Speech Science: Articulation and Acoustics

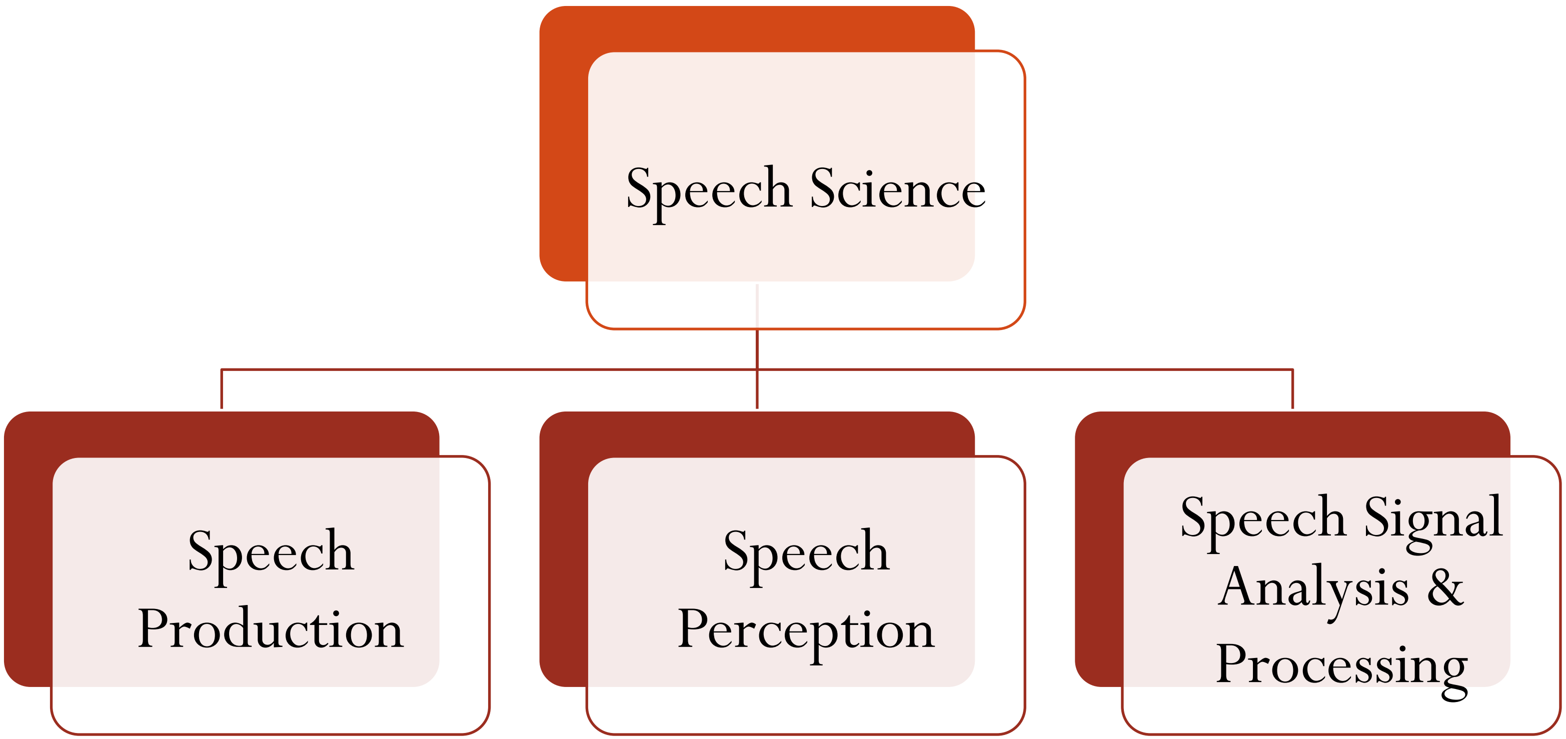
CS578
Winter Term, 2023-24
CSD UOC

Invited Lecture

Dr Anna Sfakianaki
Assistant Professor of Phonetics/Phonology
University of Ioannina
asfakianaki@uoi.gr

Speech Science

- Speech Science is the experimental study of **speech communication**.



Speech Science and Phonetics

- Speech Science has its origins in **Phonetics**
  - **Phonetics** is the branch of linguistics that studies the sounds of speech.

Field work: **Peter Ladefoged**
Language: **Toda**
Kiawiarh Village, South India, 22/01/2006
https://linguistics.ucla.edu/people/ladefoge/Remember/Index.htm

Linguistics

LEVELS OF LINGUISTIC ANALYSIS

phonetics	production and use of **speech sounds** in communication; articulatory and acoustic properties of speech
phonology	relations of **speech sounds** within the linguistic system
morphology	**word** formation and word alteration for sentence construction
syntax	grammar rules for **sentence** construction
semantics	**meaning** of words, utterances, sentences
pragmatics	influence of **context** on utterance **meaning**

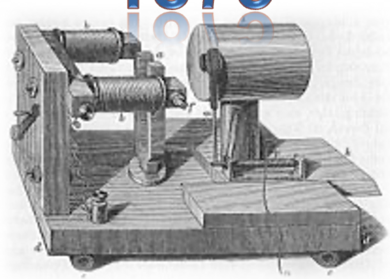
Speech Science and Phonetics

- Speech Science has its origins in **Phonetics**
  - **Phonetics** is the branch of linguistics that studies the sounds of speech.
  - The **sounds of speech** are the pieces of the linguistic code used to communicate meaning.

PHONETICS + TECHNOLOGY = SPEECH SCIENCE

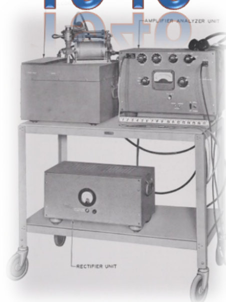
Adding Technology to Phonetics →
empirical investigation of speech production and perception

1875



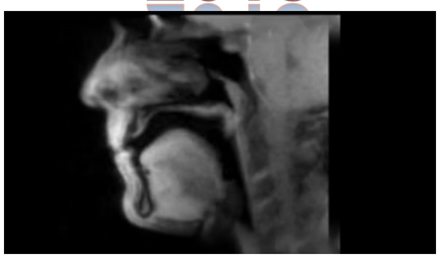
Helmholtz Resonator

1946



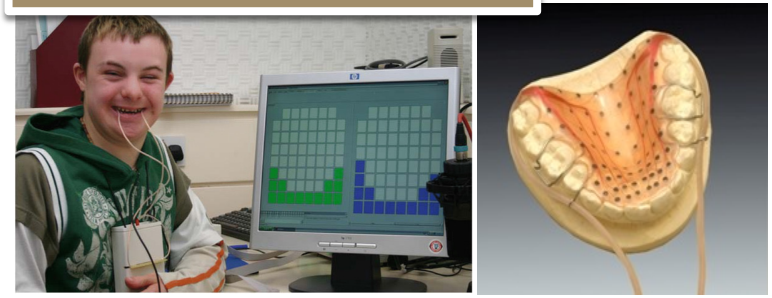
Sound Spectrograph
Bell Laboratories

2018



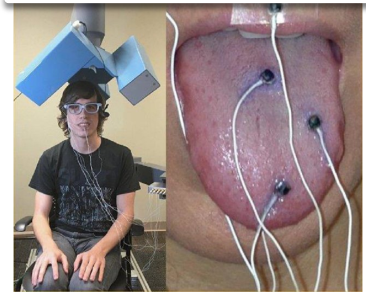
real-time MRI
Max Planck Institute

EPG-electropalatography



MRI

EMA-electromagnetic articulography

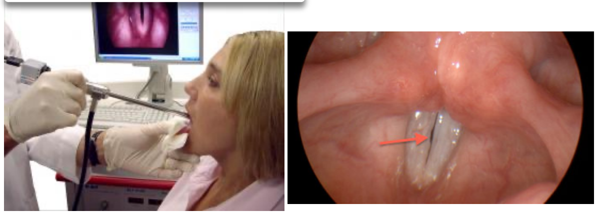


SPEECH SCIENCE

The instrumental study of speech

UTI -Ultrasound

Stroboscopy



Questions posed by Speech Science

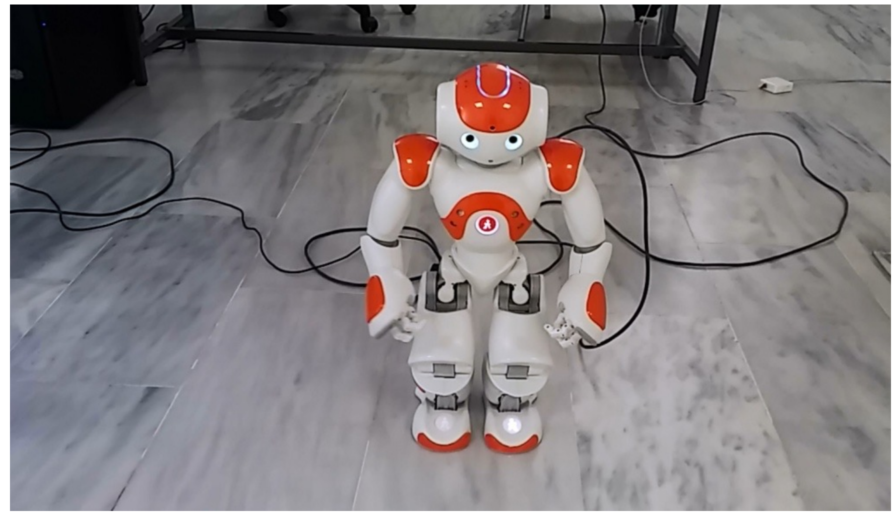
- How is speech planned and executed by the vocal system?
- How do the acoustic properties of sounds relate to their articulation?
- How and why do speech sounds vary from one context to another?
- How do listeners recover the linguistic code from auditory sensations?
- How do infants learn to produce and perceive speech?
- How and why do speech sounds vary between speakers?
- How and why do speech sounds vary across speaking styles or emotions?

UCL, PALS1004

Speech Science Applications

- Core Applications
  - Speech recognition
  - Speech synthesis
  - Speaker recognition

Nao Robot, FORTH

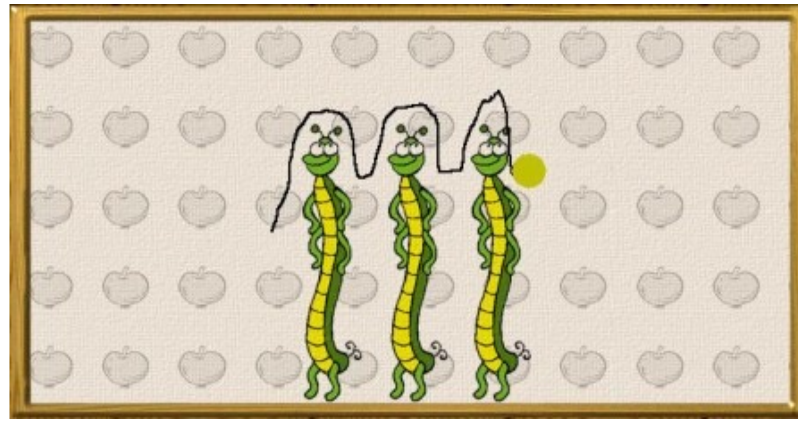


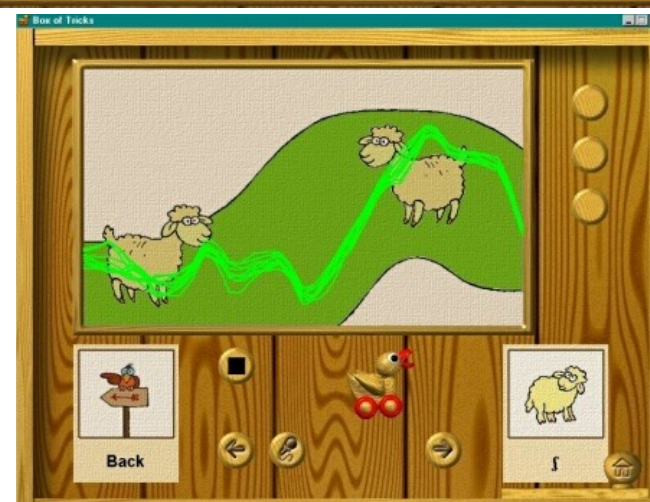
- Other applications
  - Forensic speaker comparison
  - Language pronunciation teaching
  - Assessment and therapy for disorders of speech and hearing
  - Monitoring of well-being and mood

SpeakGreek, AUTh

SPECO (SPEech COrrector)

- EU project (1998-2001)
- Visual display of acoustic information for children in need of assistance with various aspects of speech production
- Developed in 4 languages
- Multi-speaker database
- Commercial product (RCS)



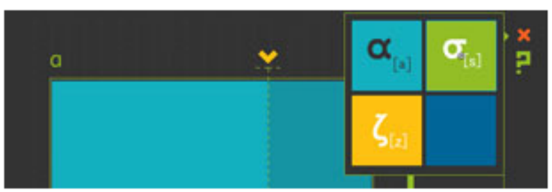


SpeakGreek

https://www.enl.auth.gr/speakgreek/index.html

- Free online pronunciation training tool for learners of Greek as a foreign/second language and for people with speech and hearing disorders
- Database of 60 speakers (men, women, children)

Voice Training



It contains applications which train users to produce sounds with appropriate voicing, to sustain sounds for as long as possible, to control the intensity and pitch of their voice.

Listen And Learn

It contains applications which train users to perceive and identify correctly the Greek vowels and consonants in syllables, words, word pairs, and sentences.

Say And Learn

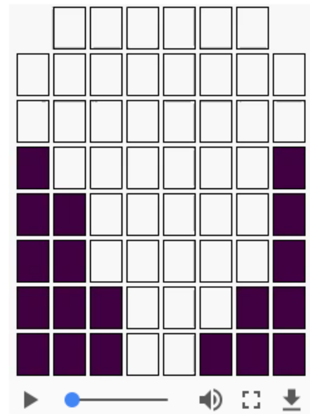
It contains applications which train users to produce correctly the Greek vowels and consonants in isolation, in syllables, words, word pairs, and sentences. It also trains users to produce the appropriate melody of Greek in statements, questions, and sentences with different focus.

SpeakGreek –Phonetic Library

[i]

Male Female Child

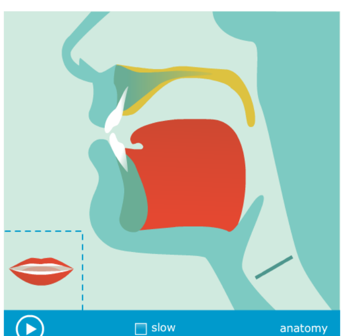
+ EPG & Ultrasound

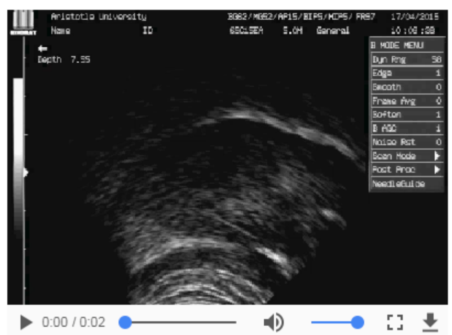


Examples:

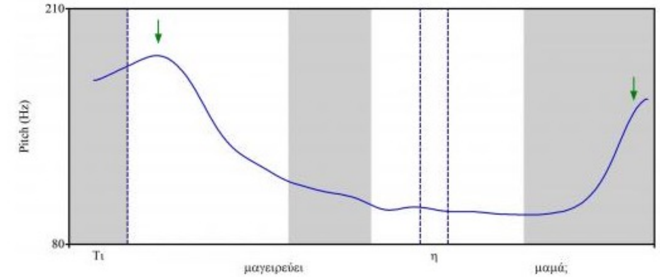
- [i]
- ήχοι
- φίλη
- φίδι
- είδηση
- ησυχία

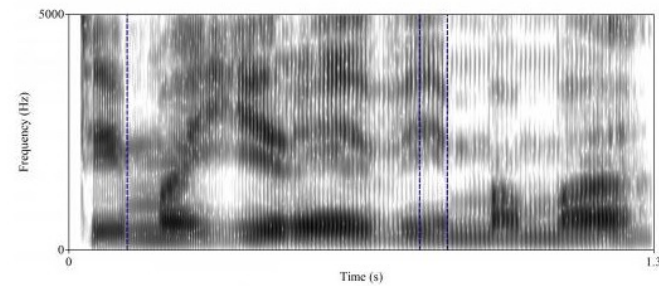
/i/: close front unrounded
The tongue front is raised towards the hard palate. The tongue is in advanced a
The sides of the tongue
lips are spread. The soft
vibrate.





intonation

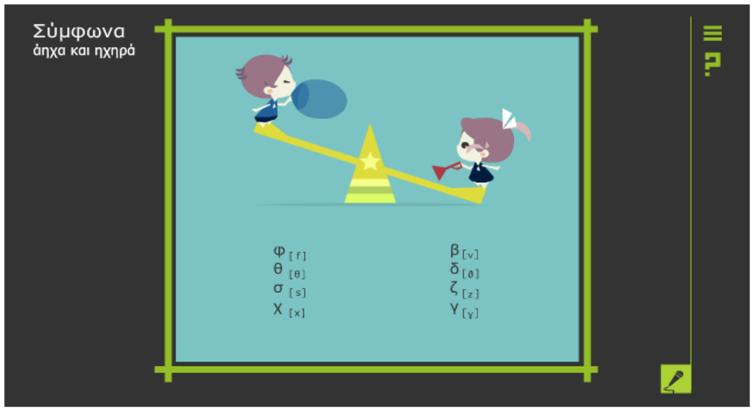




SpeakGreek –Voice Training

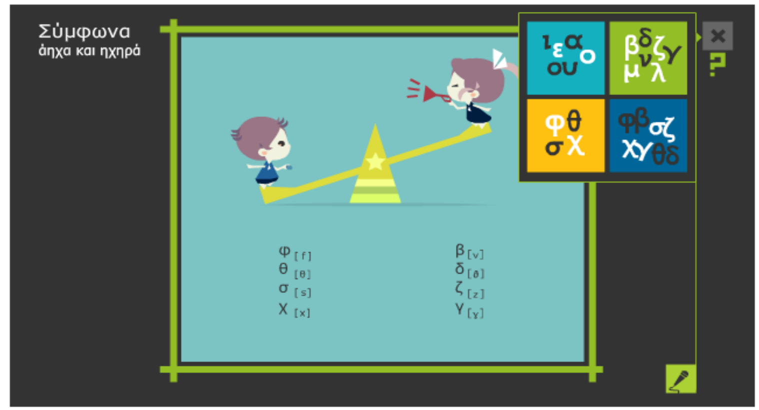
Μαθαίνω να παράγω φωνή

Πίσω στις εφαρμογές



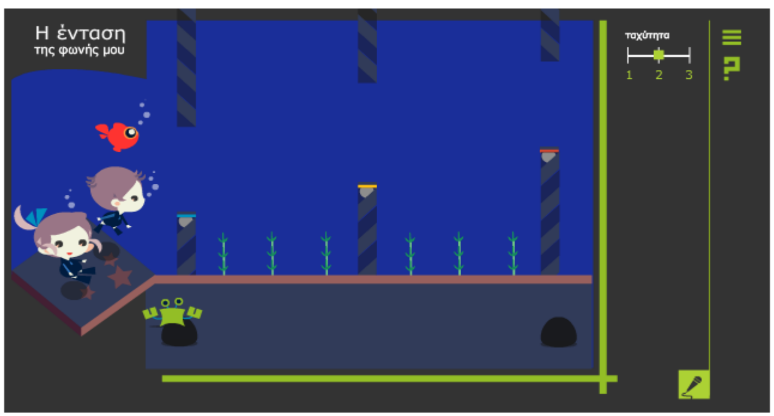
Μαθαίνω να παράγω φωνή

Πίσω στις εφαρμογές



Μαθαίνω να ελέγχω την ένταση της φωνής μου

Πίσω στις εφαρμογές



Μαθαίνω να ελέγχω την ένταση της φωνής μου

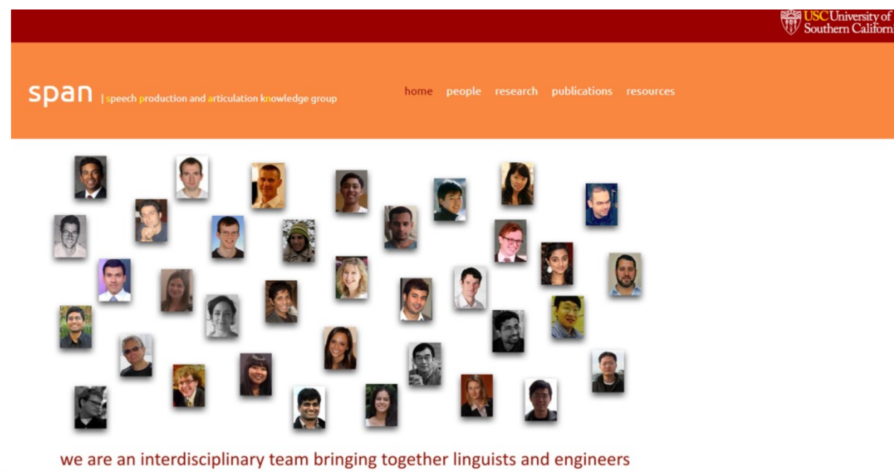
Πίσω στις εφαρμογές

Interdisciplinary Research

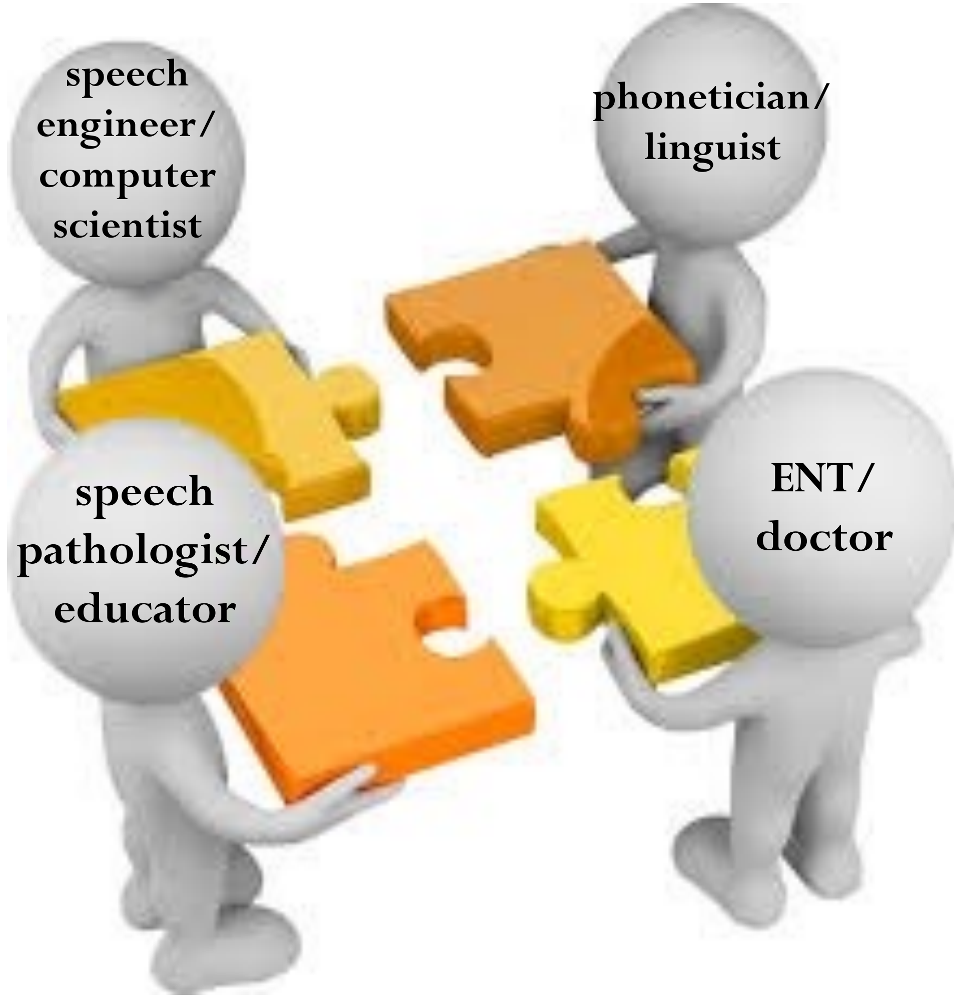
- **Phoneticians/Linguists + Engineers**
  - **ENRICH**: Speech modifications/enhancements for easier cognitive processing http://www.enrich-etn.eu/
  - **SPAN** (**S**peech **P**roduction and **A**rticulation K**n**owledge Group) University of Southern California http://sail.usc.edu/span/index.html

