The Acoustics of Nasalized Speech

JAMES F. CURTIS, Ph.D.
Iowa City, Iowa

In his classic book, *The Science of Musical Sounds,* Dayton C. Miller (*12*) began his chapter on "Physical Characteristics of Vowels" with the following statement: "The vowels have been more extensively investigated than any other subject connected with speech".

If Miller could make that statement, some 45 years ago, what might be said today? In the 1960s we look on his work as that of a pioneer, probing into a whole new era of acoustic investigation of speech. Even so, almost half a century later, there remain many unanswered questions.

The acoustic study of nasalized speech has a much shorter history than the study of vowels, and a correspondingly more limited literature. There have nevertheless been a number of attempts to search out and to describe the characteristic changes in the acoustic signals of speech, especially vowels, that result when speech is nasalized. A detailed review of these studies is outside the scope of the present discussion. However, one generalization that can be made from the acoustic studies of nasalization is of central interest; that is, that the data do not provide the basis for a simple, unequivocal, and definitive description of the acoustical effects of nasalization. On the contrary, variability and inconsistency appear to be the rule. The results reported by one investigator are frequently not corroborated by the data from another study, and the changes in the acoustic signal that appear to characterize nasal resonance under one set of conditions cannot be found for other subjects or for a different sample of speech. Thus, Dickson (*3*) stated that his study "... emphasizes the variability in the acoustic characteristics of nasality from person to person" and he adds that "It would seem that nasality can be specified in many ways depending upon the specific configurations of the oral, pharyngeal and nasal cavities".

In a later study, Kent (*9*) varied the coupling between oral and nasal

---

Dr. Curtis is Professor, Department of Speech Pathology and Audiology, The University of Iowa.

This paper was presented at the 1969 International Congress on Cleft Palate, Houston.

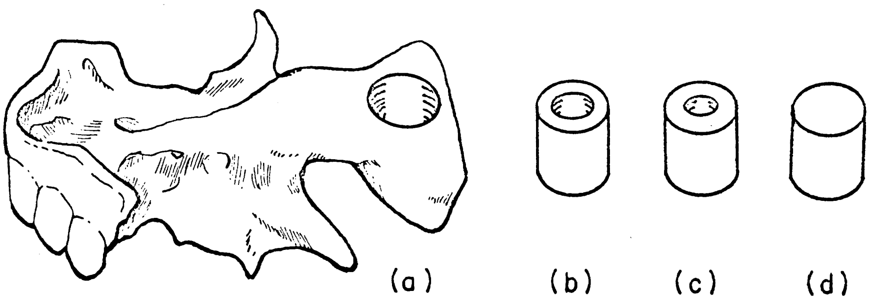


FIGURE 1. Example of specially prepared obturator for experimentally varying the coupling between the oral and nasal branches of the vocal cavity transmission system. After Kent (*9*).

portions of the vocal tract and analyzed the spectral characteristics of vowels produced with different degrees of coupling. To control the variation in coupling, she utilized cleft palate subjects who had been successfully treated with obturators. The coupling was varied by providing several diameters of holes through the posterior portions of specially constructed obturators in the manner shown in Figure 1. Although Kent was able to show that this variation in coupling was accompanied by the expected increase in *nasality*, as perceived and rated by listeners, she could not demonstrate an associated, consistent variation in spectral characteristics.

Thus, we are presented with a state of affairs which appears to be quite confusing and highly unsatisfactory. At first glance, nasalization would seem to be a relatively simple phenomenon. Physiologically, it is related to a simple valving action which controls the coupling between the pharyngeal-oral portion of the vocal tract and the nasal cavities. Since the nasal cavities cannot be varied in shape and volume, there has been a tendency to assume that they have relatively constant characteristics as an acoustic resonator or transmission system. Accordingly, it has seemed reasonable to suppose that changing this coupling should result in relatively simple and predictable variations in the acoustic output of the system. To compound the assumption that nasalization is a relatively simple matter, the perceived change in the quality of speech, usually termed *nasality*, seems quite clear and predictable. That is, there seems to be a perceptual quality that has been called *nasality* which one hears as being qualitatively very homogeneous, irrespective of variations in associated conditions, such as different speakers, different vowels, variations in pitch, et cetera.

However, attempts to analyze the acoustical signal which mediates between the physiological event and the perception have failed to yield the simple type of variation in signal characteristics that the foregoing analysis would lead one to expect. How can this be so?

Let us look first at the relationship between physiological events and acoustical effects. Intuitively, it seems reasonable to assume that a straight-forward, causal relationship must exist between vocal tract modification and acoustical variations. In fact, no other assumption makes sense. The acoustical signal is generated by the physiological events and must, therefore, be determined by them. Beyond this, however, the specific nature of the acoustic changes that we expect as a result of specified variations in physiological events depends on our assumptions concerning the particular nature of these cause and effect relations; that is to say, on our understanding of the relevant theory.

At the time when significant experimental work seeking to develop a more exact acoustical description of nasalized speech was getting underway, in the decade of the 1930s, our knowledge of the acoustic theory of speech production was still in a relatively undeveloped state. Nevertheless, such theoretical notions as were then current played an important role in shaping the character of this research—for example, in the choice of dimensions to be observed or measured, in the design of experiments and the control of experimental conditions, and in the interpretation of data. I think it is fair to say that a considerable heritage from the theoretical concepts of that time has persisted to the present and still influences our thinking, especially concerning the acoustic effects to be expected from nasalization. It should be useful therefore to give some attention to an examination of these theoretical ideas, how they came to be developed, what their implications are, and how they are to be evaluated in the light of current knowledge. Because the theoretical concepts with which we are concerned are an offshoot of the acoustic theory of vowels, we shall necessarily give some attention to the development of vowel theory.

