65

871

VAUGHN, Avery Ole, 1930-
AN EXPERIMENTAL STUDY OF ORAL AND NASAL AIR FLOW DURING SUSTAINED VOWEL PRODUCTION.

The University of Oklahoma, Ph.D., 1965
Speech-Theater

THE UNIVERSITY OF OKLAHOMA

GRADUATE COLLEGE

AN EXPERIMENTAL STUDY OF ORAL AND NASAL AIR FLOW DURING SUSTAINED VOWEL PRODUCTION

A DISSERTATION

SUBMITTED TO THE GRADUATE FACULTY

in partial fulfillment of the requirements for the

degree of

DOCTOR OF PHILOSOPHY

BY

AVERY OLE VAUGHN

Oklahoma City, Oklahoma

1965

AN EXPERIMENTAL STUDY OF ORAL AND NASAL AIR FLOW

DURING SUSTAINED VOWEL PRODUCTION

APPROVED BY

Donald Counihan

[illegible]

Floyd W. Emanuel

Bruce R. Pierce

DISSERTATION COMMITTEE

ACKNOWLEDGMENT

The writer wishes to express his gratitude to the director of this study, Dr. Donald T. Counihan, for his encouragement and invaluable advice throughout the investigation.

Appreciation is also extended to Dr. Floyd W. Emanuel and Mr. Donald Trubey for their assistance in callibration of the instrumentation and collection of the data, to Dr. Bruce R. Pierce for his helpful criticisms and suggestions in the preparation of the manuscript, and to Mr. Bruce Reed for technical assistance in maintenance of the equipment.

The writer is also indebted to Mr. Paul Costiloe, and to the other members of the staff and faculty of the University of Oklahoma Biostatistics Unit for their assistance in the design of the study and the statistical analysis of the data.

TABLE OF CONTENTS

Page

LIST OF TABLES

Table | Page

LIST OF ILLUSTRATIONS

Figure Page

AN EXPERIMENTAL STUDY OF ORAL AND NASAL AIR FLOW DURING SUSTAINED VOWEL PRODUCTION

CHAPTER I

INTRODUCTION

The advent of improved research instrumentation has enabled the speech pathologist to define more accurately the physiological and acoustical dimensions of speech. For example, the development of high-speed photographic techniques has provided a means for objective study of human vocal fold function during phonation. Moreover, the application of improved static x-ray techniques and cinefluorography has substantially increased the understanding of the physiology of the tongue and velum during speech. In a similar manner, spectrographic analyses have resulted in more definitive descriptions of certain of the acoustic parameters of the speech signal.

It is also possible to describe speech according to breath stream dynamics. It is generally recognized that speech sound production involves an interaction between physiological adjustments and the air contained in the vocal tract. The interaction between vocal fold tension and the moving air stream is basic to the process of phonation. Similarly, modifications of the breath stream above the level of the glottis are fundamental to speech sound production. However, while considerable interest has obtained regarding the role of subglottal air pressure, relatively little experimental evidence exists regarding supraglottal air flow during speech.

With respect to supraglottal air flow, there is a clear need for quantitative data concerning the expenditure of air from the nose and mouth during speech. Specifically, there is a need for base-line data, predicated on the study of normal speakers, that could serve as a reference in the study of the speech pathologies. Further, there is a need for data concerning the effect of changes in such basic acoustic parameters as intensity and fundamental vocal frequency on oral and nasal air flow. Such information may have value not only in abetting an understanding of breath stream regulation but also in providing useful data regarding other aspects of speech physiology. Air flow measures, for example, could be expected to afford a reasonably direct way of investigating the timing and degree of patency of valves downstream in the vocal tract. Of particular interest, is the use of simultaneous oral and nasal air flow measures to assess velopharyngeal function and degree of oral-nasal coupling in speech.

From the clinical viewpoint, it is recognized that subtle variations in this coupling may have a marked influence upon speech adequecy. An obvious problem confronting many individuals with cleft palate, for example, is the inability to uncouple the oral and nasal cavities during production of consonant and vowel phonemes. As a result, these persons may exhibit hypernasality and articulation errors which are associated with an inability to develop adequate intraoral air pressure. In addition, their speech proficiency may be hindered by problems of vocal pitch and intensity which may derive from an inability to regulate the patency of the naso-pharyngeal port. Thus, information regarding oral-nasal coupling in normal subjects would be expected to have valuable clinical application.

From the standpoint of the experimental phonetician, information regarding oral-nasal coupling during speech could be expected to contribute to an understanding of the speech process. The results of acoustic and physiological studies of vowel production indicate that vowels differ in inherent acoustic power. Moreover, it has been shown that these differences in power are related to a complex interplay of several interdependent variables, among which are expiratory muscle activity, subglottal pressure variations, vocal fold activity, air flow rate, and vocal tract impedance. It has also been shown that the degree of oral-nasal coupling employed in production varies among vowels. To the present time, however, there is little information relating to the differences in naso-pharyngeal patency that exist among vowels as a function of changes in vocal intensity and fundamental vocal frequency. Such information would appear to be important to an understanding of the physiology of vowel production.

The present study affords an opportunity for examining oral-nasal coupling as it is reflected by oral and nasal air flow during the production of sustained vowels at different levels of vocal pitch and intensity. A review of relevant literature, the plan of the study, the findings, and the conclusions of the study may be found in the following chapters.

CHAPTER II

REVIEW OF LITERATURE

The literature in the field of speech pathology and in related areas is replete with descriptive explanations of the breathing process during speech. For example, considerable speculation has existed concerning the preferred type of breathing for speech and the importance of vital capacity to speech production. However, quantitative data pertaining to air flow during speech is very limited. While a few investigators have been interested in objectively defining this important dimension of speech, the studies have often lacked rigorous experimental controls. Moreover, the study of air flow during speech has been hindered by inadequate instrumentation. The purpose of the present chapter is to present a review of the literature pertaining to: (1) measurements of oral air flow during speech production, (2) measurements of nasal air flow during speech, and (3) measurements of air expenditure during pitch and intensity changes.

Measurements of Oral Air Flow During Speech Production

It is well known that the respiratory process is modified during speech production. Speech is produced during exhalation and, to achieve a relatively continuous flow of speech, the inhalation phase of the breathing cycle must be shortened in relation to the exhalation phase. During speech there are fluctuations of pressure within the thoracic cavity. Slow variations occur at a rate which corresponds to breath groupings, such as those used in phrasing, while more rapid pressure fluctuations occur at rates which approximate syllabic utterances (42). Measurements of these pressure variations, along with measurements of air flow, have been utilized to study the respiratory process during speech production.

Tidal Air

The experimental evidence pertaining to the amount of air used in speaking is not conclusive. Gray (16), in summarizing several studies completed under his direction, reported:

> The amount of air actually used in breathing is quite small. The average quantity of air which passes into and out of the lungs in a single respiratory cycle is no more than about 30 cubic inches, or about 13 percent of the vital capacity. This figure varies considerably ranging from perhaps 5 to 35 percent. Furthermore, the amount of air used in uttering a single phrase (that is, the amount that is actually taken into the lungs at one time in reading and speaking) is generally little if any more than in casual breathing.

On the basis of pneumographic observations, Idol (21) noted little difference between average depth of respiratory movement during normal breathing and during speech production. The kymographic recordings showed that over half of the group of subjects employed deeper breathing movements for casual respiration than for normal speech.

Wiksell (43) utilized a spirometer and pneumograph to study thoracic, medial, and abdominal types of breathing during the production of sustained vowels. The subjects phonated the vowels [ɑ], [o], and [u] three times, first at a normal intensity and then as loudly as possible. He found only a slight relationship between maximum volume of breath expended and the ability to sustain vowels for a long period of time. This relationship obtained when his subjects used controlled thoracic breathing but was not present during controlled abdominal breathing.

In a more recent study, Benson (1) investigated the effect of postural changes on air flow during the speech of seven eight-year-old boys. He obtained spirometric measurements which indicated that the mean tidal volume during rest breathing was .33, .30, .28, and .30 liters per second for the supine, semi-recumbent, sitting, and prone positions, respectively. The mean volume of air expired during the sustained production of the vowel [ɑ] was .11, 14, .11, and .09 liters per second, respectively, for those positions.

Van Hattum (41) studied differences in air usage between a group of cleft palate subjects and a normal control group. He used a spirometer to measure the amount of air each subject could exhale following a maximal inhalation. After this quantity was determined, the subject inhaled maximally and phonated a vowel sound for ten seconds. He then exhaled the remaining air into a spirometer. A pneumograph was employed to determine whether the subject exhaled any air between the completion of his maximal inhalation and the initiation of phonation. Using this procedure, the experimenter determined the percentage of air used by each subject in the production of four vowels at different pitch and intensity levels. The normal subjects were tested with the nostrils open and then with the nostrils closed. The cleft palate subjects were tested under four conditions: (1) with a prosthesis in place and the nostrils open, (2) with a prosthesis in place and the nostrils closed, (3) with the prosthesis out and the nostrils open, and (4) with the prosthesis out and the nostrils closed.

The results of this study (41) indicated that the cleft palate subjects used the greatest amount of air when the prosthesis was removed and the nostrils were open. Also, when tested in this condition, the cleft palate subjects used a greater amount of air than normal subjects with their nostrils open. Interestingly, without a prosthesis but with the nostrils occluded, the cleft palate subjects did not use more air than the normal subjects with the nostrils occluded.

Vital Capacity

Considerable interest has existed regarding the importance of vital capacity to efficient voice production. Gray and Wise (17) stated that there is no evidence that an increase in vital capacity leads to an improvement in the quality of the voice, the strength of the voice, or the ability to control the strength of the voice. The results of Idol's study (21) indicated that the correlation between vital capacity and audibility of speech is negligible. Her findings were corroborated by Sallee (36) who reported that there appeared to be no individual or group relationship between depth of inhalation and audibility. Also, Wiksell (43) found no significant correlation to exist between intensity of isolated vowel sounds and vital capacity. On the other hand, Carrell (6) reported a difference in vital capacity between normal-speaking children and children with speech defects. He concluded that the latter group were physically inferior and failed to make adequate compensatory adjustments. Van Hattum (41) reported that the cleft palate subjects in his study had smaller vital capacities than did the normal subjects.

Oral Air Pressure

The importance of oral air pressure in the production of speech sounds has long been recognized. However, there is relatively little quantitative data concerning the subject. Black (3) has studied the amount of oral breath pressure required by normal-speaking subjects to produce certain isolated consonants and consonant-vowel combinations. He reported that oral breath pressure is greater during the production of fricatives and plosives than for other consonants or for vowel sounds. His data also suggested that intraoral breath pressure is greater for continuant than for plosive sounds except when these elements occur in the medial position of words. This experimenter also reported that voiceless consonants require significantly more intraoral pressure than voiced consonants.

The importance of adequate breath pressure in the production of speech sounds is illustrated by the articulation errors which characterize the speech of cleft palate persons. Several different investigators (5, 8, 37, 39) have reported that these individuals misarticulate most frequently those sounds which require the greatest intraoral pressure. The most probable explanation for this is that the air escapes through the velopharyngeal port, making it difficult to build up adequate intra-oral pressure.

Hardy (19) has written that the inability to produce adequate intraoral pressure contributes to the speech difficulties of many cerebral palsied individuals. He indicates that the cerebral palsied person's inability to generate adequate oral breath pressure may result from a palatal malfunction, respiratory muscular weakness, faulty use of the oral articulators, or a combination of these factors. Moreover, he points out that the diagnosis of an individual's ability to produce oral breath pressure may provide precise information regarding his physiological readiness for speech.

While it has been shown that pressure differences exist in the oral cavity during the production of various speech sounds, there is little information regarding the minimal amount of oral breath pressure required for speech production. Goddard (15) utilized an oral manometer to record the intraoral breath pressure of 200 normal children. She reported that over 90 per cent of the subjects could achieve eight ounces or more of intraoral breath pressure. Only six per cent of the subjects obtained seven or less ounces of pressure and those who did, with one exception, were five-year-olds, the youngest group tested.

Spriestersbach and Powers (37) obtained oral breath pressure measurements for 10 cleft palate children with velopharyngeal closure and 19 with no closure. An oral manometer was used to measure the breath pressure produced with the nostrils open and also with the nostrils occluded. They found that subjects with velopharyngeal closure did as well with the nostrils open as they did with the nostrils occluded, the means being 15.6 ounces psi and 15.3 ounces psi, respectively. In contrast, the group with no closure achieved a mean of 7.2 ounces psi with the nostrils open and 11 ounces psi with the nostrils closed. They suggested that eight ounces psi is the minimum pressure necessary for the satisfactory production of consonants sounds requiring oral breath pressure.

In summarizing the literature regarding the minimal requirements for intraoral breath pressure during speech production, Hardy (19) has recently commented that the data is fragmentary and indicative of wide individual differences among speakers.

Measurements of Nasal Air Flow During Speech Production

A review of the literature in the field of speech pathology and allied areas reveals a paucity of quantitative data relating to nasal air flow during speech. The literature presents conflicting opinions regarding the normal amount of nasal emission during the speaking act. An example of the disparate viewpoints is illustrated in the concepts regarding the relationship between nasal emission and hypernasality. A commonly held hypothesis was that hypernasality is directly related to the amount of nasal air flow. In discussing treatment of hypernasality, Kantner (25) indicated that the most common cause of the disorder is ". . . the escaping of the air stream through the nasal cavity in amounts and at times not typical of normal speech." Similarly, Bullen (4) has written that, ". . . nasality is due immediately to the passage of air through the nasal cavities," and that ". . . the air escaping through the nose obviously results in nasality." However, relatively recent experimental evidence (2, 32) suggests that while nasal emission and hypernasality are related, the two are not synonymous.