https://youtu.be/_2W52Y3IE_Y

ENRICH EUROPEAN TRAINING NETWORK

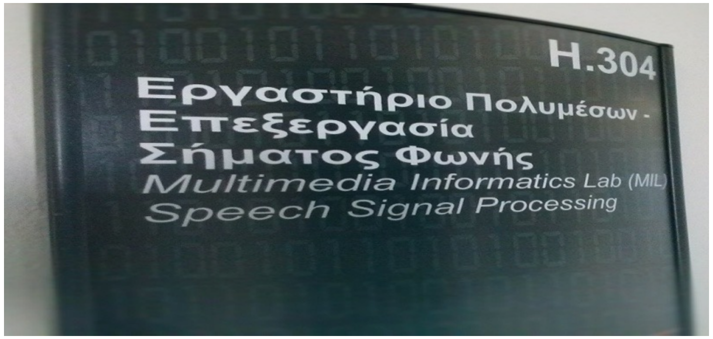


Fruitful interdisciplinary cooperation



SSPL

CSD, UoC



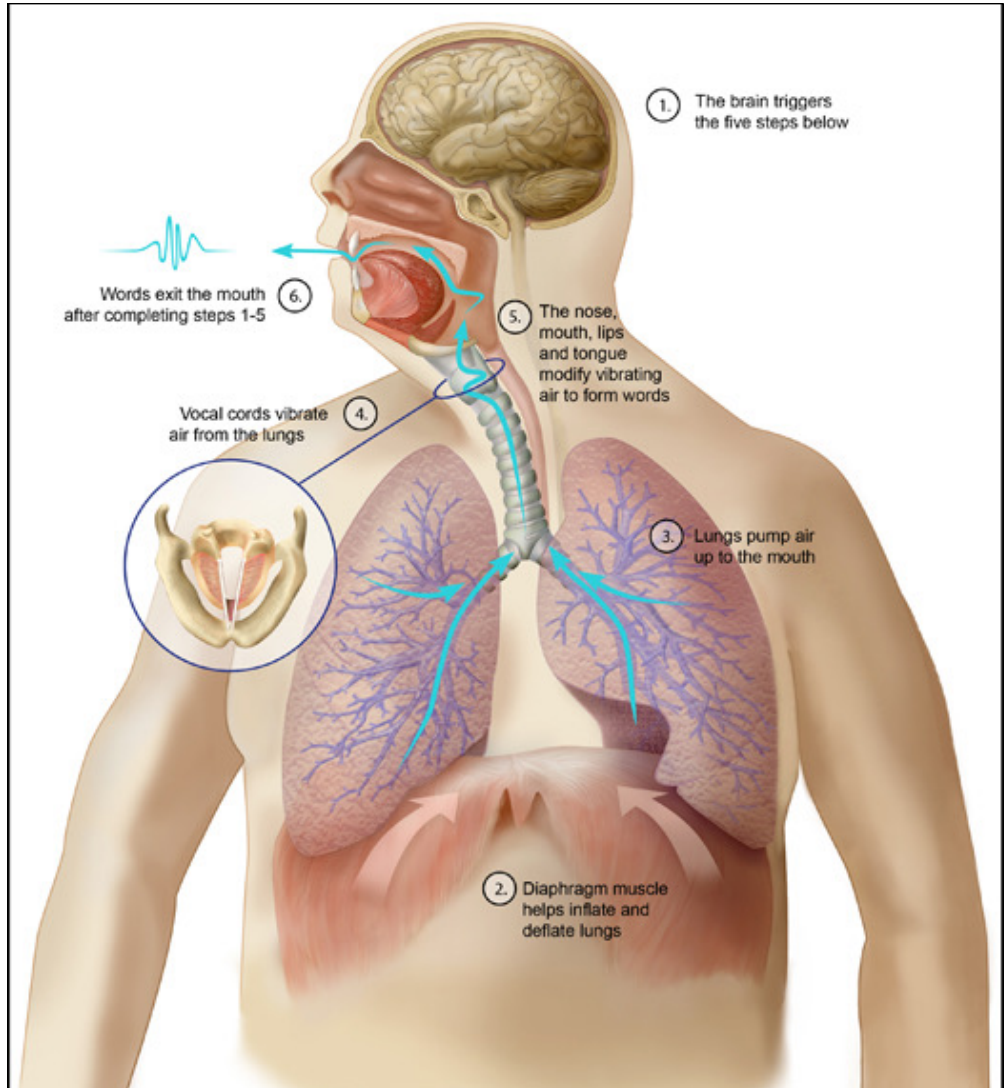
Articulation of
Vowels & Consonants

Speech Production

https://www.youtube.com/watch?v=osvE5Op1VzM&t=9s

Speech production process

- Brain
- Energy source
- Diaphragm
- Lungs
- Trachea (windpipe)
- Larynx (voice box)
- Pharynx (throat)
- Oral tract (mouth)
- Nasal tract (nose)



Zina Deretsky, National Science Foundation

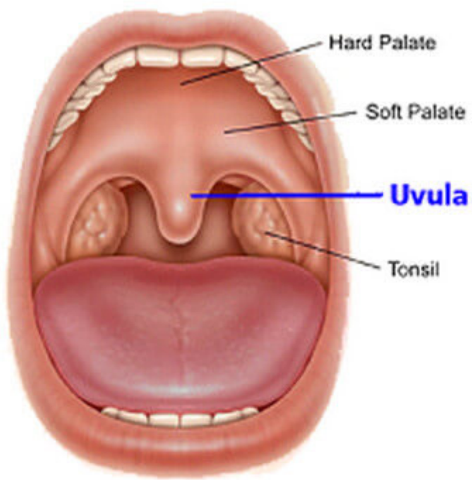
Speech Production

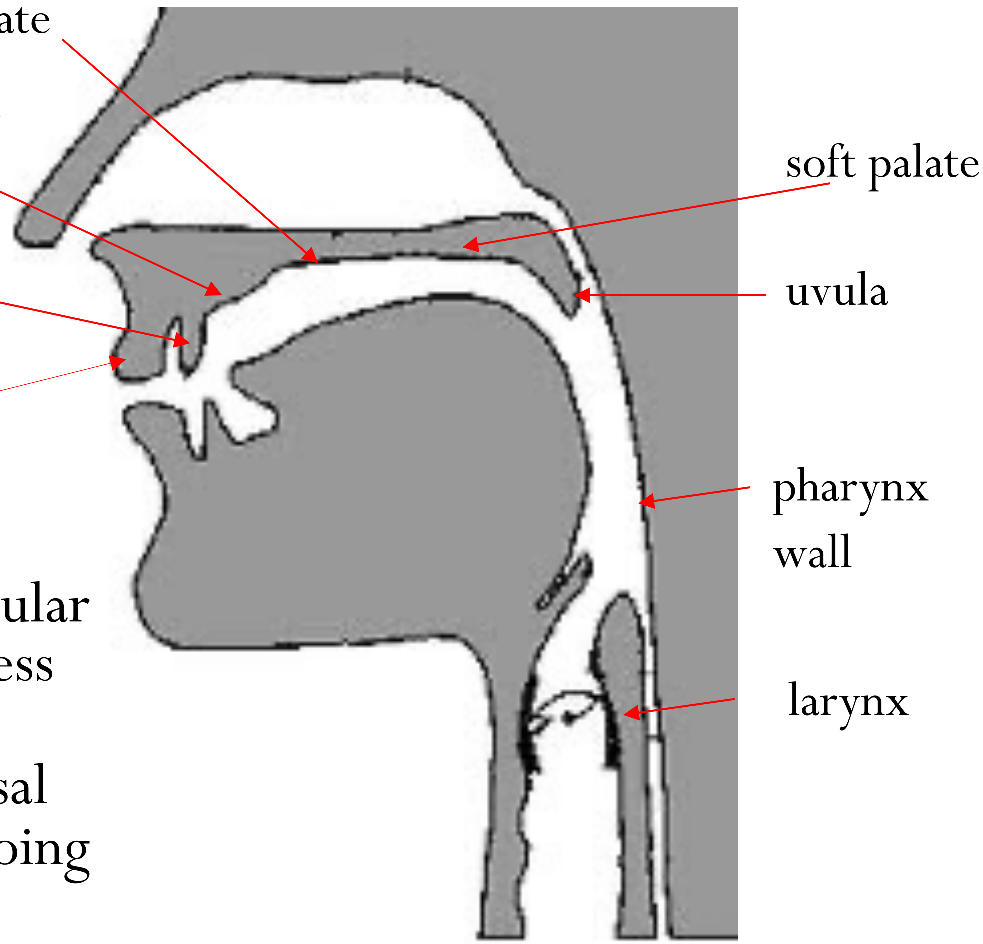
https://www.youtube.com/watch?v=SVKR3ESdAk8

Real-time MRI span, USC University of Southern California

- The tongue and lips move rapidly from one position to another.
- The actions of the tongue are among the **fastest** and the most **precise** physical movements that people make.

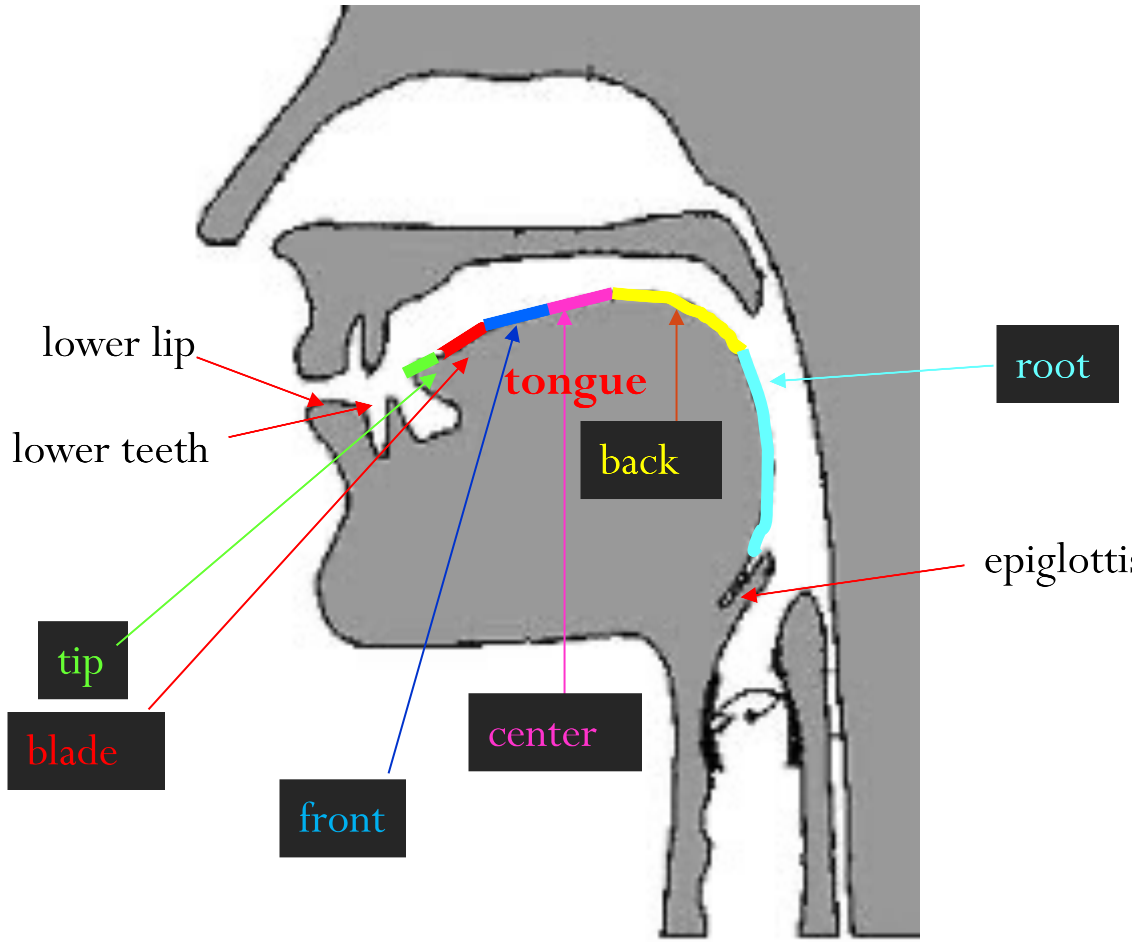
Upper surface articulators



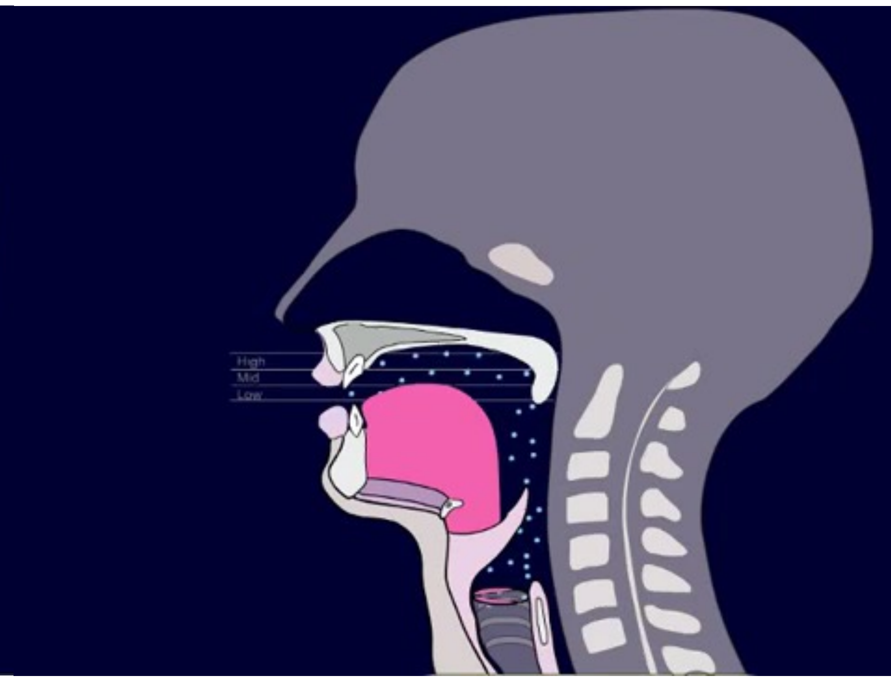


- **Soft palate/velum**: muscular flap that can be raised to press against the back wall of the pharynx and shut off the nasal tract, preventing air from going out through the nose (**velic closure**).

Lower surface articulators

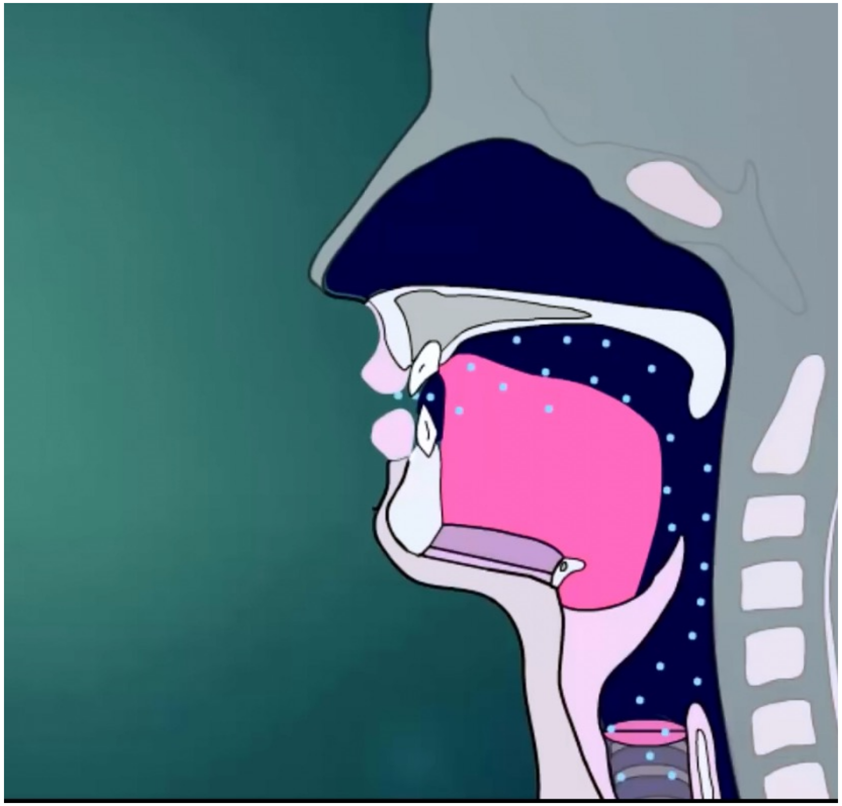


Consonants - Vowels



Consonants

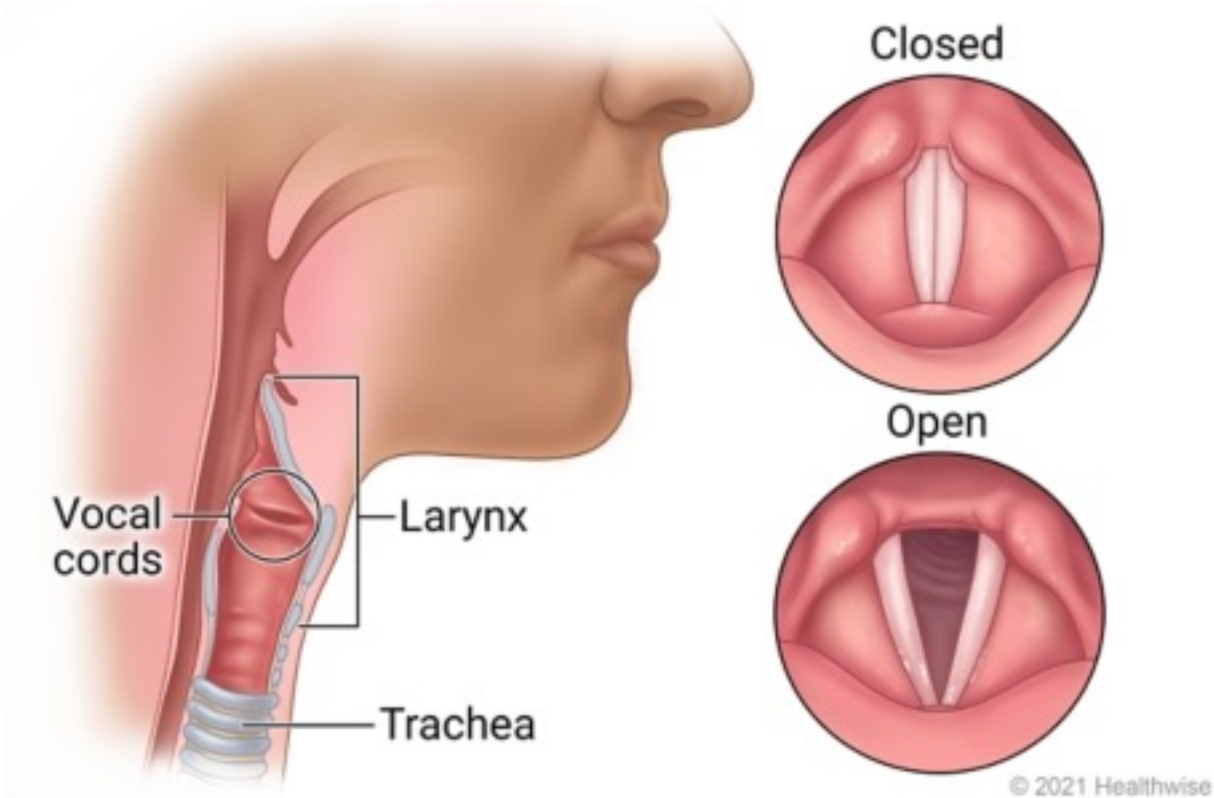
- Voicing
- Manner of articulation
- Place of articulation



Voicing

Vocal folds

- Open vocal folds:
  - breathing
  - production of voiceless sounds
- Closed vocal folds:
  - production of voiced sounds (phonation)



Exercise:
[ffffffffvvvvvvvffffffffffvvvv]

Voicing

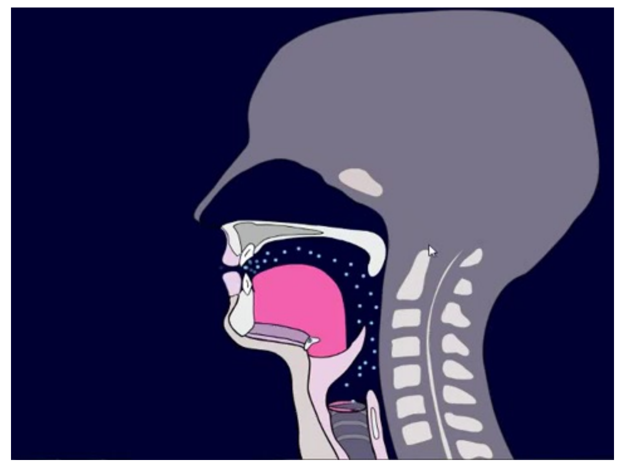
Vocal folds

- Open vocal folds:
  - breathing
  - production of voiceless sounds
- Closed vocal folds:
  - production of voiced sounds (phonation)

[p] voiceless

https://www.youtube.com/watch?v=LsAjJwC4JTQ

[b] voiced



https://www.youtube.com/watch?v=eSaT1Cg1FbU

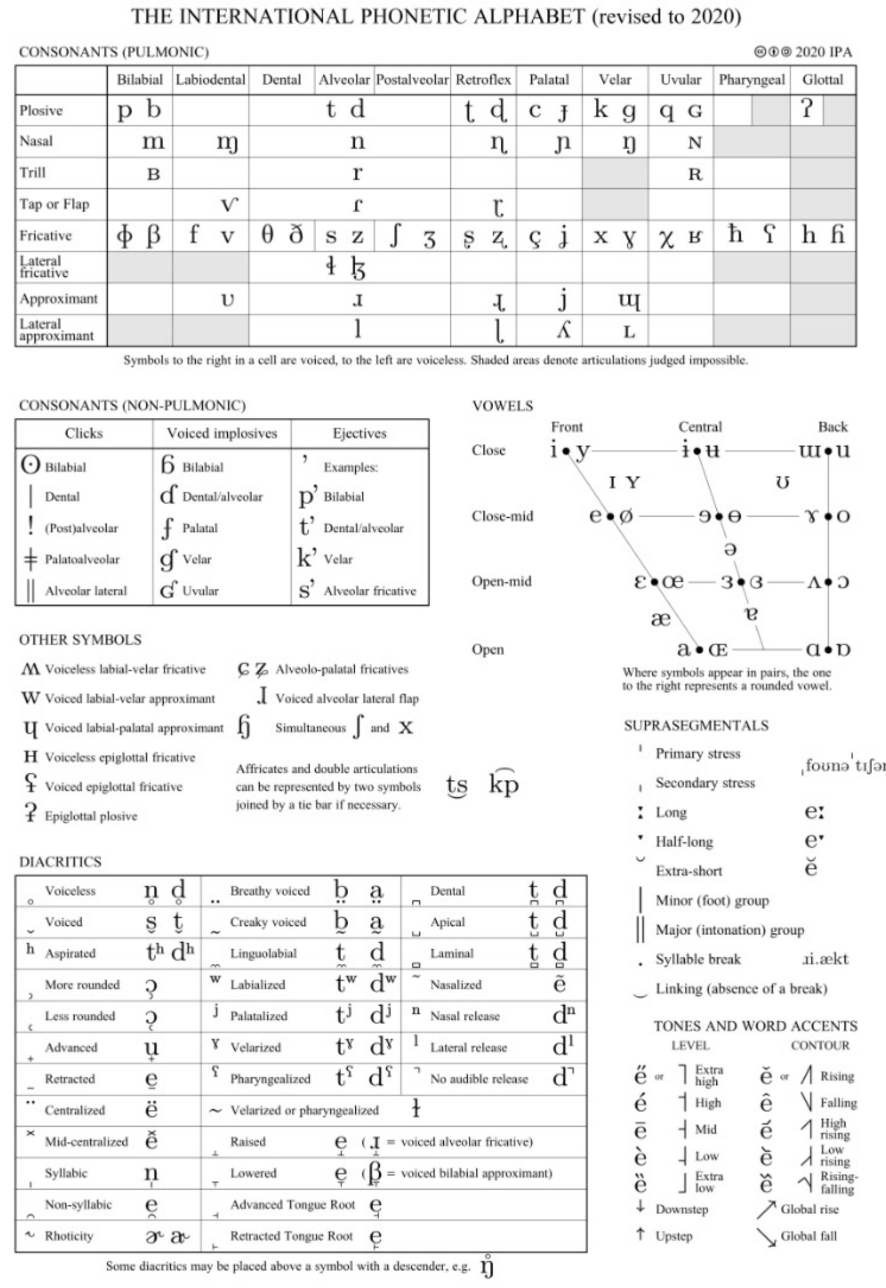
Consonants

Voicing	Are vocal folds open or closed?
Manner of articulation	How is the air constricted?
Place of articulation	Where is the air constricted?