It has long been known that the spectral distributions of vowels are characterized by frequency regions in which the sound energy is more intense than in adjacent portions of the spectrum. These regions of energy concentration have been believed by most investigators, from D. C. Miller (*12*) on, to be the result of selective transmission of the vocal cavity system. Figure 2 illustrates this point. At the top of the figure is a graph representing an approximation of the frequency spectrum of the laryngeal tone which constitutes the input to the vocal cavities. Down the left side of the figure are mid-sagittal, cross-sectional views of the vocal cavity configurations for three different vowels. On the right are the corresponding output spectra for the three vowels. The transformation which converts the vocal cord spectrum, shown at the top, to the particular spectrum associated with each vowel, as shown on the right, results from the resonant characteristics of the particular vocal cavity shape for that vowel.

The same relations may be stated symbolically as in the following equations:

$$P(f)v_1 = S(f) \cdot T(f)v_1 \tag{1}$$

$$P(f)v_2 = S(f) \cdot T(f)v_2 \tag{2}$$

$$P(f)v_n = S(f) \cdot T(f)v_n \tag{3}$$

$P(f)v_1$, $P(f)v_2$, and $P(f)v_n$ represent frequency spectra of the output acoustic pressure signals corresponding to the vowels V_1, V_2, and V_n. $S(f)$ represents the frequency spectrum of the vocal cavity input signal that results from the glottal vibration. It should be noted that it is assumed to be constant; that is, that it does not change as the vowel is varied.

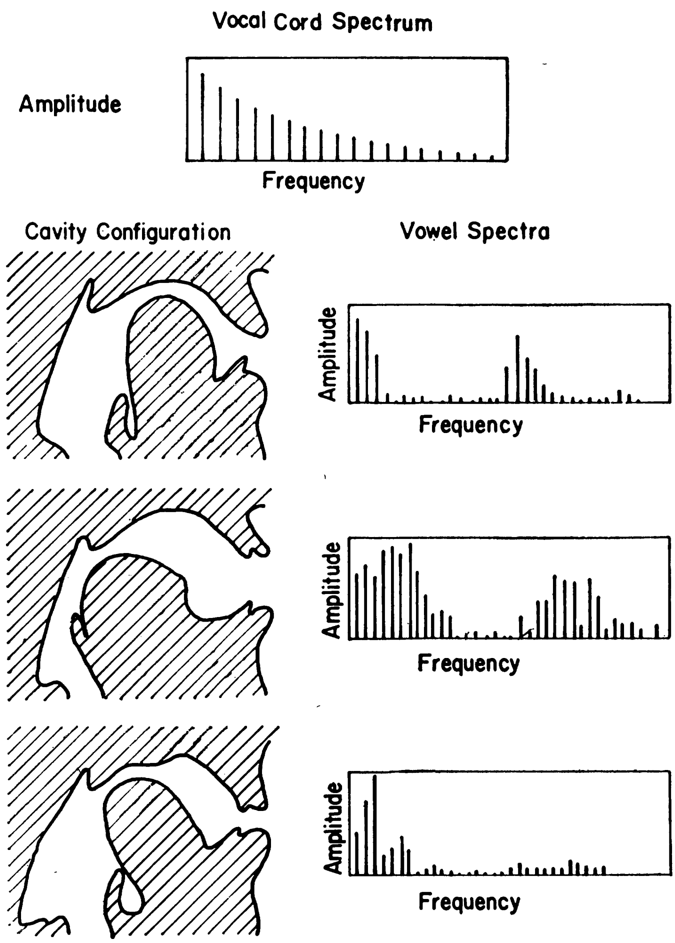


FIGURE 2. Illustrating that the spectral distribution of energy in a vowel is primarily dependent on the vocal cavity configuration for the particular vowel. Each of the acoustic spectra shown along the right side of the figure represents the output of the vocal cavity configuration paired with it when the cavities are, in each case, excited by a constant laryngeal tone whose spectrum is shown at the top of the figure.

$T(f)v_2$, $T(f)v_2$, and $T(f)v_n$ are the vocal cavity transfer functions, or transmission characteristics, which operate on $S(f)$ to produce the output spectra $P(f)v_1$, $P(f)v_2$, and $P(f)v_n$, respectively.

As previously indicated, the ideas summarized in Figure 2 and the foregoing equations are the rudiments of vowel theory that have been known and generally accepted for a long time. Any such theory must be considered to be very primitive, however, until it can state with some exactness the relationship between the cavity dimensions that are characteristic for a particular vowel and the transmission characteristic that is associated with it. That is to say, the theory must be able to specify the relation between vocal cavity dimensions (lengths, cross-sectional areas, volumes, et cetera) and the transmission characteristics of the vocal tract, expecially the resonant and antiresonant modes of the cavity system.

