The Acoustics of Normal and Nasal Vowel Production

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The number of investigators in the area of speech pathology has increased considerably in the last two decades. At the same time, the variety of instruments capable of performing sophisticated acoustic analyses has also increased. The result has been a rapid expansion of the literature dealing with acoustic analyses of defective speech.

One of the areas which has received considerable research interest is that of nasality. Acoustic studies have been made of functional (*8*), simulated (*5*), organic (*7*), and synthesized (*6*) nasal quality, and the results of these investigations, while varied, have indicated certain basic similarities. The purpose of this article is to discuss these similarities and to consider some of their implications.

The initial focus will be upon a consideration of the acoustics of the normal vowel (nasality is essentially a vowel-based phenomenon). With this information providing points of reference, four kinds of spectrum distortion which result from acoustic coupling of the nasal cavity will be considered. Comparative normal-nasal spectrum curves for several vowels will be derived and explanations to account for each of the prominent within-vowel differences will be offered. From a consideration of these differences, the paper will conclude with a discussion of possible approaches to the development of an objective measure of nasality.

The Acoustics of the Normal, Non-Nasal Vowel

A normal vowel is the product of three acoustic influences: a) the sounds produced by the larynx; b) the effect on these sounds of passage through the oral-pharyngeal resonances chambers; and c) a radiation effect present at the lips as the sounds leave the head. Each of these factors influences the shape of the overall vowel spectrum in a characteristic manner; each, therefore, will be considered separately.

THE LARYNGEAL SOUND SOURCE. It is well known that the "pitch" of the speaking voice is determined by fundamental frequency. The average frequency of the voice of an adult American male is 132 Hz, of an adult female, 224 Hz, and of a child, 265 Hz (*10*).

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High-speed motion picture studies of the action of the vocal folds during phonation reveal a highly complex pattern of movements during each vibratory cycle. The acoustic manifestation of this movement pattern is the super-imposition of a series of high-frequency vibrations upon the basic fundamental frequency. These high-frequency vibrations are called the harmonics or overtones of the fundamental frequency. Figure 1 shows the fundamental frequency and pattern of harmonics produced typically during one vibratory cycle of the vocal folds of an adult male. The portrayal is called the 'source spectrum' since it shows the frequency location and relative intensity (in decibels) of all tones generated at the larynx. The fundamental frequency is the strongest component in the spectrum and the harmonics are multiples of the fundamental frequency. In Figure 1, since the fundamental frequency is located at 125 Hz, the second harmonic is at 250 Hz, the third at 375 Hz, the fourth at 500 Hz, and so on. Above 250 Hz, the intensity of the harmonics decreases at an approximately constant rate of 12 decibels per octave. Since an octave is a doubling of frequency, it may be noted, for example, that the fourth harmonic (500 Hz) is 12 decibels weaker than the second (250 Hz), and the eighth (1000 Hz) is 12 decibels weaker than the fourth (500 Hz). The curve connecting the tops of the harmonics and the fundamental frequency is called the 'envelope' of the spectrum. Acoustic spectra are frequently indicated only by their envelopes.

The tones generated at the larynx are the 'raw material' from which the vowels are fashioned. The supra-laryngeal structures create the various vowel spectra by selectively altering the intensity of the individual laryngeal harmonics. This is accomplished through the process known as resonance.

Resonance and the Oral-Pharyngeal Cavity. When a high-quality tuning fork is struck, it vibrates at one frequency and at no other. The frequency of vibration is determined by the physical properties of the tuning fork and is not affected by the force or rate with which the fork is struck. The tuning fork is said to have one 'natural frequency of vibration' or 'resonant frequency'.

Consider a tuning fork designed to vibrate at a frequency of 500 Hz. When struck, the prongs of the tuning fork execute 500 double vibrations each second. In a double vibration the prongs: a) move away from the rest position to a position of maximum excursion in one direction, b) return past the rest position and move to a position of maximum excursion in the opposite direction, and c) return to the original rest position (as in Figure 2A). If a pen is attached to one of the prongs of the tuning fork and a tracing made on a moving roll of paper, one cycle must include maximum prong excursions in two directions (thus the term, double vibration). Figure 2B shows the response of a second and identical tuning fork struck with greater force. The frequency of vibration is the same, but the dis-

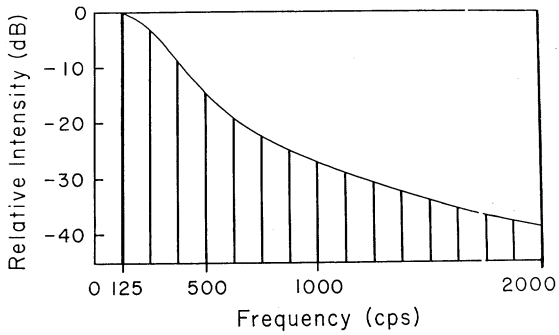


FIGURE 1. The fundamental frequency and pattern of harmonics produced at the vocal folds during one vibratory cycle (adult male).

tance of maximum excursion of the prongs from the rest position is greater. Thus, the 'amplitude of vibration' of the second tuning fork is larger. The use of a sound level meter would reveal a higher decibel reading from the second tuning fork, and, of course, the sound from it would be louder.

