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AN ACOUSTICS CURRICULUM FOR A PHONETICS COURSE

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Any course teaching introductory linguistic phonetics at the graduate level must include some discussion of the acoustics of speech even though acoustic phonetics may not be a major topic of the course. This poses a serious problem since such a course must also devote considerable time to traditional articulatory phonetics, yet the students who enter graduate programs in linguistics normally have a minimal background in mathematics and physics. Thus the instructor cannot breeze through a conventional mathematical presentation of basic acoustics and expect the students to really understand sound and the acoustic theory of speech production.

It is essential, however, that graduate students in linguistics have a clear grasp of how articulatory gestures can be encoded into sound. Only with such an understanding can students evaluate, for example, the evidence concerning the theoretical issue of active versus passive perception of speech. Standard generative phonological theory (Chomsky and Halle 1968) assumes an active, synthetic model of speech perception, yet some other approaches assume a passive model (Jakobson, Fant and Halle 1952; Stevens and Blumstein, in press). Thus the evolving concept of the scope of phonological theory (cf. Dinnsen 1979) is not independent of the evolving view of the psychological process of speech perception (cf. Pisoni 1980, and Stevens and Blumstein, in press). In this theoretical context, a hazy grasp of how articulatory gestures structure speech sounds encourages one to assume a constructive or analysis-by-synthesis model of speech perception since articulatory-phonetic information may seem to be impossible to recover from the signal. Thus to be ignorant of speech acoustics may unwittingly provide prejudice regarding matters of theoretical interest to phonology.

I have been developing a curriculum on the acoustics of speech for a graduate level introductory phonetics course. My constraints were that the material should require as little algebra and as much visualization of concepts as possible. The goals of this curriculum are:

1. to convey an appreciation of sound as a rich multidimensional field capable of carrying many kinds of information simultaneously.

2. to give students an intuitive and mechanical grasp of how the articulatory cavities act as resonators for sound. A clear understanding of the acoustic theory of speech production helps students appreciate the implications of the theory for phonology and phonetics.

3. to teach some of the basic technical concepts borrowed from physics and engineering that are widely used in this field. These include terms like pole, zero and transfer function.

4. to provide a basis for understanding sound spectrograms -- both how they are produced and how to interpret them.

In order to concentrate on these goals and to complete this material in three or four weeks of lecture (at 3 hrs/wk), several topics that are usually taught with this material are ignored or glossed over. These include such matters as psychophysics, the dB scale and the relationship between amplitude and intensity.

The lectures are structured around a set of handouts and include a large number of concrete illustrations and demonstrations with a slinky. The slinky is especially useful since the waves move so slowly. By using either transverse waves (when stretched across the floor) or longitudinal waves (when suspended from the hand), a great variety of wave and resonance phenomena can be demonstrated with a small amount of practice. Choice of text materials for this portion of the course is difficult since, depending on their background, students have quite different needs. My solution is to give students an annotated bibliography of recommended materials with suggestions about which ones to read. In addition all students are required to read chapters 2 through 5 of the Lieberman text (see Appendix C). The bibliography that is circulated to students is presented in Appendix C.

The list of topics discussed during this portion of the course is presented in Appendix A. This outline will help the reader place in better perspective the set of handouts presented in Appendix B which may be of use to other instructors of this material. The handouts included here deal with most sections of this curriculum and are distributed in class as both a guide and a memorandum for the lecture. If students must take their own notes from blackboard illustrations, they require a great deal of time and still may make many errors. In order to cover material such as this in a hurry, it is very useful to present students with fairly complete lecture notes. In addition to the lecture section, students also meet one hour a week for a laboratory course in which they are first instructed in making high quality sound recordings and then in how to make spectrograms of recorded speech.

Students then work in teams of three or four to carry out a previously developed experiment on the phonetics of Japanese. Altogether the laboratory curriculum alone takes about seven weeks while the lecture sequence requires four.

Conclusions

Given the difficulty of teaching acoustics to graduate students in linguistics through the conventional approach via mathematics, there is perhaps a tendency to leave these matters for an advanced course and to concentrate in the introductory course on classical articulatory phonetics. But linguists need a much deeper understanding of the relationship between gestures and physical sound, since without it an important link is absent from the "speech chain". It is hoped that these suggestions for topical organization and these handouts will prove helpful to other instructors.

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APPENDIX A

Outline of Curriculum in Acoustics

I. Basic acoustics

*A. Wave motion
vibration; acoustic medium; wave types

*B. Wave cycle and graph-
period; amplitude; speed; wavelength; frequency; phase angle

*C. Wave front motion-
propagation; diffraction; split reflection; additivity

*D. Spectral representation vs. waveform-
equivalence of the two graphs; Fourier's theorem; some common wave types and spectra; wave damping vs. spectral spread

II. Shaping sound

*A. Acoustic filter: an operation on sound spectrum; dependence on additivity concept; input-output concept; graph of transfer function

B. Resonator as a filter-
quarter- and half-wave uniform tubes and strings

C. Glottal oscillator as a voice source-
myoelastic-aerodynamic theory; source spectra

*D. The Acoustic Theory of Speech Production

*E. Implications of the acoustic theory of speech production

III. Acoustic analysis of speech sounds

A. Using a filter (resonator) for analysis

B. Sound spectrograph-
wide-band and narrow-band analysis; frequency and intensity scales

C. Running spectral displays (Searle; Kewley-Port)-
audition-based filters and scales

D. Common speech sounds in spectrograms

*indicates that handout material is available in Appendix B.