Benson (2) conducted an experimental study to determine the relationship between measured quantities of nasal emission during the production of isolated vowel sounds and the degree of functional nasality as identified by expert judges. A U-tube manometer was utilized in the measurements of nasal emission of air. He concluded that the amount of nasal emission was not a useful predictor of judged nasality. In an earlier study, Nusbaum, Foley, and Wells (32) concluded that it is possible to phonate vowel sounds without judged hypernasal quality even when air is intentionally emitted from the nose.

Johnson, Darley, and Spriestersbach (23) have observed that there is considerable evidence to indicate that vowels vary in their affinity for nasality. McIntosh (29) conducted an experiment in which vowels produced by a group of students were judged according to degree of nasality. He reported that the front vowels were judged more nasal than back vowels and that the vowel [u] was judged to be the least nasal of the vowels tested. In a recent study, Lintz and Sherman (27) also attempted to determine whether the degree of perceived nasality varies from vowel to vowel. Their finding that back vowels are less nasal than front vowels corroborated the results of McIntosh. Van Riper and Irwin (42) have suggested that the differences in degree of soft palate elevation and closure on different vowels ". . . may account for some of the affinity for nasality which certain sounds seem to possess."

Velopharyngeal Closure

There is conflicting evidence in the literature regarding the degree of velopharyngeal closure during vowel production. The authorities who considered nasal escape of air to be the primary cause of hypernasality usually attributed this escape to abnormal velar functioning. For example, Russell and Cotton (35) have written that . . ."nasality of any kind presupposes that the velum is not closing the passageways leading to the nose."

Nusbaum, Foley, and Wells (32) attempted to resolve the varying opinions held regarding the relative position of the soft palate during the production of vowel sounds. The degree of velar tension during the production of vowels was tested by means of a special apparatus designed to record the amount of air pressure required to "break" the velar occlusion. The authors found that the [u] and [i] vowels withstood the greatest pressure and thus, presumably, have the tightest velar seal. The "critical pressure level" became progressively less during the production of the vowels [o], [e], [a], and [ɔ]. They also found that the amount of pressure required to overcome the velopharyngeal occlusion varied greatly with individuals. Many of the subjects produced some or all of their vowels with the oro-nasal passageway open.

A radiographic method for visualizing the nasopharyngeal structures was used by Williams (44) to study the velopharyngeal closure associated with the vowel sounds [ɑ], [a], [u], and [i]. The results of his analysis of thirty normal speaking subjects seemed to refute the opinion that the nasopharyngeal valve is tightly closed for all vowel sounds. He found that in production of two of the sounds studied, [a] and [ɑ], the valve was predominately open; while for the vowels [u] and [i] the valve was predominately closed.

Moll (31) recently investigated the variations in velopharyngeal closure during vowel production as a function of the vowel produced and of the consonant context of the vowel. Cinefluorographic pictures were taken of 10 adult subjects who exhibited normal speech patterns. He concluded that the low vowels exhibit less closure than the high vowels.

The results of these studies suggest that systematic differences in the precision of velopharyngeal closure exist when subjects produce various vowel sounds. However, the available research does not indicate a direct correspondence between perceived nasality and degree of velopharyngeal closure in vowels. For example, the high vowels [i] and [u] are generally judged to be less hypernasal and exhibit more complete velopharyngeal closure than the low vowels [ɑ] and [ae], yet a relatively small increase in nasal coupling results in a marked increase in the perceived nasality for the former sounds and not for the latter.

Nusbaum (32) reasoned that it may be less important acoustically to produce the low vowels with a complete closure of the velum. He stated that, for both [u] and [i], there is a greater constriction of the exit of the tone from the mouth than for the low vowels. Hence, he maintained that, for either [u] or [i], a proportionately larger "volume of tone" is shunted through the nose with a slight opening of the velum. Thus, any degree of opening will result in an unpleasantly nasal quality during the production of the high vowels. He adds that, because of the acoustic effect, one is more apt to learn to close the nasal passage completely during the production of the high vowels. This reasoning is in apparent agreement with the results of the analog studies conducted by House and Stevens (20). They reported that small amounts of nasal coupling produced marked changes in the spectra of the vowels [i] and [u] which in turn served as cues for the identification of nasality. A greater degree of coupling was needed to produce comparable changes in [ae] and [ɑ].

Measurements of Air Flow During Pitch and Intensity Changes

The studies by Gray (16) and his associates (21, 36, 43) suggest that an increase in the intensity of the voice is not necessarily accompanied by a corresponding increase in air expenditure. Idol (21) reported that approximately one-third of the subjects in her study showed greater respiratory excursions for normal conversational voice than for loud speech. She attributed this to adjustments in resonance which resulted in a greater audibility of the tone without a corresponding increase in volume of breath used. Sallec (36) also found no individual or group relationships between depth of inhalation and audibility.

Certain relationships, however, have been found to obtain between the volume of air expended in isolated sound production and the intensity and frequency of the sound. One of the earliest studies concerned with the expenditure of air as a function of vocal frequency and intensity was completed by Roudet (34). Using a dry-gas spirometer, he measured the air expenditure during vowels of various durations produced at different pitch and intensity levels. He varied one condition at a time endeavoring to keep the other conditions constant. He found that when [ɑ] was produced at a pitch of about "C2" the air expenditure for "feeble, medium and strong" intensity levels was 11 cc, 17 cc, and 24 cc per second, respectively. Roudet's data also indicated that if [ɑ] is phonated at a constant intensity at successive pitches corresponding to "C2, E2, G2, and C3" there appeared to be less air expenditure per unit of time as pitch increased.

Luchsinger (28) utilized the pneumotachograph to obtain air velocity measurements during speech production. Sound pressure measurements were recorded simultaneously by means of a string galvanometer. Two groups of singers produced various tones of the "chest, middle, and head" registers, trying to maintain a constant vocal intensity. In general, his conclusions concurred with those of Roudet (34). The air velocity decreased as pitch was increased, while an increase in intensity resulted in greater air expenditure. However, he noted certain exceptions: weak low tones were sung with small volume velocity, while weak high tones required a greater volume velocity.

Russell and Cotton (35) constructed a sensitive six-liter spirometer to determine the volume of air utilized in producing the vowel [ɑ] at various pitches in the "chest" register. Two series of tests were performed, one at a maximum loudness level and another at a comfortable speech loudness level. The desired pitch was first determined with a xylophone which was reportedly accurately tuned (a'=440 cps). Using the spirometer, they measured the volume of breath utilized in phonating [ɑ] for a specified length of time and calculated breath flow in liters per minute. They found that "only 30% more air is required for the maximum possible voice loudness level than for the normal voice loudness level." They apparently use the term "only" because, whereas there was a 30 per cent increase in air volume, the loud voiced sounds were a hundred times more intense acoustically. In attempting to explain this increase in intensity with relatively little change in air flow, they comment:

> Obviously, this great increase in loudness cannot be due so much to a forcing of a greater amount of air thru the glottis during its open phase as to a shortening of that open phase coincident with the increased subglottal breath pressure. This could be brought about by an increased tension in the vocal cords. The resultant puff would contain little more air than in normal loudness tone production, but would possess considerably more energy thru its increased velocity and the abruptness of its 'explosion' thru the cords.

This statement is consistent with high-speed motion pictures of vocal fold activity during phonation at increased intensity levels. The Bell Laboratory films (12) showed that, as intensity was increased, the vocal folds remained closed for a proportionately longer time during each cycle. Also, Fletcher (14) indicated that the element of vibratory motion most consistently associated with intensity of voice was the closed phase of the cycle of vocal fold vibration.

Russell and Cotton (35) plotted breath flow in liters per minute as a function of vocal pitch changes. They found that the air flow during the production of [ɑ], both at a normal vocal intensity level and at a maximum vocal intensity, showed a progressive increase as vocal frequency was increased up to approximately 220 cycles. The flow subsequently decreased as the pitch was increased from 220 cycles to 300 cycles; however, the decrease was slight.

Nusbaum, Foley, and Wells (32) observed that extremes of intensity in the production of vowel sounds affected the amount of air pressure required to overcome the velopharyngeal seal. They wrote:

> It was noted that extremes of loudness or softness affected the pressure. The pressure was somewhat in proportion to the loudness of the vowel. . . . A partial explanation of the increased pressure noted on very loud vowels might be that on such vowels the velum is supported from below by increased pressure in the mouth cavity. The chief factor however, is probably the increased tension in the velopharyngeal musculature.

Van Hattum (41) reported that cleft palate subjects used less air at a 75-db intensity level than at a 90-db level, whereas the reverse was true for normal subjects. The cleft palate subjects used less air at a frequency of 300 cycles than at 200 cycles, while the normal subjects used less air at 200 cycles than at 300 cycles. Also, there was no significant difference in the amount of air used by normal subjects in the production of the vowels [i], [u], [ɑ], and [ae]. The cleft palate subjects, on the other hand, used more air in the production of [i] and [u] than for [ɑ] and [ae].

In a recent study, Isshiki (22) investigated the relationship between vocal intensity (SPL) and subglottic pressure, air flow rate, and glottal resistance. A single subject sustained the vowel [ɑ] at intensity levels ranging from 65 to 95 db (SPL) while attempting to maintain a constant pitch. This was repeated at different pitch levels from "E2" to "C5". Simultaneous recordings of vocal intensity, subglottal pressure, air flow rate, and volume of air utilized during phonation were obtained. The air flow measurements were obtained by means of a pneumotachograph, and vocal intensity was determined by placing a condenser microphone 20 cm in front of the outlet of the pneumotachograph. The subglottal pressure measurements were made by inserting a lumbar puncture needle into the trachea of the subject. The exposed end of the needle was connected to a strain gauge pressure transducer. The results of the study indicated that during very low frequency phonation the air flow rates remained essentially unchanged as vocal intensity was increased. At high frequency phonation, however, increases in vocal intensity resulted in great increases in air flow rates. Conversely, the glottal resistance, calculated from the subglottal pressure and volume velocity data, increased with increased intensity at the low pitch levels, but decreased as intensity was increased at the high pitch levels. These findings prompted Isshiki to conclude that, at very low pitch levels, vocal intensity is controlled by glottal resistance. As the pitch is raised, however, the laryngeal control lessens, until at high pitch levels the intensity is almost entirely controlled by the air flow rate.

Subglottal Air Pressure

The literature pertaining to subglottal pressure variations, especially as they relate to pitch and intensity changes during sustained vowel production, is of direct interest to the present study. The myoelastic-aerodynamic theory explains phonation as a coordinated activity of infraglottic air pressure and of vocal fold tension against such pressure. The air is conceived as a wedge which forces the taut folds apart until the diminution in air pressure, the Bernoulli effect, and the elasticity of the membranous folds bring them together again. Flanagan (13) has emphasized the relationship between infraglottic air pressure and supraglottal air flow. On the basis of data on glottal area and subglottic air pressure, he has deduced waveforms of glottal volume flow.

Several investigators have made measurements of mean subglottic pressure during phonation (9, 18, 20). For the most part, however, the data was obtained on subjects who could not phonate normally due to some pathology. Van den Berg (40) made measurements on a normal male subject during phonation of the vowel [a]. The measurements were made using both direct and indirect techniques in which catheters were inserted into the glottis and esophagus. He made measurements of subglottic pressure over an intensity range beginning with the lowest intensity the subject could sustain (liminal SPL) and increased intensity in five-db steps to the loudest level at which the subject could phonate. The pitch range employed in the measurements began with the lowest-pitched chest voice and ranged upward to falsetto.

This writer (40) found that the subglottal pressure increased as a function of increased frequency and intensity. The subglottal pressure measurements obtained at the low frequency range showed a progressive increase as intensity was increased in five-decibel steps. There was a greater increase in subglottal pressure at the high frequency range when intensity was similarly increased. However, it should be noted that the liminal SPL of the lowest pitched tone was approximately 11 db less intense than that of the falsetto production. Thus, it is difficult to determine the effect intensity had in increasing subglottal pressure in the high frequency range. Van den Berg indicated that increased intensity may be obtained from a rapid rush of air as a result of the compression of the air and the resulting greater disturbance of the supraglottal air. The recent work by Isshiki (22) supports such an interpretation.

Oral-Nasal Coupling

A review of the literature reveals virtually no experimental evidence regarding the effect of pitch and intensity changes on nasal air flow. There is reason to think that the degree of oral-nasal coupling has a direct bearing on the intensity of speech. Cotton (7) has written that:

> It is sometimes suggested that the velum be lowered slightly in order to add . . . nasal resonance. Our studies show conclusively that any amount of opening between oral and nasal cavities results in decreased loudness of the voice.

Cotton's observations (7) were based on an investigation in which a single subject simulated the "whang" and "relaxed velum" types of nasality in the production of vowel sounds. He measured the relative intensity of the oral and nasal components of the vowel sounds with a crystal microphone and observed the velar activity with a device which he described in the following manner:

> This device consists of a tambour connected with a nostril by means of a length of rubber tubing. The movements of the rubber diaphragm on this tambour are amplified by a light lever system which is capable of making and breaking an electric circuit thru oil covered mercury contacts. With this device carefully adjusted a light can be made to flash when the slightest opening between the nasal passages and oropharynx occurs.

