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Some acoustic features of nasal and nasalized vowels: A target for vowel nasalization

Gang Feng and Eric Castelli
Institut de la Communication Parlée, I.N.P.G./E.N.S.E.R.G., Université Stendhal, URA CNRS No. 368, 46 Avenue Félix Viallet, 38031 Grenoble Cedex, France

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In order to characterize acoustic properties of nasal and nasalized vowels, these sounds will be considered as a dynamic trend from an oral configuration toward an [ŋ]-like configuration. The latter can be viewed as a target for vowel nasalization. This target corresponds to the pharyngonasal tract and it can be modeled, with some simplifications, by a single tract without any parallel paths. Thus the first two resonance frequencies (at about 300 and 1000 Hz) characterize this target well. A series of measurements has been carried out in order to describe the acoustic characteristics of the target. Measured transfer functions confirm the resonator nature of the low-frequency peak. The introduction of such a target allows the conception of the nasal vowels as a trend beginning with a simple configuration, which is terminated in the same manner, so allowing the complex nasal phenomena to be bounded. A complete study of pole-zero evolutions for the nasalization of the 11 French vowels is presented. It allows the proposition of a common strategy for the nasalization of all vowels, so a true nasal vowel can be placed in this nasalization frame. The measured transfer functions for several French nasal vowels are also given.

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INTRODUCTION

A nasal vowel is produced, in articulatory terms, by the gesture of lowering the velum, which establishes an acoustic coupling between the oral cavity and the nasal cavities. One of the fundamental objectives of research into speech is to find relevant acoustic and perceptual cues for these sounds (House and Stevens, 1956; Fant, 1960; Maeda, 1982a, 1984; Hawkins and Stevens, 1985). Traditionally, simulations using transmission line models have often been carried out, since they give reasonably satisfactory results in the case of oral vowels. When using this simulation for nasal vowels, the nasal tract is connected to the oral tract with a certain degree of coupling. This connection introduces several zeros and supplementary peaks in the speech spectra. However, these simulations have not permitted a satisfactory extraction of nasal acoustic cues since there are too many poles/zeros; they vary as a function of the degree of coupling, which is a very difficult parameter to control. In addition, these simulations seem to be incapable of producing high quality synthetic nasal sounds.

In one of the first investigations of nasality, Delattre (1954, 1955) tried to characterize the role of the different formants in nasality perception and suggested that the main nasality characteristics could be found in the low-frequency region. He showed that the lowering in amplitude and widening of the first oral formant ($F1$) can considerably nasalize the oral vowel. He also observed that two fixed peaks at 250 and 2000 Hz and a variable peak at 900 Hz are the main formants of nasal sounds. The first nasal simulation study was carried out by House and Stevens (1956). They confirmed Delattre's observation concerning the lowering of the amplitude of $F1$, in particular, the fact that a low-frequency peak (at about 250 Hz) can be observed when the nasal tract is coupled to the oral one. Another cue is the appearance of a zero between 700 and 1800 Hz also due to the coupling. In 1960, following a radiographic study, Fant proposed area functions for Swedish nasal consonants. He studied nasal vowels with a complete lowering of the velum and gave an interpretation of the multiple peaks observed. The resonance frequencies of this simulated tract are at 300, 1000, 2200, and 2900 Hz. $F1$ (300 Hz) is the fundamental resonance of the pharynx cavity tuned by the nasal cavities which behave as a resonator neck. The second formant (1000 Hz) has a frequency close to that of the first nasal resonance.

Bjuggren and Fant (1964) made accurate measurements of the nasal tract area function. The main characteristics of their proposed area function are a typical length of 11 cm and an output area at the nostrils of 1.5 cm^2. This latter value is very different from that used by House and Stevens in 1956 (0.23 cm^2); they also observed an asymmetry between the two passages of the nasal tract. Complete measurements by direct acoustic methods were carried out by Fujimura and Lindqvist (1971). They obtained oral vowel transfer functions and also measured nasal consonants. The latter offers a basic data template which is used in our study.

Maeda (1982a) proposed a global flattening of the spectra in the first and the second formant region (from about 200 to 2000 Hz) as an independent cue of the nasalization. In a subsequent paper (Maeda, 1984), he suggested that the two peaks (250 and 1000 Hz) present in the nasal spectra are the most evident correlates of nasality. After examining the role of the two nasal spectral peaks in the low-frequency region, he observed that the distance between the two peaks strongly correlates with the nasal coupling magnitude (Maeda, 1993). Maeda (1982b) also studied the role of the sinus cavities in the production of nasal vowels. In order to match the sweep-tone measurement data for the nasal tract carried out by Lindqvist-Gauffin and Sundberg (1976), he introduced a sinus cavity in the simulations and suggested that the low-frequency peak in the nasal spectrum is produced by the coupling of this cavity.

Stevens *et al.* (1987) concluded that the main effect of nasalization is the perturbation of the low-frequency spectrum, the first formant having been replaced by a pole-zero-pole combination. For Hawkins and Stevens (1985), the peak at a very low frequency and the widening of its bandwidth, together with the presence of a pole-zero pair due to acoustic coupling, play a fundamental role in the perception of nasality.

The difficulty in studying the acoustic behavior of nasal vowels arises from the fact that we do not know what exactly characterizes a nasal sound. Thus it is very difficult, if not impossible, to make a comparison between a simulation result and a real nasal spectrum, even with a measured nasal transfer function. It is widely recognized that in the case of oral vowels, the comparison between a simulated transfer function and a real spectrum is possible (even though the two are often very different), because we know that an oral vowel can be characterized by its first two or three formants (mainly by their frequencies).

In order to understand the main characteristics of nasal vowels and to explain a complex nasal spectrum, it seems necessary to first find a series of simple features which truly characterize a nasal sound. This idea stems from the fact that, from an articulatory point of view, the production of nasal vowels can be considered as being very simple: the lowering of the velum (often associated with the movement of the dorsum of the tongue). In this paper, we propose the introduction of a target for nasal vowels, that corresponds to the pharyngonasal tract realized when the velum is completely lowered. A new perspective is to consider a nasal vowel as a dynamic trend from an oral configuration toward the target. It will be shown that this target possesses several pertinent acoustic characteristics that could simplify the characterization of nasal vowels.

In the first section, several considerations will be presented which support the concept of a target for nasal vowels. The main acoustic features of the target will be discussed. In Sec. II, a series of measurement results carried out by our experimental system will be presented. Measured transfer functions will be shown to confirm the resonator nature of the low-frequency peak of the pharyngonasal tract. In the last section, a series of simulations which realize the evolutions of the transfer functions from oral vowels to the nasal target will be described. Several rules can be established from these simulations which characterize the nasalization of vowels. They offer a useful guide for finding acoustic cues of nasal vowels. The measured transfer functions for several French nasal vowels will also be given.

I. A TARGET FOR NASAL VOWELS

The essential gesture for the production of a nasal vowel is the lowering of the velum, which permits the connection of the nasal tract to the oral tract. We give a new interpretation for this gesture: the lowering of the velum makes the speaker pass from an oral configuration to that of an [ŋ]-like nasal consonant, which can be seen as a target for nasal vowels (later referred to as a nasal target). The nasalization of vowels is then considered as a dynamic trend from the oral configuration toward the target, although in the case of true nasal vowels it would not ever be reached.

The idea of conceiving of nasal vowels as being related to consonants is not new, as can be seen from phonological processes: nasal vowel systems originate generally from the assimilation of oral vowels by adjacent nasal consonants (review in Ferguson, 1963, 1975). The idea of the pharyngonasal target is supported as follows: consonantal place contrasts (labial, coronal, etc.) neutralize into the so-called nasal appendix (ŋ-like); this may be explained articulatorily by the lowering of the velum toward the tongue, tending to block the oral port. This occurs before consonant deletion. In other words, when oral constriction weakens then disappears, the only remaining gesture is the velic lowering gesture (what we call the [ŋ]-like configuration, which is not the same as an active dorsal constriction as in IPA [ŋ]). This [ŋ]-like configuration is thus very similar to what phonologists would now call an ''autosegment'' or ''gesture.'' However even after complete deletion, there may remain in phonetic realizations of proper nasal vowels a somewhat evolutive (if not diphthongal) character, due to the slowness of the lowering of the velum, as shown by several authors (see Linthorst, 1973, for the French language, and also Fig. 5 in Autesserre *et al.*, 1988).