Figure 3 shows the 500 Hz tuning fork suspended on a string and in vibration. Near it are five tuning forks, similarly suspended, and designed to vibrate, when struck, at the following frequencies: 490, 500, 510, 520, and 530 Hz. Observe that while the tuning forks for which the resonant frequencies are not 500 Hz remain quiet, the 500 Hz tuning fork has begun to vibrate. This movement is called 'forced vibration' or 'forced resonance'.

Figure 4 shows a portion of one prong from each of the two 500 Hz tuning forks. Tuning fork A had originally been set into vibration by being struck sharply against a hard object. Between the two prongs, and shown in schematic form, are molecules of air. This air system acts as the medium through which forks A and B become coupled. As fork A vibrates, it alternately compresses and rarifies the air molecules about it. Each wave of compression strikes fork B, imparting a portion of its energy to it. As fork B is struck, it begins to vibrate at its resonant frequency. Since this frequency is the same as that of fork A, the next wave of compression arrives at fork B at precisely the correct moment to impart its energy to it and increase its amplitude of vibration.

To visualize this more clearly, imagine child B in a swing. At first, the swing is motionless and the situation is analogous to the originally motionless state of fork B. Child A now pushes child B. Child A is, of course, fork A, and the push represents the first wave of compression. Observe that child B and the swing represent a pendulum and as such move back and forth (vibrate) at one natural frequency. Child A starts this vibration with one push; however, the vibration will gradually decay unless another push is forthcoming. If the rate of vibration is one cycle per second, and child A exerts a push at that rate and it is applied at the height of the backswing, the amplitude or excursion of the swing will become progressively

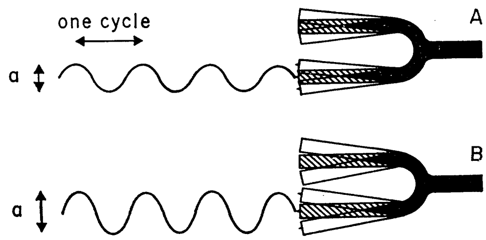
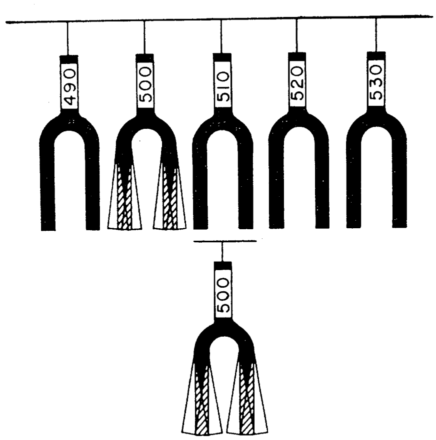


FIGURE 2. Two tuning forks in vibration. Tuning fork B has been struck with greater amplitude. A small pen, attached to one prong of each tuning fork, draws the resulting wave forms on a roll of moving paper.



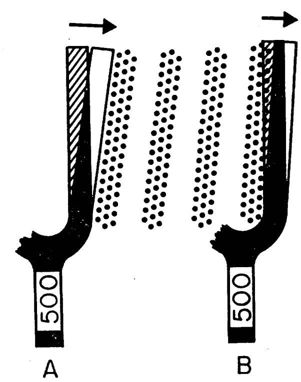


FIGURE 3 (left). A demonstration of forced resonance. The isolated 500 Hz tuning fork, when struck and placed near the originally quiet 500 Hz tuning fork, evokes a forced-resonance response from it. The other tuning forks remain motionless.

FIGURE 4 (right). Waves of air compression between two tuning forks showing an originally struck tuning fork A evoking, through the medium of air, a forced resonance response from an originally motionless tuning fork B.

greater. When this occurs we may say that child A, through the medium of his push, has caused child B to resonate.

Consider what would happen, however, if child A decided to push child B not once each second, but at some fractional rate. The push now would not always be at the height of the backswing. Instead it would occur at any point along the swing and thus in some instances would be in direct opposition to the direction of its movement. The result would be that appreciable movements would be prevented from developing and that, for all practical purposes, child B would remain motionless.