Anna Sfakianaki, University of Ioannina

IPA Chart (2020)

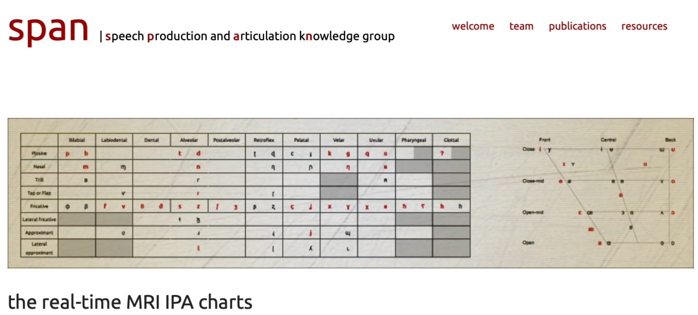
Download from:
https://www.internationalphoneticassociation.org/IPAcharts/IPA_chart_orig/IPA_charts_E.html



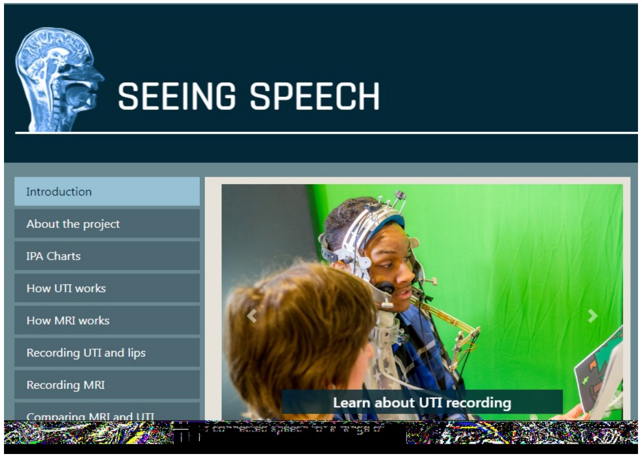
Interactive IPA Charts

IPA Online:
https://teaching.ncl.ac.uk/ipa/links.html

- **SPAN** (**S**peech **P**roduction and **A**rticulation **K**nowledge Group) University of Southern California http://sail.usc.edu/span/index.html



- **SEEING SPEECH**
6 Scottish Universities (Scottish Consortium)
https://www.seeingspeech.ac.uk/



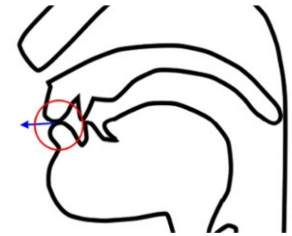
- **eNunciate** (**A Visual Language Learning Tool**) The University of British Columbia https://enunciate.arts.ubc.ca/

Manner of Articulation

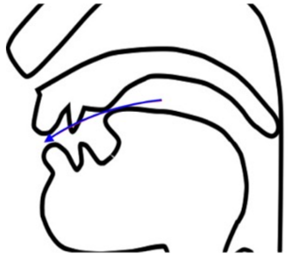
Consonants

Plosive
Nasal
Trill
Tap or flap
Fricative
Lateral fricative
Approximant
Lateral approximant

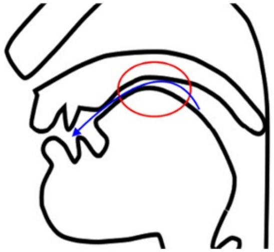
Complete blockage of air flow



Partial blockage of air flow (turbulence)

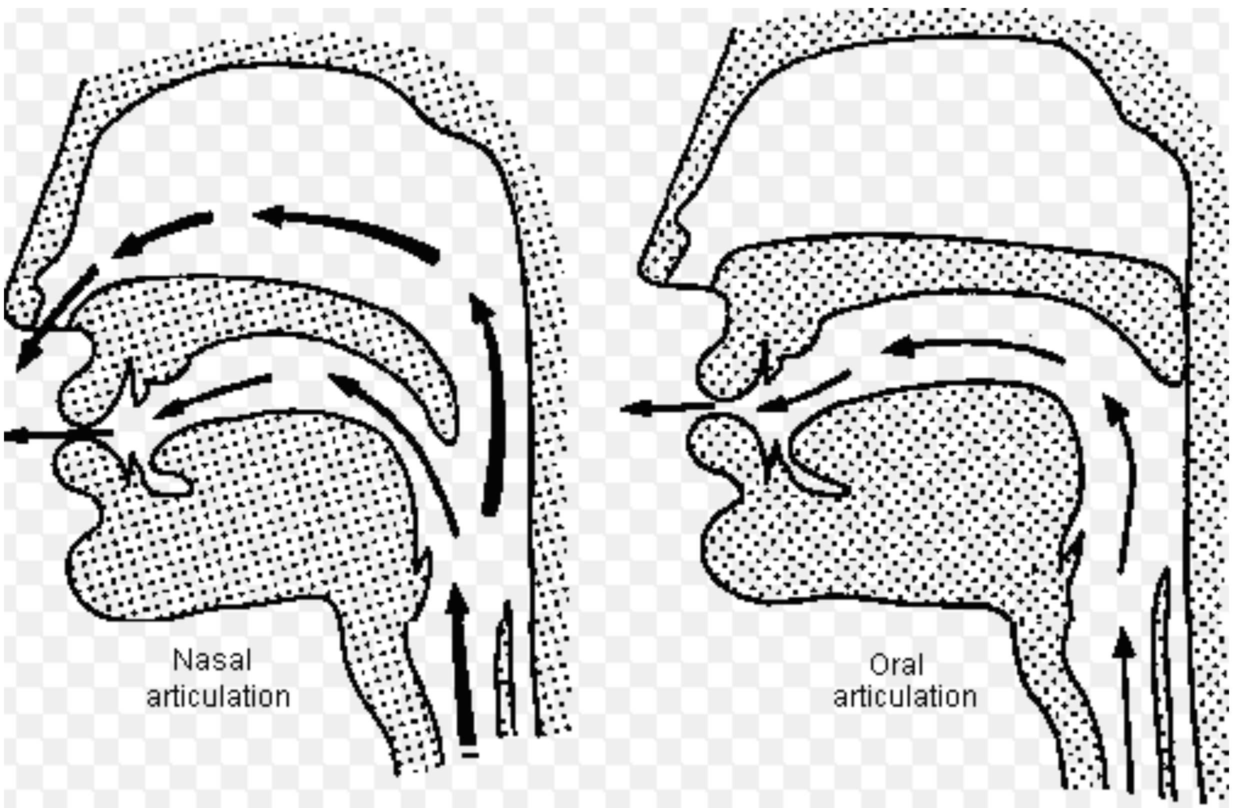


Partial blockage of air flow (no turbulence)



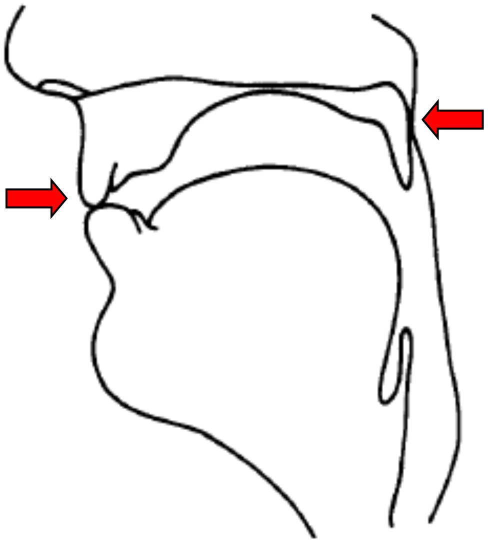
Nasal vs. oral articulation

- Nasal sounds
- Oral sounds

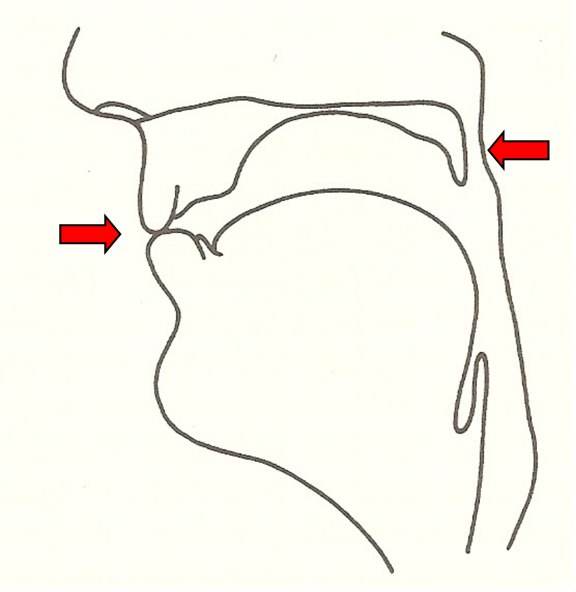


Manner of Articulation

Oral Stop



Nasal Stop



Place of Articulation

Basic places of articulation

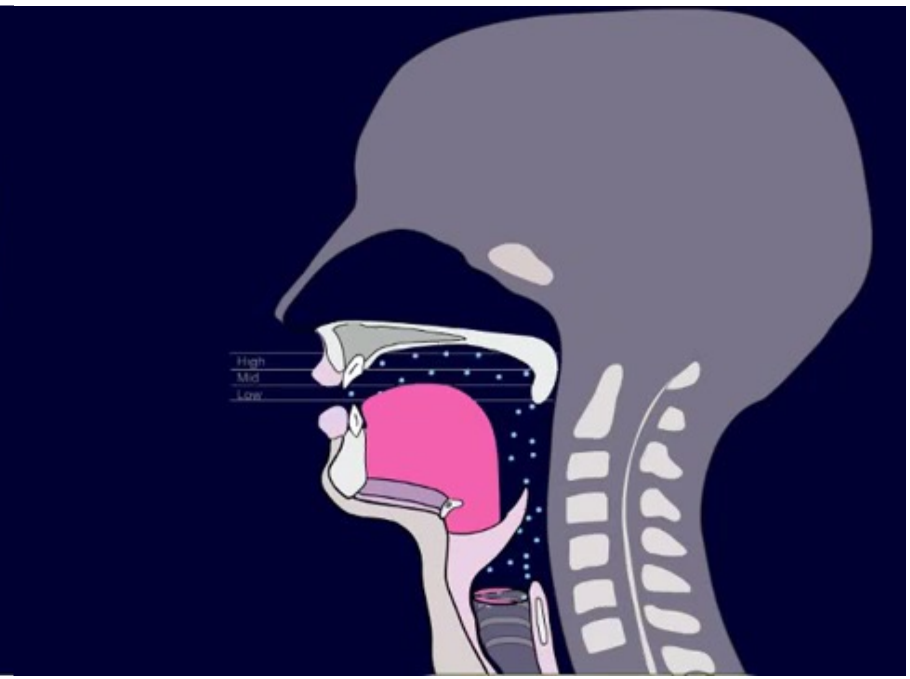
Articulator	**Articulation**
• lips	labial
• tongue tip/blade	coronal
• tongue dorsum	dorsal

Example: "**topic**"

Articulatory description of Consonants

	Voicing	Place of Articulation	Manner of Articulation
[p]	voiceless	bilabial	stop
[z]	voiced	alveolar	fricative
[ŋ]	voiced	velar	nasal

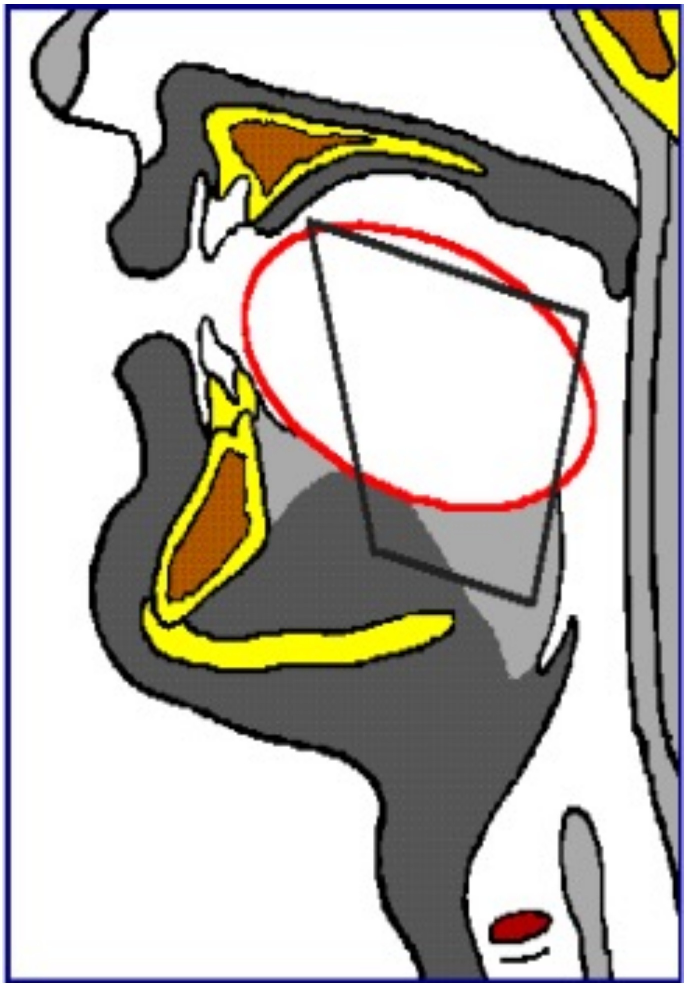
Consonants - Vowels

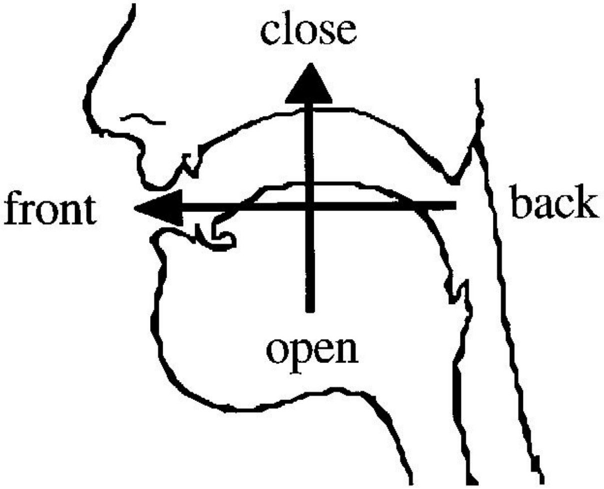


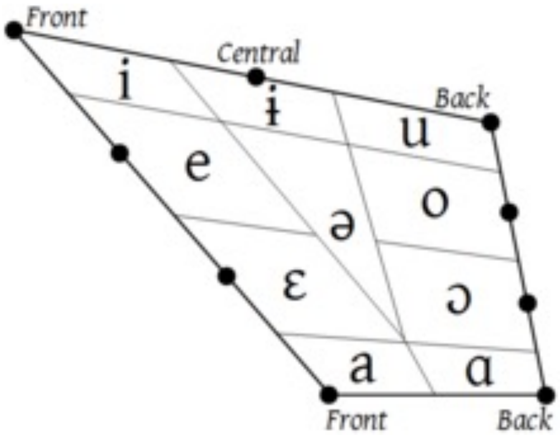
Articulation of vowels

- Articulators do not come very close together → the passage of the airstream is relatively unobstructed.
- Articulatory description focuses on
  - Position of highest point of the tongue
  - Position of the lips

Tongue position

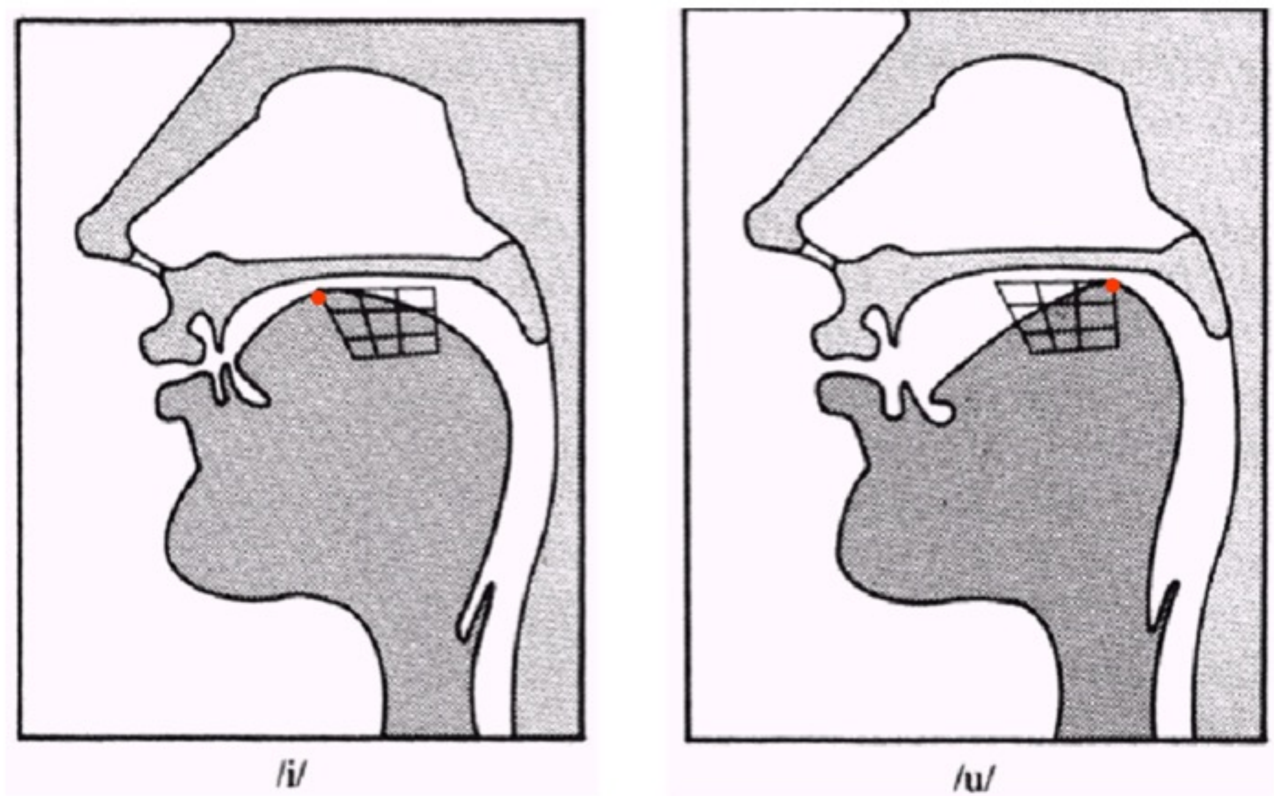






Principles of the IPA (1949)

Tongue position-vowel quadrilateral



he

who

UCLA tongue video

- X ray video of tongue and lip movement during production of vowels /i, e, a, o, u/.

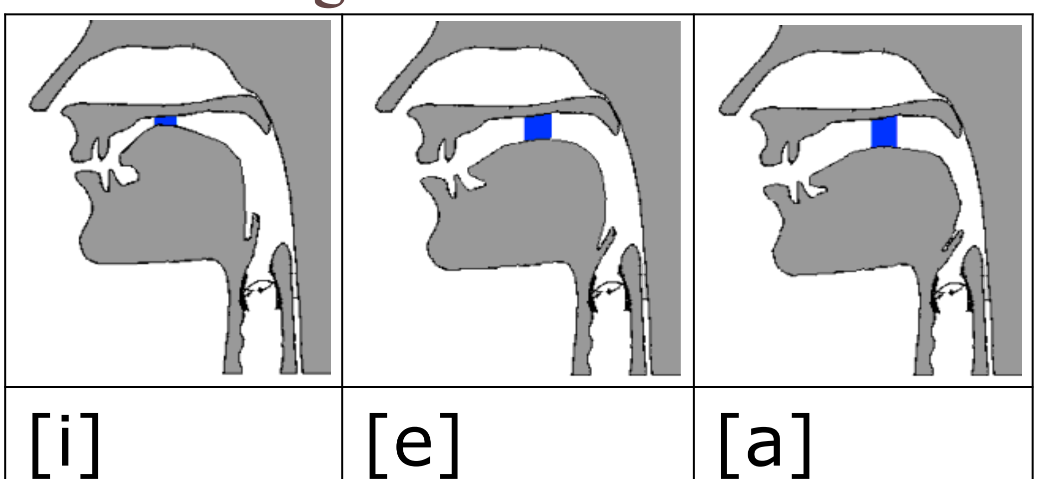
- Download from

http://www.phonetics.ucla.edu/vowels/chapter11/tongue.html

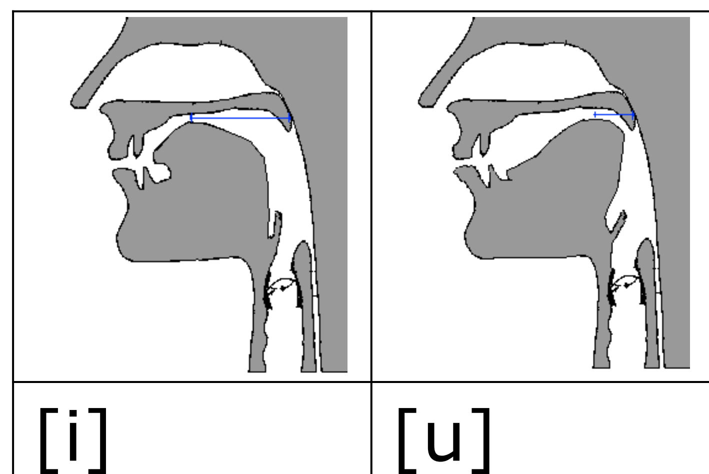
Articulatory description of vowels

1. **height** of tongue body
2. **front-back** position of the tongue
3. degree of lip rounding

high/low dimension



front/back dimension



Acoustics of Vowels & Consonants

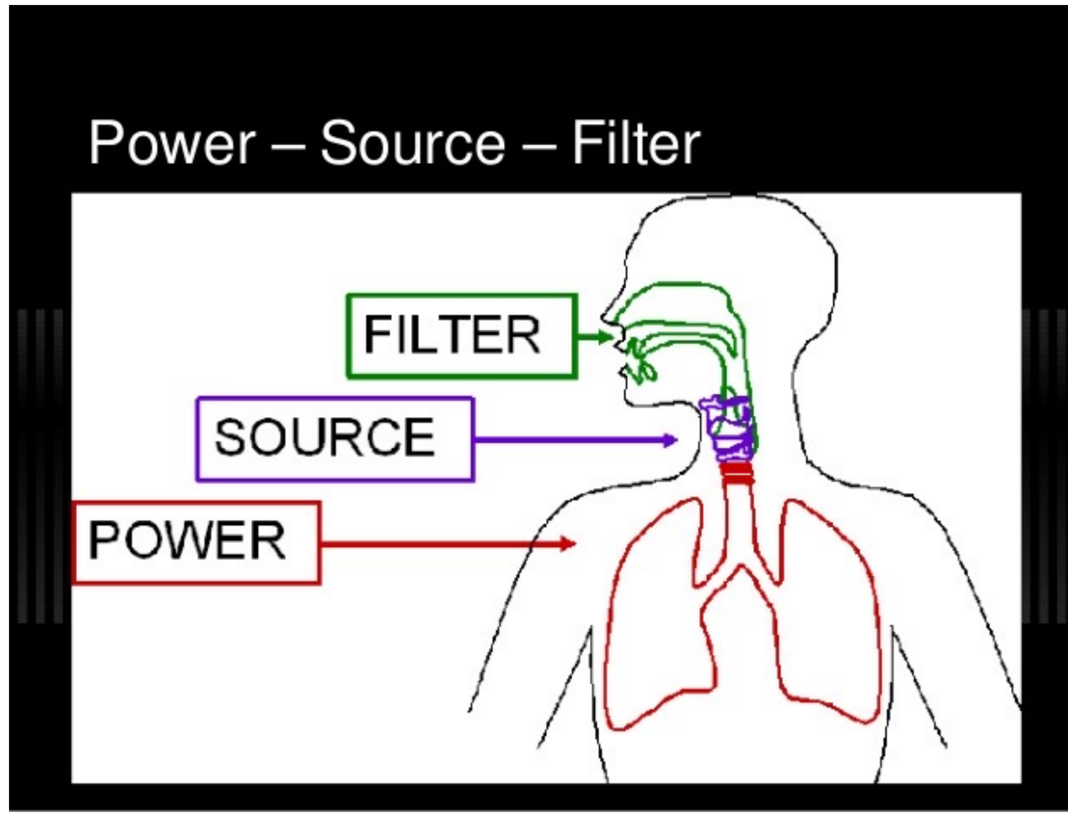
Anna Sfakianaki, University of Ioannina

Source-Filter Theory

3 Filter

2 Source

1 Energy



https://www.vocalsonstage.com/vocals-on-stage-blog/resonance-and-articulation

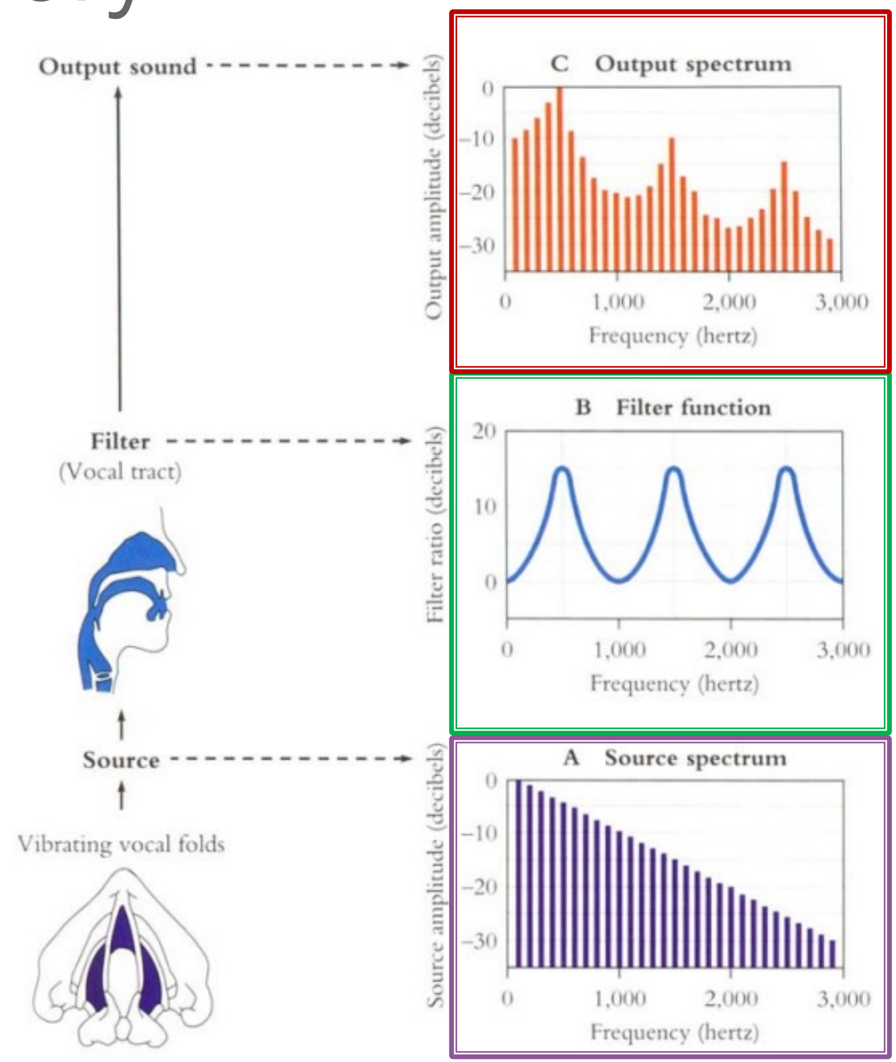
Anna Sfakianaki, University of Ioannina

Source-Filter Theory

- The output spectrum is formed by the filter and is different for each sound.