The introduction of the [ŋ]-like nasal target offers an essential advantage: the pharyngonasal configuration is a simple object compared to that of nasal vowels. This is because the pharyngonasal tract can be considered, with reasonable simplifications, as a single tract without any parallel paths. The first two resonance frequencies can thus characterize this target. This in turn allows the conception of the nasal vowel as a trend beginning with a simple configuration (the oral one), which is terminated in the same manner (the pharyngonasal one), so allowing the complex nasal phenomena to be bounded (Feng *et al.*, 1985). We do not consider the nasal tract alone as a target: the vocal source being situated at the glottis means that this tract never functions without the pharynx. On the other hand, the introduction of a nasal target allows us to envisage the following hypothesis: It could be the presence of the target in a vowel (even if it is not attained) that permits the perception of the vowel to be nasal.

Let us now examine the first two resonance frequencies of the pharyngonasal tract. Measurements carried out for the consonant [ŋ] give typical values of 300 Hz for the first peak and 1000 Hz for the second (Fant, 1960; Ohala and Ohala, 1993). The available sweep-tone measurements of the transfer functions for several nasal consonants (Fujimura and Lindqvist, 1971) also show the presence of a low resonance frequency at 250 Hz to be a common factor in all the data.

We have carried out a simulation study for the pharyngonasal tract. A lossy transmission line vocal tract model is used to calculate the transfer function of a given multiple-section tube, as in the case of oral vowels (Fant, 1960). In order to find the main characteristics of this tract, some reasonable simplifications are made: to begin with we have ignored any asymmetry of the nasal tracts and the presence of

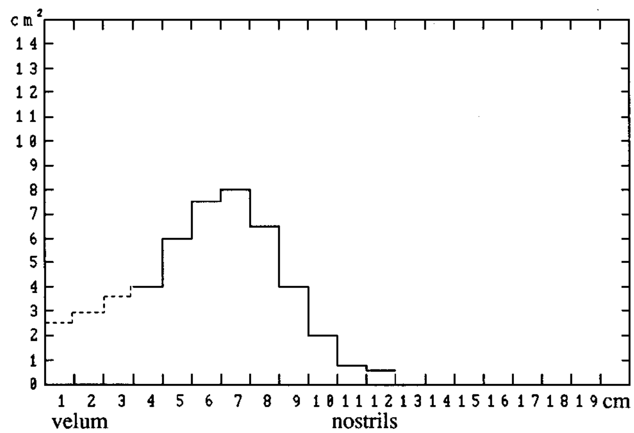

FIG. 1. Area function of the nasal tract used in our simulations. The first three sections in the velic region are variable and depend on the vowel and the degree of coupling. The nostril output area is 0.6 cm^2.

the sinuses. In this condition, the pharyngonasal tract can be viewed as a single tube without any parallel paths. The area function used for the nasal tract is as shown in Fig. 1. A value of 0.6 cm^2 for the nostril output area is chosen so that the simulation results can fit the above-mentioned measurement data. A more detailed discussion on the choice of this value is given in the Appendix. The pharyngeal section of the pharyngonasal tract is taken from the corresponding oral vowel (11 French vowels) and so varies slightly from one vowel to another. The area functions of these vowels were taken from Boë (1973) and Mrayati (1976), slightly modified by Feng (1986).

The result of this simulation is presented in Fig. 2. The first two resonance frequencies of the 11 pharyngonasal tracts are plotted in the $F1-F2$ plane, in which the 11 corresponding French oral vowels are presented. Due to the difference in the pharyngeal sections, the first two resonance frequencies of the pharyngonasal tract are not fixed, but occupy a small region in the $F1-F2$ plane, centered around 300–1000 Hz. We see that the nasal target offers a relatively stable acoustic structure, slightly sensitive to vowel variations, contrasting with the large variety of the oropharyngeal configurations. It is also interesting to observe that no French oral vowels are situated in this region.

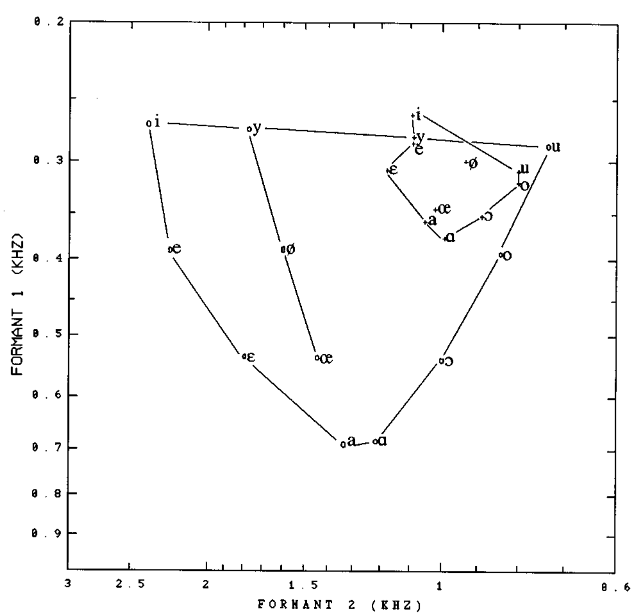

FIG. 2. Simulation results of the pharyngonasal tracts corresponding to the 11 French vowels. "+" vowels represent frequencies of the pharyngonasal tracts and "o" vowels the corresponding oral vowels. The first two resonance frequencies form a small region around 300–1000 Hz in the $F1-F2$ plane.

II. MEASUREMENTS AND CHARACTERIZATION OF THE NASAL TARGET

A new experimental process was created in order to study the acoustic characteristics of nasal sounds and to verify that the first peak in the pharyngonasal tract has a resonator nature. From this we measured vocal tract transfer functions in variable conditions, in particular, pharyngonasal tract transfer functions with different nostril areas. The measurement system was also used to determine transfer functions of French nasal vowels.

The transfer functions of the vocal tract are the ideal tools to use in order to understand articulatory and acoustic phenomena involved in speech production. These functions are not influenced by any interaction with excitation sources and are obtained directly from the subjects. They can easily be simulated by means of frequency domain vocal tract models, and compared with experimental measurements. The basic technique consists of externally exciting the vocal tract with the help of a small shaker; the resulting signal is picked up by a microphone at the lips or at the nostrils. This technique was used by Van Den Berg (1955), Fant (1960), and later by Fujimura and Lindqvist (1971). Since 1988, different aspects of such a technique have been studied (Castelli and Badin, 1988, 1989; Castelli *et al.*, 1989; Djeradi *et al.*, 1991).

Two techniques have been developed. The first is based on Gaussian white noise excitation. This method requires only a very simple signal processing procedure although the measurement duration is considerable, during which the subject must remain motionless (Castelli and Badin, 1988, 1989; Castelli *et al.*, 1989). In the second method, a pseudorandom pulse series replaces the white noise (Djeradi *et al.*, 1991). The more complex signal processing permits a shorter measurement time. These techniques allow an auditory feedback to be heard as whispered sounds. A comparison of the two methods has shown the results to be extremely consistent: formant and antiformant values can be obtained with sufficient precision and an equivalent accuracy. In this paper, transfer functions are presented without detailing the method used, since there is essentially no difference between the two results.

A. A pharyngonasal vowel corpus

A minimum of six measurements were performed for each of nine adult subjects (six males, three females, all native speakers of French) and for each of the four pharyngonasal vowels corresponding to the oral vowels [a], [i], [u], and [o]. To obtain a pharyngonasal configuration, the subjects were required to produce an oral vowel without phonation (closed glottis), and then to lower the velum completely, while moving the other articulators as little as possible, in order to attain the velar nasal consonant [ŋ] coarticulated with the given vowel. The measured tract is thus the pharyngonasal tract, formed by the pharynx and the nasal tract, the oral tract supposedly being completely disconnected by the lowering of the velum. It is sufficient to close the nostrils by hand during the production of a pharyngonasal vowel to verify the disconnection of the oral tract: The sound is stopped.

In fact the velum is not perfectly airtight. Frequently, in the case of the pharyngonasal vowel [aŋ] for example, the closure of the oral tract by the velum is not complete. Moreover, acoustic leakage can occur through the velum, due to the thinness of the membrane, but the output signal measured at the lips is always of very much lower amplitude than the signal at the nostrils.