Prior to 1950, a number of attempts were made to solve this problem by assuming that the oral-pharyngeal portion of the vocal cavity system can be likened to a double Helmholtz resonator; that is, a system consisting of a pair of interconnected bottle-shaped cavities (*1, 2*). For some vowels, this double cavity model appears quite reasonable, since the tongue forms a bulge which divides the total oral-pharyngeal tract into two relatively separated volumes, and the lips form a tube-like opening to the outer air. The resonant modes of such a system are readily found if one can specify the dimensions exactly.

However, no attempt to apply the double Helmholtz resonator model to real cases of vowel production has been more than partially successful.[1] In the early period of the acoustic study of nasalized speech, however, it was the most current and well-developed idea. A related notion that also had considerable currency in the pre-1950 period conceptualized the vocal cavities as a set of functionally independent, simple (that is, single-tuned) resonators. This view considered that there was a simple resonator in the vocal cavity system associated with each region of energy concentration of the output acoustic spectrum of a vocal sound. This idea was given considerable impetus by the studies of Lewis (*10*) and Lewis and Tuthill (*11*). These investigators showed that, after making allowance for reasonable assumptions concerning the nature of the glottal spectrum, curves representing simple resonators could be fitted with reasonably small error to the spectral peaks, or concentrations of energy, which they found in their vowel spectra. Although this notion of a set of simple, functionally independent resonators was not usually carried to the point of attributing particular spectral energy concentrations to specific vocal cavities, the assumption of a relation between cavities and simple resonators was clearly implied. Hence, if a particular vowel spectrum showed three regions of energy concentration, it was

[1] For more extended discussion of this point, see Dunn (*4*) and Stevens and House (*13*).

inferred that the vocal tract system for that sound consisted of three functionally independent cavities, one to account for each of the resonant modes whose influence seemed to be evident in the vowel spectrum.

The concept of the nasal cavities as one of the set of simple, independent resonators constituting the complete vocal tract was no more than a logical extension of the foregoing ideas concerning vocal resonance. The logical consequence of this model of nasal resonance with respect to the nasalization of vowels can be demonstrated diagrammatically as shown by Figure 3. The block diagram represents the major divisions of the voice producing system. Although the diagram is essentially noncommittal, so far as theoretical ideas are concerned, it indicates a division between a posterior cavity and an anterior cavity (the pharyngeal and oral cavities respectively) and shows the possibility of variable coupling to the nasal cavities. To make this diagram fit the theory that we have been discussing, we need only to specify that each cavity acts as a simple resonator, and that the characteristics of each cavity as a resonator are essentially independent of its coupling to the other cavities. That is to say, the resonant modes of the system response are determined by the uncoupled resonant frequencies of the individual cavities. In addition, the nasal cavities are presumed to represent a resonator having fixed characteristics. Presumably the response characteristics of the nasal system may include either antiresonant modes, which would tend to cancel energy radiation in a particular frequency region, or resonant modes that would tend to produce a concentration of energy in a particular region of the spectrum. In either case the change in the acoustic spectrum that would be expected to result from nasalization would be presumed to result from a simple addition of the fixed transmission characteristics of the nasal cavity system to the transmission characteristics for the non-nasalized version of the particular speech sound then being uttered. A symbolic representation of this concept of nasalization is shown by the following equations.

$$(4) \qquad P(f)v_1,\ \text{non-nasalized} = S(f)\cdot T(f)v_1$$

$$(5) \qquad P(f)v_1,\ \text{slight nasalization} = S(f)\cdot T(f)v_1\cdot K_1N(f)$$

$$(6) \qquad P(f)v_1,\ \text{greater nasalization} = S(f)\cdot T(f)v_1\cdot K_2N(f)$$

Equation (4) for the non-nasalized vowel (v_1) may be compared to equations (1), (2), and (3). To symbolize the effects of nasal resonance in equations (5) and (6) a nasal transmission characteristic $N(f)$ is shown. This is assumed to be a fixed factor. However, its contribution to the output spectrum varies with the value of the coupling factor, K, which is presumed to change in proportion to the opening of the velopharyngeal port.

The concept of nasal resonance that has just been reviewed is, I think, a fair statement of the theoretical assumptions that were widely accepted

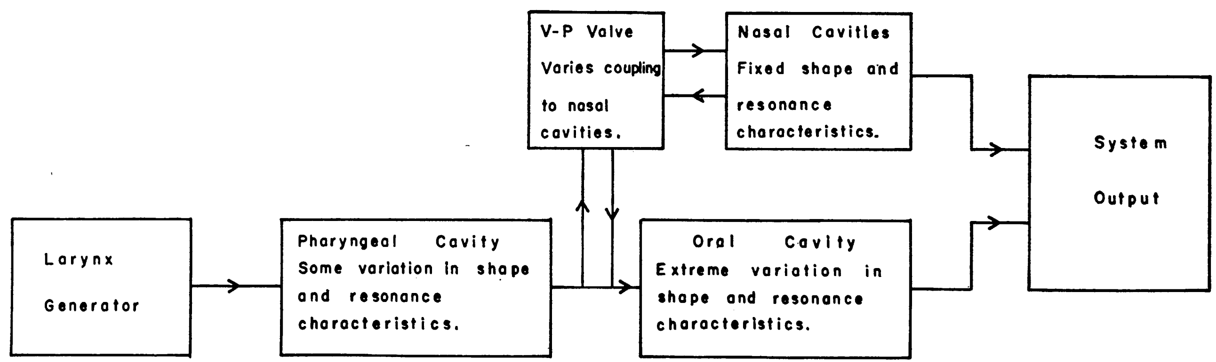


FIGURE 3. Block diagram of the voice-generating process, illustrating the vocal tract conceptualized as separated into several cavities with independent resonance properties.

at the time investigators first began to analyze the spectral characteristics of nasalized sounds as a means of searching out the resonance properties of the nasal cavities. Guided by this view, investigators searched for peaks in the spectra of nasalized vowels which could be interpreted as evidence of the fixed nasal resonance characteristics that the theory predicted. Alternatively, they searched for gaps or valleys in the spectral envelopes of nasalized vowels which could be interpreted as evidence of nasal antiresonances.

