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SOME RELATIONSHIPS AMONG VOCAL INTENSITY, NASAL SOUND PRESSURE, AND NASAL TRACT COUPLING IN A SINGLE CLEFT PALATE SPEAKER

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CHAPTER I

INTRODUCTION

In recent years, researchers have paid increasing attention to the investigation of the physiologic and acoustic correlates of nasality. This interest has arisen for several reasons. First, the measurement of nasality has been accomplished traditionally through the use of rating scale procedures which rely on averages of ratings assigned by varying numbers of judges. While these judgments are admittedly valid, in that nasality by definition is what the listener perceives as nasality, certain studies (76, 79) indicate that judgments of nasality may be confounded by the presence of misarticulations, phonatory disturbances, or other quality deviations. The question arises, therefore, whether the judge who is asked to rate nasality is responding solely to nasal voice quality or simply rating the degree of "speech difference" which is presented by the speaker. Second, although it is apparent that perceptual measurements are useful and, in fact, are necessary in studies designed to explore factors underlying the listener's perception of nasality, there appears to be a pressing need for data which relate changes in the perception of nasality to certain aspects of speech-production physiology and to those acoustic-signal alterations that are associated with nasality.

Current investigations (9, 15, 64, 88) have suggested that measures of nasal-"oral" sound pressure differences and nasal sound pressures are correlated with changes in the degree of nasality perceived by the listener, such that increased difference scores and nasal sound pressures are associated with higher nasality ratings. This relationship, however, does not appear to be linear. As difference scores and nasal sound pressures become increasingly larger, a point is reached at which a further increase in sound pressure differences and nasal sound pressures does not result in a subsequent increase in the severity of perceived nasality. It is important to note, though, that in no instance have nasal and "oral" sound pressures been studied in terms of the amount of nasal-tract coupling presented by a nasal speaker. The only previous work (64) which has attempted to investigate the effects of variations in nasal-tract coupling studied these effects in a normal-speaking, adult subject. Further, there is no available research regarding the effects of alterations in overall intensity level on nasal and "oral" sound pressure levels in nasal subjects. Many questions, consequently, remain to be considered. First, we do not know whether the relationship between the degree of nasal-tract coupling and the measured nasal and "oral" sound pressures is a linear one, and, if it is not linear, how this relationship may best be described. Second, although previous researchers (24, 39, 44) have defined a reduction of "oral" intensity as a correlate of nasality and have observed intensity changes to occur in conjunction with the process of nasal-tract coupling, the effect of controlled changes in "oral" intensity on nasal-"oral" sound pressure differences and nasal sound pressures is unknown at this time. Finally, we do not know how changes in "oral" intensity and the amount of nasal-tract coupling interact to influence the measure of nasal and "oral" sound pressure levels. It is the purpose of this study to obtain objective data which will aid in answering these questions.

CHAPTER II

REVIEW OF THE LITERATURE

The Definition and Causes of Nasality

Over the years, there has been considerable clinical observation and research relating to the resonance disturbance of the nasal speaker. Various authorities in the past (1, 2, 14, 20, 29, 30, 60, 70, 71, 89, 90, 94) have attempted to describe and define this vocal quality which has been diversely designated "hypernasality," "cul de sac resonance," "rhinolalia," or, more frequently, "nasality." There have been supplementary attempts to further divide the resonance imbalance into several types such as "relaxed velum nasality," "whang nasality," and "assimilation nasality."

Numerous factors such as air escapage through the nasal passageway (1, 12, 50, 58), lingual posture (11, 22, 31, 42, 51, 52, 56, 93), size of the oral orifice (10, 14, 22, 33, 93), and the amount of labial tension (12) have been offered as causes of nasality; however, the most universally accepted etiology of excessive nasal resonance is the failure to achieve adequate velopharyngeal valving either due to a short, immobile, or seriously scarred velum, or to the size and shape of the velopharyngeal port and the placement of the velum within the pharynx (1, 6, 7, 8, 16, 25, 26, 31, 32, 37, 61, 72, 78, 82, 56, 71). In support of this latter view, Subtelny, Koepp-Baker, and Subtelny (83) submit that those cleft palate subjects who were judged to be non-nasal evidenced essentially adequate velopharyngeal function, while those subjects who were judged to be nasal evidenced increased velum-to-pharyngeal-wall dimensions with correspondingly increased severity of nasality ratings.

Even though there is agreement that the most frequent cause of nasality is inadequate velopharyngeal function, opinions regarding the amount of velar seal which results in normal resonance are less congruent. There are those (2, 14) who support the view that the nasopharyngeal port should be tightly sealed in order to preclude nasality. In opposition to this position are those who feel that normal nasal resonance is not dependent on a complete velar seal. According to Kantner (49), ". . . there is no reason to believe that the amount of nasality in the voice increases and decreases in direct proportion to the size of the opening into the nasopharynx." Harrington (37) concluded that a complete velar seal is not a prerequisite for good production of all phonemes. This same finding is also reported by Haggerty and Hill (34), Williams (92), Nusbaum, Foley and Wells (63), Kelly (52), Bzoch, Graber and Aoba (13), Moll (59), and Lindsey (54). Haggerty and Hoffmeister (35), Lindsey (54), and Brown (7) found that nasality is not perceived until the nasopharyngeal port opening reaches a critical point. In general, these writers demonstrated that some degree of velopharyngeal opening is routinely found in the production of the low vowels in comparison to the high vowels.

Speech literature contains frequent reports of changes in the harmonic spectrum associated with nasality. Peterson (65) found "relatively marked effects" on the spectrum of an oral speech signal which was produced by coupling nasal tracts to the vocal system. Others, including Russell and Cotton (72), Kelly (52), Curtis (16), Hattori, Yamamoto, and Fujimura (38), Nakata (62), and House and Stevens (44) have noted differences in the harmonic spectra of nasal speakers, but the lack of consonance in their findings resulted in the following statement by Bloomer and Peterson (6): "Although we may presume that there is a direct relationship between the auditory signal, the physiological conditions of the utterance, and the acoustic structure of the sound, the relationship is not always clear, and varies sufficiently from individual to individual so that conclusions should be made with caution." Dickson (18) divided his findings regarding the harmonic spectrum pattern associated with nasality into four major groups: (a) an increased formant band width, (b) an increase or decrease in the intensity of the harmonics, (c) an increase or decrease in the formant frequency, or (d) a rise in the fundamental frequency. Elsewhere, Dickson (19) has concluded that the acoustic parameters of nasality differ depending on the configuration of the oral, pharyngeal, and nasal cavities of the individual.

The Objective Measurement of Nasality

One of the major problems confronting the early researchers who wished to study nasality was the need for precise instrumentation. Previous devices designed to measure the physiologic correlates of nasality were crude and resulted in equivocal and poorly defined measures. For example, pneumographs (28), spirometers (50), manometric flame devices (50, 61), air pressure sensitive tambours (58), nasometers (77), pith balls, cold mirrors, balloons, feathers (58; 61; 87, p.383; 45), oscillographs (16) and sound spectographs (36, 38, 78) were among the instruments used by early investigators.

An apparatus that has been recently employed in the study of nasality is the probe-tube microphone. This instrument is particularly useful in the measurement of sound pressure levels in small cavities (4, p.731). The probe-tube microphone is an adaptation of the condenser microphone; this adaptation usually takes the form of a length of small-bore tubing which is acoustically coupled to the diaphragm of the condenser microphone. Dunn and Farnsworth (21) who investigated the pressure field around the human head were the first to employ the probe-tube assembly. Further use of the probe-tube microphone was made by Wiener (91) in a study of sound pressures along the external auditory canal. The first investigator to utilize the probe-tube instrumentation in the study of nasality was Weiss (88) in 1954. Since Weiss, this assembly has been used by Summers (84), Pierce (66), Bryan (9), Counihan and Pierce (15), Richards (69), Olsen (64), Shelton, Knox, Arndt, and Elbert (75), and Hirano, Takeuchi, and Hiroto (41) among others to study nasal and "oral" sound pressure levels under various conditions in nasal and normal-speaking subjects.

Weiss (88) explored the relationship of nasal and "oral" pressure levels in fourteen cases of functional nasality and in three cleft palate speakers to judged ratings of the severity of nasality. Correlations were obtained among the desired scale values of nasality and four arbitrary measurements, the mean peak intensity of the sound in the nasal cavity, the mean peak intensity of the "oral" (overall) speech productions, nasal-"oral" sound pressure level differences, and the ratio between the mean peak intensity of the nasal sound and the mean peak intensity of the "oral" (overall) signal. Weiss concluded that the probe-tube microphone when used in conjunction with an amplifying system and sound pressure measuring instrumentation is effective in deriving sound pressure level measures which correlate reasonably well with judgments of nasality.

The probe-tube assembly was also used by Pierce (66) to evaluate the effectiveness of various types of prosthetic speech appliances in a group of cleft palate speakers. The correlations which he derived between the nasal-"oral" sound pressure level differences and listener evaluations of nasality prompted Pierce to state, ". . . the probe-tube assembly is effective in providing measurements of sound pressure levels which are positively related to listener judgments of nasality."

Bryan (9) correlated nasal-"oral" sound pressure level differences obtained with a probe-tube microphone with listener assessments of nasality for a group of cleft palate adults who produced a series of vowels and short sentences. He concluded that (a) greater nasal-"oral" sound pressure level differences occur for the high vowels than for the low vowels, (b) a moderate relationship obtains between sound pressure differences of vowels and sentences--the extent of this relationship being dependent on the vowel, (c) a substantially higher correlation exists between listener judgments of nasality and sound pressure differences in sentences than between the subjective impressions and sound pressure differences in vowels, (d) and sound pressure level differences are more closely related to listener evaluations in forward play than in backward play.

Counihan and Pierce (15), studying the speech of cleft palate and normal adult subjects in isolated vowels, CVC syllables, and sentences, also employed the probe-tube microphone assembly. Their pertinent findings include the following: (a) in all speaking situations (isolated vowels, syllables, and sentences) the cleft palate subjects evidenced greater nasal-"oral" sound pressure differences than the normal speakers, (b) the cleft palate subjects demonstrated a wider range of differences across the isolated vowels and the vowels in CVC syllables than the normals, (c) the means obtained for nasal-"oral" sound pressure differences were greater for the cleft palate subjects in [s] and [z] syllables than in [t] and [d] syllables, while, for the normal-speaking group, greater sound pressure differences were found for vowels in [z] and [d] syllables than in [s] and [t] syllables, (d) the means obtained for the vowels [i] and [u] were greater than for other vowels in all consonant environments for all subjects, (e) vowels in combination with the voiced consonants [z] and [d] averaged greater mean sound pressure differences than those combined with the voiceless elements [s] and [t], (f) correlation coefficients between ratings of nasality from nine judges and nasal-"oral" sound pressure differences ranged from -.08 to .25 for isolated vowels, from .19 to .34 for the CVC syllables, from .49 to .65 for the sentences during forward play, and from .43 to .63 for the sentences during backward play.

Richards (69) employed a similar instrumentation to investigate the reliability of the measure obtained with the probe-tube microphone device. Her subjects, composed of two groups of cleft palate speakers and one group of normal speakers, were required to produce four isolated vowels, sixteen CVC syllables, and one sentence containing no nasal consonant sounds during two identical testing situations. The difference between the "oral" and nasal sound pressure levels was calculated for each speech item produced by each subject and the magnitudes of the mean differences between session and trial scores across speech sample types for each subject were analyzed. She reports that the cleft palate subjects with the lower oral manometer ratios were the most variable of the three groups, the normal subjects produced the lowest nasal-"oral" sound pressure level differences, and the CVC syllables had the highest mean differences and the largest ranges for all groups. In regard to her findings regarding the reliability of this type of instrumentation, Richards asserts, ". . . it appears warranted to conclude that repeated productions of identical speech samples by cleft palate and normal speakers result in reliable nasal-"oral" sound pressure differences when averaged across groups and across speech sample types."

The probe-tube apparatus was also employed by Shelton, Knox, Arndt, and Elbert (75) to evaluate the correlation between judgments of hypernasality and measures of nasal and "oral" sound pressure levels, and to compare these measures in subjects speaking with obturators in place and removed. Correlation coefficients were computed between the mean nasality ratings and measurements of nasal sound pressure level, "oral" sound pressure level, nasal-"oral" sound pressure difference, and nasal sound pressure divided by "oral" sound pressure. The highest Pearson correlation coefficient, .52, was obtained between nasality ratings and nasal sound pressure levels. It was further noted that higher nasality ratings and nasal sound pressure levels were observed for subjects speaking with their obturators removed than for subjects speaking with their obturators in place.

Nasal sound pressures of eight, normal-speaking adults producing sixty Japanese monosyllables were measured by Hirano, Takeuchi, and Hirano (41) using a probe-tube microphone assembly. These researchers report that the amount of nasal sound pressure differs for the individual speaker, the vowel phonated, and the preceding consonants. In addition, higher nasal sound pressures were recorded during the production of nasals, voiced consonants, and a four-consonant sound.

In summary, initial crude attempts to objectively measure nasality were concerned with the quantification of nasally-emitted air. When these early efforts provided only limited information, research attention was directed toward an analysis of the acoustic aspects of nasality. In order to try to isolate those peculiar physiological events which are associated with the subjective impression of nasality, researchers have relied more and more on the probe-tube microphone assembly which has resulted in consistently high and apparently reliable correlations between nasal and "oral" sound pressure levels and listener judgments of the severity of nasality.

The Influence of Intensity and Coupling Area

It has been recently hypothesized (56) that increased nasal-tract coupling as presented in cases of velopharyngeal incompetency will influence the overall intensity of the vocal output. The resonance characteristics of the vocal tract are determined primarily by its length and configuration. Fant (24) has suggested that a reduction of formant intensities results in part from an interaction between the resonances and anti-resonances which characterize the oral and nasal cavities. The coupling of the nasal cavity to the oral cavity produces a shunting side-branch with resonances and anti-resonances at discrete frequencies determined by the cavity characteristics and the size of the coupling. When the resonant frequencies of the two cavities coincide, there is an increase in the amplitude of the formant frequency; however, if these pole frequencies do not coincide, the nasalization effects appear as added resonances in the speech spectrum. When the zero, or anti-resonance, of the nasal cavity coincides with the pole of the vocal tract, there is a reduction in the intensity of the formant frequency; when the pole and zero do not coincide, the anti-resonance effects appear as reduced intensity of the harmonics adjacent to the formant. The size of the coupling affects the frequency characteristics of the nasal pole-zero pairs. With a large area of coupling the pole and zero frequencies are widely separated and interact with vocal tract resonances and anti-resonances. If the coupling is small, the pole and zero will be so close as to permit only minimal interactions with vocal tract resonance. When there is no coupling, the pole and zero coincide and cancel out the nasal cavity influence upon the formant structure. Fant further points out that with nasal coupling the frequency of the nasal-cavity anti-resonance may coincide with the resonant frequency of the first formant of a nasalized vowel and result in a reduction of the intensity level of that formant. Since the frequency of the first formant varies among the vowels, a constant area of coupling could introduce anti-resonances in some vowels which would be at a frequency above or below the oral resonance of those vowels and not produce any intensity reduction.

The statement has been made by House and Stevens (44) that, "By virtue of its smaller size and greater damping, the nose radiates much less sound energy than the mouth when nasalized vowels are produced." These authors point out that coupling the oral and nasal cavities increases the acoustic power loss during vowel production by increasing the damping effect on the laryngeally-generated sound. In their electrical analog study, House and Stevens found that the overall intensity level of artificial vowels decreases as coupling of the oral and nasal cavities is increased. The high vowels [i] and [u] demonstrated the weakest overall intensity level, while the low vowels [ɑ] and [æ], and [ɔ] evidenced a relatively greater loss of acoustic power as the extent of coupling was increased.

Russell and Cotton (72), commenting on the frequent occurrence of laryngeal tension and associated voice problems in cleft palate subjects, have speculated that laryngeal tension is developed in an effort to talk louder and overcome a power loss caused by the coupling of the oral and nasal tracts. By measuring the intensity of "oral" and nasal speech signals during normal phonation and nasalized production of vowels, they determined that the nasal signal, when averaged across subjects and frequencies, was 30 dB less intense than the "oral" signal during the production of [ɑ], [o], [ɔ], and [æ]. For the vowel [i], the nasal signal was 17 dB less intense during non-nasal productions; however, when the vowels were nasalized, the intensity observed in the nasal signal increased by 20 to 30 dB on the average so that it equaled or exceeded the "oral" signal. Russell and Cotton conclude that these findings affirm the presence of a power loss in nasalized speech and indicate an inefficient use of the oral cavity as a resonator. Curtis (17) states that the acoustic impedance characteristics of the oral and nasal cavities produce a marked effect on the intensity of the resulting "oral" and nasal output. The relative impedances of the oral and nasal cavities will determine, in a large part, the effect that a coupling of these will have. For instance, if the nasal cavity has a high impedance while the oral cavity has a low impedance, the consequence of coupling these two resonators is minimal. On the other hand, if the opposite impedance relationship exists, coupling the two cavities will result in greater nasality.

In a study of the effects of nasalization, Fant (24) examined the influence of four nasal coupling conditions upon the spectra of four vowels, [i], [e], [ɑ], and [u]. Input impedances equal to velopharyngeal coupling area dimensions of 0.00 cm^2, 0.16 cm^2, 0.32 cm^2, 0.65 cm^2, and 2.6 cm^2 were used to evaluate the effects of coupling. Increasing the size of the coupling introduced spectral changes in the vowels including increases in formant band width and the reduction of formant intensity, but the degree of change varied according to the vowel and the size of the coupling. Generally, as the coupling increased the intensity of the first formant decreased and the intensity level of the nasal output increased.

Hess (40) considered the relationships among nasality, frequency, and intensity in a group of adult cleft palate speakers. He studied the vowels [i], [e], [æ], [ɑ], [o], and [u] when they were produced at two frequencies and two intensity levels. Judges ratings of the severity of nasality were noted to be lower at high pitch levels and at greater intensities. It was speculated by Hess that the greater effort required to produce the vowels at higher pitches and higher intensity levels resulted in increased velopharyngeal closures.

Summers (84), working with the probe-tube microphone assembly, explored the relationship between nasal and "oral" sound pressure and intensity in a group of male and female normal-speaking subjects. His subjects were required to phonate eight vowels at four intensity levels, 60, 70, 80, and 90 decibels. The following relationships were observed: (a) "oral" sound pressure levels across all sounds and intensities are lower for females than for males; the converse is true for nasal sound pressure levels, (b) the differences among "oral" sound pressure levels across all sounds and groups are greater than corresponding differences among nasal sound pressure levels, (c) across all intensities for male and female subjects, separately and in totality, the relationship of the nasal sound pressure among vowel sounds resembles the conventional vowel triangle, except that the lowest sound pressure is for [æ], (d) across oral and nasal locations, there are no sound pressure differences between males and females in producing any of the vowels at any of the four intensities, (e) there are no sound pressure differences across all sounds and between male and female groups for the four intensity levels, (f) the "oral" sound pressure for males is greater at every nominal intensity level and across all sounds than the sound pressures for females; however, except for the 90 dB intensity level, the converse is true for nasal sound pressures, and (g) across all intensity levels, the nasal sound pressures for females for each sound are larger than the nasal sound pressure for males, but the converse is true for the "oral" sound pressures. Summers reports that a connection between the intensity of speech and the amount of nasal resonance has been suggested by Buck and Steer who express the view that an inverse relationship obtains between the intensity of nasal resonance and the overall intensity of a speech signal.

Olsen (64) in 1965 investigated the influence of controlled areas of velopharyngeal coupling upon judgments of nasality and nasal and "oral" sound pressure levels of the speech of a single non-nasal speaker. After one subject with normal speech structures was fitted with a speech appliance which permitted a variable control of the velopharyngeal aperture, the subject was recorded speaking at four intensity levels for each of ten coupling conditions using eight vowels which were later retested in each of four consonant environments. Sentences and paragraphs were also recorded but were not analyzed in this study. Since the subject was unable to monitor his intensity level, only a single intensity, the subject's "comfort" level, was used in the final analysis. Olsen used an instrumentation similar to that employed by Weiss, Summers, and Pierce, the probe-tube assembly. Measurements were made of the nasal and "oral" sound pressure levels of the speaker and listener judgments of nasality were obtained. A significant relationship was found among velopharyngeal aperture dimensions and nasal-"oral" sound pressure level differences and judgments of perceived nasality. No one aperture dimension seemed to be critical for the control of nasality in all speech phonemes.

In reviewing the literature, the need for a systematic and controlled investigation of the interrelationships of nasal sound pressure levels, vocal intensity, and specified velopharyngeal apertures becomes apparent. It is with this need in mind that the present investigation is undertaken.

CHAPTER III

DESIGN OF THE INVESTIGATION

The most satisfactory instrumentation for the investigation of nasal and "oral" sound pressure levels which is available at this time appears to be the probe-tube microphone assembly. This apparatus has been used by various researchers, among them Weiss (88) studying a group of functionally nasal adults, Summers (84) investigating the effects of changes in intensity on vowel production in normal-speaking adults, Hirano, Takeuchi and Hiroto (41) measuring nasal sound pressures in normal speakers, Pierce (66) evaluating prosthetic speech appliances, and Bryan (9), Counihan and Pierce (15), and, later, Shelton, Knox, Arndth, and Ebers (75), studying nasal and "oral" sound pressure levels in cleft palate speakers. This technique has been found to be sufficiently reliable for research purposes (69). It was this assembly which was used in this research project.

The intent of the present study was to investigate changes in nasal-"oral"[1] sound pressure differences[2] and nasal sound pressures

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[1]The so-called "oral" speech signal was recorded in front of the lips and, consequently, contained components of both the oral and nasal signals. However, in this investigation this "overall" speech signal was termed the "oral" speech signal to differentiate it from the signal emitted from the nasal cavity.

