Vocal Compensation: An Ultrasonic Study of Vocal Fold Vibration In Normal and Nasal Vowels

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Hypernasality is a vocal resonance disorder in itself, but the means by which a person attempts to compensate for hypernasality due to velopharyngeal insufficiency have been implicated as possible causes of laryngeal pathology (*15*). Two lines of reasoning can be advanced in support of this possibility. The first derives from theoretical and experimental studies on the nasalization of vowels. Electrical analog studies (*6, 13*) have shown that changes in the resonating characteristics of the vocal tract, resulting from oronasal coupling, can alone cause a drop of 5–10 dB in overall vowel amplitude. A person with hypernasal resonance is thus operating at a considerable acoustical disadvantage, and in order to be heard must compensate by greater vocal effort. This point has been discussed in some detail by Curtis (*5*). There is a possibility that the additional vocal effort required actually causes vocal abuse. The second line of reasoning considers that the effort to achieve adequate velopharyngeal closure with an inadequate mechanism, may cause a person to "compensate laryngeally for velo-pharyngeal distress" (*15*). Here the emphasis is not on increased vocal effort, but on the possibility of laryngeal tension accompanying articulatory effort.

Until recently the larynx has been deemphasized in discussions of vocal (and vowel) resonance. Independence of vocal source, and vocal tract resonance characteristics has been one of the assumptions made, not only in quantitative theoretical models of vocal production, but also for articulatory voice quality classification systems, e.g. Laver's (*14*). That vocal source and tract resonance characteristics are not completely independent has been shown by Flanagan (*8*). However the interaction is described purely in terms of acoustic radiation load. Another possibility for interaction is in the mechanical pull exerted on the larynx by the positioning of the oral structures for different vocal tract configurations. Although in both cases oronasal coupling, producing nasalization, would have an effect on minor details of vocal fold vibration, it seems intuitively rather unlikely that acoustical and mechanical influences of this type would be

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responsible for laryngeal disorders secondary to nasal voice quality. However, the effort to compensate for the effect of velopharyngeal inadequacy, either by speaking louder or straining to achieve better velopharyngeal closure, could bear a causal relationship to coexisting pathology, such as vocal nodules, which are known to result from abusive vocal practices.

Multiple acoustical correlates to the nasalization of vowels have been identified, but they depend on the particular vowel spoken, and the degree of oronasal coupling. Any of the acoustical features noted could also be accounted for by vocal source or articulatory factors. In particular, a change in open quotient of the vocal fold vibratory cycle could theoretically cause the spectra of nasalized and non-nasal vowels to appear similar (*7*). Since on theoretical grounds the laryngeal component of voice cannot be determined from the recorded voice, a direct indication of laryngeal functioning is necessary to show the effect of attempts to compensate for nasality.

The present study was undertaken primarily (1) to see what changes in the details of vocal fold vibration result when the intensity of a nasalized vowel is matched to a non-nasal vowel. The expectation was that features of vocal fold vibration which are associated with louder phonation would be found for nasalized vowels. As a secondary aspect (2) evidence for a uniquely nasal mode of vocal fold vibration was looked for as well as (3) checking whether any visually obvious features of the acoustical spectrum of the voice would correspond with particular features of vocal fold vibration.

Procedures

SUBJECTS. The subjects chosen were normal adults and children, free of respiratory infection, and with normal voice quality. Children were specifically included, because there is very little physiological information available on children's voices, yet decisions on treatment for hypernasality are made during childhood. Four children were studied (three 11 year old boys, and one 6 year old girl). In addition 4 adult males, and 3 adult females were included.

MEASUREMENT TECHNIQUES. The ultrasonic method of assessing vocal fold vibration employs continuous-wave ultrasound, which is beamed laterally into the larynx by one transducer, and received by a second transducer on the opposite side (*11*). The technique is non-hazardous, painless for the subjects, and is relatively simple to use, since it requires only two external probes (the transducers) to be in contact with the skin of the neck.

With proper positioning of the transducers, the only transmission pathway through the larynx is through the closed vocal folds; when the vocal folds are open the ultrasound is reflected back from the glottal rim. Thus the received signal during phonation appears as a series of ultrasonic pulses. For recording, the received ultrasonic signal is treated as an RF amplitude modulated carrier, which is demodulated, so the recorded signal is the envelope of the received signal. Initial recording was made on an FM tape recorder, with the audible voice (microphone signal) on a second channel. Mouth to microphone distance was maintained constant by a head positioner. At a later time the data were read out on a light beam oscillograph (Visicorder) for analysis.

The form of the oscillographic raw data is shown in Figure 1, with the microphone signal above and the envelope of the ultrasonic signal below. Complete information about vocal fold vibration is not available from this type of data, but it is possible to determine the duty cycle or open quotient—the proportion of each vibratory cycle during which the vocal folds are open. It is also possible to compare the time relationships between the two waveforms and thus identify the time of major excitation of the vocal tract (*9*). Both types of information permit inferences about the acoustical nature of the vocal tone.

Since the ultrasonic signals contain information on the vertical phase difference of vocal fold vibration (*10*), there is potential for error in the measurement of open quotient, if received signals of small amplitude are not excluded. Small amplitude signals result from the ultrasonic beam passing through only the upper or lower edge of the vocal folds. This may happen, for example, if the larynx moves vertically during a sustained

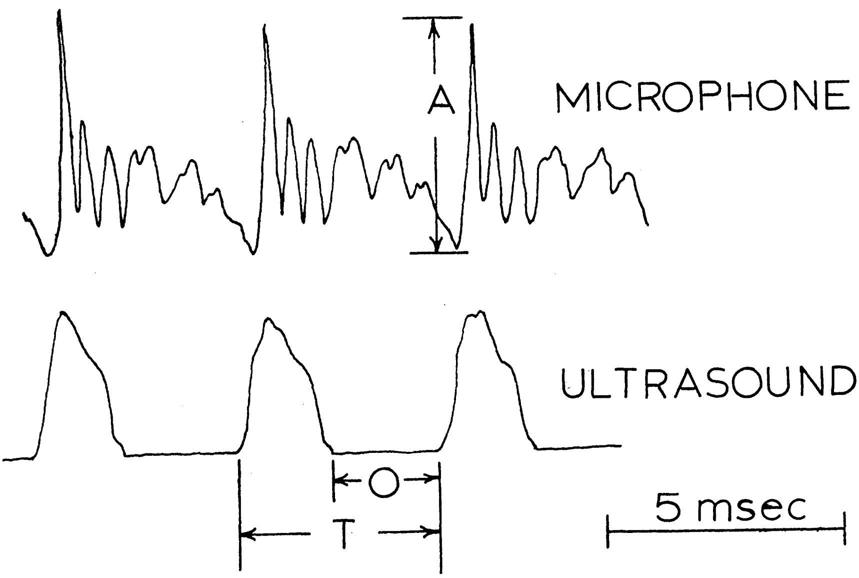


FIGURE 1. Tracing of oscillographic raw data, showing measurements made: period of the vibratory cycle (T), duration of the open phase (O), and sound pressure amplitude of the corresponding cycle in the microphe signal (A). The sharp rise in sound pressure (microphone signal) follows the instant of vocal fold closure after a delay of approximately .5 msec required for sound transmission through the vocal tract.

phonation. Small amplitude signals can also be seen for transitory vocal fold vibrations occurring as part of vowel onset and cessation, when the vocal folds manage to touch during vibration, but the steady state vibratory pattern is not reached. By considering as acceptable for analysis only those signals which were approximately as large in amplitude as the maximum seen for that individual, errors due to vertical phase difference were avoided, and a criterion provided for determining starting or stopping of the vowel.