APPENDIX B

Handouts

Handout 1 - Waves and Sound

Handout 2 - Sound Waves and Sound Spectra

Handout 3 - Acoustic Filters

Handout 4 - The Acoustic Theory of Speech Production

WAVES AND SOUND

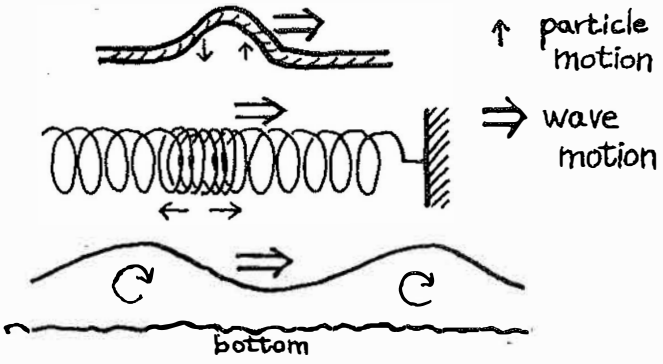
I. Wave motion: vibration of particles in a medium

A. The acoustic medium must contain particles that are elastic, i.e., "sloshy" or "springy".

B. The motion of each particle sets adjacent particles in motion. Energy is transferred over great distances in the medium by means of minute motions of particles.

C. Motion of particles with respect to motion of the wave front. Despite these differences all types exemplify the same abstract properties of waves.

1. transverse - e.g., a rope, slinky
2. longitudinal - e.g., sound, slinky
3. combination - e.g., surface waves in shallow water



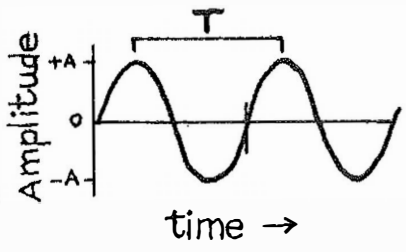
D. Number of dimensions of wave propagation

1. One dimension: Waves in a rope or slinky.
2. Two dimensions: Surface ripples in a pond.
3. Three dimensions: Sound in air; earthquakes.

II. The wave cycle and its graph

A. The period (T) is the duration between any point on a periodic wave and the same point on the next cycle.

B. The amplitude (A) is the maximum displacement of particles from their rest position. The greater the A, the greater the rate at which it can transfer energy. It has no relation to wave speed, period or frequency. Related to perception of "loudness".

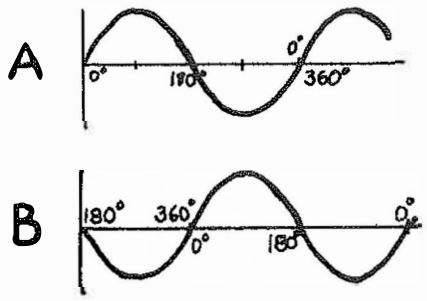


C. The speed of wave front motion (s) depends on the medium and is independent of A, T, or f. Waves are slow in slinkies, faster in air (1100 ft/sec), and sound travels 4 times faster in water than in air.

D. The wavelength (λ) is the distance between corresponding parts of adjacent pulses, i.e., the distance a wave travels in one period. Thus, it's proportional to both the speed and period: $\lambda = sT$, since distance = rate X time.

E. The frequency (f) is the number of cycles (or periods) in one second. Thus, it is the inverse of the period, $f = 1/T$, $T = 1/f$. The shorter the period, the higher the frequency. It is used simply because it is more convenient to deal with large whole numbers than with minute fractions. Closely related to perception of "pitch".

F. Phase angle refers to points within a single cycle of a wave. By analogy to a circle, a complete cycle is 360°. Two waves are in phase if they are 0° (=360°) apart measured from the same point in each. A and B here are 180° out of phase. [Thus two sinusoids can differ only in f (or T), A and ϕ (phase).]



III. Properties of wave front motion

A. Propagation. Once initiated, waves will travel through a uniform medium at a constant speed. In a 3-D medium like air the fronts are expanding spheres that decrease in A with the square of the radius. Thus at 2 ft from its source a wave has 1/4 the amplitude at 1 ft, at 3 ft it is 1/9.

B. Diffraction. Waves tend to bend around corners. Low frequency waves bend better than high frequency waves. In a tube, waves move as plane fronts that sweep around corners. Thus a bent tube is equivalent to a straight one.

C. Splitting. If resistance of the medium to passage of the wave changes abruptly, part of the wave will be reflected and part will be transmitted to the new medium.

1. "hard boundary". If the new medium has greater impedance to wave propagation than the old, waves will reflect. The reflected wave will have opposite phase (changed by 180°) from the incident wave.
   Examples:
   a) Reflection of a transverse slinky pulse when the other end is held firmly. A right-handed pulse reflects as a left-handed pulse.
   b) Sound waves reflect when they strike a wall.

2. "soft boundary". If the new medium has less impedance than the old, waves will reflect. The reflected wave will have the same phase as the incident wave.
   Examples:
   a) A suspended slinky has a soft boundary at its lower end. A right-handed transverse pulse shaken down the slinky reflects back up on the right-hand side.
   b) Waves travelling down a tube reflect from the boundary with the open air. Part of the energy is transmitted to the outside and part is reflected back into the tube to set up a "ringing" (resonance) in the tube.

3. The ratio of transmitted to reflected energy depends on the degree of difference in impedance between the old and new medium.
   Example:
   When sound strikes a heavy wall, some energy is transmitted (since some sound can be heard on the other side) and some is reflected (contributing to reverberation or echo in the room). Sound is transmitted much better through a window pane. Since low frequencies transmit better into solids from the air than do high frequencies, voices through a wall or window sound "muffled".

