Introduction to Acoustic Phonetics III

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ARTICULATION AND RESONANCE:

CONSONANTS

earlier: how the movements and positions of the articulators are shaping the **resonating cavities of the vocal tract** to modify the sound source for **vowels**

it is quite similar to that for the **resonant / sonorant** consonants:

- approximants/glides/semivowels (/w/, /j/, /r/?)
- nasals (/m/, /n/, /ɲ/, /ŋ/, /N/ …),
- liquids /l/ (lateral) and various /r/ (rhotics: approximants & vibrants = trill + tap + flap).

semivowels

the vocal tract is relatively open for the semivowels, as it is for vowels

the **semivowels** are characterized acoustically by **formants**,

but

they are consonants, not as vowels:

- behave like consonants (/jadró/ [jidró], *chiabatta*)
- occur on the **periphery of syllables**, and not in the centers or nuclei of syllables

Occasionally, though, liquids and nasals do function as the nuclei “cotton” [kɑtn.]

w, j

/j/ is a **palatal** glide: the tongue blade must approximate the palate at a position close to that for [i]

/w/ is analogous to /j/: it's starting position is characterized by a high back tongue position and protruded lips, similar to /u/.

/w/ has two places of articulation: the **bilabial** protrusion and the **lingua-palatal** approximation

The articulatory configurations for /j/ and /w/ resemble, respectively, /i/ and /u/ →

the patterns of the **formant frequency change** are usually predictable as the vocal tract configuration changes to that **of the vowel following the glide**.

The tongue is very high in the mouth and the **pharyngeal cavity is relatively large →**
F1 is very low (as it is for /i/ and /u/) for both glides.

r

/r/ is produced in syllable-initial position by raising the tongue toward the alveolar ridge,

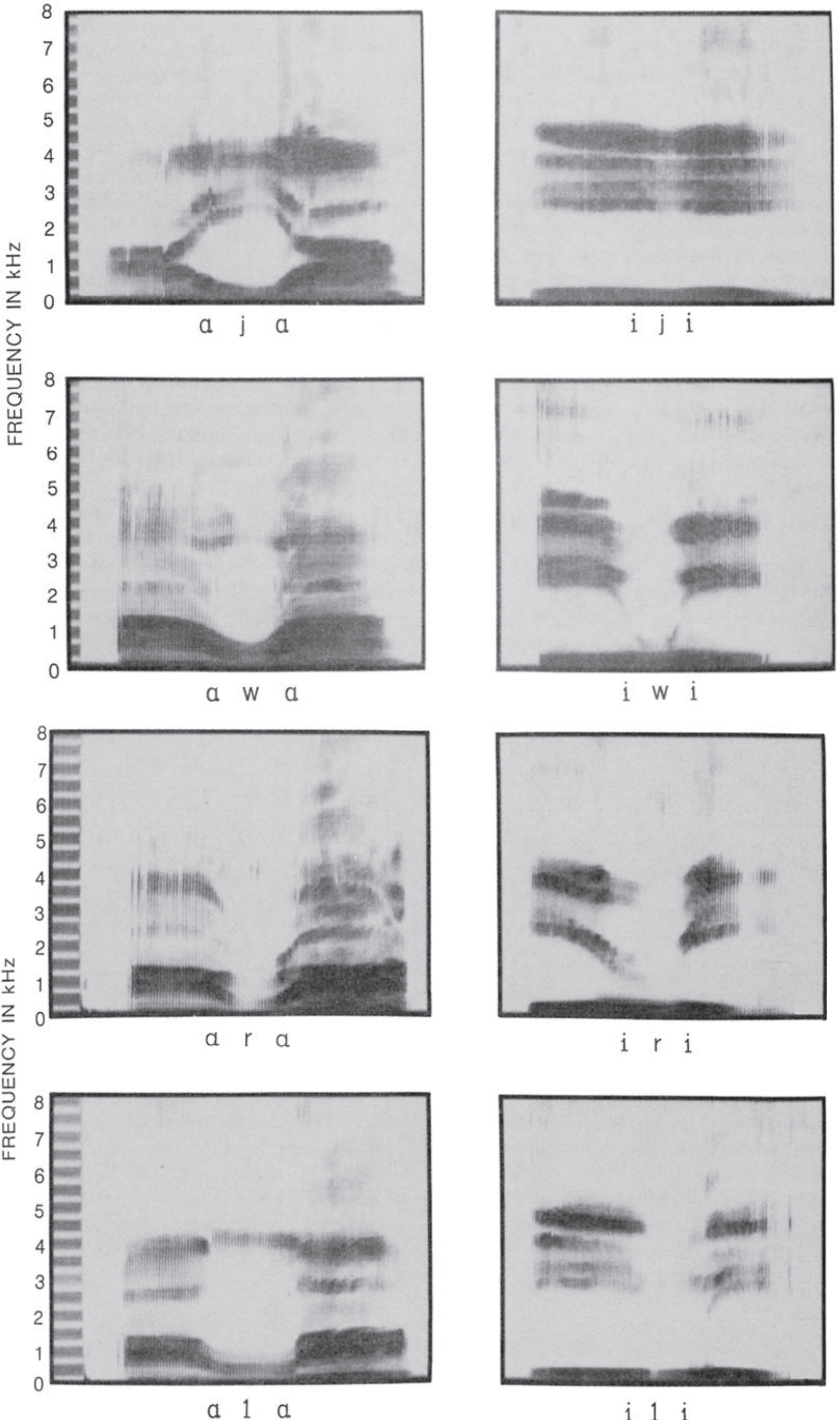
the tip does not touch the alveolar ridge, so some of the airflow and acoustic energy emerges centrally,

the lips are usually rounded and

the body of the tongue is raised toward the velum

some speakers produce a retroflex /r/

The **acoustic results** of these tongue tip adjustments are particularly obvious in the third formant: **F_3 falls** below the F_3 frequencies typical of the neighboring vowels.



[w], [j], like vowels, are the result of filtering the complex wave produced at the glottis in the resonating cavities of the vocal tract.

The articulations (only minimum constrictions in the vocal tract), and, as a result the acoustic features (formant structures) of glides resemble those of vowels.

There are, however, some differences

Small constriction in mouth → **F_1 lowering, F_2 attenuation**

/r/ 3 constrictions (lips, alveolar ridge, velum) →
+ low F_3 (300/900/1600)

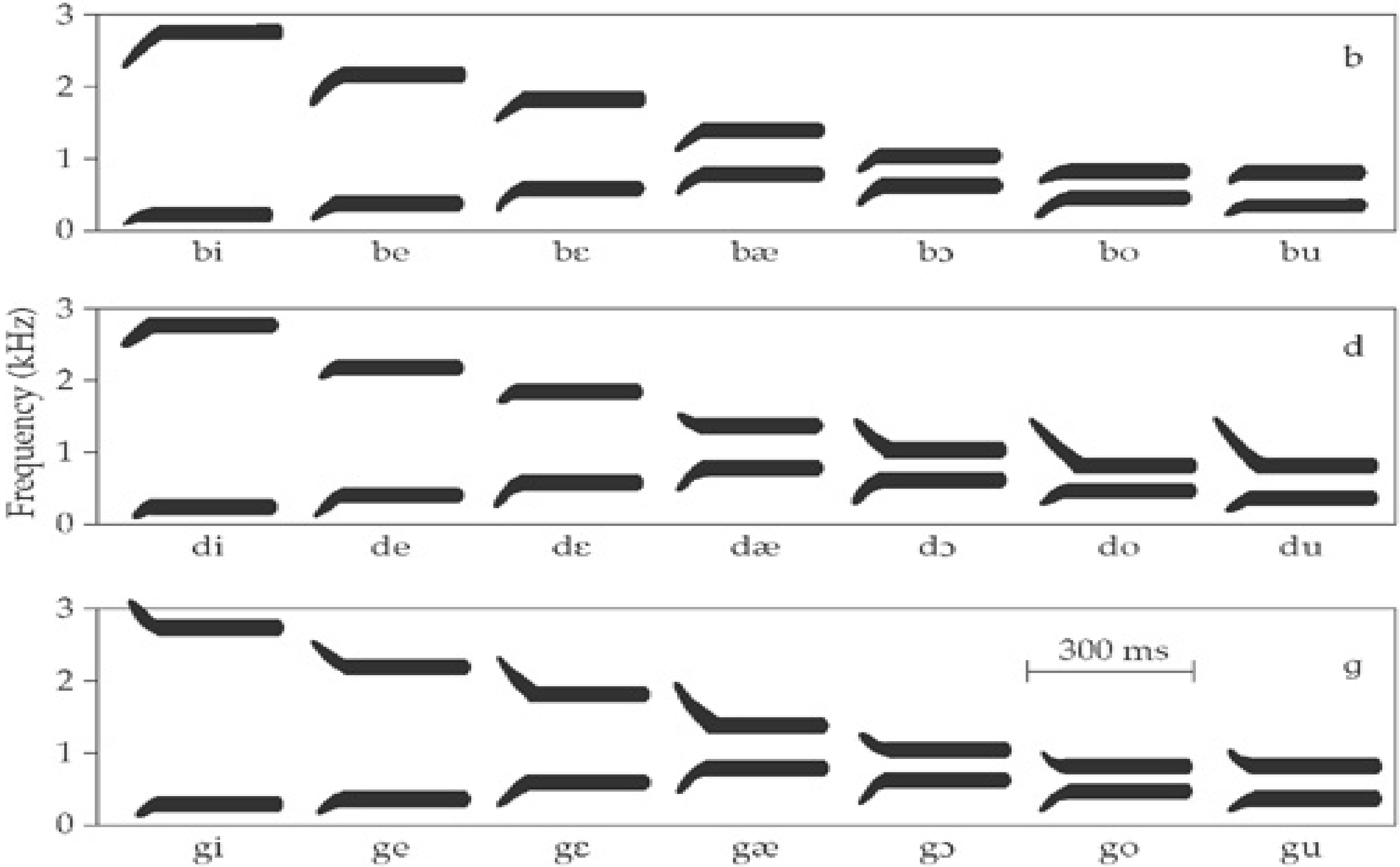
Max. duration of formant transitions: **glides**

It is the sound of the acoustic changes caused by the movements of the articulators that listeners use to recognize glides

Limited cases of such syllables as **/ji/** (as in "yeast") and **/wu/** (as in "woo"): in both cases, the starting and ending vocal tract configurations are similar.