This turned out to be a frustrating task. Although comparisons between the spectra of nasalized sounds and their non-nasal counterparts usually showed differences, they were most often not the sort of differences that one's theoretical assumptions had prepared him for. Even with relatively small numbers of carefully selected subjects, who were highly cooperative, and who were thoroughly practiced in producing the experimental variations required by the research design, and even though the experimental conditions were controlled with the greatest care, the data very seldom gave clear and consistent indications of a set of constant resonance properties that could be associated with a fixed resonance theory of nasalization. As larger numbers of subjects were studied, and the data from additional experiments became available for comparison, the apparent inconsistency and lack of agreement became greater, rather than less. Several experiments appeared to find indications of a low frequency mode, having a frequency in the range of 250 to 300 Hz. In a few studies, there was an indication of an antiresonance approximately an octave higher in frequency. These were the only resonance characteristics that seemed to appear with any consistency, and frequently even these could not be demonstrated from spectra of sounds that had been produced with substantial coupling between oral and nasal tracts.

Several plausible reasons may be advanced for this seemingly unsatisfactory state of affairs. Among these are: a) the very real fact of individual differences which must always be taken into account with respect to data on human subjects; b) the problem of observing the isolated effects of variables operating in a complex process; and c) the relatively poor resolving power of spectrographic methods of acoustical analysis. There are, thus, reasons why it is difficult to design and carry out ideal experiments on real cases, and why we can expect that comparisons among the data and interpretations of various investigators will show some measure of variability and even disagreement. In the present instance, however, these reasons do not appear to be sufficient to explain the disparity between theory and data that has been noted. Thus, the data suggest a need to question the adequacy of the theoretical model and the relevance of the predictions based on it.

While these apparently puzzling data were accumulating, investigators concerned with the general area of speech analysis and synthesis continued to search for a more satisfactory general theory of vocal resonance.

Previous note has been taken of the several attempts that were made to apply a double Helmholtz resonator model to real cases, and of the fact that these attempts served mainly to point up the shortcomings of this model. A breakthrough came with the publication of H. K. Dunn's classic paper (*4*) which for the first time not only proposed an acoustical theory of vowel resonance based on a quite different model than that of Helmholtz resonators, but which applied this model to real cases with considerable success. Instead of attempting to analyze the vocal tract as a system of bottle-shaped resonators, Dunn chose an acoustical model that approximated the shape of the vocal tract as a series of cylinders connected in tandem. He solved for the resonances of such a system by applying dynamical analogies from electrical transmission line theory. Since 1950, Dunn's approach has been developed and elaborated by a number of other investigators, most extensively by Fant in his book, *The Acoustic Theory of Speech Production* (*5*). This approach has become the standard theoretical framework for work on speech analysis and synthesis. It has been successfully applied to the solution of problems involving consonants as well as vowels, and to both periodic and aperiodic speech sounds. By means of electrical networks derived from Dunn's model, or an elaboration thereof, very natural speech has been synthesized, and such electrical vocal tracts have been utilized as analogue computers to explore physiological-acoustical relations in speech articulation that are not readily amenable to investigation with real subjects.

One of the very important differences between the acoustic transmission line theory as developed by Dunn, Fant, and others, and the earlier Helmholtz resonator ideas is concerned with the extent to which individual cavities, or segments, of the complete vocal tract system may be considered to have resonance characteristics of their own, so to speak; that is, resonant or antiresonant modes which are related only to the dimensions of those cavities and which are affected slightly, if at all, by interaction with other portions of the system. Stated somewhat differently, this point concerns the extent to which the resonant modes of the complete system can be associated with the uncoupled frequencies of individual cavities, rather than considered to be determined by an interdependence of the various portions of the complete system. Many have interpreted the Helmholtz resonator model to imply that the uncoupled frequencies of the individual cavities were the modes of the system; thus, that the system could be considered as a set of independent simple resonators. Although Fant has shown that this is, in fact, an incorrect interpretation, there is no doubt that the Helmholtz resonator model emphasized the importance of individual cavities and de-emphasized interaction with the remainder of the system. Quite the opposite is true of the transmission line theory.

With respect to the resonance effects to be expected when speech is nasalized, certain implications of the transmission line model are relatively obvious. In particular it seems clear that the widely held idea of invariant nasal cavity resonant modes is not consistent with a theory which stresses the importance of cavity interdependence in the determinations of system resonance modes. For example, since the cavity dimensions will vary radically from vowel to vowel, one should not expect that coupling in the nasal cavities will produce the same spectral result, irrespective of the vowel being nasalized.

