Introduction to Acoustic Phonetics II

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sounds are waves with

- A — amplitude
- f — fundamental frequency
- ϕ — phase
- t — time

- **Periodic Motion**: any type of motion that repeats itself after successive equal time intervals.
- **Simple Harmonic Motion**: specific type of periodic motion that arises from
    1. existence of some equilibrium position for a described object;
    2. linear restoring force that tending to pull the described object back to its equilibrium position.

closely related with the phenomena of

- **resonance** (a phenomenon in which a vibrating system or external force drives another system to oscillate with greater amplitude at specific frequencies) and
- **antiresonance** (a phenomenon in which a vibrating system or external force drives another system to oscillate with smaller amplitude at specific frequencies).

The length of a sound wave (λ)

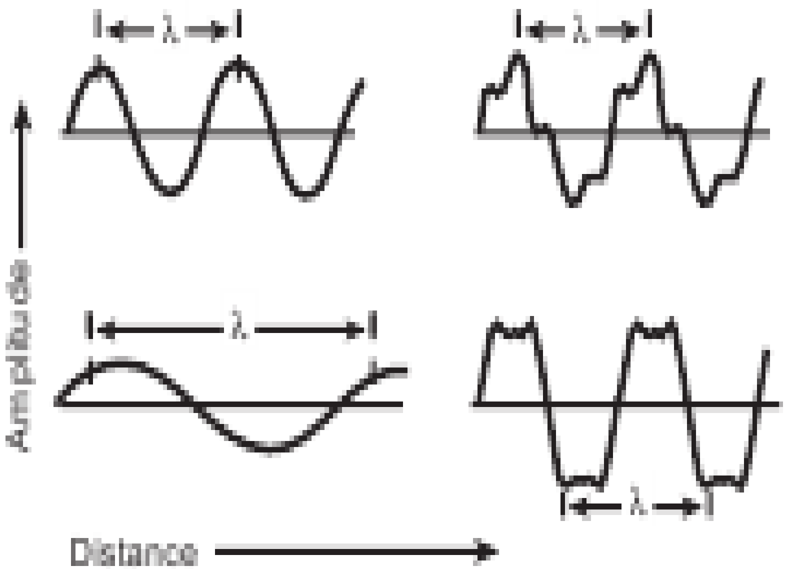


FIGURE 2.19 Wavelength (λ) is the distance occupied by one complete cycle of vibration.

- is the distance in space that one cycle occupies.

For periodic waves, the wavelength is the distance from any point in one cycle to the corresponding point in a neighboring cycle.

depends on two factors:

- the **frequency** of the vibration (***f***) and
- the **velocity** of sound wave propagation in the medium (**c**), relatively constant, approximately **344** **m**eters per **s**econd (in warm moist air).
- $\lambda = c/f$

or **c= *λ*****f***, thus,
the higher the frequency,
the less is the wavelength

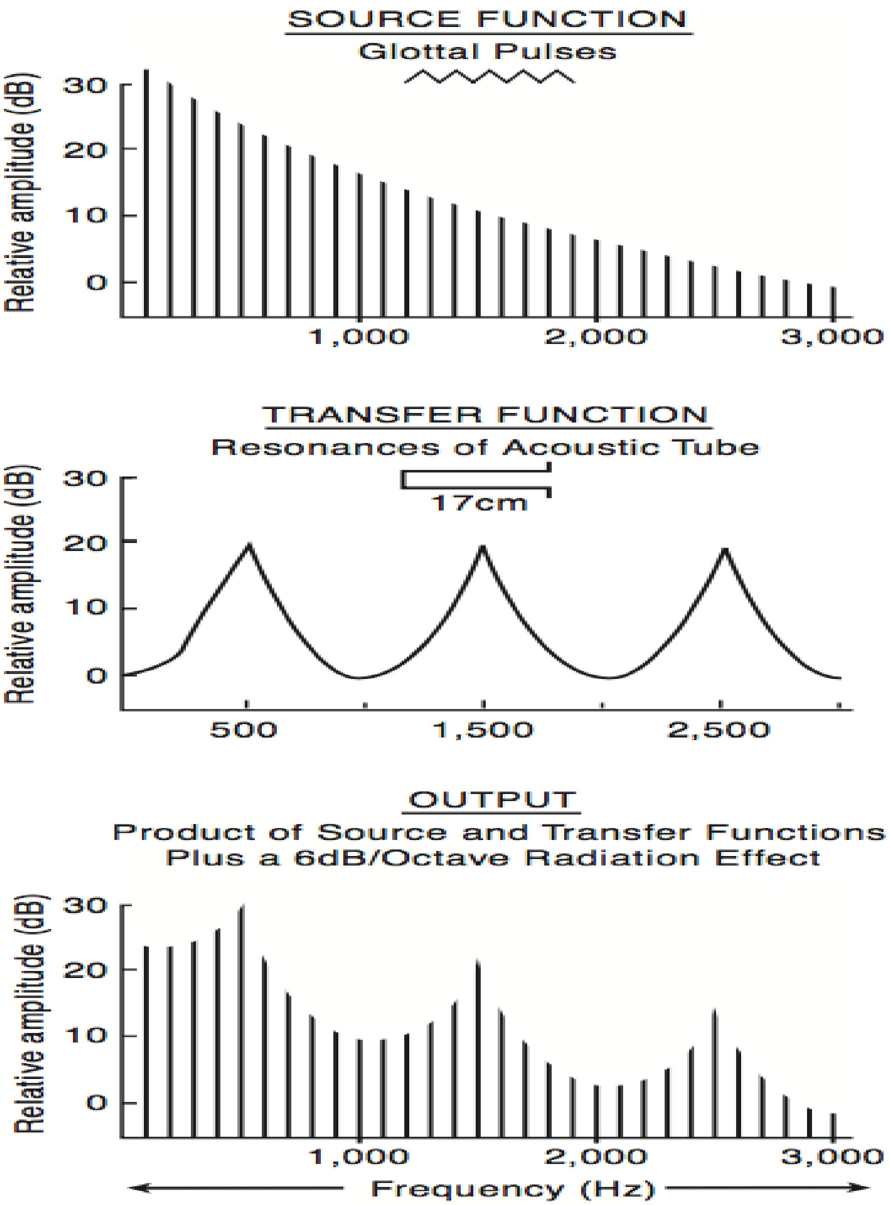


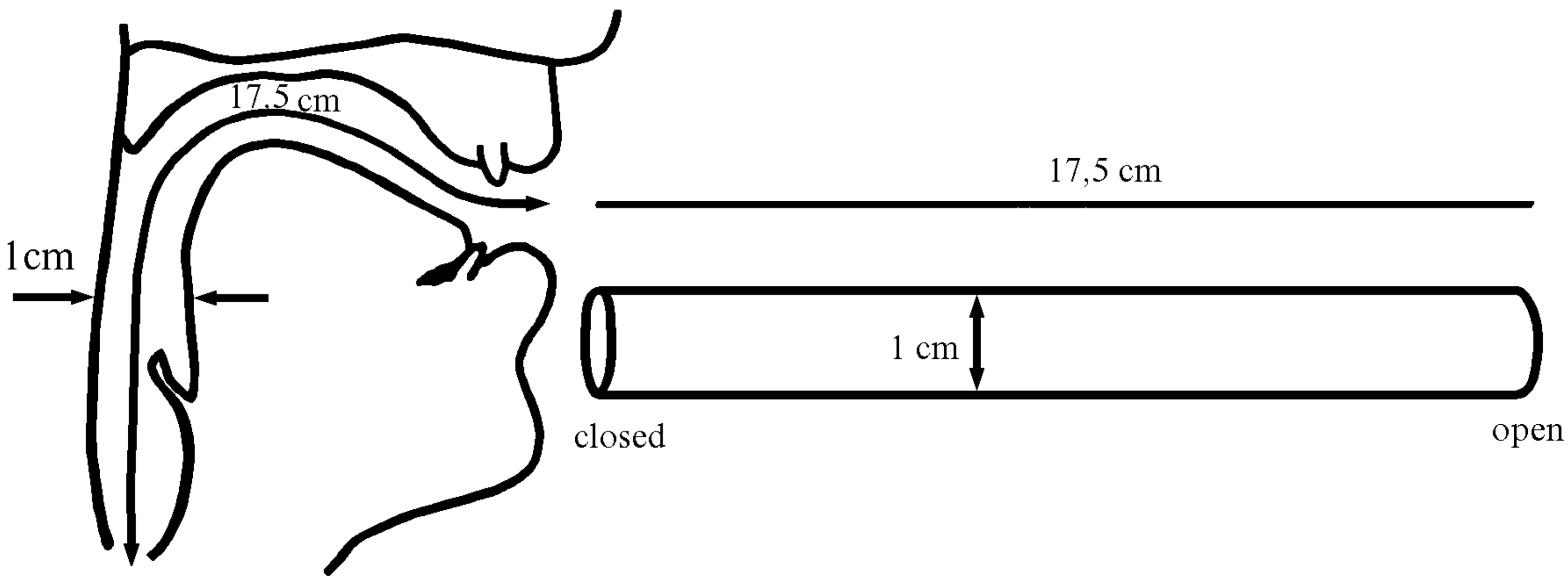
FIGURE 5.13 *Top*: The spectrum of the glottal source. *Bottom*: The spectrum of the source after filterin by a transfer function corresponding to a neutral vocal tract, with a radiation effect added. *Center*: The transfer function.

- Gunnar Fant. *Acoustic Theory of Speech Production* (1960)

- a source–filter model of vowel production based on the analysis of sound spectrograms:

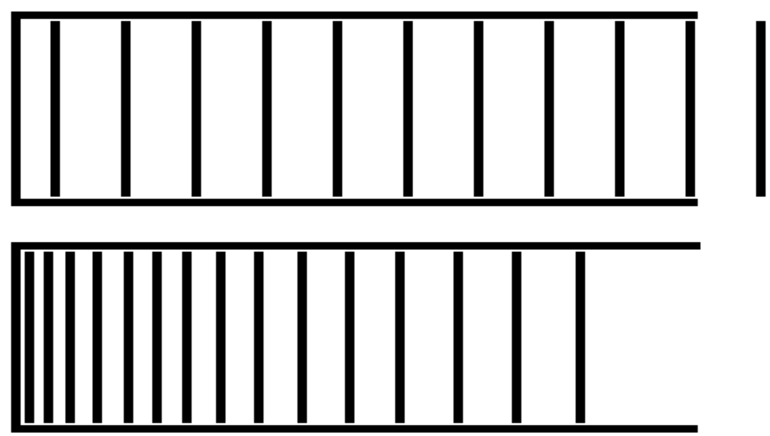
- vocal tract is a resonator that filters some frequencies of the wave produced by vocal folds vibration.

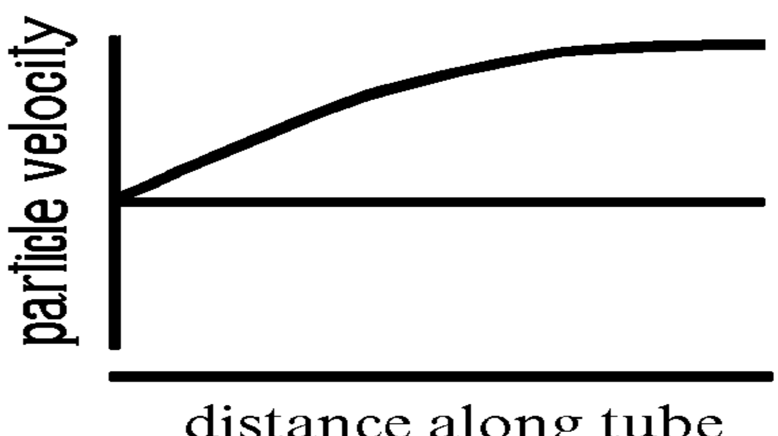
Neutral vocal tract for [ə] (no constrictions!): tube closed at one end

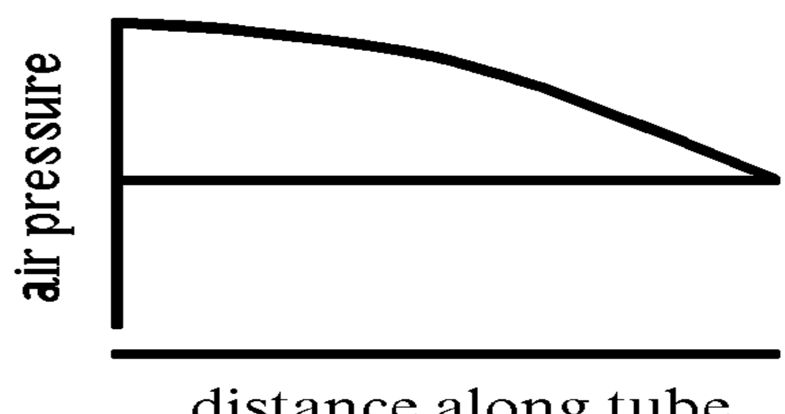


Air in a tube vibrating like a spring

maxima of velocity correspond to points where **pressure equals zero** (opened end), and maxima of pressure correspond to points where velocity equals zero (closed end)

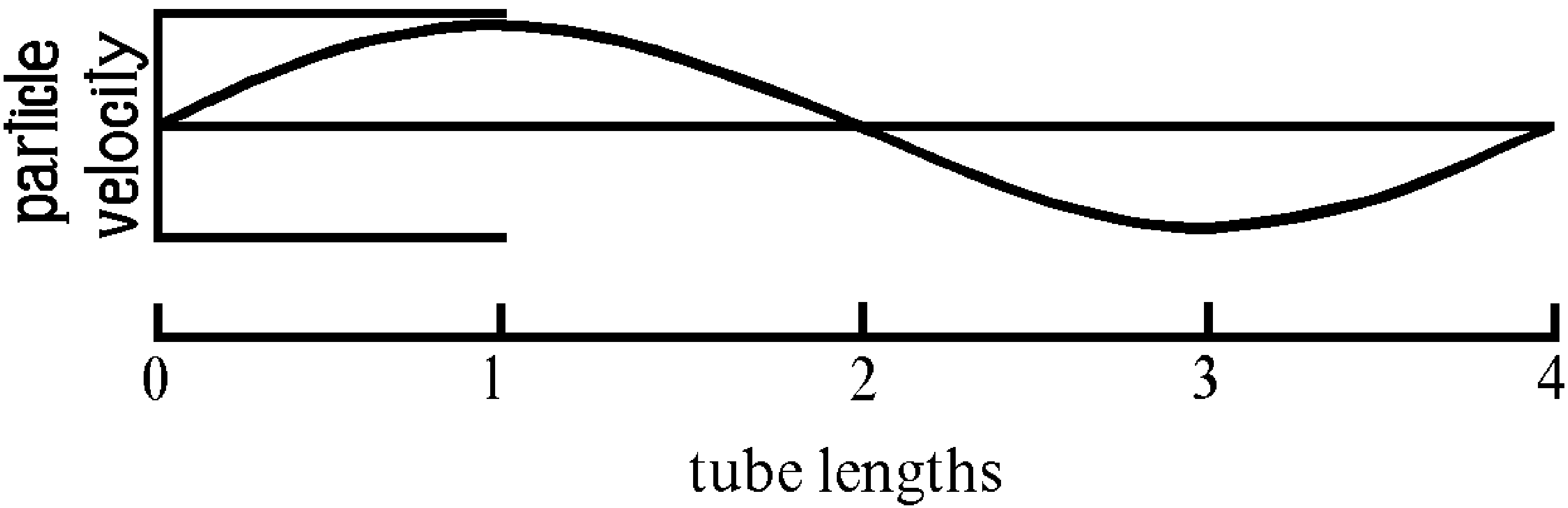






$$f = c/\lambda$$

Graf extended so as to form a complete variation in air flow:



$f = c/\lambda, \ \lambda_1 = 4L$

Thus, the lowest natural frequency at which such a tube resonates will have a wavelength (λ) four times the length of the tube (**L**).