Speakers, however, do not simply produce a long /i/, /u/

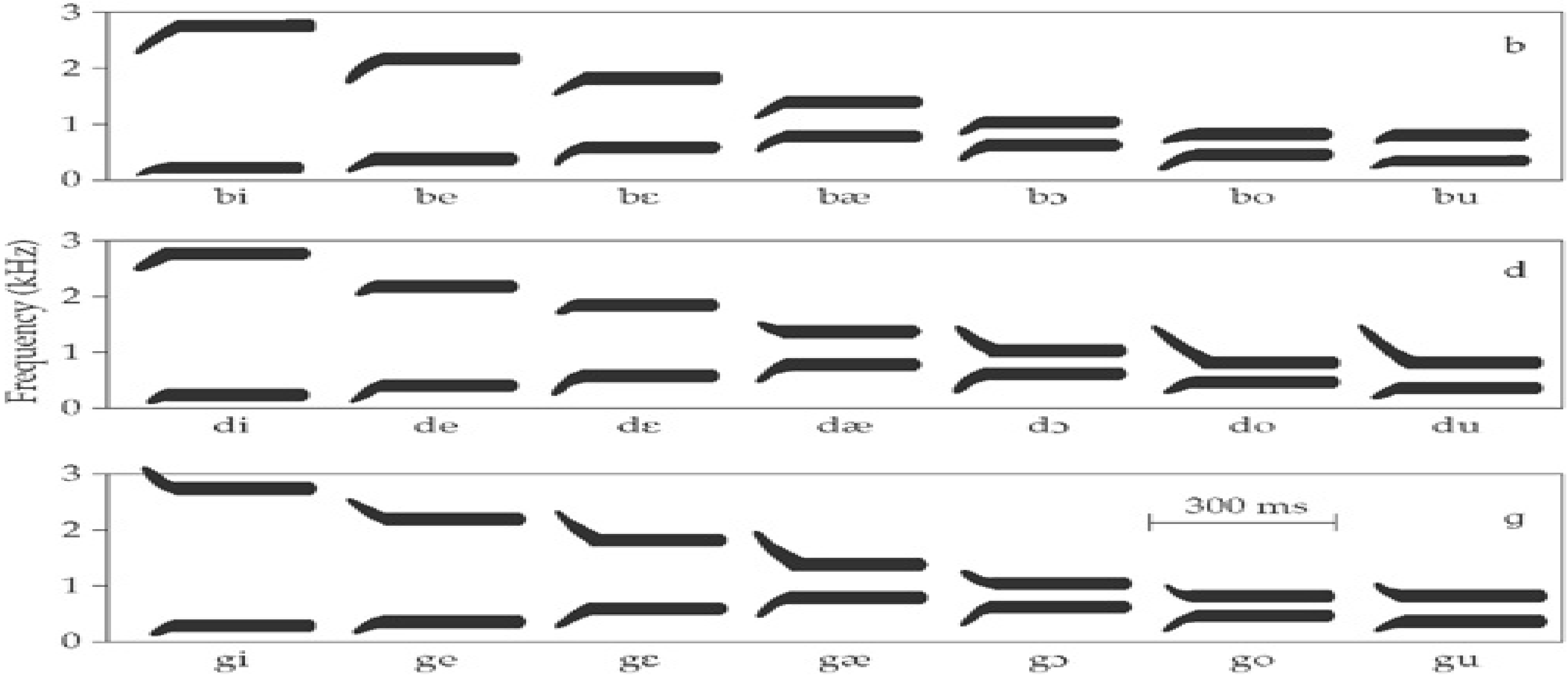
Rather, they move the articulators away from the onset configuration and then return them to approximately where they started. This articulatory movement changes the vocal tract resonances and provides the formant frequency changes needed for glide production and perception.



F1 and F2 transition patterns in stop release used to synthesize [b], [d], and [g] followed by various vowels (from Delattre et al. 1955, p. 770),

consonants consist of shutting and release **movements:**

the **information** they contain about place of articulation is seen **in formant movements, not values**

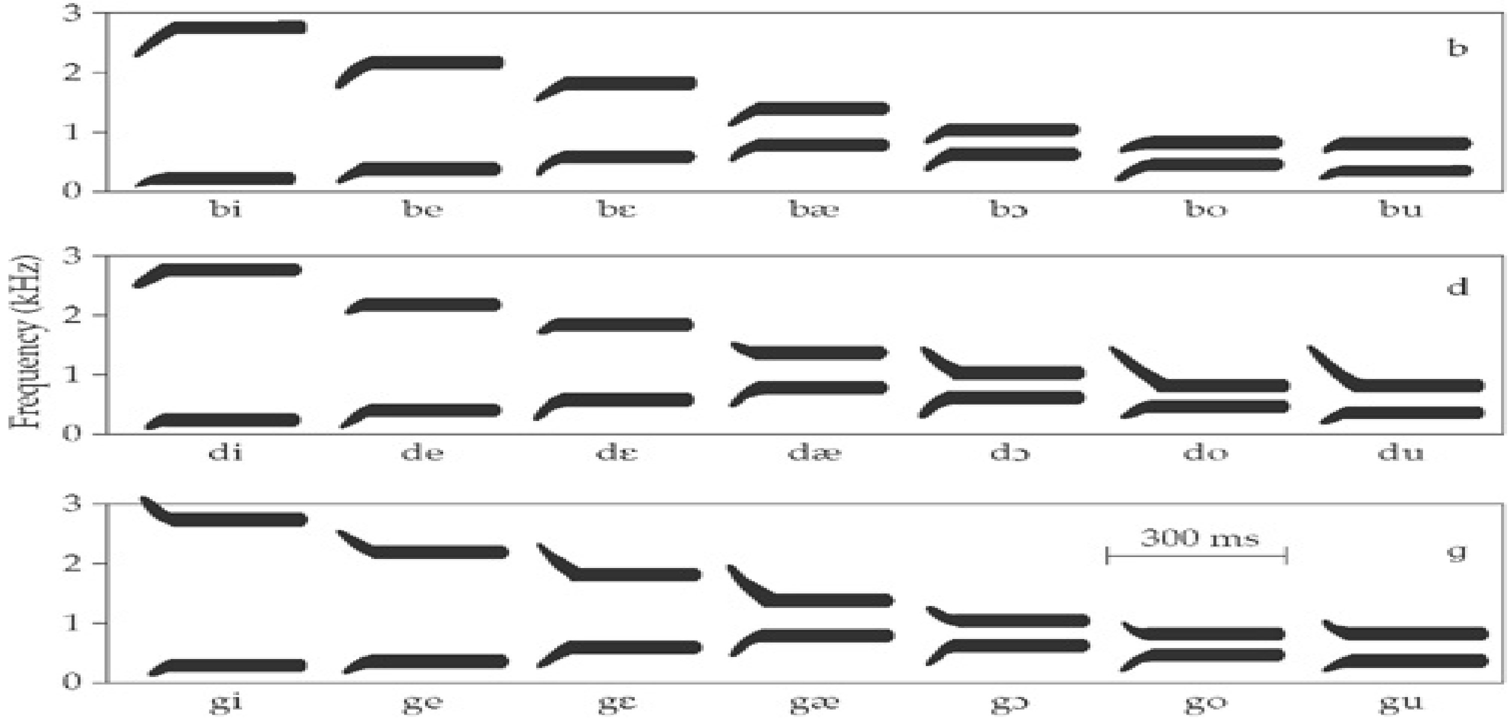


The second formant is high in the front vowels, and the first formant is high in the low vowels.

The point: the **formant transitions** (movements) that contribute to the perception of a particular consonant place of articulation depend on the identity of the following vowel.

Especially striking in the case of coronals:

when the F2 of the vowel is high, the F2 transition rises; but when the F2 of the vowel is low, the transition falls.

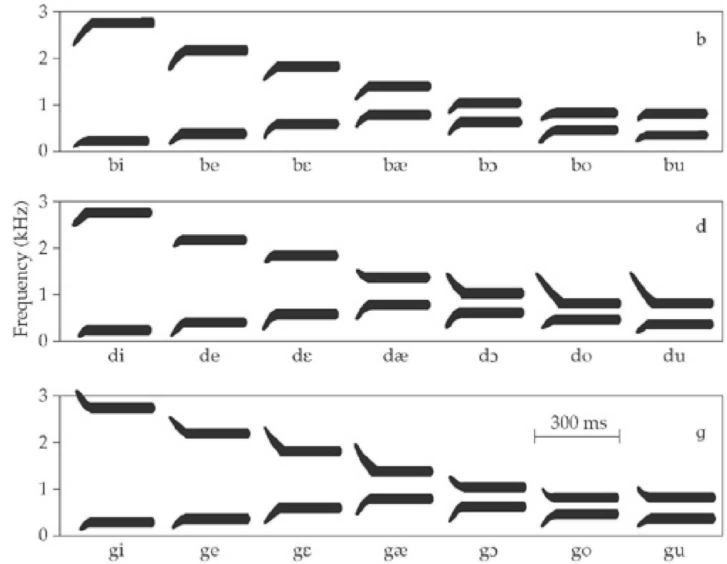


Delattre et al. (1955): the perceptually important part of the transition is not actually present in the acoustic signal, but can be derived from a set of syllables such as those shown above.