One session of measurements contains a record of the signal picked up at the lips for each oral vowel and then the two records (one for each nostril) corresponding to the pharyngonasal configuration.

B. Principal patterns of the measured pharyngonasal transfer functions

As we would expect, the resulting spectra are very complex. Figure 3 shows two such examples. However, a large number of spectral peaks and zeros seem to maintain relatively constant frequencies. For each subject, a standard pattern of the pharyngonasal tract transfer function can be defined: up to ten peaks and four zeros are present between 200 and 5000 Hz (Castelli *et al.*, 1989).

After an analysis of more than 1000 measured functions, we can roughly classify them into two groups: ''simple'' and ''complex.'' Each simple function presents 4 to 6 peaks, while each complex one 8 to 10. It is important to mention that the measured functions for a given subject almost always belong to the same group. Five subjects produce simple functions and the four others give complex functions. Figure 4 shows schematic representations of these two groups of functions. Moreover, for the ''complex'' functions, we have found two subclasses: one is represented by the solid line corresponding to 70% of the data and the second by the dashed line for 20%. The remaining 10% cannot be easily classified, due to their high dispersion (Castelli, 1989).

Due to the losses inside the pharyngonasal tract (which are very significant because the geometry and the tissue of the nasal tract are very irregular) and also due to the fact that it is impossible for the subject to remain absolutely motionless during the measurements (about 13 s using the white noise method), it is often difficult to localize zeros in the measured transfer functions.

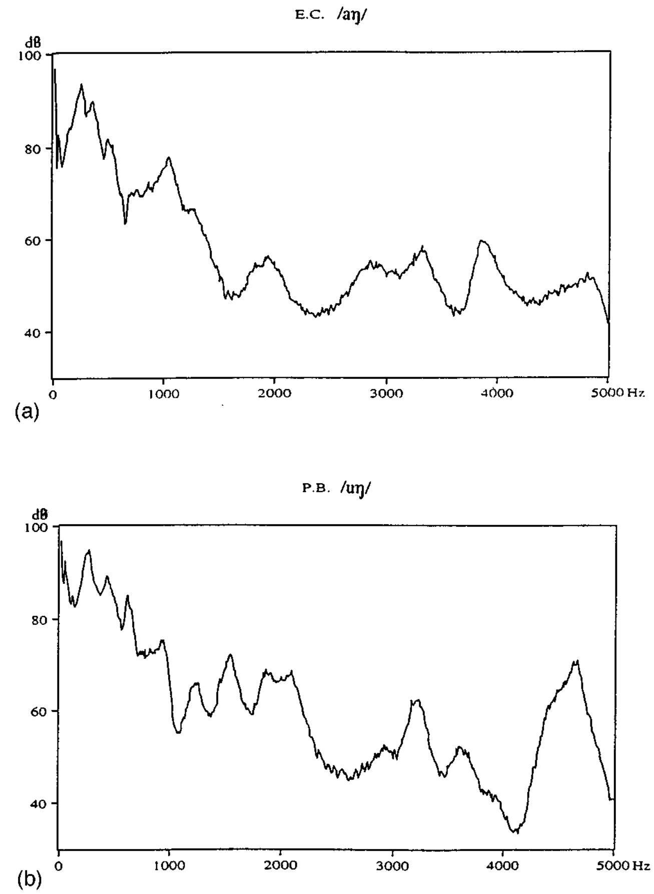

FIG. 3. Examples of measured pharyngonasal transfer functions. (a) Corresponds to the [ɑŋ] configuration for the subject EC and shows a relatively simple pattern. (b) ([uŋ] configuration) for the subject PB presents a more complex trend.

The peaks of a ''simple'' function are principally located in the following frequency regions: 250–300 Hz, 650–700 Hz, 900–1100 Hz, 1900–2200 Hz, 2800–3300 Hz, and around 4000 Hz, with a zero around 500–600 Hz in some cases. The frequency regions for the peaks of a ''complex'' function are: 250–300 Hz, 400–450 Hz, 650–700 Hz, 850–900 Hz, 1200–1300 Hz, 1800–2200 Hz, 2800–3300 Hz, and around 4000 Hz with a zero around 1200 Hz (for the 20% dashed line cases); in some cases other zeros appear between $Fn1$ and $Fn2$, between $Fn2$ and $Fn3$, and between $Fn3$ and $Fn4$. Similar peak values can be found in Ohala and Ohala's paper (1993).

For a given subject, the locations of the peaks are at almost constant frequencies for all measurement sessions. A statistical study shows for example, that for the male subject

TABLE I. Mean value of the peak frequencies and standard deviation for the pharyngonasal vowel [iŋ] (for approximately 20 measured transfer functions—subject PB).

	$Fn1$	$Fn2$	$Fn3$	$Fn4$	$Fn5$	$Fn6$	$Fn7$	$Fn8$	$Fn9$	$Fn10$
Frequency, Hz	225	440	614	923	1241	1452	1667	2167	3128	4578
Standard deviation, Hz	17	9	23	30	15	28	37	45	51	92
Standard deviation, %	7.5	2	3.7	3.2	1.2	1.9	2.2	2	1.6	2

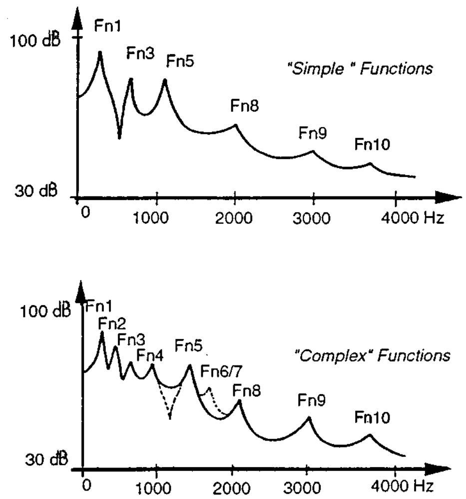

FIG. 4. Two principal patterns for the measured pharyngonasal transfer functions.

PB, the standard deviation of the 2100-Hz peak is only 50 Hz (i.e., less than 3% for 40 measured transfer functions for all pharyngonasal configurations). The spectral resolution of our data is 10 Hz. Table I confirms the stability of the standard deviation for the subject PB in the pharyngonasal configuration [iŋ].

The peaks $Fn5$, $Fn8$, $Fn9$, and $Fn10$ seem to correspond to the resonances of the pharyngonasal tract considered as a simple tube, since the measured values agree with the simulations described in Sec. I (see the highest curve of Fig. 9 for the nasalization of the vowel [i]).

$Fn2$, $Fn3$, and $Fn4$ (around 400, 600, and 800 Hz, respectively) might have their origin in the coupling with the sinus cavities. Zeros can often be found between these peaks. These peaks cause the transfer functions to resemble those measured by Lindqvist-Gauffin and Sundberg (1976) and also simulated by Maeda (1982a): they add ''flatness'' to the spectrum. The flatness might be due to the presence of secondary poles around the so-called oral formants, reducing the depth of the valleys and broadening the peaks (Stevens *et al.*, 1987). Moreover, the measured values of zeros between these peaks lie in the range of the values usually accepted as sinus resonance frequencies.

We could attribute $Fn6$ and $Fn7$ to the asymmetry of the nasal cavities, as suggested by Lonchamp (1988) and by Dang *et al.* (1994). Lonchamp's simulations have shown that this asymmetry can produce a pole/zero pair in the vicinity of 1500–1700 Hz. Simulations of Dang *et al.* show a pole/zero pair around 2 kHz.

C. Experimental verification of the resonator nature of the low-frequency peak

Certain authors suggested that $Fn1$ originates from the subglottal system, and called it a ''glottal formant'' (Maeda, 1984; Fant, 1960). The measurements carried out with a closed glottis condition permit us to avoid this consideration. The aim is thus to verify the resonance hypothesis and to establish an acoustic model.

TABLE II. $Fn1$ values (standard deviation) for five of the nine subjects. Unit is Hz.