[2]"Nasal-'oral' sound pressure difference" refers to the arithmetic difference expressed in decibels between the nasal sound pressure

produced by a single cleft palate adult speaker when the amount of nasal-tract coupling was controlled and while he phonated four isolated vowels at six intensity levels. The amount of nasal-tract coupling was accurately determined and controlled through the use of a specially designed speech prothesis which was constructed with concentric rings fitted into the pharyngeal section of the bulb allowing variations in the degree of nasal cavity coupling. Measures of the sound pressure level of the "oral" speech signal and the nasal speech signal were made utilizing two condenser microphones and their amplifiers. A probe-tube was added as a modification of the microphone for the nasal signal in order that the nasal sound pressure level could be obtained. The "oral" signal, which is actually the "overall" signal, contained components of the sound emitted from both the oral and nasal cavities since the "oral" microphone was placed approximately eight inches in front of the mouth. Simultaneous recordings of the "oral" and nasal speech signals of an adult cleft palate speaker producing four vowels, [i], [u], [ɑ], and [æ], were made using a dual-channel tape recorder; measurements of the sound pressure levels were obtained from level recorder tracings taken from the recorded "oral" and nasal speech signals. These measurements were obtained for six coupling conditions (degrees of nasal-tract coupling) and for six intensity levels (70, 75, 80, 85 dB SPL, a "comfort level"[1], and a "comfort level" with auditory masking[2]).

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and the "oral" sound pressure.

[1]The subject was instructed to produce the vowel in question at an intensity level which was a most comfortable speaking level for him.

[2]The subject was asked to produce the vowel at a most comfortable speaking level, while a 117 dB re SPL white noise signal was introduced bilaterally as a masker. The subject was cautioned not to increase his intensity in an effort to hear himself.

The Research Question

Specifically the research questions to be answered are:

1) What changes occur in the nasal-"oral" sound pressure difference levels and the nasal sound pressure levels of isolated vowels with variations in the degree of nasal-tract coupling?

2) What changes occur in the proportion of the overall sound pressure level which is occupied by the nasal sound pressure level as vocal intensity level is varied in isolated vowels?

3) What is the combined effect of varying vocal intensity levels and the degree of nasal-tract coupling on the nasal and "oral" sound pressure levels of isolated vowels?

The Speech Sample

The speech sample for this study was composed of the isolated vowel sounds, [i], [u], [ɑ], and [æ], each sustained for three seconds. These vowels were chosen because they represent various positions on the traditional vowel triangle and, consequently, allow analysis of the findings with respect to tongue height and placement within the oral cavity (67, 92). In addition, the amount of velar valving required for the production of these vowels has been found to vary (59) and these vowels also differ in their relative acoustic power (5, 23, 53, 73, 74). Further, certain investigators (55, 86) have noted variations among these vowels in the degree of nasality perceived by judges. Still other studies (9, 15, 64, 69) have demonstrated a greater mean nasal-"oral" sound pressure difference for certain of these vowels than for others.

The Research Appliance

An obturator was specially designed and constructed for the subject in this investigation. The appliance, designed to conform to the anatomical configuration of the subject's oral cavity, provided a control of the amount of nasal-tract coupling. The palatal section of the prothesis was equipped with dental clasps to permit adequate and secure placement and retention. Dental adhesive was also used to insure a secure retention. The pharyngeal section of the appliance was constructed with an area within the central portion of the bulb which contained five, concentric, aluminum rings. These rings could be removed one at a time to provide six conditions of nasal-tract coupling:

1) .0000 cm^2 of opening,
2) .0314 cm^2 of opening,
3) .1261 cm^2 of opening,
4) .2827 cm^2 of opening,
5) .5036 cm^2 of opening,
6) .7850 cm^2 of opening.

The Subject

A single adult male with a repaired congenital bilateral cleft of the lip and palate served as the subject in this study. This subject had been an appliance wearer for ten years. Intelligence and articulation competency were judged to be within normal limits. Frontal and lateral headplate X-rays were obtained which revealed the absence of a nasal passageway obstruction or a nasal ala collapse. Audiometric screening at 10 dB re ISO indicated that the subject evidenced normal hearing bilaterally.

A pilot study was conducted in which the subject produced the four vowels, [i], [u], [ɑ], and [æ], at four intensity levels, 70, 75, 80, and 85 dB SPL. It was noted that the subject was able to monitor his intensity level and produce consistently a specified intensity level. When analyzed, the tape recording revealed that the vowels retained their phonemic characteristics when phonated at each of the intensity levels. An oral examination was conducted and oral manometer ratios[1] were obtained with the following results:

1) With his permanent appliance, the subject achieved an oral manometer ratio of .7180.

2) Without an appliance, an oral manometer ratio of .0930 was obtained.

3) With the research appliance in the .0000 cm^2 coupling condition, a ratio of .9370 was obtained.

4) With .0314 cm^2 of coupling, a ratio of .8310 was attained.

5) With .1261 cm^2 of coupling, the ratio was .6750.

6) Using the research appliance with .2827 cm^2 of coupling, the subject achieved a ratio of .3067.

7) With .5026 cm^2 of coupling using the research appliance, the oral manometer ratio was .1960.

8) For .7850 cm^2 of coupling, the ratio was .0930.

The appliance was constructed so that in the no-coupling condition there was no nasal escape of air during the phonation of any of the vowels to be studied.

The Intensity Levels

Lehiste and Peterson (53) report observations of phonetic changes which affect vowel amplitudes. They speculate that since the human vocal tract is a variable acoustic tube with a non-radiating oriface, one would not expect to obtain the same pressure or power

[1] Each reported oral manometer ratio was obtained by deriving the mean of three oral manometer ratios.

outputs for identical physiologic input energies. Changes in the amplitude of a sound wave produced by phonation may be determined in two ways: (1) if a phonetic quality is constant, a change in input power may effect a change in output, or (2) if input is constant, a change in phonetic quality may change output amplitude. These observations suggest that a listener or a speaker associates an intrinsic relative amplitude (average power) with each vowel spectrum and applies a "correction factor" to the vocal output. In an effort to measure vowel production in the absence of this "correction factor," Lehiste and Peterson introduced a 130 dB SPL masking noise which was presented to the speaker via earphones while a selected group of vowels were phonated. In the present investigation, a "comfort level" intensity with bilateral auditory masking was included in order to disrupt the subject's auditory monitoring mechanism and, consequently, reduce the effects of the "correction factor" on the resulting nasal and "oral" sound pressures. The subject's "comfort level" intensity was included in the study since it was felt that this intensity, rather than a monitored intensity, would more nearly approximate a normal speaking situation. In addition to the two "comfort" intensity levels, four controlled intensity levels, 70, 75, 80, and 85 dB SPL, were included in the present investigation. These four controlled intensity levels were chosen because they represent a range of intensities from "normal" to "very loud" speech.

Instrumentation

The two principle instrumental components used in this study were:

1) an audio recording system for the oral and nasal signals,

and

2) a graphic recording system by means of which the amplitude displacement of the oral and nasal speech signals was displayed and measured.

Description

The audio recording system. The audio recording system was designed to allow the separate, but simultaneous, recording of (a) the "oral" speech signal, using a microphone eight inches from the subject's lips, and (b) the nasal signal, using a probe-tube microphone inserted into the subject's nostril. The major componetry of the audio recording system was:

1) two half-inch condenser microphone cartridges (Bruel and Kjaer, Type 4134),

2) two cathode-follower preamplifiers (Bruel and Kjaer, Type 2615),

3) two microphone amplifiers (Bruel and Kjaer, Type 2603),

4) a dual-channel magnetic tape recorder (Ampex, Model 354).

The manufacturer calibrated the frequency response of the two condenser microphones, which were designed for sound measurement in a sound field, to be flat (within ± 2 dB) from 20 to 20,000 Hz. The frequency responses of the two microphones were obtained before and after the data gathering sessions and were found to agree with the manufacturer's specifications. The original microphone cartridges were identical; however, they were modified by equipping the oral microphone with a protective grid and adding an adapter and a probe tube to the nasal microphone. The manufacturer's specifications regarding the effect of the protective grid on the frequency response of the "oral" microphone state that the microphone is little affected up to 15,000 Hz if it is placed at a 90-degree angle of incidence to the sound source (46). The addition of a probe-tube to the nasal microphone resulted in considerable high-frequency damping; consequently, an equalizing filter was utilized to minimize this effect. Steel wool was inserted into the probe-tube in order to further decrease the effect of the high frequency damping. The probe-tube itself has an inner diameter of six-tenths millimeter and an outer diameter of one millimeter, a diameter which allowed the probe-tube to be placed in the nasal cavity without contacting the nares or columella and with no substantial effect on the sound pressure level in the nasal cavity (3, 4). The wall thickness of the probe, two-tenths millimeter, permitted a signal-to-noise ratio of 44 dB from 100 to 5,000 Hz (46). The probe-tube length of three inches was long enough to allow the microphone and its preamplifier to be placed out of the path of the signal from the oral cavity thus reducing a possible source of impedance to the oral signal. The length of the probe-tube was maintained as short as possible to insure sensitivity (4).

The probe adapter was attached to the nasal microphone cartridge. Next, the probe-tube was force-fit into the adapter so that an acoustically-tight seal was achieved at each of these two connections. Both condenser microphones were attached to cathode followers which served as impedance-matching devices for the high output impedance of the microphone cartridges and the low input impedance of the succeeding microphone amplifiers. The microphone amplifiers presented linear frequency responses and amplified voltages with a potential gain of 100 dB. The amplifiers, combined with the condenser microphones and their cathode followers, served as sound level meters indicating sound pressure in decibels re .0002 dyne/cm^2 (47). In order to compensate for the high-frequency damping of the nasal signal due to response characteristics of the probe tube, the nasal microphone was equipped with a filter, consisting of a .02-microfarad condenser in parallel with a 33,000-ohm resistor, both in series with a 1,500-ohm resistor. This resulted in a flat response from the nasal microphone within ± 2 dB from 100 to 5,000 Hz.

The "oral" and nasal speech signals were recorded simultaneously by means of a dual-channel tape recorder which was impedance-matched to the microphone amplifiers and whose frequency response was reported to be ± 2 dB from 40 to 12,000 Hz when operated at a speed of 7.5 ips. At the beginning of the project, the frequency response was verified and the "record" and "reproduce" potentiometer settings were adjusted with a white noise of known intensity so that a 20-dB deflection on the microphone amplifier voltmeter would peak the recorder VU at 0 dB prior to each recording session.

The graphic recording system. The "oral" and nasal signals were reproduced by the tape recorder and introduced directly into a level recorder (Bruel and Kjaer, Type 2334) which records signal level variations within a frequency range of 20 to 20,000 Hz as a function of time. The level recorder was equipped with a 50-dB input potentiometer that was specified by the manufacturer to be accurate ± .5 dB within a 20 to 20,000 Hz frequency range (48).

Calibration

In the calibration of the nasal probe-tube microphone and amplifying system, the "oral" microphone and its amplifying system served as a reference. The "oral" microphone as calibrated by the manufacturer was flat within $\pm$ 2 dB from 20 to 20,000 Hz and, as has been previously suggested, can, when employed with its associated microphone amplifier be utilized as a precision sound level meter. The reference (oral) microphone was placed at a 90-degree angle of incidence at a distance of one inch from an amplifier-speaker (Ampex, Model 620) in a sound treated room. The nasal probe-tube microphone was placed at approximately a 45-degree angle, one-fourth inch above the reference microphone. The amplifier-speaker, driven by a beat frequency oscillator (Bruel and Kjaer, Model 1014), produced a tone which was sufficiently intense to register 100 dB SPL on the reference microphone amplifier voltmeter. Concurrently, the response of the nasal probe-tube microphone was indicated and read from the voltmeter of its associated amplifier. Readings were derived at 100-cycle intervals through 5000 Hz and at 1000-cycle intervals from that point to 10,000 Hz. The frequency response of the nasal microphone was essentially flat to 7000 Hz. The mean attenuation introduced by the probe-tube and the associated equalizing filter, derived by computing the means of the sound pressure readings up to 7000 Hz and subtracting the computed means from the intensity level of the reference sound at the oral microphone as measured on its associated amplifier voltmeter, was approximately 29 dB from 100 to 7000 Hz. The response curves of the nasal microphone and the uncompensated and compensated probe tube are shown in Figures 1 and 2, respectively.

The graphic level recorder was calibrated again employing the "oral" microphone and its amplifier as a reference. Using a white noise as the sound source, 5-dB increments on the microphone amplifier volt-

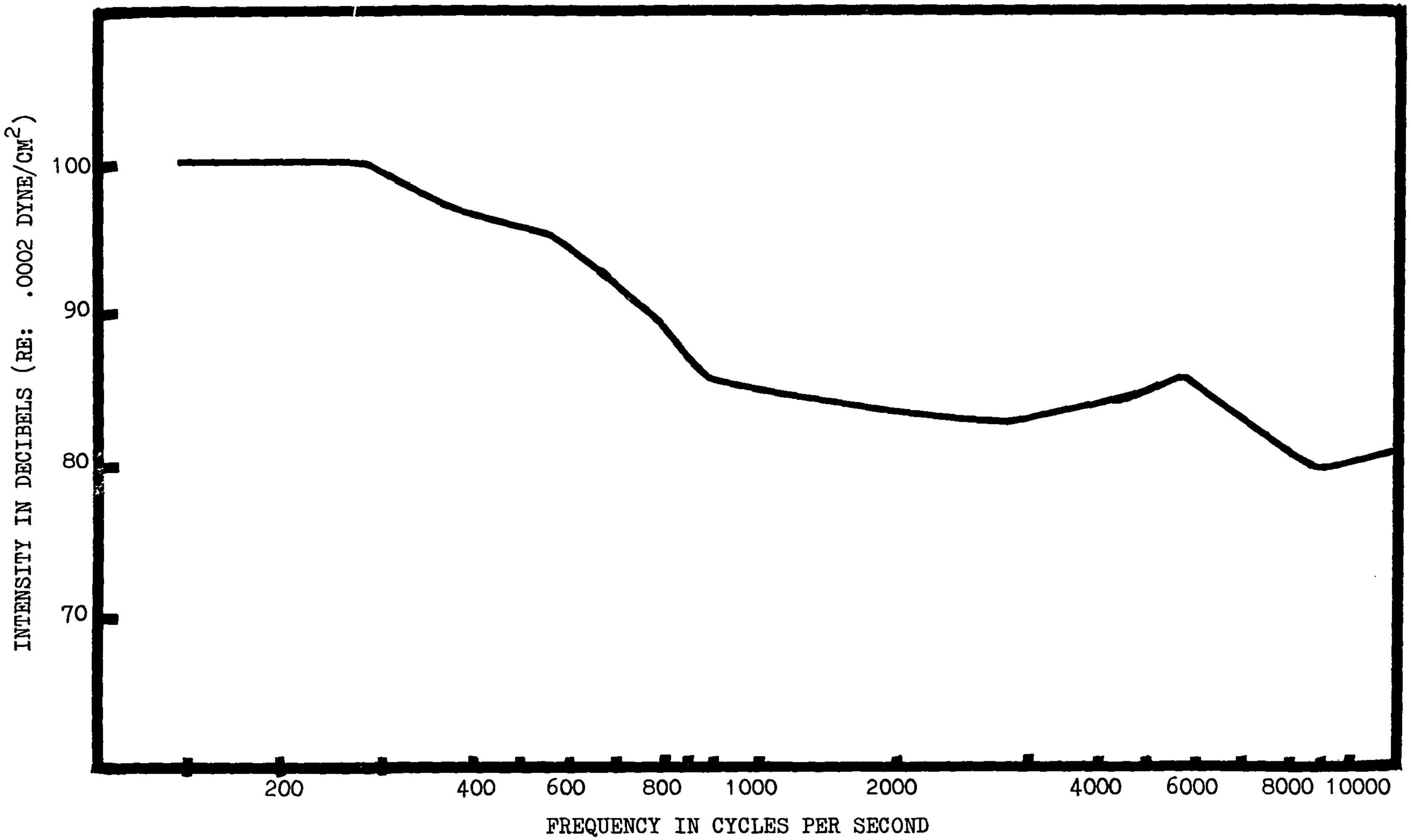

Figure 1.--Frequency response curve of the nasal microphone and an uncompensated probe tube to a 100-dB SPL tone.

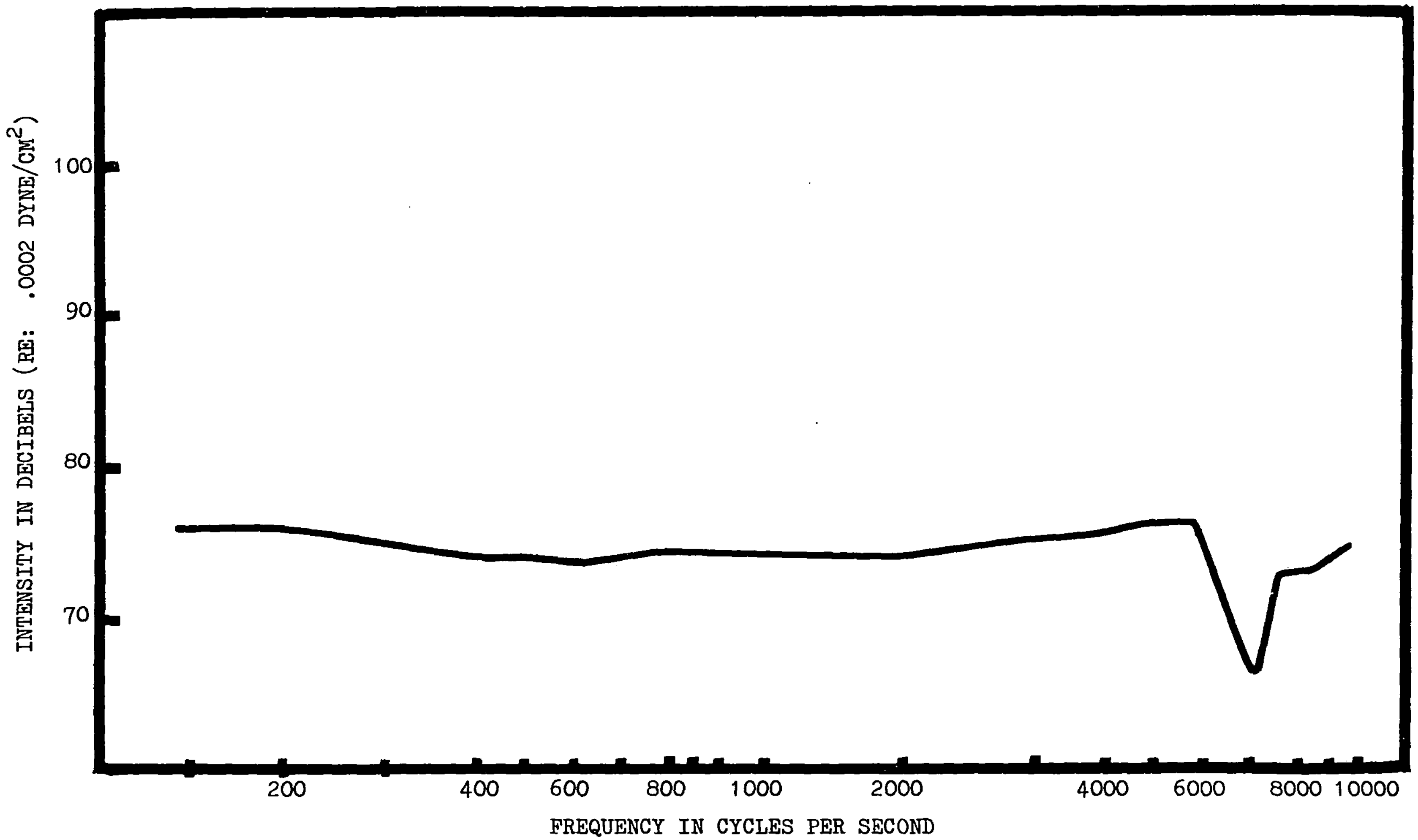

Figure 2.--Frequency response curve of the nasal microphone, probe tube and equalizing filter to a 100-dB SPL tone.

meter were observed to produce 5-dB increments on the chart paper of the graphic level recorder.

Procedures

Recording Procedures

The recording sessions were conducted in an acoustically-isolated, two-room, testing suite at the University of Oklahoma Medical Center, Department of Communication Disorders. The ambient noise level of this room was below 30 dB as measured on the "C" scale of a sound level meter (General Radio, Model 793).

The test room contained the subject's chair, the two condenser microphones with their respective cathode followers and a table on which were placed the "oral" microphone amplifier, a rack to hold the speech sample cards, and the signal lights to indicate the beginning and end of the three-second phonation period for the vowel sounds. The "oral" microphone and its cathode follower were affixed to a movable stand while the nasal microphone and its cathode follower were stationed on an adjustable, wall-mounted arm. The control room contained the nasal microphone amplifier, the dual-channel magnetic tape recorder, and a cam timer which provided the control for a test room signal light.

The subject was seated in an examination chair which was adjusted for height, inclination of the back, and position of the head-rest for suitable placement of the probe-tube. The subject's head was stabilized during the recording sessions by means of a wide elastic band placed around the subject's head and the headrest. The "oral" microphone stand was positioned so that the microphone was approximately eight inches from the subject's lips and at a 90-degree angle of incidence, that is, with the diaphragm of the microphone in a horizontal plane with the center of the mouth. The arm holding the nasal microphone was placed so that the probe-tube would insert at an acute angle (about 45 degrees) approximately one-fourth inch into the vestibule of the subject's nostril.

The microphone amplifier for the "oral" microphone was positioned in such a manner that the subject could observe the voltmeter and monitor the intensity level of his phonation. The signal light consisted of an amber-colored light of one-second duration which indicated to the subject that he should prepare for phonation and a three-second signal with a red light which remained on during the time the subject was to phonate. These lights were operated by the cam timer and were under the examiner's control.

After the subject had been given an opportunity to familarize himself with the speech material, he practiced speaking each vowel at the four intensity levels, 70, 75, 80, 85 dB, monitored on the voltmeter of the "oral" microphone amplifier.