Figure 3 may now be interpreted more fully. Of the five originally motionless tuning forks, only the 500 Hz tuning fork will move because only its vibrations will be in synchrony with the impulses arriving from the originally-struck tuning fork. The remaining four tuning forks will remain effectively motionless because cancellation effects will be engendered by the interaction of their different resonant frequencies with the 500 Hz frequency of the originally-struck tuning fork.

The example of the tuning forks and the child's swing demonstrates that acoustic resonance is a mechanical process which enables frequency energy emitted from one system to be evoked and amplified in another. We shall now proceed to discuss the mechanism of resonance involved in the production of vowels. Specifically, we shall consider which of the various frequencies emitted from the laryngeal system are evoked and amplified by the oral-pharyngeal system. To do this, we shall first have to consider the aspects of resonance of a mechanical system whose acoustic function is similar to that of the vocal tract.

Figure 5 shows the spectrum response of a hypothetical multi-frequency tuning fork. Observe that it resonates at every fifty-cycle interval frequency between 750 and 1250 Hz. The 1000 Hz component has the greatest amplitude, and the remaining frequencies show progressively weaker amplitudes as they become more remote, in frequency, from the 1000 Hz tone.

It will be recalled that if a tuning fork produces a 500 Hz tone when struck, it is also capable of being sent into a forced resonance by another vibrating 500 Hz tuning fork placed near it. The same behavior applies to the forced-resonance response of the multi-frequency tuning fork.

Consider eleven tuning forks, each designed to produce a single, separate frequency at fifty-cycle intervals between 750 and 1250 Hz. Each of these tuning forks is struck so that it vibrates with an identical amplitude and each is placed near the multi-frequency tuning fork. When the resultant behavior of this tuning fork is observed, it is discovered that each of the eleven single-frequency tuning forks has evoked a forced resonance response from it, and that the magnitudes of these responses are proportional

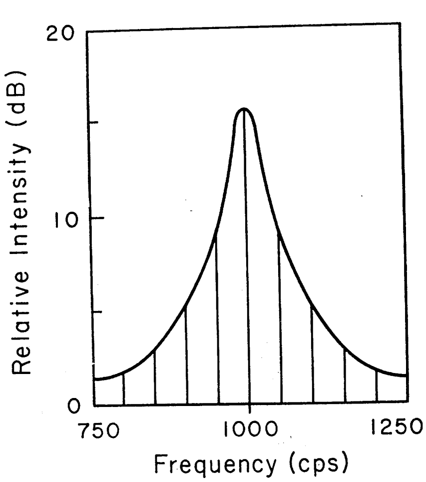


FIGURE 5. The spectrum response of a hypothetical multi-frequency tuning fork.

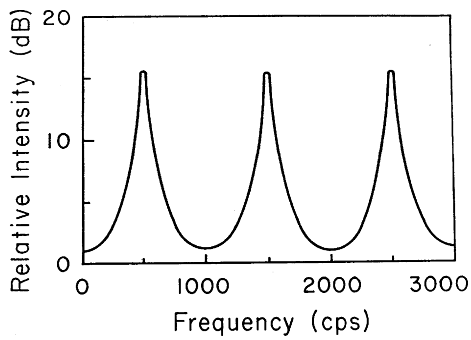


FIGURE 6. The resonances of a tube which is 17 cm in length and has a constant cross-sectional area.

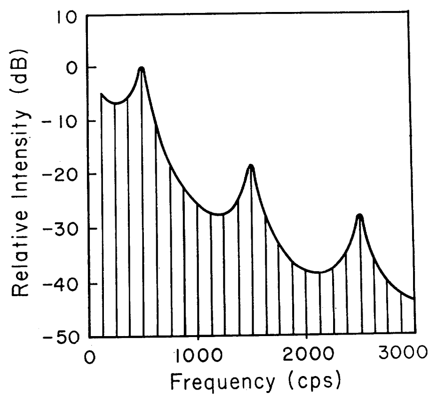


FIGURE 7. The resonances of a 17 cm long tube with a constant cross-sectional area when driven by a laryngeal source spectrum (drop-off −12 dB/octave above 250 Hz).

to the pattern of relative frequency amplitudes shown in Figure 5. Thus the tone from the 750 Hz tuning fork is resonated, but not to the same magnitude as the one from the 850 Hz tuning fork, even though both were present originally with equal amplitude.