D. Additivity (or superposition). If two waves occupy the same place at the same time, the resulting wave is simply the sum of the two waves. The positive and negative are added.

1. very different frequencies

like water waves climbing over each other

2. same frequency

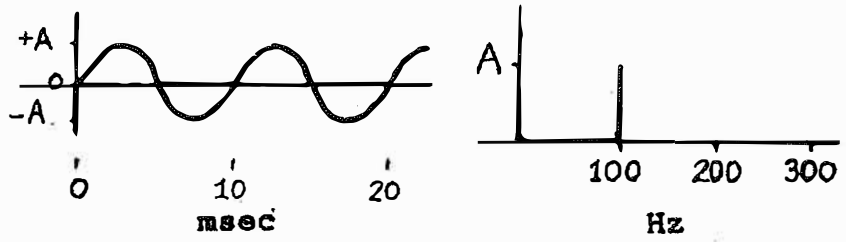
a) in phase, "reinforcement"

b) out of phase, "interference"

(Handout 2 - 1)

SOUND WAVES AND SOUND SPECTRA

A. Sinusoidal wave - characterized by f, A and ϕ (frequency, amplitude and phase). Described auditorily as a "pure tone". Mechanically, it is the simplest kind of periodic motion.



The spectrum shows the amplitude and frequency of the sinusoidal wave.

B. Fourier's Theorem. A periodic wave of any shape may be approximated as close as you please by adding together (superimposing) appropriately selected sinusoidal waves (with parameters f, A and ϕ) whose frequencies are whole number multiples (harmonics) of the fundamental frequency of the wave being analyzed.

C. Spectral display. A graphic representation of the frequency, amplitude and phase of the sinusoidal waves one could add together to create a particular waveform.

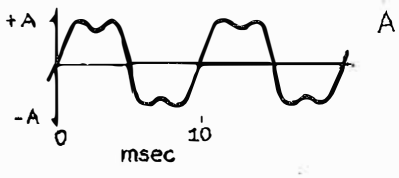
The phase is typically omitted in discussions of speech because human listeners are not much affected by changes in it.

D. Non-sinusoidal waves and their spectra.

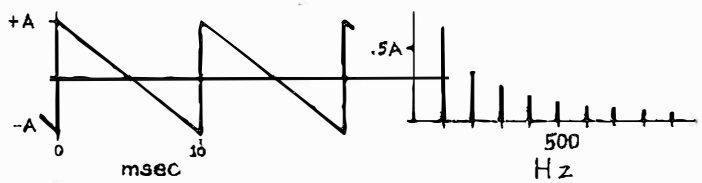
1. Periodic waves (perceived as hum, buzz or musical tone)

WAVE SPECTRUM

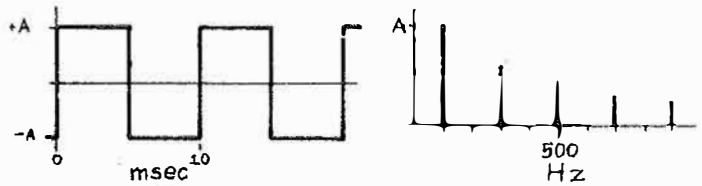
pure tone plus third harmonic

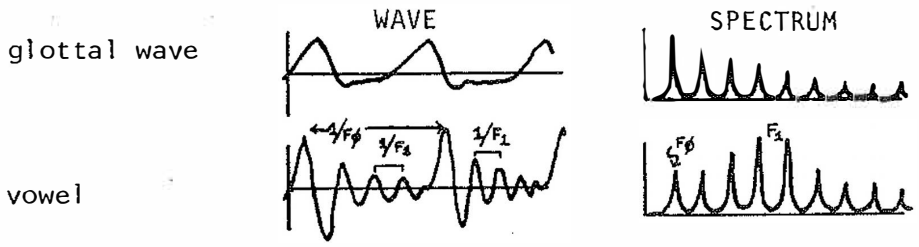


sawtooth



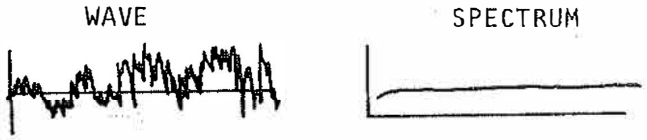
square wave



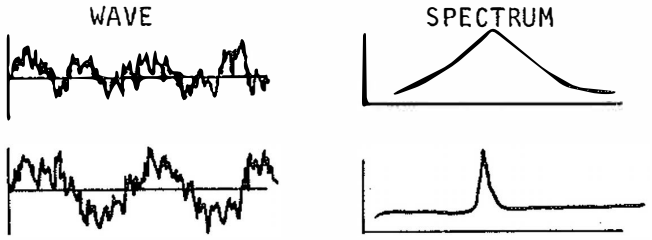


Only the last two represent characteristic naturally produced sounds. The others are produced by electrical circuits.

2. Nonperiodic waves

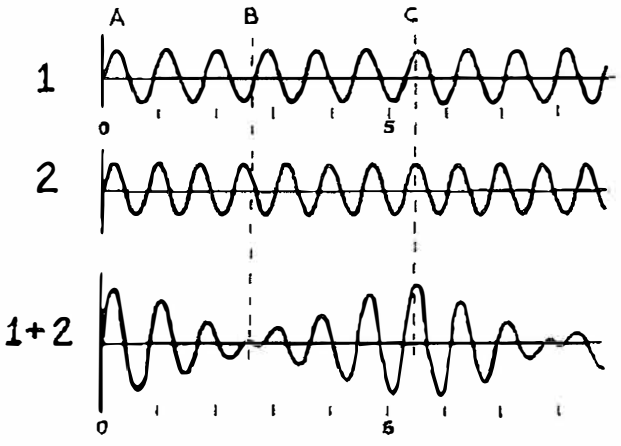


The horizontal line in the spectrum means that all frequencies are present in equal amounts.