Cotton's conclusion that a reduction of vocal intensity occurs with increased oral-nasal coupling is consistent with the results of an analog study of vowel nasalization by House and Stevens (20). These investigators concluded that, almost without exception, the overall level of the acoustic output for vowels was reduced when the nasal tract analog was coupled with the vocal tract analog.

It has been suggested previously that systematic differences in the precision of velopharyngeal closure exist when individuals produce various vowels. Information relating to oral-nasal coupling suggests that systematic differences in closure may also be evident during varying degrees of vocal pitch and intensity. Measurements of nasal air flow, made simultaneously with measurements of oral air flow, should provide valuable information regarding the nature of these adjustments.

Summary

The present review reveals disparate findings regarding the expenditure of oral air as a result of vocal pitch and intensity changes. The results of early pneumographic studies suggest that an increase in vocal intensity is not necessarily accompanied by increased air expenditure. Conversely, spirometric and pneumotachographic data suggest an increase in oral air flow with increases in vocal intensity. There is a similar lack of agreement in the literature regarding the effect of increased vocal pitch on oral air flcw. While the reasons for these divergent findings are not readily apparent, it seems probable that differences in the instrumentation employed in the various studies was a contributing factor. Moreover, the experimental control of vocal pitch and intensity varied markedly among the studies.

The present survey of the literature reveals virtually no experimental evidence pertaining to nasal air flow during speech. In view of the recognized importance of oral-nasal coupling during speech production, the limited information regarding nasal air flow is surprising. This lack of information is evident in the literature regarding the relationship between nasal emission and hypernasality. Although it is generally recognized that the two are not synonymous, the relationship has not been clearly determined. To do this, information regarding nasal air flow during normal sound production is needed. Such information would provide a basis for comparison of similar data from individuals exhibiting hypernasality, or other speech disorders. Nasal air flow data during the production of vowel sounds would be of particular interest in this respect. Various experimenters (23, 27, 29) have reported differences among vowels with regard to degree of judged nasality. Moreover, the results of x-ray and cinefluorographic studies (31, 44) have demonstrated that vowels may be differentiated on the basis of velopharyngeal closure. Nasal air flow data during vowel production by normal subjects would provide valuable corroborative findings. It could be determined whether those vowels that show an "affinity" for nasality also characteristically exhibit the most nasal air flow. Finally, measurements of simultaneous oral and nasal air flow would provide valuable information regarding the possibility of systematic changes in velopharyngeal closure during different conditions of vocal pitch and intensity. Accordingly, the present study sought to investigate oral and nasal air flows during sustained production of vowel sounds at different pitch and intensity levels. The specific vowels, pitch, and intensity levels employed and the procedures used in this study are discussed in detail in the following chapter.

CHAPTER III

DESIGN OF THE INVESTIGATION

The present study was designed to investigate the volume rates of oral and nasal air flow expended during the production of each of four vowel sounds and to determine the effects of increased vocal pitch and intensity levels on these rates of flow. More specifically stated, this study attempted to answer the following research questions:

1. How do the vowels [i], [u], [ae], and [ɑ] differ with respect to mean volume rates of oral air flow and simultaneously measured mean volume rates of nasal air flow?

2. What is the effect of increased vocal pitch on the mean volume rates of oral air flow and simultaneously measured mean volume rates of nasal air flow for these vowels?

3. What is the effect of increased vocal intensity on the mean volume rates of oral air flow and simultaneously measured mean volume rates of nasal air flow for these vowels?

4. What is the combined effect of increased vocal pitch and increased vocal intensity on the mean volume rates of oral air flow and simultaneously measured mean volume rates of nasal air flow for these vowels?

In order to answer these questions, oral and nasal air flow measurements were obtained for twenty adult male subjects during the production of each of the four test vowels. The vowels were produced at each of four pitch levels at each of two intensity levels. Instruments based upon the warm-wire anemometer principle were used to measure the volume rates of air flow occurring during the vowel productions. These data were recorded by means of a dual-channel chart recorder, which provided a graphic representation of the volume rate of oral air flow and simultaneously occurring volume rate of nasal air flow for each test vowel at the various pitch and intensity levels. The quantitative data used in this study consisted of air flow measurements made at selected points on the graphic recordings of the vowel productions. The selection of subjects, the experimental apparatus, the procedures employed in data collection, and the resulting data are described and discussed in the following sections.

Subjects

Twenty white male adults served as subjects in this study. They were selected primarily on the basis of their ability to perform the experimental task, which required the ability to sing an ascending musical scale while maintaining a relatively constant vocal intensity. Due to the difficulty of the task, it was necessary to select trained singers or persons who had previously received voice training. The subjects had varying degrees of musical training; five were professional voice teachers, eight were university students majoring in voice, and four were participating in church choirs. In addition, three graduate students in speech pathology served as subjects.

To avoid possible air flow variations due to physiological factors associated with age, young adults were chosen. The subjects ranged in age from 19 to 35 years with a mean age for the group of 26 years, 9 months. Thus, persons who had not undergone pubescent voice change and individuals who might have undergone significant physiological changes in breathing due to advanced age were not included in the study.

The speech and voice characteristics of each potential subject were carefully examined, and individuals presenting speech or voice deviations were not included. In addition, testing was deferred for persons presenting current upper respiratory infections, allergy conditions, or similar disorders which could interfere with normal air flow during speech.

In order to obtain a homogeneous group with regard to fundamental vocal frequency, the speech of each potential subject was analyzed by means of a sound spectrograph. Prospective subjects were instructed to phonate the vowel [ɑ] at a "comfortable" pitch and intensity level. Individuals with a fundamental vocal frequency of approximately 145 cps, as determined by a broad-band spectrogram, were selected as subjects.

Apparatus

Instrumentation utilized in data collection included: (a) two pneumoanemometers (Flow Corporation, Model 53AI) with a custom-built face mask containing the sensing units of the pneumoanemometers; (b) a dual-channel strip-chart recorder (Sanborn, Model 60-1300B), (c) a sound spectrograph (Sona-Graph, Kay Electric Company), and (d) a single-channel tape recorder (Ampex, Model 601). A simplified block diagram of the apparatus is presented in Figure 1.

Description

Pneumoanemometer assembly. Oral and nasal air flow data were obtained by means of a pneumoanemometer assembly consisting of two pneumoanemometer units with an associated face mask. The pneumoanemometer measures air velocity by recording voltage changes in an electrically

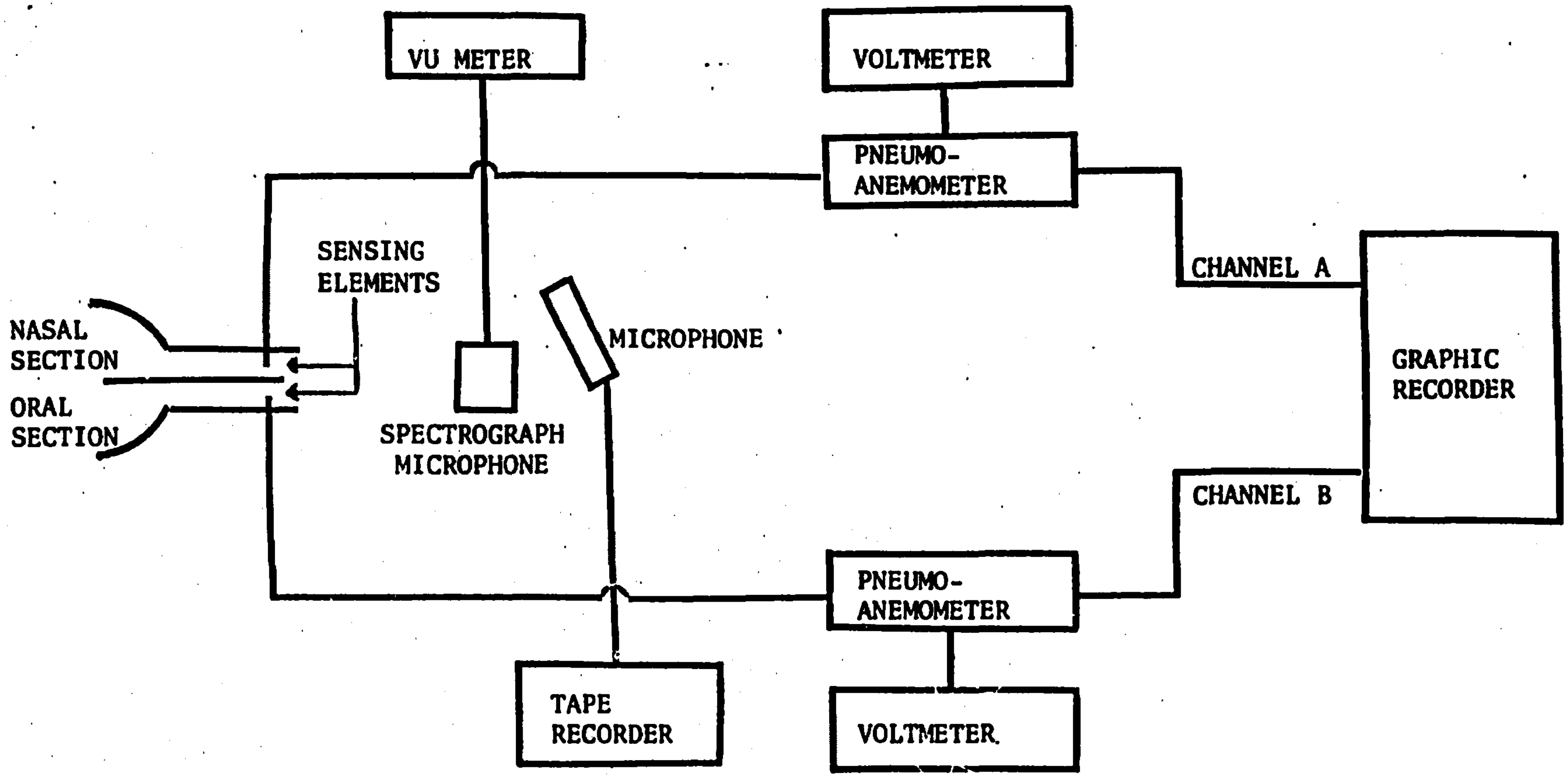

Figure 1.--Simplified block diagram of the research apparatus.

heated sensing wire. A completely transistorized feedback amplifier maintains a constant resistance ratio between a heated and an unheated wire. Any decrease in the heated wire's resistance, resulting from the cooling effect of an airstream, is counteracted by the feedback amplifier which returns the wire to its original temperature by increasing the current through it. This principle of operation is referred to as the constant-resistance ratio principle. When the flow rate is zero, the voltage at the output terminals of both wires is zero. When the flow rate increases, the electrical current required to maintain the temperature of the hot wire increases. This increase in current results in a change in voltage at the output terminals. These voltage variations are proportional to the velocity of the air stream passing the sensing wire at any given instant. Since the sensing elements are housed in a tube of constant dimensions, the voltage variations are also proportional to the volume of air passing the sensing element per unit of time.

The platinum sensing wires, .0188 inches long and 0.0005 inches in diameter, are contained in a mall metal tube, four inches long and seven-eighths inches in inside diameter, which projects from the face mask. This tube and the face mask are divided throughout their length by a thin horizontal partition. One pair of sensing wires is situated above the partition of the tube; the other is located similarly on the other side of the partition. The body of the mask is constructed of plastic and has a small inflatable rubber rim which fits against the face. When properly adjusted, the mask is held tightly against the face, and the pneumatic rim forms an essentially air tight seal. The edge of the horizontal partition separating the oral and nasal sections of the mask is covered by a rubber extension which contacts the face just above the upper lip. This partition serves to direct the oral air flow through the lower portion of the metal tube and the nasal air flow through the upper part. Thus, oral and nasal air flows can be registered separately and simultaneously.

The pneumoanemometer is powered by two rechargable batteries. According to the manufacturer's instructions, eight hours of operation are available after recharging the batteries for twelve hours. In the present experiment, the batteries were recharged prior to each session in which data were collected. In accord with the manufacturer's recommendation, data were not collected if the battery voltage reading was less than .86 volts.

The pneumoanemometer is equipped with calibration and zero adjustments which help minimize any shift in voltage readings resulting from temperature changes in the internal circuits or from battery voltage fluctuations during operation.

Recording Instruments: The pneumoanemometer output voltages were recorded by means of a dual-channel, strip-chart recorder at a paper speed of 100 millimeters per second. The manufacturer's published description indicates that the error of the recorder is less than ± .025 millimeters in the central four centimeters of the chart and less than ± 0.5 millimeters over the outer five millimeters of the chart. In this experiment, the recorder was equipped with twin DC amplifiers (Sanborn, Model 64-1300B) to amplify the direct-current output of the pneumoanemometers. The amplifiers were independently balanced and calibrated to a recording sensitivity of 50 millivolts per centimeter of stylus deflection. An amplifier attenuator setting of X5 permitted recording the entire voltage range of the pneumoanemometers on four centimeters of the five-centimeter chart width. As determined empirically, prior to and following data collection, at this setting each millimeter of stylus deflection above the baseline was equivalent to .025 volt of pneumoanemometer output.