An air-filled tube resonates in a fashion somewhat like that of a multi-frequency tuning fork. Consider a tube seventeen centimeters in length (the average distance from the vocal chords to the lips in an adult male) and of a uniform cross-sectional area. The column of air enclosed within this tube will resonate, when struck, in the manner shown in Figure 6. Note that only the envelope of the spectrum is given. This means that the resonator produces and is therefore capable of responding to every tone within the frequency range of the curve at the relative intensities shown. Observe that there are three major resonance peaks in the spectrum. As we shall see later, peaks of this type are present in all vowels, and their relative frequency position and amplitude are the keys to vowel identity. The response shown in Figure 6 is that of a resonator to tones of equal amplitude. It will be recalled that the tones from the laryngeal source are not of equal amplitude, but decrease (above 250 Hz) at the rate of 12 dB/octave. Figure 7 shows a redrawing of Figure 6 to account for this characteristic of the source spectrum. The harmonics of a fundamental frequency of 125 Hz are shown. The second and third resonance peaks are now markedly reduced in intensity. This is a common characteristic of vowel spectra.

In considering vowels, the resonance peaks are called formants (labeled F_1, F_2, etc., from low to high frequency). We shall use this term as we examine the resonance patterns of vowels. Four vowels will be considered: /i/ as in b*ee*t, /u/ as in b*oo*t, /æ/ as in b*a*t, and /ɑ/ as in p*o*t. These vowels are chosen because they represent extremes in tongue position (see Figure 8). The tongue is high (in the mouth) for /i/ and /u/ and low for /æ/ and /ɑ/; the tongue also bulges toward the front of the mouth for /i/ and /æ/ and toward the rear of the mouth for /u/ and /ɑ/. Thus /i/ is called a high-front vowel; /u/, a high-back vowel; /æ/, a low-front vowel; and /ɑ/, a low-back vowel.

These four different tongue postures affect the resonances or formants of the oral-pharyngeal cavity in characteristic ways. Figures 9 through 12 show the spectrum response of the cavity for each of the vowels. The formant data are averages taken from thirty-three adult males (*10*); the effect of the source spectrum drop-off (−12 dB/octave above 250 Hz) is included. It may be seen that there is clearly a different three-formant pattern for each vowel. While there is some variation among speakers for the formant patterns of a particular vowel, this variation is small (males, females and children considered separately) and the average pattern values obtained during isolated vowel productions may be said to define the vowels to a close approximation.

The formant center frequencies (the peaks of the resonances) are given

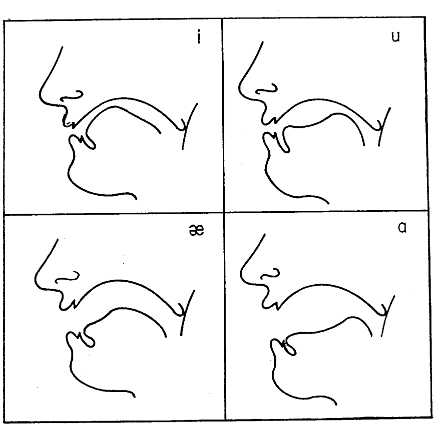
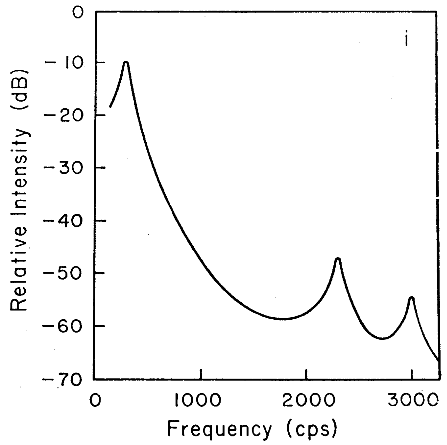


FIGURE 8. Typical tongue positions required for the production of the four vowels: /i/, /u/, /æ/, and /a/.



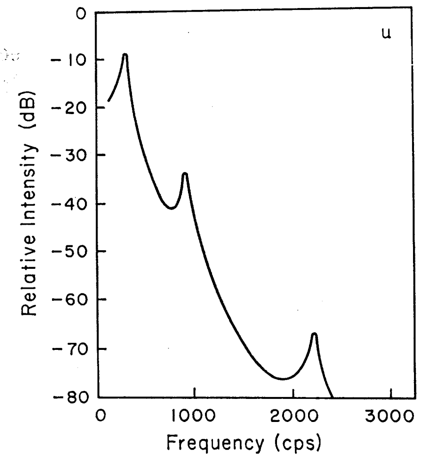
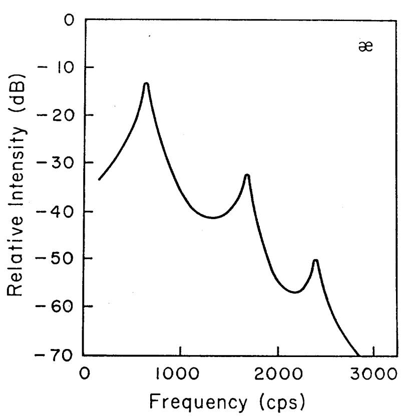


FIGURE 9. The formants of the vowel /i/. The effect of the source spectrum drop-off (—12 dB/octave above 250 Hz) is included.