In this investigation, each of four isolated vowels, [i], [u], [ɑ], and [æ], were recorded at each of six intensity levels (70, 75, 80, 85 dB SPL, "comfort" level and "comfort masked" level) for six oral-nasal coupling conditions. The vowels were phonated one at a time by the subject after the examiner during the data gathering sessions while a printed card bearing the vowel to be phonated was displayed to the subject. The vowels appeared in common words in which the vowel was underlined. The subject was instructed to produce only the underlined vowel. Magnetic tape recordings were obtained for three separate productions of each vowel at each intensity level and each coupling condition for later analysis. In so far as possible, the conditions of the three trials were kept constant except for a re-randomization of the speech sample, coupling conditions, and intensity levels for each trial. Particular care was taken to insure that the placement of the "oral" microphone and the probe-tube as well as the subject's head position were as similar as possible for the three trials. The order of presentation of the vowels, intensity levels, and coupling conditions were appropriately randomized within and among trials using a table of random numbers.

Measurement Procedures

The "oral" and nasal speech signals were introduced separately from the tape recorder into a power level recorder which provided a graphic representation of the amplitude displacement of the two signals. The level recorder was operated at a chart-paper speed of 30 millimeters per second and a writing speed of 300 millimeters per second. These speeds are fast enough to provide adequate resolving power for the intensity of the signal, but preclude the possibility of the momentum of the writing stylus causing the stylus to overshoot. The level recorder chart-paper (Bruel and Kjaer, QP 2350) was used with a 50-dB logarithmic potentiometer. This paper, two and one-half inches in width and ruled in ten equal intervals, permitted a recording range of 50 dB.

White noise of a specified sound pressure level was introduced into the "oral" and nasal channels of the tape recorder at the beginning of each recording session and each new tape. The signal provided a reference base on the level recorder tracings which allowed measurements of the recorded vowels in decibels re .0002 dyne/cm^2.

The amplitude displacement for each vowel at each intensity level and coupling condition was measured at specified intervals (three points 15 millimeters apart in the center of the steady-state portion of the vowel) and a mean amplitude displacement was derived. This derived mean value was corrected for the amount of attenuation, in decibels, of the amplifier settings. This allowed the determination of the sound pressure level of each vowel for the six intensity levels and the six coupling conditions. The "oral" and nasal tracings for each of the vowels phonated in the experimental conditions were measured twice. A third measurement was taken in those cases in which there was a lack of agreement between the first two measurements. For each vowel, the nasal and "oral" sound pressures and the arithmetic difference of the nasal and "oral" sound pressure levels were computed; the figures derived expressed in decibels the nasal and "oral" sound pressure levels and the nasal-"oral" sound pressure difference for that vowel.

CHAPTER IV

RESULTS AND DISCUSSION

This study was designed to investigate the effects of controlled variations in oral-nasal coupling and vocal intensity on the nasal sound pressures and nasal-"oral" sound pressure level differences measured in vowels produced by a single adult cleft palate speaker. An obturator was specifically designed for this subject which contained five concentric rings within the central portion of its pharyngeal section. These rings could be removed one at a time to produce six conditions of oral-nasal coupling, ranging from a no-coupling condition to an opening .7850 cm^2 in area. An adult male with a repaired bilateral cleft of the lip and palate served as the subject. The subject was required to phonate each of four vowels [i], [u], [æ] and [ɑ] at each of six intensity levels (70, 75, 80, and 85 dB SPL, a "comfort" level, and a "comfort" level with bilateral auditory masking) under each of the six coupling conditions. Each vowel was recorded by means of a high-fidelity recording system and introduced into instrumentation, previously described, which permitted the derivation of nasal and "oral" (overall) sound pressure levels for each vowel in each coupling and intensity condition. For each item of the speech sample, nasal sound pressure levels and the arithmetic difference between the nasal and "oral" sound pressure levels were obtained. These measures constituted the acoustic data of the present experiment.

In order to evaluate the research data, an analysis of variance with a factorial arrangement of treatments was utilized in which the factors were vowels, intensity levels, coupling conditions, and trials. The four-factor interaction was assumed to be zero and was used in the error term. In the analysis of variance for nasal sound pressure levels, the two "comfort" level intensities were excluded from the statistical treatment. The two "comfort" intensity levels were included in the analysis of nasal-"oral" sound pressure difference measures. A significance level of .05 was selected for this experiment.

The results of the analyses of variance of the nasal-"oral" sound pressure level differences and the nasal sound pressure level data are summarized in Tables 1 and 2. Examination of these tables revealed

TABLE 1

SUMMARY OF THE ANALYSIS OF VARIANCE FOR NASAL SOUND PRESSURE

Source	df	ms	F
Vowels (A)	3	3.431	387.655[a]
Intensity (B)	3	3.170	358.112[a]
AB	9	0.145	16.384[a]
Coupling (C)	5	8.669	979.383[a]
AC	15	0.063	7.711[a]
BC	15	0.762	86.105[a]
ABC	45	0.01045	1.501
Trial (D)	2	0.079	8.909[a]
AD	6	0.013	1.523
BD	6	0.011	1.230
CD	10	0.021	2.366[a]
ABD	18	0.005	0.589
ACD	30	0.011	1.282
BCD	30	0.007	0.763
ABCD (Error)	90	0.009	

[a] $P < .05$

TABLE 2

SUMMARY OF THE ANALYSIS OF VARIANCE FOR NASAL-"ORAL" SOUND PRESSURE DIFFERENCES

Source	df	ms	F
Vowel (A)	3	595.268	473.352[a]
Intensity (B)	5	968.875	770.441[a]
AB	15	8.666	6.891[a]
Coupling (C)	5	1330.058	1057.651[a]
AC	15	10.301	8.191[a]
BC	25	59.690	47.465[a]
ABC	75	1.936	1.633
Trial (D)	2	6.711	5.336[a]
AD	6	5.309	4.222[a]
BD	10	5.525	4.393[a]
CD	10	3.308	2.269[a]
ABD	30	1.160	1.075
ACD	30	1.473	1.172
BCD	50	1.895	1.507
ABCD (Error)	150	1.257	

[a] $P < .05$

that vowel, intensity, coupling, and trial main effects as well as vowel-by-intensity, coupling-by-intensity, coupling-by-vowel, and trial-by-coupling interactions were significant for both the nasal-"oral" sound pressure level differences and the nasal sound pressure level measures. In addition, the trial-by-vowel and trial-by-intensity interactions were significant for the nasal-"oral" difference data. All other interactions were not significant. For purposes of discussion, the findings of the study will be presented in four sections: (a) findings related to coupling, including vowel and coupling main effects and the vowel-by-coupling interaction; (b) findings related to intensity, including intensity main effects and the coupling-by-intensity and vowel-by-intensity interactions; (c) findings related to trials, including trial main effects and the intensity-by-trial, coupling-by-trial, and vowel-by-trial interactions; and (d) a discussion of the results of the study.

To facilitate the presentation of results, the area of coupling afforded by the experimental obturator, .0000 cm^2, .0314 cm^2, .1261 cm^2, .2827 cm^2, .5036 cm^2, and .7850 cm^2, will be referred to as Coupling Conditions I, II, III, IV, V, and VI in that order. The "oral" (overall) intensity levels at which each vowel was produced, 70, 75, 80, and 85 dB SPL, will be designated Intensity Levels I, II, III, and IV, respectively. The term "sound pressure difference" will be used to refer to the arithmetic difference between nasal and "oral" sound pressure levels.

Coupling Conditions

Nasal Sound Pressures

One of the objectives of the present study was to explore changes in nasal sound pressure levels of selected vowels that occurred as a result of changes in the degree of oral-nasal coupling. The significant coupling main effect for the nasal sound pressure data is presented graphically in Figure 3. Inspection of this figure indicated that, as the area of nasal-tract coupling was increased, there was an increase in mean nasal sound pressure levels. These means, averaged over all vowels, intensity levels, and trials, range from 107.8 dB for Coupling Condition I (.0000 cm^2) to 119.1 dB at Coupling Condition VI (.7850 cm^2).

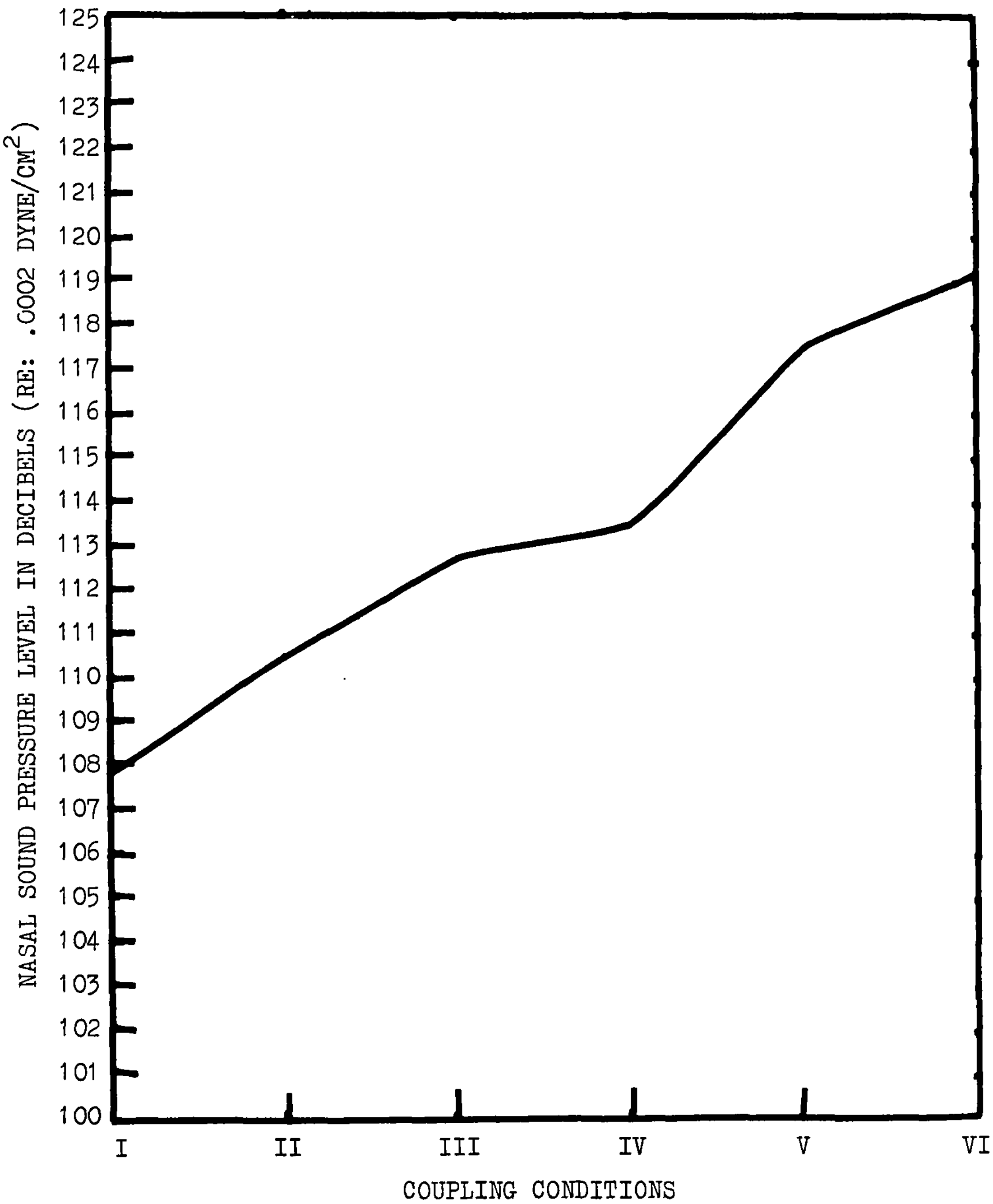

Figure 3.--Nasal sound pressure level means at each of six coupling conditions when the means are derived over all vowels, intensities and trials.

The vowel main effect is displayed graphically in Figure 4. When averaged over all other factors, the mean nasal sound pressure for [i], 116.3 dB exceeded those for [u], 114.3 dB, [ɑ], 112.3 dB, and [æ], 111.7 dB. These findings suggested that the high vowels [i] and [u] were associated with greater mean nasal sound pressure than the low vowels [ɑ] and [æ].

The trends observed in the analyses of the vowel and coupling main effects could also be seen in the vowel-by-coupling interaction that is plotted in Figure 5. It was evident that each of the four vowels displayed an increased mean nasal sound pressure from the smallest to the largest area of coupling. At each coupling condition, the greatest mean nasal sound pressure occurred for [i], followed in order by those for [u], [ɑ], and [æ]. It was seen, however, that the vowels did not respond in the same manner to increases in the area of coupling. The vowels [i] and [u], for example, demonstrated a greater increase in nasal sound pressure from Coupling Conditions I to VI than the vowels [ɑ] and [æ]. This increase amounted to 13.6 dB for [i], 12.4 dB for [u], 10 dB for [ɑ], and 9.7 dB for [æ]. This trend resulted in a greater range of vowel means at the larger than at the smaller coupling conditions. In coupling Condition I, the range of vowel means was 2.9 dB; at Coupling Condition VI, the range is 7.1 dB.

Inspection of Figure 5 also showed that, with the exception of the vowels [u], [æ] and [ɑ] between Coupling Conditions III and IV, the vowels displayed consistent increases in nasal sound pressure with each successive increase in coupling area. It could also be seen that, between any two coupling conditions, the amount of increase in nasal sound

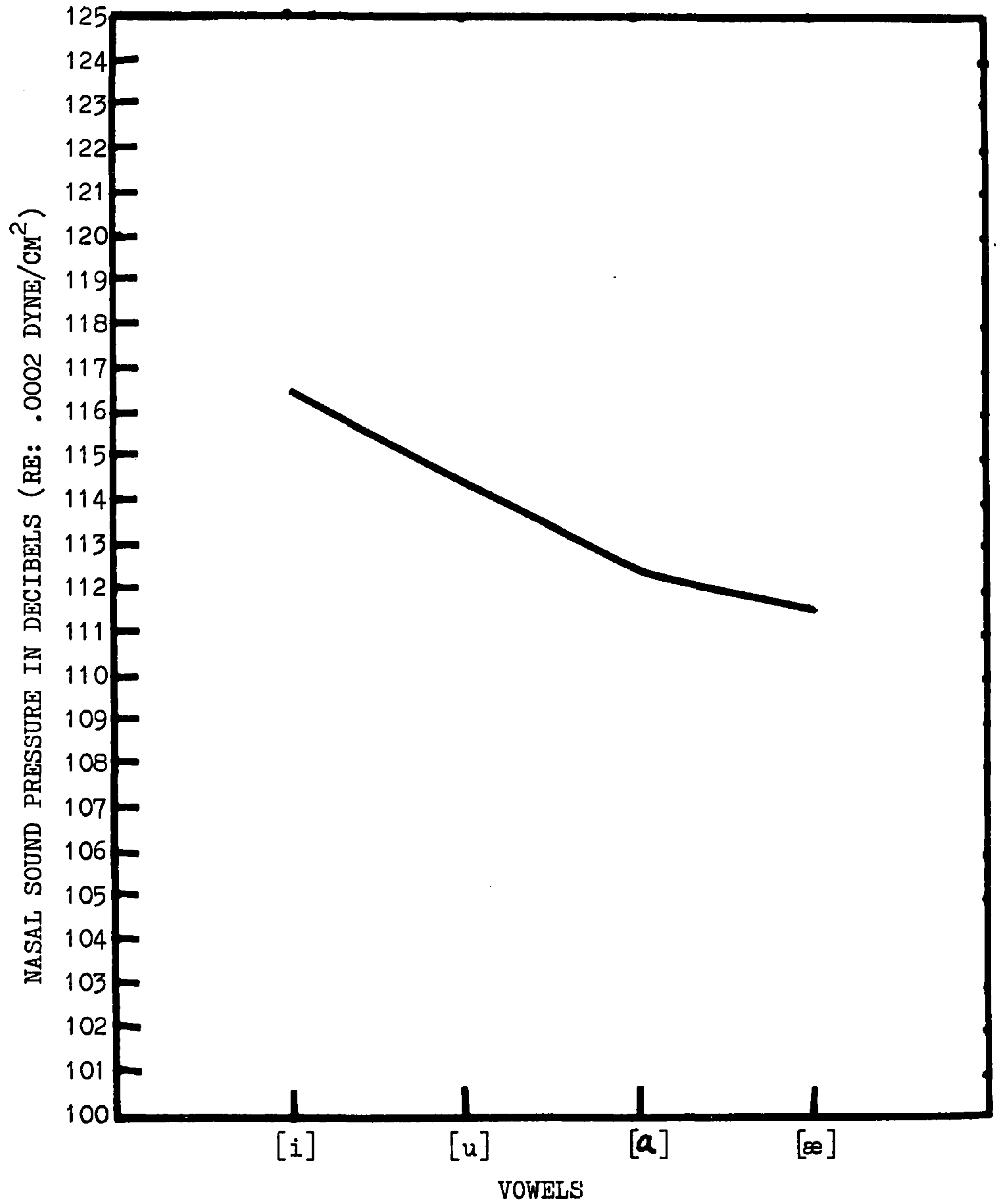

Figure 4.--Nasal sound pressure level means for each of four vowels when the means are derived over all coupling conditions, intensities, and trials.

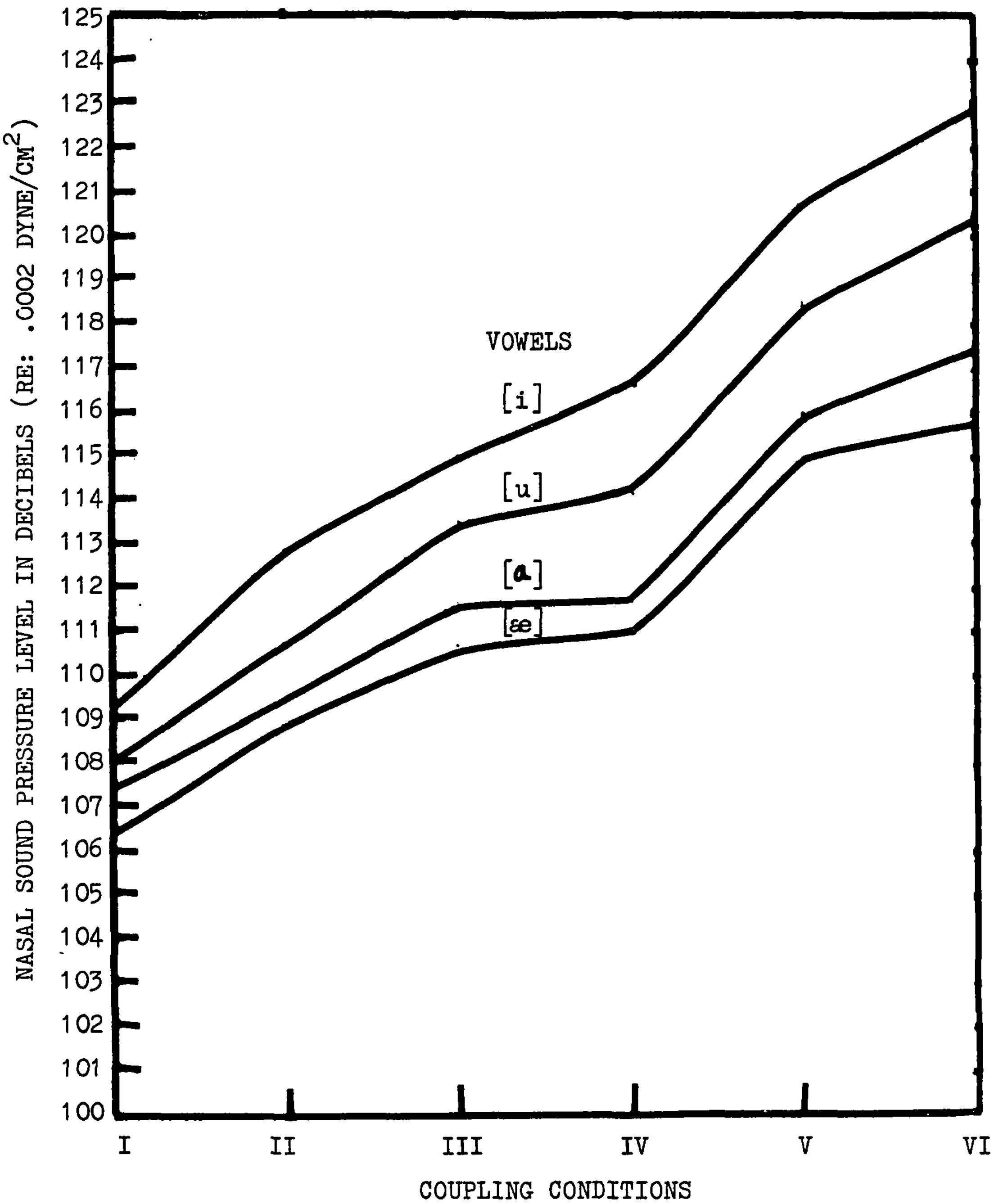

Figure 5.--Nasal sound pressure level means for each of four vowels at each of six coupling conditions when the means are derived over all intensities and trials.