	Sub. PB	Sub. TB	Sub. EC	Sub. RD	Sub. MP
Without tube	234(5)	294(5)	235(8)	278(11)	270(27)
With a 2-mm tube	201(5)	265(13)	203(10)	243(16)	202(8)

We attempted to artificially vary the *limen nasi* area by fitting the subjects' nostrils with small Plexiglas tubes which have an external diameter of 6 mm (Castelli *et al.*, 1989): the area of the plastic tube is 0.28 cm^2 for each nostril (an area of 0.56 cm^2 for the neck of the resonator). In order to avoid asymmetric effects, both nostrils were always fitted with identical tubes. In our experiment, three tubes were used which have different internal diameters: 4.5, 3.0, or 2.0 mm. For each vowel, four series of transfer functions were measured (three different diameters, plus one without any tube); the measurements were systematically carried out for each nostril.

It has been observed that only $Fn1$ and $Fn5$ noticeably decrease with nostril area. Moreover, their average frequencies are, respectively, around 250–300 Hz and 900–1000 Hz. These values seem to correspond to the first two peaks of the pharyngonasal tract. The other peaks are almost invariant.

Table II shows mean values of the measured $Fn1$ and standard deviations (without the Plexiglas tube and with the 2.0-mm-diam tube, respectively) for the [aŋ] configuration and for the five subjects.

Analysis of the data shows that this low resonance is limited to a minimum of approximately 200 Hz, which corresponds to the value associated with the wall vibration effect (Fant, 1960; Fant and Sonesson, 1964; Fant and Lindqvist, 1968; Fujimura and Lindqvist, 1971; Fant, 1972). The Helmholtz formula for the yielding wall case is given by

$$F0=(F_{\mathrm{Helm}}^2+F_{\mathrm{wall}}^2)^{1/2},$$

where F_{wall} is the closed tract resonance frequency (between 150 and 220 Hz according to Fant, 1972).

Figure 5 displays the measured variations of the first pharyngonasal peak frequency, the Helmholtz resonance frequency for the hard-wall case and the corrected Helmholtz

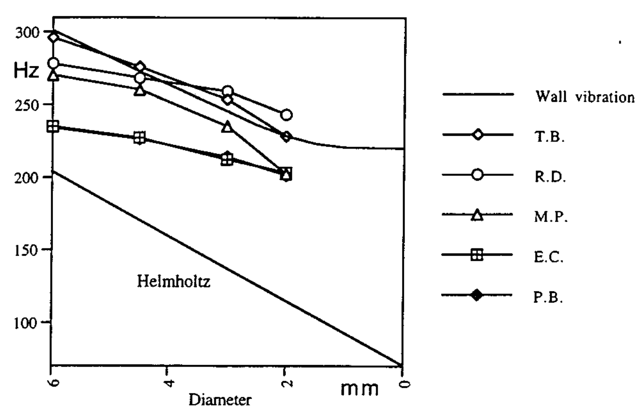

FIG. 5. $Fn1$ frequency variations versus limen nasi dimensions. It can be seen that the experimental curves fit that simulated with the inclusion of wall vibrations.

TABLE III. $Fn1$ frequencies for the [aŋ] pharyngonasal configuration. Mean values are calculated for a minimum of ten measurements for each of the nine subjects.

	Sub. PB	Sub. LJB	Sub. TB	Sub. EC	Sub. RD	Sub. MP	Sub. MR	Sub. ER	Sub. HT
Average, Hz	234	214	294	235	278	270	237	214	266

frequency (with F_{wall}=220 Hz), versus the limen nasi diameter. The good fit of this curve with the measured results confirms the validity of the resonance hypothesis (Castelli *et al.*, 1989).

The frequency of the first pharyngonasal resonance is relatively low: for nearly all of the subjects, measured values were in the range of 200–300 Hz (see Table III). This means that the frequency range for the corresponding hard-wall resonantor would be 130–200 Hz if the wall vibration values (150–220 Hz) found in the literature for the lowest formant of the vocal tract are used for its calculation.

III. NASALIZATION OF FRENCH VOWELS

Since we propose that nasal vowels can be considered as dynamic trends toward the nasal target, it is useful to study the evolution of transfer functions from oral vowels to their corresponding pharyngonasal configurations. Such a study would allow us to understand how the nasal target contributes to the nasalization and how a spectrum moves toward the nasal target. In this section, simulation results for the nasalization of the 11 French vowels will be presented. For each vowel, we start with an oral configuration, which corresponds to the highest velum position. Then we progressively change the velum position, representing different degrees of coupling. Finally the pharyngonasal configuration is attained with the velum touching the tongue. Such simulations give a continuous transfer function evolution for the nasalization of the 11 French vowels. The simulation tools and the basic area functions used in this study are the same as described in Sec. I.

With respect to classical simulation studies in which the nasal tract is connected to the vocal tract with a varying amount of coupling, the most important difference in our simulation is the introduction of the pharyngonasal tract. By using this tract as an end point, the nasalization of vowels begins with a single tube configuration (the oral one), passes through the coupling states, and ends again with a single tube configuration (the pharyngonasal one with simplifications).

In the simulations, one crucial problem was to determine the area function in the velic region for different degrees of coupling. Lacking sufficient physiological data, we were obliged to make a reasonable approximation. The area at the coupling point (i.e., around the extremity of the velum-uvula) is divided into two parts: one corresponding to the input of the nasal tract and the other to the input of the oral tract. The sum of the two parts is assumed constant. For the different velum positions, a series of area ratios (partial area/total area) is chosen as follows: 0.0, 0.025, 0.05, 0.1, 0.3, 0.7, 0.9, 0.95, 0.975, 1.0. The two sections (section length: 1 cm) just after the coupling point in both nasal and oral tracts are then determined by a linear interpolation.

A. Basic pole-zero evolution patterns

Before discussing the results of simulations for vowel nasalization, a simplified simulation is shown, which will provide essential pole-zero evolution patterns.

In this simulation, a parallel L-C(-R) electrical circuit is used to study the coupling problem (Fig. 6). Each of the two branches, composed of a fourth-order L-C(-R) circuit, has two resonance frequencies and in between them, one zero-impedance (antiresonance) frequency. The transfer function of this system is defined by the following ratio: the sum of the two output currents/input current. The coupling of these two branches will give three poles and one zero. The latter is different from the zero-impedance frequencies for each of the two branches considered independently, since the zero of the system is obtained when the sum of the two outputs is nullified. It should be mentioned that in the case of nasal vowels, the acoustical signal captured by the microphone is the result of both outputs. Consequently, the zeros (antiresonances) of each branch, which can only appear in one of the two outputs, cannot be identified in the speech signal. It is thus essential for us to study the zeros appearing in the sum of the two outputs.

In order to modify the coupling degree of this system, the impedance of one branch is multiplied by an access-coefficient d_c and the other by $1/d_c$. Although it does not change the poles and the zero of each branch (all these parameters will be slightly affected by the coupling in vowel nasalizations), this method produces an impedance variation in both branches in a very similar way to vowel nasalization cases. By continuously varying the coefficient d_c, an evolution of the system transfer functions is obtained. Figure 7 shows a typical example. The highest and the lowest transfer

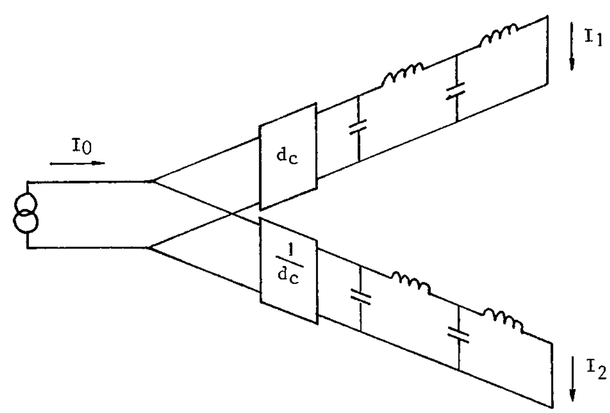

FIG. 6. A parallel electrical circuit used to study the coupling problem. The degree of coupling of this circuit is changed by modifying simultaneously the input impedances of the two branches: one multiplied by a coefficient d_c and the other by $1/d_c$.