FIGURE 10. The formants of the vowel /u/. The effect of the source spectrum drop-off (—12 dB/octave above 250 Hz) is included.



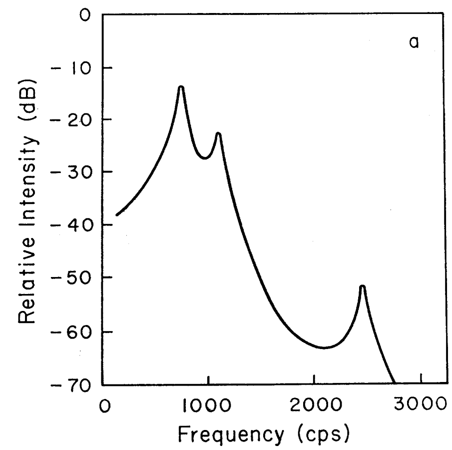


FIGURE 11. The formants of the vowel /æ/. The effect of the source spectrum drop-off (—12 dB/octave above 250 Hz) is included.

FIGURE 12. The formants of the vowel /a/. The effect of the source spectrum drop-off (—12 dB/octave above 250 Hz) is included.

by the dimensions of the oral-pharyngeal cavity. The frequency of a particular harmonic, on the other hand, is given by the fundamental frequency. Figure 13 shows the mutual independence of these two sets of values. The response spectrum (up to 1500 Hz) is shown for the vowel /ɑ/ (as in pot), spoken by one individual at two fundamental frequencies: 125 and 160 Hz. The shape of the spectrum envelope (given by the dimensions of the oral-pharyngeal cavity) remains constant, while the spacing and frequency position of the laryngeal harmonics vary with the fundamental frequency.

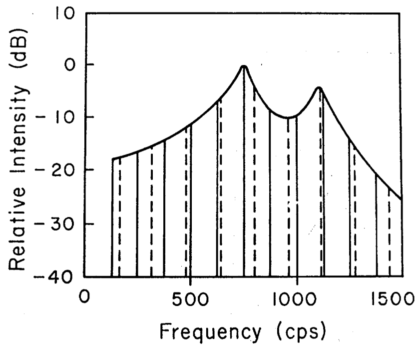


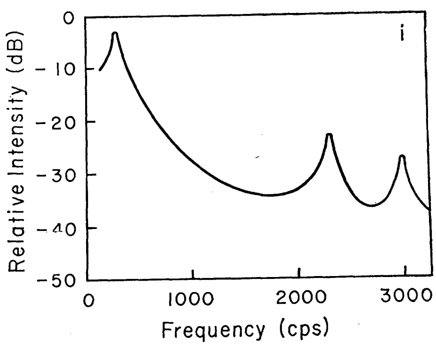
FIGURE 13. The first two formants for the vowel /a/ together with the harmonics of two fundamental frequencies (125 Hz and 160 Hz). The formant center frequencies for /a/ (750 Hz and 1095 Hz) are determined by the shape of the vocal tract and are not influenced by the changes in fundamental frequency.

One other observation may be made: unlike the source spectrum, the fundamental frequency is not the most intense component in the vowel spectrum. While in Figure 13, both F1 and F2 are more intense than the fundamental frequency, the more general statement is that the first formant is the most intense component in the spectra of vowels.

THE RADIATION IMPEDANCE FACTOR. In our discussion so far we have indicated how the various laryngeal harmonics are affected by passage through the oral-pharyngeal cavity. We must now examine the effect created by passage of these sounds from the oral-pharyngeal cavity to the environment outside of the head. This effect (created at the lips) is called the radiation impedance factor.

For our purposes, impedance may be defined simply as the resistance to the transfer of acoustic energy from one environment or system to another. The oral-pharyngeal cavity is said to have a characteristic output impedance (or resistance to the emission of sound energy) which varies with frequency; the air environment outside of the head is known to have a characteristic input impedance (or resistance to the acceptance of sound energy) which also varies with frequency. When the output impedance of the oral-pharyngeal cavity matches the input impedance of the air system outside of the head, a 'lossless' transfer of energy takes place. However, since the acoustic impedance values for both systems vary with frequency, such matches rarely occur and consequently losses almost invariably accompany sound-energy transfers.

These energy losses have been studied and have been shown to affect the low frequencies more than the high. Specifically, the radiation impedance factor for vowels has been shown to be of the order of +6dB/octave throughout the frequency range of interest (100 to 4000 Hz). Figures 14 through 17 show a redrawing of the curves of Figures 9 through 12 to account for the radiation impedance factor. Note that the second and third formants are now somewhat more intense relative to the first.