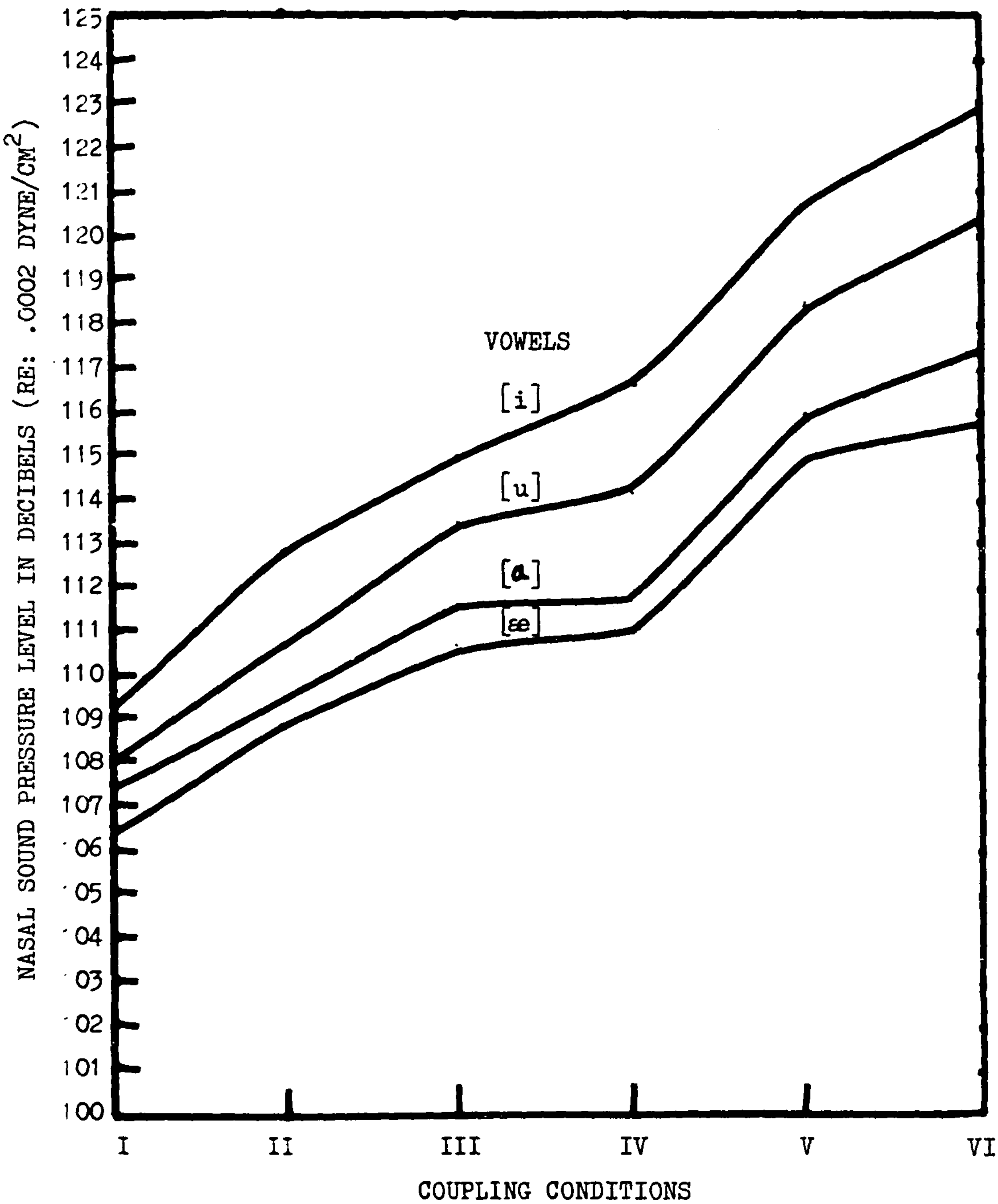

Figure 5.—Nasal sound pressure level means for each of four vowels at each of six coupling conditions when the means are derived over all intensities and trials.

pressure might differ for individual vowels. For instance, between Coupling Conditions V and VI the vowels [i] and [u] evidenced a greater increment in nasal sound pressure than [æ] and [ɑ]. Between Coupling Conditions IV and V, however, the trend was reversed.

Nasal-"Oral" Sound Pressure Differences

Statistical analysis of the sound pressure difference measures relating to coupling effects yielded results similar to those obtained for the nasal sound pressure measures. The similarity could be expected in that four of the six reference "oral" intensities were controlled. Thus, for the most part, changes in the sound pressure difference measure could be expected to reflect variations in nasal sound pressure rather than "oral" sound pressure changes.

The coupling main effect for the sound pressure difference data is presented graphically in Figure 6. Inspection of this figure indicated that, as the area of nasal coupling is increased, there was an increase in the mean sound pressure difference. These mean sound pressure differences, averaged over all vowels, intensity levels, and trials, ranged from 30.2 dB in Coupling Condition I to 41.9 dB in Coupling Condition VI.

The vowel main effect is displayed graphically in Figure 7. Examination of this plot of means revealed greater mean sound pressure differences for the high vowels [i] and [u] than for the low vowels [æ] and [ɑ]. The mean sound pressure differences, averaged over all intensities, coupling conditions, and trials were 38.0 dB, 36.45 dB, 33.75 dB, and 32.9 dB for [i], [u], [ɑ], and [æ], respectively. Reference to the vowel main effect for nasal sound pressure measures, displayed in

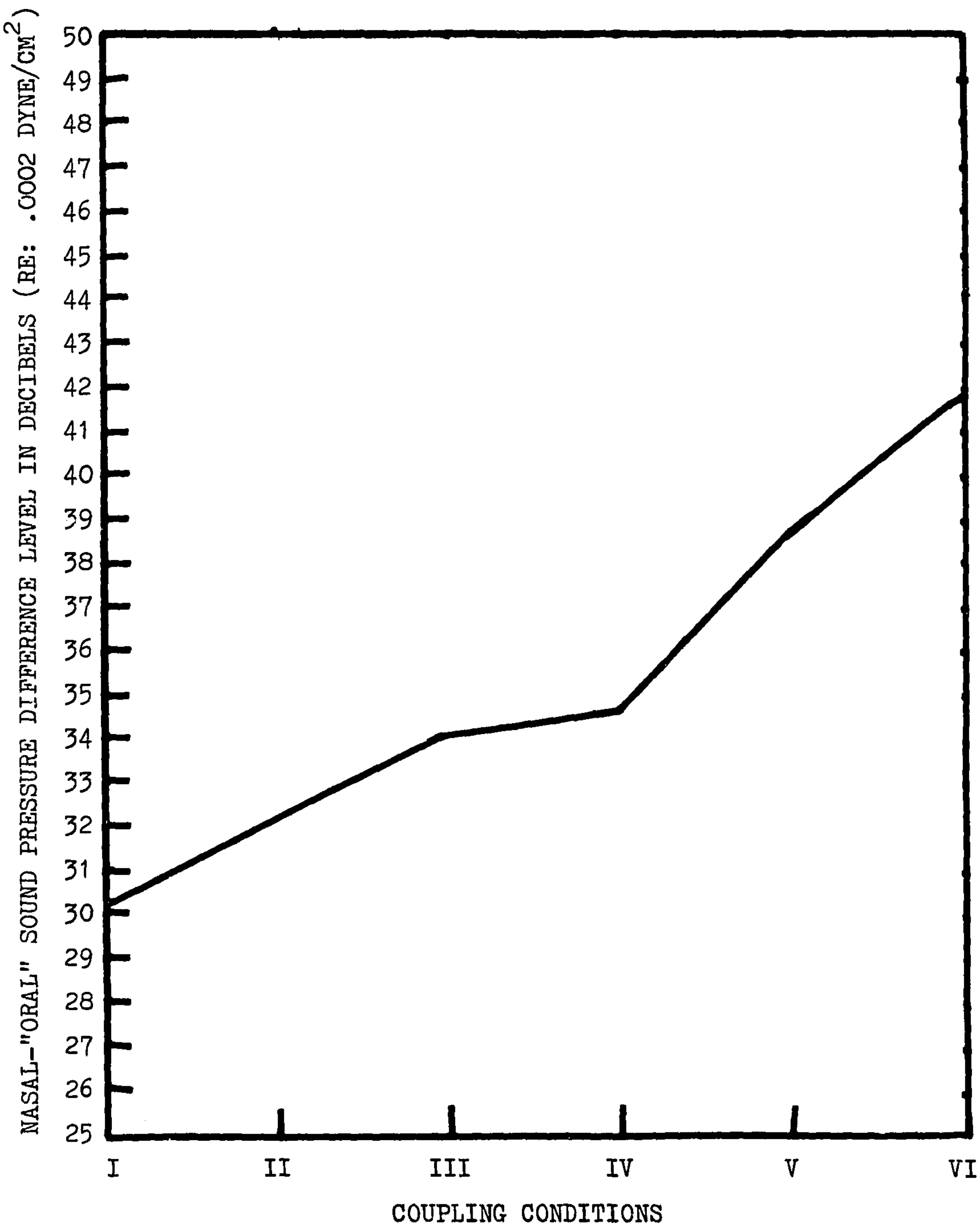

Figure 6.--Nasal-"oral" sound pressure level difference means at each of six coupling conditions when the means are derived over all intensities and trials.

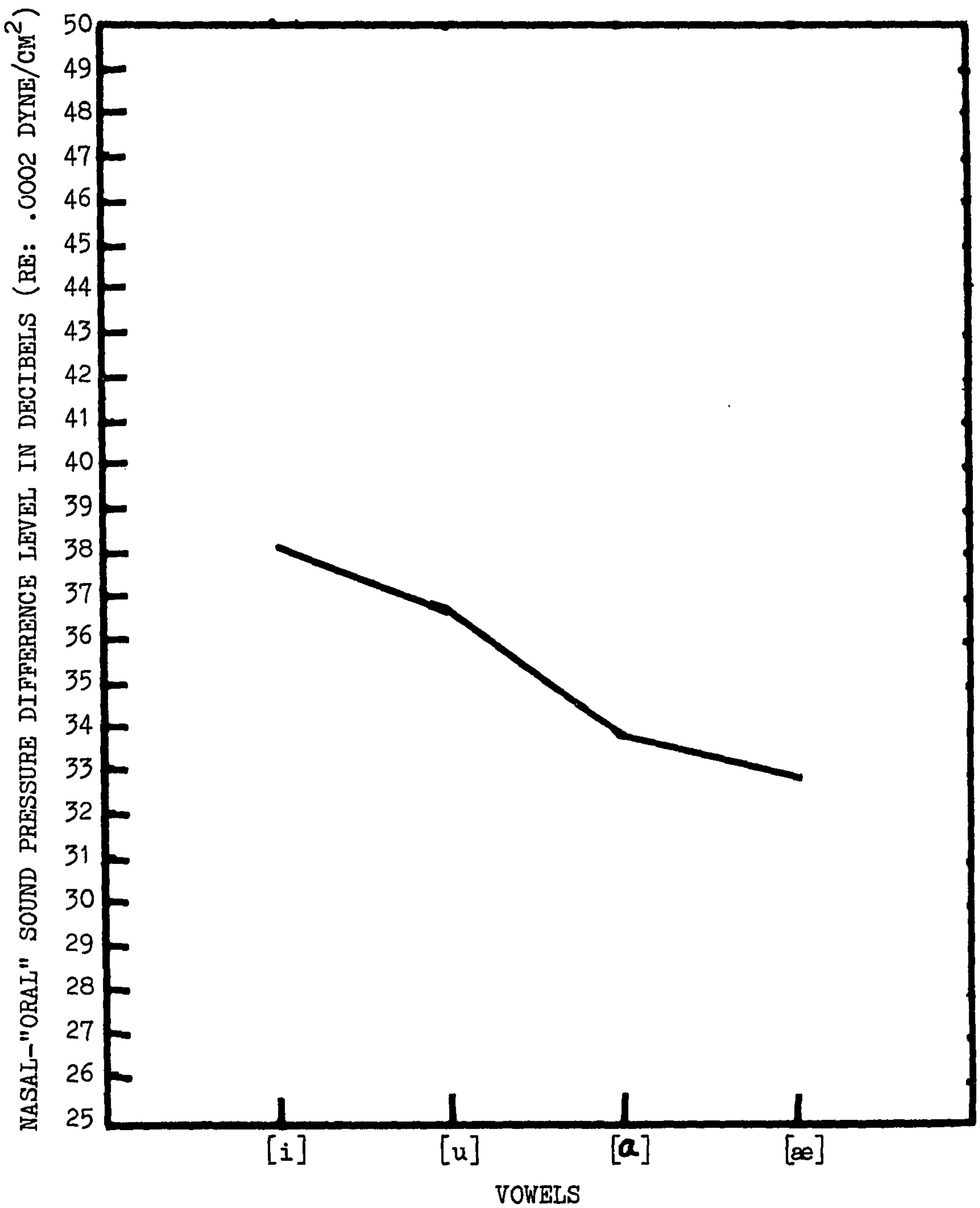

Figure 7.--Nasal-"oral" sound pressure level difference means for each of four vowels when the means are derived over all coupling conditions, intensities, and trials.

Figure 4, revealed an almost identical relationship among the vowel means.

The vowel-by-coupling interaction for the sound pressure difference measures, presented graphically in Figure 8, again revealed patterns similar to those obtained for the nasal sound pressure measures. While the mean sound pressure differences for all vowels showed a marked increase from Coupling Conditions I to VI, the amount of increase was greater for the vowels [i] and [u] than for the vowels [æ] and [ɑ]. This trend was reflected in the greater range of vowel means at the larger than at the smaller coupling conditions. It was clear, however, that the amount of increase in the sound pressure difference between any two coupling conditions varied according to the area of coupling involved and differed for individual vowels. For example, the increase for the vowel [u] between Coupling Conditions V and VI exceeded that for [æ] and [ɑ]; yet, between Coupling Conditions IV and V, the increase for [u] was somewhat less than that seen for these vowels.

On the basis of analyses of the coupling effects for the sound pressure difference and nasal sound pressure measures, averaged over intensity levels and trials, the following relationships appeared to obtain:

a) With the exception of the vowels [u], [æ], and [ɑ] between Coupling Conditions III and IV, increases in coupling area were accompanied by increases in the sound pressure difference and nasal sound pressure measures.

b) At each coupling condition, the high vowels [i] and [u] displayed greater sound pressure differences and nasal sound pressures than the low vowels [æ] and [ɑ].

c) A greater overall increase in the sound pressure difference and nasal sound pressure measures was evident for the vowels [i] and [u] than for the vowels [æ] and [ɑ] between

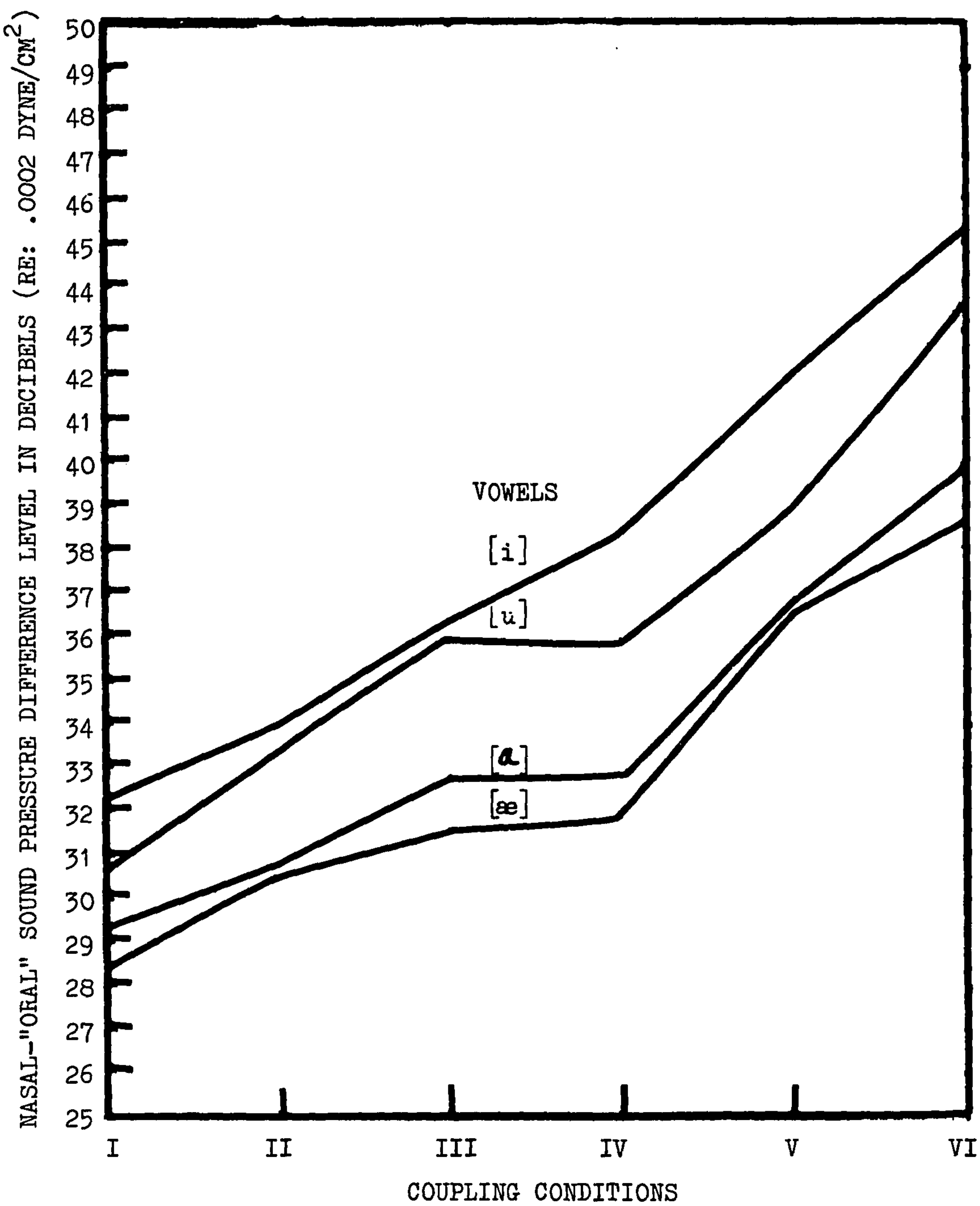

Figure 8.--Nasal-"oral" sound pressure level difference means for each of four vowels at each of six coupling conditions when the means are derived over all intensities and trials.

Coupling Conditions I and VI.

d) The amount of increase in the sound pressure difference and nasal sound pressure measured between any two coupling conditions differed for individual vowels according to the areas of coupling involved.

Intensity Effects

Nasal Sound Pressures

Another goal of the present study was to determine the effect of successive five dB increments in "oral" (overall) intensity, from 70 to 85 dB SPL, on nasal sound pressure levels obtained for each of the four vowels in each of six coupling conditions. Statistical analysis of the nasal sound pressures revealed that the intensity main effect, as well as the vowel-by-intensity and coupling-by-intensity interactions, are significant.

The intensity main effect for nasal sound pressure levels is shown in Figure 9. It was seen that, as "oral" intensity was increased from Intensity Level I (70 dB) to Intensity Level II (75 dB), no change occurred in the mean nasal sound pressure. With additional 5 dB increments in "oral" intensity, to Intensity Levels III (80 dB) and IV (85 dB), small increases (2 dB) in nasal sound pressure could be observed.

The responses of each of the four vowels to changes in "oral" intensity level could be seen in the vowel-by-intensity interaction. The nasal sound pressure means involved in this interaction, averaged over all coupling conditions and trials, are plotted in Figure 10. Inspection of this figure revealed that, at each "oral" intensity level, greater nasal sound pressures were recorded for the high vowels [i] and [u] than for the low vowels [æ] and [ɑ]. The difference between the

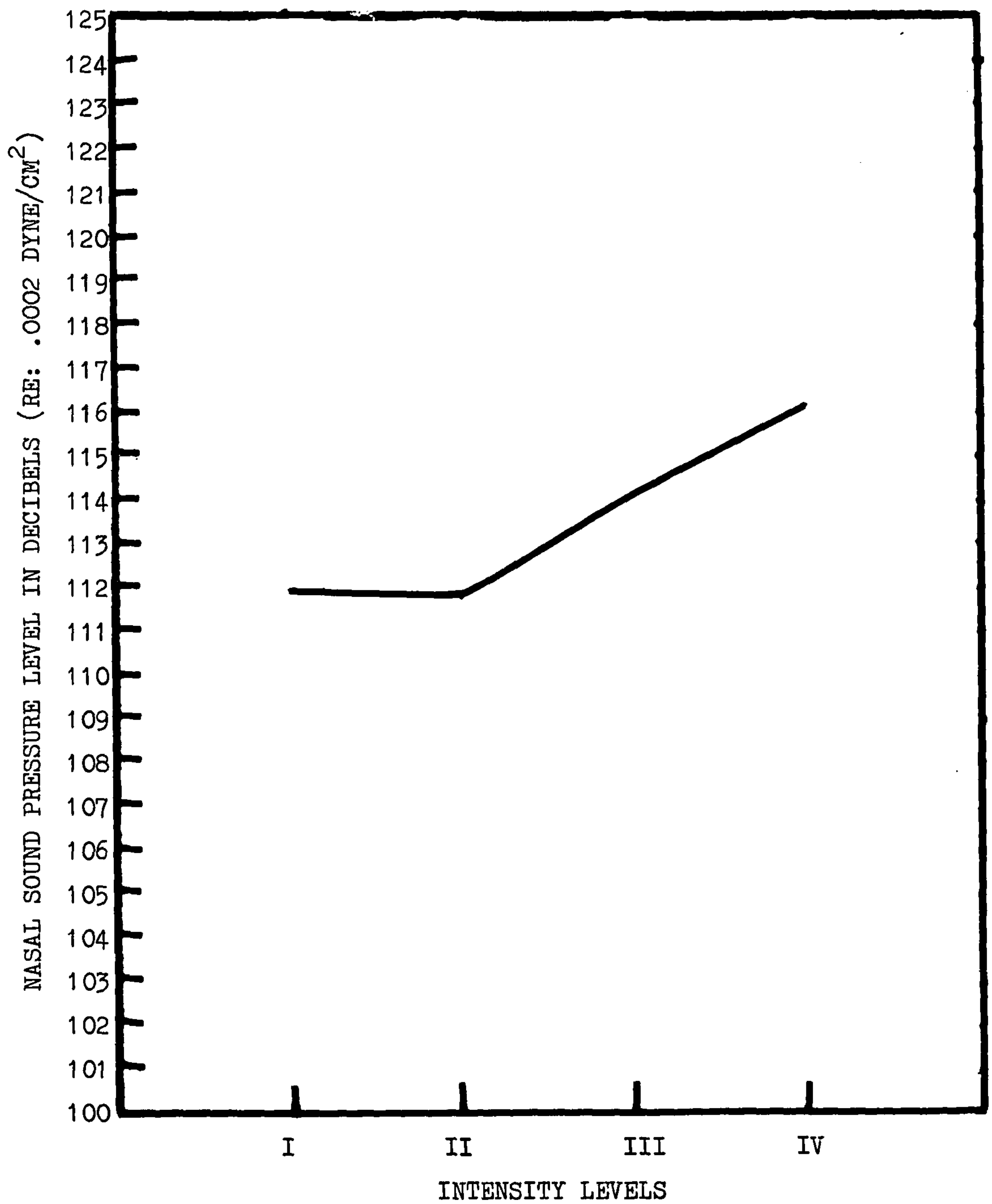

Figure 9.--Nasal sound pressure level means for each of four intensities when the means are derived over all vowels, coupling conditions and trials.