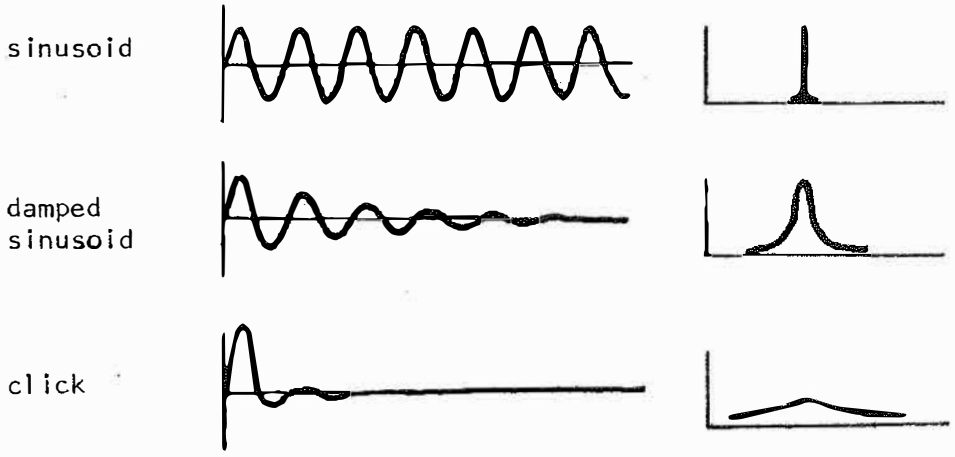


3. Spectral correlates of rapid change in waveform

a) The sum of two sinusoids of slightly differing frequencies produces periodic damping (beats).



b) The spectrum of a rapidly damped periodic wave includes energy spread continuously to adjacent frequencies.

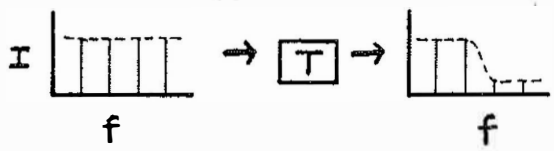


ACOUSTIC FILTERS

A. Input-output device transforms any input in a characteristic way.

equation form	$y' = 3y$	output = three times the input
black box	$y \rightarrow \boxed{T} \rightarrow 1/2y$	T cuts inputs in half, that is, $y' = y/2$
two kinds of input	$(a+b) \rightarrow \boxed{T} \rightarrow (2a + b/2)$	T doubles a but reduces b by 1/2

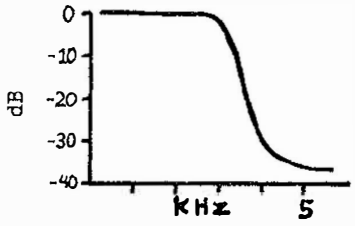
Since the sinusoidal components of a complex wave are mutually independent and summed (just like a and b above), a spectrum can be used to represent the input and output.



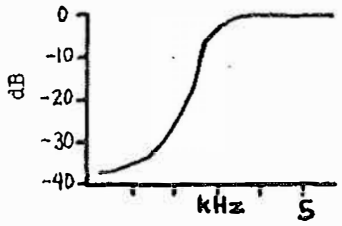
A description of T is called the transfer function.