The wavelength of a tube that is 17 cm long (average adult male's vocal tract) will thus be 4 * 17 cm = 68 cm.

The lowest resonant frequency at which the air within such a tube naturally vibrates equals the velocity of sound in air divided by the wavelength

velocity of sound is 34,400 cm/s,

the lowest resonant frequency (R1/F1) of a 17-cm tube open at one end is

- R1 = c / λ = c / 4L = 34,400 cm per sec/68 cm = 506 Hz

The lowest resonant frequency of such a tube is approximately 500 Hz.

The tube also **resonates at odd multiples** of that frequency.

Why?

resonates at odd

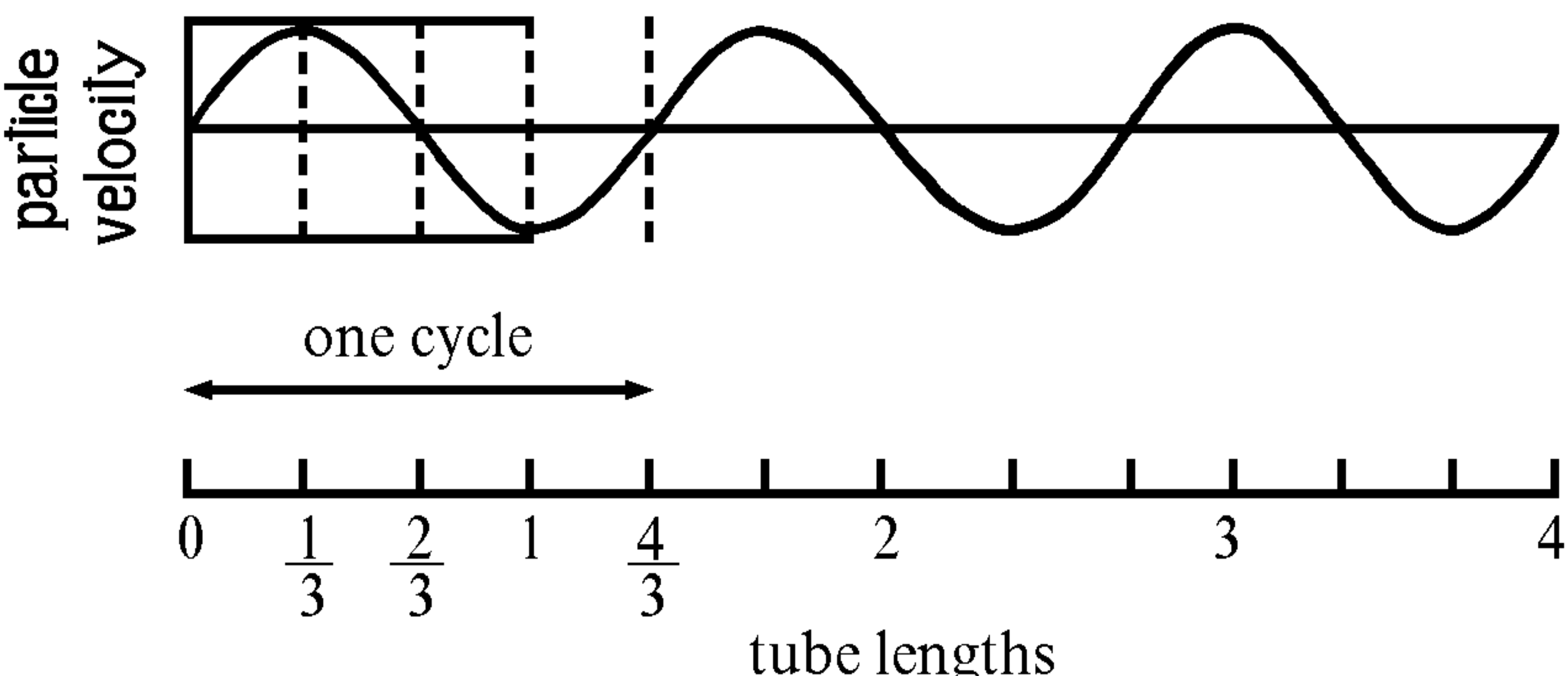
- The only constraint on the movement of air particles is that they

should be **free to move at maximum velocity** at the open end, and there should be **no movement at the closed end**

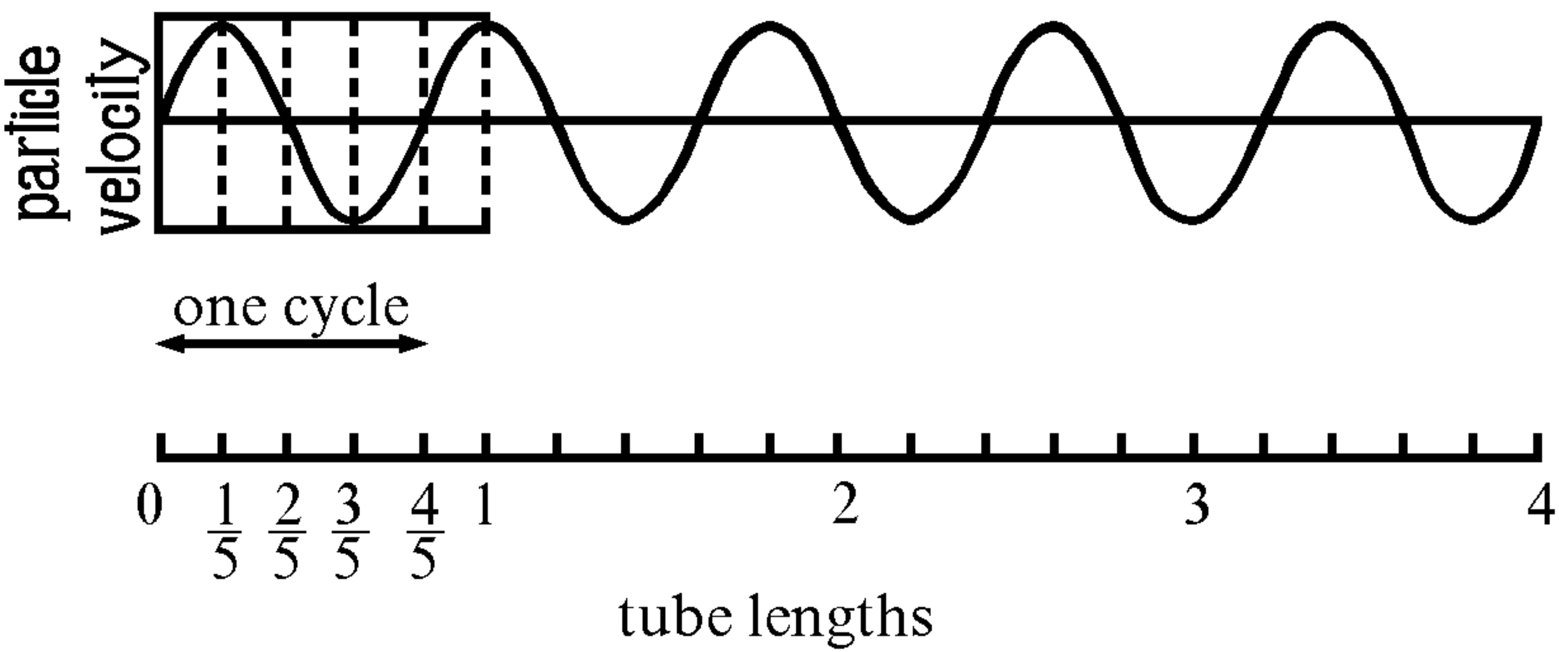
(there can be more complex variations in the middle of the tube)

- Another waves, which fit the constraint at the ends of the tube

variations in airflow such that ¾ of the wave within tube



variations in airflow such that a cycle + an extra ¼ of a cycle, total 5/4 of the wave within tube



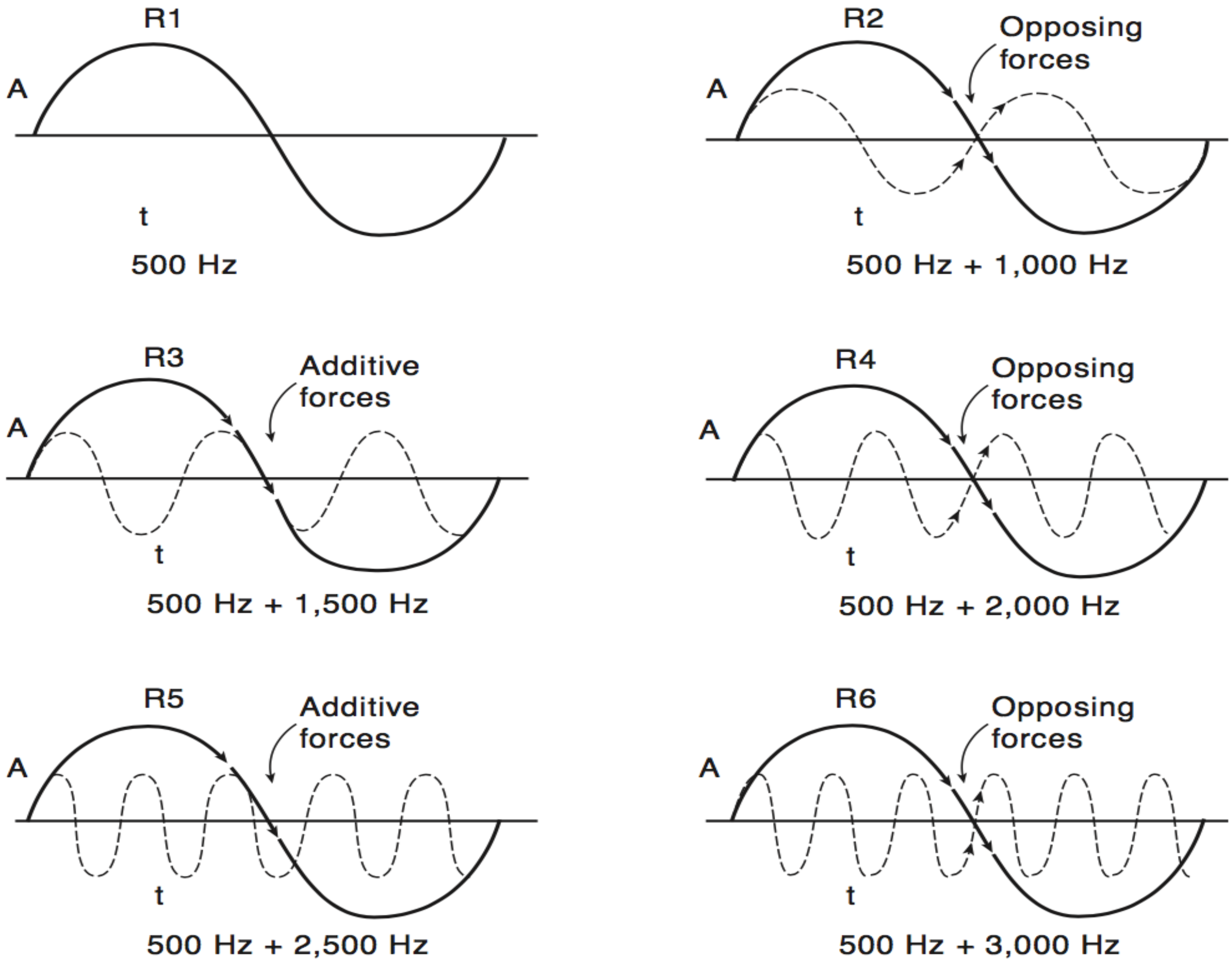
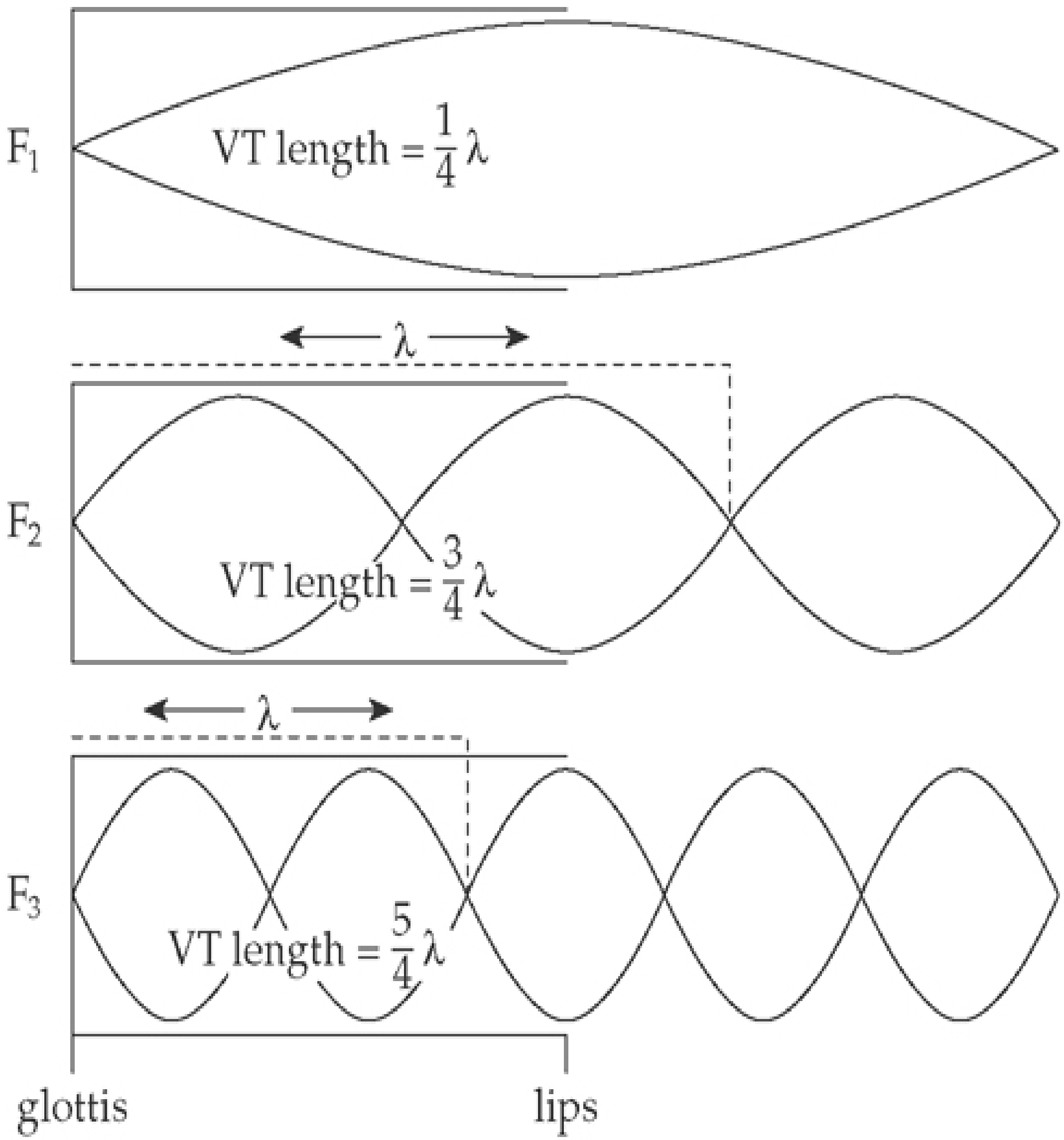
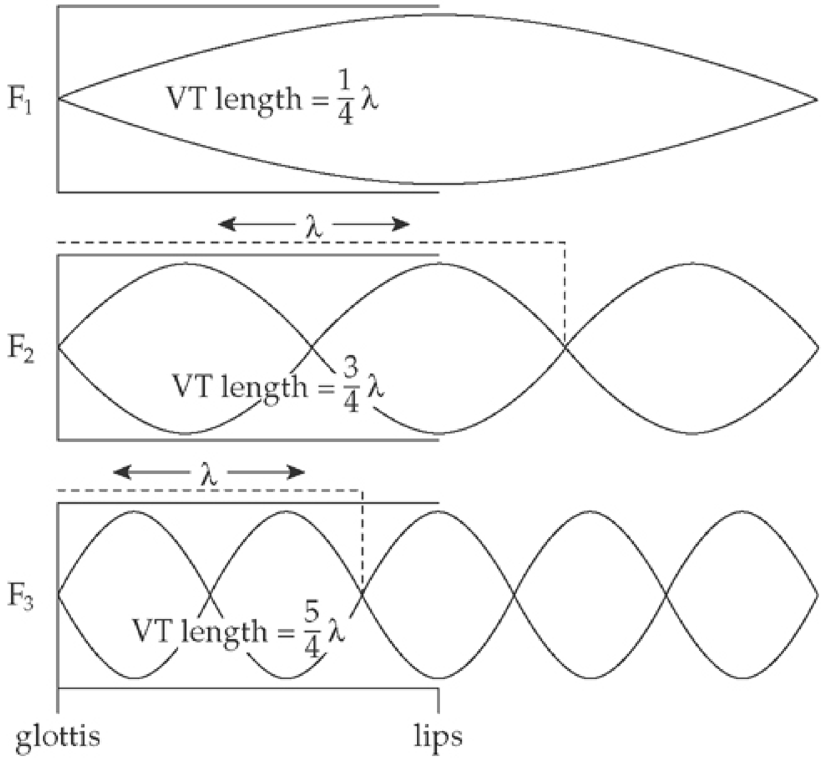