However, despite the success of the transmission line theory, it appears to have had relatively limited impact on thinking concerned with the resonance properties of the nasal cavities. There have been notable exceptions. Fant (*5*) devoted an entire chapter to nasalization, in which he presents a very complete analysis of the resonance effects of the nasal cavities together with data from the investigation of real subjects, as well as results developed by means of an electrical vocal tract analogue. House and Stevens (*8*) investigated both nasalized vowels and nasal consonants by means of an electrical vocal tract analogue that had been developed at the Massachusetts Institute of Technology. Their data clearly show the interaction of nasal resonance characteristics with the variations in vocal cavity shaping required for different vowels. Nevertheless, a major share of present day discussion concerned with resonance characteristics of the nasal cavities still seems to assume a model consisting of a system of simple, essentially independent resonators. For example, the literature on speech and voice disorders still frequently contains references to "nasal resonance" in a context which seems to imply that there are constant nasal resonance characteristics which are independent of the remainder of the vocal cavity system. Another example is provided by recent spectrographic studies of the acoustical effects of nasalization, which have had as a primary purpose the search for invariant effects associated with nasalization, again reflecting the influence of the older theoretical model rather than the relatively clear implications of transmission line theory (*3, 7*).

Figure 4 presents graphs borrowed from Fant (*5*) which will serve to illustrate the point that nasal resonance is not correctly described by a set of invariant spectral parameters. The two graphs shown in the upper half of the figure are calculated spectrum envelopes for two vowels, /i/ and /e/. These curves were obtained by means of an electrical analogue of the vocal tract under conditions of no coupling between the networks representing the oral and nasal tracts. The curves in the bottom half of the figure show the effects of coupling in the network representing the nasal cavities in a particularly interesting way. In each graph, separate spectral envelopes are shown to indicate the energy-frequency distribution of the sound radiated from the mouth and from the nares. Although the degree of coupling is the same for both vowels, the effects are quite different. The level of energy radiated from the mouth is reduced in both cases, especially in the low frequency

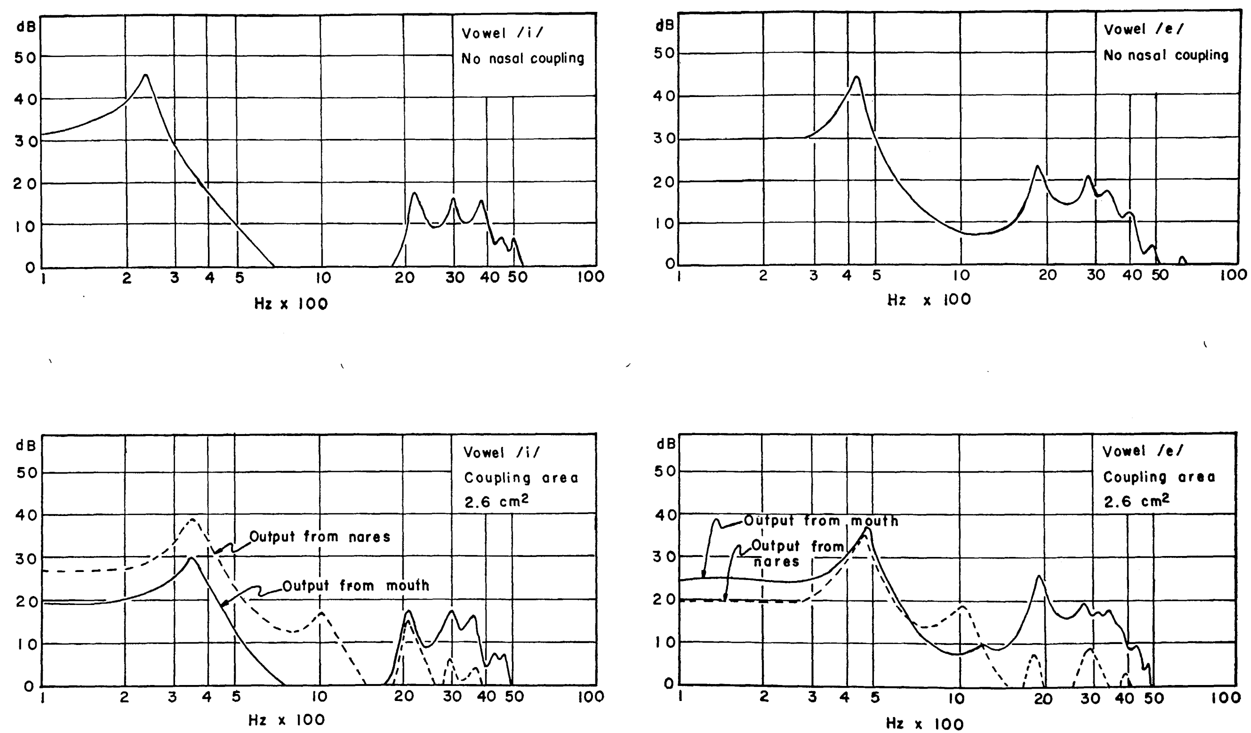


FIGURE 4. Computed spectrum envelopes showing the effects of nasal coupling on the sound transmission through the mouth and through the nasal cavities for two vowels, /i/ and /e/. Particularly to be noted are the dependence of coupling effect on the specific vowel. Adapted from Fant (*5*).