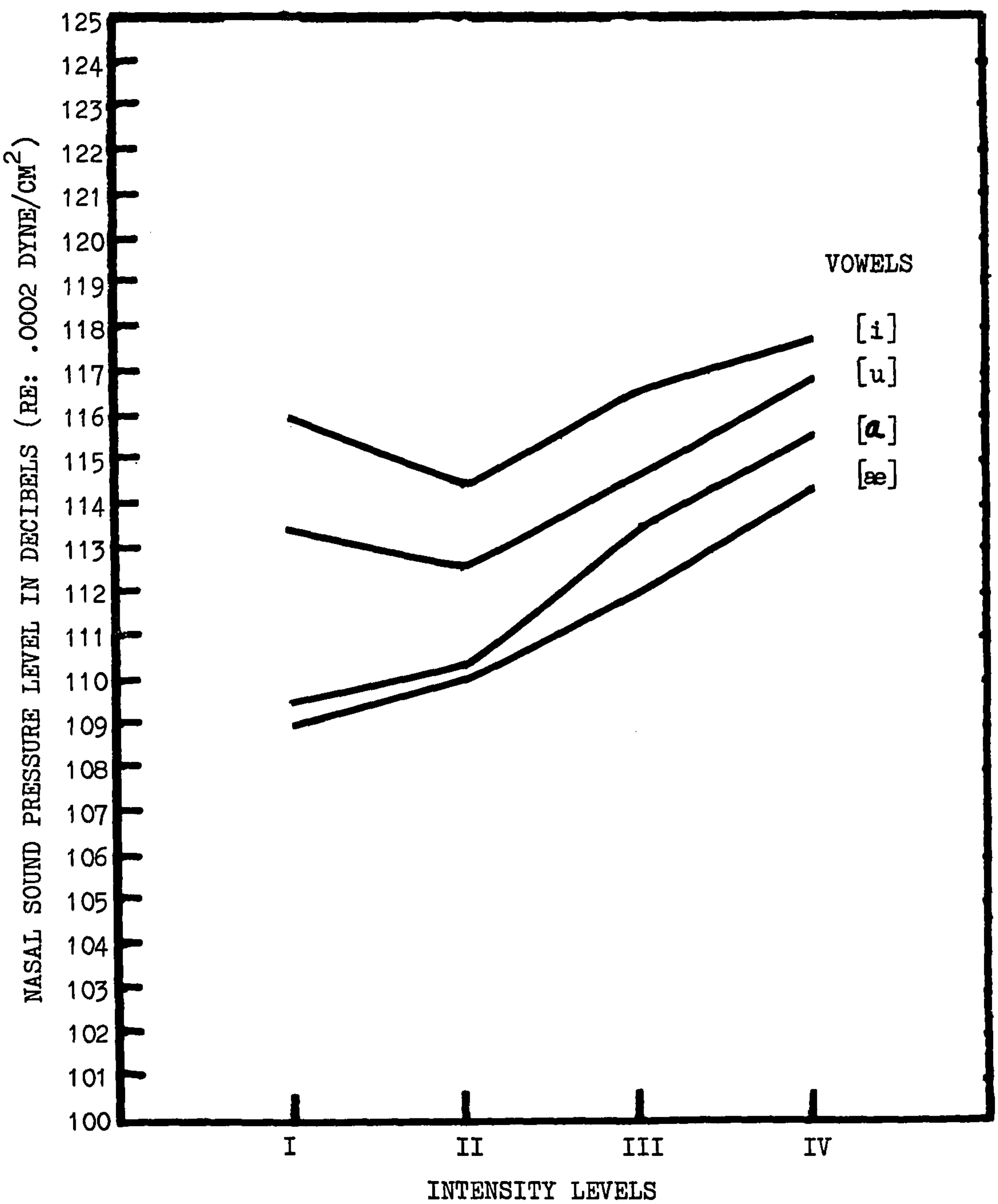

Figure 10.--Nasal sound pressure level means for each of four vowels at each of four intensities when the means are derived across all coupling conditions and trials.

highest and lowest vowel means, [i] and [æ], was greatest at Intensity Level I, 7.0 dB, and least at Intensity Level IV, 3.8 dB. Interestingly, the high vowels showed a slight drop (1 dB) in nasal sound pressure from Intensity Levels I and II while the low vowels displayed a slight increase in nasal sound pressure. Both high and low vowels showed small increments in nasal sound pressure with further increments in "oral" intensity level. These findings suggested that the effect of changes in "oral" intensity on nasal sound pressure levels varied according to the vowel produced.

The presence of an intensity-by-coupling interaction suggested that the effects of changes in "oral" intensity on the nasal sound pressure of vowels varied as a function of coupling. The nasal sound pressure means involved in this interaction, averaged over the trials and vowels, are displayed in Figures 11 and 12. Examination of these figures revealed the following trends: (a) Greater increments in nasal sound pressure were associated with increases in "oral" intensity level in Coupling Condition I (.0000 cm^2) than in any other coupling condition. (b) In Coupling Conditions I and II, increases in "oral" intensity were consistently marked by increases in nasal sound pressure. (c) In Coupling Conditions III and IV, a breakdown in this relationship occurred. Figure 11 showed evidence of a trough effect at the intermediate intensity levels such that nasal sound pressures at Intensity Levels II and III were lower than those at Levels I and IV. Nasal sound pressures at Levels I and IV were similar in magnitude. (d) There was little change in nasal sound pressure in Coupling Condition V as intensity was increased from Intensity Levels I to IV. (e) At Coupling Condition VI,

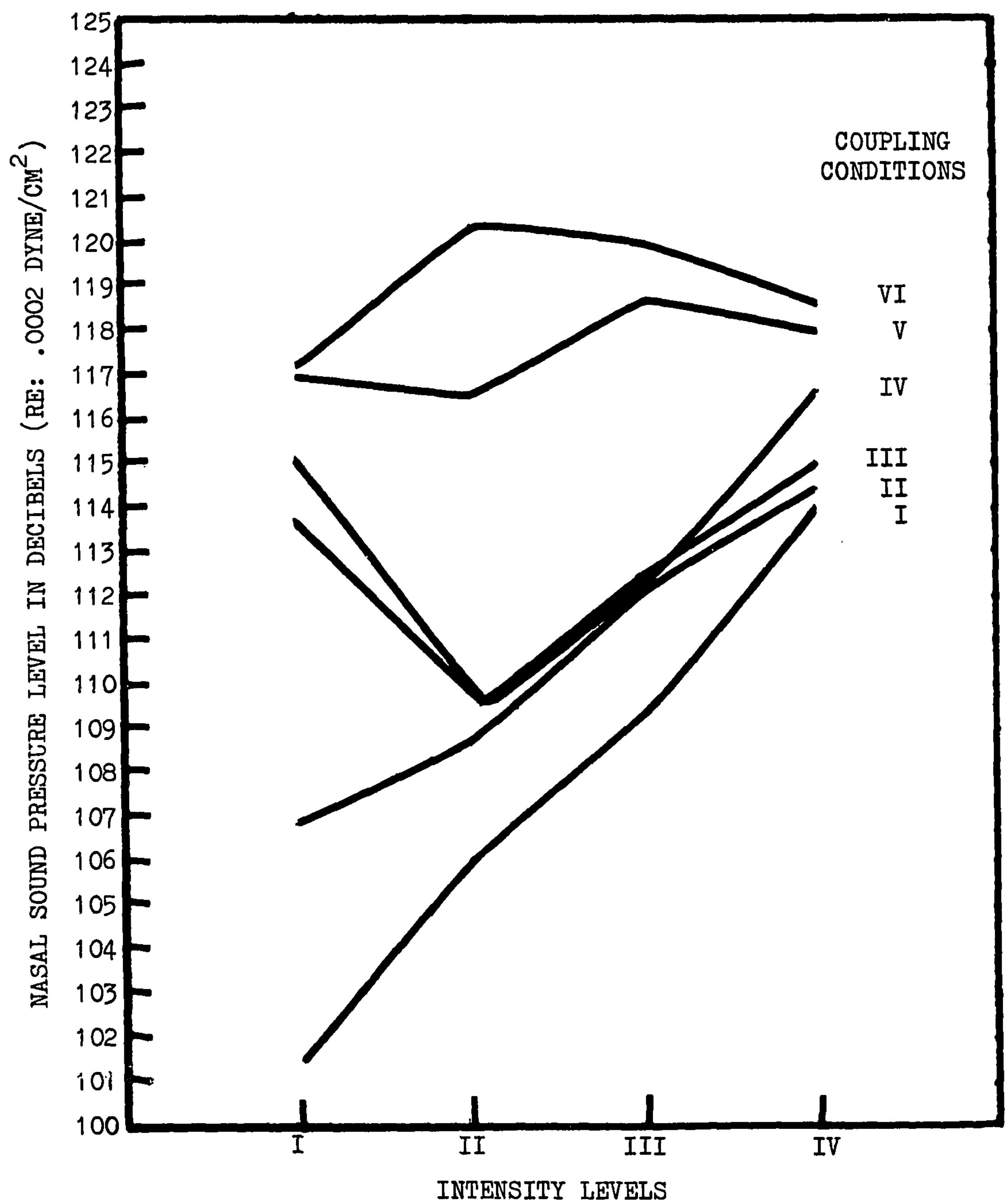

Figure 11.--Nasal sound pressure level means for each of four intensities at each of six coupling conditions when the means are derived over all vowels and trials.

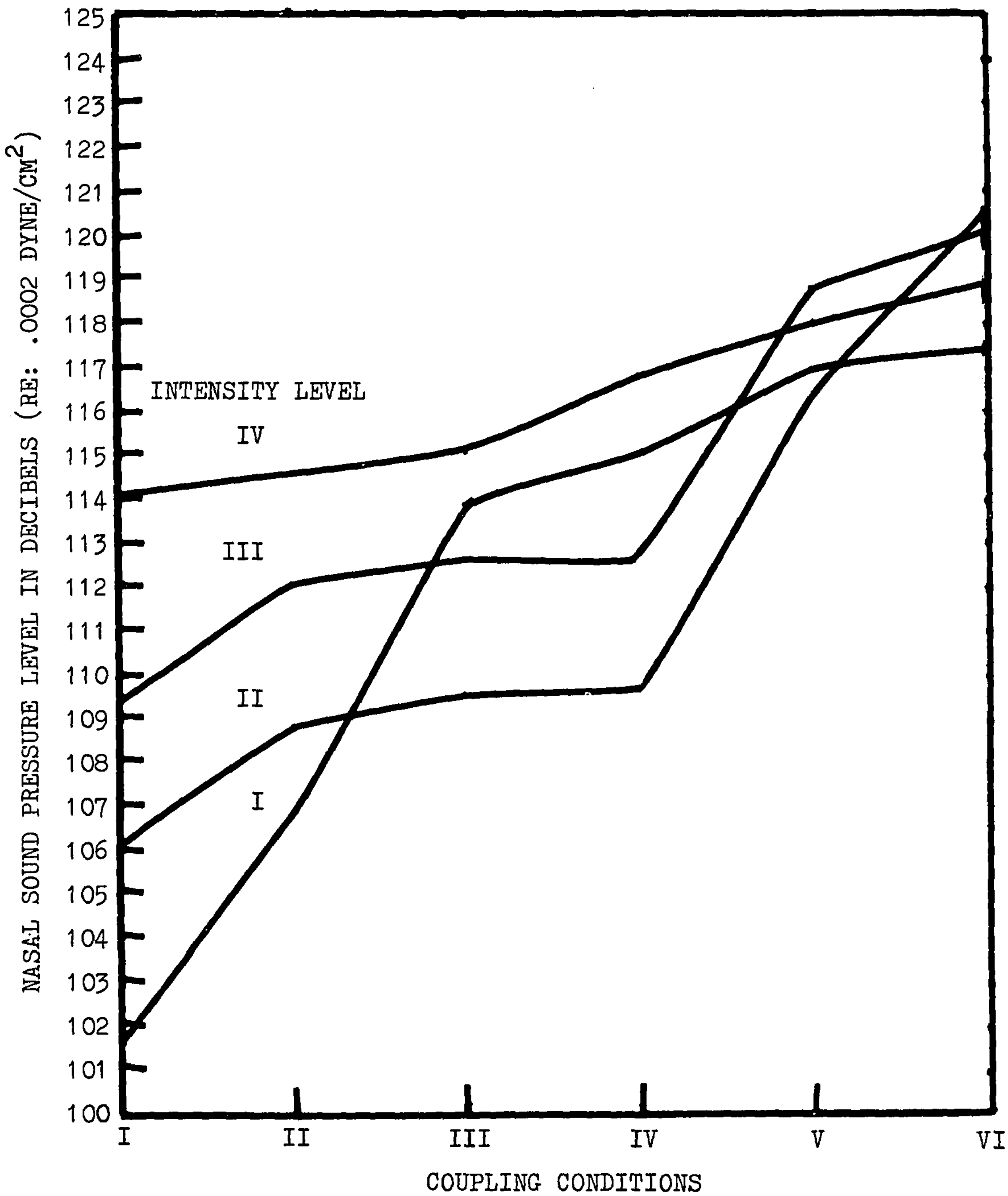

Figure 12.--Nasal sound pressure level means for each of four intensities at each of six coupling conditions when the means are derived over all vowels and trials.

the pattern of nasal sound pressures was the inverse of that seen in Coupling Conditions III and IV; nasal sound pressures at Intensity Levels II and III exceeded those at Levels I and IV.

Examination of the patterns of change in nasal sound pressures at the various coupling conditions and intensity levels in Figure 12 indicated that the effects of variations in coupling area differed for the four intensity levels. As in the case of the coupling main effect graphed in Figure 3, it could be seen that, at each intensity level, there was an increase in nasal sound pressure from the smallest to the largest coupling condition. The amount of increase, however, differed for the four intensity levels. At Intensity Level I (70 dB), the increase in mean nasal sound pressure from Coupling Conditions I to VI amounted to 15.7 dB. At Intensity Levels II (75 dB), III (80 dB), and IV (85 dB), increases in nasal sound pressure amounted to 14.4, 10.6, and 4.7 dB, respectively. From these data, it could be generalized that increases in the area of coupling resulted in substantially smaller increases in nasal sound pressure at the higher than at the lower intensity levels.

Figure 12 also showed a marked difference in the pattern of sound pressure changes that occurred at the 70 dB intensity level and those that occurred at the three highest intensity levels (75, 80, and 85 dB). At the higher intensity levels, there was a substantially greater increase in mean nasal sound pressure between Coupling Conditions III and VI than between Coupling Conditions I and III. At the 70 dB level, this relationship was reversed. Between Coupling Conditions I and III, nasal sound pressure was increased 12 dB as compared with an increase of only 3 dB between Coupling Conditions III and VI. The increments in nasal sound pressure between Coupling Conditions I and III at the 70 dB level were substantially larger than any other increment seen between coupling conditions at any of the intensity levels studied.

The relationships displayed in Figure 12 are interesting from another point of view. If the mean values at the 70 dB level were excluded from consideration, it could be seen that as "oral" intensity was increased smaller increments in nasal sound pressure tend to occur in the larger than in the smaller coupling conditions. At Coupling Conditions I and II, for example, 5 dB increments in "oral" intensity from 75 to 85 dB were accompanied by somewhat smaller increments in nasal sound pressure (2 to 4 dB). In Coupling Conditions IV and V, 5 dB increments in "oral" intensity resulted, at the maximum, in 2 dB increments in nasal sound pressure. At times, "oral" intensity increments resulted in no increase or slight decrements in the nasal sound pressure level. The consistent pattern of increased nasal sound pressures with increased "oral" intensity level which was seen in the smallest two coupling conditions was not consistently seen at the larger coupling conditions.

Inspection of Figure 12 clearly indicated that, when the area of coupling was .0314 cm^2 (Coupling Condition III) or greater, increases in "oral" intensity did not always result in an increase in the nasal sound pressure level. It could be observed that the nasal sound pressure means at the 70 dB intensity level were somewhat greater than those at the 75 dB level in Coupling Conditions III, IV, and V and were also greater than the means in the 80 dB level in Coupling Conditions III and IV. It could also be seen that the means at the 75 dB level were similar to those at the 80 dB level in Coupling Conditions IV through VI. The means at the 80 dB level were similar to those at the 85 dB level in Coupling Conditions V and VI.

It could be seen in Figure 12 that the effects of increases in coupling area on the nasal sound pressure level differed at each of the four intensity levels. At each of the four intensity levels, there was a point at which a further increase in coupling area resulted in a sharp increase in nasal sound pressure. This point seemed to occur at a smaller coupling area for vowels produced at lower intensities and at progressively larger coupling areas as vocal intensity was raised in 5 dB steps.

Nasal-"Oral" Sound Pressure Differences

Evaluation of the effects of successive five dB increments in "oral" (overall) intensity, from 70 to 85 dB SPL, on sound pressure differences measured for each of four vowels in each of six coupling conditions yielded results that might be anticipated from the preceding analysis of nasal sound pressure measures. The statistical analysis of the sound pressure differences revealed that the intensity main effect, and the vowel-by-intensity and coupling-by-intensity interactions were significant. It will be recalled that data obtained at the "comfort" and "comfort-masked" intensity levels were included in the analysis of variance for the sound pressure differences. In order to understand the findings related to the "comfort" and "comfort-masked" intensities, it is helpful to review the raw scores and average "oral" sound pressure of the two "comfort" intensities. When averaged across vowels, coupling conditions, and trials, the mean "comfort" intensity was 76.2 dB; for the "comfort-masked" intensity level, the mean intensity was 77.3 dB. For any mean, however, the raw scores from which that mean was derived could range from 70 to 82 dB. It should be pointed out that, in all coupling conditions, when the raw scores at "comfort" and "comfort-masked" intensity levels were compared to those obtained at an equivalent controlled "oral" intensity, within the same trial, the recorded sound pressure differences varied by no more than two to three dB.

A graphic representation of the intensity main effect for sound pressure differences is depicted in Figure 13. For clarity in the graphic presentation, the "comfort" and "comfort-masked" intensity levels were not included in the plot of means.

Examination of the intensity main effect reveals that, averaged across vowels, coupling conditions, and trials, the mean sound pressure difference for the controlled intensity levels (70, 75, 80, and 85 dB) was 41.7, 36.7, 34.0, and 30.8 dB, for Intensity Levels I, II, III, and IV, respectively. The mean sound pressure difference was 34.5 dB for the "comfort" intensity level and 34 dB for the "comfort-masked" intensity level. This finding suggested that, the mean sound pressure differences obtained at the two "comfort" intensity levels closely resembled each other and were similar to those obtained at Intensity Level III (80 dB).

Inspection of the mean sound pressure differences at Intensity Level I through IV presented in Figure 13 suggested that there is a substantial decrease in the sound pressure difference measured with each five dB increment in "oral" intensity from 70 to 85 dB. The greatest decrease in the sound pressure measure occurred between Intensity Levels

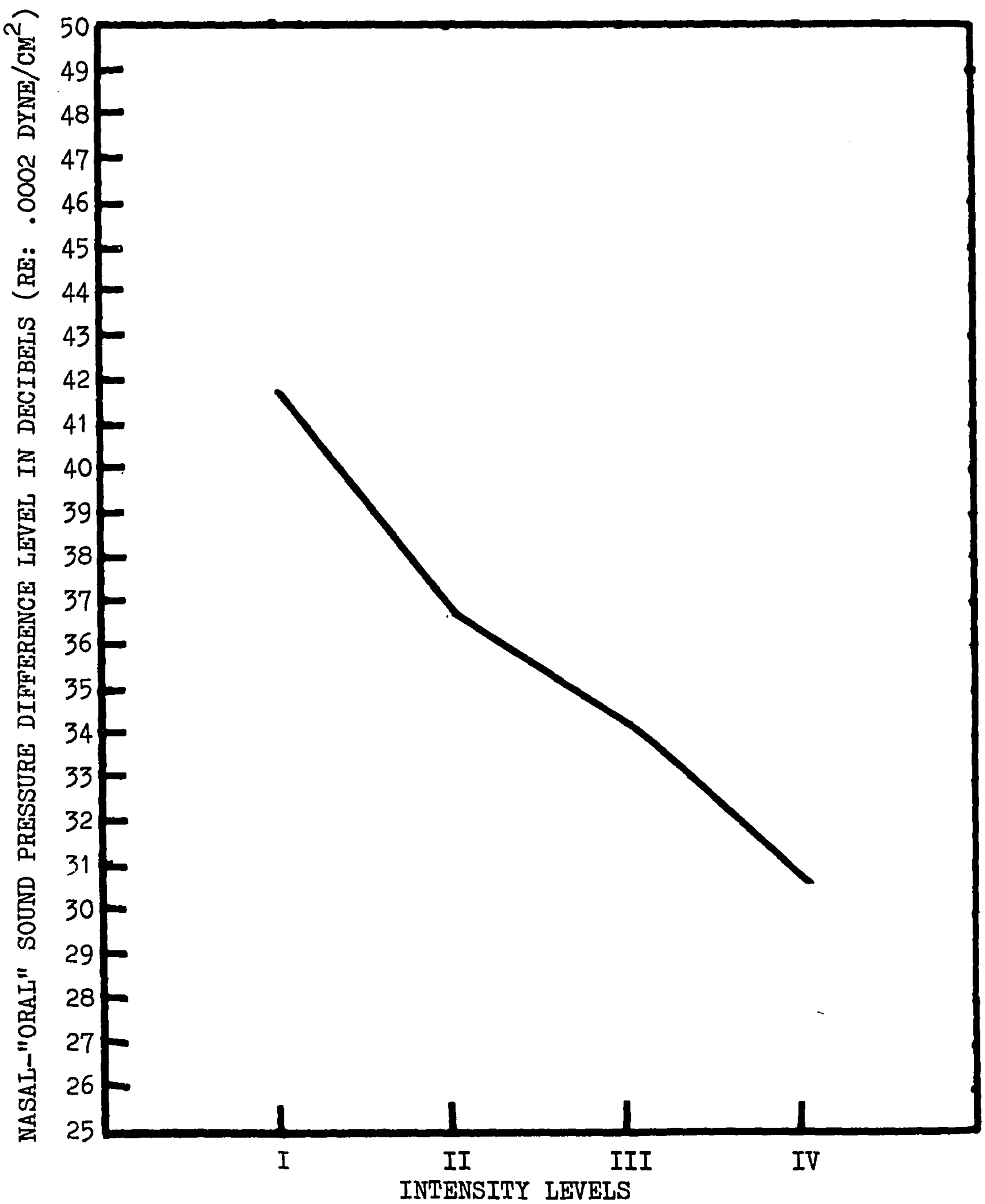

Figure 13.--Nasal-"oral" sound pressure level difference means for each of six intensities when the means are derived over all vowels, coupling conditions and trials.