FIGURE 5.9 The resonant frequencies of a tube open at one end and closed at the other. The even harmonics are not effective resonant frequencies because they are canceled at the entrance to the tube (opposing forces), whereas the odd harmonics are compatible (additive forces).



- The three lowest-frequency pressure waves that meet the boundary conditions for resonating, in an unconstricted vocal tract as in the vowel [ə].
- They are labeled F1,–F3 for vowel "formants" 1–3.



For all the vocal tract resonances, standing waves has minimum particle displacement at the glottis and maximum particle displacement at the lips.

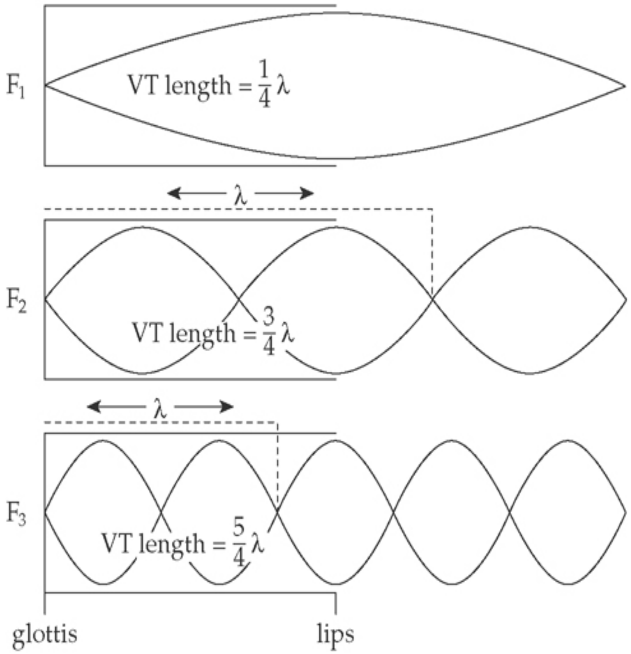
The lowest resonant frequency (F1) has a wavelength that is four times the length of the tube.

The lengths that are shown in the figure are selected out of all possible wavelengths because they meet the boundary conditions for resonance in the vocal tract.

f **= c/λ,** λ may be calculated if we know the length of the tube,

The first three resonant frequencies of a uniform tube that is closed at one end and open at the other are easily derived from the length of the tube.

$$F_1 = c/\lambda_1 = c/(4L) = c/4L$$
$$F_2 = c/\lambda_2 = c/(4/3L) = 3c/4L$$
$$F_3 = c/\lambda_3 = c/(4/5L) = 5c/4L$$



$$F_1 = c/\lambda_1 = c/(4L) = c/4L$$
$$F_2 = c/\lambda_2 = c/(4/3L) = 3c/4L$$
$$F_3 = c/\lambda_3 = c/(4/5L) = 5c/4L$$

$$F_n = \frac{(2n-1)c}{4L}$$

The first expression of each of these resonant frequencies is in terms of the wavelength of the standing wave in the vocal tract.

The second defines the standing wave's wavelength in terms of the length of the vocal tract, and the last expression is an algebraic simplification of the second (each resonance has a wavelength that is an odd multiple of the speed of sound divided by four times the length of the vocal tract).

In the summarized expression ***n*** is the number of the formant, ***c*** is the speed of sound in warm, moist air (35,000 cm/s), and ***L*** is the length of the tube in cm.

$$F_n = \frac{(2n-1)c}{4L}$$

So, for a particular male vocal tract with an effective length of 17.5 cm

the lowest resonant frequency is 35,000 cm/s divided by 4 times 17.5 cm, or 500 Hz.

If the vocal tract is shorter (say 15 cm), the lowest resonant frequency is higher (583 Hz).

The second vocal tract resonance is calculated by multiplying the speed of sound by 3 and then dividing by $4L$. For a 17.5 cm vocal tract this comes to 1,500 Hz.

The resonant frequencies of the vocal tract are also called **formants**, and are labeled **F1**, **F2**, **F3**, etc., starting from the lowest resonant frequency.

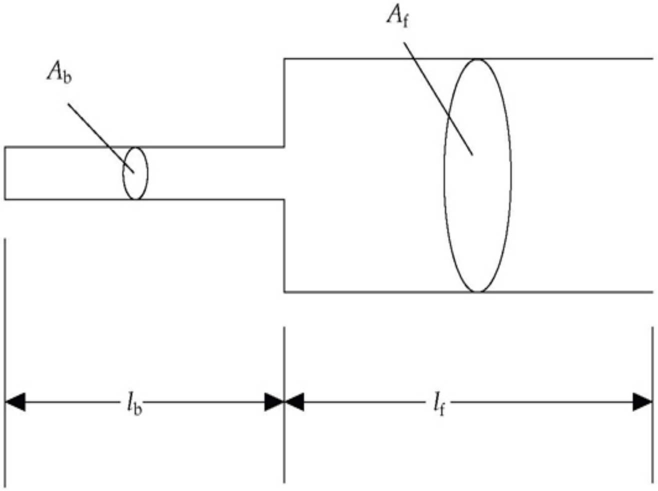
Tube Models of Vowel Production

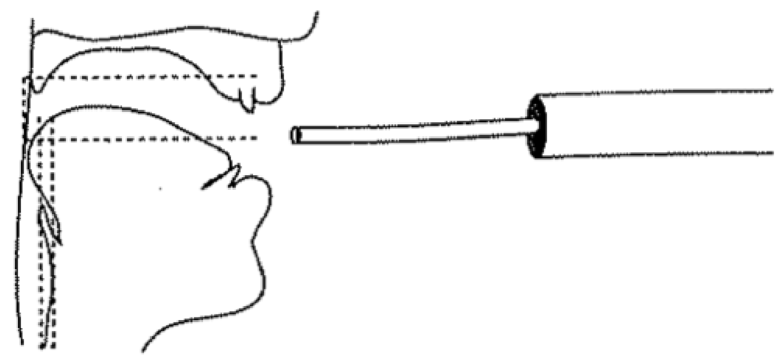
- The **source-filter theory** predicts the resonant frequencies of the vocal tract (the formant values) if the **cross-sectional area is uniform**, as in schwa.
- there are a couple of articulations that alter the overall length of the vocal tract (lip protrusion and larynx lowering) for which this analysis is relevant.
- to account for the acoustic properties of other vowels, it is necessary to extend the theory to include vocal tract configurations that involve **constrictions**.
- One way of modeling the acoustic effects of constrictions in vowels is to think of the vocal tract as a set of tubes rather than as a single tube (Fant, 1960).
- **Tube models** of the vocal tract that can be used to model certain aspects of vowels.
- Still the resonant frequencies of a tube can be calculated from its length.

vocal tract length

- formant frequencies in schwa can be calculated given the length of the vocal tract.
- therefore, if you know the formant values, you are able to estimate the length of the vocal tract.
- exact vowel quality of the neutral vocal tract varies from person to person,
- make spectrograms of [ə] and note the frequency values of the formants
- a vocal tract has a nearly uniform cross-sectional area, the neutral vocal tract shape, when the formants are evenly spaced – that is, when the interval between F1and F2 is the same as the interval between F2 and F3, and so on.
- So, now that you have found your neutral vocal tract vowel, you can calculate the length of your vocal tract.
- Take the formula for formants ($Fn = (2n - 1)c/4L$) and rearrange so L is on the left side ($L = (2n - 1)c/4Fn$).
- For instance, for F3 in neutral vowel 2,600 Hz, vocal tract is about 16.8 cm long.

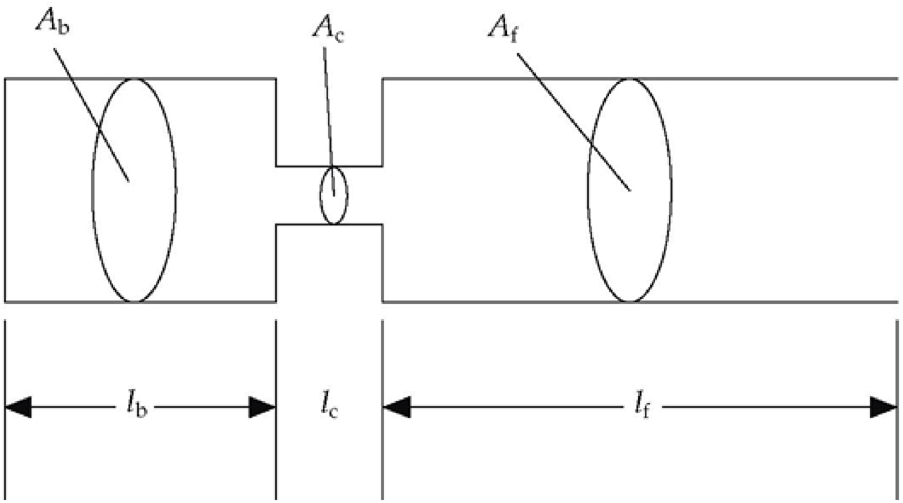
Two-tube model of the vocal tract that approximates the shape of the vocal tract for [a]

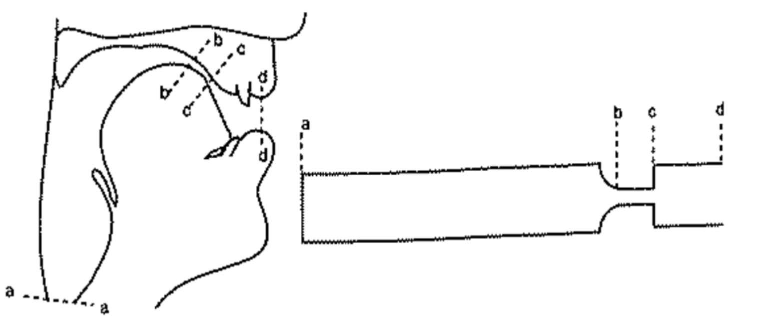




- the vocal tract divided into two tubes.
- the back tube has a cross-sectional area, A_b, that is very much smaller than the cross-sectional area of the front tube, A_f, so we can consider the back tube to be closed at the glottis and open at the junction with the front tube;
- the front tube is at the junction with the back tube and open at lips.
- Therefore, because both tubes are closed at one end and open at the other, we can use the vocal tract resonances formula ($Fn = (2n - 1)c/4L$) to calculate the resonances of the front and back tubes (or cavities) separately from their lengths, l_b and l_f.
- So the **resonances of the back cavity are: ($F_{bn} = (2n - 1)c/4_{lb}$)**, and
- **the resonances of the front cavity are: ($F_{fn} = (2n - 1)c/4_{lf}$).**

Tube model of vocal tract configurations that have a short constriction at some point in the vocal tract





$$f = \frac{c}{2\pi}\sqrt{\frac{A_c}{A_b\, l_b\, l_c}}$$

- The back tube and the constriction form a resonant system called a **Helmholtz resonator**

- The noise produced when blow across the top of a bottle is the result of Helmholtz resonance (with turbulence as the sound source). The neck of the bottle is analogous to the constriction, and the body of the bottle is analogous to the back cavity of the vocal tract.

