units) is the (maximum) distance by which vibrating particles are displaced from their equilibrium position.

Example: If the distance from crest (highest point) to trough (lowest point) in a water wave is 6 feet, what is the wave's amplitude?

For sound waves this cannot be directly observed. A different measure of amplitude (discussed below) is used instead.

- The *period* of a wave is the length of time it takes to complete one cycle in the vibration pattern.
- The *frequency* of a wave is the number of full cycles completed per second.

If F is the frequency in cycles per second, and T is the period in seconds, then $F = 1/T$.

Example: If it takes 4 milliseconds to complete one cycle of a wave, what is the wave's frequency in cycles per second?

Note: in dealing with speech sound waves, time is most commonly measured in milliseconds, and frequency in cycles per second, or hertz (abbreviated Hz).

- The *wavelength* of a wave is the distance between adjacent corresponding points on the wave, e.g. the distance between adjacent crests (amplitude maxima) or adjacent troughs (amplitude minima).
- The *velocity* of a wave is the rate at which the disturbance propagates.

If V is the velocity, F the frequency, and λ the wavelength, then these three quantities are related by the formula:

$$V = \lambda F$$

Example: If a wave has a velocity of 500 feet per second and a wavelength of 10 feet, what is its frequency?

4. Sound waves

Sound waves involve the propagation of a disturbance of air molecules. Propagation of the disturbance takes place as a result of collisions among neighboring air molecules.

Sound waves are longitudinal. The pattern of vibration is similar in key respects to that of the longitudinal spring & sphere wave pattern seen earlier on the web site http://physics-animations.com/Physics/English/waves.htm.

The back-and-forth motion of air particles leads to an alternating pattern of 1) points in space where molecules are compressed together (*compressions*) and 2) points at which the molecules are further apart (*rarefactions*).

Example: Where are the compressions and rarefactions in the diagram below?