Theoretically there should also be some variability among measurements made with transducers located at different positions in the horizontal plane. However, pilot work indicated that small differences in horizontal transducer placement did not produce a measurable difference in open quotient, so long as extreme anterior or posterior placements were excluded. These placements can be identified, because at extreme anterior or posterior transducer locations part of the beam passes through a wall of the larynx. The received signal then has a continuous carrier, which appears as a dc component in the rectified signal. In children the length of the vocal folds is not much greater than the diameter of the ultrasonic beam (approximately 6 mm), so horizontal transducer placement becomes quite critical. Determination of correct transducer placement is greatly facilitated by monitoring the received signals (before demodulation) on an oscilloscope.

Open quotient was computed from measurements made on the oscillographic traces (see Figure 1). For each vocal fold vibratory cycle, the peak-to-peak amplitude of the corresponding cycle in the speech wave was also measured. The open quotient and amplitude data for each cycle were then plotted graphically to show open quotient as a function of vocal intensity. Since several cycles in a given vowel phone often had the same open quotient and amplitude values, each point generally represents more than one vibratory cycle. Data from repetitions of a given vowel utterance were plotted on the same graph. Thus at any amplitude, variability in open quotient represents measurement error, cycle-to-cycle differences within a single vowel utterance, and variability between different vowel utterances. Sound pressure amplitude, appearing on the ordinate of the graphs, is expressed in millimeters on the oscillographic trace. Because of differences in recording and readout levels for different subjects, comparisons generally cannot be made between graphs for different subjects.

Acoustic spectra were made of the recorded vowels (amplitude-frequency sections produced on a Kay Sonagraph). Spectra for the nasal and non-nasal vowels of the same sound pressure amplitude were compared visually to check whether certain features might correlate with particular characteristics of vocal fold vibration.

Vocal Task. All of the results reported here are from sustained vowels spoken in isolation. Ideally, voice during connected speech should be studied, and the methodology used would permit that with some modification in approach. However, the experimental task becomes fatiguing after too long, especially when head position cannot be changed, so the more expedient method of sampling from sustained vowels was chosen.

Subjects were asked to say, not sing, one of the vowels /a, i, o, u/, and to sustain it while searching for the best transducer position on the neck. Many times the best transducer position was found only when the vowel was sustained for so long that the subject was beginning to run out of breath. For that reason the vowel was immediately repeated to make sure vocal samples were available from the beginning and middle as well as the end of expiration. The exact stage of the respiratory cycle was not monitored. The subject was then asked to say the vowel louder and louder until shouting, then softer and softer, etc., each time locating the best transducer position. For each vowel, more than one sample for a particular vocal intensity was available for analysis. Data on the full complement of vowels is not available for all subjects, however.

After recording with normal vocal quality, the entire procedure was repeated with two types of nasalization of the vowel: (a) assimilative nasality as in /ma/ and (b) nasal twang or whine. These two types of nasalization are not always distinguished in descriptions of nasality. When they are, whine may be mentioned as a dialectical variant, the nasal twang of certain New England accents (*12*), as a harsh, metallic sounding voice with a perceptually nasal component (*2*), or it may be labeled "hyperrhinolalia spastica" (*20*). In articulatory terms whine is said to be produced by "tightening the muscles in the upper part of the throat and drawing the tongue backward" (*4*). Whine is palpably different than assimilative nasality in terms of greater pharyngeal tension. In singing whine has been called a "twangy" as opposed to "honky" nasalized tone. Twang shows electromyographic evidence of greater levator veli-palatini action, and less vocalis and lateral cricoarytenoid action than honk (*18, 19*). The nasal quality in whine is not always attributed to nasal cavity resonance. For example, Boone (*2*) suggests that it may result from cul de sac pharyngeal resonance.

Subjects were instructed to produce one or the other type of nasalization by imitation and verbal description. For assimilative nasality they were asked to say /ma/ or /na/ and to sustain the vowel while "keeping the nose open." Whine was described as the voice a "crabby little kid" or "spoiled brat" uses when complaining. To the author's knowledge, there is no information on how reliably listeners are able to distinguish the two types of nasal quality. However, subjects did not express any uncertainty about whether they were, in fact, producing one or the other type according to instructions.

The vowels spoken were judged to be nasal or non-nasal by perceptual criteria during the recordings. The relationship between phonetic judgments of nasality and the actual presence of nasal resonance is not clear, however. There are reports of adjudged nasality when velopharyngeal closure is present, or when the velopharyngeal opening was the same as for a non-nasal vowel (*1, 3*). For this reason a test for nasal resonance during nasalization of vowels was made separately on several normal speakers, including some of the subjects used in this study. A contact microphone, commonly used for voice recordings from the throat, can pick up nasal vibration when placed against the side of the nose. The nasal vibration is marked for nasal consonants and both types of nasalized vowels, small or absent for other consonants and non-nasal vowels. Thus the nasalized vowels produced by subjects in this study can be safely assumed to represent true nasal resonance.

For the data to be interpretable it was necessary to try to control vocal pitch. This is difficult for people to do in speech, because the strong tendency is to raise fundamental frequency with increased vocal intensity. Subjects were constantly coached to maintain the same vocal pitch, and the only samples used for comparisons were within three semitones, including cycle to cycle variations in vocal fundamental.

The extent of mouth opening has a marked effect on vocal intensity. Whether mouth opening should be controlled depends on the purpose of a study. In this study the purpose was to discover whether there are laryngeal signs of increased vocal effort when the intensity of nasalized and non-nasal vowels are matched. If people in fact try to match intensity by greater mouth opening for nasalized vowels, the true extent of the laryngeal effect would be misrepresented if mouth opening were artificially controlled. The decision was made to allow mouth opening to vary naturally, but to also obtain comparative data for some subjects with mouth opening controlled by a bite block or tube between the lips. The bite block used was a short piece of hard dental wax, 4 mm thick. It was placed between the back teeth on one side to control jaw movement on the vowel /a/. An oval acrylic tube (2 cm^2 external area, 1.3 cm^2 internal opening) was placed between the lips and front teeth to control mouth opening for the vowel /o/.

Results

In any study of voice, individual differences can be anticipated, because the voice contributes to individual speaker recognition. Numerous interesting individual variations were noted, but certain common trends could also be identified.