- The natural resonant frequency of this Helmholtz resonator is determined by the relative volumes of air in the back cavity and in the constriction, and can be calculated by formula to the left

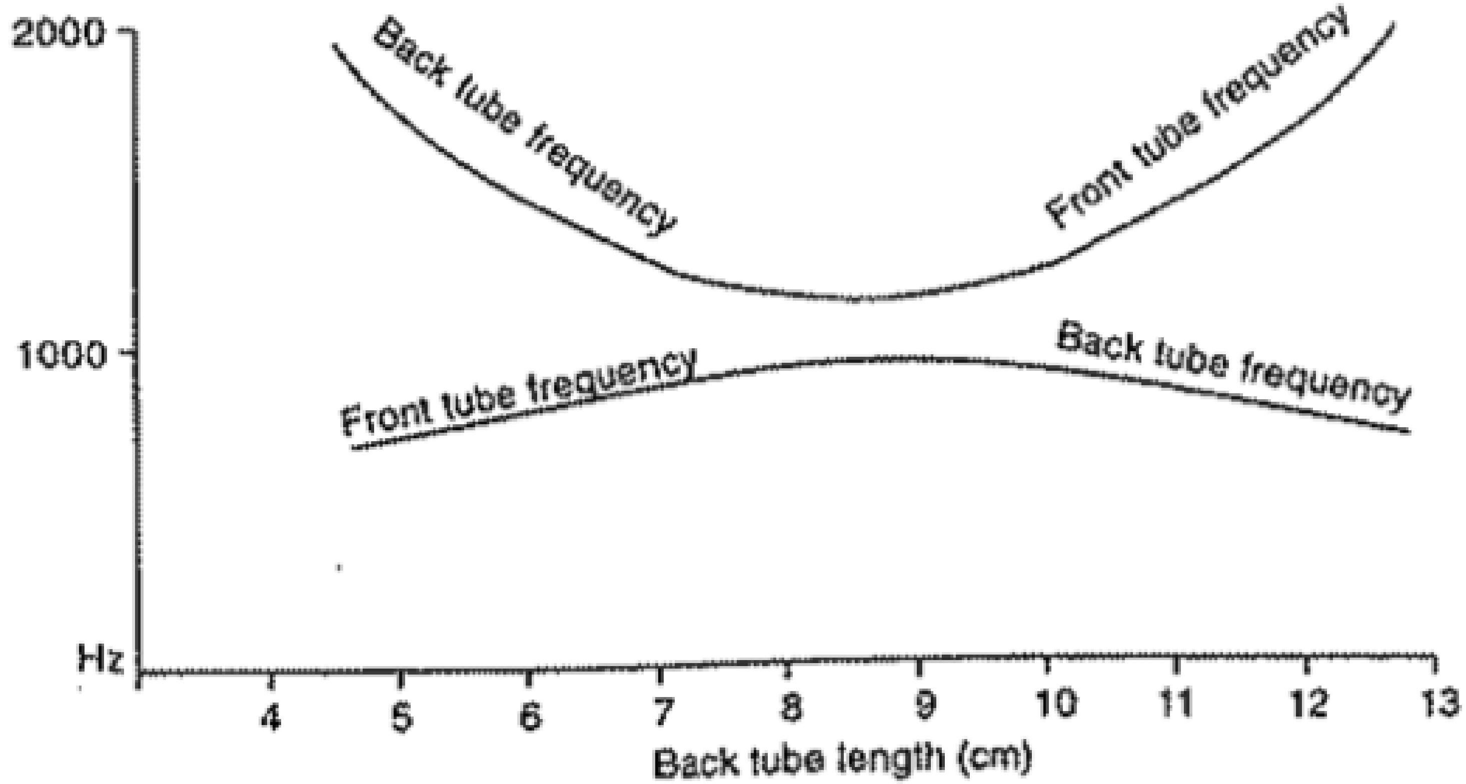
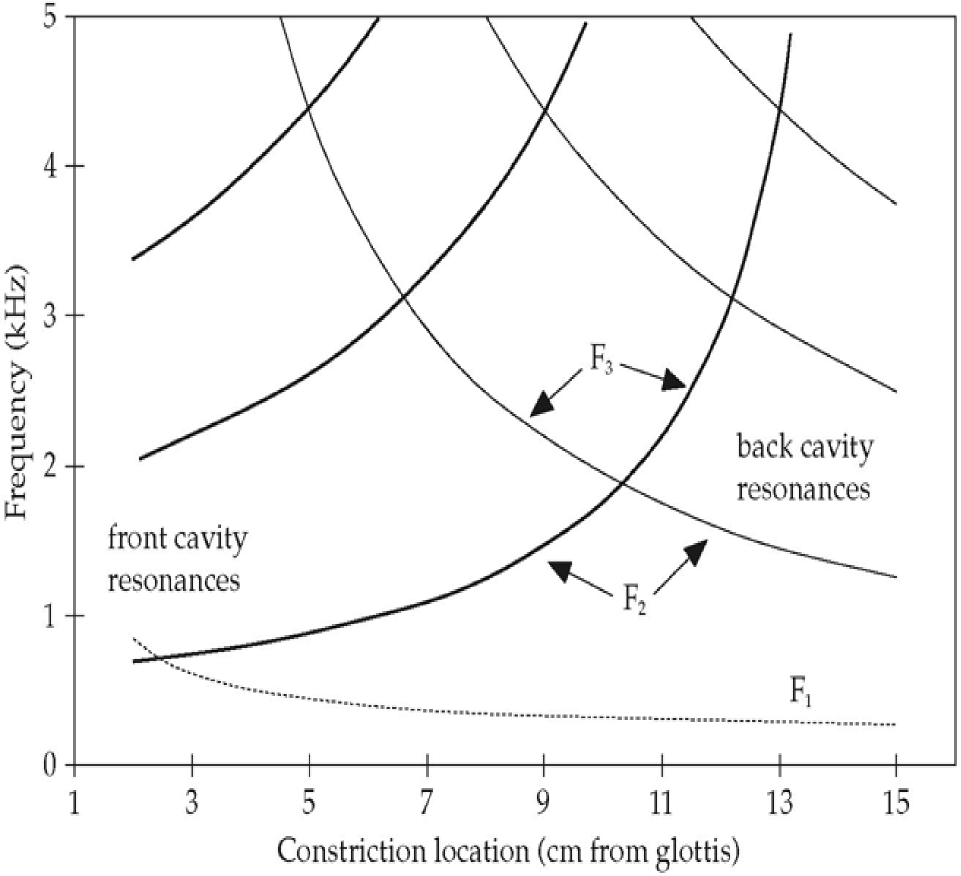


Fig. 8.8. The resonances of two tubes, one being taken as equivalent to part of the vocal tract in the back of the mouth and the pharynx, the other as equivalent to that in the front of the mouth.



- Resonant frequencies of the back tube (light lines), front tube (heavy lines) and Helmholtz resonance (dashed line) in the tube model
- Frequencies are plotted as a function of different back tube lengths (*l*b), with the length of the constriction fixed at 2 cm and the total length of the model fixed at 16 cm

- The vocal tract is a variable resonator, and as its shape changes because of changes in articulator placement, the formants change in frequency, producing a variety of sounds.

Simply by changing the vocal tract shape, you can make all of the vowel sounds. This is true, even if you whisper, that is, use an aperiodic sound source.

To better understand the production of the vowels we hear, let us consider the sounds /i/, /ɑ/, and /u/

- These vowels represent extremes in articulation and thus in the shaping of the vocal tract that filters the glottal source of sound (amplifying some harmonics and attenuating others) to produce different vowel sounds

The sound /i/

The sound /i/ in “see” is distinctive because of the high-frequency energy from the resonances in the oral cavity. To resonate at such high frequencies, the oral cavity must be made small. That is why the speaker fronts the tongue toward the alveolar ridge.

The tongue mass fills most of the oral cavity, leaving a small volume of air to vibrate in the space anterior to the constriction formed by the tongue. The pharynx, in contrast, enlarges because the posterior part of the tongue has been raised, that is, lifted out of the pharyngeal space.

- A different speaker, of course, with a different-size vocal tract and slightly different articulatory habits, would produce different formant frequencies, but the pattern of one very low formant (F1) and two relatively high formants (F2, F3) would remain the same as long as the articulation conforms to the pattern for /i/ have been described.

A typical formant pattern for this vowel is F1, 300 Hz; F2, 2,300 Hz; and F3, 3,000 Hz

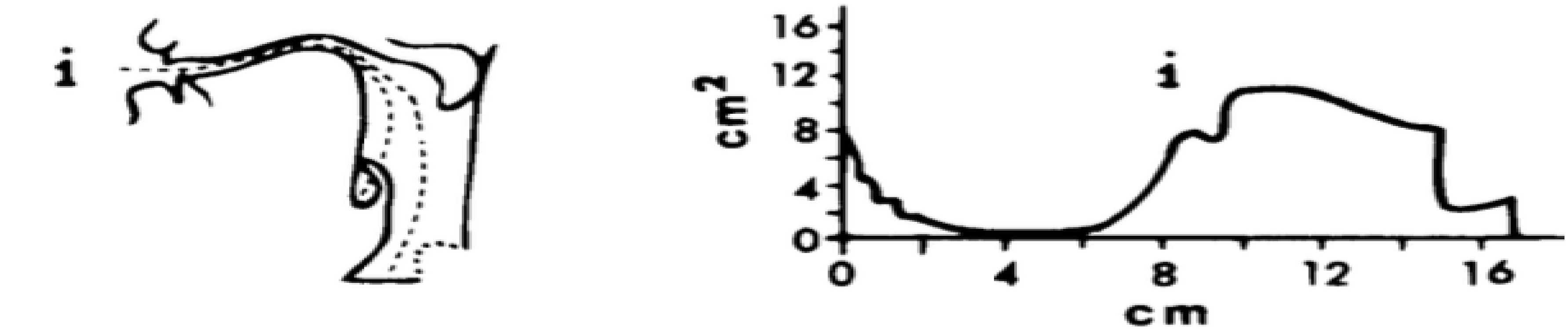


FIGURE 5.14 *Left*: Lateral view of the tongue for the vowel [i]. *Right*: The cross section of the vocal tract for [i]. The abscissa indicates distance from the lips. (Adapted with permission from Fant, G., *Acoustic Theory of Speech Production*. The Hague, The Netherlands: Mouton, 1970.)

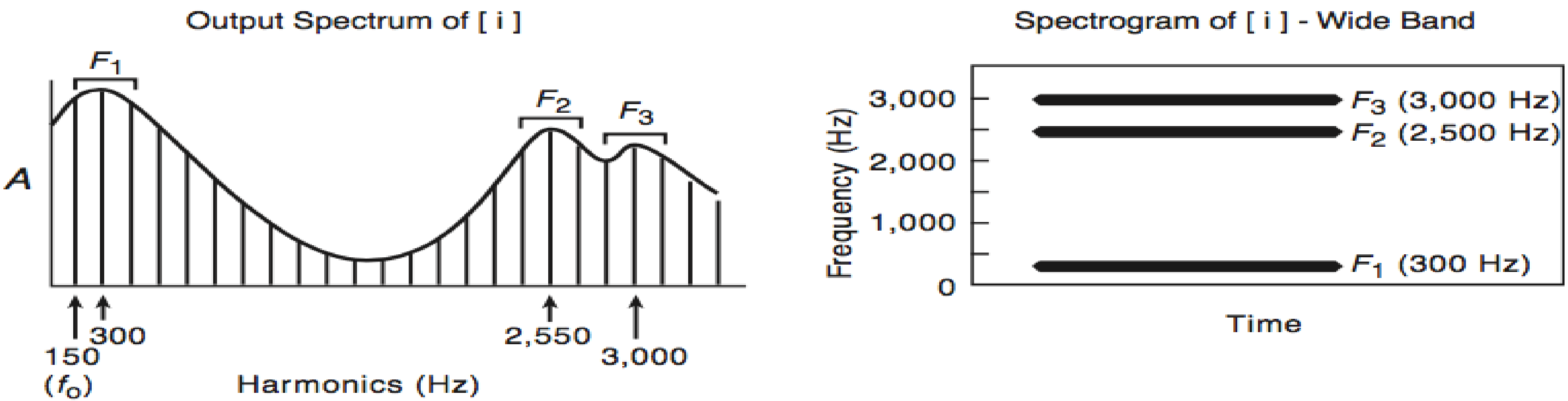
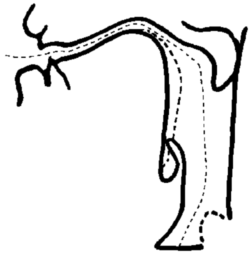
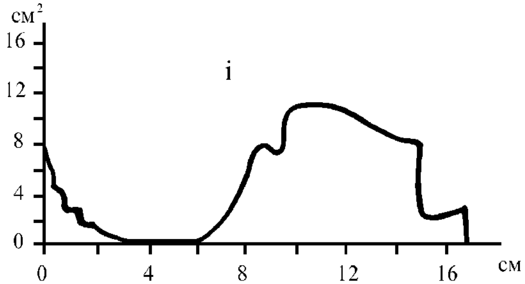


FIGURE 5.16 *Right*: Schematic spectrogram of the vowel [i] as in the word "beat." *Left*: A spectrum of the same sound. F_1, F_2, and F_3 represent the vocal tract resonances. The spectrogram shows frequency (f) changes in time. The spectrum shows the amplitude (A) of the component frequencies or harmonics. The center frequency of the formants does not always match the frequency of an individual harmonic.

i


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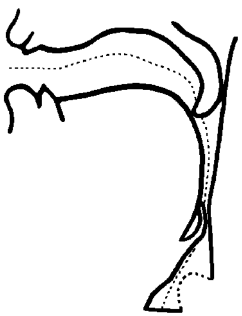
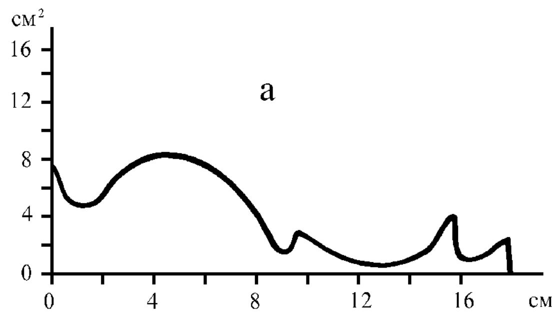
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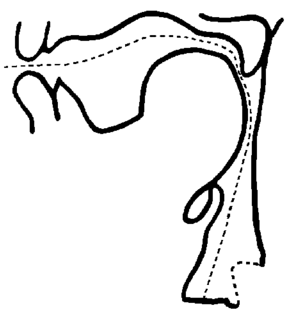
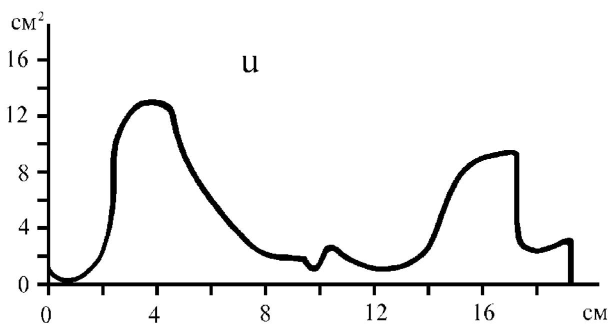
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/ɑ/

The oral cavity is larger and the pharyngeal cavity smaller for the vowel /ɑ/ than for /i/. The size of the oral cavity for /ɑ/ may be increased in two ways: lowering the tongue passively by lowering the jaw or actively by depressing the tongue. It is also possible to combine these two strategies.