I and II, 5.0 dB. Between Intensity Levels II and III the decrease was 2.6 dB, and between Intensity Levels III and IV, 3.2 dB.

The large decrease in the sound pressure difference measure between Intensity Levels I and II was not unexpected when the intensity main effect for nasal sound pressures was considered. It will be recalled that between Intensity Levels I and II, there was no increase in nasal sound pressure, while small increases in nasal sound pressure were found between all other intensity levels. The sound pressure difference measure was derived by subtracting "oral" intensity from nasal intensity. If "oral" intensity was raised with no accompanying increase in nasal sound pressure, therefore, a greater decrease in the sound pressure difference would be observed.

Figures 14 and 15 are graphs of the vowel-by-intensity interaction for sound pressure differences. The "comfort" and "comfort-masked" intensities were included in Figure 14, but were excluded from Figure 15.

Inspection of the vowel-by-intensity interaction in Figure 14 showed that the mean sound pressure differences at the "comfort" and "comfort-masked" intensity levels clustered around the mean sound pressure differences recorded for Intensity Level III (80 dB). It could be observed that, for the high vowels [i] and [u], the mean sound pressure differences were essentially the same for both "comfort" intensities. For the low vowels [æ] and [ɑ], a smaller mean sound pressure difference was obtained at the "comfort-masked" intensity level than at the "comfort" intensity level. Upon inspection of the raw data, it was noted that the "oral" intensities measured for [i] and [u] were

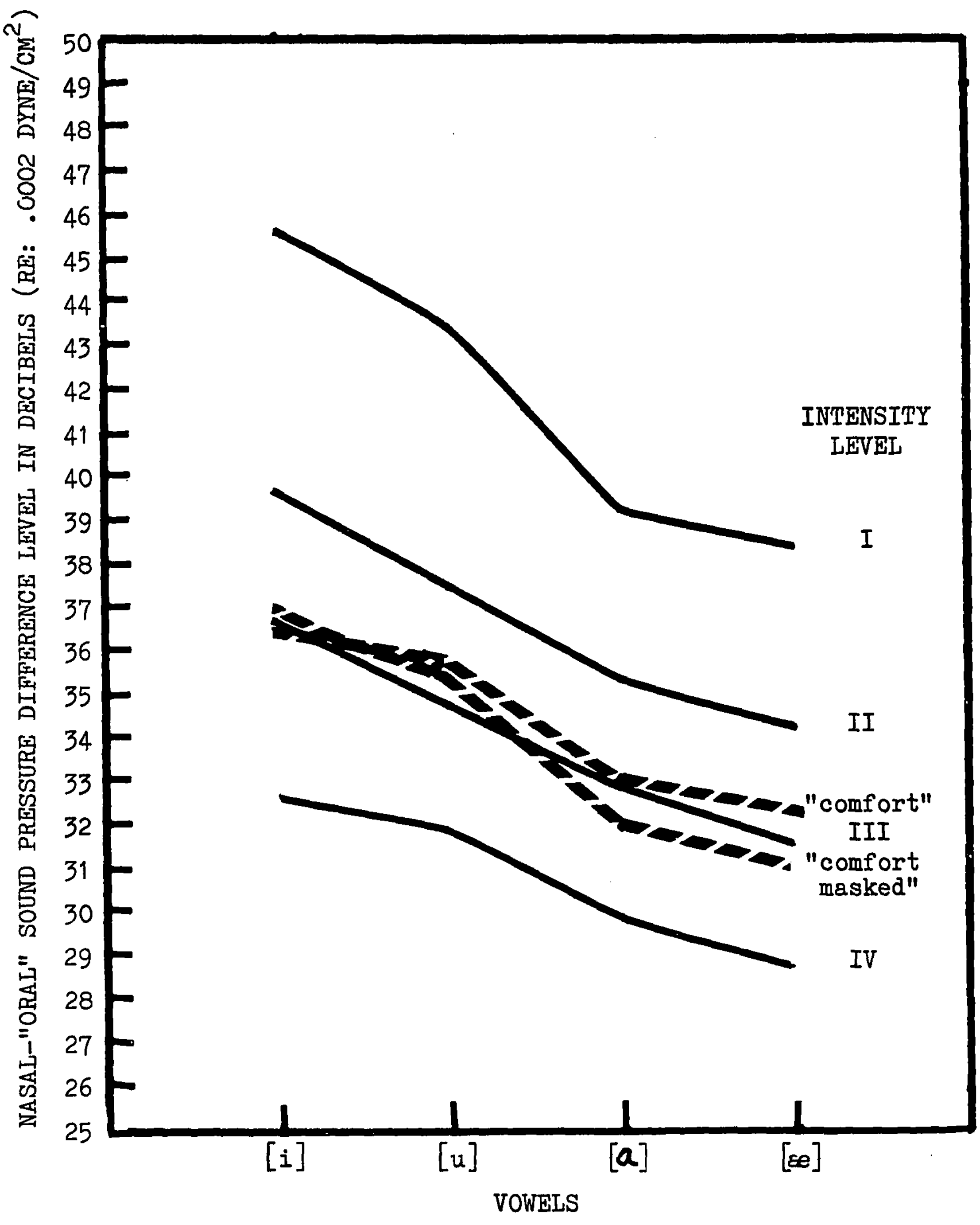

Figure 14.--Nasal-"oral" sound pressure level difference means for each of four vowels at each of four intensities when the means are derived across all coupling conditions and trials.

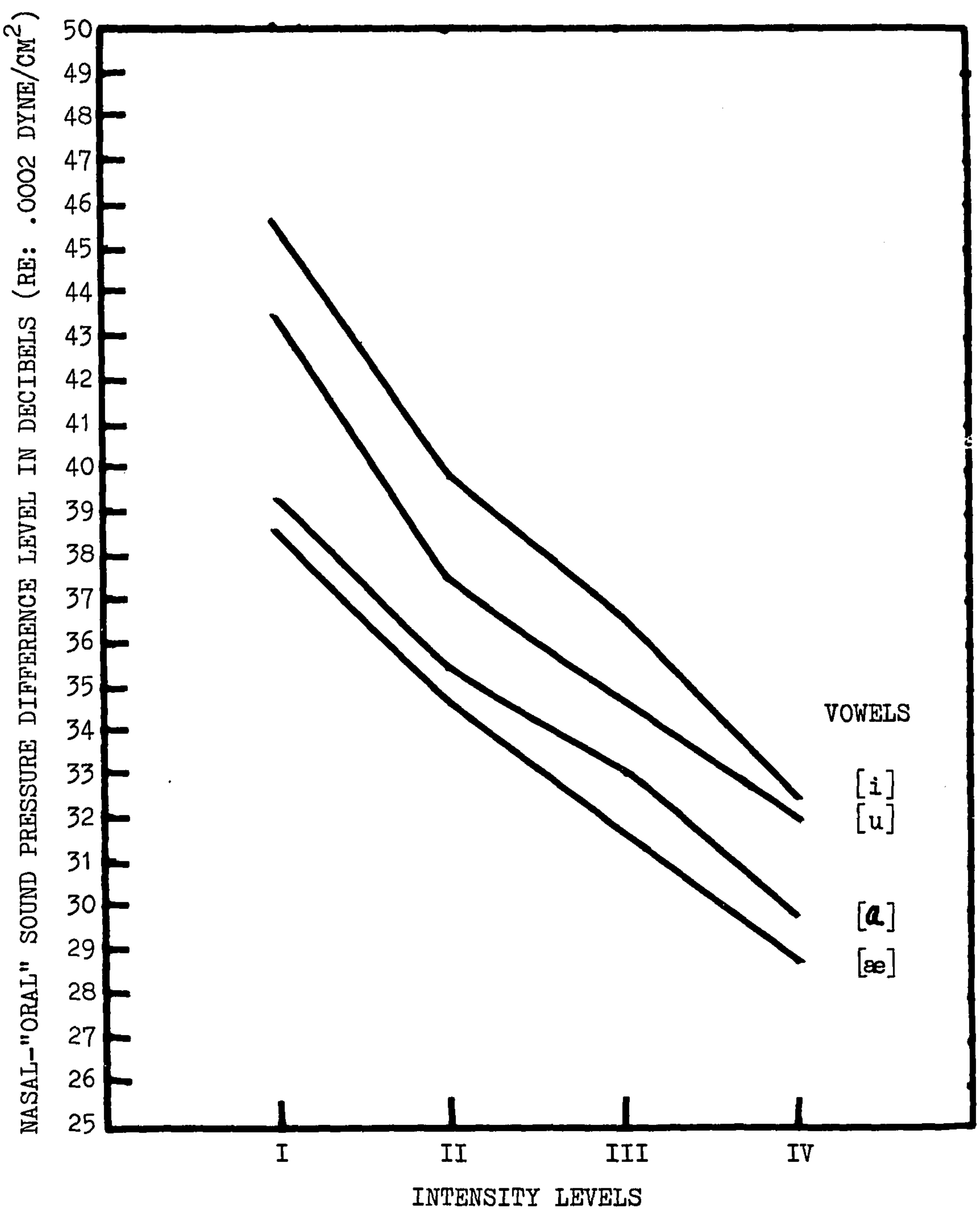

Figure 15.--Nasal-"oral" sound pressure level difference means for each of four vowels at each of six intensities when the means are derived across all coupling conditions and trials.

approximately the same for the "comfort" and "comfort-masked" intensity levels. For the vowels [æ] and [ɑ], higher "oral" intensities were measured at the "comfort-masked" intensity level than at the "comfort" intensity level. This pattern of "oral" intensity variation could explain smaller sound pressure differences at the "comfort-masked" intensity level for the vowels [æ] and [ɑ]. It may be speculated that the greater "oral" intensities recorded for [æ] and [ɑ] at the "comfort-masked" intensity level could be due to the fact that the relative amplitudes for [æ] and [ɑ] are higher than for [i] and [u].

The trend observed in the analysis of the intensity main effect could be seen in the vowel-by-intensity interaction. The mean sound pressure differences at Intensity Levels I through IV are plotted in Figure 15. It was evident that an inverse relationship obtained between the sound pressure difference measure and "oral" intensity for each of the four vowels. Each of the vowels displayed a decrease in the sound pressure difference measure as "oral" intensity was raised. It was apparent, however, that the amount of decrease in the sound pressure difference measure with each five dB intensity increment varied for individual vowels, being greater for the high than the low vowels. The total decrease in the sound pressure difference from the lowest to the highest "oral" intensity was 13.1 dB for [i], 11.4 dB for [u], 9.6 dB for [æ], and 9.4 dB for [ɑ]. For all vowels the greatest decrease occurred between Intensity Levels I and II; the smallest decrease occurred between Intensity Levels II and III.

Figure 15 also showed that the range of mean sound pressure differences for the vowels was decreased as "oral" intensity was elevated.

At Intensity Level I, the difference between the highest and lowest mean was 7.2 dB; at Intensity Level II, 5.3 dB; at Intensity Level III, 4.9 dB; and at Intensity Level IV, 3.7 dB.

These findings for sound pressure differences might be anticipated on the basis of the preceding nasal sound pressure data. Sound pressure differences were derived by subtracting "oral" sound pressure from nasal sound pressure. In an instance, therefore, in which there was no increase or only a slight increase in nasal sound pressure as "oral" intensity was increased, smaller sound pressure differences would be recorded. It was noted that with increases in "oral" intensity, smaller increases in nasal sound pressure were observed for the high vowels than for the low vowels. This could account for the greater decrease in the sound pressure differences for high than for low vowels found in the present study. The smaller increase in nasal sound pressure found for the high than for the low vowels also could account for the reduction in the range of sound pressure differences as intensity was raised.

The interaction between coupling and intensity for sound pressure differences was presented in Figures 16 and 17. The "comfort" and "comfort-masked" intensity levels were displayed in Figure 16, but were excluded from Figure 17.

Inspection of Figure 16 again revealed that, in general, the mean sound pressure differences at the "comfort" and "comfort-masked" intensity levels were similar to those obtained at Intensity Level III (80 dB). The exceptions which exist could be explained when the raw data for "oral" intensity at the "comfort" levels was examined. For

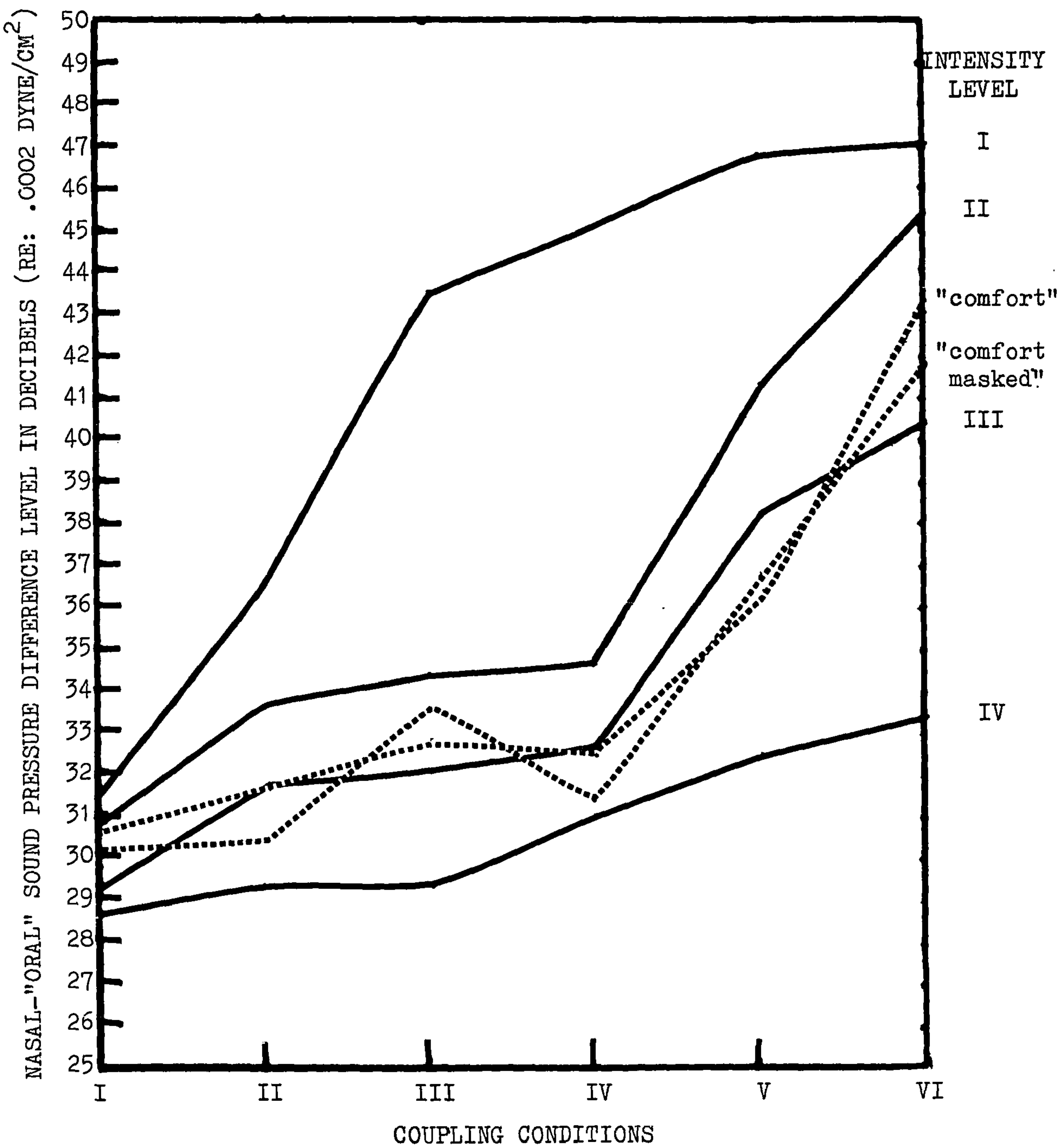

Figure 16.--Nasal-"oral" sound pressure level difference means for each of six intensities at each of six coupling conditions when the means are derived over all vowels and trials.

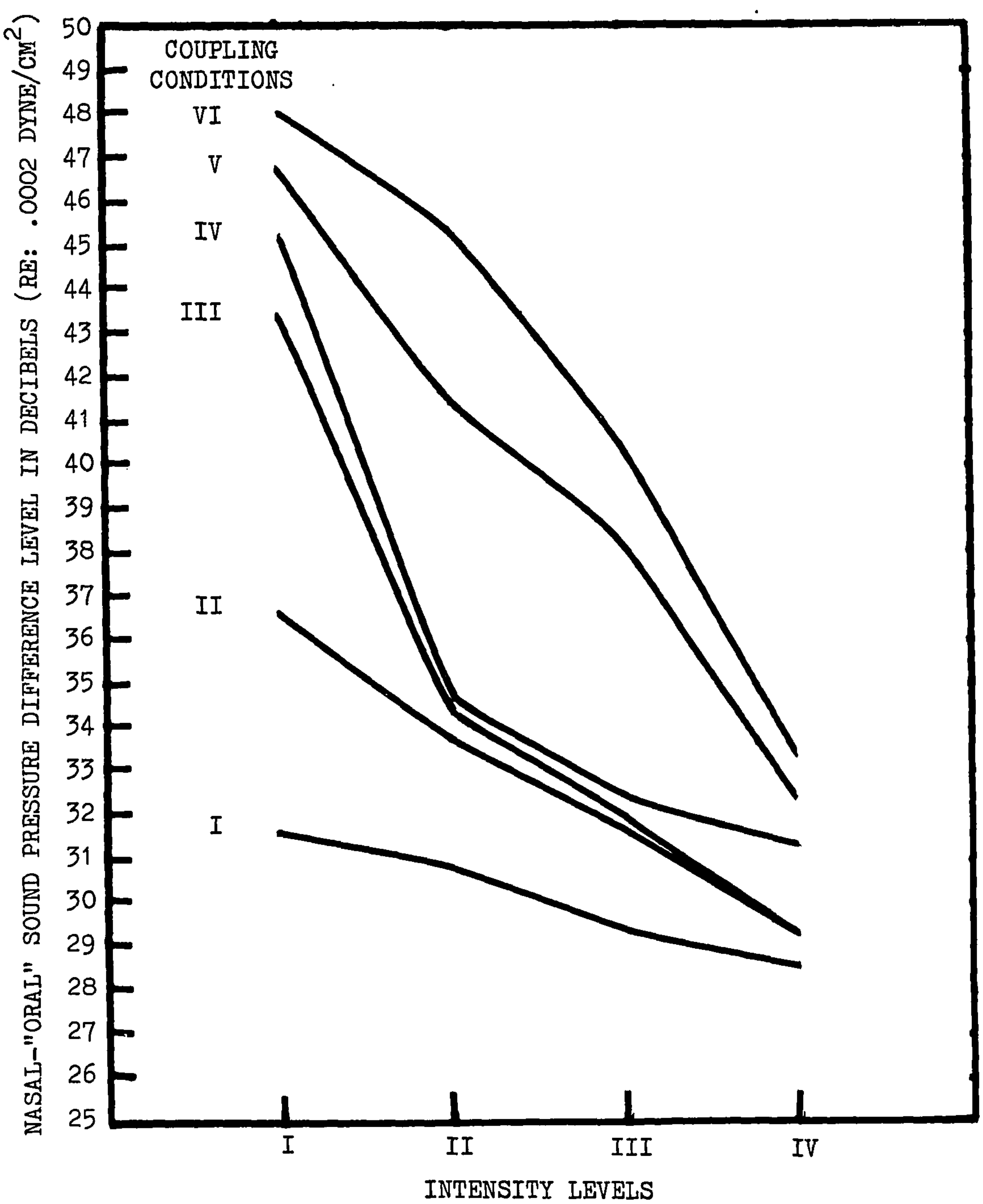

Figure 17.--Nasal-"oral" sound pressure level difference means for each of four intensities at each of six coupling conditions when the means are derived over all vowels and trials.

example, in Figure 16 it could be observed that in Coupling Condition V, the mean sound pressure differences at the "comfort" intensity levels were lower than those found at Intensity Level III (80 dB); whereas, in Coupling Condition VI, greater sound pressure differences were found for the "comfort" intensities than for Intensity Level III. These minor variations were likely to be explained by the fact that "oral" intensity for the "comfort" intensities was higher than that for the 80 dB intensity level at Coupling Condition V and lower than that for the 80 dB level at Coupling Condition VI.

Examination of the sound pressure differences for Intensity Levels I through IV presented in Figure 17 indicated that at all intensity levels, higher sound pressure differences occurred as coupling increased; however, as intensity was increased, the effects of coupling on the resulting sound pressure differences were reduced. Put somewhat differently, greater increases in the sound pressure difference measure occurred at the lower than at the higher intensity levels as coupling was increased. The difference between the means for Coupling Conditions I and VI were 15.5, 14.5, 11.1, and 4.6 dB for Intensity Levels I, II, III, and IV, respectively.