- The filter **amplifies** or **diminishes** frequency components and varies according to **vocal tract shape**.

- Vocal fold vibration (for voiced sounds) produces the source spectrum.
  - **Spectrum:** Energy of the signal distributed with frequency



Xavier Anguera Miró
http://www.xavieranguera.com/tdp_2011/4-Source-Filter-Models.pdf

Formants

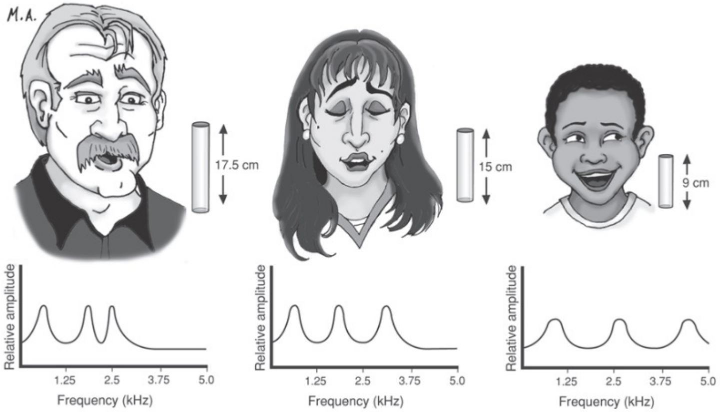
- Sounds differ from each other in three ways
  1. **pitch/frequency**
  2. **loudness**
  3. **quality**
- A vowel sound contains a number of different pitches simultaneously
  - pitch at which it was spoken
  - various overtone pitches that give it its distinctive quality
- Vowel Quality ⟺ Overtone Structure
- **<u>Overtones = Formants</u>**
- The lowest 3 formants distinguish vowels from each other
  - **F1 F2 F3**

Fundamental Frequency (F0)

- **Fundamental frequency**: number of vocal fold vibrations per second.
- Vocal folds must be vibrating in order to have F0.
- It corresponds to variations in pitch (speech melody or intonation).
- Vocal folds may vibrate faster or slower giving higher or lower pitch to the sound, BUT the formants of the sound remain the same as long as vocal tract shape remains unchanged.

- Male voice: 120 Hz
- Female voice: 220 Hz
- Child voice: 260-280 Hz

- All voiced sounds are distinguishable due to their formants.



Behrman (2021)

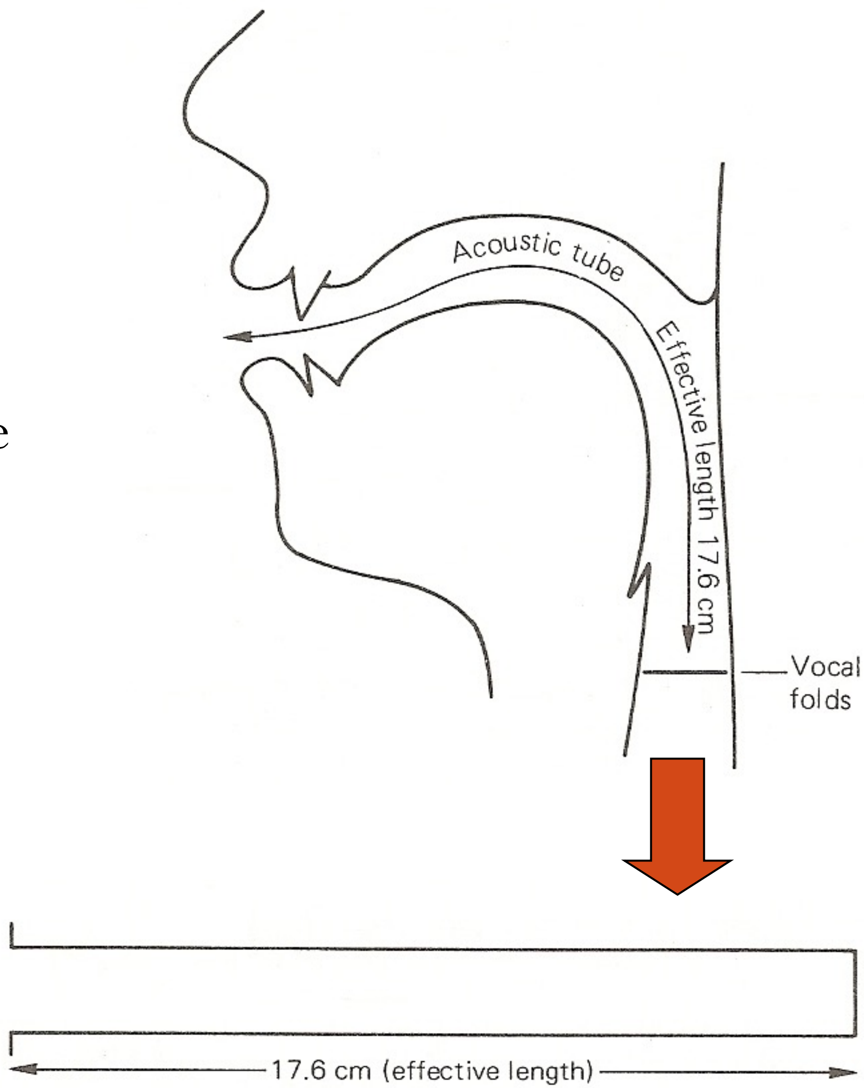
How do formants arise?

- The air in the vocal tract acts like the air in a bottle.
  - Tap on a bottle.
  - Open your mouth, make a glottal stop and flick a finger against your neck just to the side and below the jaw.

  What do you observe?

  - Articulate [i, e, a, o, u] without producing sound.

  What do you observe?



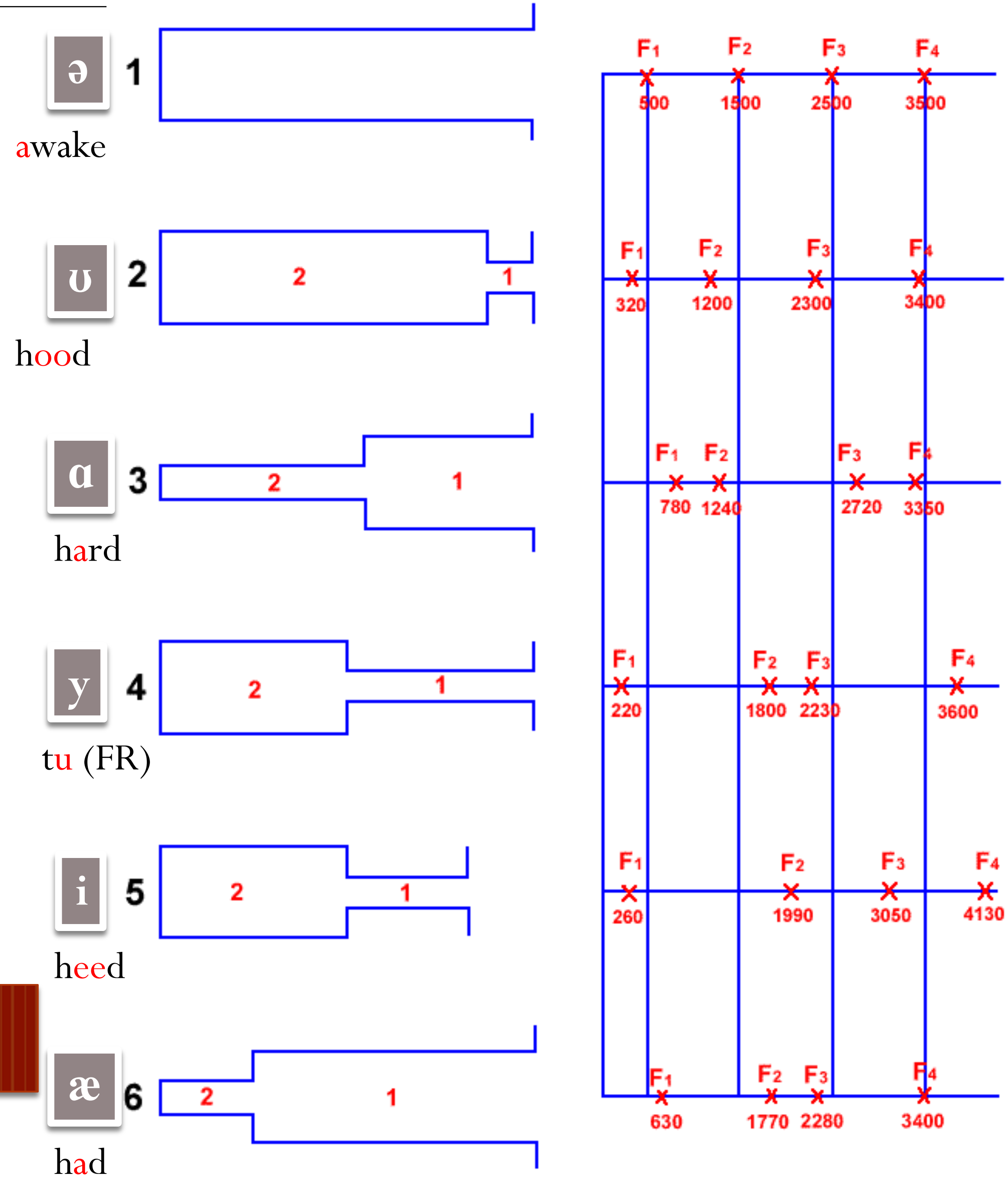
Pitch of F1 going up for [i, e] and down for [a, o, u]

Tube models

- Formants that characterize different vowels are the result of the different shapes of the vocal tract.
- Any body of air will vibrate in a way that depends on its size and shape.
  - Blow across the top of
    - an empty bottle
    - partially filled bottle

    What do you observe?

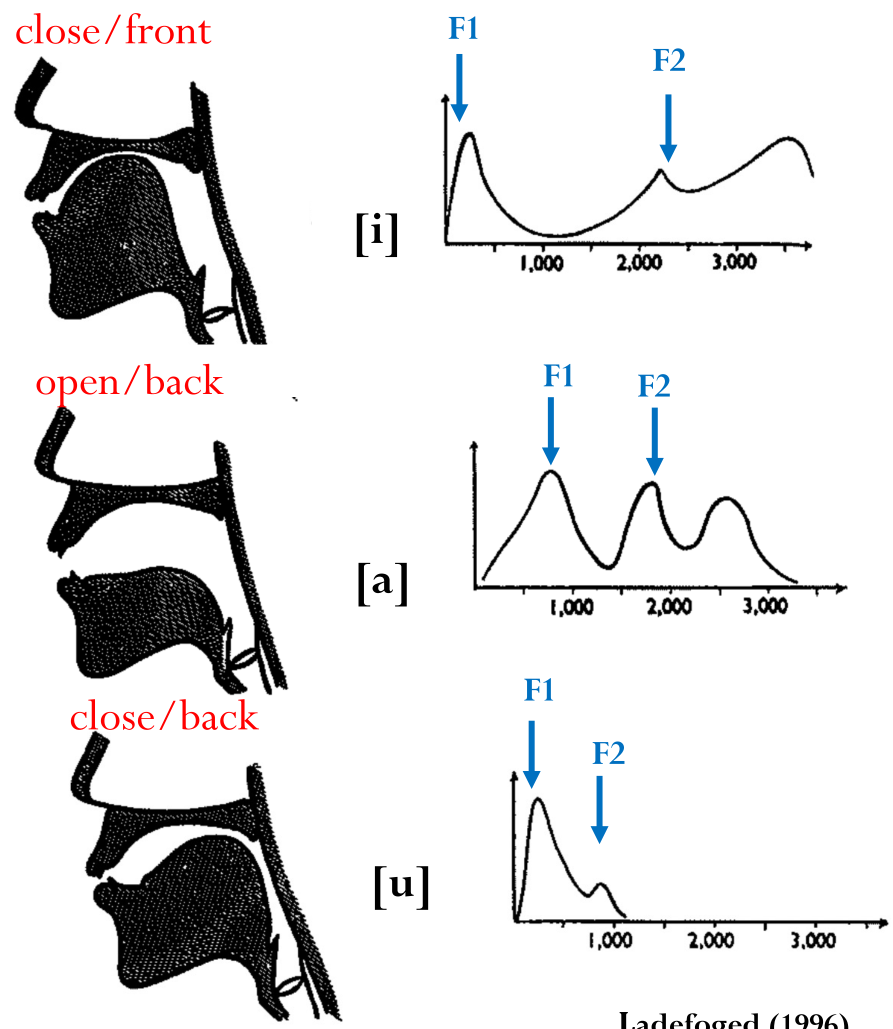
Great volume of air → low-pitched note
Small volume of air → high-pitched note



Adapted from Fant (1960)

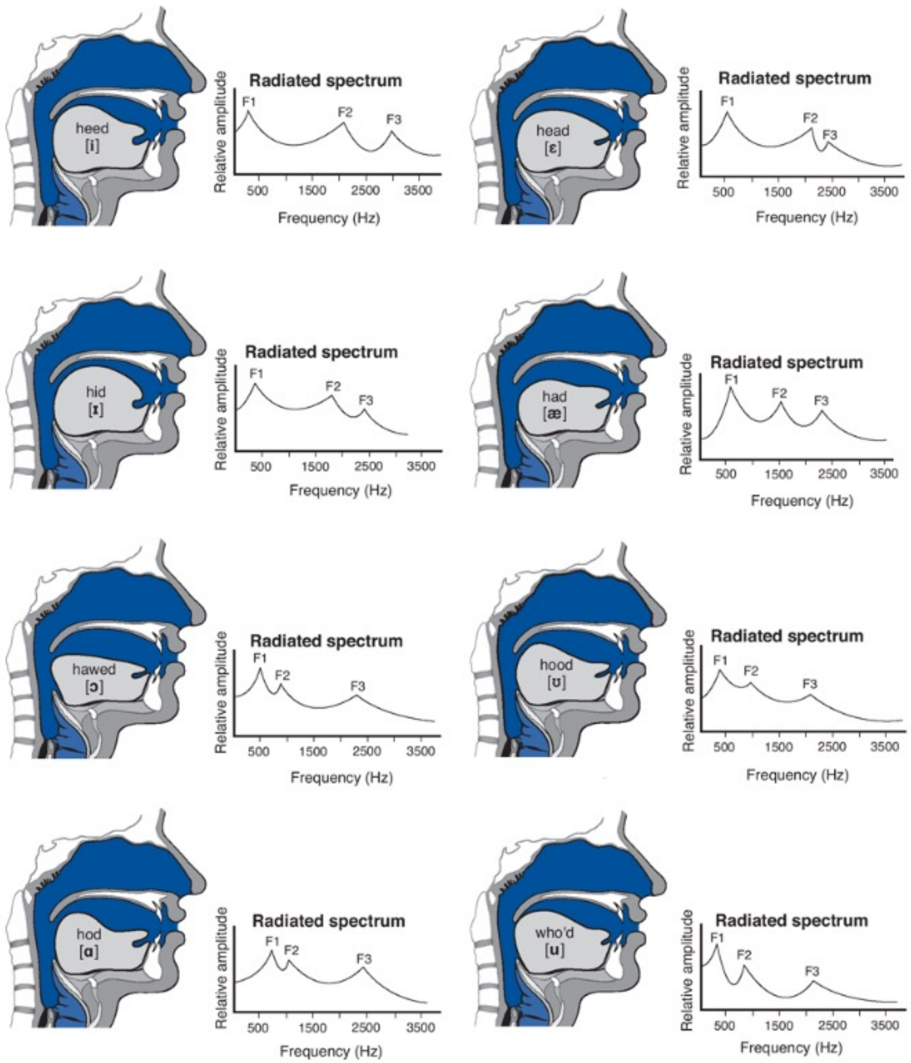
Spectra and Formants

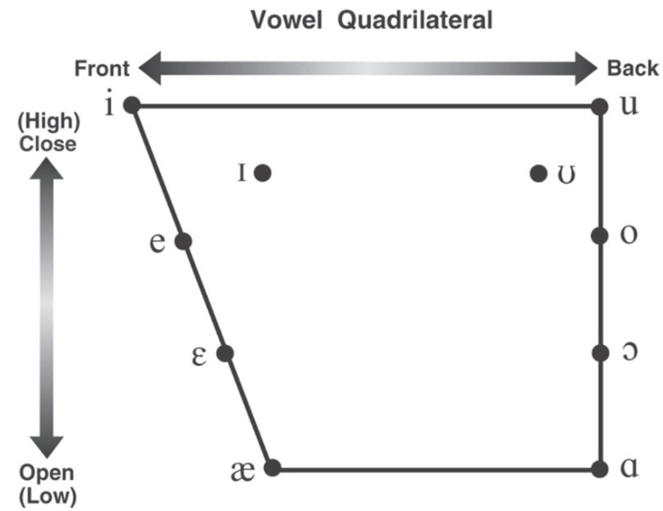
- Frequencies that are amplified, receive more energy and correspond to **formants**.
- Thus every speech sound corresponds to a different spectrum, and different formants.
    - [i]: F1 and F2 at a distance
    - [a]: F1 and F2 close
    - [u]: F1 and F2 close



Ladefoged (1996)
(altered)

Spectra and Formants

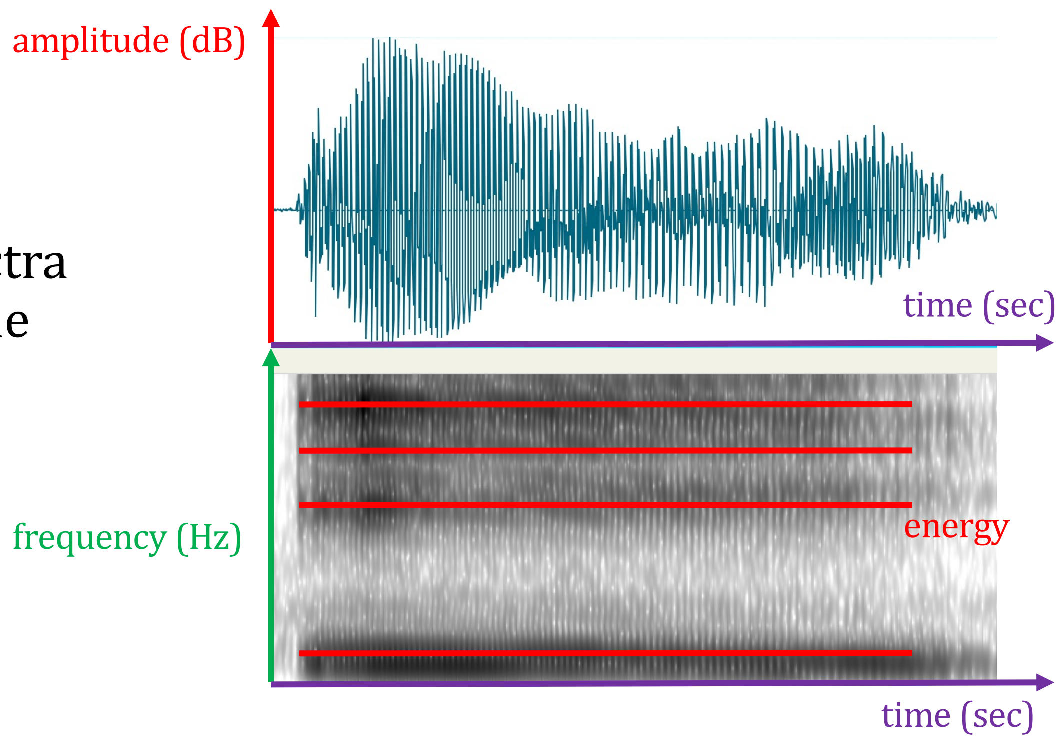




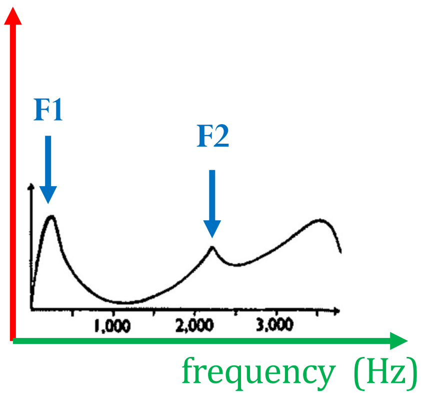
Behrman (2021)

Spectrum vs Spectrogram

- Spectrum: distribution of energy with frequency
  - (amplitude vs frequency) **[2D] two-dimensional**
- Spectrogram: series of spectra at consecutive points in time
  - (frequency vs time vs amplitude/energy) **[3D] three-dimensional**