region, due to the division of energy between the mouth and nose tracts, but the reduction of mouth radiation is much greater for /i/ than for /e/. It should also be noted that the spectral peak associated with the first formant of both vowels shows an upward shift as a result of coupling. Again, this effect appears to be greater for /i/, where the shift appears to be approximately 100 Hz in extent. In both vowels the spectral envelope shows a broadening of the contour in the vicinity of this peak, which results from the increased damping due to coupling in the highly damped nasal cavities. It may also be noted that the shapes of the spectral envelopes reflecting the nasal transmission are different for the two vowels. The frequency location of the first spectral peak is clearly vowel dependent, approximately 350 Hz for /i/ and nearly 500 Hz for /e/. Also, high frequency portions of the spectrum envelopes for the nares output differ in detail, and the amplitudes of nasal transmission are clearly different for the two vowels; the nares output for /i/ is as much as ten dB greater than for /e/ in the vicinity of the first spectral peak.

The system output for the nasalized vowel is, of course, the combination of these separate outputs. The spectral envelopes for the combined mouth and nasal outputs are shown in Figure 5 by the dashed lines and contrasted to the spectra for the non-nasal vowels shown by the solid lines. Once more, the point to be emphasized is the difference between the two vowels. Clearly the change in spectrum resulting from nasalization is considerably different for /i/ than for /e/. Finally, it should be remarked that this is not an isolated nor an extreme case. In fact, the particular selection of vowels used in the illustration probably minimizes these variations, since both are front vowels, and the vowel dependence of the changes associated with nasalization would doubtless have appeared greater if a back vowel and a front vowel had been compared.

As previously mentioned, the interdependence of nasal cavity resonance effects and vocal cavity configurations for different vowels had also been shown by the data from the study by House and Stevens (8). Figure 6 shows spectral envelope curves which they obtained by means of the MIT electrical vocal tract analogue. With this device they could control the coupling to the nasal cavities in exactly graduated steps, and the several curves on each graph show the effects of thus varying the nasal coupling. It should be noted on the first set of curves, showing the spectral changes associated with increasing nasalization of the vowel /i/, that not only does the general level of the curve change with increasing nasalization, but the location of resonance peaks shifts and changes radically. The second set of curves, shown on the lower part of Figure 6, illustrates the same points in the case of the vowel, /ɔ/; once more it should be noted how much the effects differ from one vowel to another. Thus, the resonance characteristics of nasaliza-

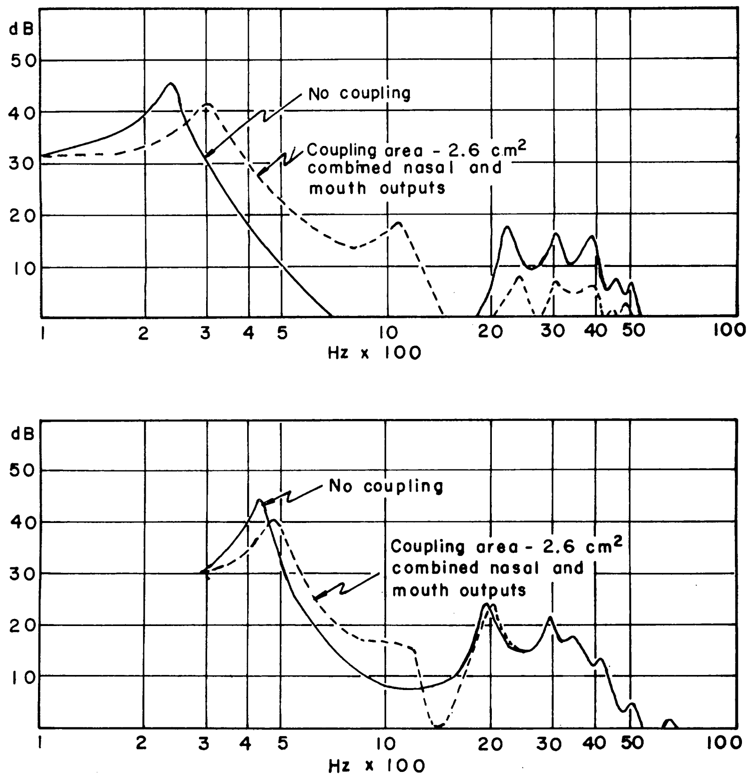
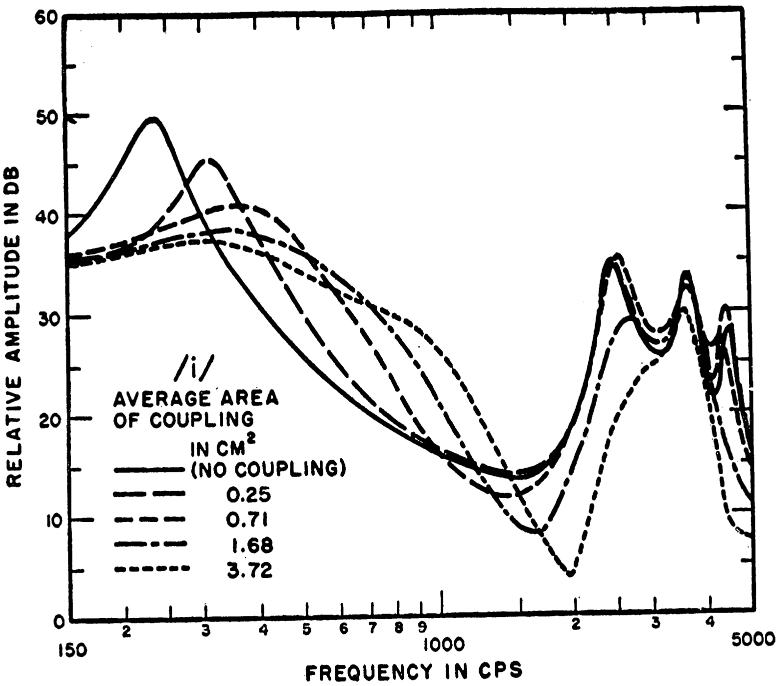