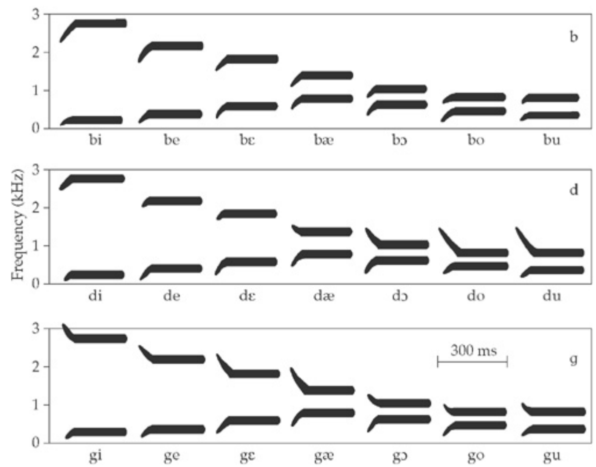
Superimpose the F2 trajectories of syllables, starting with [d], and extend the F2 trajectories back in time, they seem to intersect at about 1,800 Hz.

This hypothetical starting frequency – the F2 locus **frequency:**

- **Labials**: 700 Hz, a l**ow**-frequency locus
- **Coronals**: 1800 Hz, a **middle**-level locus
- **Velars**: **higher** F2 locus.



- The release burst of [d] is shaped by a front cavity resonance (which has a high frequency), but the F2 locus is associated with a back cavity resonance. Both the burst and the F2 locus of [g] are associated with a front cavity resonance ([b] has no resonance)
- The rapid change in the coupling of front and back cavities also explains why all stop consonants have a low-frequency F1 near the stop closure interval. During closure the two cavities are uncoupled, thus there is no first formant (because the first formant is a Helmholtz resonance – see chapter 6). The Helmholtz resonator that gives us F1 starts with a very narrow neck (and thus a low F1). As the constriction widens, the neck of the Helmholtz resonator increases, and thus the frequency of F1 increases. Also, as the closure is released and the constriction becomes wider, the front and back cavities become acoustically coupled. The opposite happens during the shutting stage. The first formant starts relatively high, and falls as the constriction is formed.



All formants are lower near the stop closure in **bilabial**s. In terms of perturbation theory, it is a result of a constriction located at a velocity node (at the lips) for all the resonances

The F2 locus for **coronal** stops is a bit higher than the second resonant frequency of a uniform tube. The F3 near the closure in coronal stops is also higher than in the uniform tube. These effects are predicted in a two-tube model with a constriction in front of the vocal tract.

In **dorsal** (palatal + velar) stops there is a convergence of F2 and F3 near the closure, because the location of the closure is near the intersection of the front and back cavity resonances.

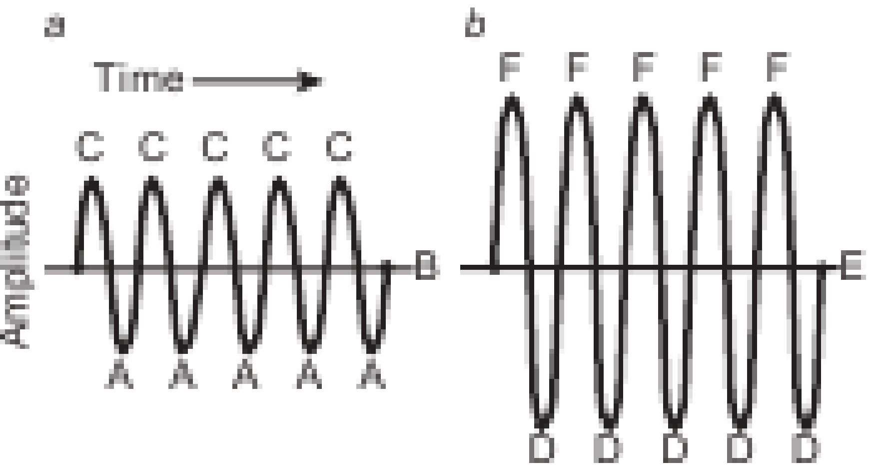
Nasals and Laterals

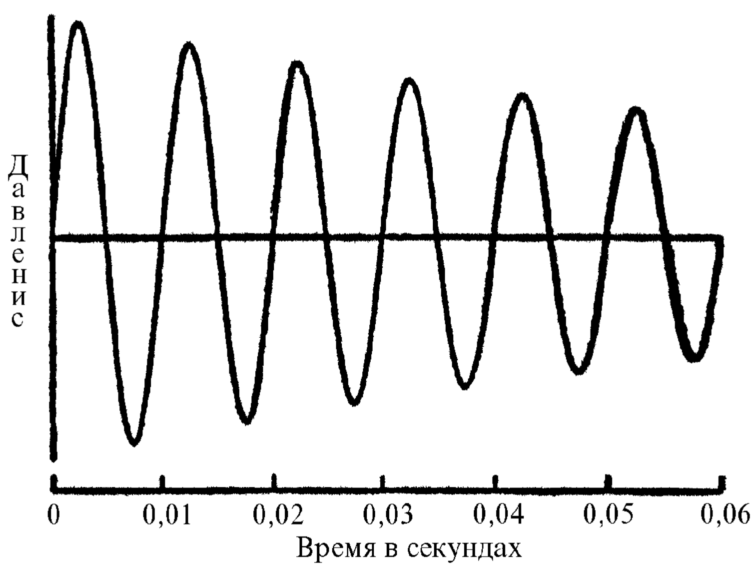
are more complicated than vowels:

(it is their vocal tract filtering characteristics that are more complicated).

One way in which the vocal tract filtering function in **nasals** is different from that in oral vowels is that the width of the resonance peak (the **bandwidth)** of the first formant is larger in nasals as a result of **damping**

damping





<u>Simple periodic wave</u>:

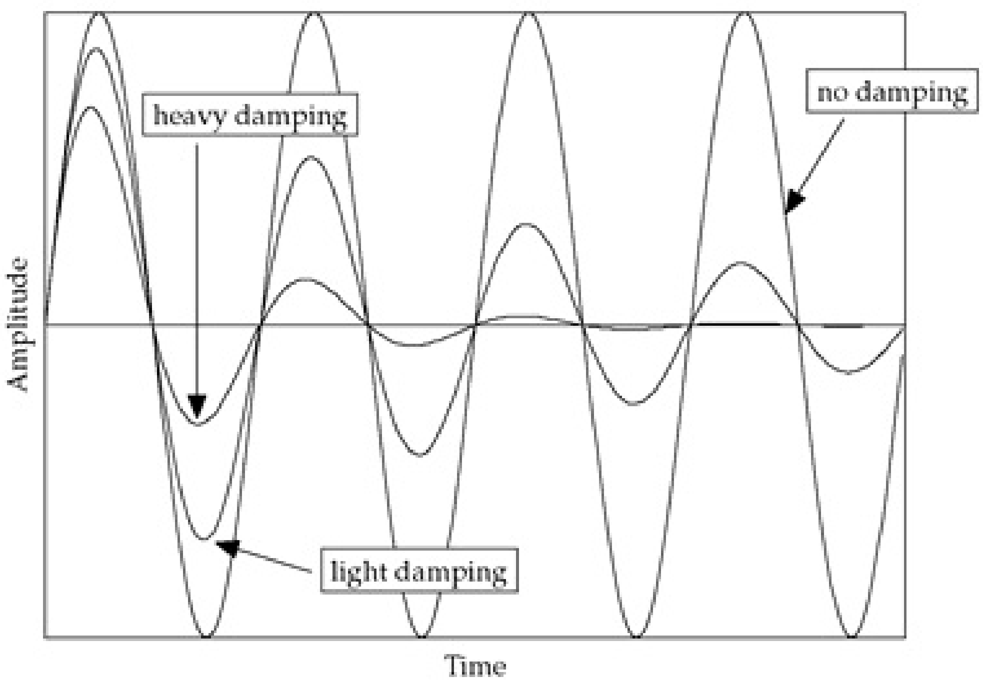
the same amplitude and
the same frequency
all over the time

Amplitude in the **damped sine waves**
decreases over time.

like pushing smb on a swing:

energy you put into the push is dissipated by a natural resistance to the swinging motion – the pull of gravity and the friction as the swing moves through the atmosphere.

damping



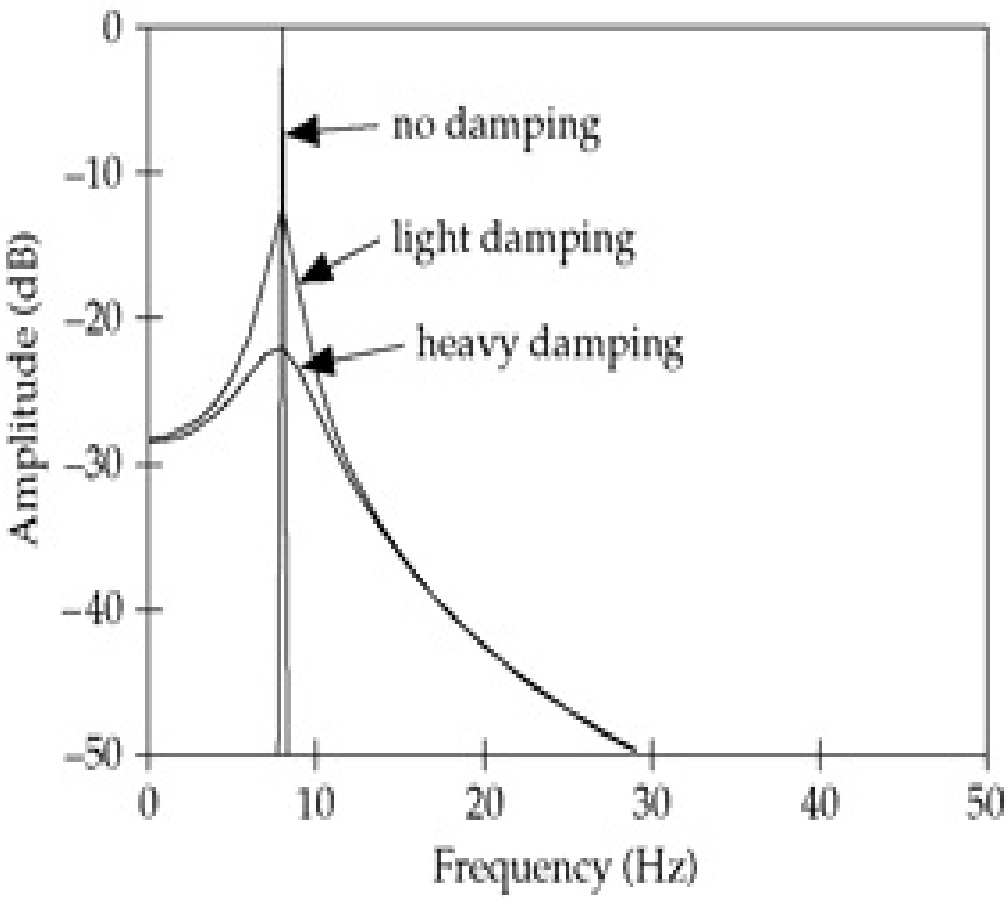
An undamped sine wave and two damped sine waves.