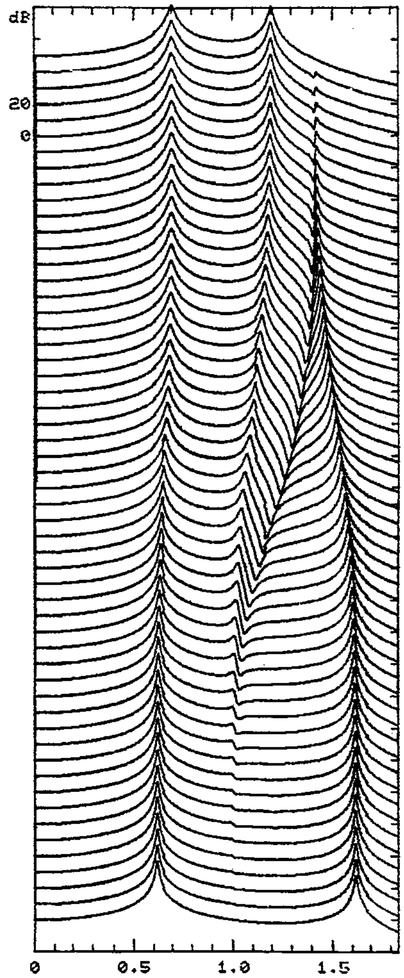

FIG. 7. An example of transfer function evolutions for the system shown in Fig. 6, when the coefficient d_c varies from 0 to infinity. The two extreme transfer functions correspond, respectively, to the transfer function of each branch without coupling. The medial one corresponds to the maximum degree of coupling.

functions of this evolution correspond to two extreme situations in which one of the two branches is completely connected and the other completely cut off. In this case, the system transfer function corresponds to only one of the two branches, thus giving two poles and no zero. Between these two extremities, the transfer functions show three poles and one zero. The medial one corresponds to the maximal coupling since the two branches possess the same access-coefficient $(d_c=1)$.

Different evolution patterns are obtained as the system parameters are changed. All of the evolutions can be classified by the structures shown in Fig. 8. Since the zero-impedance (antiresonance) frequency of one branch ($Z1$ for example) can be to the left, in between or to the right of the frequency range determined by the two poles of the other branch ($F21$–$F22$ for example), nine configurations are possible [Fig. 8(a)–(i)]. However, Fig. 8(a) and (i) are impossible cases, since both $Z1$ and $Z2$ are outside the pole ranges of the two branches and located on the same side. A general rule for these pole-zero evolution patterns can be described as follows: the system zero always evolves between $Z1$ and

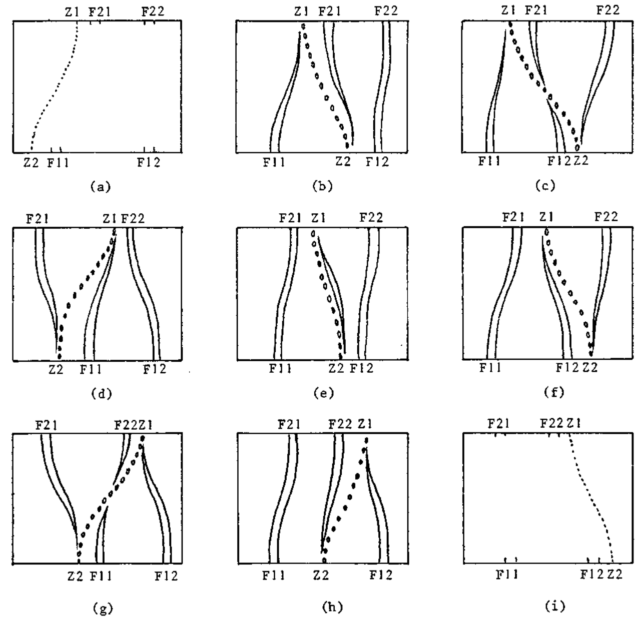

FIG. 8. All possible pole-zero evolution patterns of the coupling system shown in Fig. 6. Plain lines represent pole evolutions, dotted lines zeros. These patterns depend on the parameters of the two branches. $F11$, $F12$, and $Z1$ denote, respectively, the two resonance frequencies and the zero-impedance (antiresonance) frequency for one branch, and $F21$, $F22$, $Z2$ for the other.

$Z2$, weakens and then disappears at the two extremes by joining one of the system poles.

Naturally, the real coupled vocal tract model is more complex than this simplified system. However, it has been found that the impedance variations of the nasal and oral tracts for different degrees of coupling are very similar to the system described above. Moreover we are mainly interested in the region containing the first two formants, so these pole-zero evolution patterns remain instructive for the real simulation studies.

B. Nasalization of the eleven French vowels

Simulation results for the nasalization of the 11 French vowels are now examined. First, the extreme vowels [i], [u] and [ɑ] will be discussed, since they determine the limits of the vocalic space. For each vowel, ten transfer functions have been calculated, corresponding to the series of area ratios described above. These are presented in Fig. 9. The bottom curve represents the transfer function for the oral vowel and the top one that for the corresponding pharyngonasal tract. Between these two extremes, transfer functions for the nasalized vowels with different degrees of coupling are shown.

For [i], starting from the first two formants (240 and 2270 Hz), the pharyngonasal structure is attained with 240 and 1090 Hz. The evolution first shows the appearance of a ''shoulder'' to the right of $F1$ for [i], this peak then forms the second characteristic pole of the pharyngonasal tract. Concerning the $F2$ of [i], it ends by joining up with the zero and then disappearing. This evolution is very similar to the pattern presented in Fig. 8(h). In such a transition, analysis

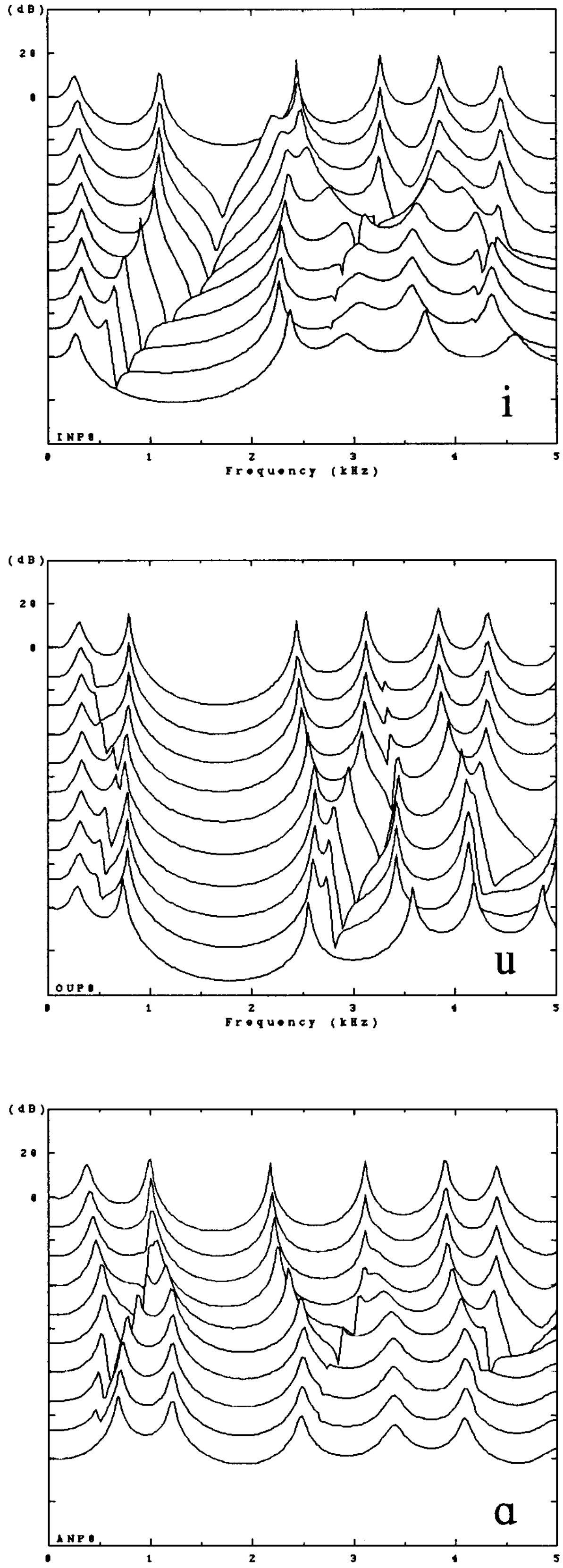

FIG. 9. Simulated transfer functions for nasalization of the three vowels [i], [u], and [ɑ].

and perceptual knowledge provide a domain where the vowel can be validated as nasal according to the patterns presented by Hawkins and Stevens (1985).