FIGURE 5. Computed spectrum envelopes illustrating the effects of nasal coupling on total system output of the vocal mechanism for two vowels, /i/ and /e/. Vowel dependence of the nasal coupling effects should again be noted. Adapted from Fant (*5*).

tion are shown to change radically with both degree of coupling and vowel configuration.

The conclusion from the foregoing discussion seems self-evident. An adequate theoretical model for vocal resonance gives little reason to predict that nasalization will lead to invariant changes in the acoustic spectra of speech. On the contrary, the spectral changes which are to be expected will depend very considerably on what is happening in other portions of the vocal cavity system. If one accepts this conclusion, the apparent inconsistency and lack of invariance in the data concerning the acoustic effects of nasalization are not mystifying. This lack of invariance is in fact consistent with theory and should have been expected.

Finally, let us consider the relationships between nasalization considered as an acoustic phenomenon and the perception of the voice quality variation that may be called nasality. In an introductory statement mention was made of the fact that nasality, as a perceptual phenomenon, appears to have a kind of unity, despite the variations in



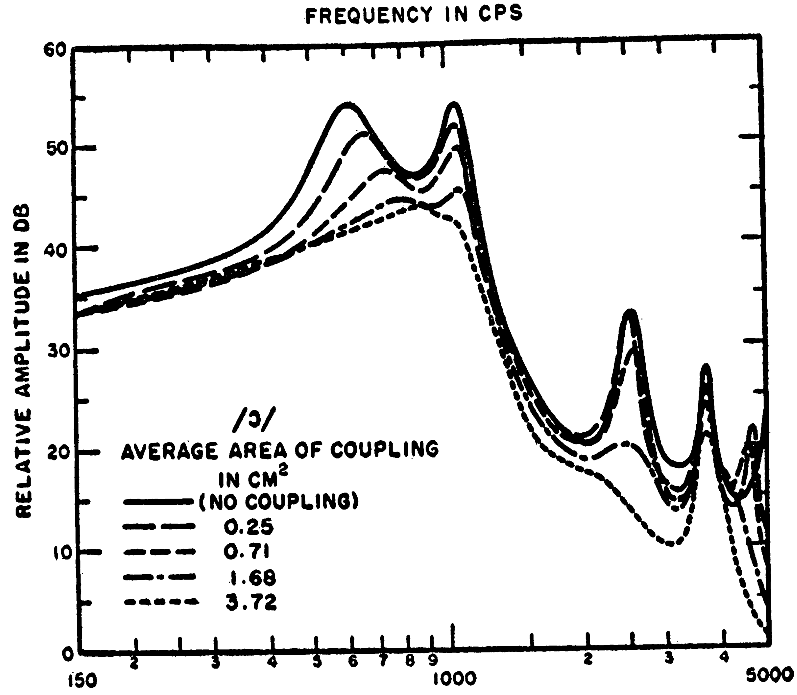


FIGURE 6. Showing the effects of varying the degree of velopharyngeal port coupling on the spectra of two vowels, /i/, *top*, and /ɔ/, *bottom*. Data were obtained by means of an electrical analogue of the vocal tract. After Stevens and House (*13*).

the physical stimuli that give rise to it. How can this be? If the physical characteristics of nasalization vary so greatly, how can they act as stimuli for a quality change which always sounds so much the same? This is an intriguing question and one that needs far more discussion than can be given to it in this article.

It is probably relevant that there is an increasing amount of evidence indicating that the recognition of auditory signals which have a linguistic reference appears to involve a different kind of perception process than is required by the discrimination experiments of classical psychoacoustics, Flanagan (*6*). In the latter case one is required to make a discrimination between two acoustic stimuli which differ along a single, unidimensional continuum (frequency or intensity). The perception of speech, on the other hand, appears to involve a classification process in which multidimensional stimulus patterns covering a substantial range of variations are assigned to absolute categories. An attempt to represent this difference symbolically is shown in Figure 7.

The expressions in the upper part of the figure represent the relationships assumed in the discrimination experiments of classical psychoacoustics. A given stimulus is clearly and consistently related to a particular perceptual response. A change in the stimulus can be expected to give rise to a related change in the perception, provided only that the change is greater than the difference limen for that stimulus dimension. It should be noted that the variation in this instance is relatively simple and unidimensional.