Further inspection of the changes in the mean sound pressure differences at the four intensities in Figure 17 revealed that increments in "oral" intensity were associated with greater decrements in the sound pressure difference measure when the area of coupling was large than when it was small. At Coupling Condition I, a 2.7 dB decrease in the sound pressure difference was obtained with a 15 dB increase in "oral" intensity. The same increment in "oral" intensity resulted in decreases of 7.3, 14, 13.7, 14.3, and 13.6 dB in the sound pressure difference for Coupling Conditions II, III, IV, V, and VI, respectively.

These findings for the sound pressure difference data might be predicted on the basis of the analysis of the nasal sound pressures. At each intensity level, there was an increase in nasal sound pressure from the smallest to the largest coupling condition, however, substantially smaller increases in nasal sound pressure were measured at higher than lower intensity levels with the same increase in coupling area. This smaller increase in nasal sound pressure at higher intensity levels would account for the relatively smaller increase in sound pressure differences at higher intensity levels. The greater decrease in sound pressure differences at the more open coupling conditions also would be predicted on the basis of the smaller increase, lack of increase, or, at times, decrease in nasal sound pressure observed at more open coupling conditions.

On the basis of the analysis of the intensity effects for the sound pressure difference and nasal sound pressure measures, the following relationships appeared to obtain:

a) When means were averaged over all trials and vowels, there was an increase in the sound pressure difference and nasal sound pressure measures from the smallest to the largest coupling conditions at each of the four intensity levels.

b) When means were averaged over all trials, vowels, and coupling conditions, 5 dB increments in "oral" intensity were usually associated with smaller increments (at most 2 dB) in nasal sound pressure. No increase in nasal sound pressure, however, occurred between Intensity Levels I and II.

c) When means were averaged over all trials, vowels, and coupling conditions, 5 dB increments in "oral" intensity result in progressive decrements (3 to 5 dB) in the sound pressure difference measure. The greatest decrease in the sound pressure difference (5 dB) occurred between Intensity Levels I and II.

d) When means were averaged over all trials and vowels, 5 dB increments in "oral" intensity were usually accompanied by greater increments in nasal sound pressure in the smaller than in the larger coupling conditions.

e) When means were averaged over all trials and vowels, 5 dB increments in "oral" intensity were accompanied by proportionally greater decrements in the sound pressure difference measure when the coupling area was large than when it was small.

f) When means were averaged over all trials and vowels, the overall increase in sound pressure difference and in nasal sound pressure from the smallest to the largest coupling condition was greater at the lower (70 and 75 dB) than at the higher (80 and 85 dB) intensity levels.

g) When means were averaged over all trials and vowels, for the higher intensity levels (75 dB, 80 dB, and 85 dB) greater increments in the sound pressure difference and in nasal sound pressure occurred at the larger than at the smaller coupling conditions.

h) When means were averaged over all trials and vowels, for the lowest intensity level (70 dB), greater increments in sound pressure differences and nasal sound pressure were found at the smaller than at the larger coupling conditions.

i) When means were averaged over all trials and coupling conditions, the high vowels [i] and [u] displayed greater sound pressure differences and nasal sound pressures than the low vowels [æ] and [ɑ] at each of the four intensity levels.

j) When averaged over the trials and coupling conditions, the high vowels [i] and [u] displayed a greater decrease in the sound pressure difference measure than the vowels [æ] and [ɑ] as "oral" intensity was increased from 70 to 85 dB.

k) When means were averaged over all trials and coupling conditions, a 15 dB increment in "oral" intensity, from 70 to 85 dB, resulted in slightly greater increases in nasal sound pressure for the vowels [æ] and [ɑ] than for the vowels [i] and [u].

l) Mean sound pressure differences found at the "comfort" and "comfort-masked" intensity levels were similar, for the most part, to those obtained at Intensity Level III (80 dB).

m) There was little difference observed in the pattern or in the magnitude of mean sound pressure differences and nasal sound pressures obtained at the two "comfort" intensity levels.

Trial Effects

Nasal-"Oral" Sound Pressure Differences

The results of the analysis of variance revealed a significant trial main effect for the sound pressure differences. In addition to the trial main effect, trial-by-vowel, trial-by-intensity, and trial-by-coupling interactions were significant. It will be recalled that the "comfort" and "comfort-masked" intensity levels were included in the statistical analysis of the sound pressure difference data.

When the means included in the trial main effect were examined, it could be observed that the range of the means for the three trials was .4 dB. Averaged across vowels, intensities, and coupling conditions, the means for the three trials were 35.2 dB for Trial I, 35.5 dB for Trial II, and 35.1 dB for Trial III.

When the means included in the trial-by-vowel interaction were inspected, the range of means for the three trials for each vowel was at most 1.6 dB. Averaged across intensities and coupling conditions, the range of means for each vowel was 1.6 dB for [i], 1.1 dB for [u], .8 dB for [æ], and .4 dB for [ɑ].

In reviewing the means that comprise the trial-by-intensity interaction, in only one instance, at the "comfort-masked" intensity level, do the range of mean values for the three trials exceed 1 dB. For the "comfort-masked" intensity level, the means varied from 33 dB to 35 dB, a difference of 2 dB.

When the means that comprise the trial-by-coupling interaction were examined, the range of means between the three trials for each coupling condition was no more than 1.2 dB. Differences between the highest and lowest means for the three trials for each coupling condition, averaged across vowels and intensity levels, were .5, 1, .7, .6, .5, and 1.2 dB for Coupling Conditions I, II, III, IV, V, and VI, respectively.

When the raw scores for the sound pressure difference data were examined at controlled intensity levels (70, 75, 80, and 85 dB

SPL), in only three of 288 measures do the recorded variation among the three trials exceed 2 dB; in these three instances, a range of 3 dB was found. When the raw scores for the sound pressure data at the "comfort" and "comfort masked" intensity levels were inspected, the range of means among the three trials was, at times, as great as 10 dB. This amount of variation was not unexpected in view of the fact that, at the "comfort" level intensities, the subject was not required to maintain a uniform intensity. This resulted in highly variable "oral" intensities, and, consequently, considerable variation in the computed difference scores. The inclusion of the "comfort" and "comfort-masked" intensity levels in the analysis of variance for the sound pressure difference data could be responsible for a major part of the significant trial differences.

Nasal Sound Pressures

For nasal sound pressure levels, only the trial main effect and trial-by-coupling interaction were significant. In the statistical analysis of the nasal sound pressure means, the "comfort" and "comfort-masked" intensity levels were excluded from the statistical analysis.

When the means exhibited in the trial main effect for the nasal sound pressure data were examined, it was found that the range of values for the means among the three trials was .5 dB. Averaged across vowels, intensities, and coupling conditions, the mean nasal sound pressure values were 113.8 dB, 113.5 dB, and 113.3 dB, for Trials I, II, and III, respectively.

For the trial-by-coupling interaction, the greatest variation among the three trials for nasal sound pressure means occurred in

Coupling Condition VI in which a range of 1 dB was noted. In all other coupling conditions, the variation among the three trials was less than 1 dB. The reduction in the observed variation and the fewer number of significant interactions involving trials seen for the nasal sound pressure data, when compared to the sound pressure difference data, could well relate to the exclusion of the "comfort" level data from the statistical analysis.

The differences among trials for both nasal sound pressures and sound pressure differences, while statistically significant, were small. The variation in the mean measures from trial-to-trial was in all instances less than the potential instrumentation and measurement error alone. It could be assumed, then, on the basis of examination of trial differences that the relationships presented in the preceding sections existed to a similar degree in each of the three trials of the study.

Discussion

The findings of the present investigation dealing with the effects of coupling on the relationship between "oral" and nasal sound pressure measures were consistent with the results of previous studies in which these measures had been employed. Olson (64) reported high rank correlations (Kendall Tau) between nasal-"oral" sound pressure difference measures and the size of the naso-pharyngeal aperture. For vowels as a group, a correlation of 1.0 was found between these measures. Correlations for individual vowels ranged from .32 to 1.0.

The findings presented by Olson (64) and those of the present study indicated that increases in the area of nasal tract coupling were accompanied by increases in nasal sound pressure level. Certain differences, however, existed in the findings of the two investigations. Olson reported an essentially linear increase in mean nasal sound pressure level for vowels as a group as the diameter of the nasal aperture was increased from 0/16 inch (.0000 cm^2) to 4/16 (.3165 cm^2). A similar finding was obtained in the present study except that a plateau was found between Coupling Conditions III and IV (.1261 cm^2 and .2827 cm^2). Differences between the two studies also occur at larger coupling areas. Olson reported only minimal changes in nasal sound pressure for the vowels as a group with coupling areas larger than .3165 cm^2 of opening (4/16 inch diameter). In the present study, a substantial increase in nasal sound pressure was seen from Coupling Conditions IV through VI (.2827 cm^2 to .7850 cm^2).

When the pattern of mean nasal sound pressure for each vowel in each of the coupling conditions studied by Olson (65) was compared to those observed in the present study, certain differences were apparent. Olson reported an essentially linear increase in nasal sound pressure for the vowels [u], [æ], and [ɑ] from the 0/16 inch to the 4/16 inch apertures (.0000 cm^2 to .3165 cm^2). Minimal changes in nasal sound pressure occurred for these vowels when the aperture size exceeded 4/16 inch. The mean nasal sound pressure for the vowel [i] increased linearly as the aperture size was increased to 2/16 inch (.0789 cm^2) but there was little increase in nasal sound pressure with further increases in coupling area to 8/16 inch (1.25 cm^2).

In the present study, with the exception of a plateau between Coupling Conditions III and IV (.1261 cm^2 and .2827 cm^2), there was an essentially linear increase in the mean nasal sound pressure for the vowels [u], [æ], and [ɑ] as the coupling area was increased from .0000 cm^2 to .7850 cm^2. For the vowel [i], there was an essentially linear increase in nasal sound pressure with this increase in coupling area.

The relationship between the area of nasal tract coupling and measures of the nasal-oral sound pressure difference reported by Olson (65) was the opposite of that reported in the present study. Olson found that the size of the sound pressure difference decreased as the area of coupling increased. In the present study, an increased sound pressure difference occurred as the coupling area was increased. This difference in findings is attributable to the magnitude of nasal sound pressure levels obtained in the Olson study. The mean nasal sound pressures were found to range from 50 to 78 dB SPL. These sound pressure levels are approximately 30 to 40 dB lower than those obtained in the present investigation and in other studies (9, 15, 69) in which the probe-tube microphone has been employed. Because of the magnitude of these nasal measures, increases in nasal sound pressure that occurred with increased nasal tract coupling resulted in a decrease in the sound pressure difference measure.

In spite of these differences in findings, it seems reasonable to assume that, at least for individual subjects, both of these acoustic measures provide an index of the degree to which the oral and nasal tracts are coupled during speech. Since both investigations employed but a single subject, generalizations are necessarily limited to measures made within the same speaker.

The sensitivity of the sound pressure difference and nasal sound pressure measures to nasal tract coupling in individual speakers can also be seen in studies of cleft palate speakers with and without speech appliances in place. Shelton, Knox, Arndt, and Elbert (75) have reported consistently greater nasal sound pressures in cleft palate subjects when their appliances were removed than when they were worn. Similar findings were reported by Pierce (66) who studied the effects of speech appliance modifications on sound pressure differences in vowels produced by cleft palate speakers. Since a larger nasal aperture can be expected when a speech appliance is removed, these data are consistent with the findings of the present investigation.

There is also evidence that the magnitude of the sound pressure difference and nasal sound pressure measures also differs for groups of normal and cleft palate speakers. Counihan and Pierce (15) compared mean sound pressure differences obtained for normal and cleft palate speakers in production of isolated sustained vowels. They reported that the mean sound pressure difference for the normal group was approximately 10 dB lower than that obtained for their cleft palate group. Somewhat smaller differences between groups of normal and cleft palate speakers are reported by Richards (69) who compared mean sound pressure differences for normal and cleft palate subjects. Richards reports that the mean sound pressure difference for her normals was approximately 7 dB lower than that obtained for the cleft palate group. In both of these investigations, a uniform "oral" intensity level (75 dB SPL) was employed so that intergroup differences could be assumed to reflect differences in nasal sound pressure. It can be speculated, on the basis of these data, that these acoustic measures may be useful in discriminating speakers with abnormally large velar openings from those whose velar apertures are small.

The present study reveals that greater sound pressure differences and nasal sound pressures occur in production of the high vowels than for the low vowels, regardless of the area of coupling. These findings are compatible with those reported by Summers (84) and Counihan and Pierce (15) who studied normal speakers and those of Bryan (9), Richards (69), and Counihan and Pierce (15) for cleft palate speakers. These investigators reported consistently greater mean sound pressure differences for high than for low vowels. Again, since the "oral" intensity level in these studies was controlled, the differences among the vowel means can be attributed primarily to changes in nasal sound pressure level.

The present study also revealed that greater differences between the mean sound pressure differences and nasal sound pressures for high and low vowels existed at the larger than at the smaller coupling conditions. That is, the means for [i] and [u] exceeded those for [æ] and [ɑ] to a greater extent when the area of coupling was large than when it is small. Similar relationships could be seen in studies of groups of normal and cleft palate subjects. Summers (84) and Counihan and Pierce (15) reported greater mean sound pressure differences for high than low vowels in normal speakers. They reported ranges among the vowel means of 3 dB and 3.8 dB, respectively. These ranges were similar to those found in the present study at the smallest two coupling conditions. In Coupling Conditions I and II, the range of mean sound pressure differences for the vowels was 3.8 dB and 3.4 dB, respectively.

Wider differences among the means for high and low vowels were reported in studies of cleft palate groups. Counihan and Pierce (15) indicated that the range of mean sound pressure differences for vowels produced by their cleft palate group was approximately 10 dB. Somewhat smaller ranges were found by Bryan (9) and by Richards (69). Bryan obtained a range of 6 dB and Richards (69), a range of 8.3 dB between the mean sound pressure differences for vowels produced by their cleft palate subjects. In the present study, at the largest coupling condition (.7850 cm^2) the range of vowel means was 6.6 dB.

The above comparisons suggested that the range of mean sound pressure differences reported for vowels produced by normal speakers is similar to the range of vowel means at the smallest coupling areas in the present study. The range of vowel means reported for cleft palate groups was also similar to that found in the largest coupling area in the present investigation. It could be speculated, therefore, that the wider range of mean sound pressure differences for vowels in cleft palate than in normal groups reflects differences in the sensitivity of vowels to coupling effects. The present study suggested that a greater overall increase in nasal sound pressure occurred for high than for low vowels as coupling area was increased from .0000 cm^2 to .7850 cm^2.

It was evident, however, that direct comparisons between the findings of the present study and studies of cleft palate groups could only be made on the most tentative basis. The degree of coupling in subjects included in the latter group of studies was unknown. Similarities in the sound pressure differences recorded at specified coupling conditions in the present study and those found in studies of cleft palate groups in which the degree of nasal coupling was unknown may, therefore, represent a chance relationship. It seems reasonable to assume, however, that the relationships found in the present study may provil basis for explaining the increased differences between high and low v els in cleft palate speech.

It seems likely that differences in the sound pressure measures between high and low vowels are traceable to differences in the manner of production. Since the high vowels are produced with relatively greater impedance to the transmission of sound energy, it might be expected that, given a constant area of nasal coupling, proportionally greater energy would be transmitted through the oral tract. The importance of oral impedance was clearly seen in the greater nasal sound pressure found for high vowels even in Coupling Condition I (.0000 cm^2) of this experiment.

The present findings dealing with the effects of vocal intensity changes on sound pressure differences and nasal sound pressure measures were compatible with the results of previous investigations of normal and cleft palate speakers. In general, the present study indicated that increments in "oral" (overall) intensity were not accompanied by equivalent increments in the nasal sound pressure level. The difference between oral and nasal sound pressures, therefore, was found to decrease as the intensity of the oral signal was raised.

The inverse relationship between the size of the sound pressure difference and the intensity of the "oral" signal varied somewhat according to the area of nasal coupling. At the smallest two coupling conditions used in the present study (.0000 cm^2 and .0314 cm^2), 5 dB increments in "oral" intensity (from 70 to 85 dB) were accompanied by somewhat smaller increments (2 to 4 dB) in the intensity of the nasal signal. At the largest two coupling conditions (.5036 cm^2 and .7850 cm^2), 5 dB increments in "oral" intensity were associated with smaller increments and, at times, decrements in the nasal sound pressure level. As a result of these relationships, the same increment in the level of the "oral" signal was marked by a proportionally greater decrease in the sound pressure difference measure at the larger than at the smaller areas of nasal opening.

The existence of an inverse relationship between the sound pressure difference measure and the intensity of the "oral" signal was first reported by Summers (89). This investigator reported that the mean sound pressure difference for normal vowels decreased from 35 to 28 dB as "oral" intensity was increased from 57 to 84 dB, a decrease amounting to 7 dB. As in the present investigation, greater sound pressure differences were found at the lower than at the higher "oral" intensity levels. A comparison of Summers' data for normal speakers with the findings of the present study at the smallest two coupling conditions (.0000 cm^2 and .0314 cm^2) revealed similar relationships. In the present study total decrease in the sound pressure difference as "oral" intensity was increased from 70 to 85 dB was 2.5 dB at Coupling Condition I and 7 dB at Coupling Condition II.

There is evidence in previous research that greater sound pressure differences occur in speakers with less intense than with more intense voices. Sugawara (85) measured the amplitude of vibrations on the dorsum of the nose in speakers with "soft" and loud voices.

He reported that the former group of speakers evidenced a greater amplitude of nasal vibrations than the latter. Studies of normal and cleft palate groups (15, 69) consistently reveal greater sound pressure differences for female than for male speakers. The differences between the means for the sexes have been found to be inversely related to reported differences in the relative power of male and female voices (23, 74).

The pattern of sound pressure differences for vowels that has been reported in studies of normal speakers was inversely related to reported differences in vowel intensity, *i.e.*, less intense vowels were associated with greater sound pressure differences than vowels with greater relative power. Interestingly, the range of mean sound pressure differences in normal speakers was similar to the range of differences in the relative power of vowels. The range of sound pressure differences in nasal speakers was reported to be approximately 3 to 4 dB (15, 69, 84); the range of relative vowel power is variously reported as 3 to 5 dB (23, 53, 74).

The patterns of sound pressure differences reported for vowels produced by cleft palate speakers were similar to those reported for normals except that there was a greater range among the vowel means. Less intense vowels were characterized by even greater sound pressure differences than those for the more intense vowels. While there has been no direct investigation of the relative power of vowels produced by cleft palate speakers, studies of vocal tract analogs (24, 49) suggested that differences in relative vowel power may be exaggerated under conditions of nasal tract coupling. These studies indicated that the act of coupling the oral and nasal tracts resulted in a loss of overall power for all vowels. The degree of power loss was, however, not the same for all vowels. House and Stevens (44) reported a greater reduction in the intensity of the first formant for the high vowels [i] and [u] than for the low vowels [æ] and [ɑ]. If it is assumed that high vowels experience a greater power loss than low vowels with a similar increase in coupling area, greater differences in the relative power of vowels may exist when the area of coupling is large. It is possible that the magnitude of the mean sound pressure differences in cleft palate speakers varies in a manner that is directly related to the differences in vowel power that occur with increased coupling.

It is interesting to note that, in the current study, in coupling conditions greater than .0314 cm^2, increments in "oral" intensity were associated, at times, with an unchanged or even decreased nasal sound pressure level. A definitive explanation of these findings requires additional research data. It can be speculated, however, on the basis of data presently available, that adjustments of structures within the vocal tract could produce results like those obtained in the present investigation.

It might be expected that an increase in "oral" (overall) intensity, measured some distance from the lips, requires an increase in sound energy at the glottal source. With a constant area of coupling, it might be assumed that this increased sound energy would be reflected in an increase in the intensity of the nasal signal. Curtis (17) pointed out, the sound energy generated at the glottis is transmitted to the outside air through two channels: the oral and nasal cavities. The proportion of the signal that is transmitted through each of the cavities is dependent both on the area of coupling of the nasal and oral tracts and on the impedance characteristics of the oral cavity. The greater proportion of energy will be directed through the cavity having the lesser impedance, i.e., the ratio of energy between the oral and nasal cavities will be inversely proportional to the ratio between their respective impedances. The amount of energy transmitted through the nasal tract, therefore, is not determined simply by the dimension of the nasal aperture. Vocal tract impedance is also important.

House and Stevens (44) point out the nose, by virtue of its smaller size and greater damping, radiates much less energy than the mouth when nasalized vowels are produced. One of the primary features of the nasal tract coupling is to increase the damping of the vocal tract. It is reasonable to assume that the speaker, under conditions of nasal coupling, is put in the position of having to overcome this loss of power by either increasing the sound energy at the glottal source or by decreasing the impedance to the transmission of glottal source energy through the vocal tract.

Curtis (17) has indicated that "the only way that these losses can be made up is for the input from the source to be increased in proportion." Since increased vocal effort and source intensity were associated with an increased vocal pitch, he suggested that the pitch of cleft palate speakers may be expected to be higher than normal. Studies by Rampp (68) and by Flint (27), however, indicated that, if pitch differences exist between normal and cleft palate speakers, they are in the direction of lower pitch levels for cleft palate speakers. Rampp

(68), for instance, reported a lower mean fundamental frequency for female cleft palate speakers than for normal females. This relationship obtained at each of four intensity levels (70, 75, 80, and 85 dB SPL). It is possible, therefore, that increased source intensity is not the sole mechanism the cleft palate speaker uses to overcome the loss of power imposed by nasal tract coupling. Put somewhat differently, if glottal source energy is increased to compensate for this power loss, it may not be reflected in an elevated pitch level.