Lowering of the tongue for /ɑ/ provides the large oral cavity and small pharyngeal cavity volumes that characterize this vowel. As we would expect, the small pharyngeal cavity resonates to higher frequency harmonics in the source, generating a relatively high-frequency first formant, whereas the large oral cavity resonates to low-frequency harmonics in the source and thus generates a relatively low-frequency second formant/

Typical frequencies for the first three formants of /ɑ/ are F1, 730 Hz; F2, 1,100 Hz; and F3, 2,400 Hz.

Thus, the articulatory differences between /i/ and /ɑ/ are reflected in the acoustic differences.

(Remember that /i/ has a large pharyngeal cavity and low-frequency F1 and a small oral cavity and high-frequency F2.)

/u/

The third articulatory extreme in vowel production is /u/. This vowel is articulated with the dorsum of the tongue raised toward the roof of the mouth near the juncture between the hard palate and the velum.

Speakers also round and protrude the lips.

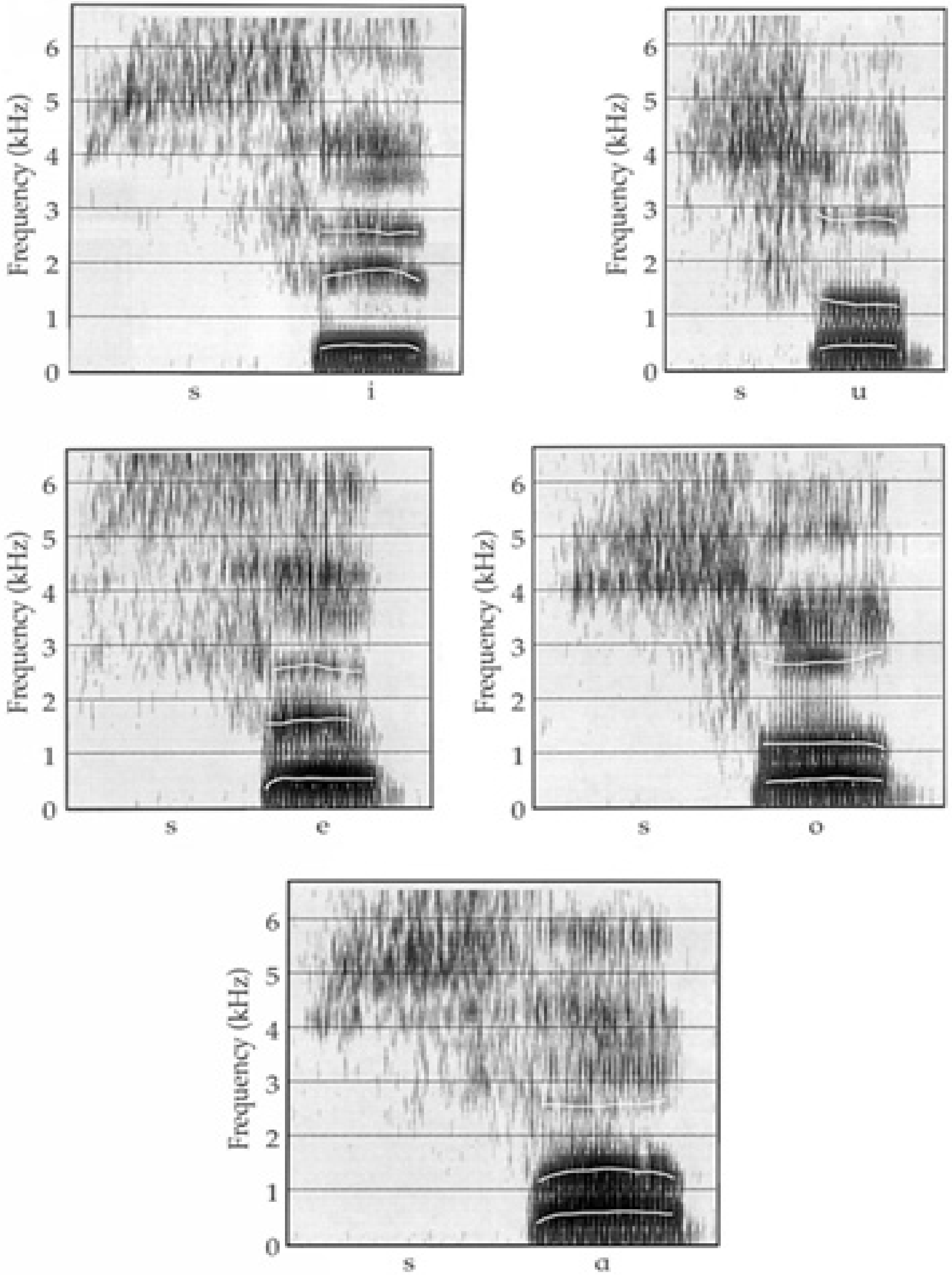
The acoustic effect of this positioning of the lips and tongue is threefold:

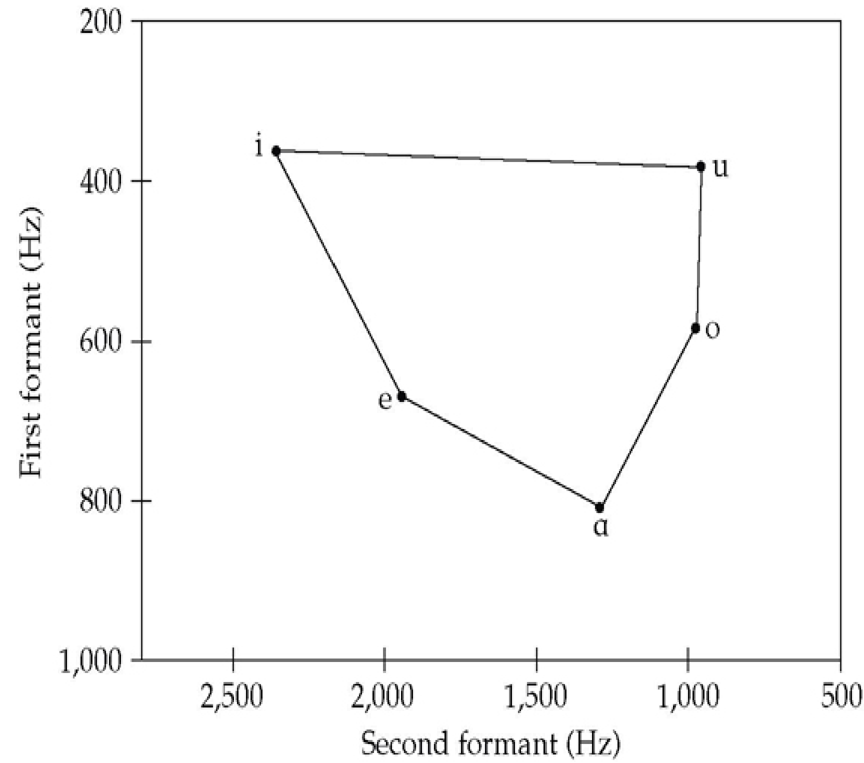
- the protrusion of the lips increases the overall length of the vocal tract and thus lowers the frequencies of all the formants.
- the raising of the tongue dorsum pulls the bulk of the tongue out of the pharyngeal cavity, enlarging it and allowing it to resonate to the low-frequency harmonics composing the first formant of this vowel
- the posterior constriction formed by the raised tongue dorsum and the protrusion of the lips lengthen the oral cavity, allowing it to resonate to the relatively low-frequency har monics that make up the second formant of/u/.

Typical frequencies for the first three formants of /u/ are F1, 300 Hz; F2, 870 Hz; and F3, 2,240 Hz.

At normal rates of speech, /u/ is frequently produced with little or no lip pro-trusion. To achieve the appropriate elongation of both the oral cavity and the vocal tract as a whole, speakers must therefore resort to alternative articulatory strategies.These include a greater degree of tongue retraction than would be used if the lips were protruded. This permits the speaker to attain an oral cavity length that is equivalent to that produced when the lips are rounded and protruded and the tongue is in a more fronted position. Thus, it is possible to generate the second resonant frequencyfor /u/ by more than one articulatory strategy. Similarly, a vocal tract length equivalent to that produced by lip protrusion can be attained by lowering the larynx.

Jalapa Mazatec words (an Otomanguean language, Mexico)





The Relationship Between Acoustics and Articulation

- The sounds /i/, /ɑ/, /u/ occupy a special place in traditional articulatory-based descriptions of most languages. The earliest were based almost entirely on the impressionistic, introspective evidence of tongue shape and tongue and lips position
- more objective techniques: the importance of the tongue root and jaw position
- acoustic analysis: the relationships among articulation, the dimensions of the resonating cavities, and the acoustic features of speech, especially formant frequencies.
- now: general agreement that the frequencies of formants cannot be attributed solely to a particular resonating cavity within the vocal tract
- the **formants** are understood as the **acoustic response of the vocal tract as a whole** to the components of the source:

(see about **perturbation theory** below).

The Relationship Between Acoustics and Articulation

In practice, it is impossible to ignore the well established correlations among

- (1) the frequencies of the first two formants,
- (2) the dimensions of the oral and pharyngeal cavities, and
- (3) the traditional description of the tongue, the jaw, and the lip position in vowel articulation.

Next: basis of these correlations

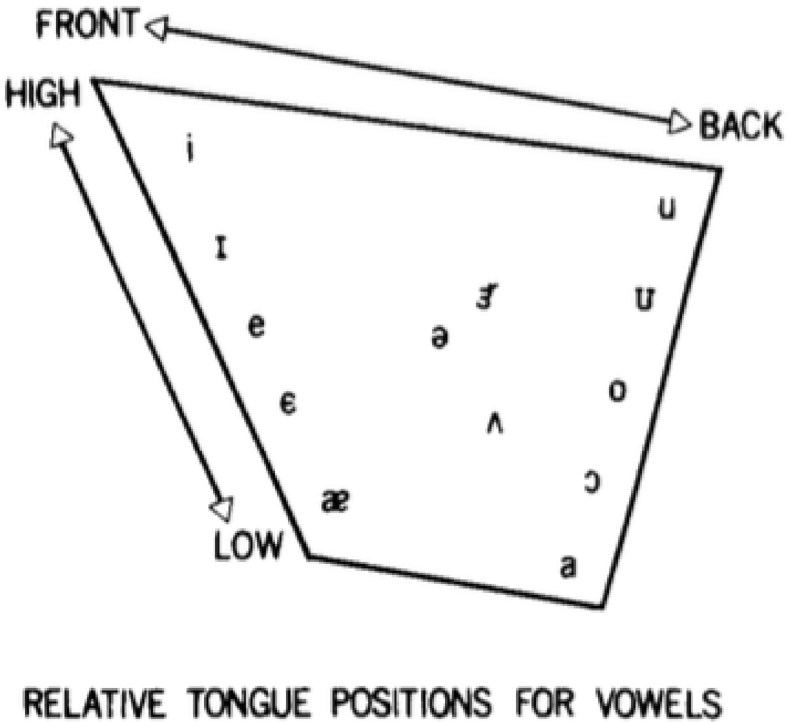


FIGURE 5.22 The traditional vowel quadrilateral. The location of each phonetic symbol represents the position of the high point of the tongue within the part of the oral cavity in which vowel constrictions are formed.

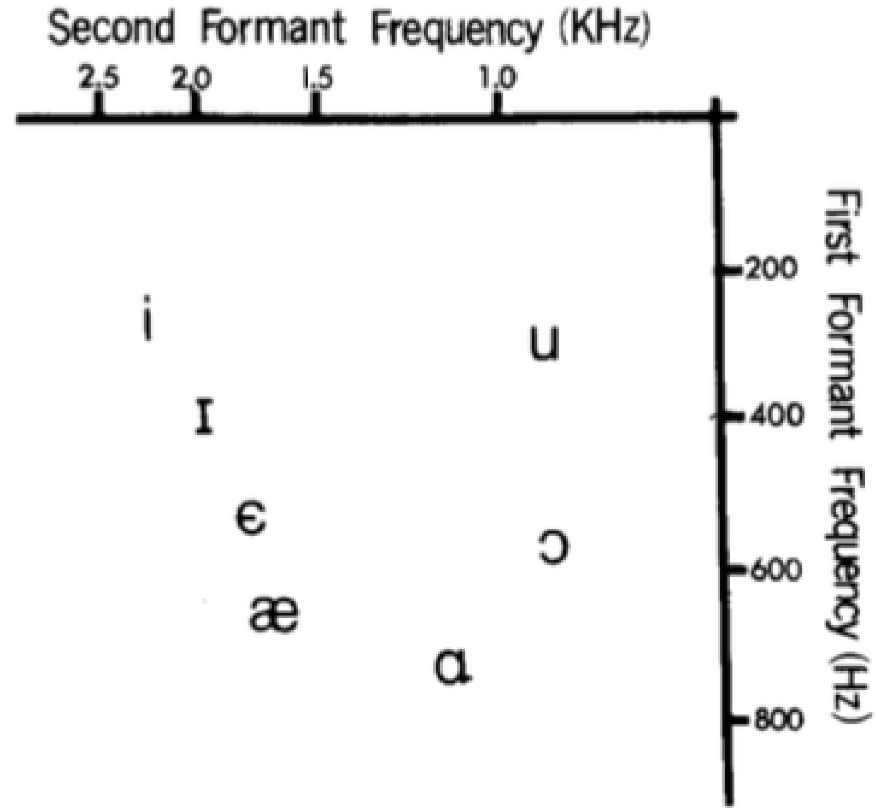


FIGURE 5.23 Average formant frequencies of 33 adult male speakers of English. (Data from Peterson, G. E., and Barney H. L., Control Methods Used in a Study of the Vowels. *J. Acoust. Soc. Am. 24,* 1952, 183.)