The heavy damping sine wave loses amplitude more quickly than the light damping one

the more heavily damped wave corresponds to swinging on the earth,

the lightly damped wave to swinging on the moon (where gravity is weaker and the atmosphere is less dense).

damping

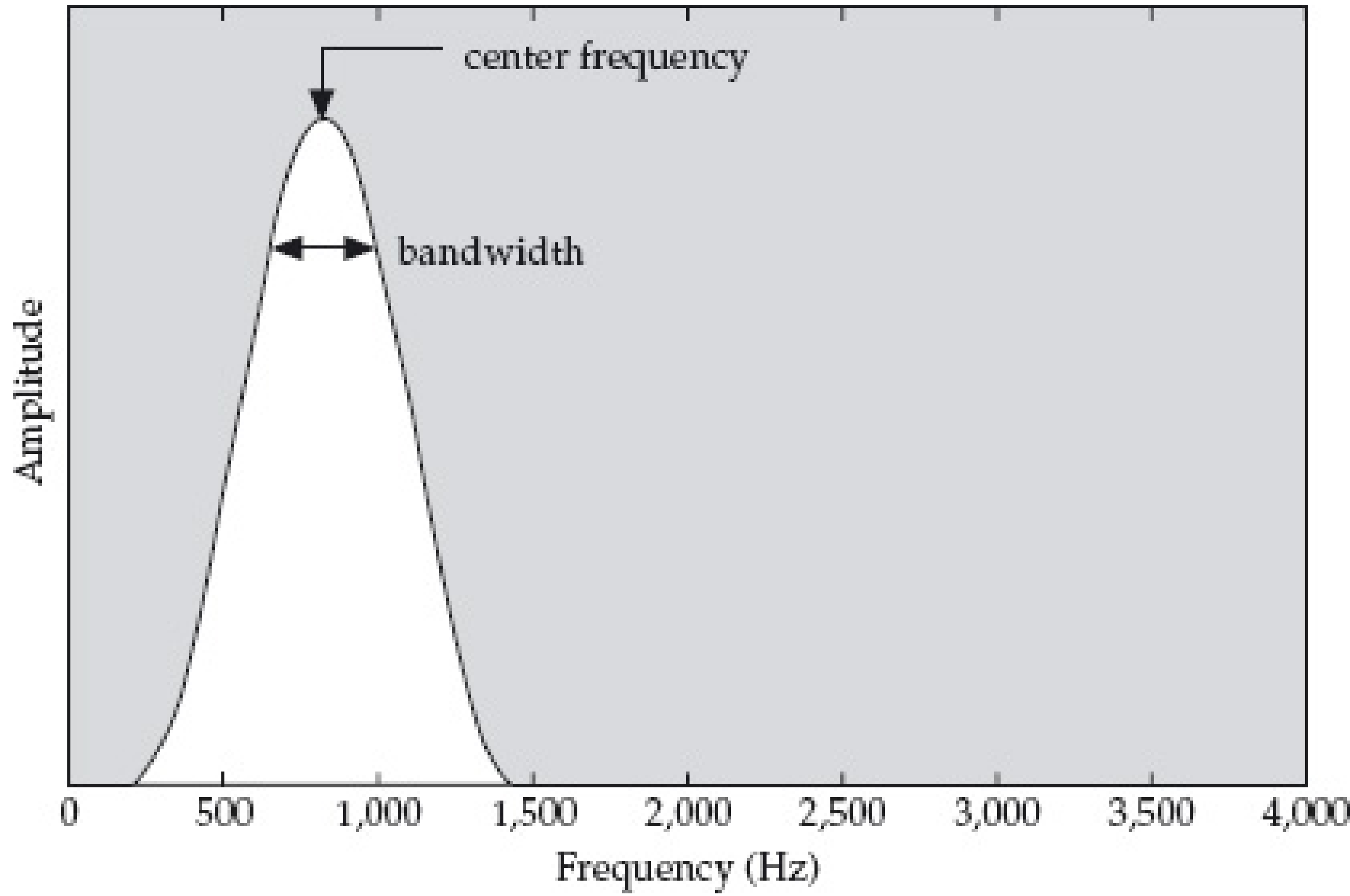


An undamped sine wave, two damped sine waves identical in frequency and phase

- the spectrum of a sine wave: a line
- a damped sine wave does not have an exactly sinusoidal form → more complex spectra
- energy spread over other frequencies near the peak.

The "light damping" waveform is more similar to a sine wave than the "heavy damping" waveform: it has a narrower peak.

bandwidth



- The spectral result of **damping** the sine wave is **to broaden the peak around the sine wave's frequency**: with more damping the peak gets wider.

formant bandwidths

The sound waves that resonate in the vocal tract might go on vibrating infinitely, but

- the **sound energy is absorbed by the soft walls and the inertia of air**

Thus, formants have certain **bandwidths**, because the resonant **frequencies** of the vocal tract are **damped**

In **nasals**

the **greater** surface **area** of the vocal tract means that the walls of the **vocal tract absorb more energy** than in non-nasal sounds, and

the **greater volume of air** means that the **inertia of air** within the vocal tract **absorbs more sound** as well.

Nasal Stops

Uvular nasal [N] is the **simplest** nasal consonant to describe.

When the uvula is lowered and the dorsum of the tongue raised to produce an uvular nasal, the <u>vocal tract</u> can be described as a <u>uniform tube</u> that is closed at the glottis and open at the nostrils.

If we know the length of the tube, we can calculate its resonant frequencies, because this is a quarter-wave resonator (like the vocal tract configuration for schwa)

Nasal Stops → low F_1

Fant (1960):
the distance from the uvula to the nares is 12.5 cm,
the distance from the uvula to the glottis is 9 cm →
a total length from glottis to nares ≈ 21.5 cm.
The four lowest resonant frequencies of the tube
(**c** is the speed of sound in air in cm/s):

$$F_1 = c/4L = 35{,}000/4 \times 21.5 = 35{,}000/86 = 407 \text{ Hz}$$
$$F_2 = 3c/4L = 1{,}221 \text{ Hz}$$
$$F_3 = 5c/4L = 2{,}035 \text{ Hz}$$
$$F_4 = 7c/4L = 2{,}849 \text{ Hz}$$

The assumption that the vocal tract can be modeled by a uniform tube is wrong: there is a **constriction** of the nasal tract **at the nostrils** (the nose has permanent "lip rounding" ☺).

Perturbation theory:

there is a velocity maximum at the nostrils →

each of the resonant frequencies will be lower

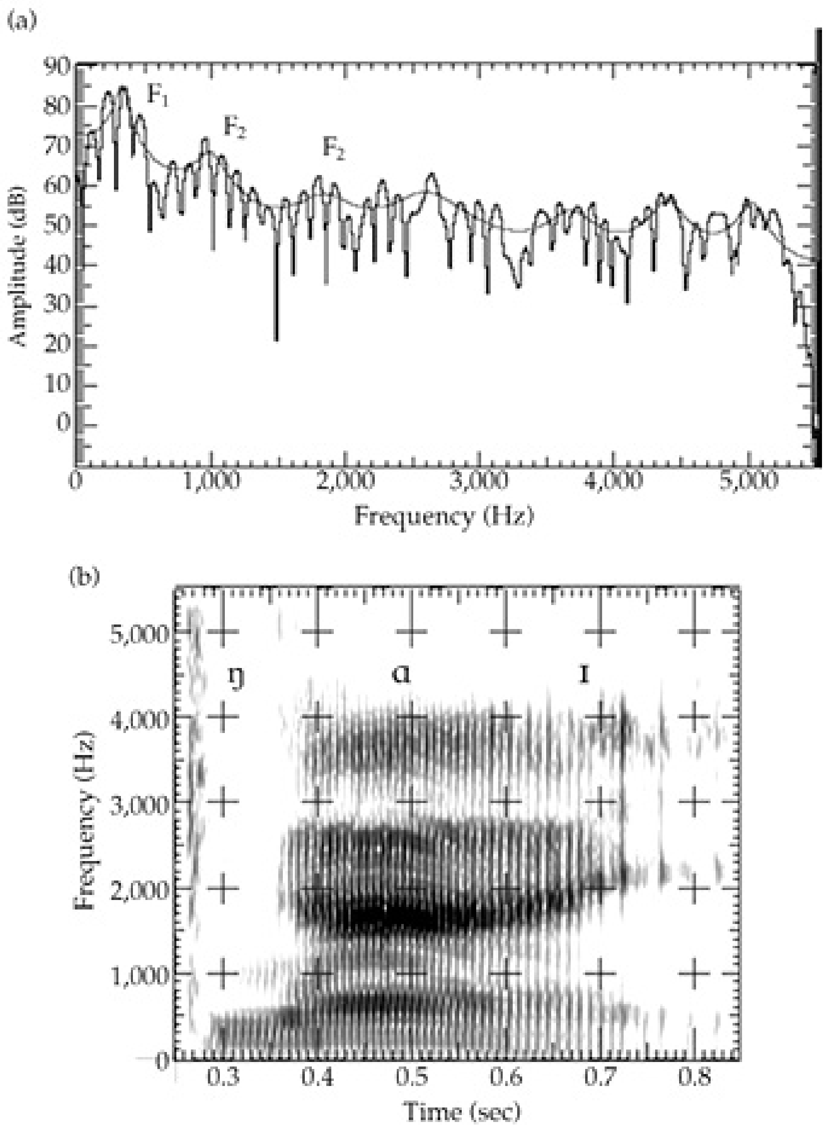
than the calculations above suggest.