B. Acoustic filter. Selectively modifies the intensity (or amplitude) of one region of the spectrum.

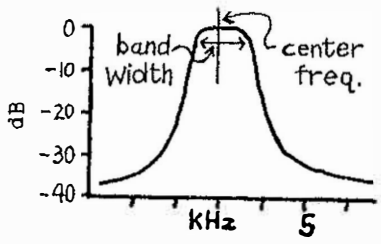
Low-pass filter



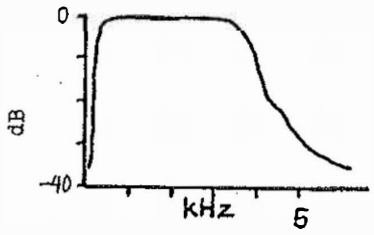
High-pass filter



Band-pass filter



Telephone system filtering



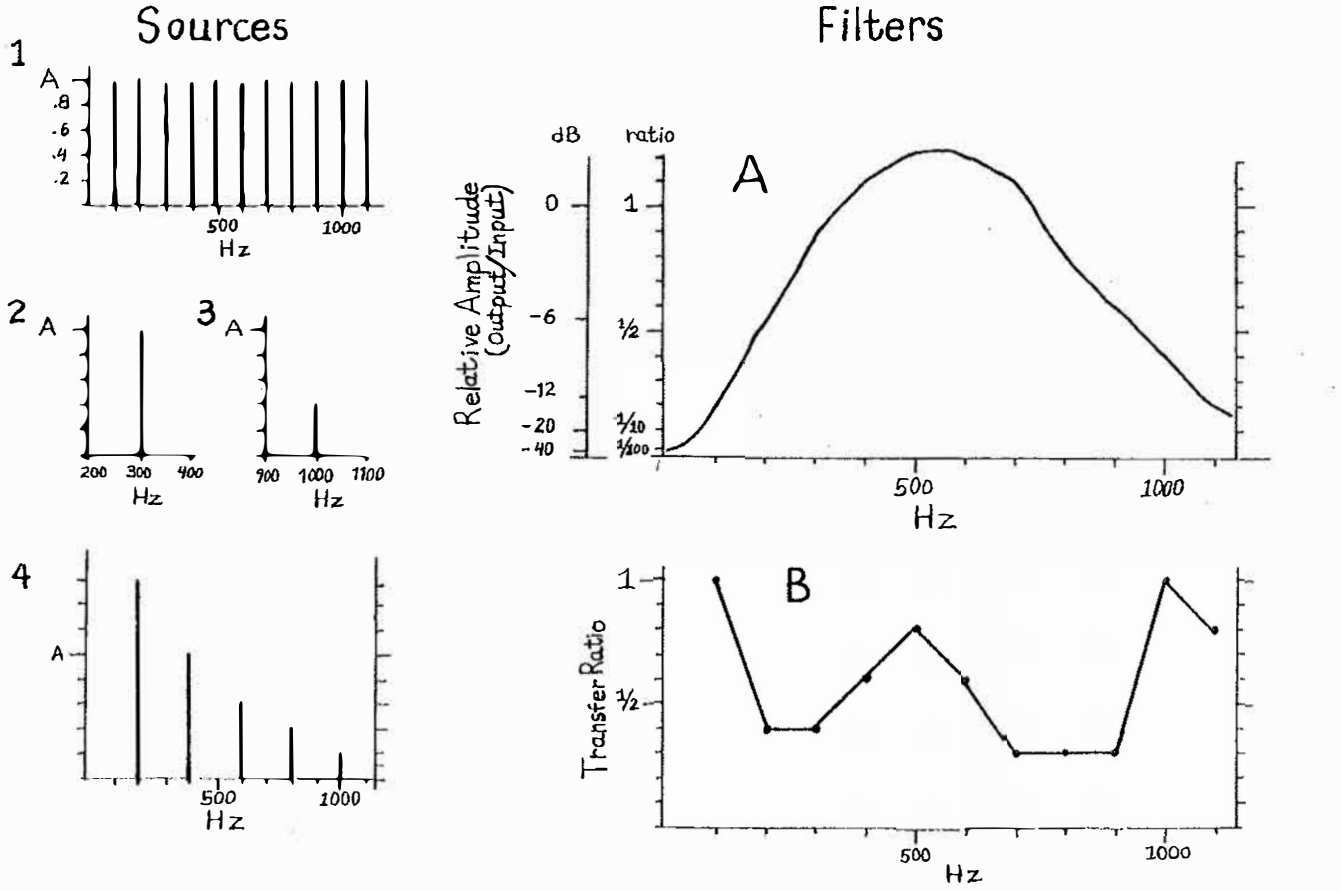
BW = 200 - 3500 Hz

(Handout 3 - 2)

PROBLEMS ON ACOUSTIC FILTERS

1. Using a single sheet of graph paper, plot an output spectrum for each of the following sound sources passing through each of the two filters. Output = input X transfer function of filter. Four sources X two filters yields eight graphs.

2. On the basis of your results, consider which of your output spectra reveal information about the shape of the filter. Write a brief essay about how sources and filters must be matched to permit their output to reveal the shape of the filter itself.