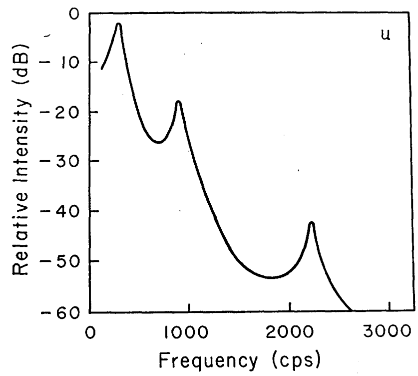


FIGURE 14. The overall spectrum of /i/. (source spectrum plus formant structure plus radiation impedance factor).

FIGURE 15. The overall spectrum of /u/. (source spectrum plus formant structure plus radiation impedance factor).

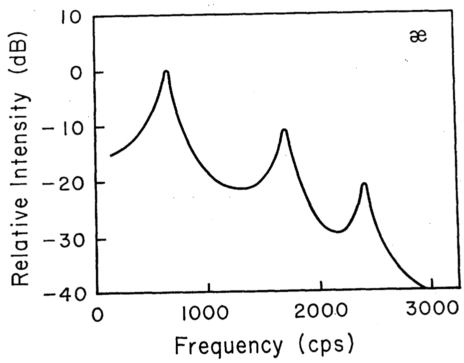


FIGURE 16. The overall spectrum of /æ/. (source spectrum plus formant structure plus radiation impedance factor).

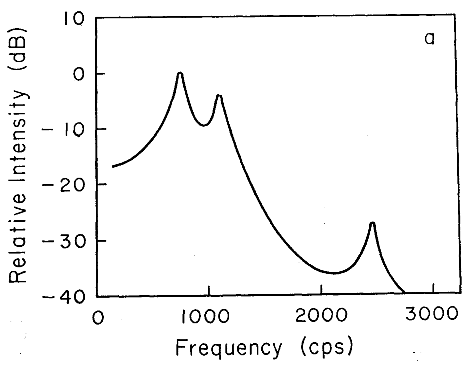
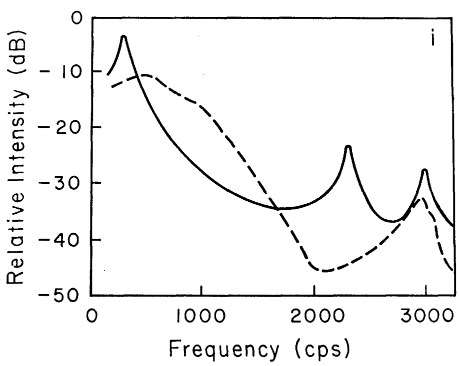


FIGURE 17. The overall spectrum of /a/. (source spectrum plus formant structure plus radiation impedance factor).



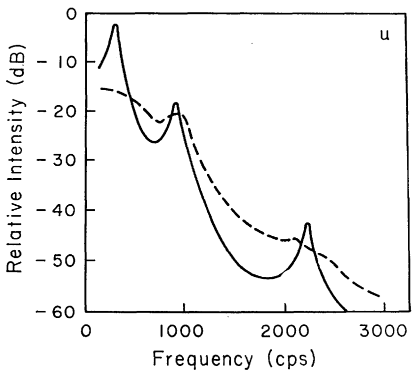


FIGURE 18. Overall spectra of a normal and a nasal production of /i/.
FIGURE 19. Overall spectra of a normal and a nasal production of /u/.

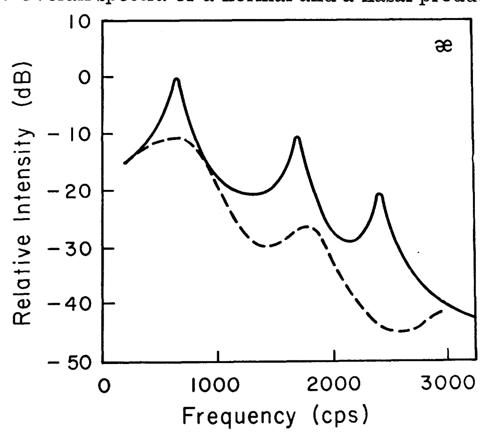


FIGURE 20. Overall spectra of a normal and a nasal production of /æ/.

The set of curves referred to above constitute what may be considered to be the normal spectrum patterns for the four vowels to be studied in this paper. We shall now examine some of the ways in which the shapes of these curves are altered by the presence of conditions of acoustic coupling between the nasal and oral-pharyngeal cavities.

Features of the Nasal Spectrum

To discuss the acoustic features found commonly in the spectra of nasal vowels we shall refer to the set of curves shown in Figures 18 through 21. Responses for the vowels /i/, /u/, /æ/, and /ɑ/ are indicated for two conditions of velopharyngeal closure: total, and with a patency of 3.7 cm². The nasal curves are adapted and modified from results obtained through the use of an electronic speech synthesizer (*6*).