The larynx is raised on whine. For assimilative nasality, if the position is different than for non-nasal vowels, the larynx is lowered. These effects were not quantified, but rather were observed by noting transducer placement search procedures. There was no measurement of tongue position in this study, but in view of the raised larynx for whine, we might infer that tongue position was raised also.

By far the most typical relationship between open quotient of the vocal fold vibratory cycle and vocal intensity for the three vowel conditions is illustrated in Figure 2. The filled circles, keyed as "nasal," refer only to assimilative nasality, with whine represented by x's. As vocal intensity increases, open quotient decreases—a trend which has also been found using other techniques for vocal fold study. At matched vowel amplitude, open quotient is smaller for the nasalized vowels, i.e., more like normal loud phonation. These general trends conform nicely to theoretical expectations, since greater vocal effort is necessary to produce an equally intense nasalized vowel.

Figure 3 contains examples of exceptions to the common trends. In Figure 3a and 3b it can be seen that open quotients for assimilative nasality are at times the same or greater than those for the non-nasal vowel. In this case there is evidently a different laryngeal adjustment used when producing the assimilative type of nasalization.

The values for open quotient at a given vowel amplitude are generally different for the two types of nasalization. The usual finding is that open quotient is smaller for whine (see Figure 2). An exception is shown in Figure 3c, where the open quotient values for assimilative nasality are lowest. Subject ET, in Figure 3c, was the only subject showing that trend throughout the whole intensity range. For other subjects, lowest open quotients occasionally occurred on assimilative nasality, even with mouth opening controlled, but not over the entire intensity range.

As was stated above, variability in open quotient at each vowel amplitude stems from several sources: measurement error, cycle-to-cycle variations, and repetitions of the vowel at the same intensity. Because different samples are represented, a direct indication of short-term reliability is present. Repetitions of the same nasality conditions at the same vowel amplitude yield similar open quotient results within a single recording session.

Mouth opening was controlled for some of the subjects, to see whether the findings would be materially different. On the whole, there was little change in the results, other than in the slope of the curves. With mouth opening controlled, open quotients decreased more rapidly with an increase in intensity, i.e., the slope of the curves was more toward the horizontal. This change is consistent with a wider mouth opening at higher vocal intensities when mouth opening is allowed to vary naturally.

Relative position of the curves for the three conditions was not usually affected by controlling mouth opening. There was one subject, however, for whom control of mouth opening caused a marked change (see Figure 3a and 3b). Sound pressure amplitudes for the two sets of data can be directly compared. The major differences are attributable to changes in open quotient values for assimilative nasality. For this subject, lip and jaw position are apparently important variables in one type of nasalization, and control of mouth opening caused compensatory production.

Figure 4 shows the similarity in results for the vowel /o/ spoken by a 6 year old girl, with and without mouth opening controlled. The recordings

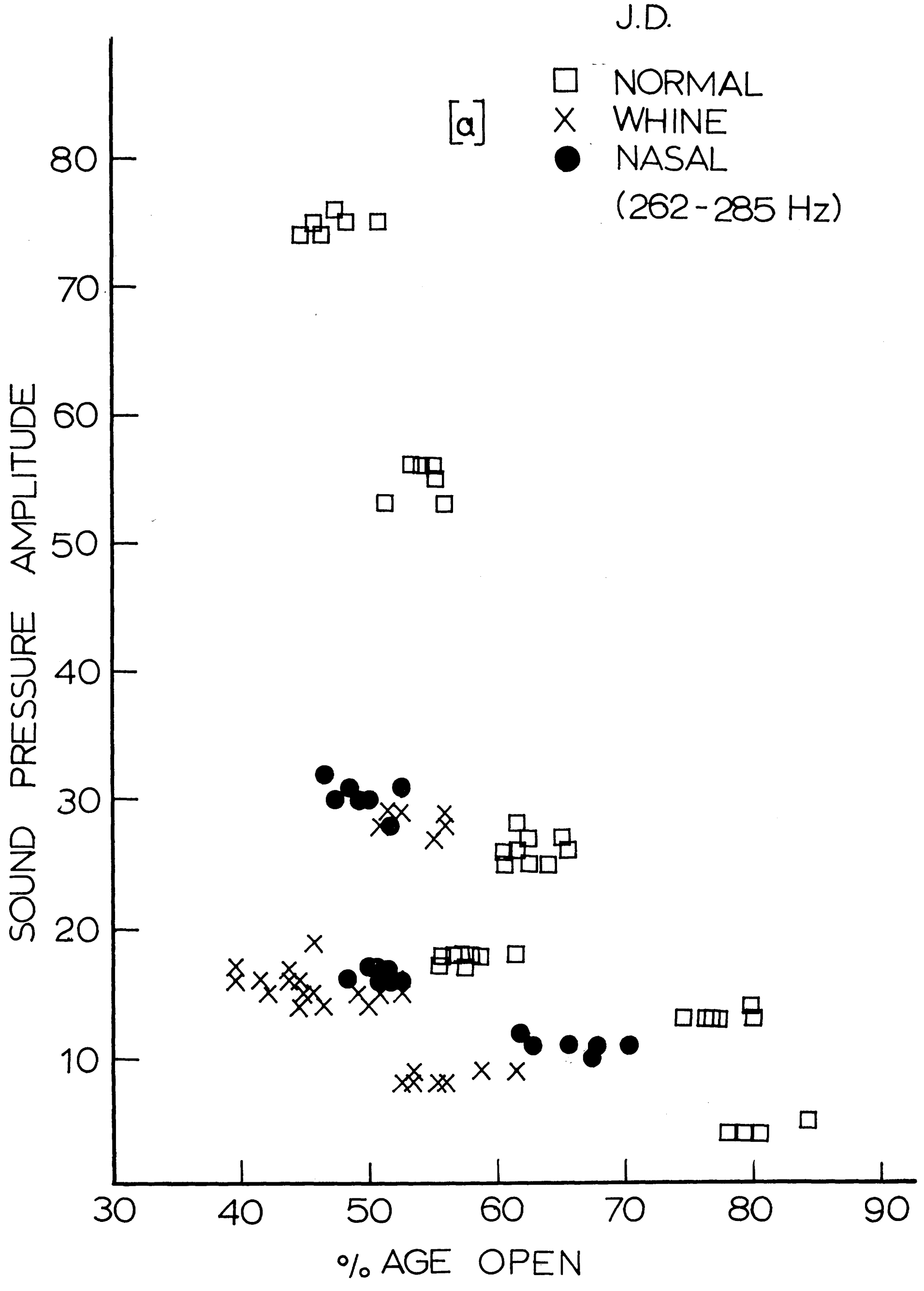


FIGURE 2a

FIGURE 2 (a–c). Graphs of percentage of time during the vocal fold vibratory cycle the vocal folds are open (open quotient) as a function of amplitude of the spoken vowel. Graphs (a) and (b) are for boys, age 11, graph (c) is for an adult male.