A single-channel tape recorder was employed to obtain an acoustical record of the vowel productions. Each of these tape recorded vowels was subsequently recorded on a sound spectrograph for an analysis of fundamental vocal frequency. The sound spectrograph analyzes a complex acoustical signal as a function of frequency, intensity, and time. The resulting spectrogram displays frequency along the vertical axis, time along the horizontal axis, and intensity by the darkness of the trace. The spectrogram normally portrays the frequency region from 85 to 8000 cps in a vertical distance of four inches, while a time period equivalent to 2.4 seconds is represented in a horizontal distance of approximately 12 1/2 inches. The speech sample to be analyzed is first recorded on a magnetic disc and then reproduced repeatedly at a speed that is 3.33 times as fast as the recording speed. In each repetition, a different portion of the signal spectrum is scanned by either a 45-cycle or 300-cycle band-pass filter. The output of the analyzing filter is then recorded on dry facsimile paper that is fastened around a drum rotating sychronously with the magnetic disc. A recording stylus shifts gradually along the frequency scale in synchrony with the scanning oscillator. In the present study, the 300-cycle band-pass filter was used.

Calibration

In order to calibrate the pneumoanemometer units, the air outlet valve of a compressed air source was connected, by means of a rubber coupling hose, to the input of a positive displacement air volume meter (American Meter Company, Model AS-8-11). A second rubber coupling hose, attached to the outlet of the air-volume meter, was connected to a plastic hose in which the metal tube of the face mask was inserted.[1] The sensing wires housed in the metal tube were then connected to the pneumoanemometer units. The open end of the metal tube was occluded by means of cork plugs, one in each portion of the divided tube, and the pneumoanemometer unit to be calibrated was adjusted for zero voltage reading at zero air flow. When this had been accomplished, the cork plug was removed from the part of the tube housing the sensing wire being calibrated. The air control valve was opened until there was a flow of air sufficient to deflect the pneumoanemometer voltmeter to .04 volts. The flow was maintained at this level for one minute and the volume of air required to maintain the .04 volt reading was read from the dial of the air volume meter. This procedure was repeated at increments of .04 volts until the air volume measurements were obtained at each of twenty-five intervals throughout the one volt range of the pneumoanemometer. The same procedure was repeated for the other pneumoanemometer unit. The pneumoanemometer units were numbered and care was taken to insure that the same unit was used with the same sensing wire throughout the experiment. The entire calibration procedure was performed prior to data collection and upon completion of the experiment. In addition, periodic checks were made at .10-volt intervals throughout the range of the pneumoanemometers to determine whether the units remained in calibration. The results of the initial and final calibration procedures are presented in Table 11 of Appendix A. It may be observed that the results of the two calibration procedures are in

---

1. The air compressor had a tank capacity of five cubic feet of air at thirty pounds per square inch.

close agreement.[1]

Calibration Curve: Upon completion of the calibration procedures, a calibration curve relating each of the twenty-five pneumoanemometer voltage readings to corresponding volume rates of air flow was constructed. A separate curve for oral and nasal air flow was constructed on the basis of the initial calibration data. The two curves are presented in Figures 2 and 3.

Since each millimeter of stylus deflection above the baseline was equivalent to .025 volts, it was possible to convert millimeter measurements to pneumoanemometer output voltages by the formula: Voltage = .025 X millimeters of deflection. These voltage values could then be converted to equivalent flow rate values in liters per minute in accordance with the calibration curve for each instrument. In order to simplify the task of performing the above mentioned conversions, a mathematical curve of calibration was fitted to the initial calibration data for each pneumoanemometer unit using a least squares fit to a quadratic equation: $F=aE + aE^2$ where F = Air Flow and E = .025 millimeters of stylus deflection. The calibration data was fitted to the mathematical curve by means of an electronic computer. To obtain a satisfactory fit, the calibration data for each pneumoanemometer unit was considered separately for each of

1. To determine how accurately pneumoanemometer output voltages were recorded on the Sanborn chart recorder, the stylus deflections resulting from each of ten voltage readings (.1, .2, .3, .4, 15, .6, .7, .8, .9, and 1.0 volts) were examined. This was done by employing the same procedure used in calibrating the pneumoanemometers. The air control valve was adjusted to achieve each of the desired voltage readings. These voltages were recorded on the Sanborn chart recorder and the resulting stylus deflections examined. The stylus deflections were found to reflect accurately the pneumoanemometer output voltages.

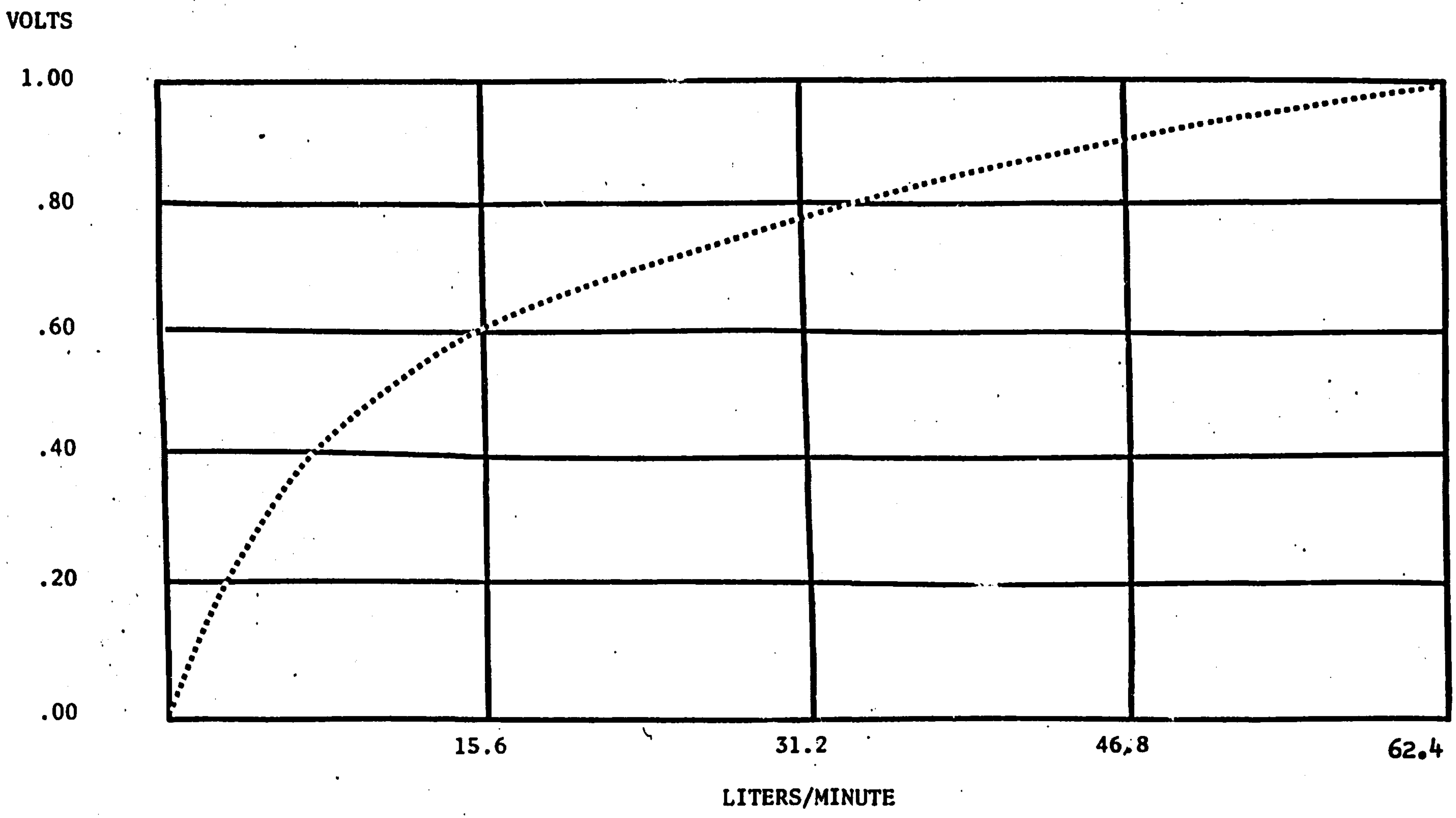

Figure 2.--Calibration curve for the nasal air flow.

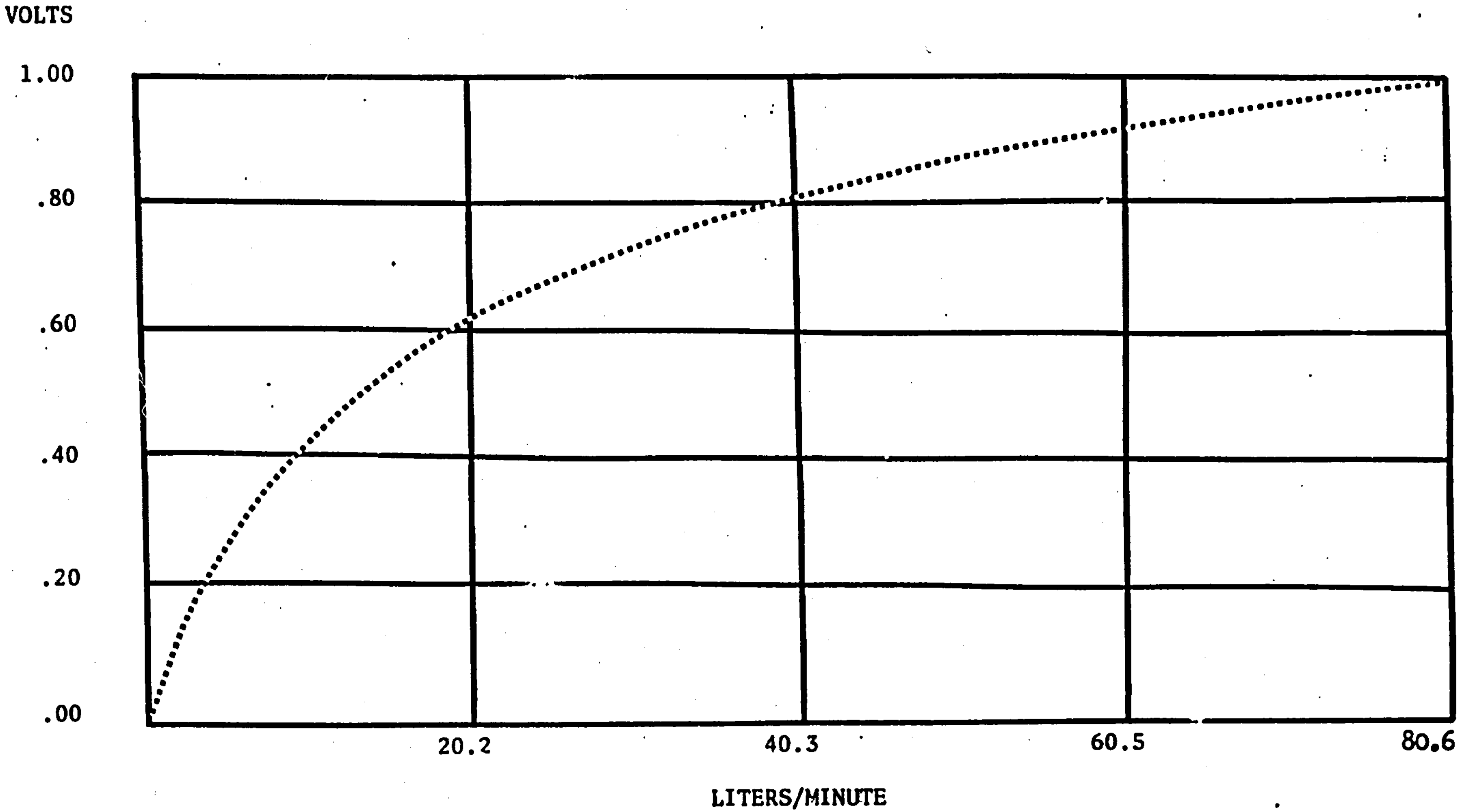

Figure 3.--Calibration curve for the oral air flow.

four voltage ranges: from .04 to .20, from .24 to .40, from .44 to .80, and from .84 to 1.0 volt. The formula was used to fit a curve to each of these ranges. A comparison between the initial calibration data and the air flow values based on the mathematical curve is presented in Tables 1 and 2.

Inspection of Table 1 reveals a mean difference of 1.2% between the initial oral pneumoanemometer calibration data and the values obtained mathematically. Similarly, examination of Table 2 shows a mean difference of 0.9% between the initial nasal pneumoanemometer calibration data and the mathematically obtained values. Furthermore, it may be observed that in those instances in which the observed values and the computed values differed by more than 3%, the values were associated with low flow rates and the actual air flow differences were small. In view of the close agreement, the mathematical curve was used in converting voltage values to equivalent flow rate values because of the greater simplicity of this method.

Speech Sample

The results of x-ray studies (31, 44) indicate that vowel sounds differ with respect to degree of velopharyngeal closure. The high vowels [i] and [u] are reportedly produced with a relatively tight closure, whereas the velum is more relaxed in the production of the low vowels [ae] and [ɑ]. In order to determine whether these findings are corroborated by measurements of nasal air flow during isolated vowel production, the [i], [u], [ae], and [ɑ] sounds were selected for study.

Since fundamental frequency of phonation was an experimental variable, considerable care was taken to insure that subjects maintained

TABLE 1.--A comparison between the initial oral calibration data and air air flow values based on a mathematical curve.