There are four features of importance in nasal spectra. The first of these, and by far the most frequently noted, is the reduction in the intensity of the first formant (*4*, *6*, *3*, *8*, *7*). This effect may be seen for each of the

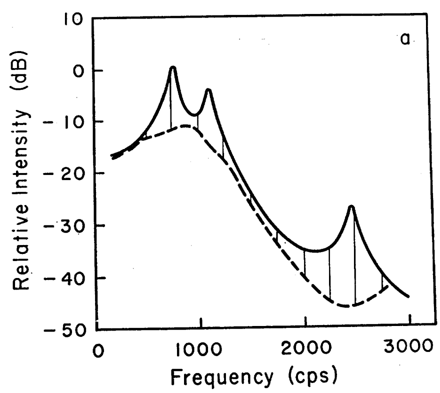


FIGURE 21. Overall spectra of a normal and a nasal production of /a/. The harmonics of a fundamental frequency of 125 Hz are shown.

vowels. The magnitude of the reductions range from 7 dB for /i/ to 13 dB for /u/. The effect is thought to be largely the result of the addition of the damping characteristics of the nasal cavity wall surfaces.

The second acoustic feature commonly reported is the presence of an anti-resonance within the vowel spectrum (*3*, *5*, *7*). An anti-resonance, or sharp drop in the intensity of a portion of the spectrum, is an acoustic phenomenon which occurs when a tube (such as the oral-pharyngeal cavity) is coupled to a side-branching tube (such as the nasal cavity). An anti-resonance may be seen for /ɑ/ at 2400 Hz, where it has eliminated the third formant; another may be seen for /i/ at 2100 Hz, where it has eliminated the second formant; and still another may be seen for /æ/ at 1400 Hz, where it has sharply reduced the intensity of the second formant. The frequency location and magnitude of energy reduction of an anti-resonance vary with the vowel, the speaker, and the size of the velopharyngeal opening.

The third feature of the nasal spectrum is the presence of reinforced harmonics at frequencies where energy is not normally expected (*2*, *3*, *5*, *6*, *11*). These reinforced frequencies may be considered the resonances of the nasal cavity. Extra-resonances may be seen between the first and second formants of /i/ in Figure 18, and between the first, second and third formants of /u/ in Figure 19. Like the anti-resonances, the frequency positions and relative amplitudes of extra-resonances vary with the vowel, the speaker, and the size of the velopharyngeal opening.

The fourth feature of the nasal spectrum is a shift in the relative frequency positions of the formants (*3*, *5*, *6*, *7*, *11*). A shift of this kind is expected since coupling of the nasal cavity effectively changes the dimensions of the oral-pharyngeal cavity. Figures 18 through 21 show that each of the vowel formants is shifted in frequency under the nasal coupling condition.

Other features of the nasal spectrum have been reported, but they occur too sporadically or too unpredictably, or both, to merit serious consideration. In general, it is safe to say that whenever an isolated vowel is perceived as nasal, its spectrum will show at least one of the four features just described.

Observe that since the larynx is not considered to function differently under the nasal coupling condition (*3*), the frequency positions of the harmonics of nasal vowels may be expected to be the same as those of normal vowels. The basic difference, then, between a normal and a nasal vowel is to be found in a consideration of harmonic intensities, not harmonic frequencies. This fact is seen as potentially important to the clinician working with the problem of nasality since it implies that an objective measure of the disorder can be developed by means of some form of harmonic-intensity-measurement-procedure.

Let us consider this matter further. Observe that one way of specifying the difference between the normal and nasal versions of a vowel (assuming similar if not identical fundamental frequencies) is simply to calculate the difference in dB for each harmonic and then add them to obtain a total difference. The resulting measure, called a spectrum difference score (SDS), indicates the extent to which the nasal coupling has affected the overall spectrum. Assuming a relationship between extent of vowel spectrum deviation and perceived nasality, the SDS would be seen as a possible objective measure of nasality.

Let us consider another possibility. Research has indicated and Figures 18 through 21 show that many aspects of the spectrum are changed by nasal coupling. For example, in Figure 18, all four of the nasal spectrum features discussed are present. The question is raised as to whether all of these features are equally important to the perception of nasality. Although there have been several attempts to answer this question, the results have been far from conclusive (*3*, *5*, *6*). One possible approach, and one which does not seem to have been attempted, is to selectively alter the intensity of various portions of the spectrum of a nasal vowel while studying the effect of such manipulation upon judges' ratings of severity.