Categorical perception as symbolized in the lower part of Figure 7 appears to be much more complex. To interpret the expressions in Figure 7, it should be noted that the symbols for the stimuli, shown in parentheses, represent ranges in values for three different stimulus dimensions, S', S'', and S'''. The first item in the top line $(S'_1 - S'_{10})$ should

A. Simple, unidimensional relationship between stimuli and corresponding perceptual responses.

$$S_1 \rightarrow P_1,\ S_2 \rightarrow P_2,\ S_3 \rightarrow P_3$$
$$\text{if}\quad S_1 > S_2,\quad \text{then}\quad P_1 > P_2$$
$$\text{if}\quad S_1 < S_2,\quad \text{then}\quad P_1 < P_2$$
$$\text{if}\quad S_1 = S_2,\quad \text{then}\quad P_1 = P_2$$

B. Categorical relationship between complex, multidimensional stimulus patterns and corresponding perceptual categories.

$$(S'_1 - S'_{10}) + (S''_3 - S''_6) + (S'''_8 - S'''_{12}) \rightarrow P \text{ category } \#1$$
$$(S'_{11} - S'_{15}) + (S''_1 - S''_3) + (S'''_5 - S'''_7) \rightarrow P \text{ category } \#2$$
$$(S'_1 - S'_6) + (S''_7 - S''_{12}) + (S'''_1 - S'''_4) \rightarrow P \text{ category } \#3$$

FIGURE 7. Symbolic representation of two types of perceptual processes: A. Simple, unidimensional relationship between stimulus magnitude and magnitude of corresponding perceptual response. B. Complex relationship between multidimensional stimulus patterns and perceptual categories. The latter case seems more nearly like that for recognition and identification of linguistically related stimuli, such as speech.

be read as the range of values for stimulus dimension are between S'_1 and S'_{10}, and similarly for the other S terms. This type of perception involves recognizing that a complex pattern of stimuli belongs to a single category. The pattern may be multidimensional and each significant stimulus dimension may vary over some range without changing the classification assigned to the percept. Presumably we learn to make such categorical judgments as we learn to speak and as we learn to decode the speech of others. It can be shown that the acoustic stimuli corresponding to speech sounds, or syllables, or words are such multidimensional patterns. Such speech segments appear to be perceived in a categorical fashion. The perceptual response tends to be absolute and invariant despite very considerable ranges of variation in the stimulus dimensions composing the patterns.

Nasality, which is a quality variation associated with speech perception, may be a case involving such categorical perception. A good deal of work remains to be done in the area of the perception of language stimuli, and to date no one has been able to propose a satisfactory and comprehensive theory of speech perception. However, it is relevant to this discussion that if nasality is perceived categorically, in a fashion that seems to be characteristic of other stimuli having a linguistic reference, the clear recognition of nasality as something sharply contrasting with non-nasality does not require that the associated stimulus pattern be essentially uniform and invariant. Hence, the perceptual character of nasality cannot be taken as an indication of physical constancy.

Summary

The discussion presented here has sought to reconcile some apparently anomalous relationships between the physiological, acoustical, and perceptual phenomena associated with the nasalization of speech. It has attempted to show that, if viewed from an appropriate theoretical perspective, the complexity of the acoustical effects is not inconsistent with the apparent simplicity of the physiological event. It also appears probable that the perception of nasality as a unitary, categorical response can be explained even though the corresponding acoustical stimuli may be a rather variable set of complex, multidimensional patterns. The discussion has sought also to show that a complex, multidimensional variation in the acoustic characteristics associated with nasalization is to be expected from the currently most acceptable theory of vocal resonance.

reprints: *Dr. James F. Curtis*
Department of Speech Pathology
and Audiology
University of Iowa
Iowa City, Iowa 52240

References

1. Benton, W. E., Appendix I. In *Human Speech* (Paget, S. R., ed.). New York: Harcourt, Brace and Co., Inc., 1930.
2. Chiba, T., and M. Kojiyama, *The Vowel: Its Nature and Structure*. Tokyo: Tokyo-Kaiseikan Publishing Co., Ltd., 1941.
3. Dickson, R. D., An acoustic study of nasality. *J. speech hearing Res., 5,* 103–111, 1962.
4. Dunn, H. K., The calculation of vowel resonances and an electrical vocal tract. *J. acous. Soc. Amer., 22,* 740–753, 1950.
5. Fant, G., *Acoustic Theory of Speech Production*. 's-Gravenhage: Mouton and Co., 1960.
6. Flanagan, J. L., *Speech Analysis, Synthesis and Perception*. New York: Academic Press, 1965.
7. Hattori, S., K. Yamamoto, and O. Fujimura, Nasalization of vowels in relation to nasals. *J. acous. Soc. Amer., 30,* 267–274, 1958.
8. House, A. S., and K. N. Stevens, Analog studies of the nasalization of vowels. *J. speech hearing Dis., 21,* 218–232, 1956.
9. Kent, Louise, The effects of oral-to-nasal coupling on the perceptual, physiological, and acoustical characteristics of vowels. Unpublished Ph.D. dissertation, University of Iowa, 1966.
10. Lewis, D., Vocal resonance. *J. acous. Soc. Amer., 8,* 91–99, 1936.
11. Lewis, D., and C. Tuthill, Resonance frequencies and damping constants of resonators involved in the production of sustained vowels 'o' and 'ah'. *J. acous. Soc. Amer., 11,* 451–456, 1940.
12. Miller, D. C., *The Science of Musical Sounds*. New York: Macmillan, 1916.
13. Stevens, K. N., and A. S. House, An acoustical theory of vowel production and some of its implications. *J. speech hearing Res., 4,* 303–320, 1961.