It is hard to make quantitative predictions about the formant frequencies of [N] (the shape of the nasal passage varies), but

the **formant values will be spaced more closely** in the uvular nasal than they are in [ə];

for a male vocal tract the interval between formants in [**ə**] is ≈ **1,000** Hz, whereas in [**N**] it is ≈ **800** Hz.

Thai [ŋâːɪ] ‘*easy*’



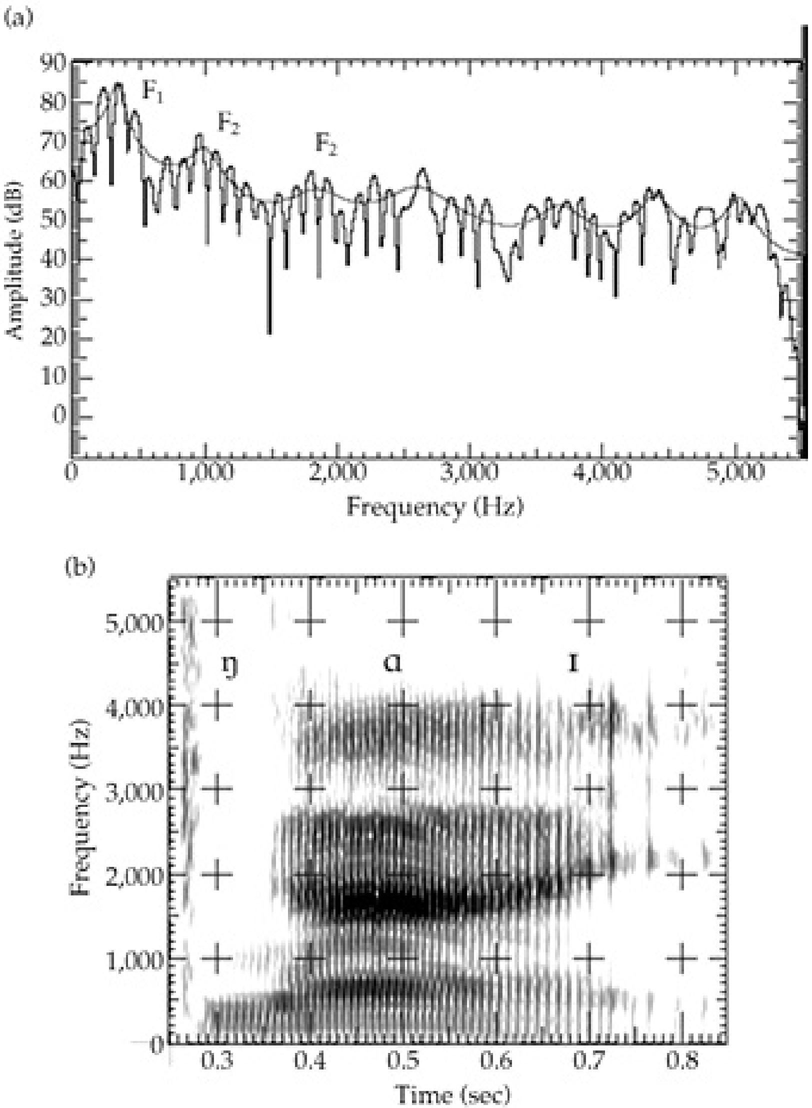
as predicted, four evenly spaced formants below 3 kHz,

their frequencies are about the same as for a uniform tube 21.5 cm long.

[ŋ] has lower F_1 and F_2 than [a]

an apparent gap in the nasal spectrum at about 2,000 Hz, corresponding to the weakened F3, and the formants above 3 kHz are too weak to appear in the spectrogram

Thai [ŋâːɪ] ‘*easy*’



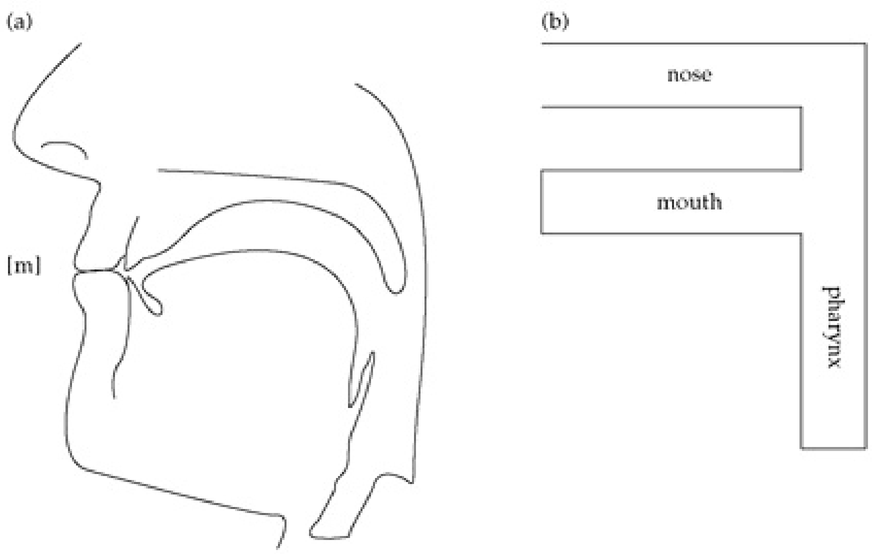
Nasal consonants have **lower amplitude** (than vowels):

larger resonant passageway → <u>damping</u> of the formants

the **vocal tract is more constricted** at the opening to the nasal passages

the vocal tract has **side cavities** like the sinuses (not only those)

[m]



The main difference between [N] and [m] is that **the mouth cavity forms** a **side branch** in the resonant tube.

The mouth cavity can be modeled as a tube closed at one end (the lips) and open at the other (the uvula), with a length of about 9 cm.

We can therefore calculate the resonances of the mouth cavity as we did for [ə], [N]:

$$\boldsymbol{c/4L} = 35{,}000 / (4 \times 9) = \mathbf{972}$$

$$\boldsymbol{3c/4L} = \mathbf{2{,}917}\ \mathrm{Hz}$$

anti-resonance

The resonant frequencies of the mouth cavity in nasals are not like that we've seen before:

the mouth cavity **is a side branch** of a larger resonantor: it doesn't open directly to the atmosphere.

So frequency components in the sound source that are near the **resonant frequencies of a side cavity**

resonate in the side branch without making an appearance in the acoustic output of the acoustic tube system

They are "**absorbed**" in the side branch →

anti-resonance

the **frequency components** in [m]

that are **near the resonant frequencies of the mouth cavity are canceled**, and

become **anti-resonances** (anti-formants**)** in the acoustic output.

Formants show up in the spectrum as **peaks** of sound energy, and **anti-formants** show up as pronounced spectral **valleys**.

There are valleys in the spectrum of schwa, but these are the result of a lack of resonance; some frequency components are simply not enhanced as much as others.

In contrast to this, there are some frequency components **in [m]** that are **actively subtracted** from the spectrum.

Another effect of an anti-formant in the spectrum:

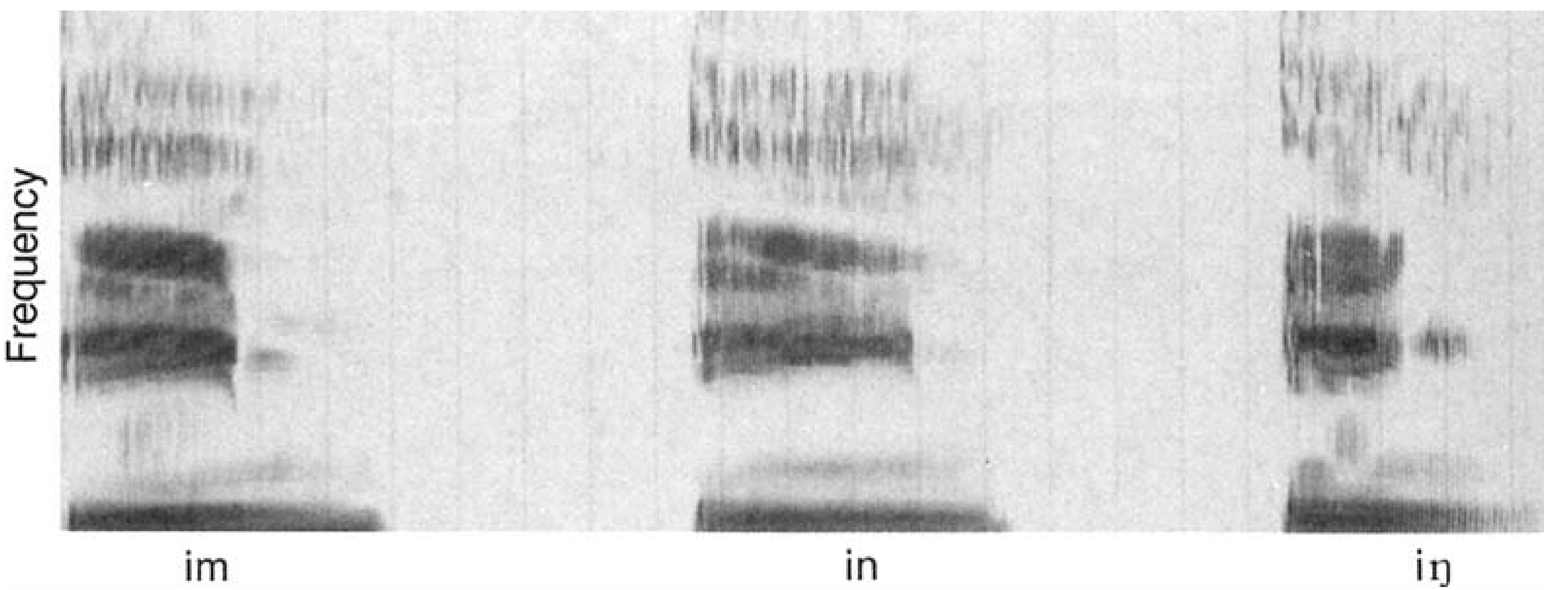
amplitudes of all the formants **above** it are reduced:

nasals have **more energy at the low end** of the spectrum

(+ increased bandwidths also cause the formant amplitudes to be reduced) →

in spectrograms nasals are **lighter than the nearby oral vowels**

The **frequencies of anti-formants** in the spectrum of a nasal stop **depend on the length of the mouth cavity**



[n], [m]

- the mouth cavity in [n] is about 5.5 cm long.