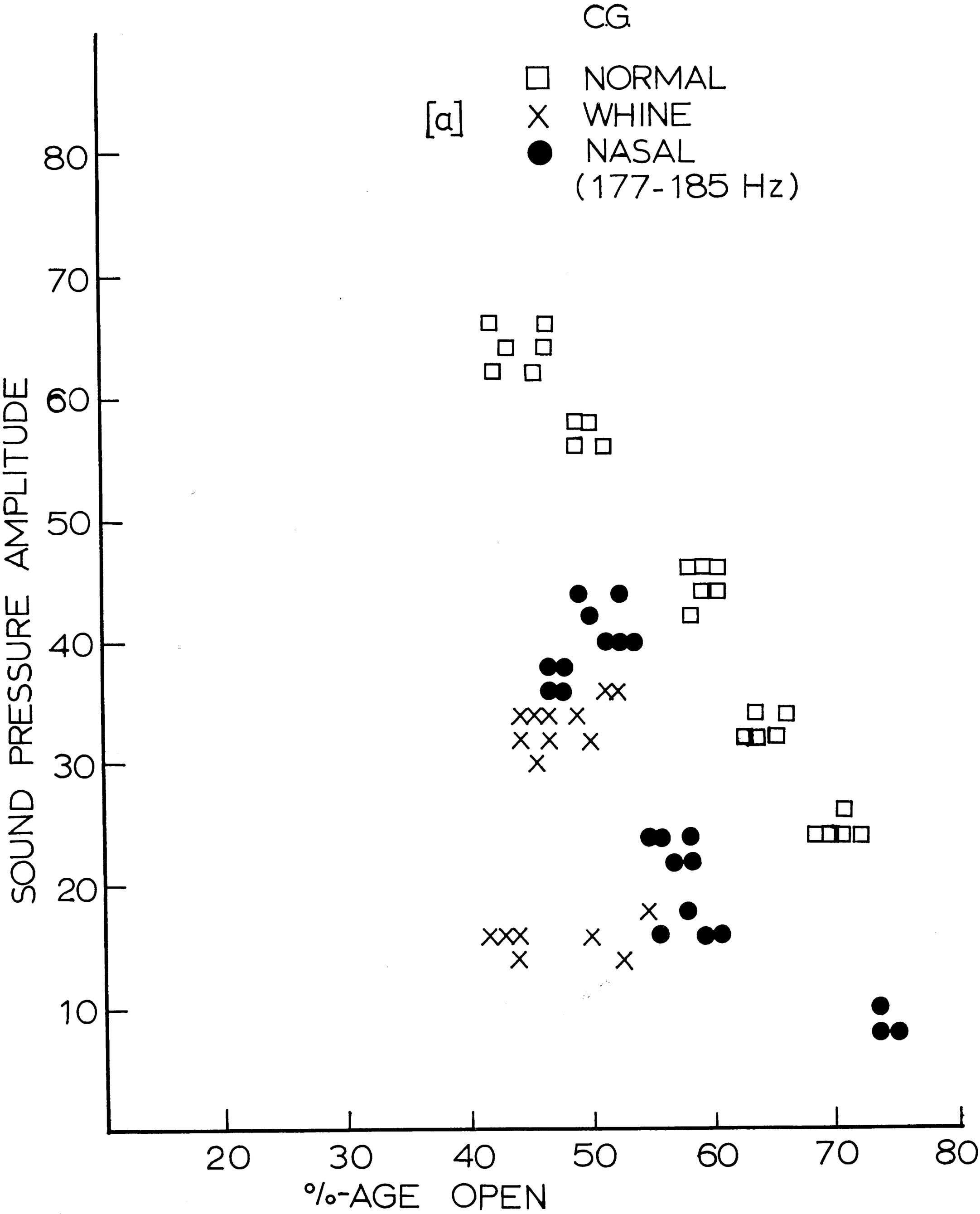

C.G.
NORMAL
[a]
WHINE
NASAL
(177-185 Hz)
SOUND PRESSURE AMPLITUDE
80
70
60
50
40
30
20
10
20
30
40
50
60
70
80
%-AGE OPEN