Voltage	Observed Air Flow	Estimated Air Flow	Differences	Percentage Difference
.04	.20	.22	.02	10.0
.08	.45	.44	.01	2.2
.12	.89	.91	.02	2.2
.16	1.15	1.14	.01	0.9
.20	1.50	1.52	.02	1.3
.24	2.40	2.32	.08	3.3
.28	3.30	3.22	.08	2.4
.32	3.60	3.52	.08	2.2
.36	5.60	5.50	.10	1.8
.40	7.10	6.95	.15	2.1
.44	8.25	8.01	.24	2.9
.48	11.00	11.27	.27	2.5
.52	13.30	13.11	.19	1.4
.56	15.50	15.14	.36	2.3
.60	18.35	18.46	.11	0.6
.64	22.70	23.08	.38	1.7
.68	27.20	26.99	.21	0.8
.72	32.10	32.17	.07	0.2
.76	36.00	35.66	.34	0.9
.80	40.00	40.43	.43	1.1
.84	46.10	45.50	.60	1.3
.88	54.00	53.51	.49	0.9
.92	61.00	61.45	.45	0.7
.96	70.00	70.95	.95	1.4
1.00	84.00	83.03	.97	1.2
			Mean Percentage Difference	1.2

TABLE 2.--A compariscn between the initial nasal calibration data and air flow values based on a mathematical curve.

Voltage	Observed Air Flow	Estimated Air Flow	Difference	Percentage Difference
.04	.29	.31	.02	6.9
.08	.65	.64	.01	1.5
.12	1.05	.99	.06	5.7
.16	1.15	1.14	.01	0.9
.20	1.50	1.52	.02	1.3
.24	2.15	2.26	.11	5.1
.28	3.20	3.22	.02	0.6
.32	4.50	4.32	.18	4.0
.36	5.50	5.35	.15	2.7
.40	6.40	6.50	.10	1.6
.44	7.95	7.80	.15	1.9
.48	9.60	9.51	.09	0.9
.52	11.60	11.53	.07	0.6
.56	13.30	13.57	.27	2.0
.60	15.80	15.38	.42	2.7
.64	18.80	19.20	.40	2.1
.68	21.85	22.28	.43	2.0
.72	25.50	25.56	.06	0.2
.76	28.80	29.05	.25	0.9
.80	33.70	33.77	.07	0.2
.84	38.80	38.93	.13	0.3
.88	43.90	44.09	.19	0.4
.92	50.20	49.56	.64	1.3
.96	55.10	55.32	.22	0.4
1.00	61.30	61.39	.09	0.1
			Mean Percentage Difference	0.9

the desired pitch levels. An effective method of determining fundamental vocal frequency is suggested by Potter, Kopp, and Green (33), who indicate that pitch may be displayed on a wide-band spectrogram

> . . . in the disposition of the vertical striations or 'pitch lines' of the voiced sounds. When vertical striations are close together, the pitch is high; when they are far apart, it is low. The number of striations for a given time interval determines the frequency of the fundamental pitch. Variations in pitch appear in this integral form of display as changes in the spacing of the vertical lines.

All vowel productions were recorded on a single-channel tape recorder simultaneously with the recording of the air flow measurements. These recordings were made with the Ampex microphone situated seven inches in front of the face-mask tube. The gain setting on the tape recorder was left constant. Upon completion of testing, these tape recorded vowel productions were analyzed spectrographically for determination of fundamental frequency. A frequency-by-time record was made employing the 300-cycle filter.

The sound spectrograph was also employed to control vocal intensity. This instrument has an attenuator, which is calibrated in 2-db steps from zero to 32 db, and a VU meter which may be utilized to monitor vocal intensity visually. Each subject was instructed to monitor vocal intensity by maintaining the VU meter needle at a zero reading during production of the test vowels. The attenuator was preset to deflect to a zero reading at a predetermined vocal intensity level found to be comfortable for a group of normal speakers. In a preliminary procedure, each of ten male adults was instructed to sustain a vowel at his normal vocal intensity. As the speaker sustained the vowel, the experimenter adjusted the spectrograph attenuator until the VU meter peaked at zero. The attenuator dial setting resulting in the zero VU meter reading was recorded and the procedure was repeated. Each of the ten subjects performed the task three times, resulting in a total of 30 attenuator dial readings. The median attenuator dial reading was selected as the "comfort level" setting which was subsequently employed in the experiment.

During the experiment, subjects sustained each vowel production for three seconds. To avoid subjective evaluation, each subject monitored the duration of phonation by observing a signal light controlled by a cam timer (Industrial Company) which was activated by the experimenter. A warning light preceded the signal light by approximately one second to prepare the subject for phonation. The lights were situated immediately above the sound spectrograph VU meter to facilitate the task of monitoring duration and intensity simultaneously. In actual practice, the subjects experienced little difficulty in monitoring both duration and intensity.

Procedure

The procedure followed in this experiment consisted of the following five steps: (1) necessary equipment adjustments were made, (2) the subject was instructed in the experimental task, (3) the subject was seated and the face-mask fitted, (4) the experimental procedure was practiced, and (5) the speech sample was recorded.

The Sanborn strip-chart recorder was turned on approximately 30 minutes prior to calibration to allow it time to warm up. Then, the DC amplifiers were independently balanced and calibrated to a recording sensitivity of 50 millivolts per centimeter of stylus deflection at an attenuator setting of X5. Next, the pneumoanemometers were attached to the sensing wires housed in the dual face mask and the battery voltages were checked. If the voltage readings were .86 volt or greater, the face mask was covered to eliminate ambient air flow and the pneumoanemometer units adjusted to a zero voltage reading at zero air flo. by means of the "calibration" and "zero" adjustment knobs. Care was taken to insure that these adjustments were made within a pointer width of true zero. These adjustments were made prior to each data collection and were checked periodically during the recording procedure.

Each subject was instructed to sing an ascending musical scale using each of the four test vowels, [i], [u], [ae], and [ɑ], at both the predetermined comfort level and at a level approximately 6 db more intense. Since it was essential that vocal pitches at each of the two intensity levels be closely matched, each subject was instructed to begin each scale at the same pitch. To assist the subjects, a reference pitch was provided. The reference pitch was obtained by instructing each subject to produce the vowel being tested at a comfortable level. This production was tape recorded and subsequently played back to the subject just prior to his attempt to sing the scale at either the comfort or intense level. This procedure minimized the tendency for subjects to increase pitch during productions at the intense level.

Each subject was instructed as follows:

> You will sing each of four vowels (i,u,ae,ɑ) over a one-octave range. This will be done once at a comfortable level and once at a louder level. You will be able to judge how loud you are singing by looking at this meter (VU meter). Try to keep the needle at zero. Sing with as little vibrato as possible. You can judge how long to hold each sound by watching these lights. First, an amber colored light will come on. When this light comes on, take a breath and prepare to sing. When the red light comes on, begin singing at your natural pitch and hold it until the light goes off.

Then, when the amber light comes on-again take a breath and sing the next highest note as soon as the red light comes on again. Remember, try to produce a steady tone which peaks at zero on the meter. Continue this procedure, taking a breath between each note, until you sing the octave.

The instruction to breathe between each vowel production was used to avoid a possible difference in air flow on successive pitch levels as a result of reduced breath supply. Each vowel was to be phonated for three seconds.

Following a successful completion of the practice trials, the subject was seated and the face mask attached. The rationale for collecting data with the subject seated was based on Benson's finding (1) that this position facilitates the respiratory process and yields less variable air flow measurements than when subjects are placed in supine, prone, or semi-recumbent positions.

The subjects were seated in a standard dental examination chair which was elevated or lowered to allow for individual differences in sitting height. A head rest attached to the back of the chair was adjusted forward or backward to facilitate proper head positioning. A horizontal bar, supported on either end by an adjustable microphone stand, was placed in front of the subject. The face mask was secured to the center portion of this bar and the tube of the face mask was attached, by means of a metal clamp, to a third microphone stand situated in front of the horizontal bar. The spectrograph microphone was placed on top of the stand, and the clamp served as a spacing bar, maintaining a distance of two inches between the microphone and the end of the face-mask tube. The microphone of the Ampex tape recorder, used to obtain an acoustical record of the vowel productions, was placed on a table immediately behind the the spectrograph microphone. The sound spectrograph was situated so that it was possible for the subjects to observe the needle of the VU meter which indicated the intensity at which the vowel sound being tested was produced.

The face mask was tightly fitted to the subject by means of a rubber strap, and the head position was maintained relatively fixed by means of the head rest. To insure a proper fitting of the mask, each subject was instructed to (1) blow through the mouth without accompanying nasal air flow, and (2) to breathe through the nose with the mouth closed. Chart recordings were taken during each performance. If the mask was properly fitted, a baseline reading was obtained on the chart record for that portion of the mask not being tested. This procedure was performed prior to data collection and upon completion of each vowel series. If an air leak was detected the entire series was repeated.

When a proper face mask fit was achieved, the subject was instructed again and the experimental data was collected. To minimize possible order effects, intensity and vowel orders were randomized.

During the data collection procedure, there were occasional recording errors. The subject would begin phonation at an improper intensity level, fail to monitor intensity during production of the scale, or produce the wrong vowel sound. When this occurred, the experimenter marked the chart record and the subject was instructed to start again. The recording procedure required approximately 45-60 minutes for each subject.

Experimental Data

Oral and nasal air flow measurements were obtained for each of four vowels, [i], [u], [ae], and [ɑ], at each of four pitch levels, approximately 145, 175, and 260 cps, at each of two intensity levels. The measurements were made in terms of millimeters of stylus deflection at the beginning, middle, and end of the middle .75-second segment of each three-second vowel record. This segment of the vowel was selected as being the least affected by onset and terminating influences. These measurements were processed by an electronic computer which was programmed to convert from millimeters of stylus deflection to pneumo-anemometer voltage equivalents and then to mean volume rates of air flow in accordance with the previously described mathematical calibration curve for each unit. The decision to measure at the beginning, middle, and end of the segment was not arbitrary. The mean volume rates of oral and nasal air flow for each of thirty-two randomly selected vowel productions were computed by taking the average of seventy-five measures made at one-millimeter intervals over the .75-second segment. Then, the average of fifteen measures taken at five-millimeter intervals over the .75-second segment was computed. The air flow values thus obtained were compared to those obtained when mean volume rate of flow was calculated on the basis of measurements made at the beginning, middle, and end of the .75-second segment. The differences in mean rate of air flow yielded by the three methods, as determined by an analysis of variance, were not statistically significant. Therefore, the mean air flow rates for the remaining sustained vowels were computed by using three points because of the greater simplicity of this method.

The reliability with which the millimeter measurements could be made was estimated by a standard measure-remeasure reliability procedure. The experimenter measured thirty-two randomly selected vowel productions at the beginning, middle, and end of the .75-second segment. These measurements were repeated after a period of two weeks. The agreement between the two measurements was high, with a maximum discrepancy of .5 mm at any point. A further reliability check was made by comparing the experimenter's measurement of these vowel samples with those of two independent observers. Again, the agreement was close, and in no instance was there a discrepancy of more than .5 mm. Hence, the final measurements were made to the closest one-half millimeter.

The fundmental frequency of each vowel production was determined by counting the vertical striations over a one-inch interval in the mid-portion of each wide-band spectrogram. The mid-portion was selected to correspond, approximately, to the segment where the air flow measurements were made. To determine whether this portion was representative of the entire spectrogram, the fundamental frequency for each of thirty-two randomly selected vowels was determined by measurements taken at one-inch intervals at the beginning, middle, and end of each spectrogram. It was found that the measurements made at each of these three portions of the spectrograms yielded estimates of fundamental frequency that differed by less than 5 cps.

The validity of the procedure used to determine fundamental frequency was verified by making wide-band spectrograms of a series of pure-tones tape recorded at 5-cps intervals from 135-290 cps. The frequency of each pure tone was estimated by counting the vertical striations within a one-inch segment of the wide-band spectrogram for that pure tone. The results of this procedure indicated that the frequency of the pure tone could be estimated within $\pm$ 2 cps by means of spectrographic analysis. This procedure was performed prior to the spectrographic analysis of the experimental data and upon completion of the analysis to determine the stability of the sound spectrograph.

The reliability with which the spectrogram measurements could be made was also determined by a standard measure-remeasure procedure. The fundamental frequency of each of thirty-two randomly selected vowel productions was determined by measurements made over a one-inch interval in the mid-portion of each spectrogram. These measurements were compared with measurements of the same spectrograms made two weeks later and the results were highly similar. As a further check, the experimenter's measurements of the same vowels were compared with those made by two independent observers and again the results were in close agreement.

The results of the spectrographic analyses of the subjects' fundamental vocal pitch levels during production of the vowel sounds revealed a remarkable degree of consistency. The subjects achieved the desired pitch levels with great accuracy. In no instance did a subject vary by more than five cps from the desired pitch level.

The tape recordings also served as a check on whether the subjects used the correct vowel sound. In addition, when making the spectrograms, the intensity level of each vowel production was observed on the VU meter. This provided additional confirmation of the accuracy with which the subjects monitored the intensity level of the vowel production.

CHAPTER IV

RESULTS AND DISCUSSION

This study was designed to investigate oral and nasal air flow during the production of sustained vowels. Twenty normal-speaking young adult males produced each of the vowels [i], [u], [ae], and [ɑ] at each of four pitch levels at two intensity levels. The pitch levels corresponded, within five cycles, to the following fundamental vocal frequencies: 145, 175, 220, and 260 cps. The intensity levels were (1) a reference intensity level which was a predetermined uniform level that was found to be comfortable for all subjects, and (2) a level approximately six decibels more intense. Instruments based upon the warm-wire anemometer principle were used to measure the volume rates of oral and nasal air flow occurring during production of the vowels. These data were recorded by means of a dual-channel chart recorder which provided a graphic representation of the volume rate of oral air flow and simultaneously occurring volume rate of nasal air flow for each test vowel at each of the four pitch levels at both intensity levels. The quantitative data used in this study consisted of measurements of oral and nasal air flow at selected points on the graphically recorded vowel productions.