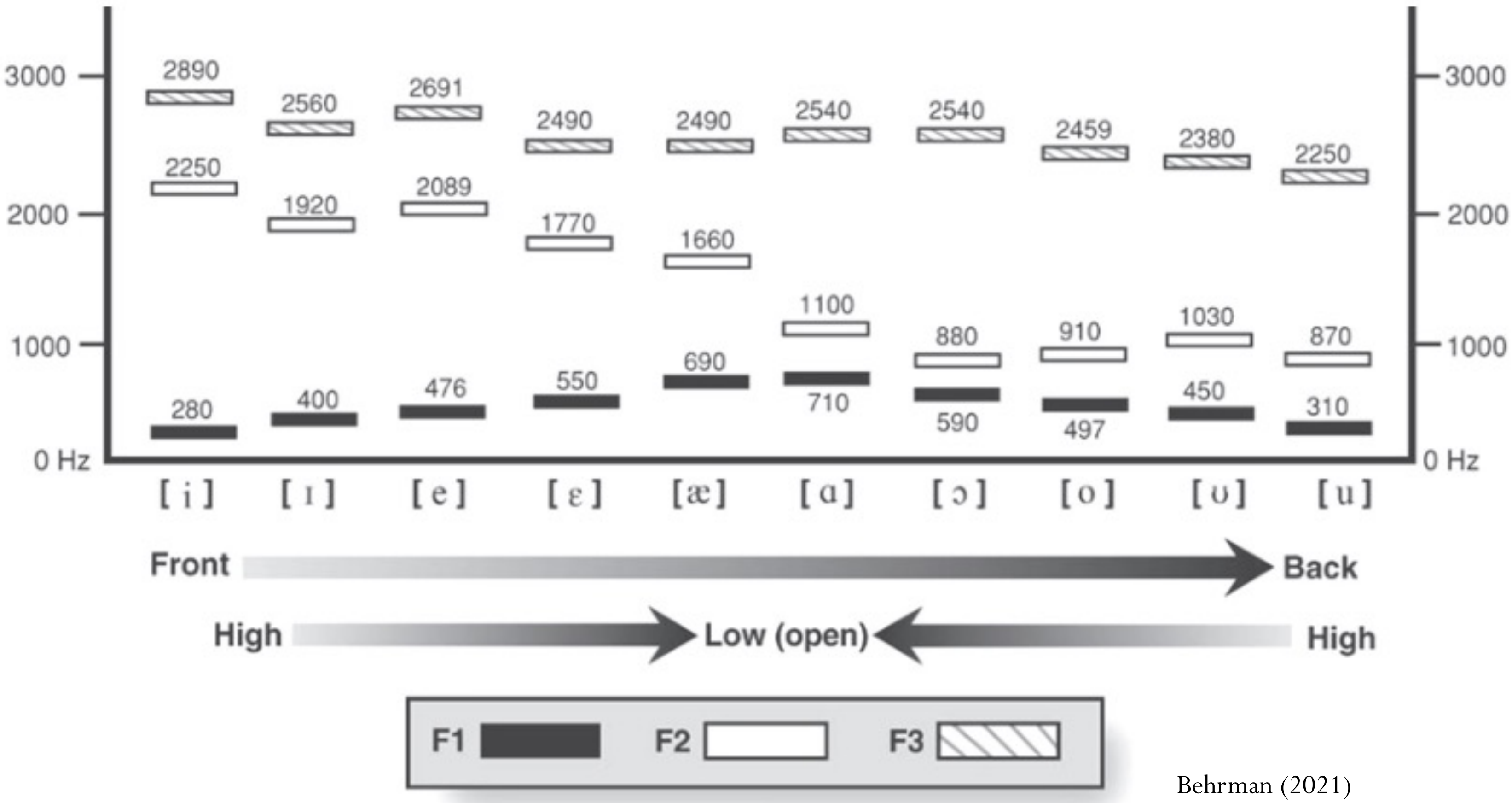
[i]



Spectrograms

Dark bands for concentrations of energy at particular frequencies showing the source and filter characteristics of speech

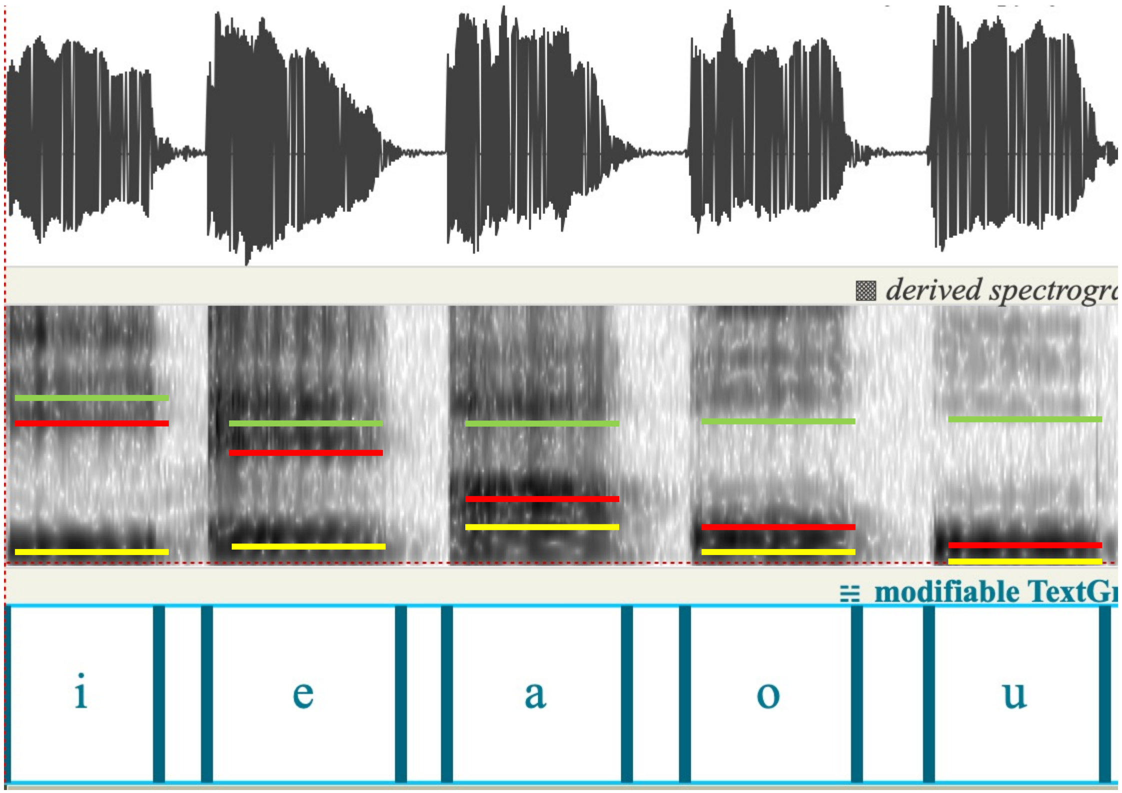
Acoustics of vowels



Behrman (2021)

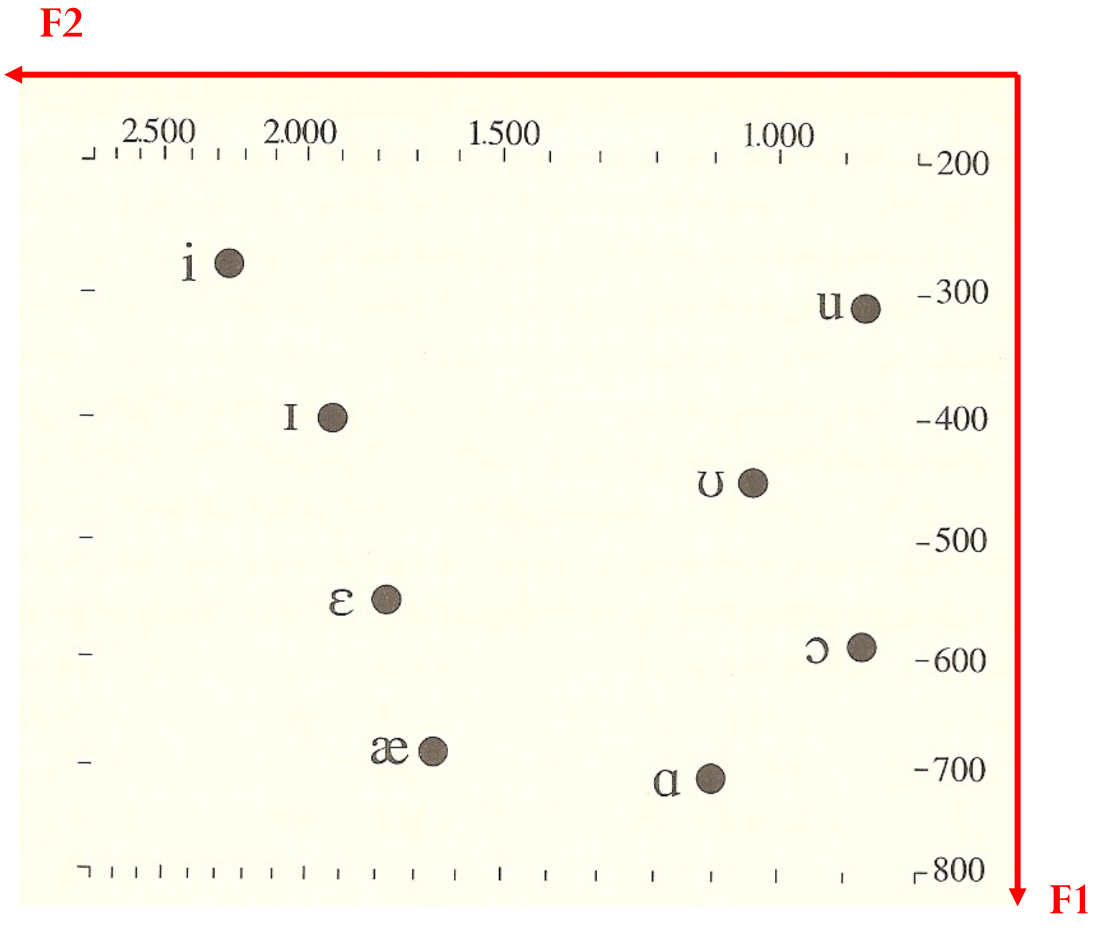
Acoustics of Greek vowels

- F1: Formant 1
  Inversely related to tongue **height**.
  High values = low (open) vowel
- F2: Formant 2
  Related to frontness (or rather F2-F1)
  High values = front vowel
- F3: Formant 3
  Related to roundedness and rhotacization
  Low values = rhotacization / roundedness



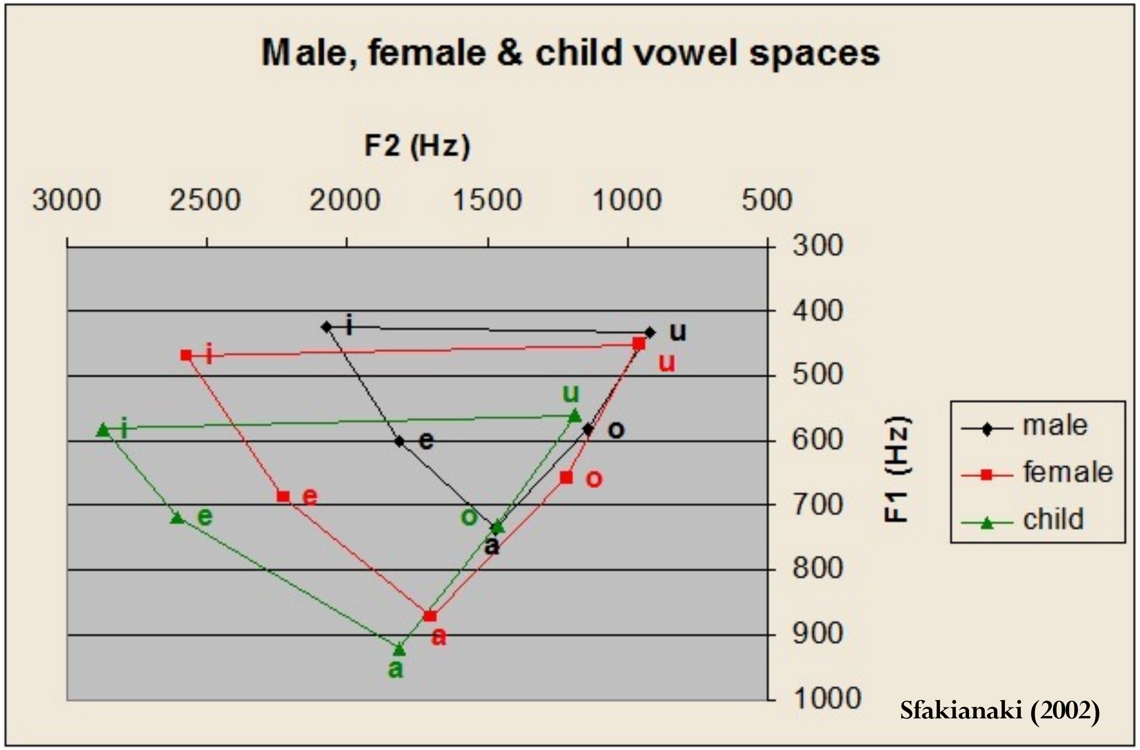
F1 by F2 plot

- Zero frequency is placed at the top right corner because formants are inversely related to traditional articulatory parameters.
- F2 scale not as expanded as F1, due to less prominent energy (F1: 80% of vowel energy).



Greek vowel space

- Formant values are influenced by anatomical characteristics (vocal tract and vocal fold size, etc.)
  - Lower in men, higher in women, even higher in children
- Formant values are also influenced by phonetic context.



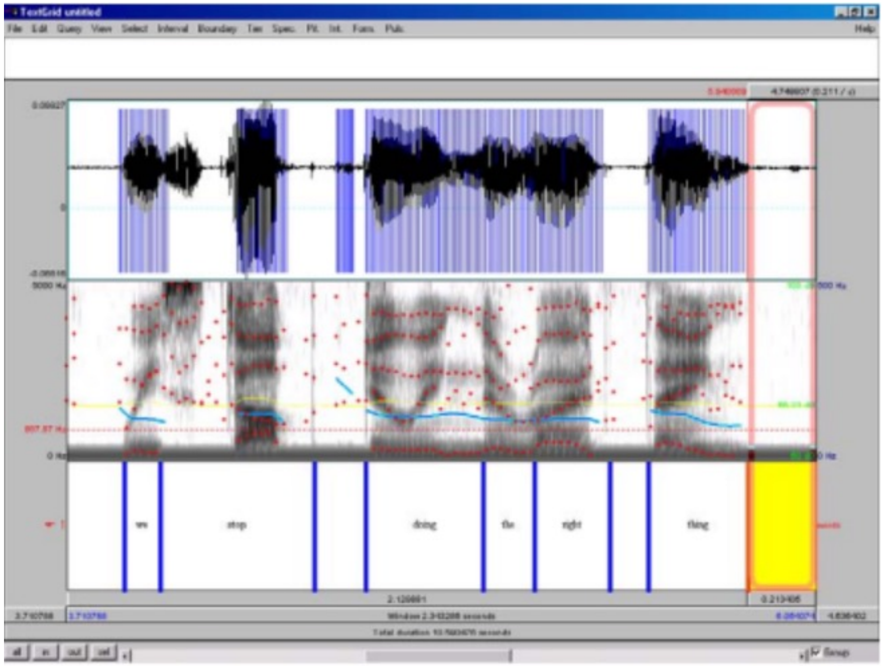
Sfakianaki (2002)

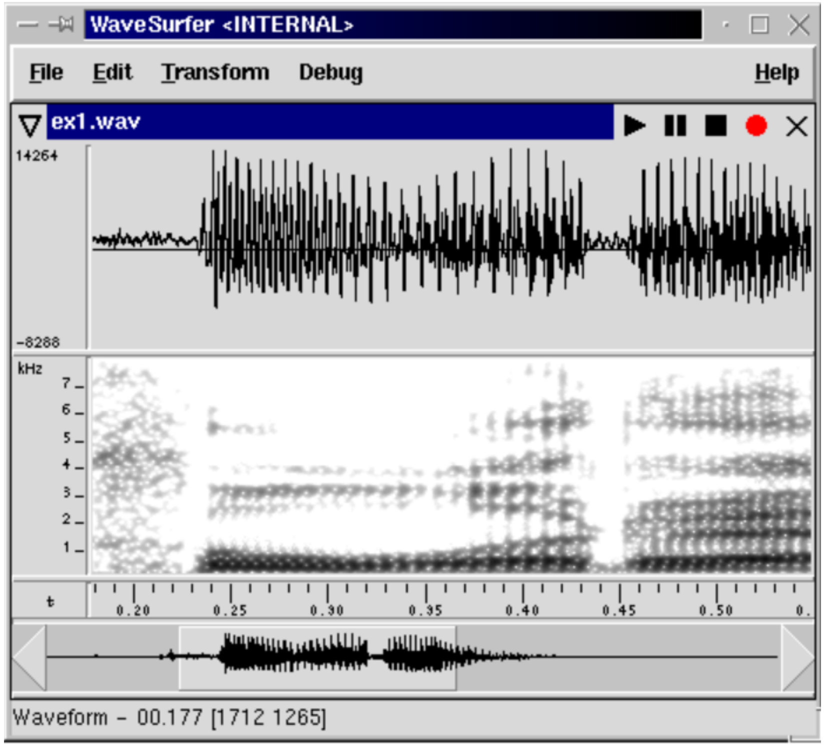
Speech synthesis demo

- The notion that vowels contain several different pitches at the same time is difficult to appreciate.
- The demo shows how a sentence is built from its component waves.
- This speech was synthesized in 1971 by Peter Ladefoged on a synthesizer at UCLA.
- **"A bird in the hand is worth two in the bush"**
  «Κάλιο πέντε και στο χέρι παρά δέκα και καρτέρει» (Greek translation)
- See the demo here: https://linguistics.berkeley.edu/acip/course/chapter8/speechbird/

Computer Programs for acoustic analysis (free access)

- **Praat**
  http://www.fon.hum.uva.nl/praat/
  University of Amsterdam





- **Wavesurfer**
  http://www.speech.kth.se/wavesurfer/

  KTH (Royal Institute of Technology, Stockholm)

F1, F2 and F3 of English vowels

Vowel	F1(Hz)	F2(Hz)	F3(Hz)
iː	280	2620	3380
ɪ	360	2220	2960
e	600	2060	2840
æ	800	1760	2500
ʌ	760	1320	2500
ɑː	740	1180	2640
ɒ	560	920	2560
ɔː	480	760	2620
ʊ	380	940	2300
uː	320	920	2200
ɜː	560	1480	2520

Adult male formant frequencies in Hertz collected by J.C.Wells around 1960.
Note how F1 and F2 vary more than F3.

Traditional vowel chart

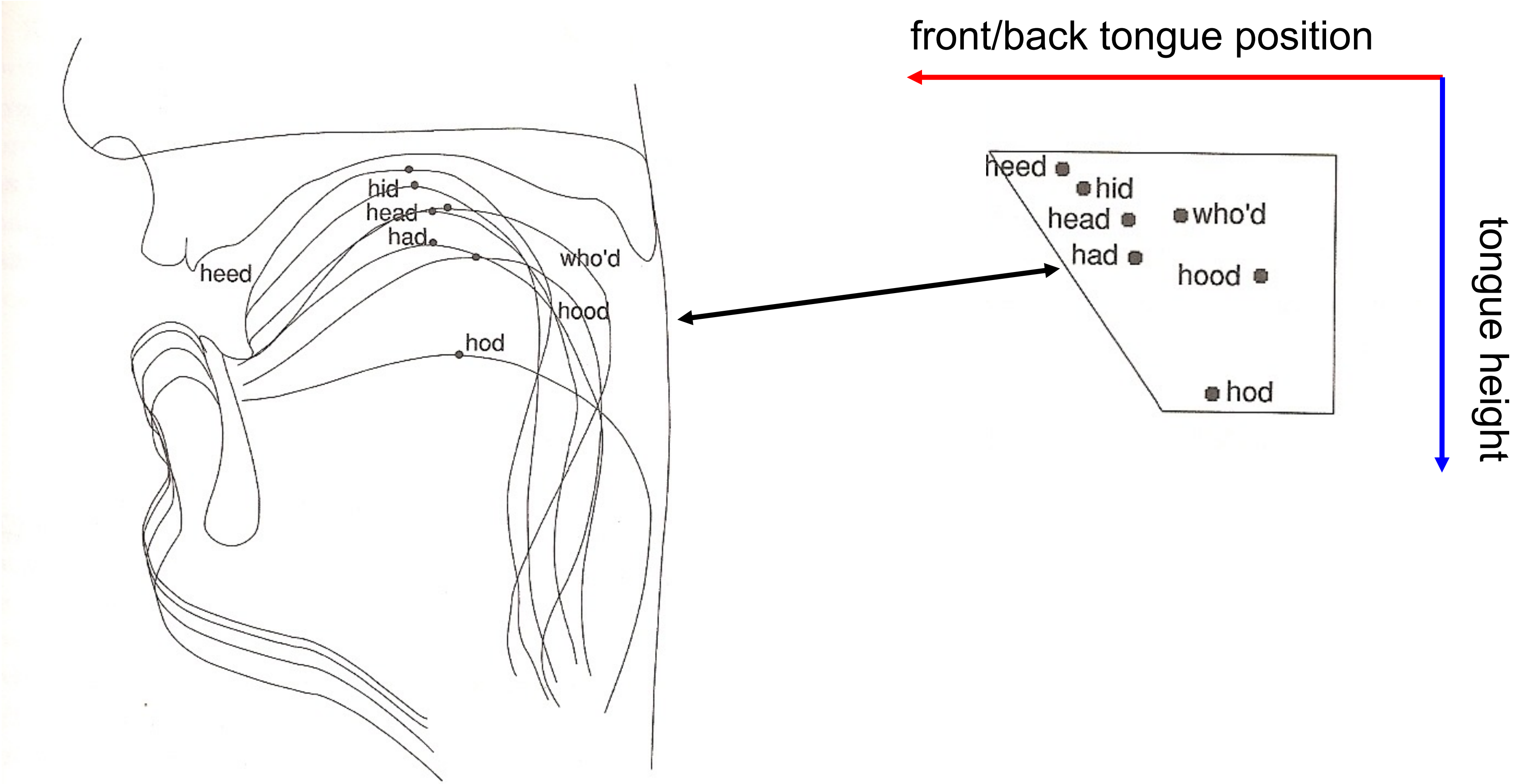
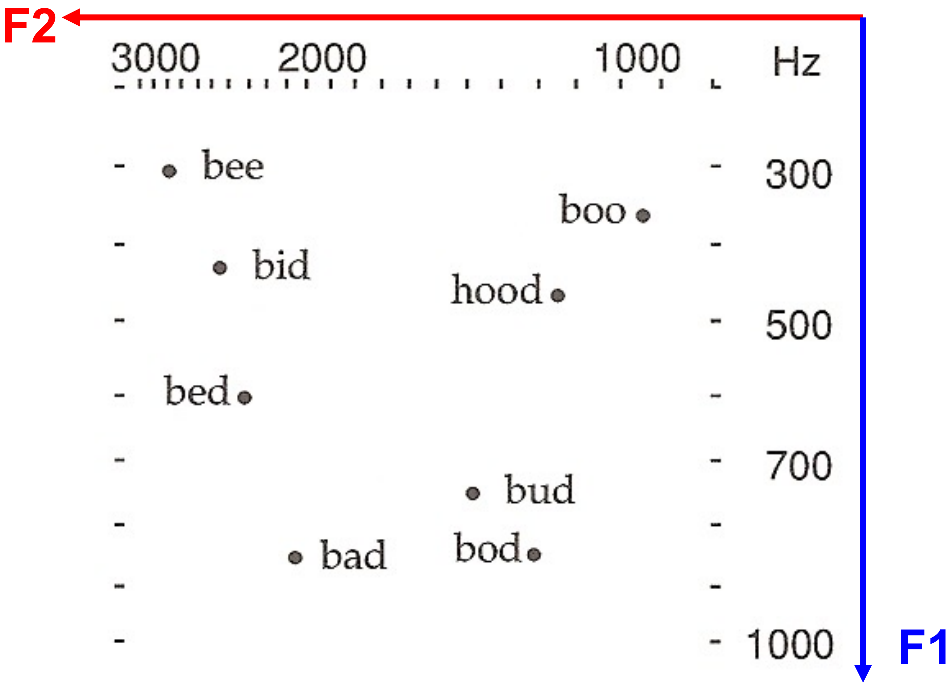
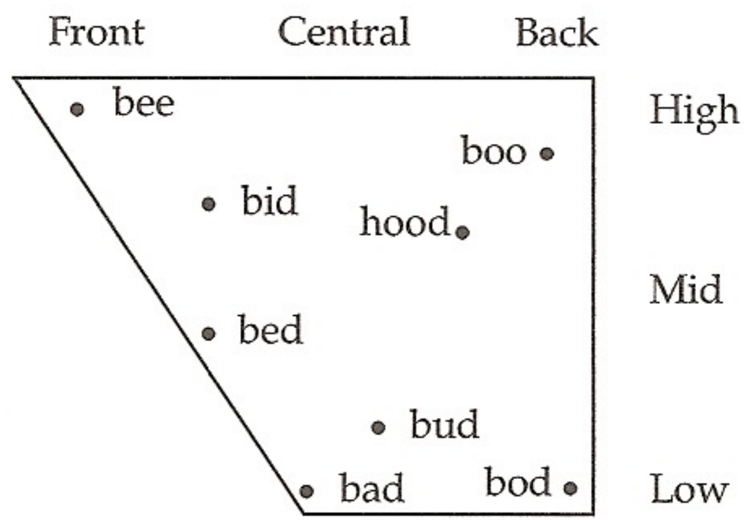


Chart based on X-ray data

Ladefoged, ***Vowels & Consonants***, (2001:115)