FIGURE 2b

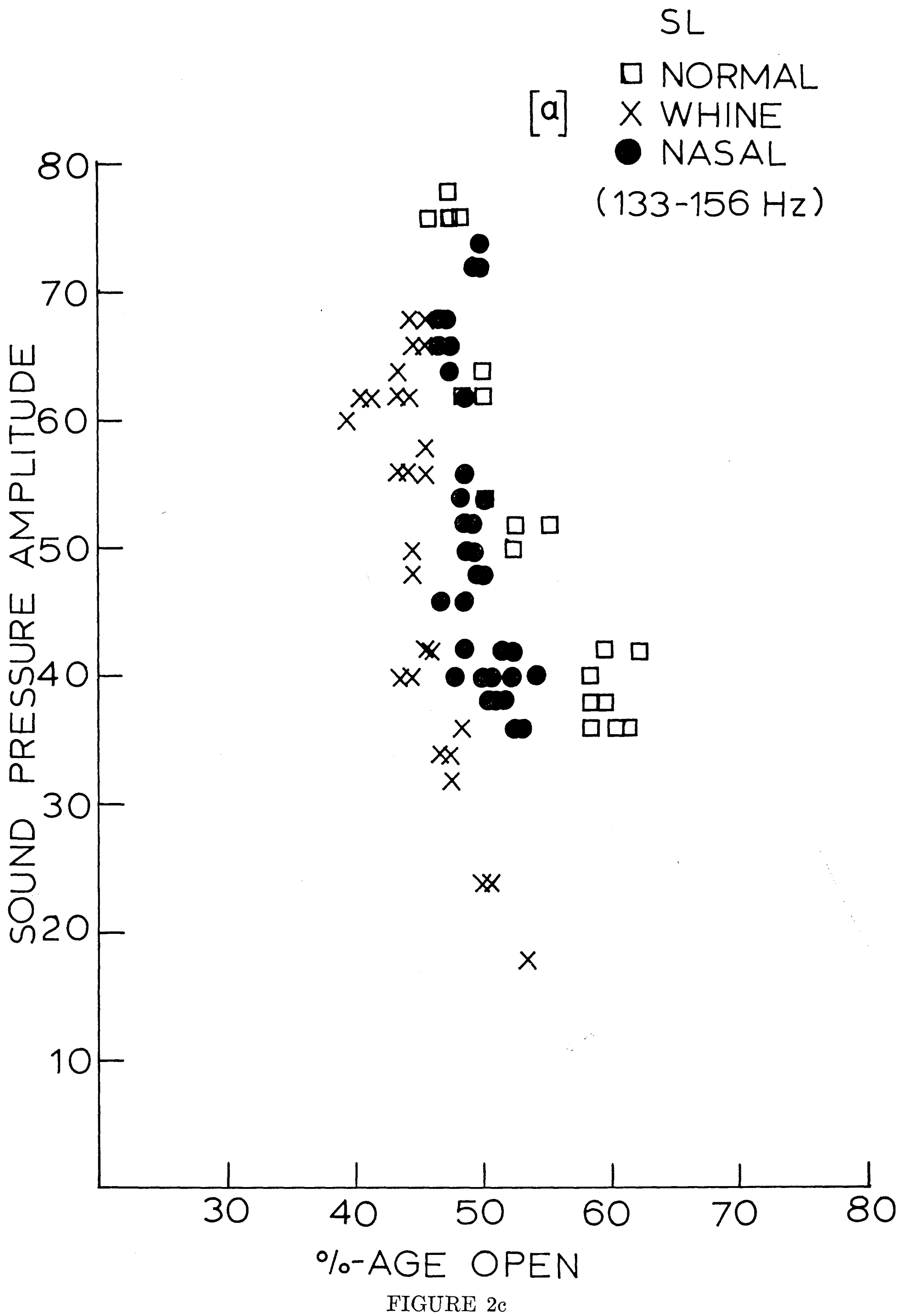

SL
NORMAL
WHINE
NASAL
[a]
(133-156 Hz)
SOUND PRESSURE AMPLITUDE
80
70
60
50
40
30
20
10
30
40
50
60
70
80
%-AGE OPEN

FIGURE 2c

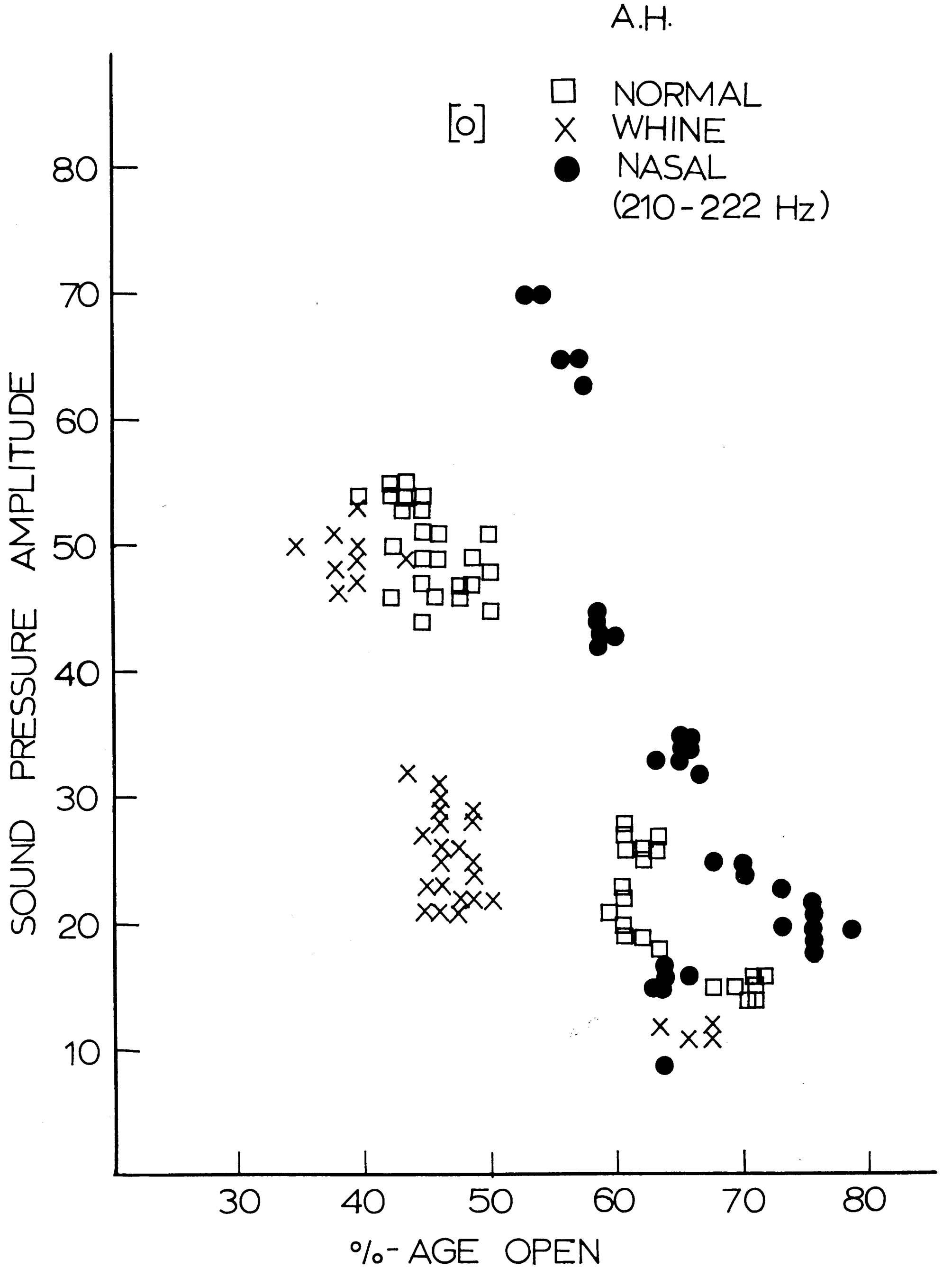


FIGURE 3a

FIGURE 3 (a–c). Exceptions to common trends. Graps (a) and (b) show evidence of compensatory production for assimilative nasality when mouth opening is controlled (boy, age 11). Graph (c) shows open quotient for assimilative nasality lower than for whine in data from an adult female.