THE ACOUSTIC THEORY OF SPEECH PRODUCTION

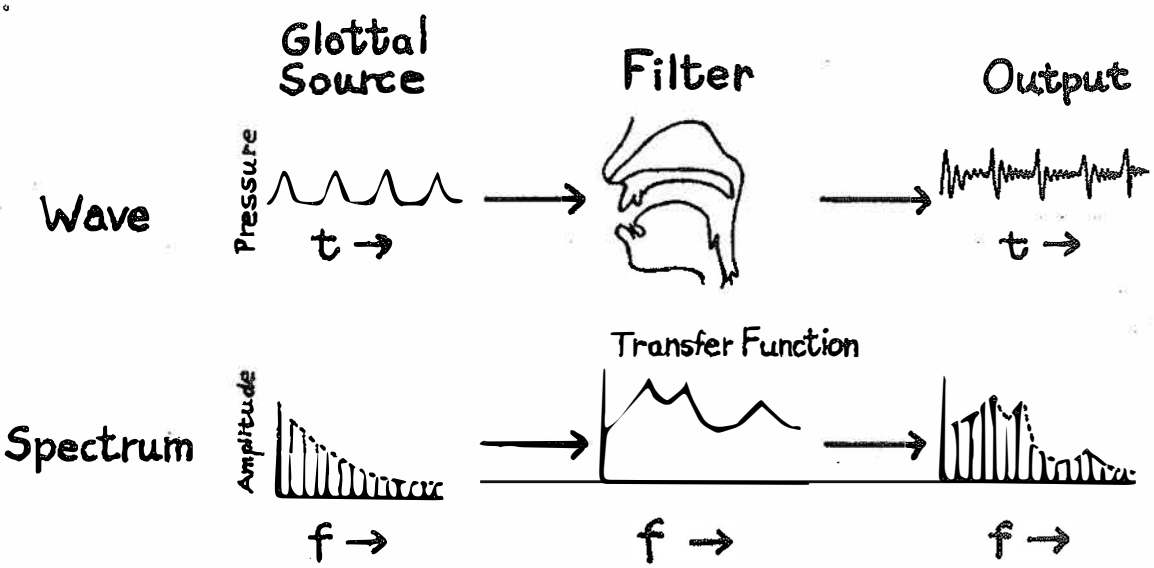
A. Algebraic statement

$$R(f) = S(f) * T(f)$$

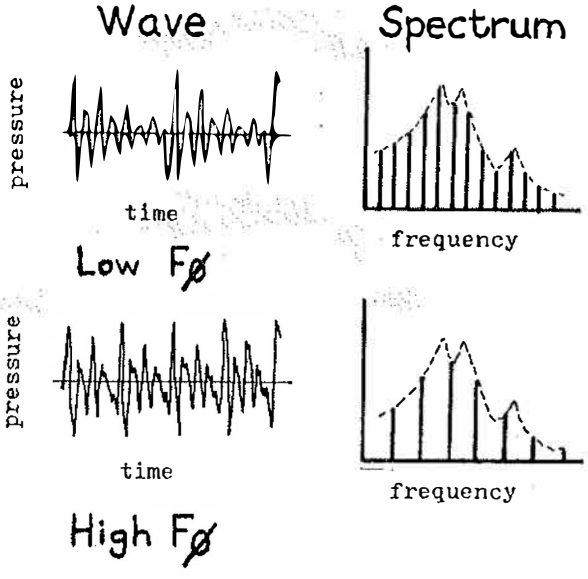
where
- R "radiated signal"
- (f) "as a function of frequency"
- * means multiply

thus
- R(f) simply means the spectrum of the radiated wave.
- S(f) = source spectrum
- T(f) = transfer function

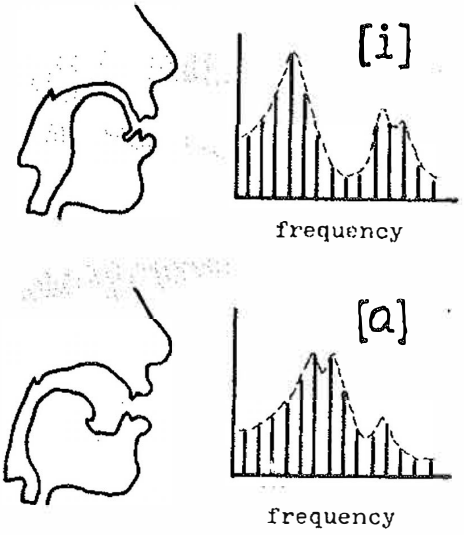
B.



C. Change only in source

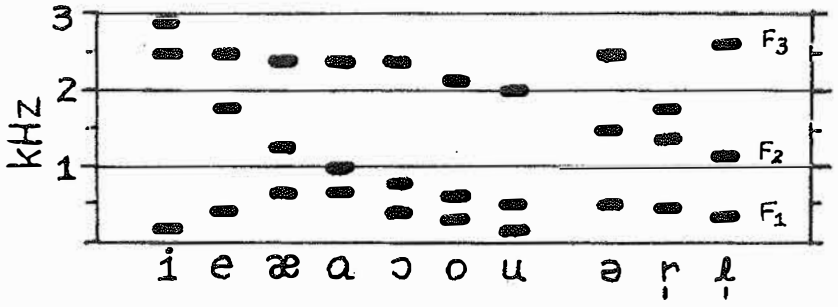


D. Change only in filter



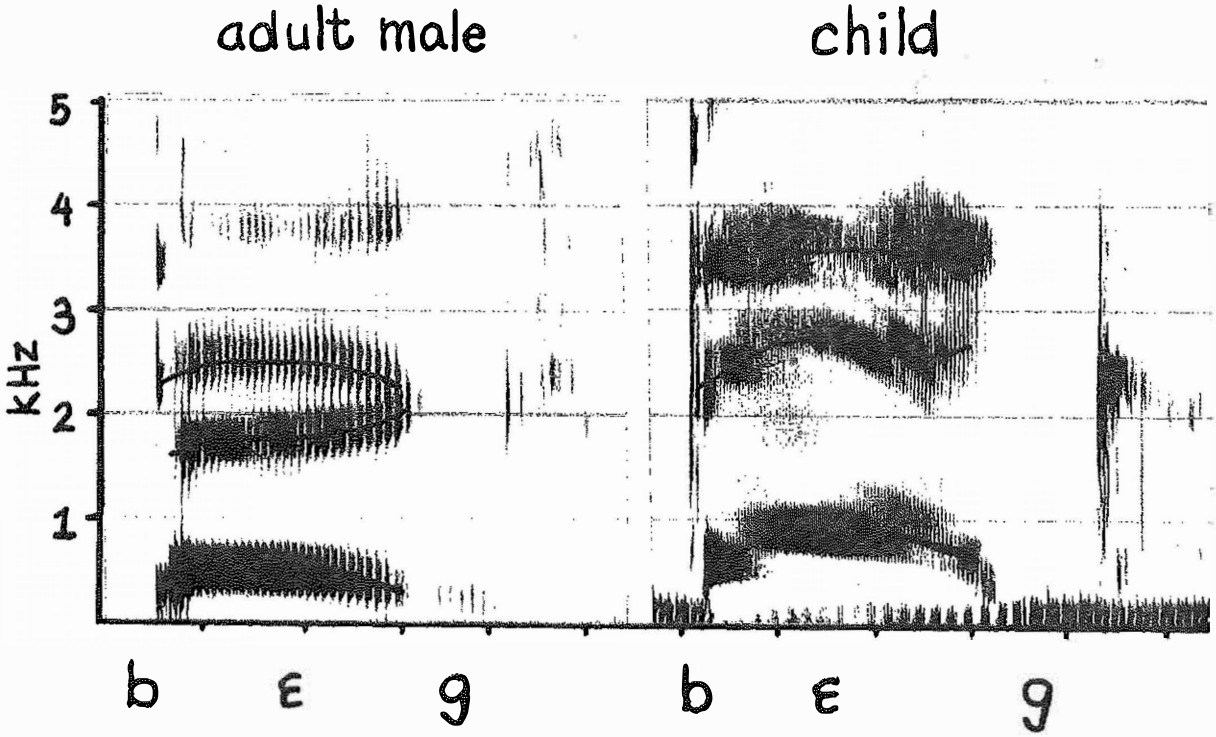
IMPLICATIONS OF THE ACOUSTIC THEORY OF SPEECH PRODUCTION

A. Changes in vocal tract <u>shape</u> cause changes in its filter. Here are formant centers for some vowel-like sounds of a male speaker:

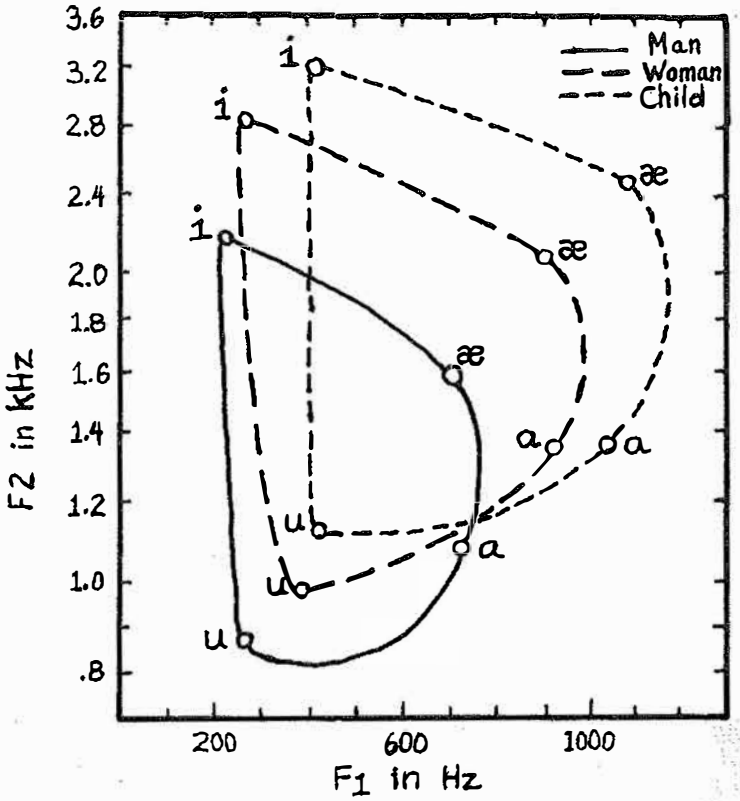


B. Differences in overall vocal tract <u>size</u> cause differences in acoustic output for a given gesture <u>and</u> for phonetically same speech sounds.

1) Here are sound spectrograms of the word <u>beg</u> produced by an adult male and his 5-year-old daughter. The child's production has the same phonetic vowel but much higher formant frequencies.

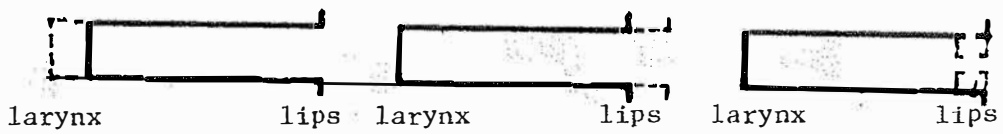


2) Thus, if a full set of vowels is plotted on the F_1 X F_2 plane, there are considerable differences in formant values between adult men, women and children that are due to differences in vocal tract size.



C. Certain pairs of articulatory gestures have essentially identical acoustic effects.

1) Larynx lowering = lip protrusion = lip rounding.
All lengthen the vocal tract acoustically and thus lower formants.



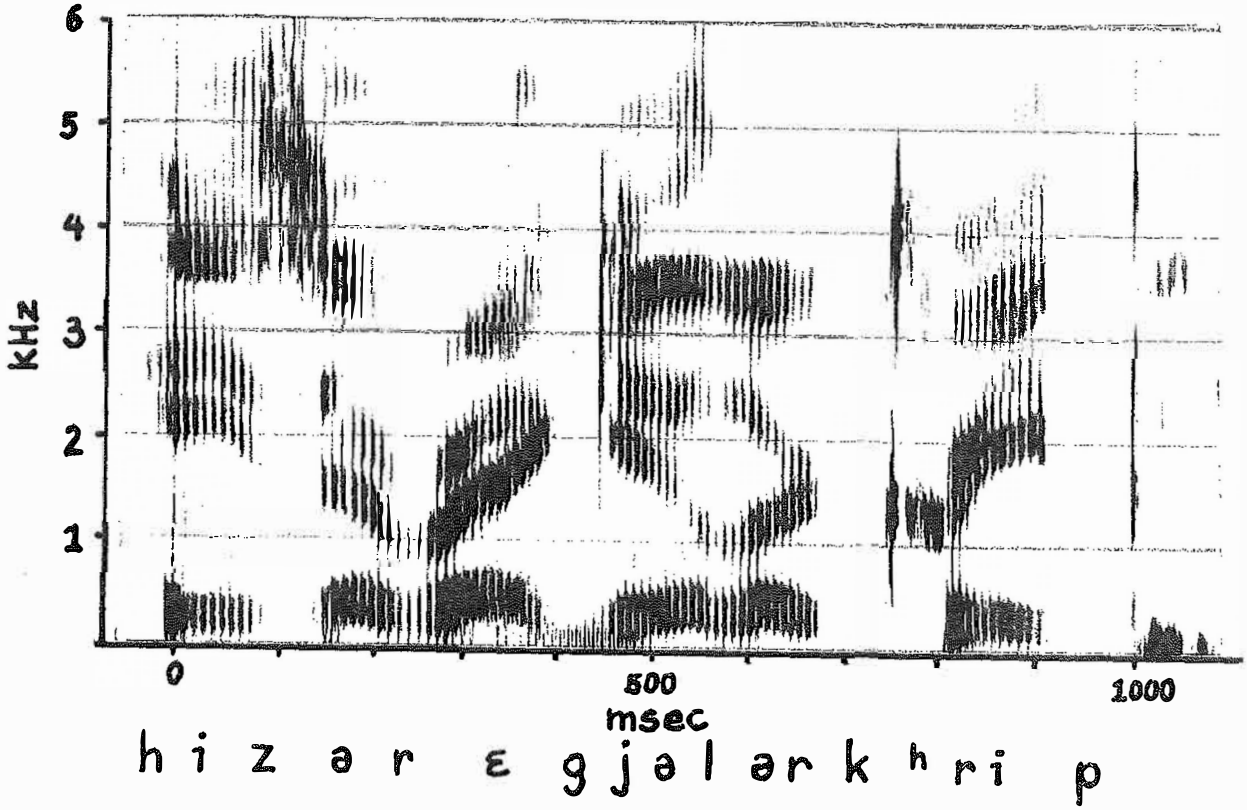
2) Tongue raising (relative to the mandible) can be traded for mandible raising (relative to the skull).