In order to answer the research questions stated in Chapter III, the data were analyzed by means of an analysis of variance with a factorial arrangement of treatments. Main effects in the analyses were vowels, pitch, and intensity. The alpha level was set at .05. The error term for each main effect consisted of the interaction of the term involving subjects with the appropriate main effects and interactions. To locate significant differences revealed by the analysis of variance, the Duncan Multiple Range Test was used. Although the oral air flow and nasal air flow data were collected simultaneously, the data were analyzed separately. In this chapter, the results pertaining to oral air flow are presented first, followed by the findings regarding nasal air flow. Finally, a comparison is made between the oral and nasal air flow data.

To facilitate the presentation of results, the reference intensity level previously described is referred to as the "Comfort Level" and the level which was approximately six decibels more intense as the "Intense Level." Also, the pitch levels corresponding to the fundamental vocal frequencies 145, 175, 220, and 260 cps are referred to as Pitch Levels I, II, III, and IV, in that order. The terms "oral air flow" and "nasal air flow" are substituted for the more accurate terms "mean volume rate of oral air flow" and "simultaneously measured mean volume rate of nasal air flow." Finally, the abbreviation "lpm" is used in place of the more complete expression, "liters per minute".

Vowel Oral Air Flow

The results of the analysis of variance for oral air flow data are presented in Table 3. Examination of this table indicates that the vowel, pitch, and intensity main effects, and the vowel-by-intensity interaction are significant. The vowel-by-pitch, intensity-by-pitch, and vowel-by-pitch-by-intensity interactions are not significant.

Vowel Main Effect

The oral air flow means for each of the four vowels, averaged over the four pitch levels and both intensity levels, are presented in Figure 4. A comparison of these means reveals that the greatest oral air flow, 13.1 lpm, occurs during the production of the vowel [u], followed in order of decreasing flow by [ɑ], [i], and [ae] with means of 12.5, 12.1, and 11.5 lpm, respectively. The analysis of variance summary for the oral air flow data is presented in Table 3.

TABLE 3.--Summary of the analysis of variance for the vowel oral air flow data from twenty male subjects.

Source	df	ms	F
Vowel (V)	3	72.48	4.24*
Intensity (I)	1	996.05	58.24*
VI	3	52.65	3.09*
Error A	133	17.10	
Pitch (P)	3	364.60	41.75*
IP	3	9.45	1.08
VP	9	3.38	.39
IVP	9	6.90	.80
Error B	456	8.73	

*P = .05

Inspection of Table 3 indicates that the vowel main effect is significant. The presence of this significant main effect indicates that, when oral air flow means are averaged over all pitch and intensity levels, there is a significant difference among the vowel means. In order to determine the location of these differences, analysis was made using the Duncan Multiple Range Test. The results of this analysis are presented in Table 4.

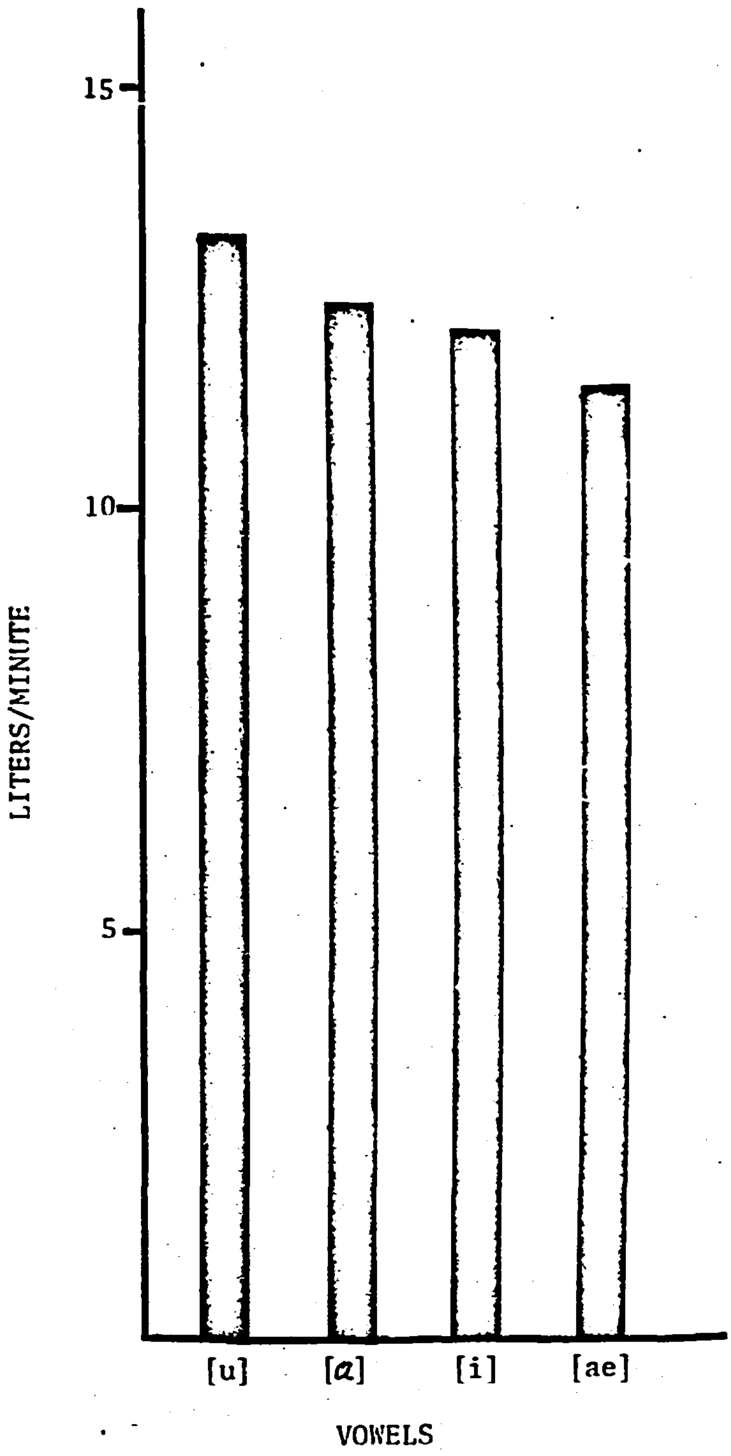

Figure 4.--Oral air flow means for each of four vowels produced at each of four pitch levels at each of two intensity levels, for twenty male subjects. The means are averaged over all pitch and intensity levels.

TABLE 4.--Duncan Multiple Range Test for differences in oral air flow means for each of the four vowel sounds produced at each of four pitch levels at each of two intensity levels, for twenty male subjects. The means are averaged over all pitch and intensity levels.

a) Shortest Significant Ranges

p:	(2)	(3)	(4)
Rp:	.915	.974	1.01

b) Results

Vowels:	[ae]	[i]	[ɑ]	[u]
Means:	11.52	12.17	12.52	13.13

Note: Any two means not underscored by the same line are significantly different at the .05 level.

Any two means underscored by the same line are not significantly different.

Inspection of Table 4 reveals that when oral air flow means are averaged over the four pitch levels and both intensity levels, the vowels [i], [ɑ], and [u] do not differ significantly. Further inspection indicates that the means for [ae] and [i] are not significantly different, but that the mean for [ae] does involve significantly less oral air flow than those for either [ɑ] or [u].

Pitch Main Effect

To determine the effect of different pitch levels on oral air flow during vowel production, the mean oral air flow at each of the four pitch levels was analyzed. Figure 5 presents the oral air flow means for the twenty subjects at each of the four pitch levels, averaged over the four vowel sounds and both intensity levels. Inspection of this figure reveals air flow means of 10.7, 11.7, 12.7, and 14.2 lpm for Pitch Levels I, II, III, and IV, respectively, thus indicating a progressive increase in oral air flow as pitch level increases.

The analysis of variance summarized in Table 3 indicates a significant pitch main effect. Thus, a difference among the air flow means for the four pitch levels is evident. To determine the location of the significant differences, the Duncan Multiple Range Test was used. The results of this test, as shown in Table 5, reveal a significant difference among the air flow means for all vocal pitch levels indicating that, when oral air flow means are averaged over all four vowels and both intensity levels, there is a progressive increase in oral air flow as vocal pitch is increased. The absence of either a pitch-by-intensity or pitch-by-vowel interaction indicates that the increase in oral air flow with increased pitch is present regardless of the vowel being produced

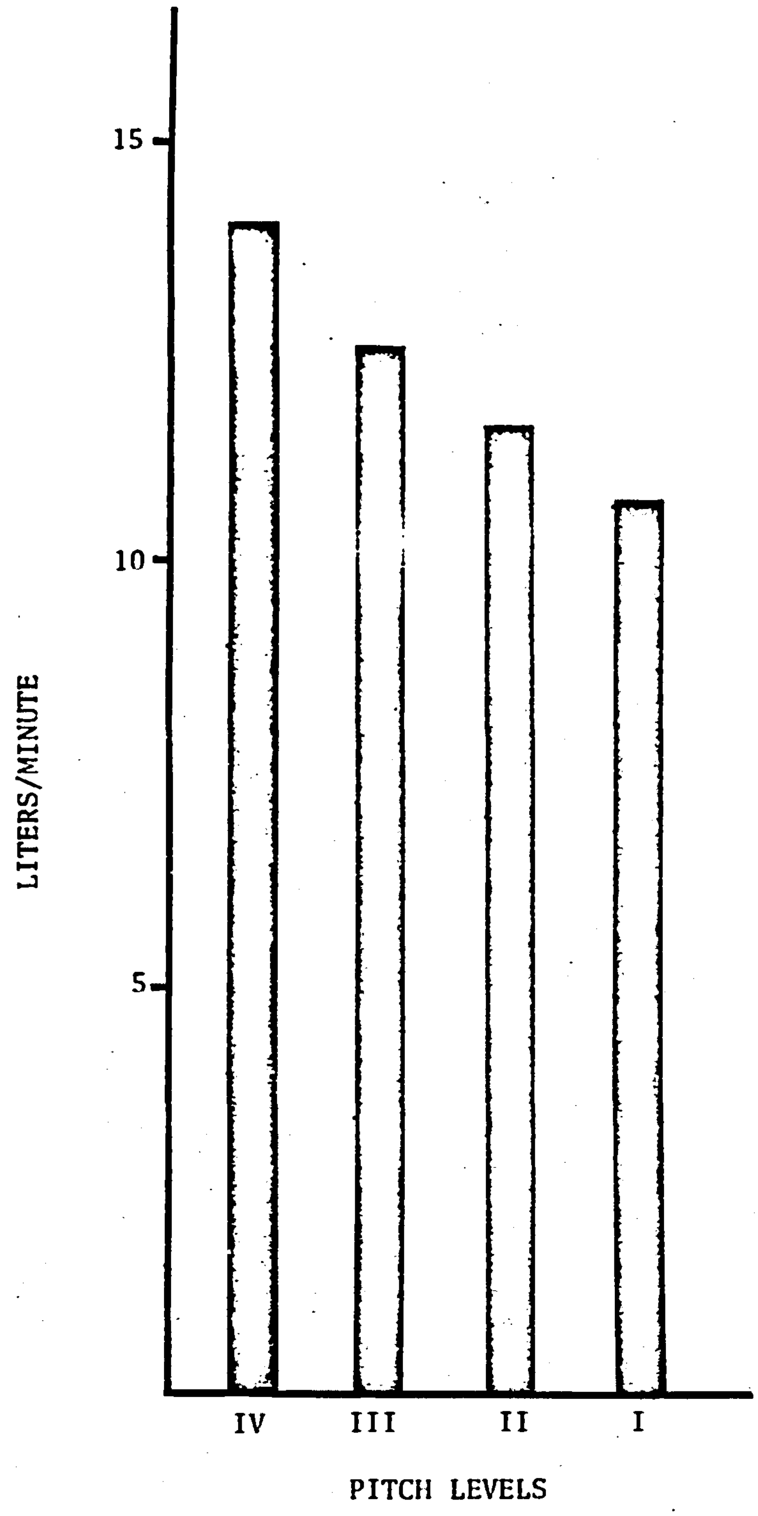

Figure 5.--Oral air flow means for each of the four vowels produced at each of four pitch levels at each of two intensity levels, for twenty male subjects. The means are averaged over all vowels and intensity levels.

TABLE 5.--Duncan Multiple Range Test for differences in oral air flow means for each of the four vowels produced at each of four pitch levels at each of two intensity levels, for twenty male subjects. The means are averaged over all vowels and intensity levels.

a) Shortest Significant Ranges

p:	(2)	(3)	(4)
Rp:	.66	.70	.73

b) Results

Pitch Levels:	I	II	III	IV
Means:	10.68	11.72	12.70	14.23

Note: Any two means not underscored by the same line are significantly different at the .05 level.

Any two means underscored by the same line are not significantly different.

or the intensity level being employed.

This finding disagrees with those of Roudet (34) and Luchsinger (28) who report a decrease in oral air flow as a result of increased vocal pitch. It is, however, consistent with the findings of an early study by Russell and Cotton (35) and a recent investigation by Isshiki (22) both of which indicate that increases in vocal pitch are accompanied by increases in oral air flow. The present finding is also corroborated by the work of Van den Berg (40) and Isshiki (22) regarding subglottal air pressure variations with increased pitch. Both of these investigators found an increase in subglottal air pressure as a result of increased pitch level. Since subglottal pressure is considered an analog of supraglottal air flow, these findings also suggest that an increase in vocal pitch results in increased oral air flow.