Figure 22 shows a block diagram of the instrumentation which might be used for this purpose. The vowel /i/ is recorded at a fundamental frequency of 250 Hz and is placed on a tape-loop playback. The playback feeds the repeated signal to an audio analyzer which consists of a bank of band-pass acoustic filters. A band-pass filter is an electronic device which permits a selected group of adjacent frequencies to pass through its circuitry, while blocking the passage of all others. The frequency location and the width of the band in such a filter is variable. In this instance the analyzing filters have band widths of 100 cycles.

Let us examine the first band-pass filter. It is designed to pass frequencies only between 200 and 300 Hz. When the vowel signal from the playback loop is presented to it, only one frequency, the 250 Hz fundamental, is passed; all other frequencies are rejected because they fall outside the pass

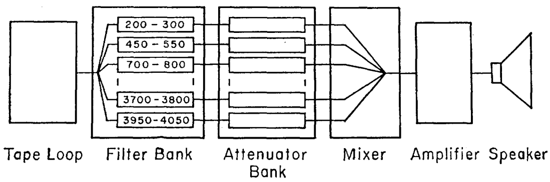


FIGURE 22. Spectrum-shaping instrumentation for use in listener-judgment studies of the acoustic correlates of nasality.

band. If we examine the frequency location of the other filters we see that each is designed to pass a different vowel harmonic. Thus the filter bank separates and isolates each of the frequency components of the vowel.

The output from each filter is sent to a separate attenuator which controls its intensity in one-decibel steps. The outputs from all of the attenuators are then combined, amplified, and sent to a loudspeaker. The attenuators permit the selective alteration of the intensity of the fundamental frequency and of each of the harmonics. In other words, the total instrument permits the shaping of the spectrum of any vowel as well as providing an immediate auditory presentation (via loudspeaker) of the effect the shaping has produced.

It will be recalled that the basic difference between a normal and a nasal vowel lies in the intensities of the harmonics. The instrument described here enables one to manipulate the intensity of each of the harmonics independently and to study the effect of such manipulation upon the perception of nasality. Thus, for example, Figure 21 shows that the difference between the nasal and normal versions of the vowel /ɑ/ can be eliminated by raising the intensities of harmonics 2 through 11 of the nasal vowel until each is equal in intensity to its counterpart in the normal version of the vowel. As each harmonic is adjusted, its contribution to the reduction of perceived nasality can be evaluated by listening to the combined attenuator output at the loudspeaker. In this fashion, it is possible to determine which of the spectral features is most important to the perception of nasality.

Let us consider still another possibility. The nasal curves for /æ/ and /ɑ/ are consistently weaker than their corresponding normal curves, while the nasal curves for /i/ and /u/ exceed the amplitude of their corresponding normal curves at various points along the spectrum (Figures 18 through 21). This excess of energy, which was discussed earlier under the heading 'extra-resonances' calls attention to the possible importance of considering the direction of the amplitude changes which accompany nasality. One might suggest, for example, that a nasal spectrum which is consistently weaker than its normal counterpart is less distorted than a nasal spectrum (with an identical spectrum difference score) which is alternately weaker and stronger. The nasal versions of /i/ and /u/ show greater distortion (as just defined) than the nasal versions of /æ/ and /ɑ/.

This finding is typical and is due in part to the wide spacing between the formants of the high vowels. The fact that /i/ and /u/ are generally perceived as more nasal than /æ/ and /ɑ/ (*6*, *12*) suggests the possibility that direction of amplitude change may be a factor worth considering in the development of an objective inter-vowel measure of nasality.

Comments

The number of possible approaches to the development of an objective measure of nasality is large. The ones described in this paper are offered not only because they seem to hold likely promise for a resolution of this problem, but also because the underlying rationale for each emerges from the consideration of normal and nasal vowel acoustics. It is for this reason that such a consideration is felt to be important.

It must be pointed out that the information presented in this paper is merely a general first approximation. 'Real' speech is unfortunately not quite as straightforward as the descriptions offered would lead one to believe. For example, the source spectrum may, in reality, drop off at any rate between 8 and 16 dB/octave (*1*), and may have anti-resonances present within it (*9*). However the 12 dB/octave factor adequately represents an average fall-off value, and the majority of sources do not possess anti-resonances. Recognizing that the purpose of this paper is to present a general framework for future thought on the subject of the acoustics of nasality, it is considered reasonable to neglect these sources of variability. Subsequent reports will pursue some of these areas in greater detail.

Summary

The acoustics of normal and nasal vowels is discussed. Starting with a consideration of the factors responsible for the normal vowel spectrum, four basic kinds of spectrum distortion associated with perceived nasality are considered. Comparative normal-nasal spectrum envelopes are derived for each of several vowels, and explanations are offered to account for each of the prominent within-vowel differences. These differences form the basis for a discussion of objective measures of nasality.

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