The evolution of the vowel [u] toward the pharyngonasal tract behaves with a slight elevation of the frequency of the second pole, the frequency of the first one remaining relatively stable, as is the case for [i]. The first pole-zero pair moves between these two poles: this is very similar to the basic structure of Fig. 8(e). We can also obtain here a large domain for validation of nasality (Hawkins and Stevens, 1985).

The transition for the vowel [ɑ] has some similarity with that of the vowel [i], but corresponds to the basic structure of Fig. 8(d): an additional peak emerges, as is the case for [i], however here it concerns a low pharyngonasal peak; the disappearance of a formant, as for [i], but here it concerns the first formant. The second formant shifts downward and becomes the high pharyngonasal peak.

Sweep-tone measurement data (Fujimura and Lindqvist, 1971) confirm that the typical vocalic domain for [ɑ̃] (for an explanation of its perception, cf. Beddor and Strange, 1982) is quite close to a configuration with a maximum velopharyngeal opening—contrary to [i] and [u] which offer a wider validation domain. These simulation results thus correspond to the fact that the low vowels demand a greater velopharyngeal opening in order to be categorized as nasal vowels (reviewed in Reenen, 1982).

The disparity of nasal correlates for these three types of extreme vowels seems to make any attempt to simplify the articulatory-acoustic correspondence very difficult, as has already been mentioned in the literature. The addition of so-called ''nasal poles'' (a high one for [i], a low one for [ɑ]), the evolution of the second pole (lowering of ''$F2$'' for [ɑ], elevation of ''$F2$'' for [u]) are consistent only when considered as one trend toward a single objective: the acquisition of the two essential nasal target poles.

The remaining vowels would be situated between these three extremes, with the following major modifications (Feng, 1987; Feng and Abry, 1987):

(1) acquisition of a high pole (1000 Hz) and disappearance of $F2$ for [i], [y], [e], [ø], [ɛ], and [œ];
(2) lowering of $F1$ and/or elevation of $F2$ for [u] and [o];
(3) acquisition of a low pole (250–300 Hz), disappearance of $F1$ and lowering of $F2$ for [a], [ɑ], and [ɔ].

To further summarize, we are faced with two topological criteria: $F1$ becomes a low pole, the case in [i,...,œ] and [u, o], or disappears [a, ɑ, ɔ]; $F2$ becomes a high pole, the case for [a, ɑ, ɔ], and also [u, o], or disappears [i,...,œ]. Consequently, when $F1$ disappears the vowel acquires a low pole [a, ɑ, ɔ]; if such is the case for $F2$, the vowel acquires a high pole [i,...,œ]. These acquisitions are, in the final analysis, the most crucial properties. The topology of these acquired poles thus remains the most useful technique for categorizing nasal vowels.

It is certain that a continuous passage from one of these categories to the other is possible; or a discontinuous one if emphasis is made on topological ''catastrophies,'' namely,

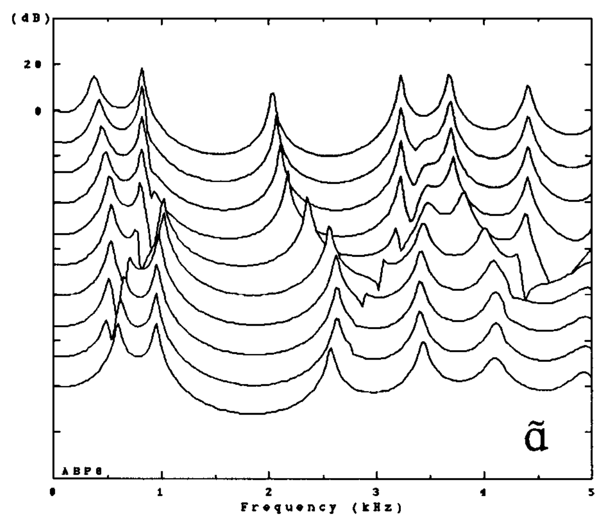

FIG. 10. Simulated transfer functions for the nasalization of the nasal vowel [ɑ̃].

the appearance of a pole to the right or the left of a formant (the case of [ɛ] versus [a], etc.).

C. The nasal vowel [ɑ̃] in the nasalized vowel frame

We now examine how true French nasal vowels are inserted into the nasalized vowel frame. The vowel [ɑ̃] will be taken as an example since it is a typical case from which both the realizations of [ɛ̃] and [ɔ̃] can be derived (Martinet, 1969; Brichler-Labeye, 1970; Lonchamp, 1979).

In its oral section, the area function of [ɑ̃] (according to Zerling, 1984), is close to [ɔ] as concerns the vocal tract length (protrusion and closure of the lips, lowering of the larynx), but differs when it comes to pharyngeal constriction size. [ɑ̃] seems to be different from [ɑ], both for vocal tract length ([ɑ] is less protruded for the two speakers according to Zerling, 1984) and for pharyngeal constriction (the same speaker has a tendency to narrow this part of the vocal tract).

In our study, the available radiographic data (Zerling, 1984) were converted to area functions for their oral section (using coefficients from Sanchez and Boë, 1984). The corresponding transfer functions were then calculated. The oral configuration of [ɑ̃] presents a smaller distance between the first two poles, compared with the [a] configuration.

A transition from the oral configuration of [ɑ̃] to its pharyngonasal one is then simulated using the same procedure as previously presented. The transfer functions obtained show a similar evolution pattern (Fig. 10) as for those of the nasalized vowels [a, ɑ, ɔ]. A lower pole appears below the first formant and then tends toward the first pharyngonasal peak. Only the evolution of the zero presents a slight difference, having the (g)-type structure shown in Fig. 8. However, the acquisition of a low pole to the left of $F1$ puts this vowel in the phonetic category already containing [a, ɑ, ɔ].

D. Simulations with a sinus

The preceding simulations without sinuses provide a clear image of pole-zero evolutions for the nasalized vowels.

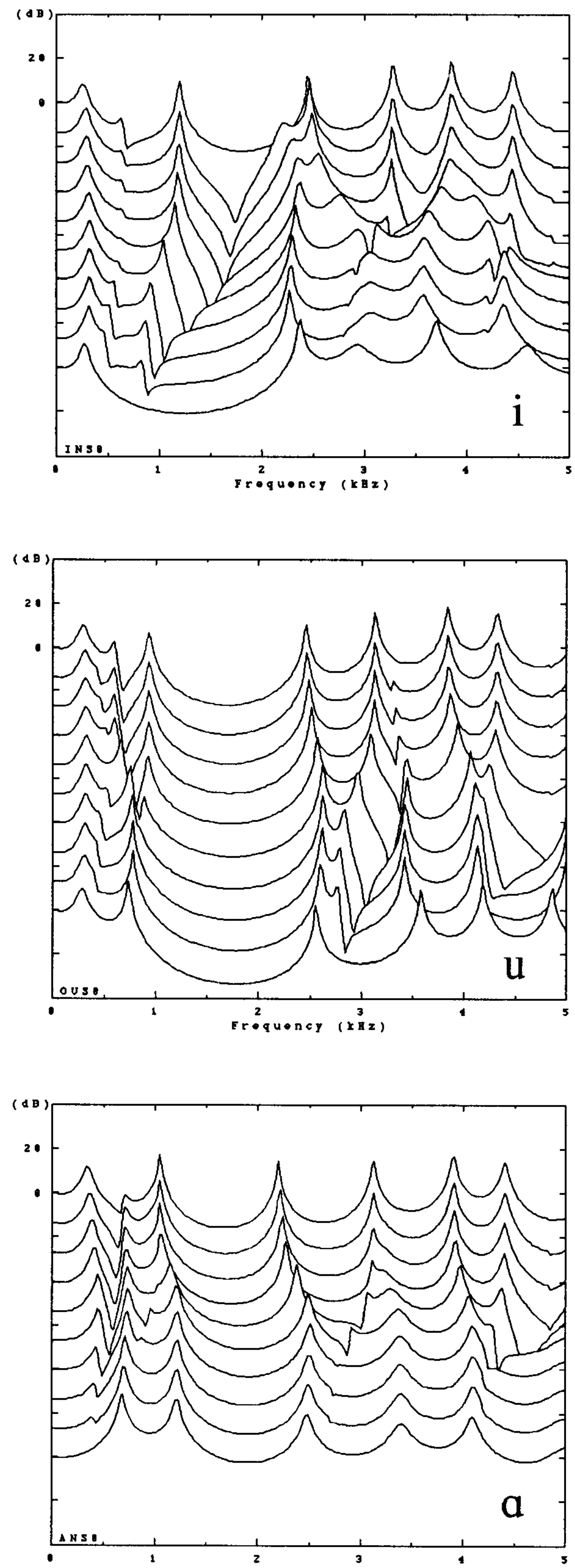

FIG. 11. Simulated transfer functions for nasalization of three vowels [i], [u] and [ɑ] with a sinus volume of 18 cm^3.