Intensity Main Effect

The oral air flow means at each of the two intensity levels used in this experiment, averaged over the four vowels and four pitch levels, were examined in an effort to determine the effect of vocal intensity increases on oral air flow. These means are presented in Figure 6. An inspection of this figure reveals a mean of 11.1 lpm for the Comfort Level productions and of 13.1 lpm for the Intense Level productions. The analysis of variance summary presented in Table 3 reveals that the difference between the means for the two intensity levels is significant, indicating that, when oral air flow means are averaged over the four vowels and four pitch levels, there is an increase in oral air flow as intensity level is increased.

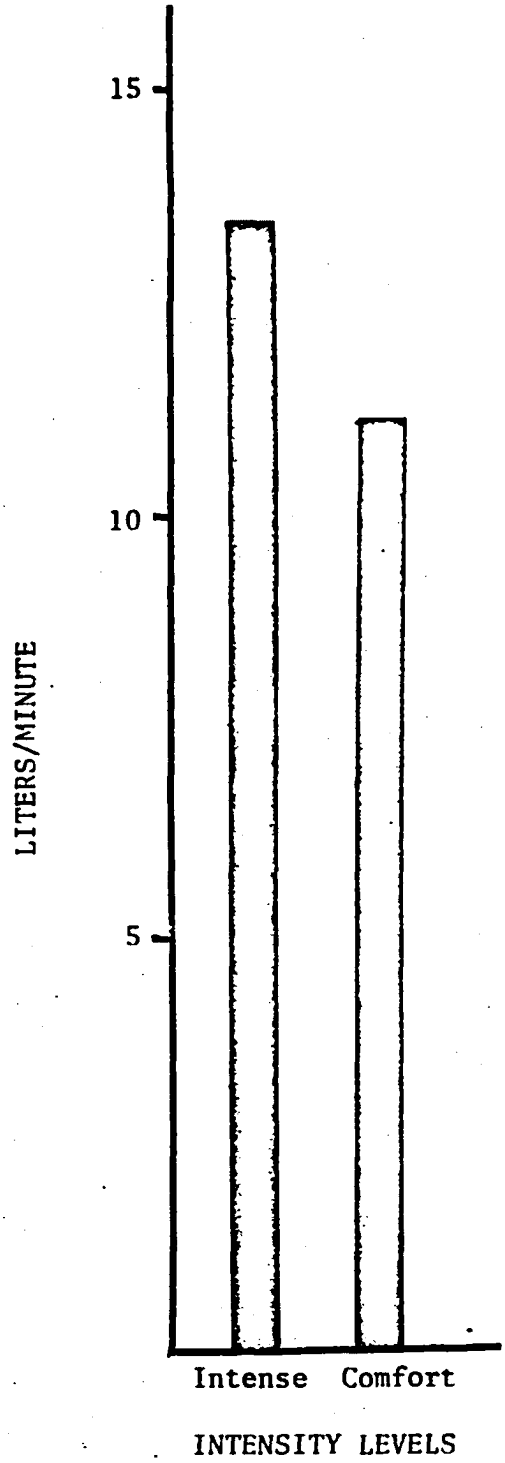

Figure 6.--Oral air flow means for each of the four vowels produced at each of four pitch levels at each of two intensity levels, for twenty male subjects. The means are averaged over all vowels and pitch levels.

Vowel-by-Intensity-Interaction

Inspection of the analysis of variance summarized in Table 3 reveals a significant vowel-by-intensity interaction. Thus, while both the vowel and intensity main effects are significant, the presence of this interaction indicates that the effect of intensity level on oral air flow varies according to the vowel being produced. To facilitate interpretation of the vowel-by-intensity interaction, the data is graphically presented in Figure 7. This figure displays the oral air flow means for each of the four vowels at each of the two intensity levels, averaged over the four pitch levels. Figure 7 indicates that the difference in oral air flow between the Comfort and Intense Level productions of the vowel [u] is an important source of the significant interaction. Careful examination of this figure shows an increase of over 4.1 lpm in the oral air flow mean for [u] when the vocal intensity level is increased from the Comfort to the Intense Level. The next greatest increase is shown for the vowel [i] with a difference of 2.5 lpm between the Comfort and Intense Level productions, followed closely by [ɑ] with a difference of 2.2 lpm. Finally, the vowel [ae] shows an increase of only 1.2 lpm when vocal intensity is increased from the Comfort to the Intense Level.

To further illustrate the vowel-by-intensity interaction, a laddergram is presented in Figure 8. Again, an increase in mean oral air flow for each vowel sound is evident with increased vocal intensity. Also, it may be noted that the means for each of the four vowels at the Comfort Level are similar, while the means for the vowels at the Intense Level show a wide range. The mean oral air flow for the vowel [u] is again shown to be the most markedly affected by the increase in vocal

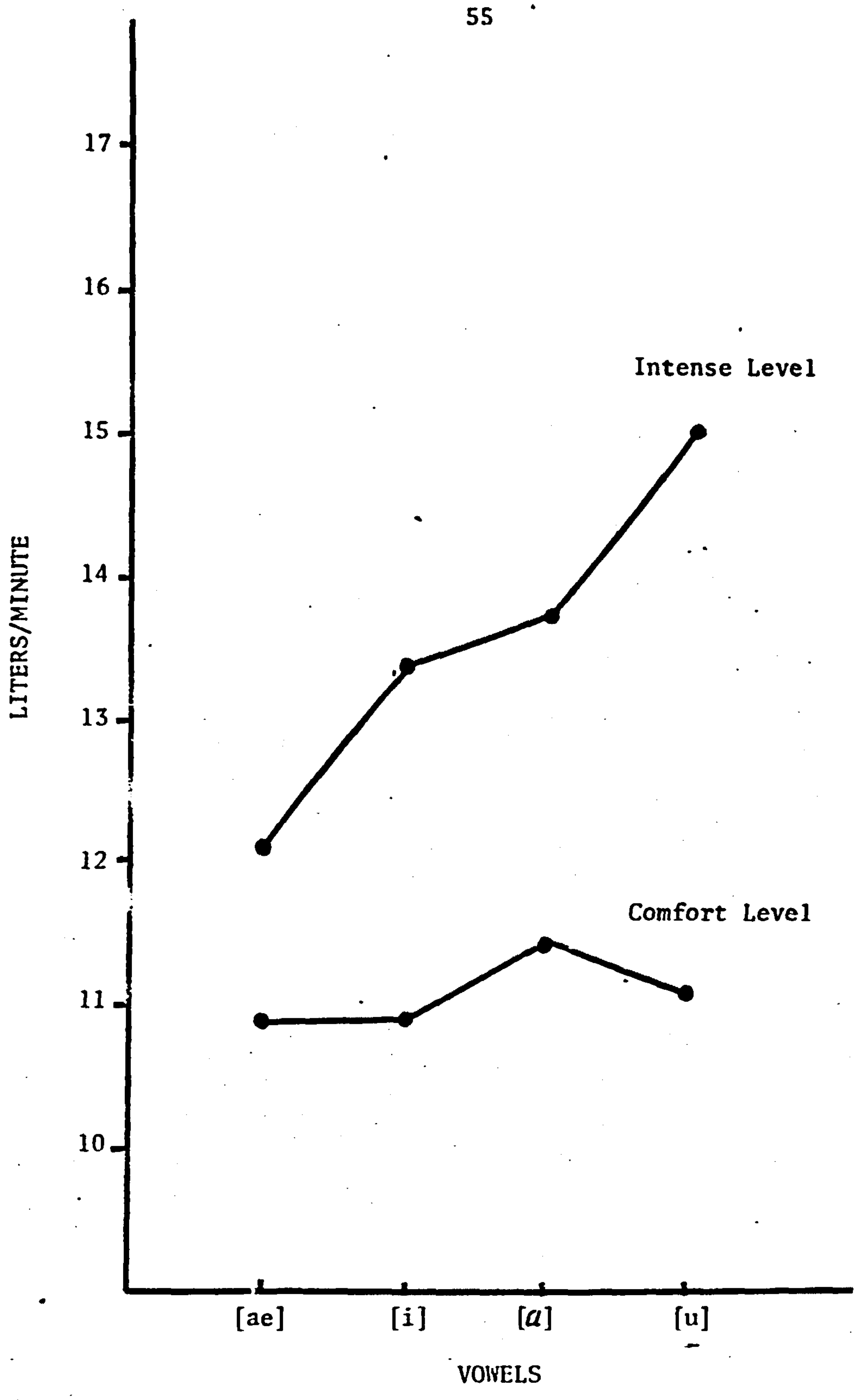

Figure 7.--Oral air flow means for each of the four vowels produced at each of four pitch levels at each of two intensity levels, for twenty male subjects. The means are averaged over the four pitch levels.

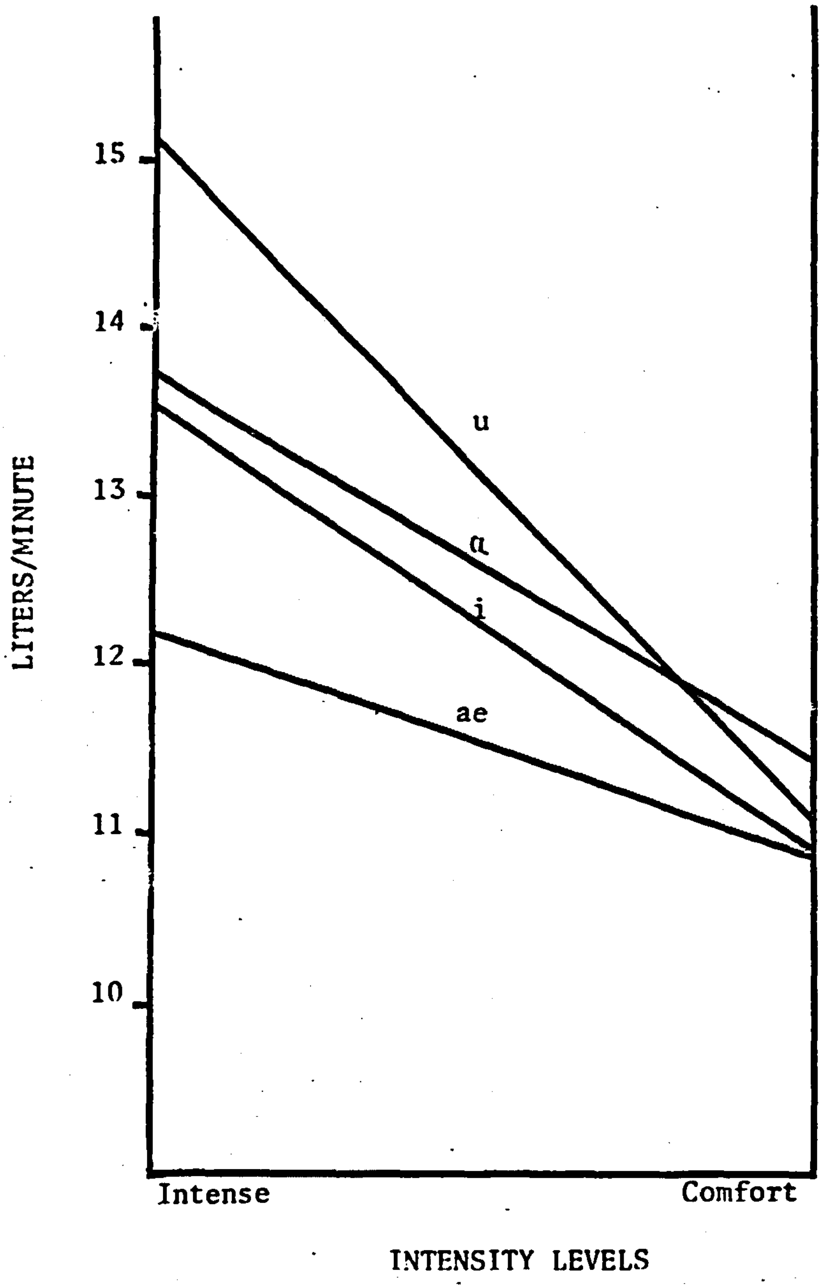

Figure 8.--Oral air flow means for each of the four vowels produced at each of four pitch levels at each of two intensity levels, for twenty male subjects. The means are averaged over the four pitch levels.

intensity. Oral air flow means for the vowels [i] and [ɑ] are relatively less affected, and the vowel [ae] is apparently least influenced, by the changes in vocal intensity.

The Duncan Multiple Range Test was used to locate the significant differences among the vowel means at the two intensity levels. The results of this test are shown in Table 6. Inspection of this table indicates that the mean for the vowel [u] at the Intense Level is significantly greater than the means for the other vowels, regardless of intensity level. The means for [i] and [ɑ] at the Intense Level are significantly greater than the means for all vowels produced at the Comfort Level and that for the vowel [ae] at the Intense Level. Other differences among the vowel means are not significant. It is interesting to note that the mean for the intense production of [ae] is not significantly greater than any of the vowel means at the Comfort Level. These results indicate that the oral air flow means for the vowels [u], [ɑ], and [i] are significantly affected by the increased vocal intensity, while the mean for the vowel [ae] is not significantly affected. Moreover, the previously reported vowel main effect may be attributed primarily to the increased air flow for the vowels [u], [ɑ], and [i] that occurs as a result of increased intensity.