A uniform 5.5 cm tube that is closed at one end and open at the other has resonant frequencies at 1,591 and 4,773 Hz;

thus we expect

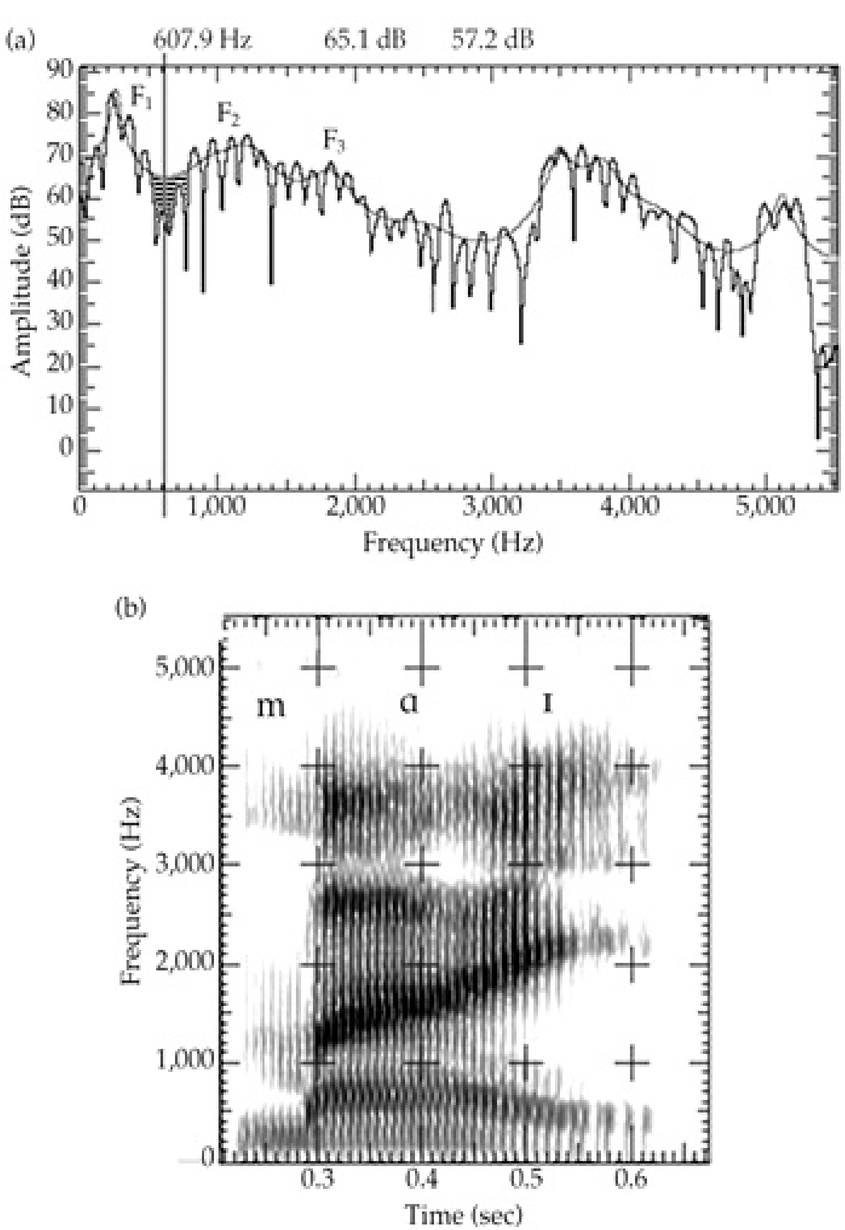
the spectrum of **[n]** to have an **anti-formants** at **≈1,600** Hz and **≈4,800** Hz.

The mouth cavity in **[m]** is about 9 cm long, →

anti-formants at less than **1,000** and **≈3,000** Hz.

The frequencies of the anti-formants are cues to the place of articulation in these (isolated) nasals.

[mâɪ] “no”



the first anti-formant is indicated by shading and a vertical cursor

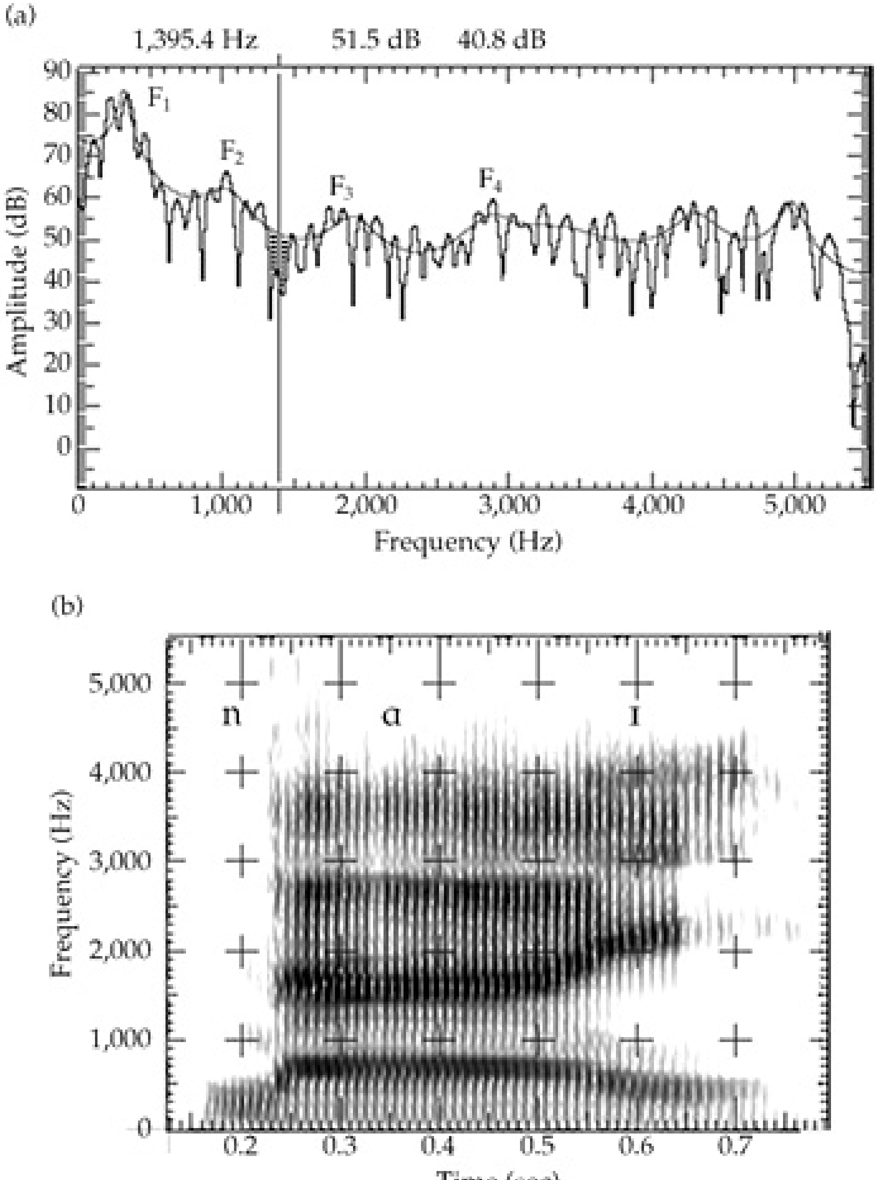
an **anti-forman**t may or may not appear as a white band in the spectrogram

if there are no formants near the anti-formant, it appears **white** in the spectrogram (here);

but if the frequency of the anti-formant is about the same as the frequency of a formant, the net result is to

weaken the formant peak

[naːɪ] “master”



the spectrum of [n] should have anti-formants at higher frequencies

(1,600 Hz and 4,800 Hz)

the main properties of nasals

- **low F1** (sometimes called the “nasal formant”),
- **close spacing** between formants, and
- the presence of **anti-formants**, whose frequencies are determined by the place of articulation

sinuses

anti-formants are caused by side cavities in the vocal tract

the importance of the nasal sinuses?

their resonant frequencies –anti-formants – depend on the volume of the sinus and the dimensions of its opening, so

it is difficult to give any firm estimates of the frequencies of the anti-formants contributed by the sinuses.

Lindqvist-Gauffin & Sundberg (1976):

the maxillary sinus → an anti-formant at ≈500 Hz, and

the frontal sinus → an anti-formant at ≈1,400 Hz.