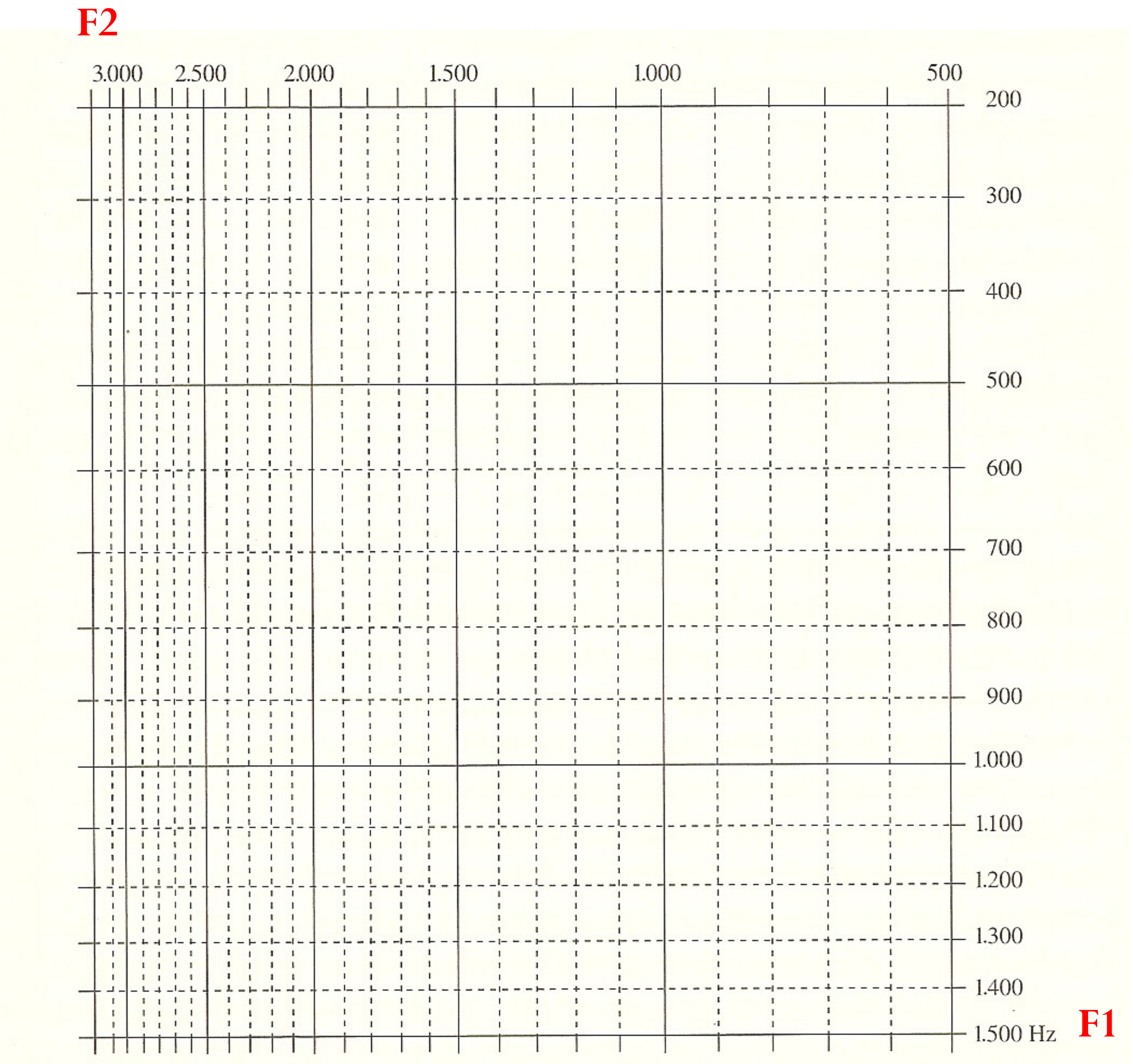
Comparison





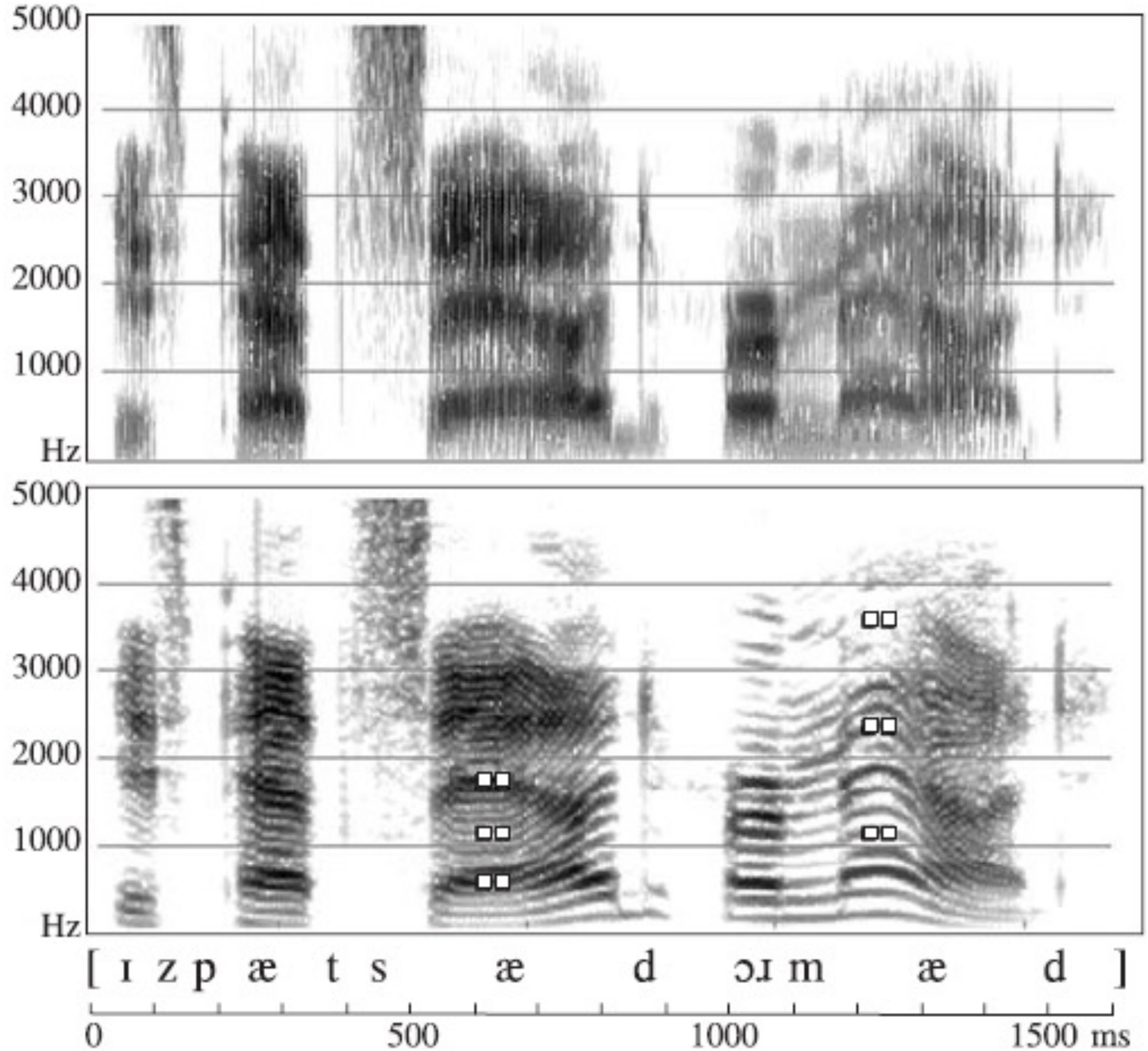
- *"Traditional vowel diagrams express acoustic facts in terms of physiological fantasies."* Oscar Russell (1930s)
- **Vowel height ⇔ F1, not actually tongue height**
- **Front – back dimension** { backness + lip rounding
- Degree of backness⇔ F1-F2 difference
- The closer together F1 and F2, the more "back" a vowel sounds.

Exercise: Make your own F1 by F2 plot



Types of spectrograms

"Is Pat sad or mad?"



wide-band spectrograms

- Very accurate in the time dimension
- Less accurate in the frequency dimension

narrow-band spectrograms

- More accurate in the frequency dimension (at the expense of accuracy in the time dimension)

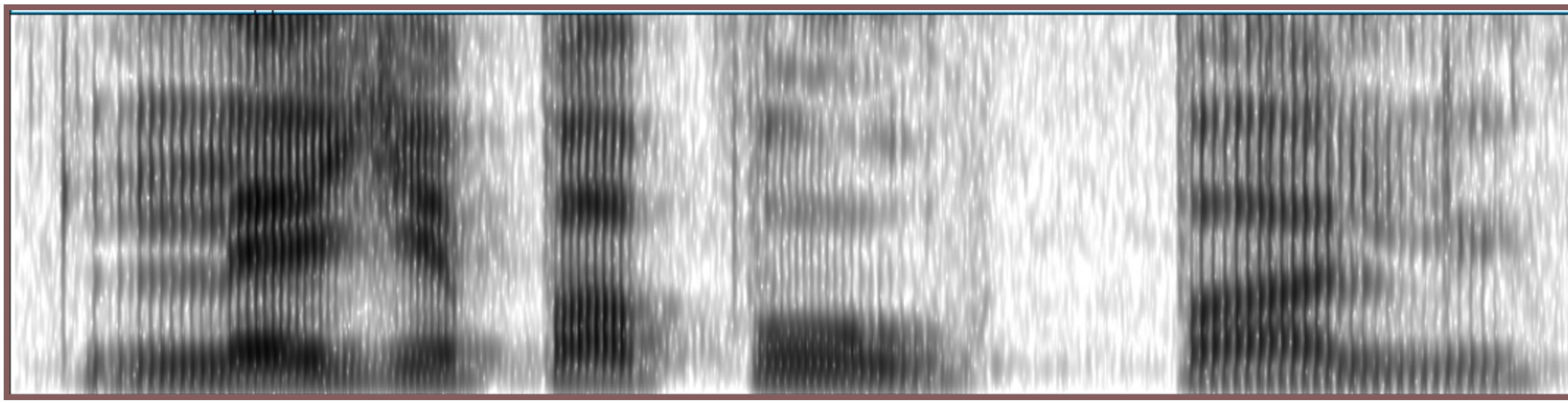
Male vs Female voice

- Women's voices usually have a higher pitch.
- The higher the F0 the more difficult it is to locate formants, because the harmonics interfere with the display of formants.

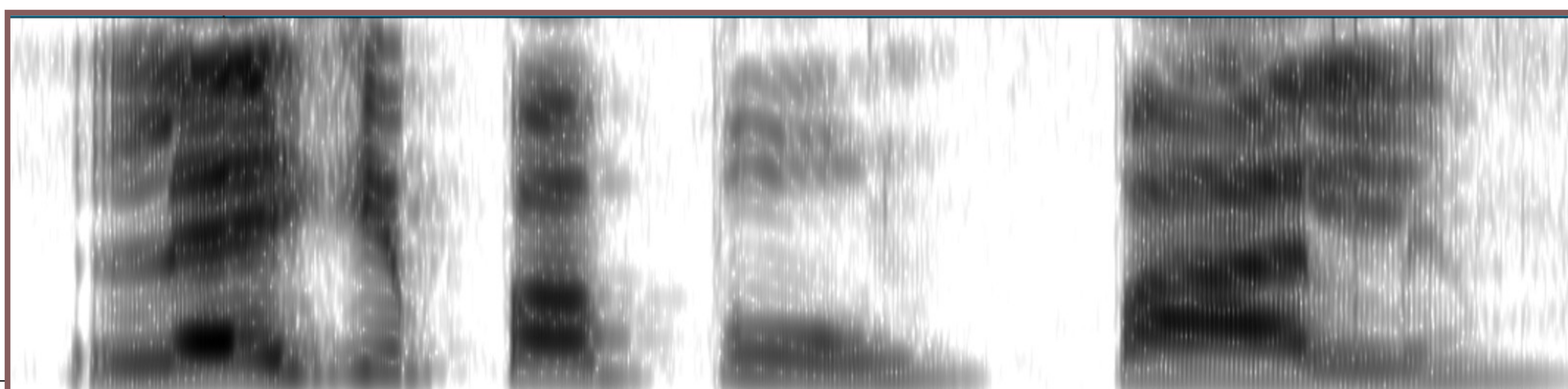
Greek phrase uttered by a male and a female Greek adult.

Λέγε «παππού» πάλι. (*Say "grandfather" again*)

male



female



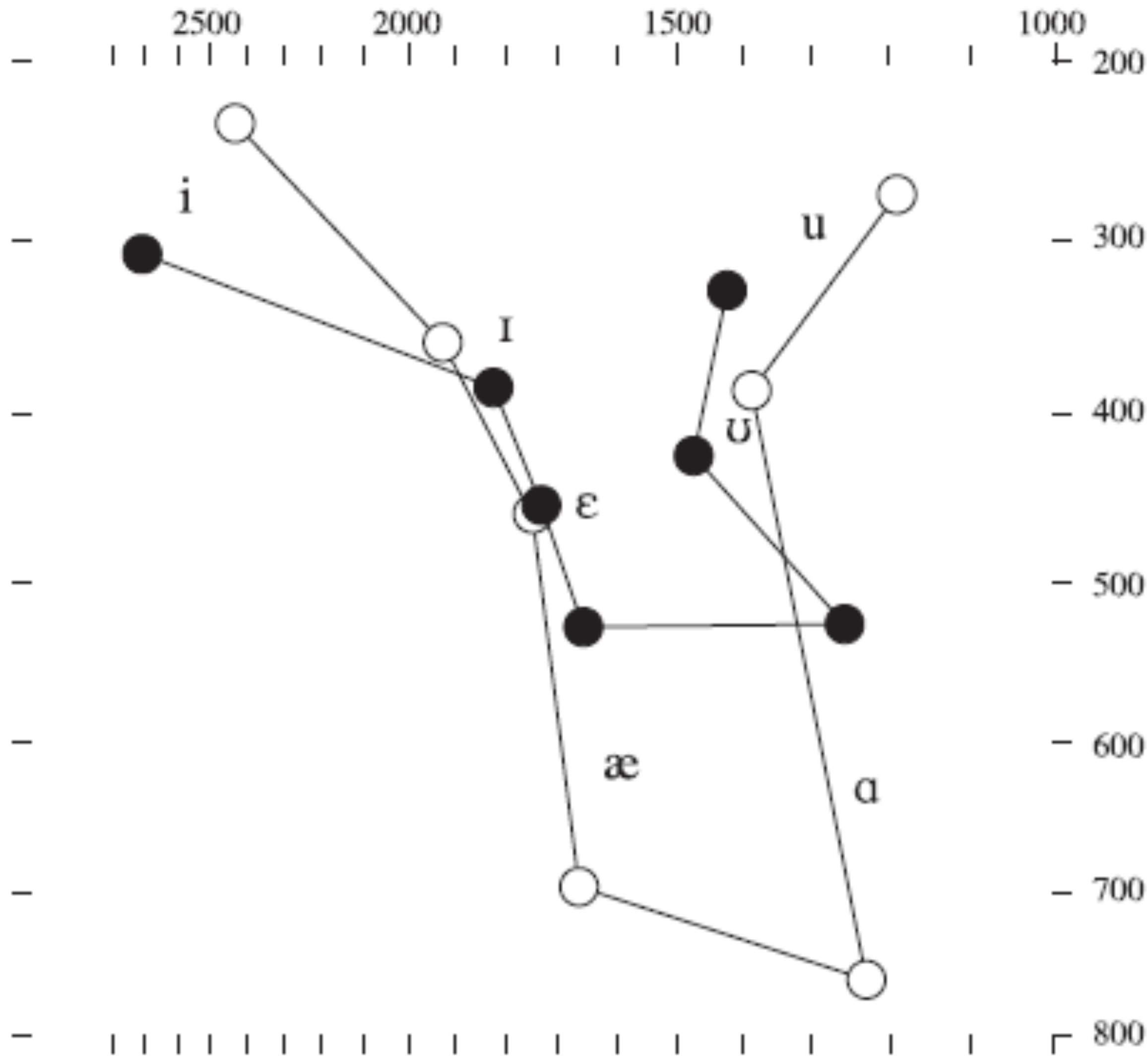
Individual Differences

- It is important to know what sort of differences exist between different speakers.
  1. When trying to measure features that are linguistically significant, one must know how to discount purely individual features.
  2. When trying to find out whether a speaker has speech problems.
  3. For valid speaker identification in forensic situations.

- Individual variation is readily apparent when studying spectrograms → **relative quality**

Individual Differences

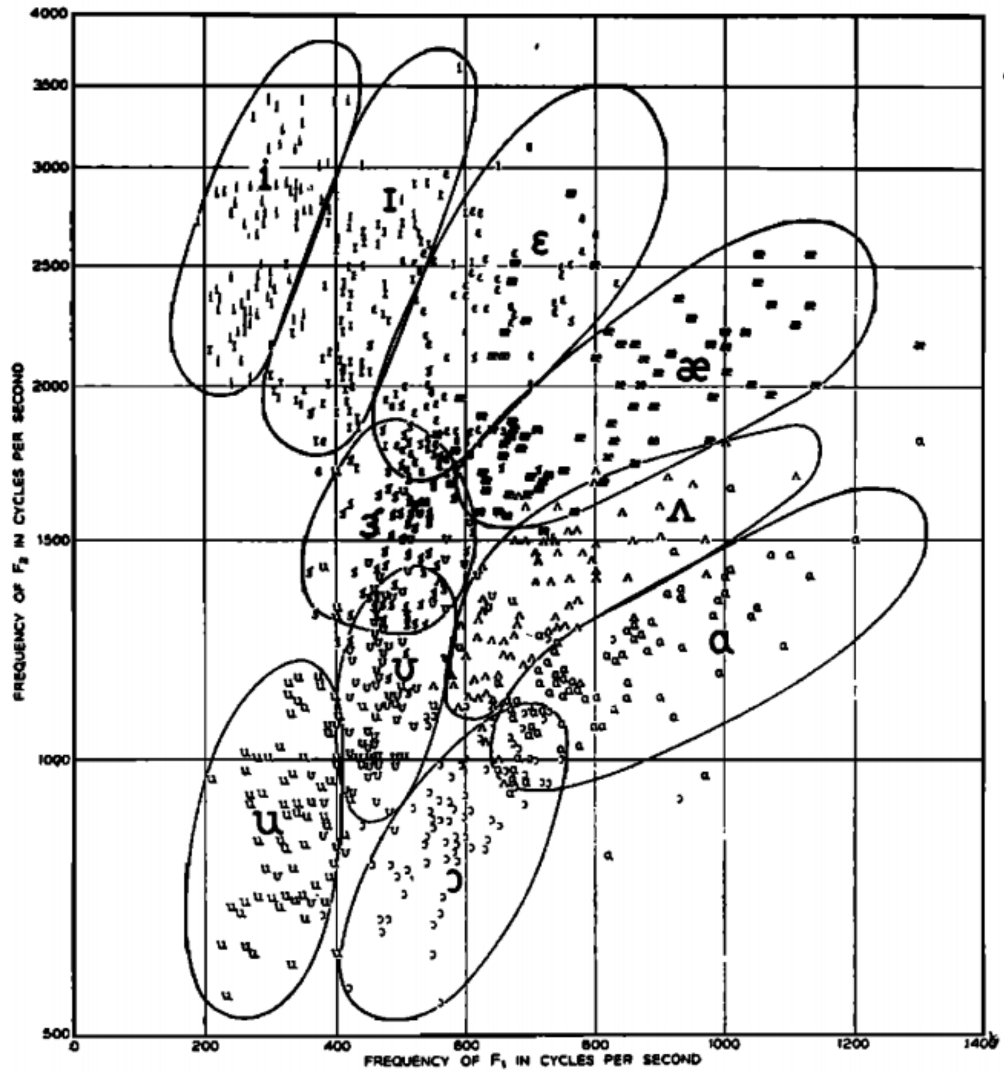
- Same phonetic quality
  - Similar relative positions
  - Different absolute values



Vowels pronounced by
2 speakers of Californian English.

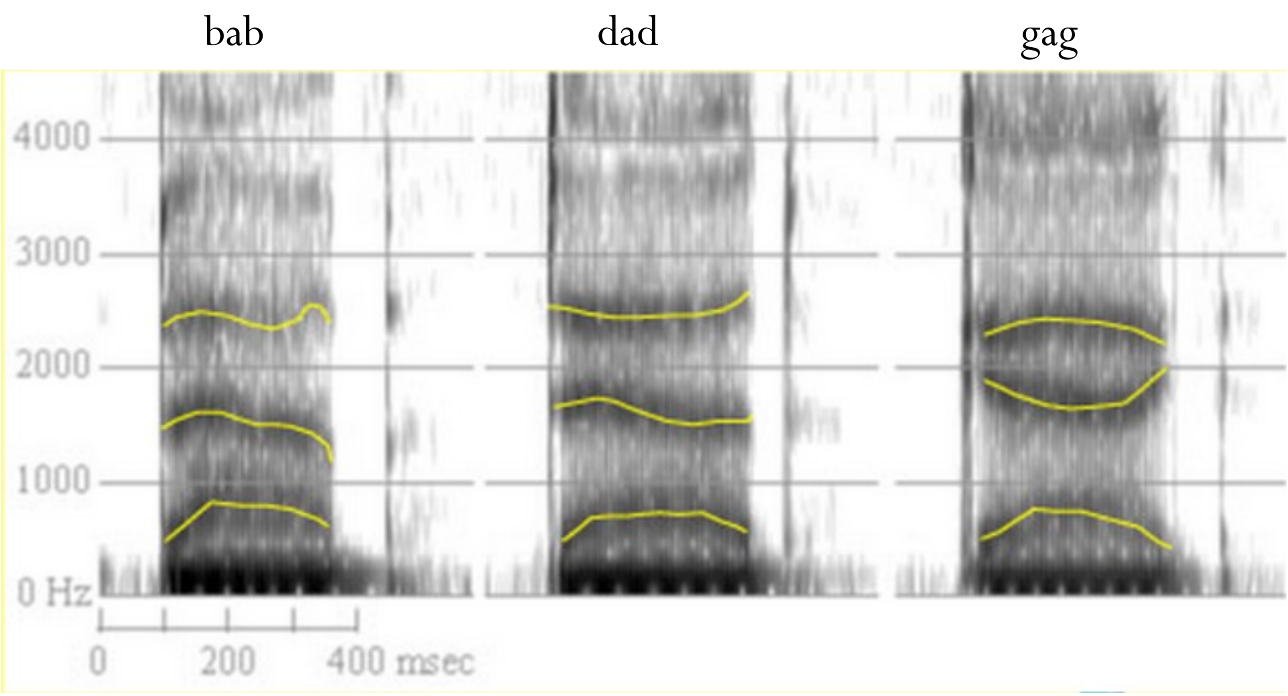
Speaker variation

- Peterson & Barney (1952)
  - 76 speakers
    - 33 men, 28 women, 15 children
  - Variability in vowel production
  - Overlap in formant frequencies



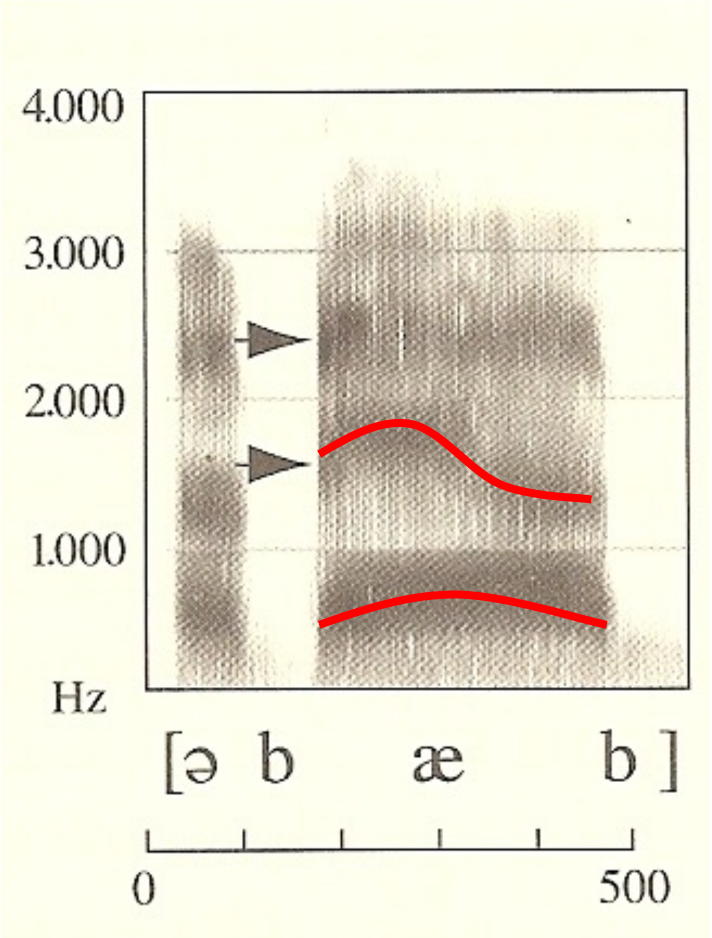
Acoustics of Consonants

- The acoustic structure of consonants is usually more complicated than that of vowels.
- In many cases, there is no distinguishable feature during the consonant articulation itself, e.g. silence part of [p, t, k].
- We have to look for the identity of the consonant at the beginning or the ending of the vowel beside it.