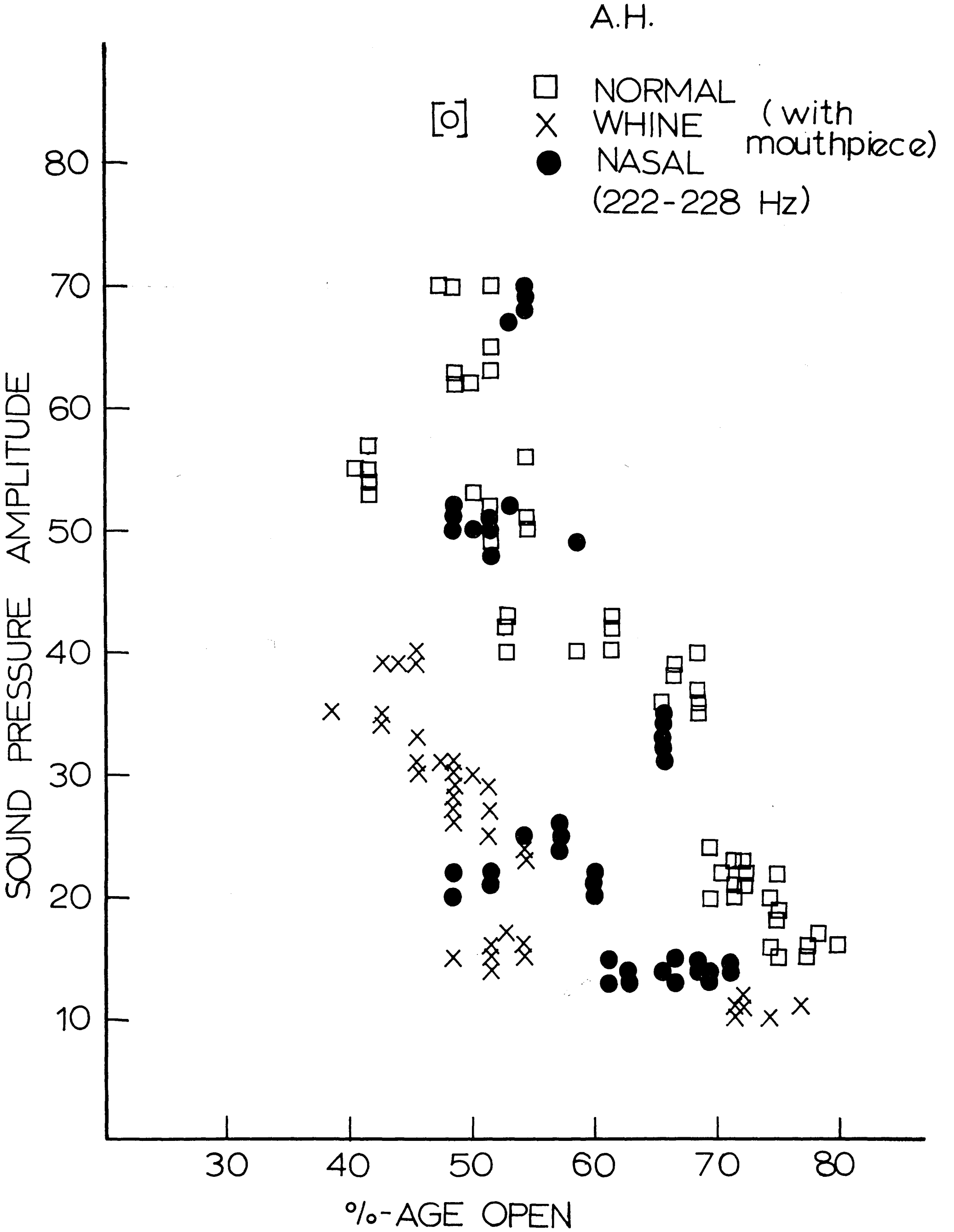

A.H.
[o]
NORMAL
WHINE
NASAL
(222-228 Hz)
(with mouthpiece)
SOUND PRESSURE AMPLITUDE
80
70
60
50
40
30
20
10
30
40
50
60
70
80
%-AGE OPEN