It can be hypothesized that at lower overall intensity levels, and smaller coupling conditions, less vocal effort is needed on the part of a cleft palate speaker to successfully attain the specified "oral" intensity. As higher overall intensity levels are required and coupling is increased, the demands on the system are increased and adjustments within the oral-nasal tract may be necessary in order to reach the specified intensity level. It is possible that cleft palate speakers increase intensity, in part, by changing the cross-sectional area of mouth opening and by lowering the tongue. Such a possibility has been suggested by X-ray studies (10, 81) which report that cleft palate subjects carry the tongue lower in the mouth than normal speakers. This would result in a greater proportion of sound energy being channeled through the oral cavity. With additional increases in intensity, the height of the tongue could be reduced still further resulting in even greater proportions of the overall signal being directed through the oral tract. The low vowels which are already produced at a lower relative height within the oral chamber might demonstrate larger increments in nasal sound pressure level as "oral" intensity is increased, since these vowels have a reduced potential adjustment range when compared to the high vowels.

The modifications in tongue height and mouth opening that occur with pitch and intensity changes deserve further investigation. Cineradiographic studies of vocal tract adjustments in vowels produced by cleft palate speakers could be expected to add measurably to our understanding of these relationships.

It may be speculated on the basis of these findings that, at least for those cleft palate subjects with greater nasal tract coupling, substantial reductions in sound pressure differences can be obtained by raising overall intensity. If sound pressure differences provide an index to the listener's perception of nasality, nasal voice quality could be reduced by raising the "oral" intensity level. The existance of such a relationship has been suggested by Weiss (88) who reports a negative correlation between measures of "oral" sound pressure and judgements of nasality and by Hess (40) who reports a decrease in ratings of nasality with increases in overall intensity. Consideration of the interrelationships among "oral" intensity changes, sound pressure measurements, and nasality ratings would appear to be a profitable area for further research.

CHAPTER V

SUMMARY AND CONCLUSIONS

The purpose of the present investigation was to explore the relationships among controlled variations in nasal tract coupling and vocal intensity on nasal sound pressure levels and nasal-"oral" sound pressure differences measured in four vowels produced by a single adult cleft palate speaker. An appliance, specifically designed for this subject, contained five concentric aluminum rings within the central portion of its pharyngeal section. By removing one or more of the rings, six conditions of oral-nasal coupling, ranging from .0000 cm^2 to .7850 cm^2 area of opening, could be produced. An adult male with a repaired bilateral cleft of the lip and palate served as the subject of this investigation. The subject was required to phonate four vowels, [i], [u], [æ], and [ɑ] at each of six intensity levels (70, 75, 80, and 85 dB SPL, a "comfort" level, and a "comfort" level with bilateral auditory masking) under each of the six coupling conditions. Three trials of each vowel at each intensity and each coupling condition were conducted in order to obtain an estimation of the trial variation. Each vowel was sustained for three seconds, recorded using a high-fidelity tape recorder, and subsequently analyzed by instrumentation that provided a graphic representation of "oral"[1] and nasal sound pressure

[1] The so-called "oral" signal is actually an overall signal

levels. For each item of the speech sample, nasal sound pressure levels and the arithmetic difference between the nasal and "oral" sound pressure levels were obtained. These measures constituted the acoustic data of the present experiment.

In order to evaluate the research data, an analysis of variance with a factorial arrangement of treatments was utilized in which the factors were vowels, intensity levels, coupling conditions, and trials. In the analysis of variance for nasal sound pressure levels, the two "comfort" level intensities were excluded from the statistical treatment. Two two "comfort" intensity levels were included in the analysis of nasal-"oral" sound pressure difference measures. A significance level of .05 was selected for the experiment.

The results of the statistical analysis indicated that the vowel, intensity, coupling, and trial main effects as well as the vowel-by-intensity, coupling-by-intensity, coupling-by-vowel, and trial-by-coupling interactions were significant for both the nasal-"oral" sound pressure difference and nasal sound pressure measures. Analyses of these main effects and interactions revealed that, for all vowels, at all intensity levels and trials, an increment in the size of the nasal aperture from .0000 cm^2 to .7850 cm^2 was associated with increments in the nasal sound pressure level and sound pressure difference measures. The effect of changes in coupling area on these acoustic measures was more pronounced at lower (70 and 75 dB SPL) intensity levels than at

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since it is the sound pressure level measured by a microphone positioned eight inches from the speaker's lips. It is referred to as the "oral" signal in order to differentiate it from the nasal signal measured by a microphone equipped with a probe tube which was placed approximately one-quarter inch inside the nares.

the higher (80 and 85 dB SPL) intensity levels. At the highest intensity level (85 dB SPL), changes in the size of the nasal aperture resulted in relatively small changes in these sound pressure measures.

From the smallest to the largest area of opening, the high vowels [i] and [u] displayed a greater overall increase in the sound pressure difference and nasal sound pressure measures than the low vowels [æ] and [ɑ]. The high vowels were associated with greater nasal sound pressures and sound pressure differences than the low vowels at each of the coupling conditions employed in this investigation. These trends obtained at each of the four intensity levels and in each of the three trials.

Increments in "oral" intensity level were not accompanied by equivalent increments in nasal sound pressure. This resulted almost uniformly in smaller sound pressure difference scores at the higher than at the lower intensity levels. In general, increments in "oral" intensity resulted in greater increments in nasal sound pressure when the area of coupling was small than when the area of coupling was large. Greater decrements, therefore, in the sound pressure difference measure occurred when "oral" intensity was increased in the larger than in the smaller coupling conditions.

At times, increments in "oral" intensity level resulted in an unchanged or decreased nasal sound pressure level. These instances were more conspicuous at the larger than at the smaller areas of coupling. As might be expected, an unchanged or decreased nasal sound pressure level, occurring as the "oral" intensity level was raised, resulted in a sharply decreased sound pressure difference score. Little difference was observed between sound pressure differences or nasal sound pressures obtained at a "comfort" level of intensity and those obtained at a "comfort-masked" intensity level. Data obtained at both of these intensity levels approximated those obtained at Intensity Level III (80 dB).

The differences in means for the three trials, while statistically significant, were found to be small in magnitude, the greatest variation from trial-to-trial amounting to 2 dB. On the basis of an examination of trial differences, it could be assumed that the relationships described above existed to a similar degree in each of the three trials of the study.

The findings and conclusions of this investigation are necessarily limited to the conditions of the present experiment and cannot be extrapolated to either the normal-speaking or cleft palate populations.

For future studies, some alterations in the design of the present study might be considered. First, no attempt was made in the present investigation to control the fundamental vocal frequency of the research subject. Since the adjustment of fundamental frequency is an ordinary mechanism in intensity regulation, an understanding of fundamental frequency changes associated with variations in vocal intensity under different coupling conditions such as these used in the present study would be useful.

Second, the effect of controlled coupling must be considered a potential source of error. The concentric rings in the experimental appliance were of a constant diameter, whereas the velopharyngeal port varies in terms of its anterior-posterior, vertical, and transverse diameters.

Third, information regarding the presence and nature of possible alterations in tongue position within the oral cavity, the size of mouth opening, and the degree of posterior and lateral pharyngeal wall contraction would have greatly abetted the formulation of a cogent explanation of certain relationships, particularly the interrelationship of "oral" and nasal levels.

Fourth, the use of a single adult male cleft palate subject as the subject sample sharply limits the generalizations that can be derived from the present data. Additional data obtained from larger numbers of subjects representing both sexes is needed.

Last, concomitant physiologic data such as subglottic pressure and oral-nasal air flow data would have proved beneficial in interpreting certain findings of the present study. The need for an understanding of the physiologic events that contribute to the acoustic end-product remains a vital area of further inquiry.

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APPENDIX A

Oral Sound Pressures

TABLE 3

ORAL SOUND PRESSURE LEVELS FOR THE FOUR SUSTAINED VOWELS AT THE SIX INTENSITY LEVELS AND THE SIX COUPLING CONDITIONS PRODUCED BY A SINGLE SPEAKER FOR TRIAL 1

	Vowel			
	[i]	[u]	[ɑ]	[æ]
Coupling Condition I (.0000 cm^2)				
Intensity 70	70	70	72	70
75	75	75	74	77
80	82	80	81	79
85	83	85	88	87
"comfort"	75	76	77	75
"comfort masked"	77	75	87	80
Coupling Condition II (.0314 cm^2)				
Intensity 70	70	70	72	70
75	75	76	75	77
80	79	80	82	82
85	85	83	87	87
"comfort"	75	78	79	75
"comfort masked"	79	80	78	80
Coupling Condition III (.1261 cm^2)				
Intensity 70	70	70	71	72
75	75	74	76	76
80	80	80	80	81
85	86	86	85	86
"comfort"	75	77	80	76
"comfort masked"	79	75	76	77
Coupling Condition IV (.2827 cm^2)				
Intensity 70	70	70	70	70
75	74	74	77	75
80	80	79	81	80
85	85	86	87	87
"comfort"	79	80	80	75
"comfort masked"	77	79	77	77
Coupling Condition V (.5036 cm^2)				
Intensity 70	70	70	71	70
75	74	74	75	75
80	80	80	81	81
85	85	86	86	85
"comfort"	74	77	74	75
"comfort masked"	77	78	77	77
Coupling Condition VI (.7850 cm^2)				
Intensity 70	71	71	70	70
75	76	76	74	75
80	78	81	80	80
85	87	85	87	86
"comfort"	80	77	80	74
"comfort masked"	75	80	80	80

TABLE 4

ORAL SOUND PRESSURE LEVELS FOR THE FOUR SUSTAINED VOWELS AT THE SIX INTENSITY LEVELS AND THE SIX COUPLING CONDITIONS PRODUCED BY A SINGLE SPEAKER FOR TRIAL 2

	Vowel			
	[i]	[u]	[ɑ]	[æ]
Coupling Condition I (.0000 cm^2)				
Intensity 70	70	70	69	70
75	74	75	75	76
80	79	79	80	80
85	85	84	85	85
"comfort"	76	76	80	74
"comfort masked"	75	76	80	77
Coupling Condition II (.0314 cm^2)				
Intensity 70	70	70	70	70
75	74	74	75	76
80	80	80	80	80
85	86	84	85	85
"comfort"	74	77	75	75
"comfort masked"	74	75	81	76
Coupling Condition III (.1261 cm^2)				
Intensity 70	70	70	70	72
75	75	76	74	77
80	80	80	82	82
85	86	86	87	86
"comfort"	80	77	80	76
"comfort masked"	80	70	79	77
Coupling Condition IV (.2827 cm^2)				
Intensity 70	69	69	70	71
75	74	75	74	75
80	79	80	80	80
85	85	84	86	85
"comfort"	75	74	80	75
"comfort masked"	76	75	76	75
Coupling Condition V (.5036 cm^2)				
Intensity 70	70	70	70	71
75	75	76	75	77
80	81	80	82	80
85	85	87	85	85
"comfort"	80	77	79	82
"comfort masked"	80	81	80	74
Coupling Condition VI (.7850 cm^2)				
Intensity 70	70	69	69	70
75	75	74	75	75
80	80	79	80	79
85	85	83	85	85
"comfort"	75	73	76	77
"comfort masked"	76	74	80	75

TABLE 5

ORAL SOUND PRESSURE LEVELS FOR THE FOUR SUSTAINED VOWELS AT THE SIX INTENSITY LEVELS AND THE SIX COUPLING CONDITIONS PRODUCED BY A SINGLE SPEAKER FOR TRIAL 3

	Vowel			
	[i]	[u]	[ɑ]	[æ]
Coupling Condition I (.0000 cm^2)				
Intensity 70	70	71	70	70
75	75	74	75	76
80	80	81	80	80
85	86	86	85	86
"comfort"	74	75	77	74
"comfort masked"	77	77	77	75
Coupling Condition II (.0314 cm^2)				
Intensity 70	70	70	71	70
75	75	75	76	75
80	80	79	81	81
85	86	85	85	85
"comfort"	73	78	77	73
"comfort masked"	79	80	78	75
Coupling Condition III (.1261 cm^2)				
Intensity 70	70	70	71	71
75	75	75	76	75
80	81	80	81	80
85	85	85	86	85
"comfort"	77	75	73	70
"comfort masked"	77	77	77	75
Coupling Condition IV (.2827 cm^2)				
Intensity 70	71	70	70	70
75	76	75	75	75
80	80	80	79	80
85	85	85	85	85
"comfort"	77	76	75	75
"comfort masked"	77	77	75	75
Coupling Condition V (.5036 cm^2)				
Intensity 70	70	70	71	70
75	75	76	75	75
80	80	80	81	80
85	86	85	86	85
"comfort"	76	78	78	76
"comfort masked"	76	78	77	77
Coupling Condition VI (.7850 cm^2)				
Intensity 70	70	70	69	70
75	75	75	75	75
80	80	79	80	79
85	86	85	86	85
"comfort"	73	74	74	70
"comfort masked"	75	77	75	70

APPENDIX B

Nasal Sound Pressures

TABLE 6

NASAL SOUND PRESSURE LEVELS FOR THE FOUR SUSTAINED VOWELS AT THE FOUR INTENSITY LEVELS AND THE SIX COUPLING CONDITIONS PRODUCED BY A SINGLE SPEAKER FOR TRIAL 1

		Vowel			
		[i]	[u]	[ɑ]	[æ]
Coupling Condition I (.0000 cm^2)					
Intensity	70	104	102	102	100
	75	108	106	105	106
	80	113	110	109	106
	85	113	115	116	113
Coupling Condition II (.0314 cm^2)					
Intensity	70	110	108	106	104
	75	111	111	107	109
	80	112	112	112	111
	85	116	112	116	115
Coupling Condition III (.1261 cm^2)					
Intensity	70	118	117	112	112
	75	111	109	109	108
	80	115	113	110	111
	85	118	117	114	115
Coupling Condition IV (.2827 cm^2)					
Intensity	70	121	118	112	111
	75	112	110	110	108
	80	115	113	113	111
	85	119	118	117	117
Coupling Condition V (.5036 cm^2)					
Intensity	70	122	119	114	113
	75	120	116	115	113
	80	122	118	118	117
	85	120	121	117	115
Coupling Condition VI (.7850 cm^2)					
Intensity	70	123	120	115	114
	75	124	123	118	118
	80	123	123	119	117
	85	123	121	118	116

TABLE 7

NASAL SOUND PRESSURE LEVELS FOR THE FOUR SUSTAINED VOWELS AT THE FOUR INTENSITY LEVELS AND THE SIX COUPLING CONDITIONS PRODUCED BY A SINGLE SPEAKER FOR TRIAL 2

	Vowel [i]	[u]	[ɑ]	[æ]
Coupling Condition I (.0000 cm^2)				
Intensity 70	103	102	100	101
75	108	105	105	106
80	111	110	110	106
85	115	114	114	113
Coupling Condition II (.0314 cm^2)				
Intensity 70	112	107	105	104
75	111	109	106	108
80	114	114	110	111
85	117	115	114	113
Coupling Condition III (.1261 cm^2)				
Intensity 70	116	116	112	110
75	112	112	108	109
80	114	113	113	113
85	117	116	116	114
Coupling Condition IV (.2827 cm^2)				
Intensity 70	119	116	113	112
75	112	110	107	107
80	114	113	111	111
85	119	117	116	115
Coupling Condition V (.5036 cm^2)				
Intensity 70	122	118	113	116
75	118	118	116	116
80	123	118	120	117
85	121	122	116	115
Coupling Condition VI (.7850 cm^2)				
Intensity 70	123	118	114	113
75	124	121	118	118
80	123	120	118	115
85	120	118	118	117

TABLE 8

NASAL SOUND PRESSURE LEVELS FOR THE FOUR SUSTAINED VOWELS AT THE FOUR INTENSITY LEVELS AND THE SIX COUPLING CONDITIONS PRODUCED BY A SINGLE SPEAKER FOR TRIAL 3

	Vowel			
	[i]	[u]	[ɑ]	[æ]
Coupling Condition I (.0000 cm^2)				
Intensity 70	103	103	100	100
75	108	104	105	106
80	111	111	109	107
85	115	115	114	113
Coupling Condition II (.0314 cm^2)				
Intensity 70	111	107	105	103
75	111	109	108	106
80	114	112	111	111
85	116	114	114	112
Coupling Condition III (.1261 cm^2)				
Intensity 70	117	116	111	110
75	112	109	109	107
80	115	112	112	110
85	115	114	114	111
Coupling Condition IV (.2827 cm^2)				
Intensity 70	121	117	111	110
75	114	111	107	107
80	115	113	110	110
85	118	116	115	115
Coupling Condition V (.5036 cm^2)				
Intensity 70	121	118	113	115
75	120	118	115	113
80	121	118	118	116
85	120	119	117	114
Coupling Condition VI (.7850 cm^2)				
Intensity 70	123	119	113	113
75	124	122	118	117
80	124	120	122	116
85	121	120	118	116

APPENDIX C

Nasal-"Oral" Sound Pressure Differences

TABLE 9

NASAL-"ORAL" SOUND PRESSURE DIFFERENCES FOR THE FOUR SUSTAINED VOWELS AT THE SIX INTENSITY LEVELS AND THE SIX COUPLING CONDITIONS PRODUCED BY A SINGLE SPEAKER FOR TRIAL 1

	Vowel			
	[i]	[u]	[ɑ]	[æ]
Coupling Condition I (.0000 cm^2)				
Intensity 70	34	32	30	30
75	33	31	31	29
80	31	30	28	27
85	30	30	28	26
"comfort"	33	32	31	30
"comfort masked"	34	32	25	27
Coupling Condition II (.0314 cm^2)				
Intensity 70	40	38	34	34
75	36	35	32	32
80	33	32	30	29
85	31	29	29	28
"comfort"	33	33	31	30
"comfort masked"	30	30	28	27
Coupling Condition III (.1261 cm^2)				
Intensity 70	48	47	41	40
75	36	35	33	32
80	35	33	30	30
85	32	31	29	29
"comfort"	36	35	32	29
"comfort masked"	36	36	35	27
Coupling Condition IV (.2827 cm^2)				
Intensity 70	51	48	42	41
75	38	36	33	33
80	35	34	32	31
85	34	32	30	30
"comfort"	37	35	31	29
"comfort masked"	36	31	29	28
Coupling Condition V (.5036 cm^2)				
Intensity 70	52	49	43	43
75	46	42	40	38
80	42	38	37	36
85	35	35	31	30
"comfort"	41	35	45	34
"comfort masked"	39	36	36	34
Coupling Condition VI (.7850 cm^2)				
Intensity 70	52	49	45	44
75	48	47	44	43
80	45	42	39	37
85	36	36	31	30
"comfort"	45	45	36	41
"comfort masked"	45	40	37	33

TABLE 10

NASAL-"ORAL" SOUND PRESSURE DIFFERENCES FOR THE FOUR SUSTAINED VOWELS AT THE SIX INTENSITY LEVELS AND THE SIX COUPLING CONDITIONS PRODUCED BY A SINGLE SPEAKER FOR TRIAL 2

	Vowel [i]	[u]	[ɑ]	[æ]
Coupling Condition I (.0000 cm^2)				
Intensity 70	33	32	31	31
75	34	30	30	30
80	32	31	30	26
85	30	30	29	28
"comfort"	32	30	30	29
"comfort masked"	33	32	30	28
Coupling Condition II (.0314 cm^2)				
Intensity 70	42	37	35	34
75	37	35	31	32
80	34	34	30	31
85	31	31	29	28
"comfort"	40	34	33	32
"comfort masked"	42	35	29	30
Coupling Condition III (.1261 cm^2)				
Intensity 70	46	46	42	38
75	37	36	34	32
80	34	33	31	31
85	31	30	29	28
"comfort"	33	33	31	28
"comfort masked"	33	45	31	31
Coupling Condition IV (.2827 cm^2)				
Intensity 70	50	47	43	41
75	38	35	33	32
80	35	33	31	31
85	34	33	30	30
"comfort"	37	35	30	28
"comfort masked"	36	34	29	28
Coupling Condition V (.5036 cm^2)				
Intensity 70	52	48	43	45
75	43	42	41	39
80	42	38	38	37
85	36	35	30	30
"comfort"	38	37	36	33
"comfort masked"	38	37	35	41
Coupling Condition VI (.7850 cm^2)				
Intensity 70	53	49	45	43
75	49	47	43	43
80	43	41	38	36
85	35	35	33	32
"comfort"	43	47	41	43
"comfort masked"	47	48	37	40

TABLE 11

NASAL-"ORAL" SOUND PRESSURE DIFFERENCES FOR THE FOUR SUSTAINED VOWELS AT THE SIX INTENSITY LEVELS AND THE SIX COUPLING CONDITIONS PRODUCED BY A SINGLE SPEAKER FOR TRIAL 3

	Vowel			
	[i]	[u]	[ɑ]	[æ]
Coupling Condition I (.0000 cm^2)				
Intensity 70	33	32	30	30
75	33	30	30	30
80	31	30	29	27
85	29	29	29	27
"comfort"	32	31	30	28
"comfort masked"	33	30	29	28
Coupling Condition II (.0314 cm^2)				
Intensity 70	41	37	34	33
75	36	34	32	31
80	34	33	30	30
85	30	29	29	27
"comfort"	39	32	30	30
"comfort masked"	33	30	29	30
Coupling Condition III (.1261 cm^2)				
Intensity 70	47	46	40	39
75	37	34	33	32
80	34	32	31	30
85	30	29	28	26
"comfort"	35	34	32	36
"comfort masked"	34	34	30	29
Coupling Condition IV (.2827 cm^2)				
Intensity 70	50	47	41	40
75	38	36	32	32
80	35	33	31	30
85	33	31	30	30
"comfort"	35	33	29	29
"comfort masked"	35	34	28	28
Coupling Condition V (.5036 cm^2)				
Intensity 70	51	48	42	45
75	45	42	40	38
80	41	38	37	36
85	34	34	31	29
"comfort"	40	34	35	37
"comfort masked"	40	34	35	36
Coupling Condition VI (.7850 cm^2)				
Intensity 70	53	49	44	43
75	49	47	43	42
80	44	41	42	37
85	35	35	32	31
"comfort"	48	46	45	40
"comfort masked"	49	43	44	40