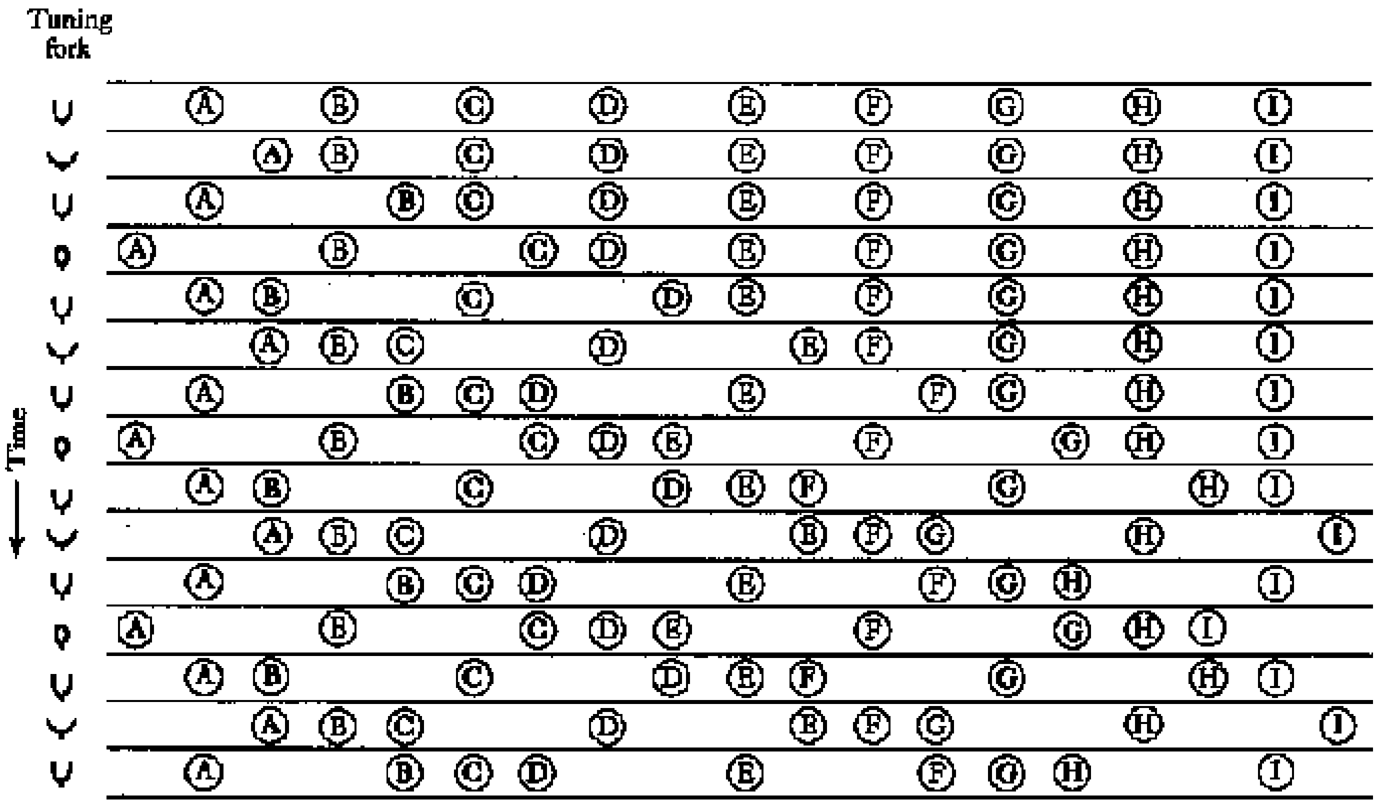


FIGURE 3.8 The propagation of a wave along the particles of a medium.

-- From Denes & Pinson (1993:27)

Another way of looking at it: At any given point in space, the air molecules will be alternately compressed together and pulled apart.

The time that elapses between two maximum states of compression or between two minimum states of compression (rarefactions) at that point is the wave's period.

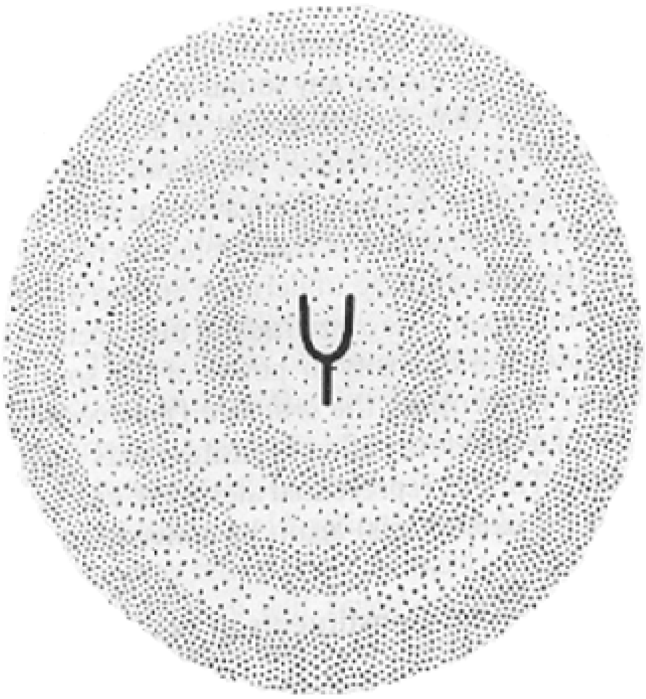
At a point of compression, the air *pressure* will have its maximum value for the sound in question; at a point of rarefaction it will have its minimum value.

Note that the maximum pressure value (at a compression) is higher than ambient atmospheric pressure, while the minimum pressure value (at a rarefaction) is lower than atmospheric pressure (i.e., has a negative value, if atmospheric pressure is taken as zero).

Sound wave cycles are symmetric; the time that it takes for air pressure at a given point to rise from its minimum to maximum values (= half a cycle) is the same length of time it takes for it to fall again from maximum to minimum.

Microphones record sound waves by converting variations in sound pressure to variations in electrical voltage.

In contrast to the simple examples we have looked at, real sound waves are three-dimensional; a sound disturbance spreads out in all directions from the source.



-- From Borden et. al. (1994:29)

5. Sound pressure, amplitude & intensity
How is the strength ("loudness") of a sound measured?

Intuitively, this should depend on how far one is from the sound source.