However, from knowledge of the complexity of the nasal tract labyrinth, it seems unrealistic to neglect the sinus cavities (mainly the maxillaries). We present here a simulation result (Fig. 11) in which the maxillary sinuses were taken

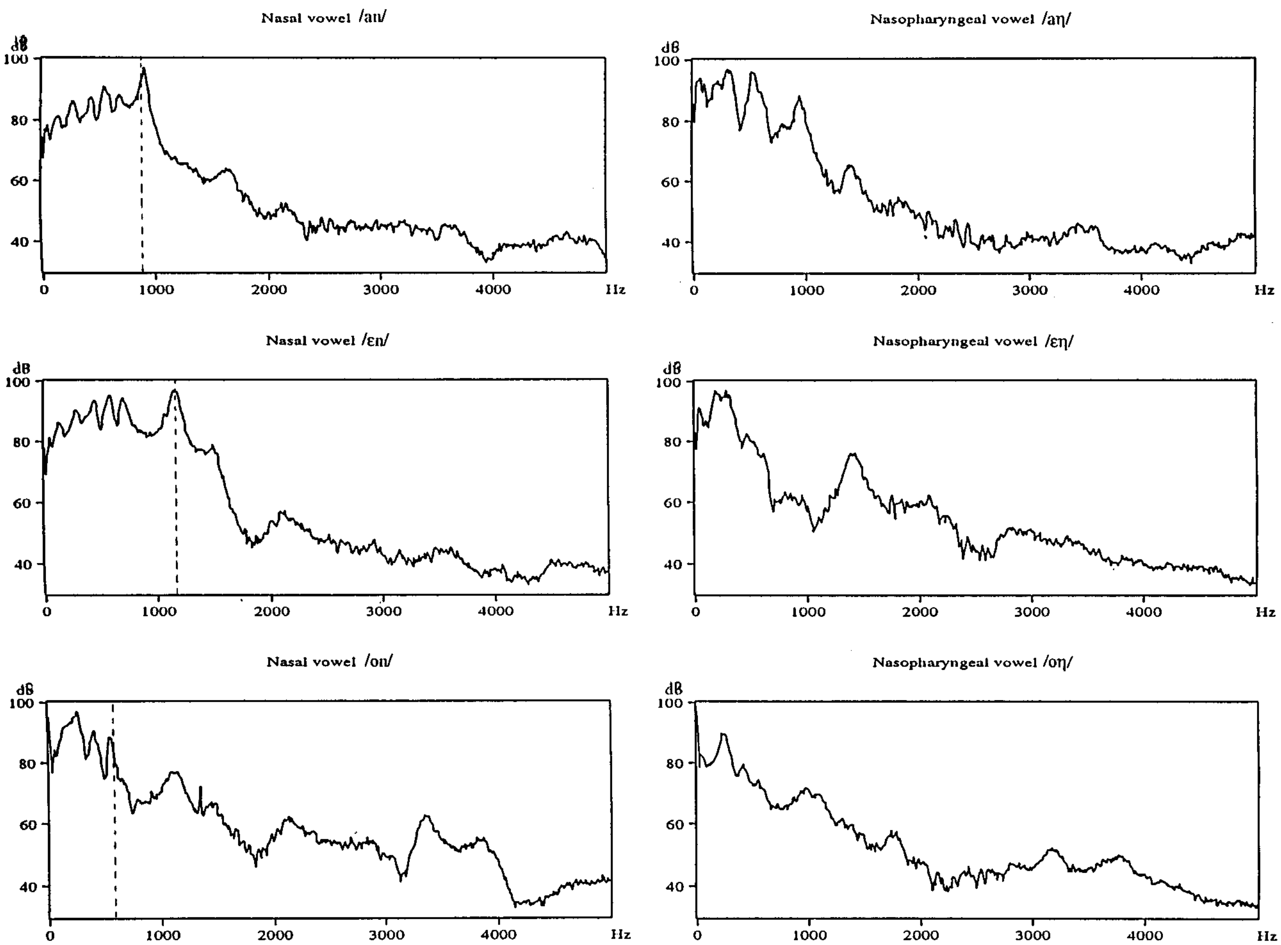

FIG. 12. Measured French nasal vowel transfer functions for [ɑ̃, ɛ̃, ɔ̃] and their close pharyngonasal transfer functions [aŋ, ɛŋ, ɔŋ].

into account. Due to the large variability of sinus sizes, and consequently of their acoustic properties, we took as an example a sinus having a volume of 18 cm^3 and a resonance frequency of about 650 Hz.

Comparing these results with Fig. 9, we can see that a supplementary pole-zero pair, resulting from the presence of the sinus, is added to the transfer functions, thus slightly changing their structure. However, the basic pattern of the pole evolutions are preserved in the simulations with this sinus. The main effect of this sinus seems only to be an addition to the complexity of the nasal spectrum.

E. Measured French nasal vowel transfer functions

It is of great interest to measure true French nasal vowel transfer functions. To do this, a series of acoustic transfer function measurements was carried out with the same experimental setting. In the experiment, five of the nine subjects were asked to pronounce a nasal vowel and to maintain the position after stopping the pronunciation. The data acquisition is performed at this instant (initiated by the subject himself). The microphone is placed halfway between the mouth and the nostrils, close to the face. Figure 12 shows three typical examples of these measurements concerning the French vowels [ɑ̃, ɛ̃, ɔ̃] compared with their close pharyngonasal configurations [aŋ, ɛŋ, ɔŋ] for the subject TB.

The characteristics of these measured curves correspond to descriptions found in the literature (Delattre, 1954; House and Stevens, 1956; Fant, 1960). These transfer functions present a complex pattern of peaks, very similar to that obtained in the pharyngonasal case. Several peaks in the low-frequency range even show the same peak value as for the pharyngonasal transfer functions. The main difference among the nasal vowels can be found in the distance between the first peak and the peak in the 1000-Hz region. The plateau range is about 250–700 Hz for [ɔ̃], 250–950 Hz for [ɑ̃], and 250–1200 Hz for [ɛ̃], the lower limit of which is the pharyngonasal first peak. The flatness of the plateau is certainly due to the contribution of the sinuses. It seems that the oral tract contributes toward the resulting variation in the peak around 1000 Hz. In the case of [ɔ̃] the effect of this contribution is so strong that the 1000-Hz peak is considerably attenuated. The oral tract, being the only variable part, is tuned to produce a maximum distinction between different nasal vowels. This is consistent with the fact that the oral part of a French nasal vowel does not correspond to any true French oral vowel (see Zerling, 1984). Another characteristic of these measured transfer functions is the attenuation or even the absence of energy for frequencies higher than 2000 Hz. This may be due to the coupling with the nasal tract which enhances the low-frequency range.

IV. CONCLUSIONS

The introduction of a [ŋ]-like configuration as a target for vowel nasalization seems to offer a powerful tool for analyzing acoustical properties of nasal and nasalized vowels. This is essentially based on the fact that the pharyngonasal tract, with reasonable simplifications, can be seen as a single tube and can be characterized by the first two resonance frequencies. This modeling allows us to emphasize the main characteristics of the pharyngonasal tract (the two peaks) with respect to other secondary effects caused by the great complexity of the nasal tract (mainly the presence of sinuses and asymmetry). The relative stability of the target, i.e., the small variation in the frequencies of the two peaks, seems advantageous for the characterization of the nasalization phenomena.