FIGURE 3b

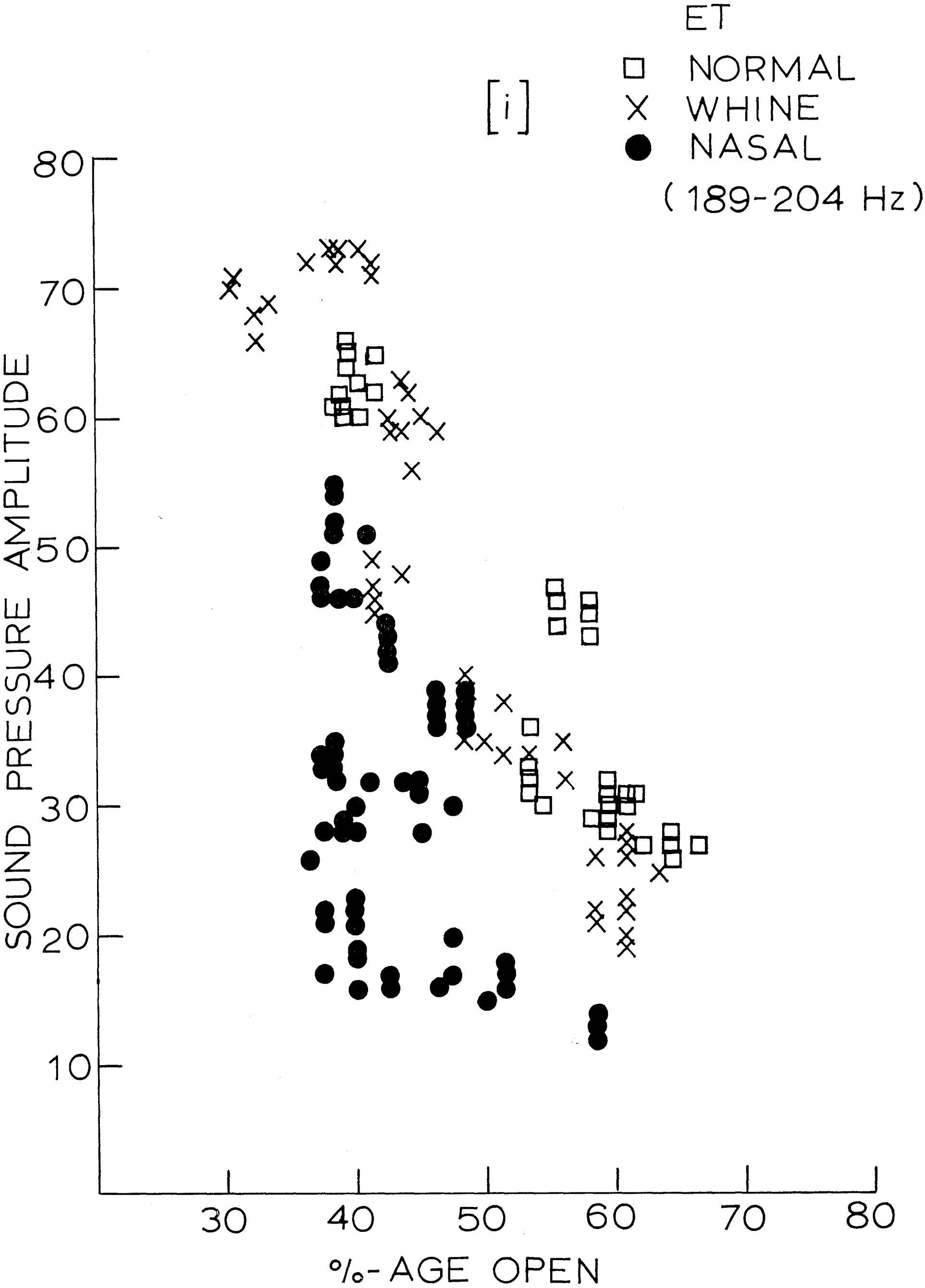

ET
NORMAL
WHINE
NASAL
(189-204 Hz)
[i]
SOUND PRESSURE AMPLITUDE
10
20
30
40
50
60
70
80
30
40
50
60
70
80
%-AGE OPEN

FIGURE 3c

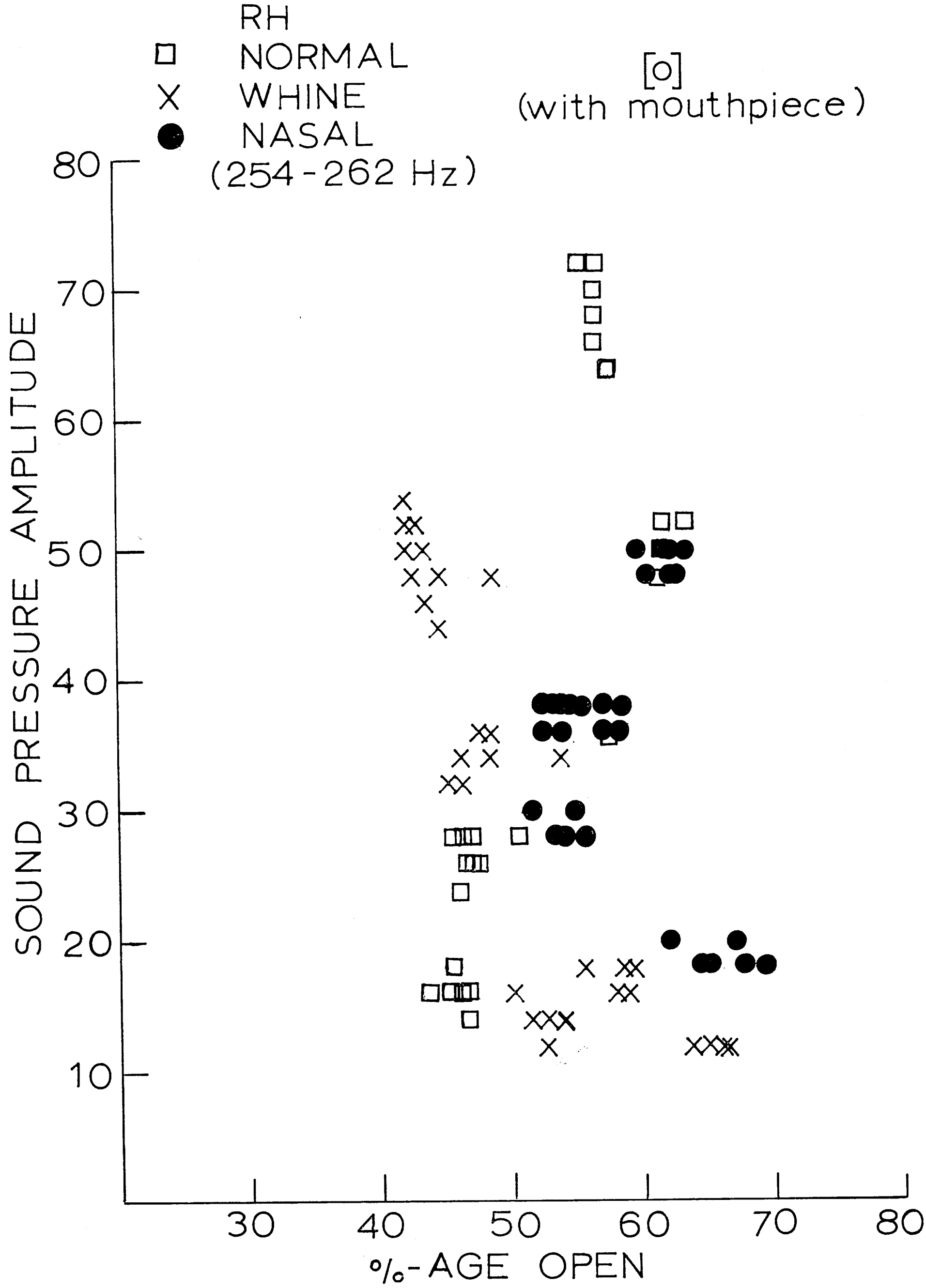
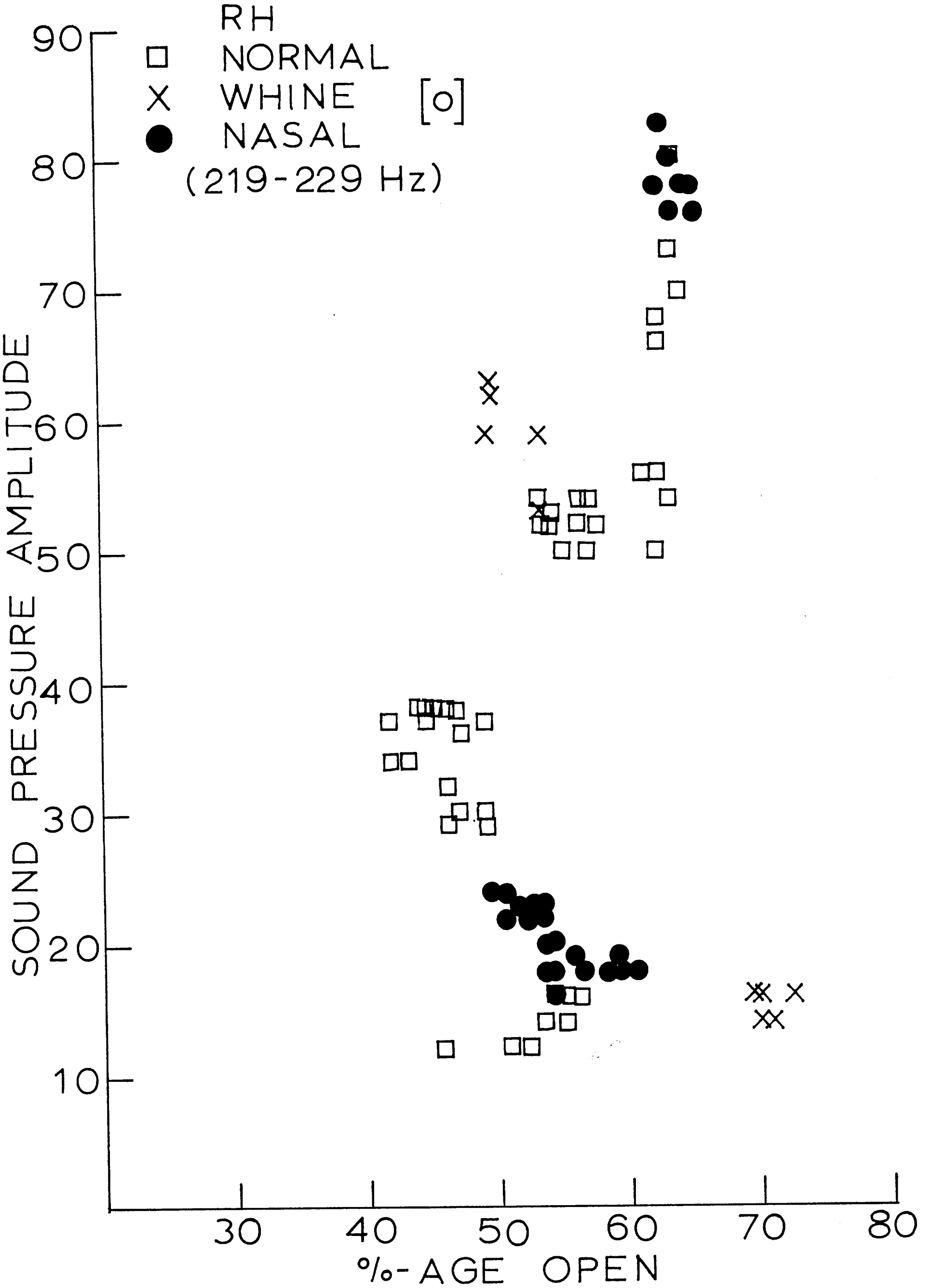


FIGURE 4a

FIGURE 4 (a–b). Data from a 6 year old girl, showing an unusual trend for open quotient as a function of vowel amplitude, not affected by controlling mouth opening. Graph (a) shows results when mouth opening is controlled.