A natural measure (commonly used in physics) is *intensity*. Intensity is defined as the *power* (rate at which energy is being generated) expended *per unit area.*

Intensity is commonly measured in watts per square centimeter (watts / cm^2).

A practical problem with using intensity is that it is not that easy to measure directly.

A more useful measure in practice is *pressure.*

The pressure exerted by a sound disturbance is the *force* it exerts *per unit area.*

Pressure is commonly measured in dynes per square centimeter (dynes / cm^2).

The range over which both sound intensity and sound pressure vary for audible sounds is enormous.

- Audible sound intensities vary from about 10^{-16} watts / cm^2 to about 10^{-4} /cm^2.
- Audible sound pressures vary from about .0002 dynes / cm^2 to about 200 dynes / cm^2.

These enormous ranges of variation pose practical problems for using either intensity or pressure scales to directly quantify sound strength.

"If a sound pressure varied over a range of 10 to 1000 dyne/cm^2, it would be difficult to plot the range on any reasonable sized paper. If we, for example, plotted this range of amplitude variation using a scale value of 1mm for each dyne/cm^2, the graph would be a metre high. If we wanted to be able to plot a range of amplitudes that corresponded to the total dynamic range of the human auditory system, we would need a graph that was about 100 metres high."

-- Lieberman & Blumstein (1988:28).

A more useful measure is one that uses a condensed logarithmic scale.

This quantity is called *sound pressure level*. It is measured in *decibels* (dB).

SPL (in dB) $= 20\ (\log_{10} (P_1/P_2))$

Note: Sound pressure level (measured in dB) is not the same thing as sound pressure (measured in dynes / cm^2).

Strictly speaking, sound pressure level is a *relative* quantity.

If two sounds have pressure values given by P_1 and P_2 respectively, then the formula above can be used to compute the decibel difference in their sound pressure levels.

Note: logarithms are exponents. The logarithm of a number is the exponent that the number 10 must be raised to yield that number.

If $x = \log_{10} y$, then $10^x = y$.

Where necessary, logarithms can be determined with a calculator.

Example: If the pressure exerted by sound 1 is 100 times greater than that exerted by sound 2, how many decibels greater is the SPL of sound 1 than that of sound 2?

Although sound pressure levels are in principle relative quantities, it is possible to define an *absolute* SPL in practice by adopting a fixed reference pressure as P_2.

A reference pressure (P_r) commonly used in practice is the pressure level of a sound that is just barely audible, which is about .0002 dynes/cm^2:

P_r = .0002 dynes/cm^2

An "absolute" SPL for some sound whose pressure is P is then definable by using this reference pressure P_r as P_2:

Absolute SPL (in dB) = 20 ($\log_{10}$ (P/P_r))

Or, more specifically:

Absolute SPL (in dB) = 20 ($\log_{10}$ (P / .0002 dynes/cm^2))

Example: What is the sound pressure level of a sound that has a pressure of 2 dynes/cm^2?

Some sound pressure levels of real world sounds (Borden et. al. 1994:39):

0 dB	Threshold of hearing
20 dB	Rustling of leaves
30 dB	Whisper (3 feet)
35 dB	Residential area at night
45 dB	Typewriter
60 dB	Conversation
75 dB	Shouting, singing (3 feet)
100 dB	Approaching subway train (from platform)
120 dB	Jet airplane (standing on runway)
130 dB	Painfully loud sound

The values in the table above are based on sounds within a few feet of the listener.

In addition to allowing for a more practical measurement range (about 0 to 130 instead of 10^{-4} to 10^2), the decibel SPL scale has the advantage that it corresponds fairly closely to how humans hear differences in *loudness*. That is, a given decibel increase in SPL always seems to increase the loudness by (roughly) the same amount.

References

Backus, John. 1969. The acoustical foundations of music. New York: W. W. Norton.

Borden, Gloria J., Katherine S. Harris & Lawrence J. Raphael. 1994. Speech science primer: Physiology, acoustics, and perception of speech. Baltimore: Williams & Wilkins.

Denes, P.B. & Pinson, E.N. 1993. The speech chain. 2nd edition. New York: W.H. Freeman.

Lieberman, Philip & Sheila E. Blumstein. 1988. Speech physiology, speech perception, and acoustic phonetics. Cambridge: Cambridge University Press.