The new measurements carried out confirm the resonator nature of the low-frequency peak of the pharyngonasal tract. This result favors the proposition of the nasal target. In fact, it is certain that the sinuses and the complex form of the nasal tract affect the transfer function of the nasal tract, resulting in many peaks/dips, as we can see in all measurement data. However it seems clear that the main low-frequency peak, linked to the pharyngonasal tract, plays a fundamental role for a nasalized sound.

With the concept of the nasal target, the nasalization of vowels is considered as a dynamic trend from an oral configuration toward the pharyngonasal configuration. The acoustic properties of the latter allow a topological schema of pole-zero evolution patterns to be established for the nasalization of the 11 French vowels. It now seems possible to propose a common strategy for the nasalization of all vowels, so a ''true'' nasal vowel can be placed in this nasalization frame. This study is thus a fundamental step toward the interpretation and modeling of real nasal vowel spectra, although the high complexity of the latter requires more elaborate simulations, in which the nasal tract would be better modeled, and the effects of the source be taken into account.

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APPENDIX: ACOUSTICAL MODELS OF THE FIRST PHARYNGONASAL PEAK

In this Appendix, the use of a 0.6-cm^2 nostril output area in our simulations will be justified and some problems which occurred when modeling the first pharyngonasal peak will be discussed.

It is easy to show that a large nostril output (e.g., 2 cm^2) raises the first resonance frequency (to about 420 Hz instead of 300 Hz), shifting the pharyngonasal zone to the center of the acoustic space in the $F1-F2$ plane and giving a rather different result with respect to the available measurement data. The use of a value of 0.6 cm^2 is essentially based on this consideration. It is difficult to validate this choice: without accurate anatomic data on the nasal tract, values given in the literature vary from 0.23 cm^2 (House and Stevens, 1956) to 2 cm^2 (Maeda, 1982b). We remark that the value of 0.6 cm^2 may occur at *linen nasi* (the most constricted passage in the nostrils, see Palacios *et al.*, 1980, SA-12-A). This choice is also guided by the fact that acoustic sensitivity to anatomic variations decreases slowly up to 0.5 cm^2 which seems to be a ''boundary.'' According to Lonchamp (1988), it is unreasonable to suppose a smaller area for the nostril output.

In our experiment, only one subject was capable of putting an 8-mm-diam tube in his nostrils without pain (0.5 cm^2 area for each nostril, so 1.0 cm^2 for the two). It is thus reasonable to consider an area in the range of 0.6–1.0 cm^2. The recent measurements made by Dang *et al.* (1994) show that the nasal tract presents a region of relatively small area (about 0.8 cm^2). This supports the small nostril hypothesis.

Given that the first pharyngonasal peak has a resonator nature (see Sec. II), a simple model can be used to characterize this peak, such as the Helmholtz resonator. As we know, in the case of a hard-wall resonator, the resonance frequency is determined by only three parameters: the area and the length of the neck, and the body volume of the resonator. As discussed above, we only consider the range of 0.6–1.0 cm^2 for the neck area. It is difficult to evaluate the effective neck length of the resonator. The method proposed by Fant (1960, p. 80) for the area function used in our simulations gives an equivalent length of 2.7 cm. Measured nasal tract area functions by Dang *et al.* (1994) for /m/ and /n/ also show that the narrow region at the nostrils has a length of about 3 cm. From these data, we consider a value of 3 cm for the neck length.

We now evaluate the volume of the resonator as a function of its resonance frequency (Fig. A1). In order to take into account the wall vibration effects, the resonance frequency is corrected using two typical wall vibration frequencies (150 and 220 Hz). For each frequency, three curves are drawn which correspond to the following neck areas: 0.6, 0.8, and 1.0 cm^2. An extreme sensitivity can be seen in the volume-frequency relation with respect to the wall vibration frequency. The volume required to obtain a resonance frequency of 250 Hz is not less than 150 cm^3 for $F_{\text{wall}}=150$ Hz and becomes considerably larger for $F_{\text{wall}}=220$ Hz.

The real pharyngonasal volume estimated from measurements of three-dimensional shapes of the nasal cavity by Matsumura (1992) gives values of 70 cm^3 for the [aŋ] configuration and 120 cm^3 for the [iŋ]. Recent measurements by the magnetic resonance imaging technique (Dang *et al.*, 1994) show that the shape of the nasal tract in living condition can be different from that of previous data. These values appear insufficient to obtain a low resonance frequency (typically 250 Hz) according to the Helmholtz formula with the wall vibration correction (Fig. A1). Due to the large complexity of the nasal tract, it is possible that an oversimplified model such as that presented by the Helmholtz formula is unsuitable for the modeling of this cavity.

It seems unlikely that the required volume is obtained

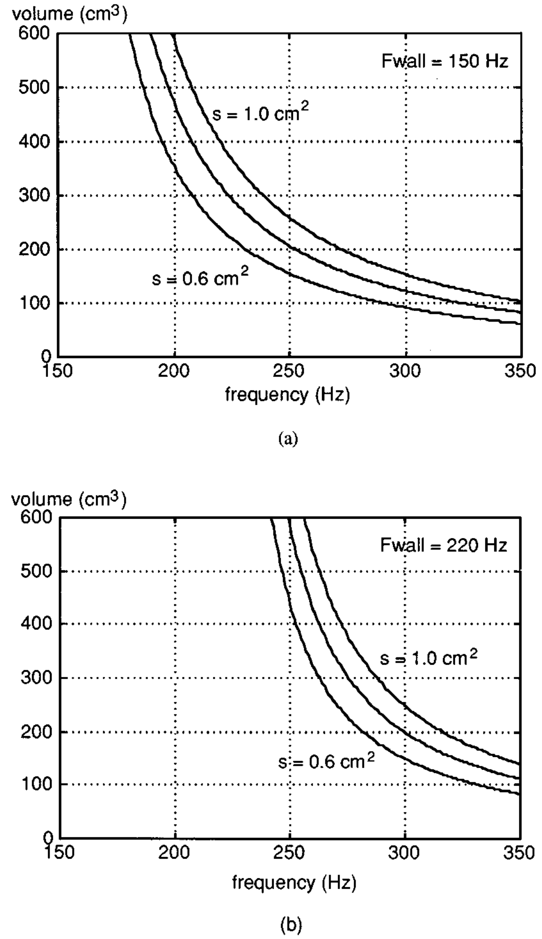

FIG. A1. The volume of a Helmholtz resonator as function of its resonance frequency. The neck length is 3 cm and the neck areas are 0.6, 0.8, and 1.0 cm^2, respectively, for the three curves in each figure. The wall vibration effects are taken into account by using the formula mentioned in Sec. II C. Two values of F_{wall} are used to calculate these curves: 150 Hz (a) and 220 Hz (b).

from any single cavity other than the nasal tract. The sinuses can be disregarded since a single sinus is generally smaller than 20 cm^3 (Takeuchi *et al.*, 1975). We know that the cranial cavity has a volume of 1300 cm^3 for females and 1700 cm^3 for males. However, this cavity is filled with brain and cephalic liquid which are assumed to absorb the sound vibration. Such a role for the cavity is thus negligible. We now examine other possibilities where several cavities act together in the production of the low-frequency peak.

A recent study has reported the existence of an oral-nasal coupling through the closed velum (Suzuki *et al.*, 1992). Anatomy studies show that the walls between the different face cavities are very thin, even translucid. It could be supposed that the coupling phenomena through the velum can be applied to this case given the thiness of the walls. Further studies are necessary to elucidate this point.

If the volume of sinuses does not contribute to the total volume in an additive manner since the sinus cavities have their own necks, is their connection to the nasal tract the cause of the first peak, as proposed by other authors? The sinus, which behaves like a Helmholtz resonator coupled with the nasal tract, introduces a pole-zero pair which can lower the first peak (Maeda, 1982b). However, a detailed examination has shown that the use of sinuses to obtain the low-frequency peak (450 Hz) in simulating the nasal tract would produce no great difference in the first peak (400 Hz) of the pharyngonasal tract (Feng *et al.*, 1986). The sweep-tone measurements available for nasal and pharyngonasal tracts have clearly indicated that the first peaks in the two cases are quite different (450 and 300 Hz, respectively, Lindqvist-Gauffin and Sundberg, 1976; Fujimura and Lindqvist, 1964). This supports the hypothesis that the first peak in the nasal (or pharyngonasal) tract has a resonator nature, since its frequency decreases considerably when the pharynx is connected to the nasal tract.

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