Stops

- Each of the stop sounds conveys its quality by its effect on the adjacent vowel.
- The formants of [æ] correspond to the particular shape of the vocal tract.
- During the production of [bæ] the formants correspond to the particular shape that occurs the moment the lips come apart.
- Closure of the lips causes a lowering of all formants.
- The syllable [bæb] will begin with formants in a lower position, then they will rapidly rise to the positions of [æ], and finally descend again as the lip closure is formed.



Anticipatory Coarticulation and Loci

- For the production of e.g. [bib] or [bab], the tongue will be in position for the vowel even when the lips are closed at the beginning of the word.
- This happens because the part of the tongue not involved in the formation of the consonant closure is already in position for the following vowel.
- The formants at the moment of consonantal release will vary according to vowel.
- The apparent point of origin of the formant for each place of articulation is called the **locus** of that place of articulation.
- The locus depends on adjacent vowels.

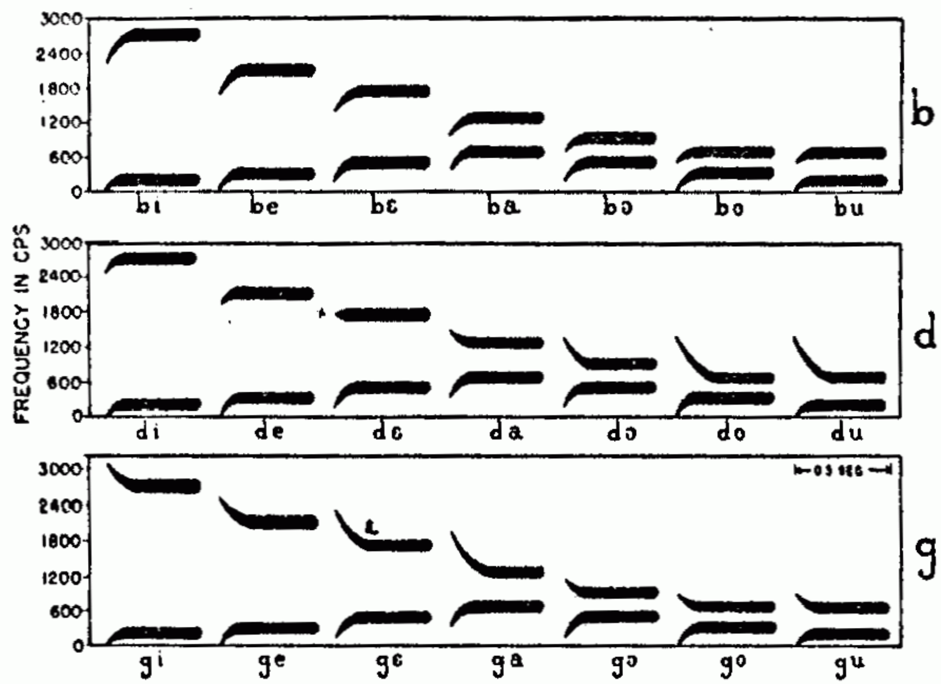
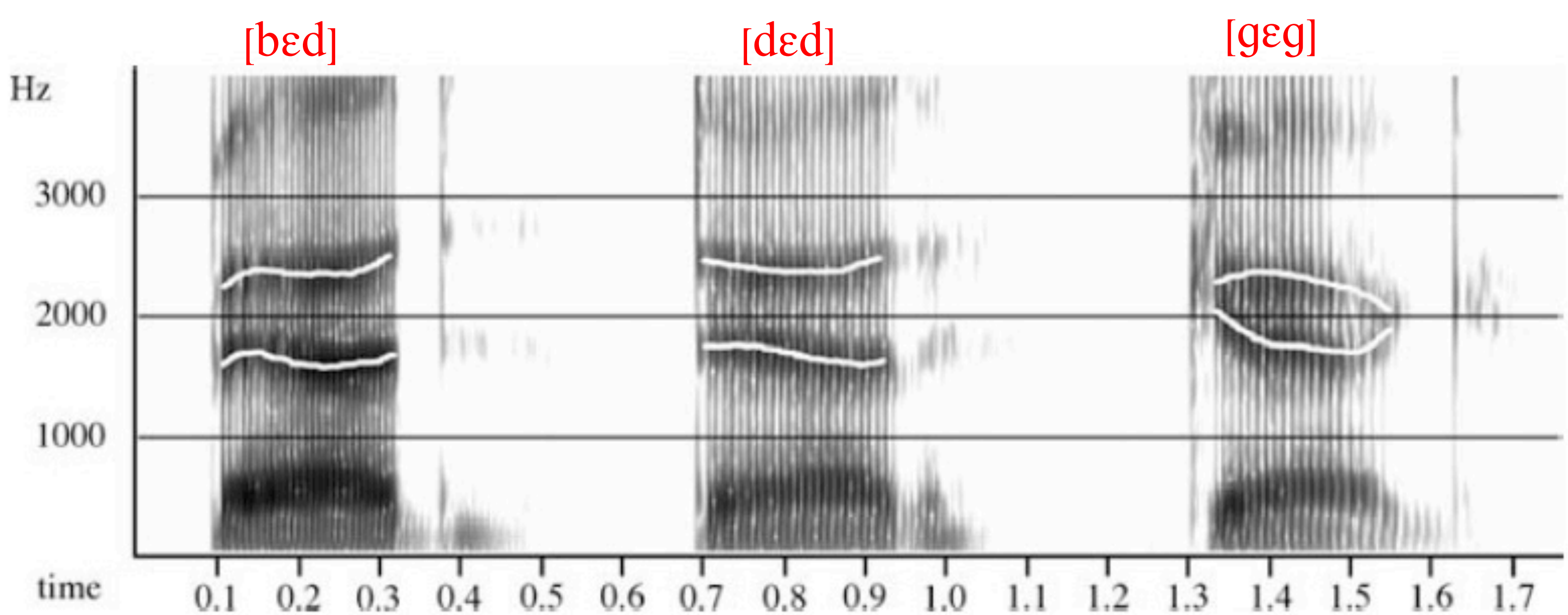


FIG. 1. Synthetic spectrograms showing second-formant transitions that produce the voiced stops before various vowels.

Delattre, 1969

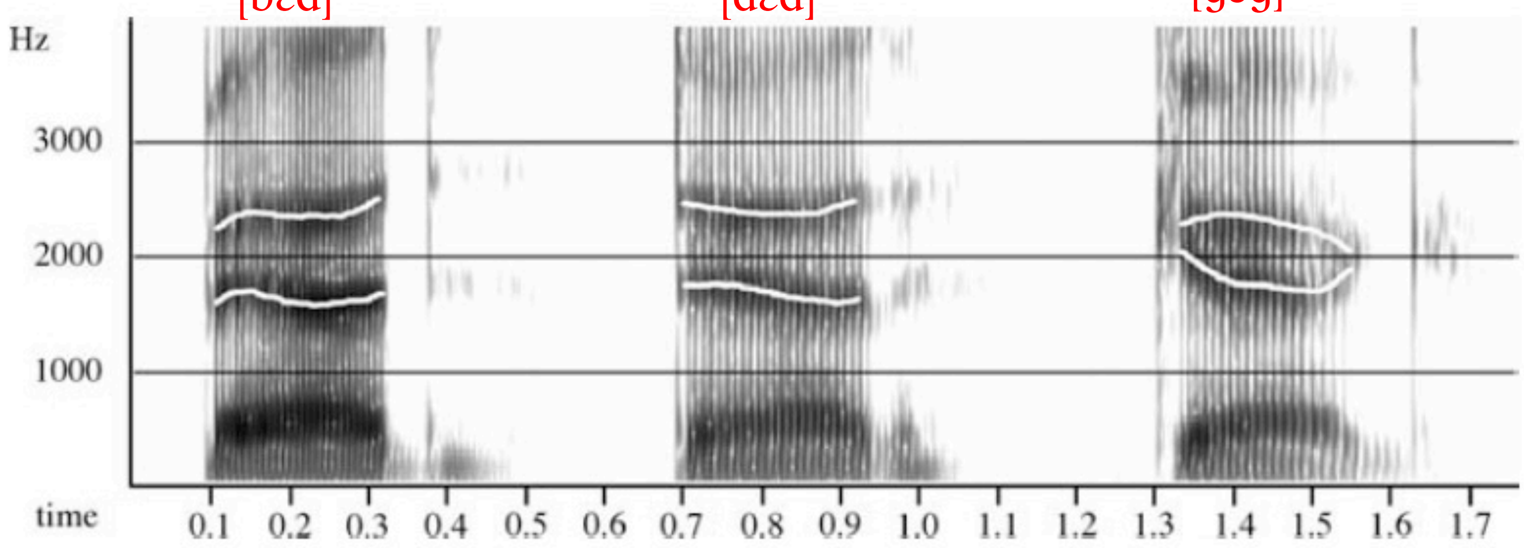
Formant transitions

- Faint voicing striations near the baseline for each of the stops [b, d, g] (voice bar).
- In all three words, F1 rises from a low position due to consonant closure, hence it does not distinguish one place of articulation from another.
- What distinguishes the three stops are the onsets and offsets of F2 and F3.



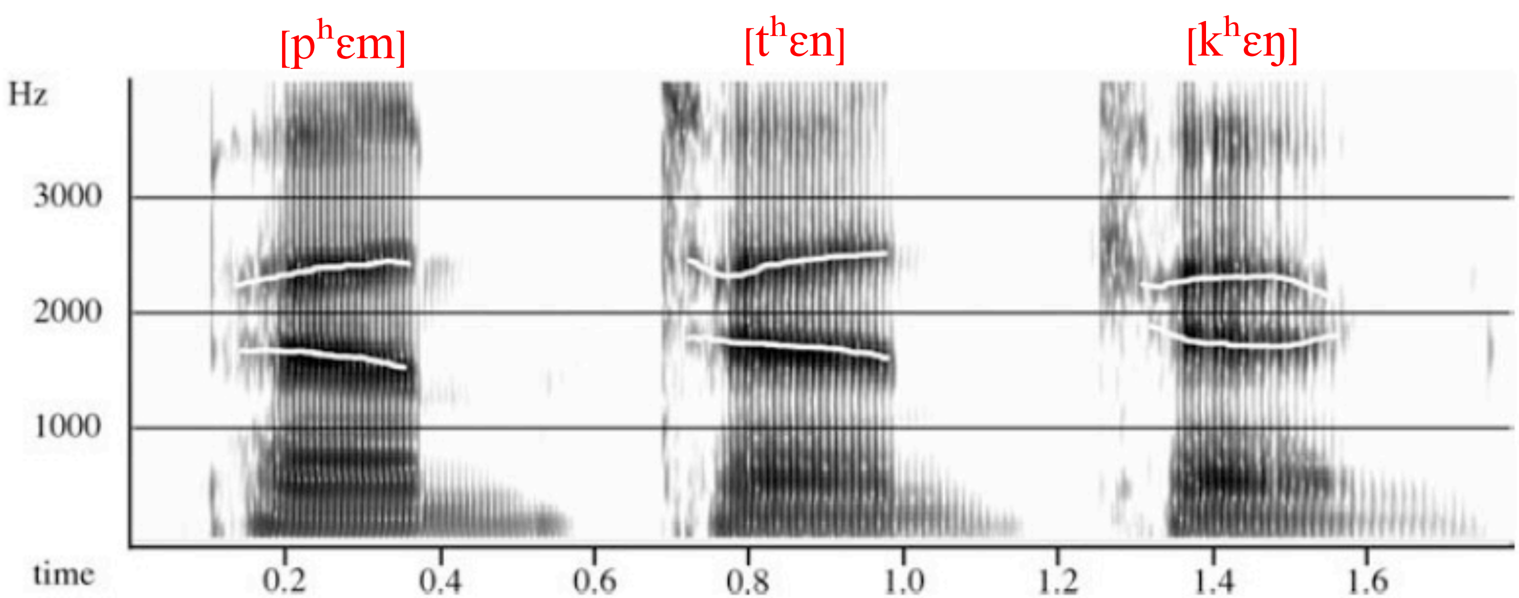
Voiced stops

- [bɛd]
  - F2 & F3 start at a lower frequency than in [dɛd].
  - F2 & F3 are noticeably rising from a low locus.
- [dɛd]
  - F2 is fairly steady at the beginning.
  - F3 drops a little.
- [gɛg]
  - Characteristic coming together of F2 & F3 → **velar pinch**



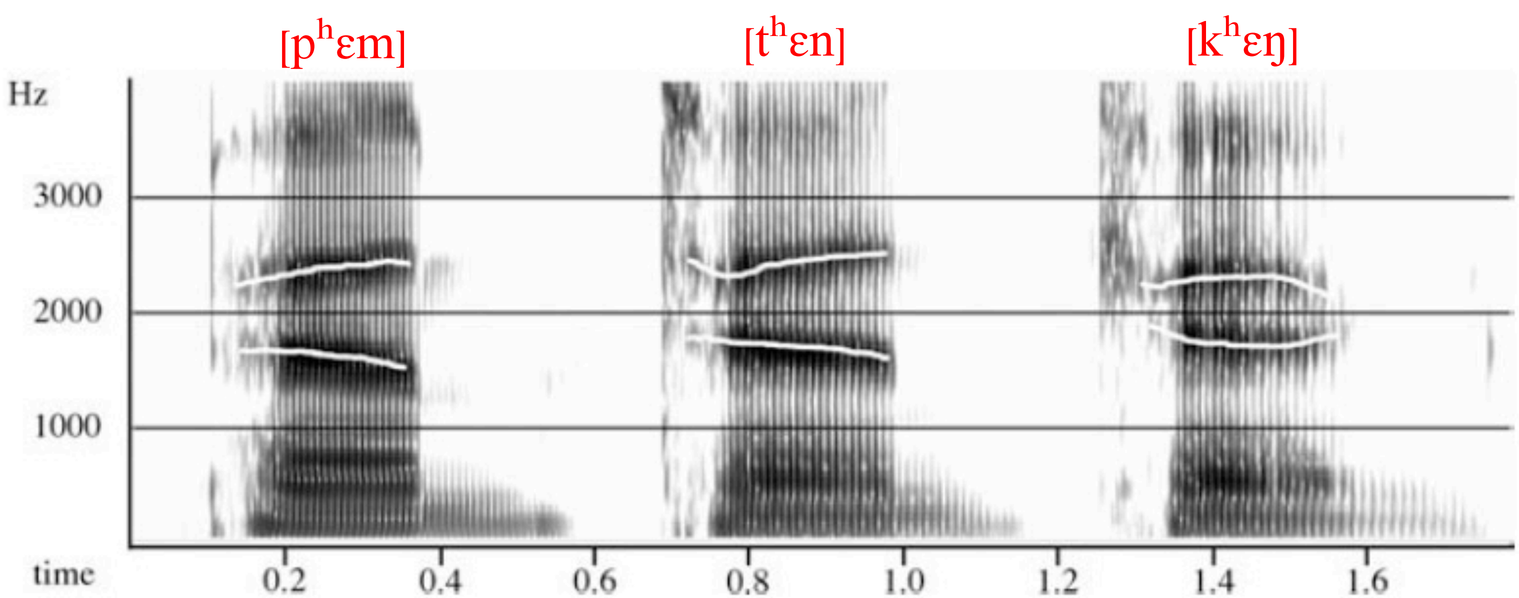
Voiceless stops

- The release of aspirated stops is marked by a sudden sharp spike→ lean vertical line.
- Period of aspiration noise→ absence of energy in F1 & no vertical striations
- Frequency & intensity
  - **[t] > [k] > [p]**
- Intensity of [p] burst is sometimes so low that there is no evidence of it on a spectrogram.



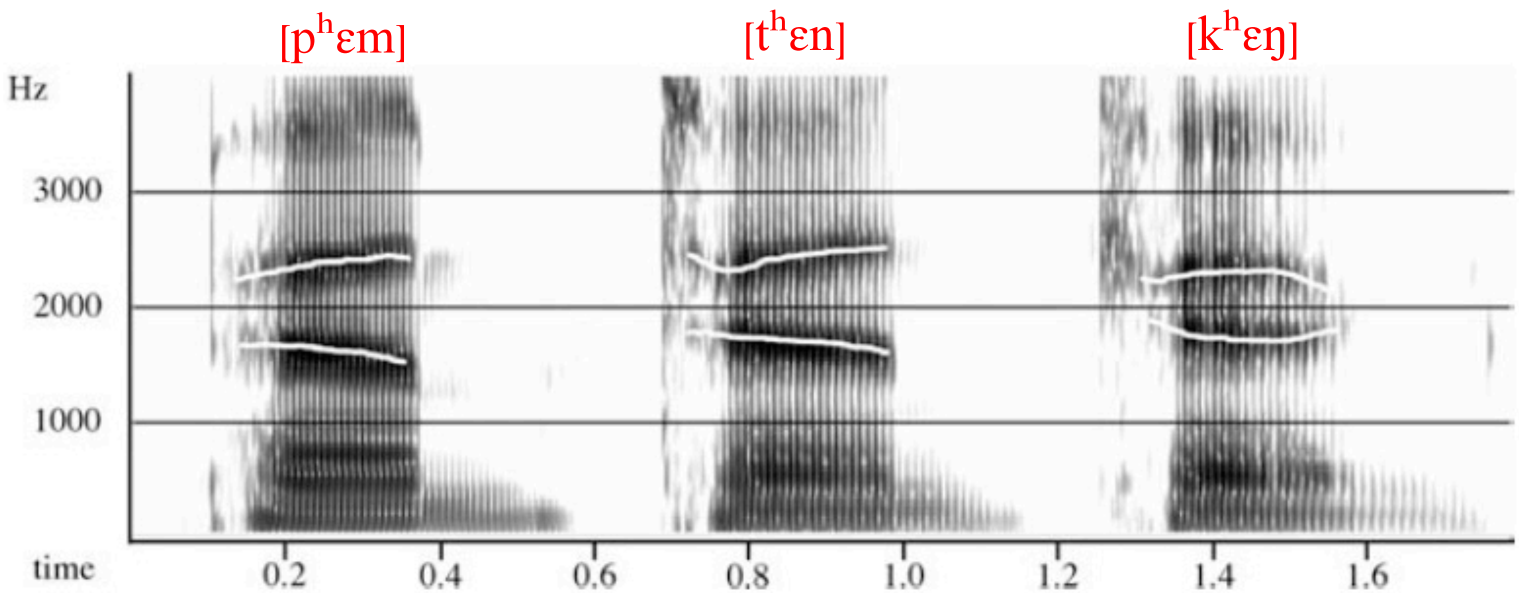
Voiceless stops

- Formant transitions also present in aspiration noise.
- [pʰɛm] : F2 & F3 rising into the vowel.
- [tʰɛn] : F2 steady, F3 dropping and then rising.
- [kʰɛŋ] : characteristic velar pinch



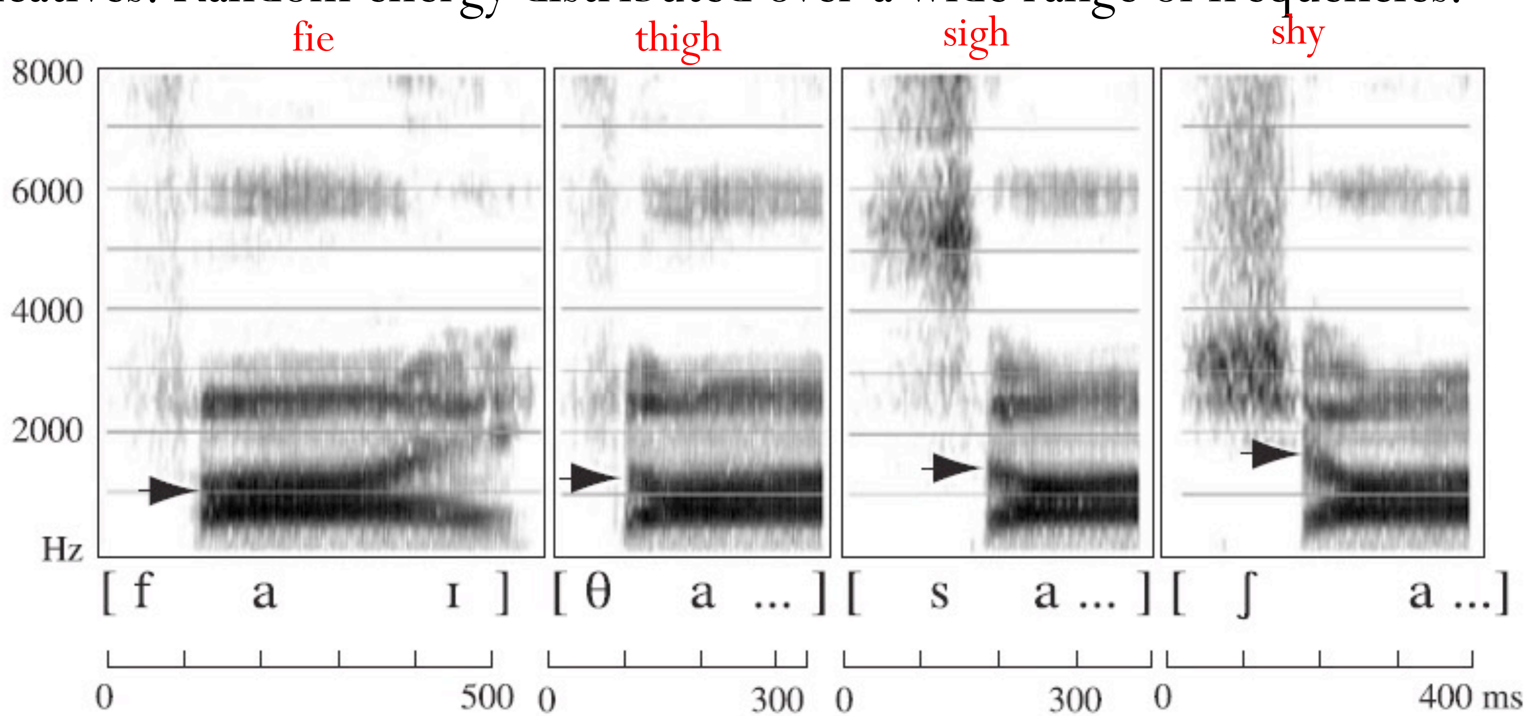
Nasals

- A clear mark of a nasal (and a lateral) is an abrupt change in the spectrogram at the time of the formation of the articulatory closure.
- A nasal has a formant structure similar to that of a vowel. Differences:
  - Bands are fainter.
  - Bands located in particular frequency locations depending on characteristic resonances of the nasal cavities.
- F1: around 250 Hz
- Large region above F1 with no energy.
- F2 etc: varying according to speaker (here around 2000 Hz).
- Place cues sometimes not very clear.