Perceiving anti-formants

Repp (1986):

listeners could identify nasal murmurs extracted from syllables starting with [n] and [m] correctly 72% of the time.

when the vowel formant transitions were included, performance was 94% correct

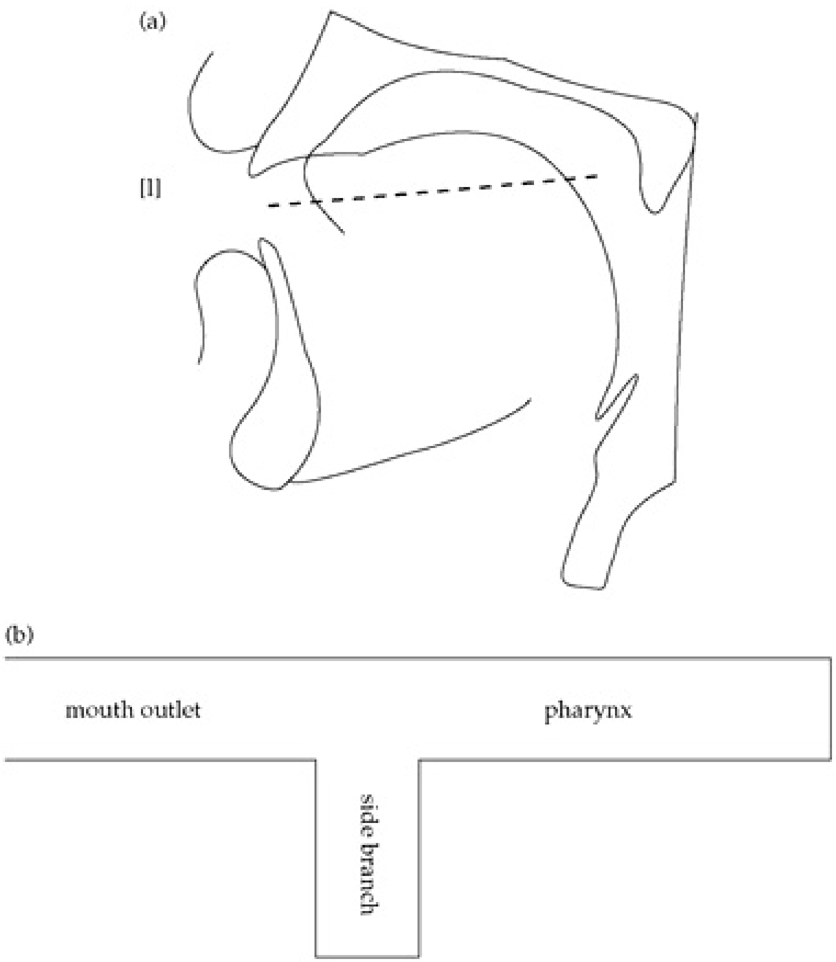
(with only 10 ms of the vowel)

→ the frequencies of the anti-formants in [m] and [n] are not really very important perceptual cues for these consonants.

Laterals:

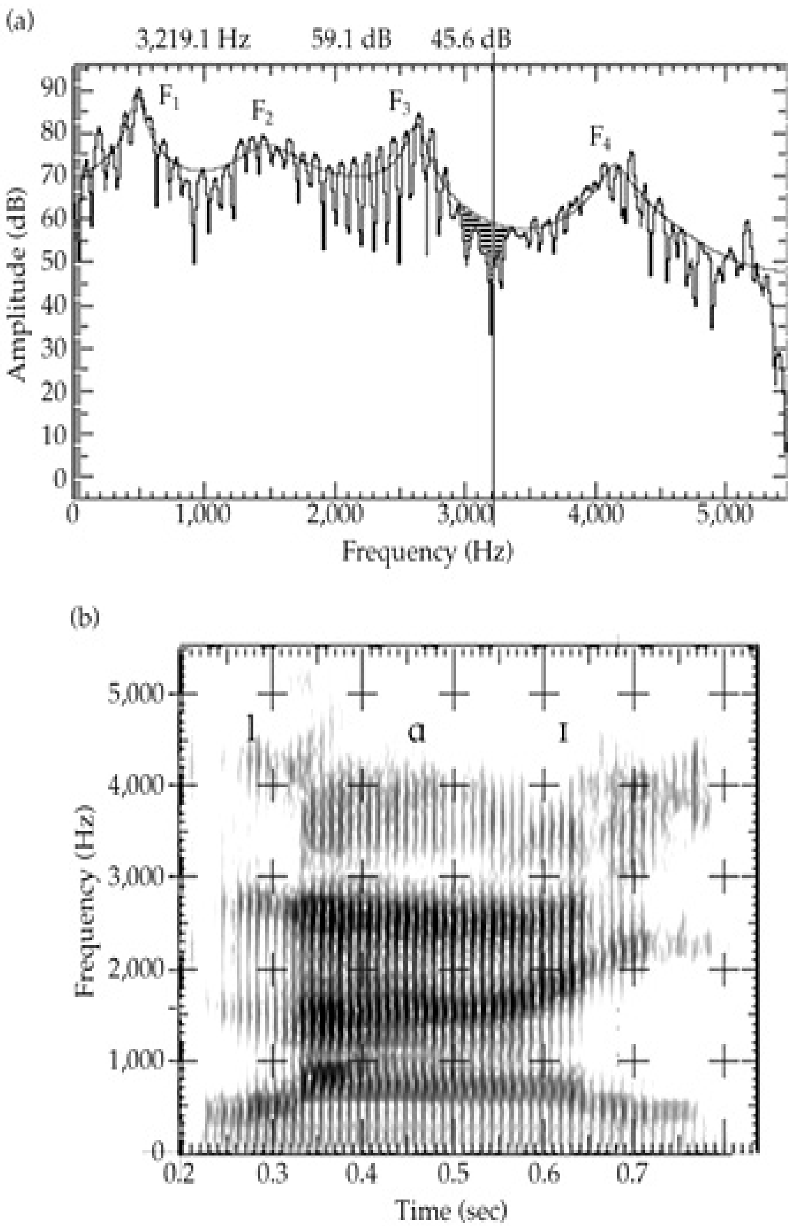
similar to the analysis of nasals:

A small **pocket of air on top of the tongue** acts as a **side branch** (to the main acoustic channel which curves around one or both sides of the tongue) produce **anti-formants** in the spectrum, just as the mouth cavity does in nasals



There may be some asymmetry in the sizes of lateral openings on the left and right sides of the tongue: the opening around one side is more open than the other.

[laːɪ] “stripes”



vocal tract can be modeled as a uniform tube that has

a short side branch

$$F = c/\lambda$$

Fant: pocket 4 cm, vocal tract 16 cm

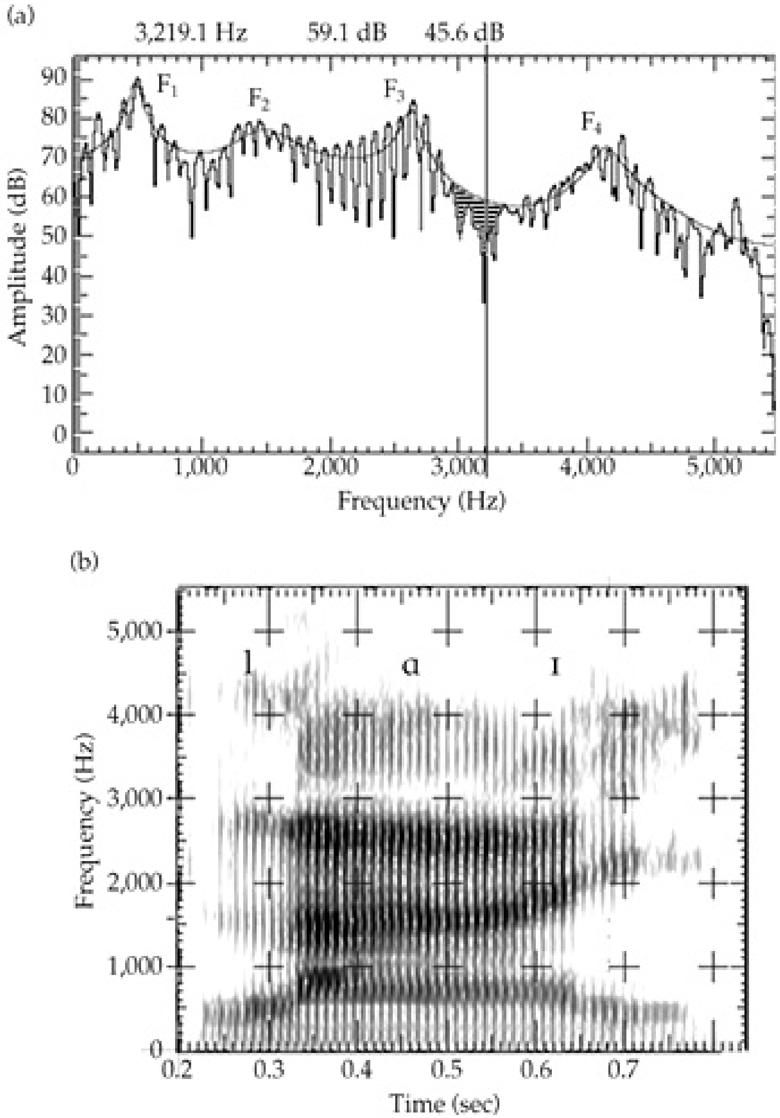
(10 cm from the glottis to the branch and a lateral outlet cavity of 6 cm)

The resonances

of the vocal tract: 531 / 1,594 / 2,656 Hz, (≈ [ə])

of the pocket: **c/4L = 2,125 Hz**

Since this is a **side cavity**, this resonance becomes **an anti-resonance** in the output.



oversimplified, of course:

the outlet cavity has a smaller diameter than does the tube from the glottis to the lateral constriction →

the frequency of the F1 is lower than it would be in a uniform tube,

syllable-final [l] is also produced with a dorsal constriction that lowers the frequency of the second formant.

Still, the tube model's basic prediction is that

the spectral "signature" of laterality **– an anti-formant near** the frequency of **F3.**

Laterals & Nasals

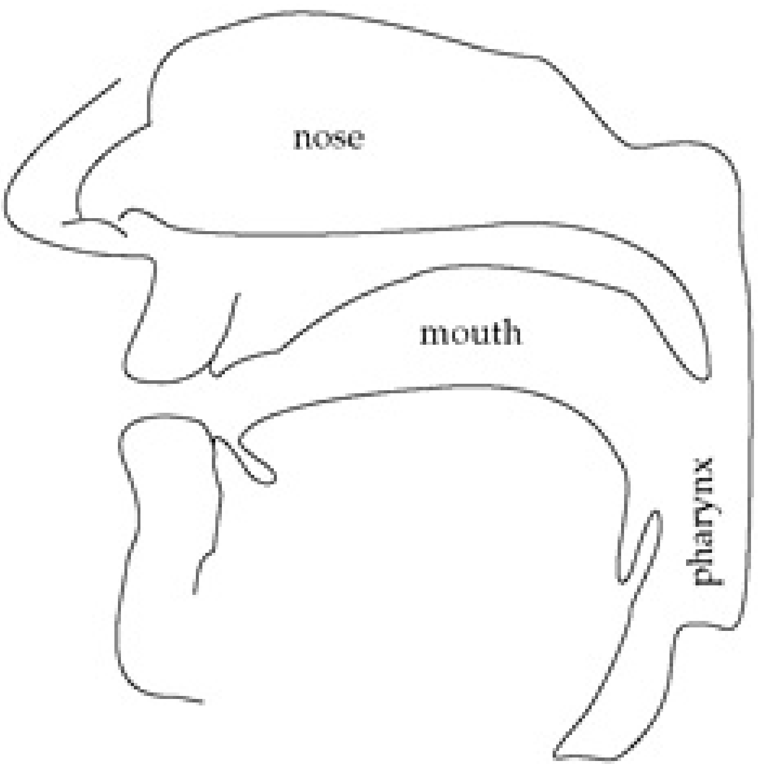
As with nasal sounds, the presence of an anti-formant causes the amplitudes of all higher formants to be reduced.