RH
NORMAL
WHINE
NASAL
[o]
(219-229 Hz)
SOUND PRESSURE AMPLITUDE
90
80
70
60
50
40
30
20
10
30
40
50
60
70
80
%-AGE OPEN

FIGURE 4b

were made on different days, so the sound pressure amplitudes cannot be directly compared. The vocal pitch is also different for the two sets of data. The expected trend of decreasing open quotient with louder phonation is not apparent here, except for whine. Nevertheless, this unusual result is not due to spurious variations in mouth opening, because the same general pattern appears with mouth opening controlled. Other child subjects, who were older, showed trends basically the same as the adults.

Inspection of the time relationships between the microphone and ultrasonic signals revealed that in all cases the major excitation of the vocal tract occurred on vocal fold closure, (see Figure 1). Ultrasonic data of the type obtained in this study do not give a complete picture of vocal fold vibration, but it appears that the vibratory pattern for normal and nasalized vowels is at least grossly similar.

Acoustic spectra of the nasalized vowels showed the expected signs of nasality, i.e., reduction in amplitude of the first formant, extra formants, and diffuse spectral energy. However, the two types of nasality differed in that the spectra for whine showed a greater amount of energy in the frequencies above 1500 Hz. Even though the spectra were being compared for one of the unusual cases when open quotient was smaller for assimilative nasality, the spectral energy in the high frequencies was still greater for whine. Formant frequencies were sometimes different for the two types of nasality, but not always. The lower first formant amplitude and extra formants in the nasalized vowels were sufficient to consistently distinguish nasalized vowels from non-nasal vowels. The nasalized vowels in this study were grossly nasal, and there was always the ability to compare to the normal. With slighter degrees of nasalization, the differences in the spectra for nasal and non-nasal vowels might not be as distinct.

Discussion

The most controlled studies of nasalization are electrical analog studies. Oral configuration can be held constant for nasal and non-nasal vowel pairs, and the glottal excitation function can be the same also. Providing the same glottal excitation corresponds to controlling vocal effort and phonation type, e.g., breathy, tense, whisper, etc. For real speakers, however, phonatory details do not remain constant. Not only do people speak louder and softer, but different laryngeal sets can be used semi-interchangably to produce a relatively muffled, or strident voice quality. There is evidence that this ability is used to contribute to linguistic stress contrasts (*16*), with greater glottal tightness present on stressed syllables.

The results of this study revealed that, in general, open quotients for the two types of nasality differ when vowel amplitude is matched. Moreover, even with mouth opening controlled, open quotients for nasal vowels may coincide with those for normal vowels. In this latter case particularly, it is evident that phonatory details are different than for the normal vowel, i.e., toward a more "breathy" type of phonation perhaps. In view of the differences in open quotient and laryngeal position (raised for whine) between the two types of nasality, it is also likely that phonation is different for whine and assimilative nasality. This conclusion is not inevitable from the data presented, since different degrees of velopharyngeal opening may also have been present. However, electromyographic data (*19*) indicate that velopharyngeal opening may be smaller for whine, based on slightly greater levator veli-palatini activity for twangy as opposed to honky phonations. If velopharyngeal opening is smaller, less vocal effort should be necessary for matching intensity to a non-nasal vowel, and the open quotient should thereby be larger than for assimilative nasality. Since the opposite trend was noted, a distinct laryngeal component to whiny voice quality is suggested.

Saying that phonatory details for nasal vowels are different from normal, or that there may be a laryngeal component to whiny voice quality, does not imply that there is a peculiarly nasal type of vocal fold vibration, i.e., that the glottal source may contain cues to nasality in itself. From the evidence available, there is no way to distinguish glottal excitation for nasal and non-nasal vowels, that could not be accounted for by other factors.

The lowest values of open quotient are associated with the nasal quality whine, although there are some striking exceptions. The nasal whine has a perceptually strident quality, and the acoustic spectra show a greater concentration of energy in the high frequencies. However, lowest open quotients at times occurred on assimilative nasality, when the relative concentration of energy was in the lower frequencies, and the high frequency energy was not as pronounced as for whine. It may be that the marked high frequency spectral energy for whine is largely attributable to vocal resonance (not necessarily nasal cavity resonance), rather than to glottal source characteristics. Reduced open quotients per se may not be an adequate or consistent index of the presence or spectral location of unusually strong higher partials (sharpness) in the glottal source. Exceptions are being dwelt upon here to emphasize that reduction of open quotient cannot be predicted with certainty from comparison of the acoustic spectra for the two types of nasal vowels. However, the general trend of lowest open quotients occurring on whine still holds.

Although the data are suggestive only, the following theoretical framework might be proposed for the purpose of structuring further research: lowest values of open quotient at a given vowel amplitude represent a type of phonation characterized by glottal tightness (strong muscular adductory forces). Further, it might be proposed that this particular feature of glottal tightness, not merely increased vocal effort, contributes to vocal abuse leading to hoarseness, harshness, and vocal nodules secondary to hypernasality.

The unusual results from the 6 year old girl raise the question of whether the phonation of young children is fundamentally the same as in older children and adults. Van den Berg (*17*) has remarked on the greater efficiency of children's voices. This suggests the possibility of isolating criteria for vocal maturity, other than vocal mutation at puberty, for example, whether or not phonatory activity reveals the same trends as the adult population. It also suggests that major decisions on secondary surgical or dental treatment for hypernasality may require consideration of the degree of vocal maturity. Much more research on the characteristics of children's voices is indicated.

A different experimental approach could have been taken, using the same type of data to answer slightly different questions, or by providing more rigid controls on some aspects of the experimental situation. The possibility of sampling vowels in speech rather than as sustained phonations has already been mentioned. Since much voice research is done with a non-articulated vocal task, and the results simply assumed to apply to voice in speech, replication of these results for a speech context would add a great deal. A common sound pressure reference was not used, so comparisons across subjects could not be made. Statistical comparisons across subjects would provide normative information, however, there is likely to be great variability. Nevertheless, normative data should be sought, using a much larger number of subjects than studied here.

In this study, comparisons could be made among different voice qualities produced by the same individual. Extension of the findings to a clinical diagnostic situation, where a nasal voice quality must be judged in absolute terms, is not justifiable until evidence is available that the same distinctions can be made under those conditions also.

Summary

Characteristics of vocal fold vibration were investigated ultrasonically to determine the effect of vocal effort required to match intensity of nasal to non-nasal vowels. Subjects were normal adults and children. Results showed that the open quotient of the vibratory cycle is generally lower for nasalized vowels. In addition, two types of nasalization can be distinguished on the laryngeal level.

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