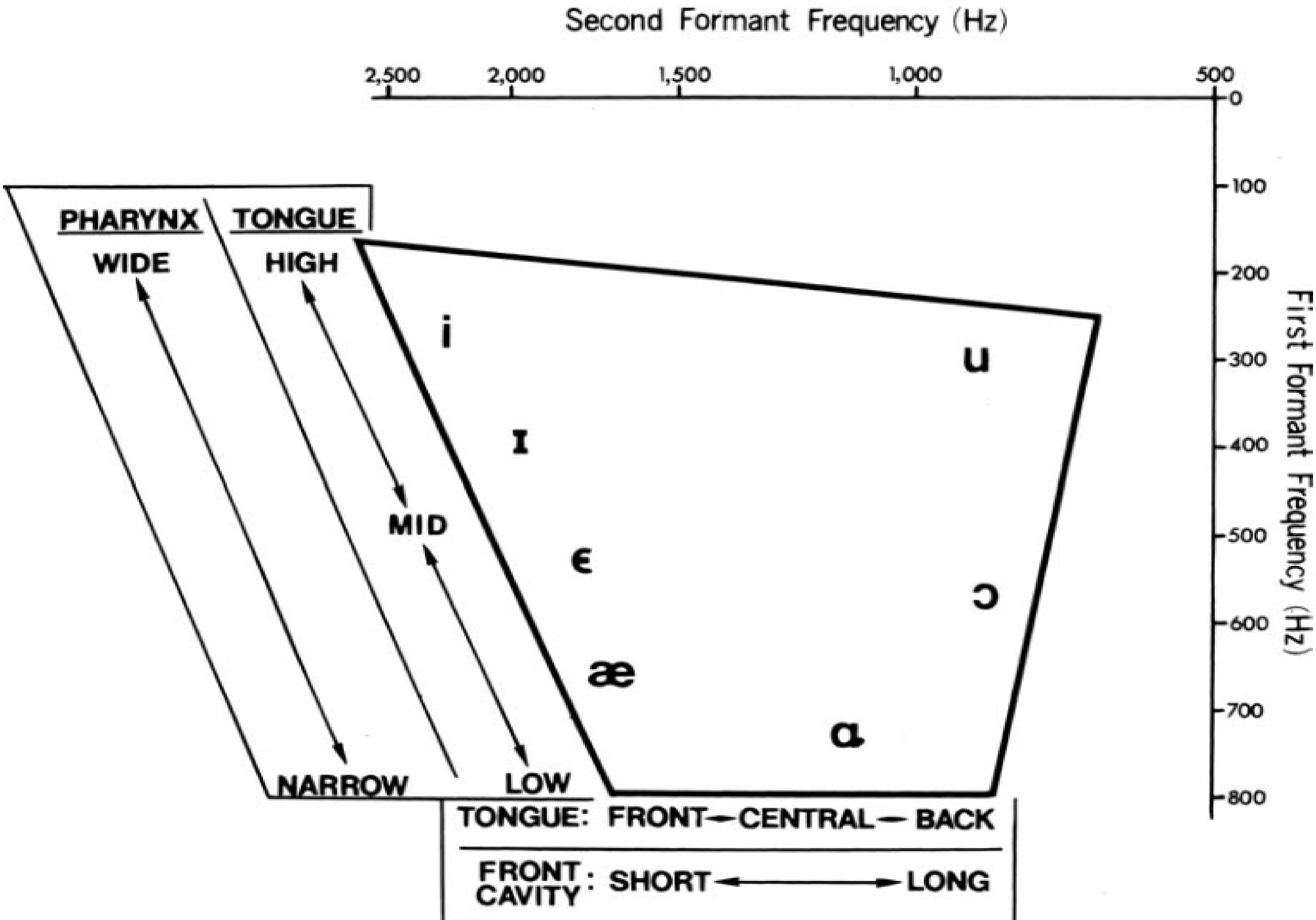
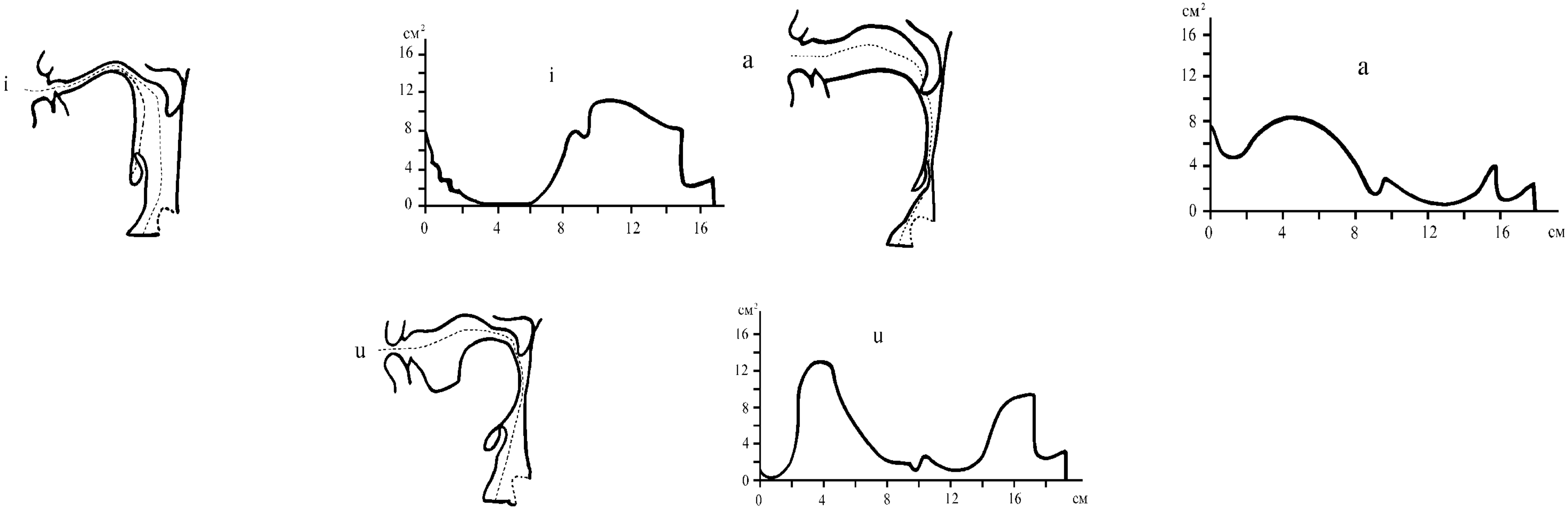


FIGURE 5.24 The relationships among tongue position, cavity size, and formant frequency for some English vowels.



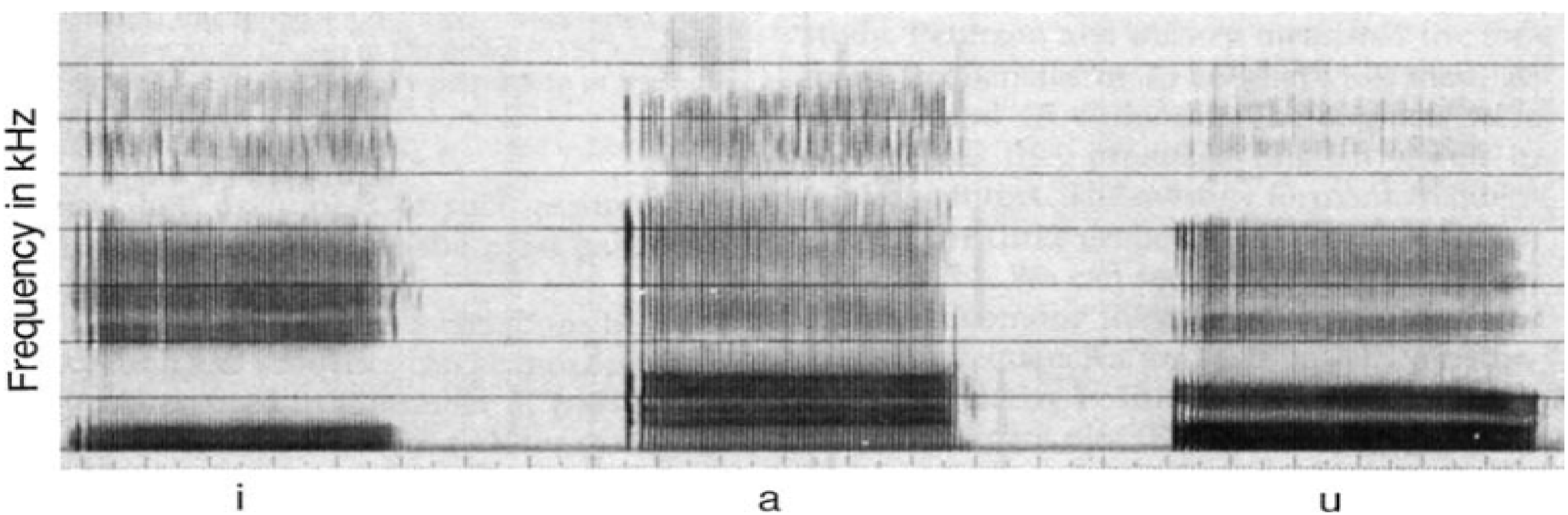


FIGURE 5.26 Spectrogram of steady-state productions of the vowels [i], [a], and [u]. A 1-kHz calibration tone is indicated. (Spectrogram courtesy of Kay Elemetrics.)

The Relationship Between Acoustics and Articulation

A generally consistent lowering of F2 as the front (oral) resonating cavity is enlarged because of tongue retraction (and lip protrusion) and

A general raising of F1 from /i/ through /ɑ/ as the pharyngeal cavity size is decreased (because of tongue lowering) and the lip aperture is increased (because of jaw lowering), and a lowering of F1 from /ɑ/ through /u/ as the pharyngeal cavity size is increased (as the tongue rises) and the lip aperture is diminished (as the jaw rises)/

- *It may well be that phoneticians have been unconsciously charting the vowels according to their acoustic reality rather than their articulatory reality.*

The Relationship Between Acoustics and Articulation

- Vowels with higher tongue positions have larger pharyngeal cavities that will resonate to lower frequencies in the source. Vowels with lower tongue positions will have smaller pharyngeal cavities that will resonate to higher frequencies in the source.
- The correlation between lip opening and F1 frequency can be inferred from the articulation, as the higher vowels are characterized by raised jaw positions and smaller lip apertures, whereas the lower vowels display low jaw positions and larger lip apertures.
- The second formant frequencies of the vowels correlate in a straightforward way with the length of the oral resonating cavity.

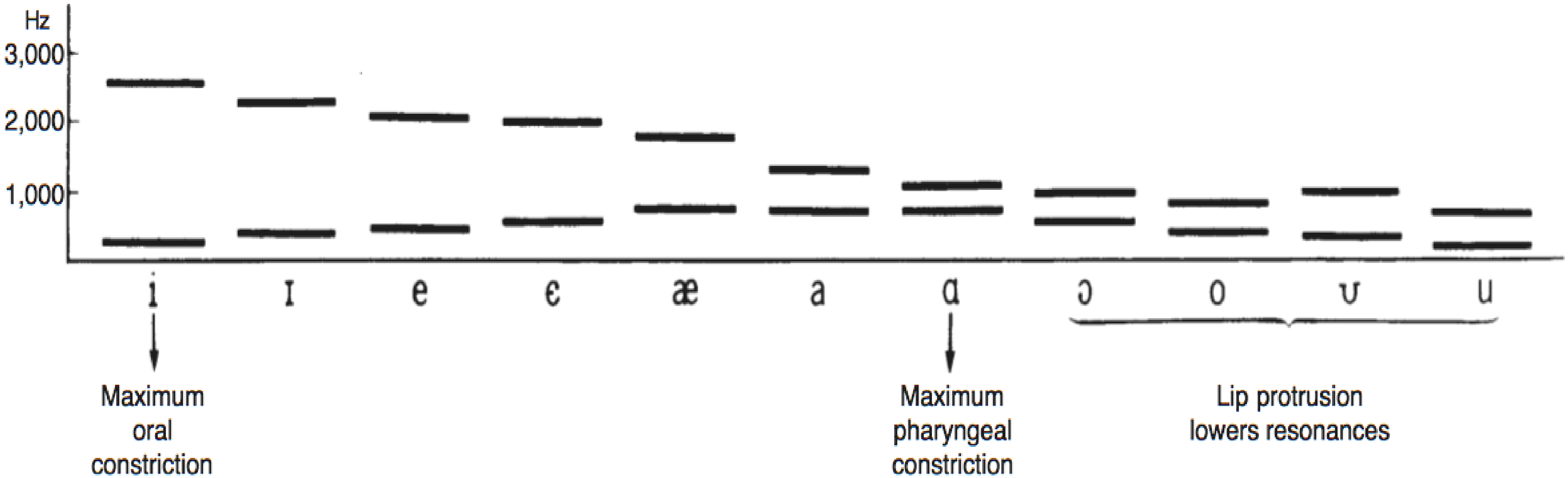


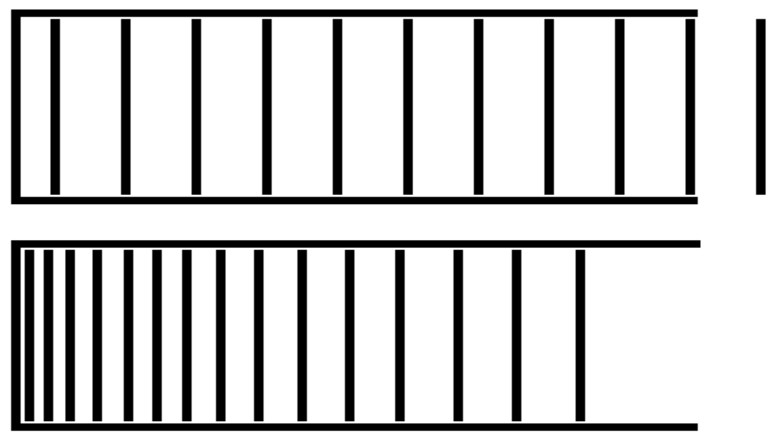
FIGURE 5.27 Two-formant vowels, synthesized on the Pattern Playback. The symbols indicate the identificatio of each pattern by listeners. The lettering indicates the vocal tract characteristics of the corresponding vowels.