Differencies:

the **average spacing of the formants is wider in laterals** than it is in nasals ← the primary resonant tube in nasals is longer than it is in laterals.

the average spacing between formants in nasals is about 800 Hz, while in laterals it is 1,000 Hz.

Nasal vowels:



the most complicated configuration of the vocal tract: **2 resonant systems at once**:

the pharynx cavity + the mouth cavity,

the pharynx cavity + the nasal cavity.

- the pharynx + mouth system – the **oral tract** – has resonances at about 500 Hz, 1,500 Hz, and 2,500 Hz;
- the pharynx + nose system – the **nasal tract** – 400, 1,200, 2,000 Hz.

All these formants are present in the spectrum of nasalized vowels.

Of course, the resonant frequencies of the oral tract can be modified by movements of the tongue and lips, constriction of the nose at the nares.

Still, the tube model predicts that

the spectrum of a nasalized vowel will have a lot of formants.

	Nasal formants	*Oral formants*	*Anti-formants*
	(L = 21.5 cm)	(L = 17.5 cm)	(L = 12.5 cm)
F_1	407	500	680
F_2	1,221	1,500	2,040
F_3	2,035	2,500	–

Above with nasal consonants: closed mouth has resonances that become **anti-resonances** (anti-formants) in the spectrum

In nasalized vowels:

the **resonances of the nasal cavity become anti-formants**, analogous to the anti-formants in nasal consonants, but now

the **mouth is more open than the nose**, so the acoustic coupling between the mouth and the atmosphere is greater than between the nasal passage and the atmosphere.

	Nasal formants	*Oral formants*	*Anti-formants*
	(L = 21.5 cm)	(L = 17.5 cm)	(L = 12.5 cm)
F_1	407	500	680
F_2	1,221	1,500	2,040
F_3	2,035	2,500	–

The frequencies of the anti-formants in nasalized vowels are a function of **the degree of coupling between the nasal cavity and the pharynx**.

With weak coupling the anti-formant frequencies are only slightly higher than the resonances of the nasal tract (400 Hz, 1,200 Hz, 2,000 Hz), but with stronger acoustic coupling – with the **velopharyngeal port open wide** – the frequencies of the nasal anti-formants can be calculated assuming a tube that is open at one end (velopharyngeal port) and closed at the other (the nostrils):

the distance from the uvula to the nostrils is about 12.5 cm, the two lowest resonant frequencies of the nose cavity are about ($c/4L$ =) 680 and ($3c/4L$ =) 2,040 Hz.

below 1,000 Hz non-nasalized vowels have one resonance (F1), nasalized vowels have three: an oral formant (F1o), a nasal formant (F1n), and an anti-formant (A1).

- F1o depends on the positions of the lips and tongue, and
- **A1 depends on the degree of nasalization:** increases as the degree of nasal coupling increases → may cancel F1n when there is slight nasalization and cancel F1o at a higher degree.

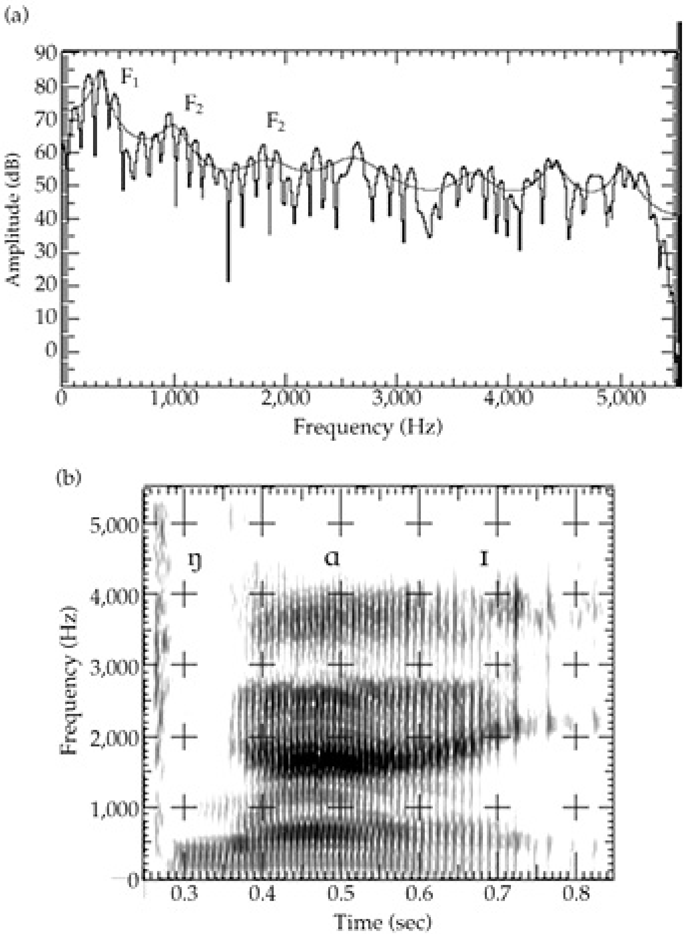
[a] with heavy nasalization can appear on a spectrogram to have a much lower F1 than normal because F1n is low (and will always be low, regardless of the vowel) and A1 is high enough to cancel some energy of F1o.

This type of complicated interplay between nasal formants, oral formants, and nasal anti-formants that occurs in the region of F1 also happens at other Fs.

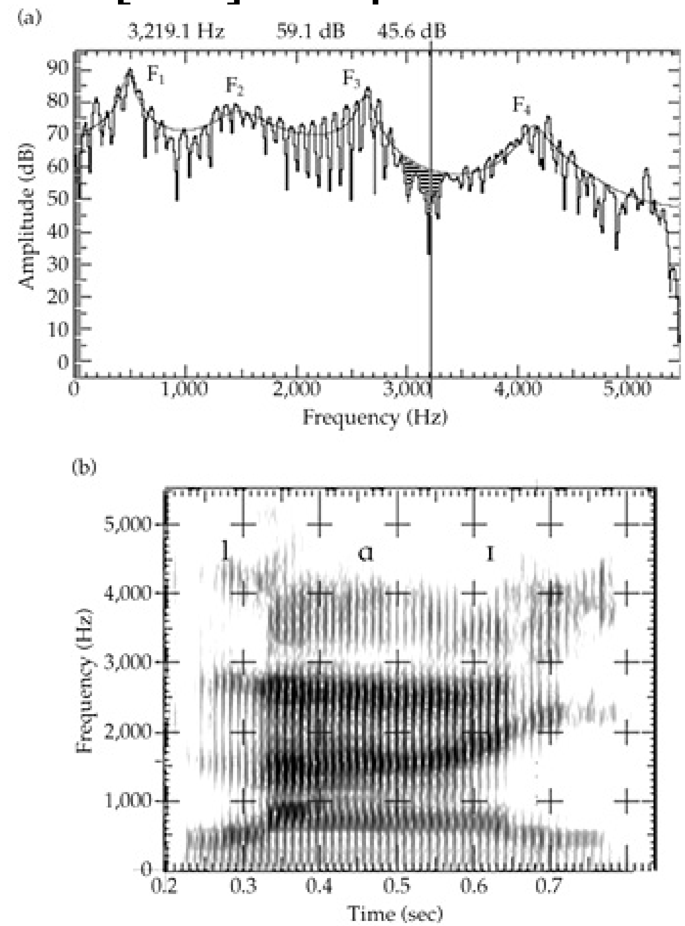
no surprise that **the number of distinctive nasal vowels in languages is usually smaller (and never larger) than the number of oral vowels.**

There is **no articulatory problem** in producing nasalized vowels, but they are **acoustically and perceptually more complex** than oral vowels.

[naːɪ] “master”



[laːɪ] “stripes”



interplay of formants and anti-formants in the F1 region of nasalized vowels:

- bandwidth of F1 is increased: usually two formants in the region, not one [na:i] vowel is very nasalized, closely spaced formants are like the F1 and F2 of [u], seem to merge into one
- the F1 of [laːɪ] is easier to identify than the F1 in the nasalized vowel

+ the amplitudes of the formants are decreased because of the presence of an anti-formant.

Phonological patterns due to the acoustic properties of vowel nasalization:

a tendency for vowel distinctions to be lost in nasal environments:

in some dialects of American English, *pen* and *pin* have merged:

nasalized high vowels are lower in the space than are their non-nasalized counterparts, and nasalized low vowels are higher in the space than are their non-nasalized counterparts

Some speculations

about the acoustic origin of vowel shift patterns.

Vowels in several languages, including English, have undergone chain shifts, in which vowels rise by one step and the high vowels break into diphthongs.

Nondistinctive vowel nasalization may play a role in initiating these chain shifts, because low vowels tend to have a certain amount of **passive nasalization** – the velum is pulled open when the tongue is lowered.

This passive nasalization may lead to a perceptual re-evaluation of the quality of low vowels because, with the nasalization, they get an additional nasal tract formant and anti-formant.

In this way a chain shift may get a start as a push chain, because of the acoustic and perceptual effects of vowel nasalization.

Based on:

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