jaw high - tongue low

jaw low - tongue high

3) Bunched-tongue [r] = retroflexed-tongue [r].

D. Since articulators move in overlapping time-varying gestures, acoustic correlates of most phonetic "segments" are also time-varying and overlapping rather than static and discrete. Note the dynamic formant motions and the absence of any steady state corresponding to many of the segments in the sentence "He's a regular creep".



APPENDIX C

Acoustics of Speech:

Recommended Readings

Basic Introductions

Denes, Peter and E. Pinson. 1963/1973. *The Speech Chain*. New York: Doubleday.

Introductory. The classic book on this topic. Very well written but very elementary.

Ladefoged, Peter. 1962. *Elements of Acoustic Phonetics*. Chicago: University of Chicago Press.

Chapters 1 - 5 are on basic acoustics and are very clear.

Fry, D. B. 1979. *The Physics of Speech*. London: Cambridge University Press.

Excellent, up-to-date introduction. Pages 1 - 60 cover basic acoustics very carefully and non-technically with many concrete examples.

Lieberman, P. 1977. *Speech Physiology and Acoustic Phonetics*. New York: Macmillan.

Chapters 3 and 4 present a good nontechnical introduction to acoustics of speech.

Borden, G. J. and K. S. Harris. 1980. *Speech Science Primer: Physiology, Acoustics and Perception of Speech*. Baltimore: Williams and Wilkins.

An excellent survey of many topics - especially of the physiology of speech production. Good discussions of acoustics are found in Chapter 3 and pp. 74-123. There is also a succinct summary of acoustic cues for various classes of speech sounds plus a description of research instruments such as the sound spectrograph. Particularly valuable are the many excellent topical bibliographies.

Diamond, Shelton. 1970. *Fundamental Concepts of Modern Physics*. Amsco.

A very clear and widely-marketed high-school review text. To really understand acoustics you must understand simple mechanics. I recommend chapters 1 - 7, 11 and 12. Be sure to do some of the problems.

Joos, Martin. 1948. *Acoustic Phonetics*. Linguistic Society of America Monograph No. 23. Baltimore: Waverly.

The introduction to acoustics is dated but still quite good. A classic monograph full of provocative ideas about phonetics and speech perception. Some ideas have held up over the years, others have not.

Roederer, Juan. 1975. *The Physics and Psychophysics of Music*, 2nd edition.

Outstanding text with good material on psychophysics. For the more technical student.

Backus, John. 1969. *The Acoustical Foundations of Music*. New York: Norton.

An outstanding text by a physicist for a liberal arts readership that doesn't shrink from difficult concepts. Especially recommended are chapters 1 - 7, 9 and 15. There's not much on speech but then 'acoustics is one'.

Benade, Arthur. 1976. *Fundamentals of Musical Acoustics*. New York: Oxford University Press.

Another very good introduction for musicians by a well-known researcher in musical acoustics. Good chapters on voice and room acoustics.

Speech Acoustics

Broad, David and Gordon Peterson. 1974. The acoustics of speech. In Lee Travis (ed.) *Handbook of Speech Pathology and Audiology*, 2nd edition. New York: Appleton - Century - Crofts.

A more advanced review of basic acoustics, good introduction to acoustic theory of speech production and discussion of the speech signal for various speech sounds.

Fant, Gunnar. 1960. *Acoustic Theory of Speech Production*. The Hague: Mouton.

A classic, and very difficult for a nonengineer. Don't be frightened, just read Chapter 1.1, skip 1.2 and push slowly through other portions. You can still get a lot from it because he always explains discursively what he has done with mathematics.

Fant, Gunnar. 1968. Analysis and synthesis of speech processes. In B. Malmberg (ed.) *Manual of Phonetics*. Amsterdam: North-Holland. pp. 173-277.

A good review but recommended as a reference, not a text.

Heinz, John. 1974. Speech acoustics. In Abramson (ed.) *Current Trends in Linguistics*, vol. XII (T. Sebeok, General Editor). The Hague: Mouton. pp. 1817-56.

Highly recommended as a fairly technical overview.

Collections of Articles

Lehiste, Ilse. 1967. *Readings in Acoustic Phonetics*. Cambridge, MA: MIT Press.

Fry, D. B. 1976. *Acoustic Phonetics: A Course of Basic Readings*. Cambridge: Cambridge University Press.