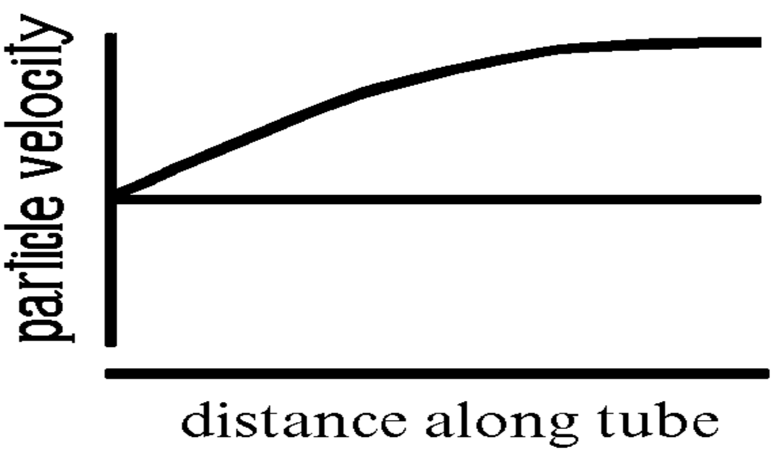
Perturbation Theory

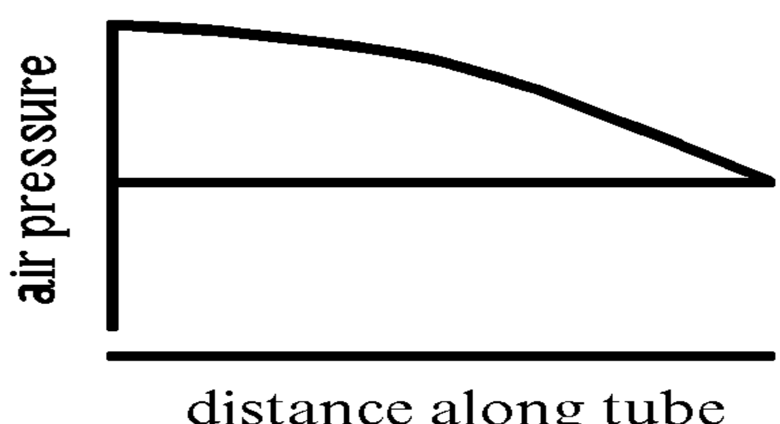
- another way of modeling the acoustic consequences of vocal tract constrictions, commonly called **perturbation theory;**
- in this approach to modeling vowel acoustics, the relationship between air pressure and velocity plays an important role.
- resonant frequencies are determined by the shape of the vocal tract ***as a whole*** rather than by the relative volumes of air,
- Chiba and Kajiyama, 1941; Mrayati et al., 1988

Air in a tube vibrating like a spring (maximally expanded/contracted)

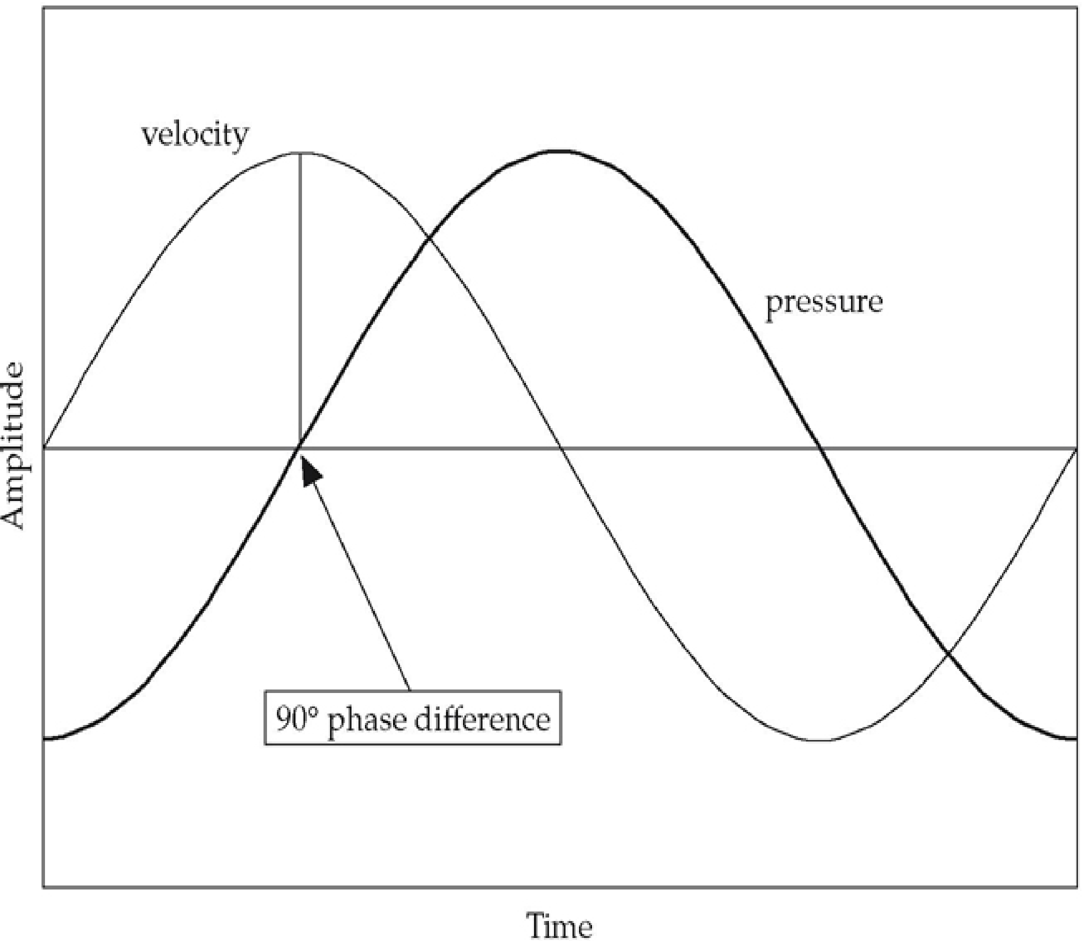
Maxima of velocity correspond to points where pressure equals zero, and maxima of pressure correspond to points where velocity equals zero.







The relationship between velocity and pressure.



- **nodes** (least particle displacement, maximum pressure) and
- **antinodes** (most particle displacement minimum pressure)

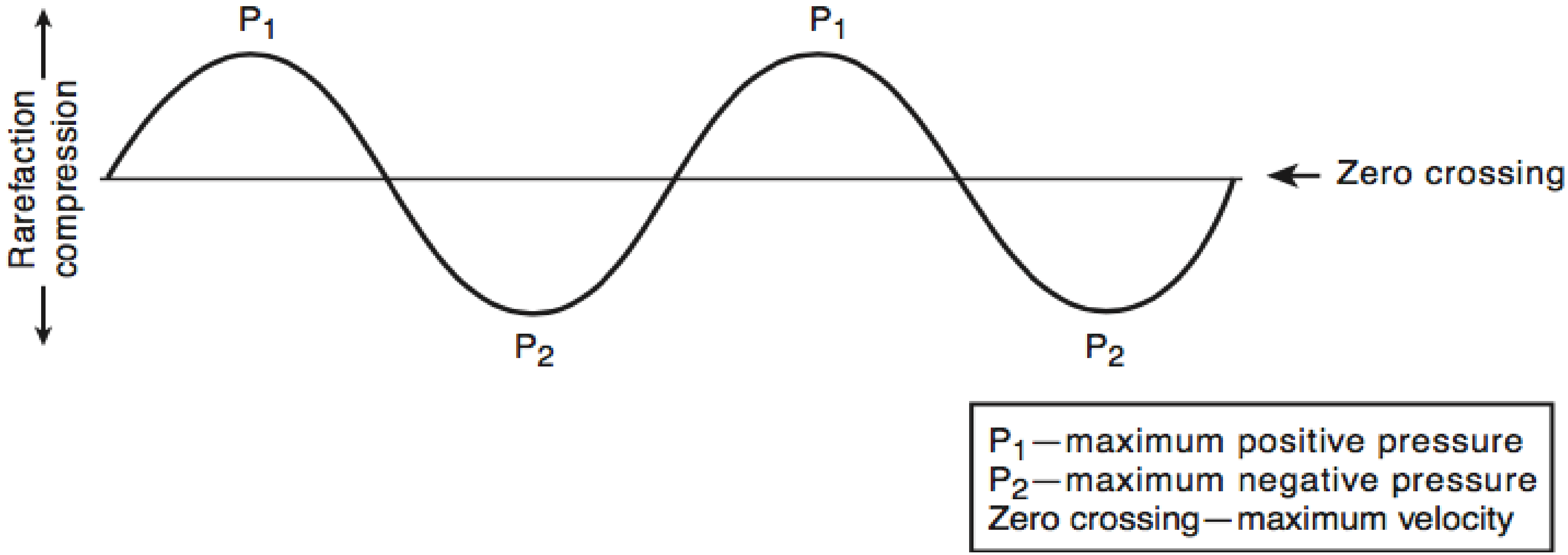


FIGURE 5.11 The inverse relationship between pressure and velocity for a sine wave. Pressure is greatest at points P_1 and P_2 for positive and negative values. Velocity is greatest at zero crossings and at a minimum at P_1 and P_2.

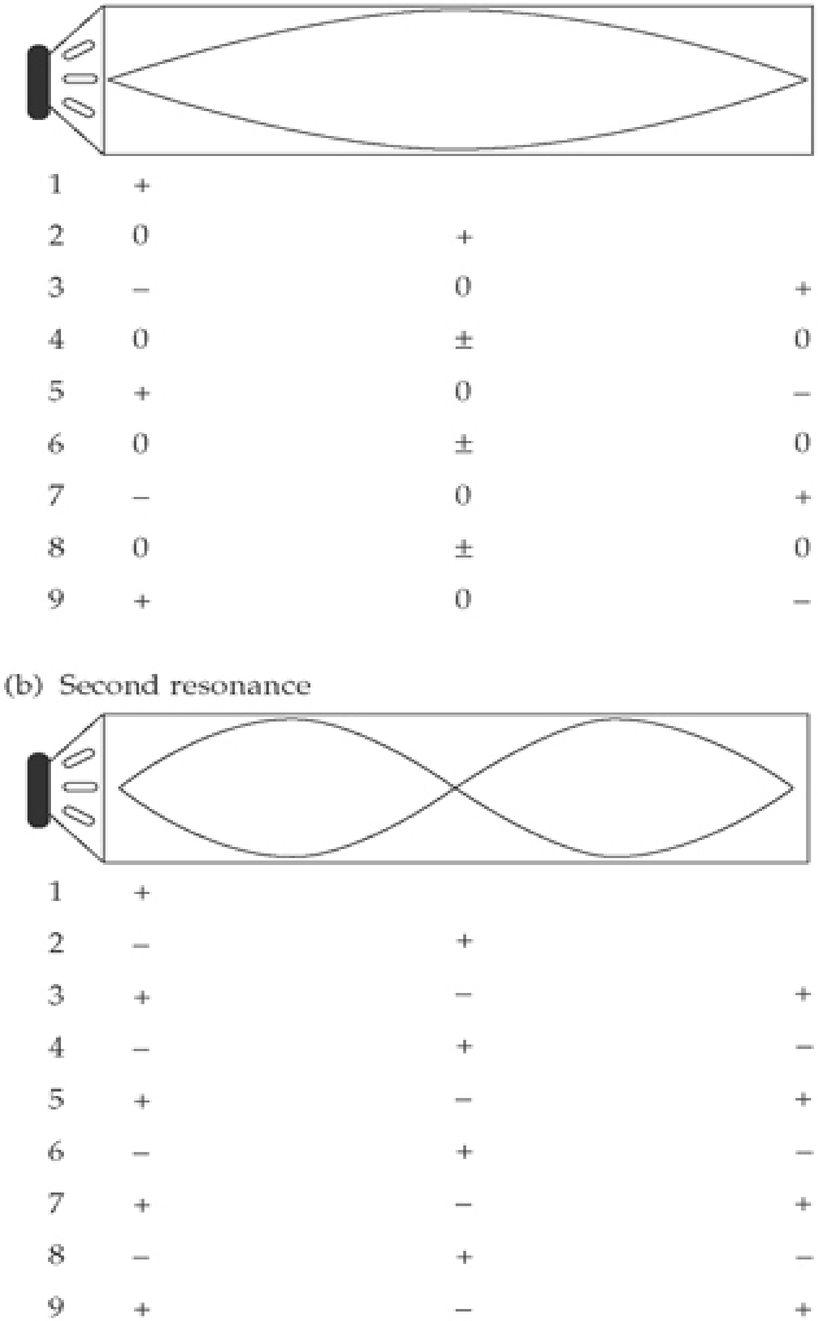
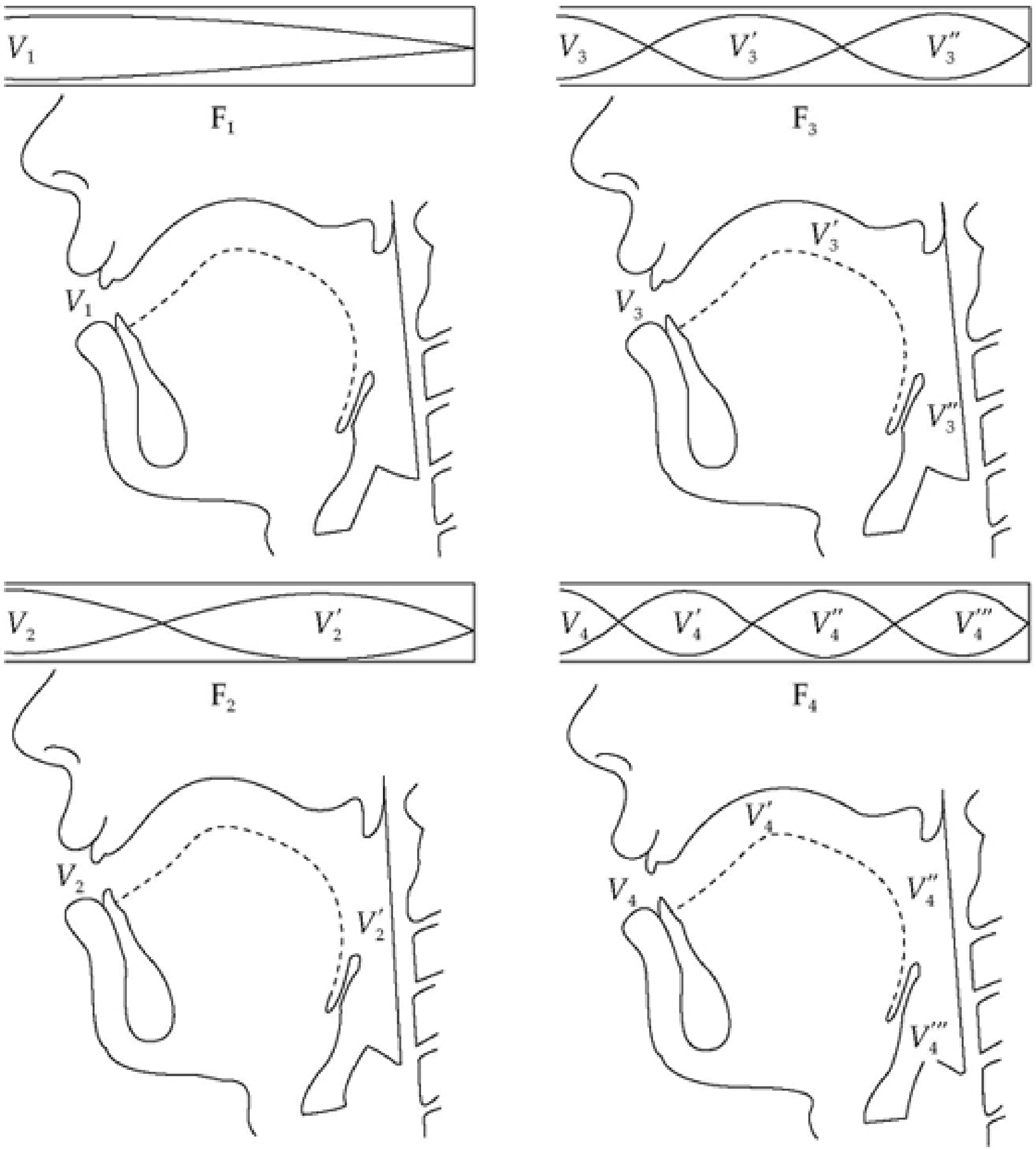