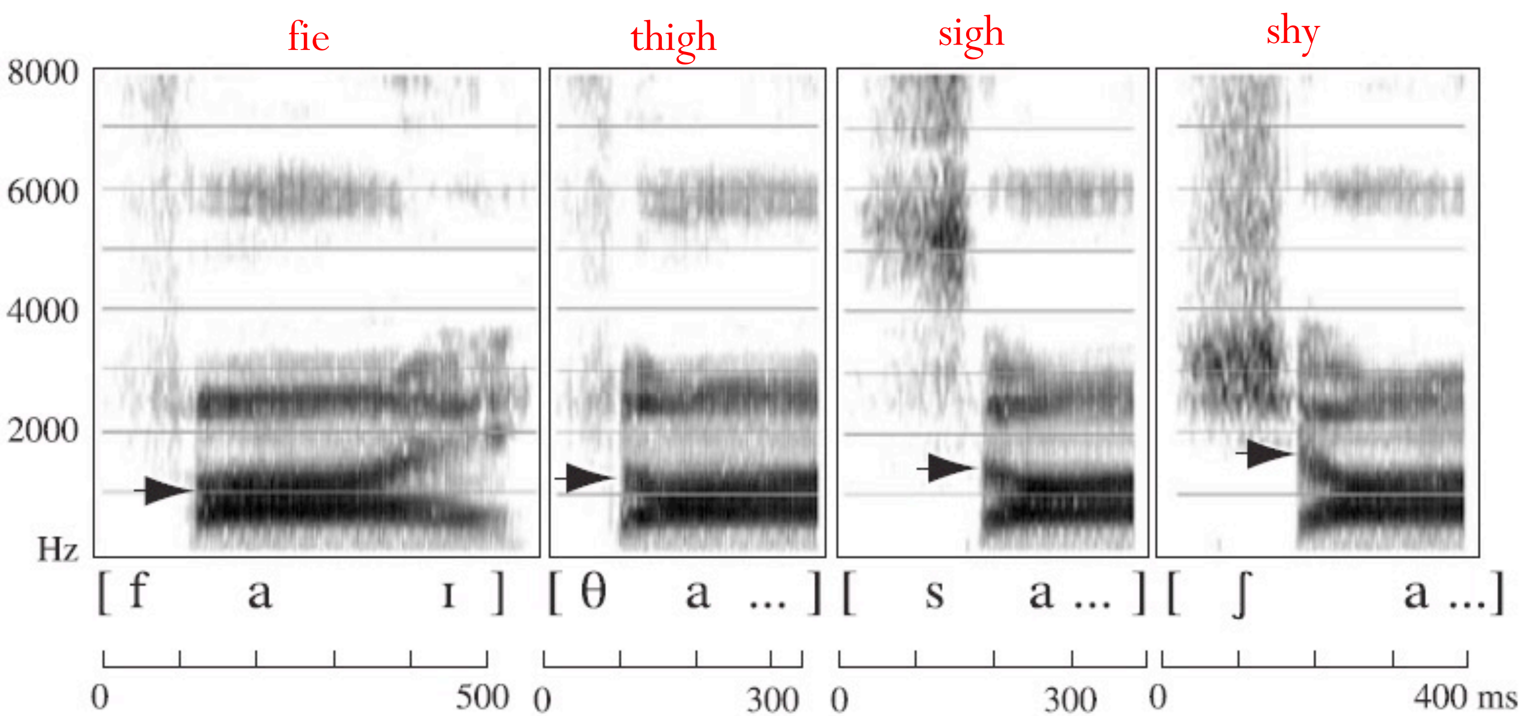
Voiceless fricatives

- Highest frequencies in speech occur over fricatives.
- Frequency scale increased to 8000 Hz.
- Diphthong [aɪ] : F1 & F2 start close together for low central [a] and move apart for high front [ɪ].
- Fricatives: Random energy distributed over a wide range of frequencies.



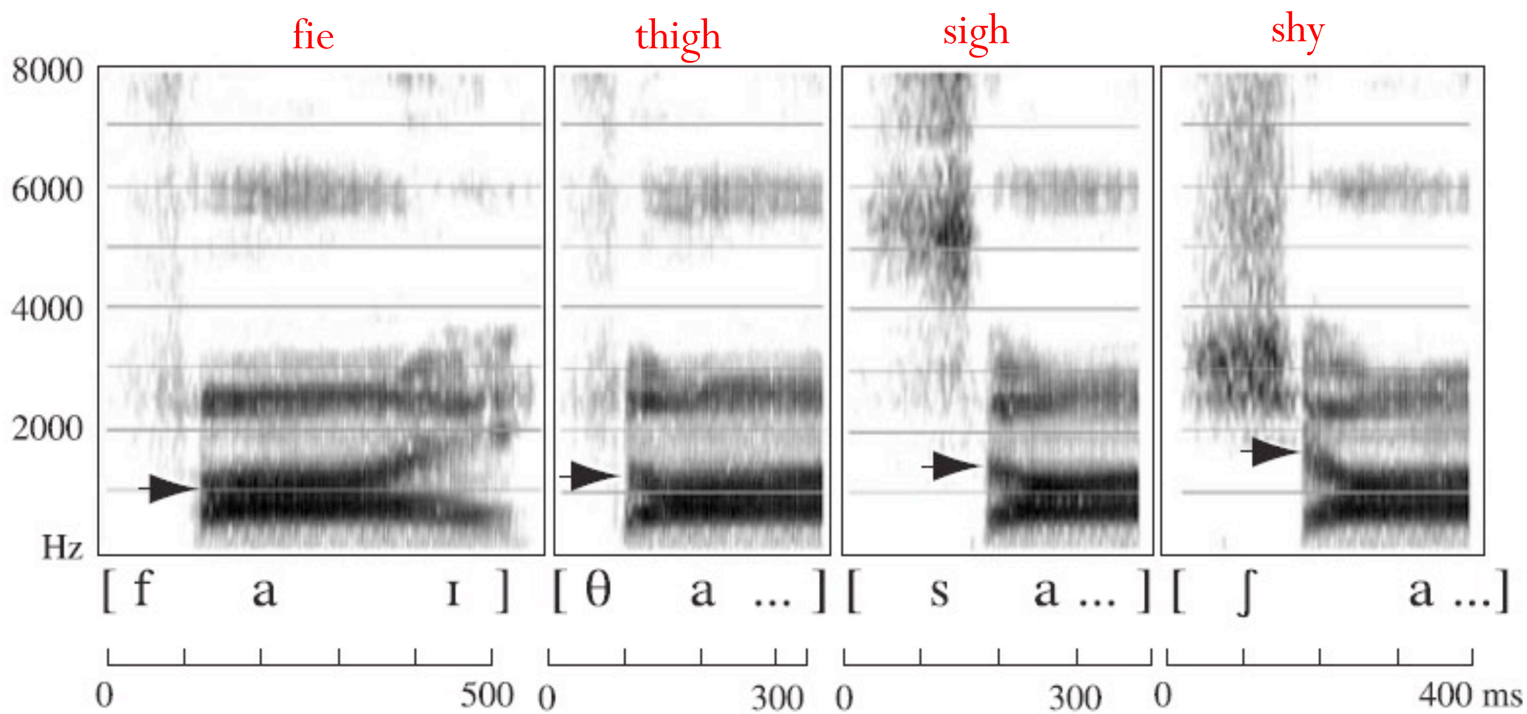
Voiceless fricatives [f, θ]

- Same pattern in [f] and [θ].
- Difference: Movement of F2 into following vowel.
  - Very little movement in [f].
  - In [θ], F2 starts around 1200 Hz and moves down.
- Often confused in noisy settings.
- Fallen together in some accents of English, such as London Cockney
  - *fin* and *thin* both pronounced with a [f].



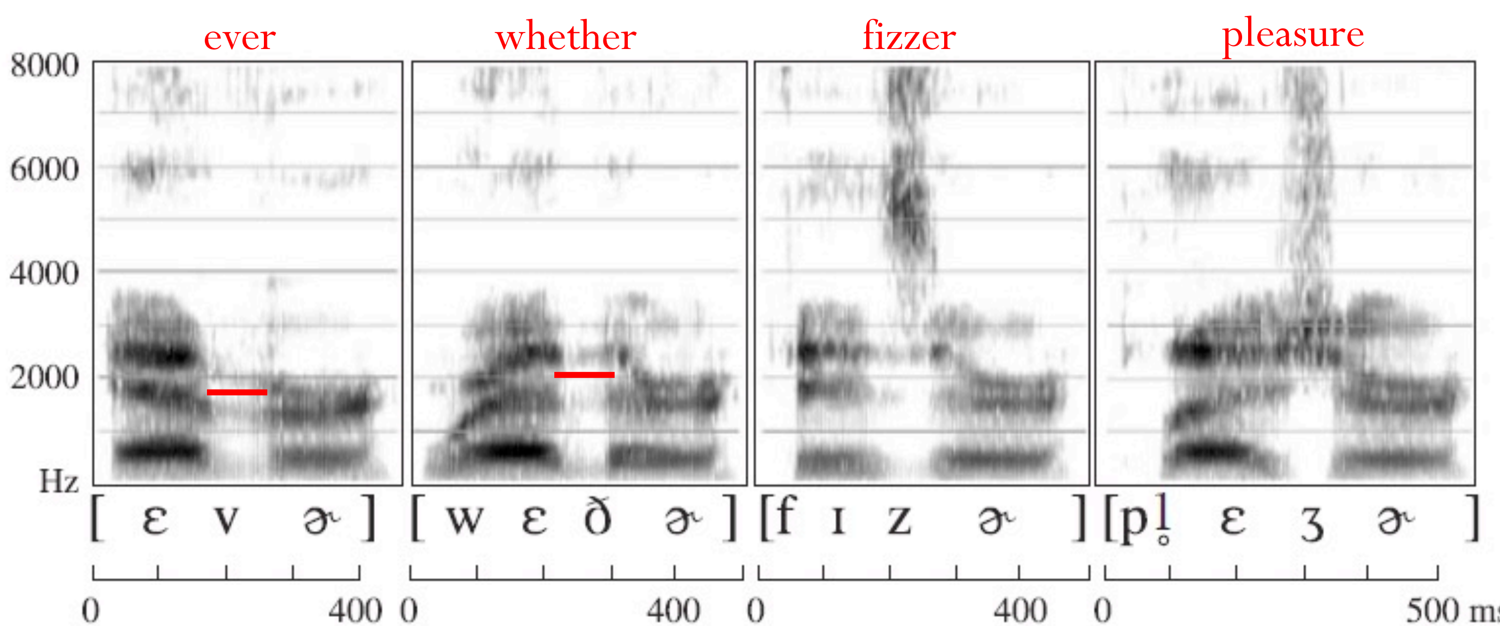
Voiceless fricatives [s, ʃ]

- The noise in [s] is centered at a high frequency, 5000 – 6000 Hz.
- In [ʃ] it is lower, extending down to about 2500 Hz.
- Both [s, ʃ] have **larger acoustic energy** and produce **darker patterns** than [f, θ]
- Both [s, ʃ] are marked with distinctive formant transitions.
- The locus of F2 transition increases throughout the words
  - [f] < [θ] < [s] < [ʃ] (see arrows in fig.)
- Before [ʃ] F2 of [a] is in a position comparable to its location in [i].



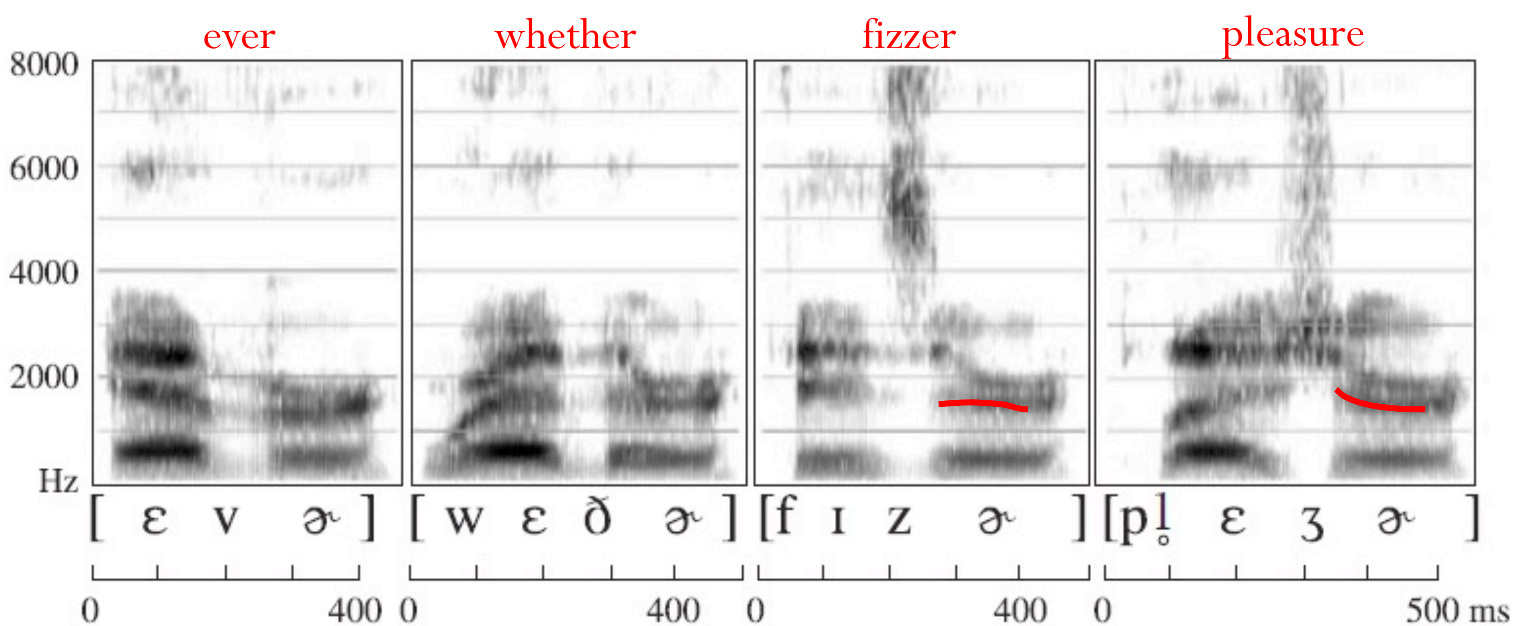
Voiced fricatives [v, ð]

- Voiced fricatives [v, ð, z, ʒ] have patterns similar to their voiceless counterparts [f, θ, s, ʃ].
- Voiced fricatives also have vertical striations indicative of voicing.
- Vertical striations due to voicing are apparent throughout [v] and [ð].
- The fricative component of [v] is very faint.
- F2 higher around [ð] than [v].



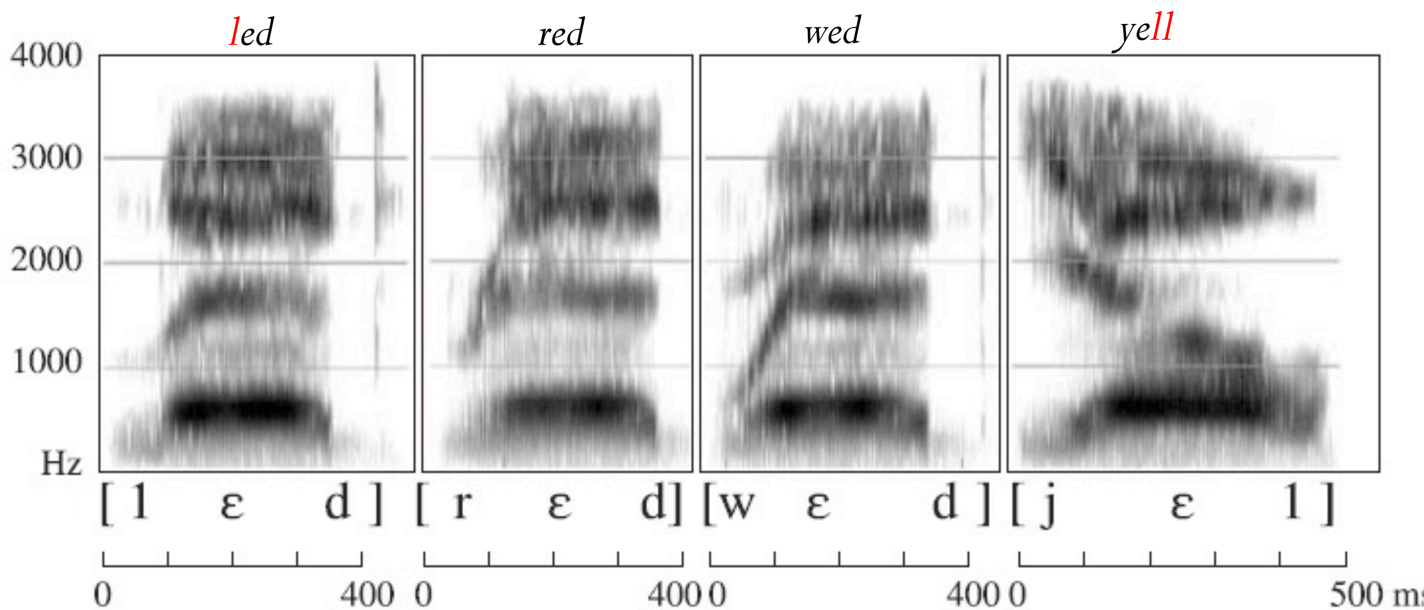
Voiced fricatives [z, ʒ]

- Fricative energy in higher frequencies very apparent in [z, ʒ].
- Voice bar
  - faint in [z]
  - hard to see in [ʒ] –vertical striations due to voicing in 6-8 kHz.



Lateral and central approximants

- Voiced approximants have formants not unlike those of vowels.
- The initial [l] has formants with center frequencies of approx. 250, 1100 & 2400 Hz, which change abruptly in intensity at the beginning of the vowel.
- **A marked change in formant pattern** is characteristic of voiced nasals and laterals.
- A final lateral may have little of no central contact, making it not really a lateral but a **back unrounded vowel**.
- A formant around 1100 or 1200 Hz is typical of most initial laterals for most speakers.



Lateral and central approximants

- The most obvious feature of approximant [ɹ] is the low frequency of F2 and F3.
- F3 begins at 1600 Hz!
- There is great similarity between *red* and *wed*. Young children have difficulty trying to distinguish them.
- The approximant [w] also starts with a low position for all three formants.
- F2 of [w] has the sharpest rise, as if it were a very short [u].
- The movements of formants for [j] are like those of a very short [i].
- This is why [w] and [j] are appropriately called **semivowels**, that is, semi versions of vowels [u] and [i] respectively.

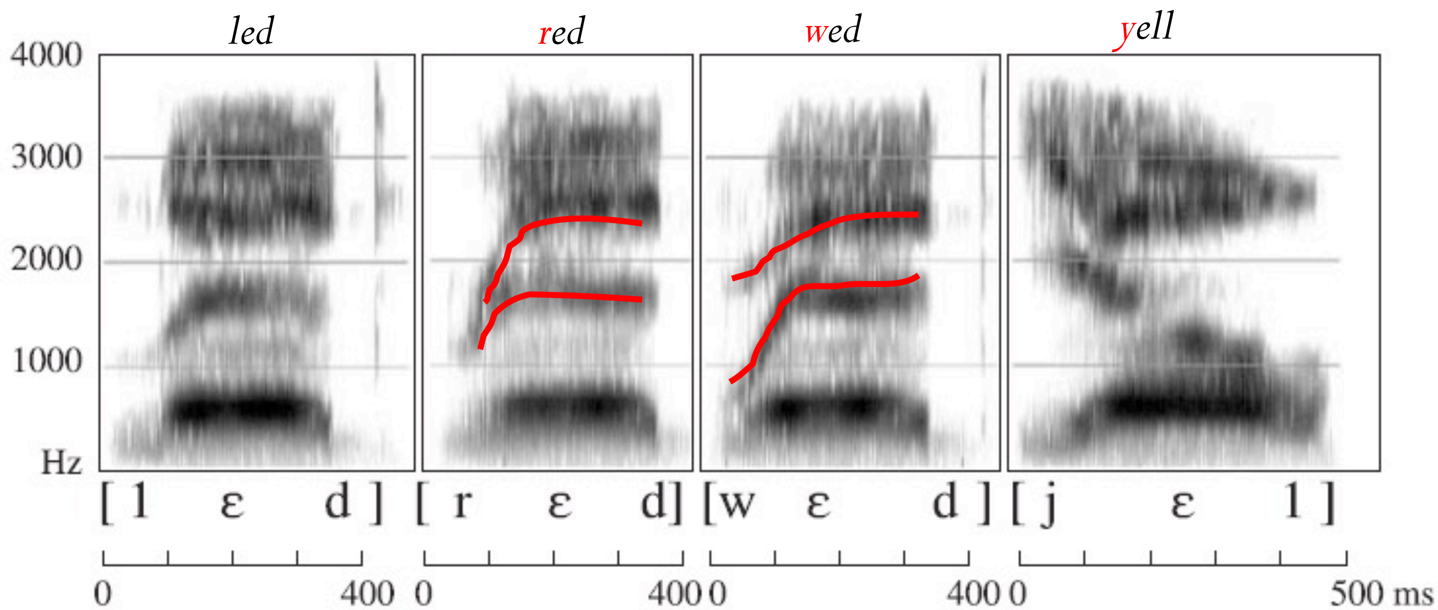


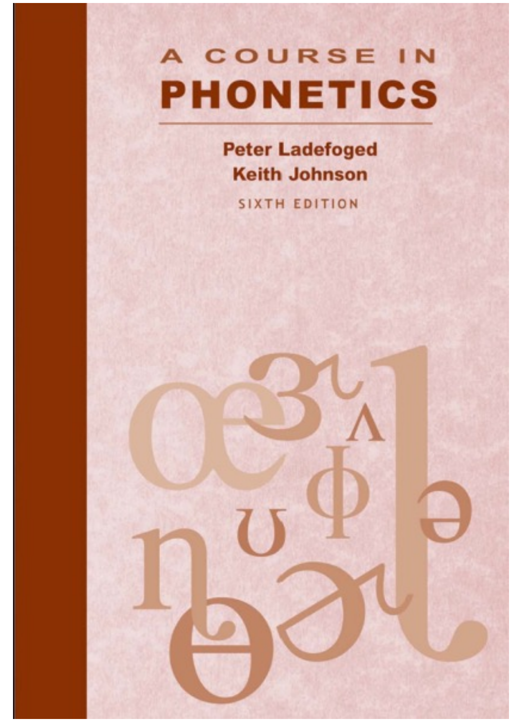
TABLE 8.1 Acoustic correlates of consonantal features. Note: These descriptions should be regarded only as rough guides. The actual acoustic correlates depend to a great extent on the particular combination of articulatory features in a sound and on the neighboring vowels.

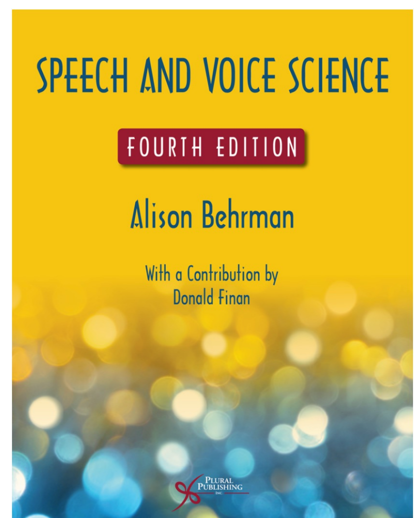
Voiced	Vertical striations corresponding to the vibrations of the vocal folds.
Bilabial	Locus of both second and third formants comparatively low.
Alveolar	Locus of second formant about 1700–1800 Hz.
Velar	Usually high locus of the second formant. Common origin of second and third formant transitions.
Retroflex	General lowering of the third and fourth formants.
Stop	Gap in pattern, followed by burst of noise for voiceless stops or sharp beginning of formant structure for voiced stops.
Fricative	Random noise pattern, especially in higher frequency regions, but dependent on the place of articulation.
Nasal	Formant structure similar to that of vowels but with nasal formants at about 250, 2500, and 3250 Hz.
Lateral	Formant structure similar to that of vowels but with formants in the neighborhood of 250, 1200, and 2400 Hz. The higher formants are considerably reduced in intensity.
Approximant	Formant structure similar to that in vowels, usually changing.

Ladefoged & Johnson, 2011:204

Acknowledgements

- Material for this presentation has been adapted <u>mainly</u> from chapters 1 and 8 of
  - Ladefoged, P., & Johnson, K. (2011). *A course in phonetics.* (6th ed.). Canada: Wadsworth, Cengage Learning
- Figures/pictures on slides 44, 48 and 50 from
  - Chapter 3 of Behrman, A. (2021). *Speech and voice science.* (4th ed.). Plural Publishing.





Read & visit…

- Ladefoged & Johnson "Articulation & Acoustics", chapters 1 and 8 (A course in phonetics", 6th ed.)

- Visit the websites (for Articulation)
  - https://corpus.linguistics.berkeley.edu/acip/course/chapter1/ (Material from UC Berkeley Linguistics for the book "A course in phonetics")
  - http://soundsofspeech.uiowa.edu/index.html#english (Mobile App: Interactive Phonetic Library for American English)
  - https://www.enl.auth.gr/speakgreek/library.html (Interactive Phonetic Library for Greek)
  - http://smu-facweb.smu.ca/~s0949176/sammy/ (Interactive Sagittal Section)

- Visit the websites (for Acoustics)
  - https://www.compadre.org/books/?ID=46&About=1
    An Interactive eBook on the physics of sound (Indiana University Southeast)
  - http://zonalandeducation.com/mstm/physics/waves/waveAdder/WaveAdder1.html
    Wave Adder
  - http://www.youtube.com/watch?v=Gg4IHbiITd0
    Introduction to spectrogram analysis (FloridaLinguistics.com)
  - http://www.linguistics.ucla.edu/people/hayes/103/SpectrogramReading/ShortComparisons/
    Spectrogram reading practice (by Bruce Hayes, UCLA)
  - http://home.cc.umanitoba.ca/~robh/howto.html
    Monthly Mystery Spectrogram Webzone –Rob Hagiwara's professional web-space
  - http://www.acoustics.hut.fi/publications/files/theses/lemmetty_mst/chap4.html
    Problems in Speech Synthesis (Helsinki University of Technology)