Figure 2.8 Standing waves of the two lowest resonant frequencies of a tube closed at both ends with a loudspeaker at one end. Time is shown vertically from earlier (1) to later (9). Pressure peaks are represented by plus (+), pressure valleys by minus (-), and zero, atmospheric pressure, by zero (0) or in the case of canceling peaks and valleys by plus-minus (±). (a) shows the first resonance corresponding to the wave shown in the previous figure, (b) the next higher resonant frequency of the tube, The sine waves inside the tube illustrate the standing wave. In this type of display, nodes in the particle displacement profile are illustrated as locations where the sine waves cross each other (least particle displacement) and antinodes are illustrated as locations where the sine waves are furthest apart from each other (most particle displacement).



- Locations of standing wave
- **antinodes** (points of maximum velocity) and
- **nodes** (points of maximum pressure)
- in a straight tube open at one end and in the unconstricted vocal tract.
- **Antinodes** are labeled ***Vn*** (numbered by primes from the front of the vocal tract),
- **nodes** are indicated by the intersections of the sine waves in the uniform tube.
- Nodes and antinodes are shown in separate graphs for each of the first four formants (labeled F*n*).
- After Chiba and Kajiyama (1941).

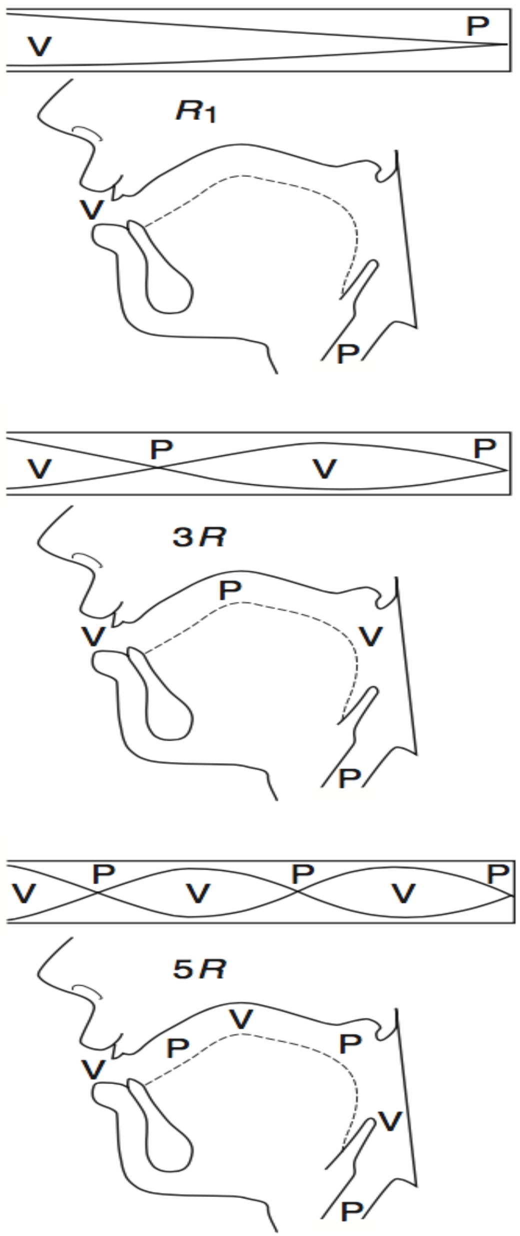


FIGURE 5.10 The resonances of the vocal tract. V, points of maximum velocity; P, points of maximum pressure; R, resonances. (Adapted with permission from Chiba, T., and Kajiyama, M., *The Vowel: Its Nature and Structure.* Tokyo: Kaiseikan, 1941.)

The Perturbation Theory

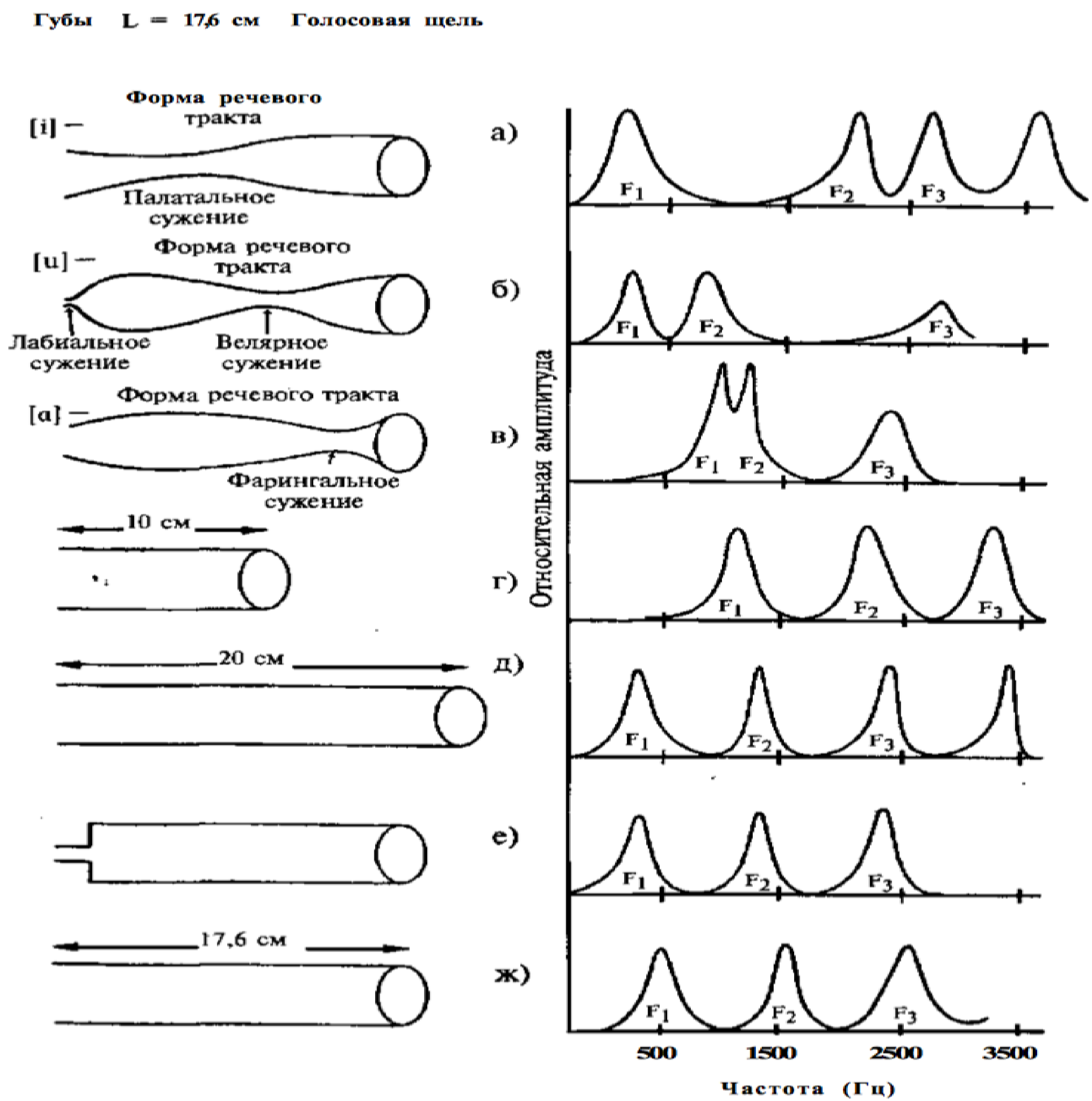
- Chiba and Kajiyama relates vocal tract constrictions to formant frequencies by taking into account the kinetic energy present at points of maximum velocity and the potential energy present at points of maximum pressure.
- If the vocal tract is constricted at a point of high kinetic energy (velocity maximum), air particle movement is impeded, and consequently the frequency of the movement decreases;
- while, on the other hand, if the vocal tract is constricted at a point of high potential energy (pressure maximum), air particle movement is enhanced, and consequently the frequency of the movement increases.
- These effects of constrictions on vocal tract resonant frequencies can be summarized by two rules of thumb:
- 1 Constriction of the vocal tract near a point of maximum velocity (the **antinodes** labeled V*n*) **lowers** the formant frequency.
- 2 Constriction of the vocal tract near a point of maximum pressure (the **nodes**, where the lines cross) **raises** the formant frequency.

The Perturbation Theory

- The perturbation theory rules of thumb apply separately for each of the formants.
- For instance, a constriction in the pharynx falls near a pressure maximum in the F1 resonance, and thus the perturbation model predicts that the F1 of [ɑ] is higher than the F1 found in the neutral (constrictionless) vocal tract configuration.
- At the same time a constriction in the pharynx falls near a velocity maximum in the F2 resonance, and thus the model predicts that the F2 of [ɑ] will be lower than the F2 produced by the constrictionless vocal tract.
- So, perturbation theory and the tube model give the same result for [ɑ]

Perturbation Theory and Tube Models compared

- for the vowels [i] and [ɑ] make similar predictions for vowel formant frequencies.
- when there is more than one vocal tract constriction, as in [ɹ] it is easier to apply perturbation theory for a particular vocal tract configuration, while for less complicated vocal tract configurations, it is simpler to derive quantitative predictions of the formant values for a range of articulations using tube models.
- the assumptions of tube models are more closely met in articulations that have relatively narrow constrictions, and thus not too much coupling between the tubes.
- the assumptions of perturbation theory are more closely met by articulations in which the vocal tract is mainly unobstructed.


Губы L = 17,6 см Голосовая щель
[i] — Форма речевого тракта
Палатальное сужение
[u] — Форма речевого тракта
Лабиальное сужение
Велярное сужение
[a] — Форма речевого тракта
Фарингальное сужение
10 см
20 см
17,6 см
а)
б)
в)
г)
д)
е)
ж)
F1
F2
F3
Относительная амплитуда
500
1500
2500
3500
Частота (Гц)

Quantal theory

- Stevens (1989):

regions of stability in the mapping between articulation and the frequency of F2 define as the most acoustically stable vowels (that is, the vowels that have the most room for slop in their productions) the corner vowels [i], [ɑ] and [u].

These are also the vowels that occur most frequently in the languages of the world (Maddieson, 1984).

Lindblom's (1990) theory of **adaptive dispersion**

- offers a different explanation for the cross-linguistic preference for the corner vowels. In the adaptive dispersion view, the corner vowels are most common in the languages of the world precisely because they are the corner vowels. That is, given the range of possible F1 and F2 values that can be produced in vowels, the vowels that can be most reliably distinguished from each other are those that are maximally distinct. So, if we assume that listeners' abilities to hear vowel distinctions provide a selectional pressure on segment inventories (in the diachronic development of language), we would predict that the most common vowels in the languages of the world would be the ones that have extreme formant values.
- Adaptive dispersion is a theory about stability in communication, taking into account the role of the listener; while quantal theory is about stability in only one aspect of communication, the articulation-to-acoustics mapping. Although adaptive dispersion makes predictions about preferred vowels, the theory has not been extended to other speech sounds. Quantal theory, on the other hand, while focusing on a narrower aspect of speech communication, has been applied to several types of segments.

Based on:

Johnson,_Keith. *Acoustic and Auditory Phonetics. 3rd edition*. Wiley-Blackwell (2011)

Ladefoged Peter. *Elements of Acoustic Phonetics*. University Of Chicago Press, 1995.

Speech science primer : physiology, acoustics, and perception of speech / Lawrence J. Raphael, Gloria J. Borden, Katherine S. Harris. – 6th ed. Lippincott Williams & Wilkins. 2007.