The findings of Fairbanks, House, and Stevens (11) may be relevant in regard to the vowel-by-intensity interaction reported above. These investigators have reported different acoustic power levels for each of the American vowel sounds. The power for each vowel is expressed in terms of its mean intensity level relative to the mean intensity level of the weakest vowel [I], which is assigned a power of 0.0 db. On this scale, [ae] is given a power of 4.5 db, followed by [ɑ], [u], and [i] with powers

TABLE 6.--Duncan Multiple Range Test for differences in oral air flow means for each of the four vowel sounds produced at each of four pitch levels at each of two intensity levels, for twenty male subjects. The means are averaged over the four pitch levels.

a) Shortest Significant Ranges

p:	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Rp:	1.29	1.38	1.42	1.45	1.48	1.50	1.52

b) Results

Vowel-by-Intensity*	[ae]-C	[u]-C	[u]-C	[ɑ]-C	[ae]-I	[i]-I	[ɑ]-I	[u]-I
Means:	10.90	10.91	11.12	11.40	12.10	13.43	13.62	15.15

Note: Any two means not underscored by the same line are significantly different at the .05 level.

Any two means underscored by the same line are not significantly different.

*C=Comfort Level and I=Intense Level

of 3.7 db, 1.9 db, and 1.0 db, respectively. It is of interest that when the same four vowels are ranked according to the difference in mean oral air flow at the Comfort and Intense Levels for each vowel, the rank order is nearly the reverse of the order described above. Thus, the vowel [u] shows the greatest increase in oral air flow as vocal intensity is increased from the Comfort to the Intense Level and is ranked first, followed by [i], [ʊ], and [ae]. One possible explanation for this finding is that the subjects need to exert less physiological effort, and, consequently, utilize less air flow in producing the vowel [ae] than the vowel [u] at the Intense Level due to the greater inherent power of the former sound. It was observed frequently during the course of the experiment that certain subjects experienced difficulty in producing the vowel [u] at the Intense Level but did not exhibit a similar difficulty with the other vowels.

Discussion of Oral Air Flow Results

When comparisons are made between the results of the present investigation and the findings of previous studies relating to oral air flow, there are a number of interesting implications. The present finding that an increase in vowel oral air flow results from an increase in either vocal frequency or intensity is partially at variance with the results of certain studies (28, 34) and in accord with others (35, 41, 22). Roudet (34) and Luchsinger (28) reported an increase in oral air flow as a result of increased intensity but a decrease in air expenditure as pitch level is increased. On the other hand, Russell and Cotton (35) reported a progressive increase in oral air flow as pitch level is increased from approximately 88 cps to 220 cps at both a "normal speech loudness level", and at a "maximum loudness level". Also, Van Hattum (41) reports that the normal subjects in his study used more air at 300 cps than at 200 cps but less air at 90 db SPL than at 75 db SPL.

It is difficult to account for the disagreement among the previously cited studies or, moreover, to explain the differences between the results of certain of these studies and the findings of the present investigation. One possible source of disagreement could derive from the differences in instrumentation used and, consequently, in the types of measurements made in the various studies. A second source of disagreement could originate with the experimental controls of vocal pitch and intensity employed in the different studies. Since many of the earlier studies relied primarily upon subjective methods to control these two variables, a pitch-by-intensity interaction was certainly possible. In this event, the influence of either vocal pitch or intensity would have been obscured. For example, Luchsinger (28) noted an exception to his finding that oral air flow decreased with increased pitch, reporting that low-intensity, low-frequency tones involved less air expenditure than low-intensity, high-frequency tones.

The recent research by Isshiki (22) regarding the regulatory mechanism of vocal intensity variation is also relevant to the interpretation of the present findings. His study was designed to explore the relationship between vowel intensity at different pitch levels and such factors as glottal resistance, glottal efficiency, flow-rate, and subglottic air pressure. He noted that, at low pitch levels, an increase in the intensity of the voice is accompanied by an increase in glottal resistance, while at high pitches increased intensity is accompanied by an increase in flow rate. This prompted him to hypothesize that at low pitch levels the vocal folds are relaxed and the resistance at the glottis is so low that intensity can be increased by increasing glottal resistance. At high pitch levels, however, the glottal resistance is probably near maximum so that further increases in resistance would result in increased vocal fold tension and, consequently, increased pitch. He concludes, therefore, that intensity of the voice at high pitch levels may be controlled by the air flow rate. This speculation is consistent with the findings of the present study.

As previously noted during the discussion of the vowel-by-intensity interaction, the relatively greater increase in vowel air flow for [u] and [i] at the Intense Level may be due to the fact that these vowels have less acoustic power and, therefore, require greater effort in production. It may also be that the area of the mouth opening is an important factor in the determination of vowel intensity. As pointed out by Fairbanks (10), the larger the mouth opening, the greater the transfer of sound energy due to the relatively smaller radiation impedance. Related to this is a consideration of the sources of damping in the vocal tract described by House and Stevens (20), who demonstrated an inverse relationship between the magnitude of the impedance for the vowel and the height of the vowel in a traditional vowel triangle. That is, the greatest impedance was demonstrated for the vowels [i] and [u], while the [ae] and [ɑ] yielded the lowest impedance. These findings suggest that subjects can increase the vocal intensity level of [ae] and [ɑ] with relatively less physiological effort than would accompany a similiar increase for [i] or [u]. Consequently, it might be anticipated that greater air expenditure would occur during the production of [i] and [u] than would occur for [ae] and [ɑ] at more intense levels of production. It is possible that the greater relative increase in air flow for [i] and [u] at the Intense Level found in the present study could be explained on this basis.

Vowel Nasal Air Flow

An apparent shortcoming of previous investigations of air flow during speech has been the absence of data regarding nasal air flow. Such information would appear to be essential to a thorough understanding of breath stream dynamics. In addition, data pertaining to nasal air flow would provide valuable corroborative information for x-ray and cinefluorographic studies of velopharyngeal closure during speech production.

The nasal air flow data were analyzed in the same statistical manner as the corresponding oral air flow data. The main effects in this analysis were vowels, pitch, and intensity. Results of the analysis of variance for nasal air flow are presented in Table 7.

TABLE 7.--Summary of the analysis of variance for the vowel nasal air flow data for twenty male subjects.

Source	df	ms	F
Vowel (V)	3	3.31	3.45*
Intensity (I)	1	1.50	1.56
VI	3	.53	.56
Error A	133	.96	
Pitch (P)	3	.22	1.15
VP	9	.50	2.64*
IP	3	.69	3.65*
VIP	9	.14	.73
Error B	456	.19	

*P≤.05

Inspection of Table 7 indicates that only the vowel main effect, the vowel-by-pitch interaction, and the intensity-by-pitch interaction are significant. Neither the pitch or intensity main effects nor any of the remaining interactions are significant.

Vowel Main Effect

The nasal air flow means for each of the four test vowels, averaged over four pitch and two intensity levels, are presented in Figure 9. A comparison of these means shows that the greatest nasal air flow occurs during the production of [ɑ], followed in order of decreasing flow by [ae], [u], and [i]. Since the analysis of variance presented in Table 7 indicated a significant vowel main effect, the Duncan Multiple Range Test was employed to locate the significant differences among the vowel means. The results of this analysis are presented in Table 8.

Inspection of Table 8 reveals that, when nasal air flow means are averaged over the four pitch levels and both intensity levels, the means for the vowels [i] and [u] do not differ significantly, nor do those for the vowels [ɑ] and [ae]. However, the nasal air flow means for [i] and [u] are shown to be significantly lower than the means for [ɑ] and [ae].

Pitch Main Effect

The analysis of variance summarized in Table 7 indicates that the pitch main effect for nasal air flow is not significant. However, in view of the significant vowel-by-pitch and pitch-by-intensity interactions, the nasal air flow data at the four pitch levels is of interest. The nasal air flow means at each of the four pitch levels studied are shown in Figure 10. The means are averaged over the four vowels and both inten-

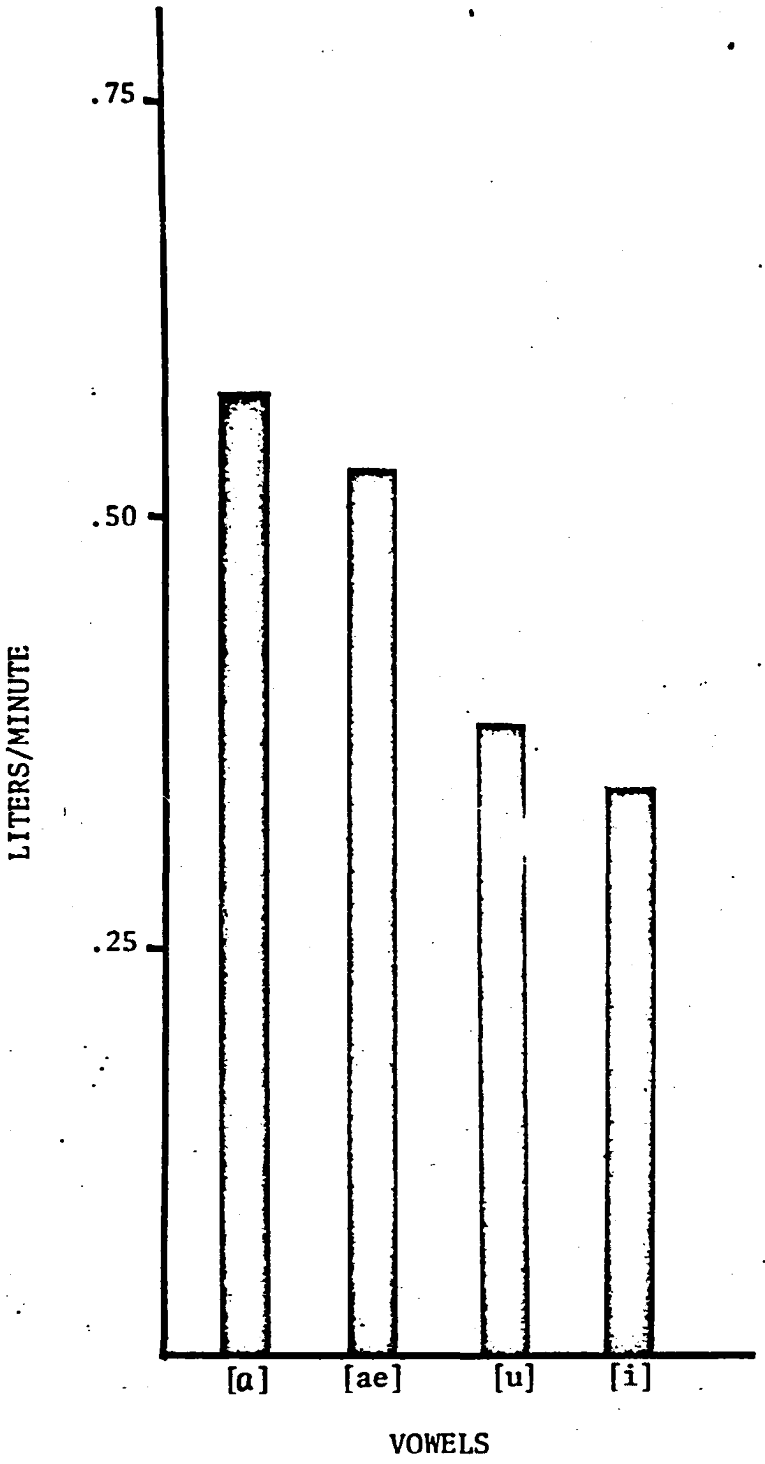

Figure 9.--Nasal air flow means for each of the four vowels produced at each of four pitch levels at each of two intensity levels, for twenty male subjects. The means are averaged over all pitch and intensity levels.

TABLE 8.--Duncan Multiple Range Test for differences in nasal air flow means for each of the four vowel sounds produced at each of four pitch levels at each of two intensity levels, for twenty male subjects. The means are averaged over all pitch and intensity levels.

a) Shortest Significant Ranges

p:	(2)	(3)	(4)
Rp:	2.80	2.95	3.05

b) Results

Vowels:	[i]	[u]	[ae]	[ɑ]
Means:	.32	.36	.53	.56

Note: Any two means not underscored by the same line are significantly different at the .05 level.

Any two means underscored by the same line are not significantly different.

sity levels. Inspection of Figure 10 reveals essentially equal nasal air flow means at Pitch Levels I, II, and IV with a decreased mean at Pitch Level III. A possible explanation for the absence of a pitch main effect is provided by an analysis of the vowel-by-pitch interaction.

Vowel-by-Pitch Interaction

The analysis of variance summarized in Table 7 reveals a significant vowel-by-pitch interaction. Thus, while the pitch main effect is not significant, the presence of this interaction indicates that the vowel nasal air flow means, obtained by averaging over both vocal intensity levels, are not similar at all four pitch levels. To facilitate interpretation of the vowel-by-pitch interaction, the data are presented graphically in Figures 11 and 12.

Inspection of Figure 11 reveals marked differences among the nasal air flow means for each of the four vowels according to pitch level. It may be observed that there is a trend toward decreased nasal air flow with an increase in pitch level for the vowels [i] and [u]. For the vowel [i], the nasal air flow means are .43, .37, .26, and .24 lpm for Pitch Levels I, II, III, and IV, respectively. The nasal air flow means for the vowel [u] are .45, .42, .31, and .25 lpm for Pitch Levels I, II, III, and IV, respectively. The vowels [ɑ] and [ae], on the other hand, fail to exhibit similar trends. For the vowel [ɑ], the nasal air flow means are .61, .52, .54, and .59 lpm for Pitch Levels I, II , III, and VI, in that order. The most divergent nasal air flow means are evident for the vowel [ae]. For this vowel, the means are .42, .54, .47, and .70 lpm at Pitch Levels I, II, III, and IV, respectively.

Inspection of Figure 12 clearly indicates that the vowels [i]

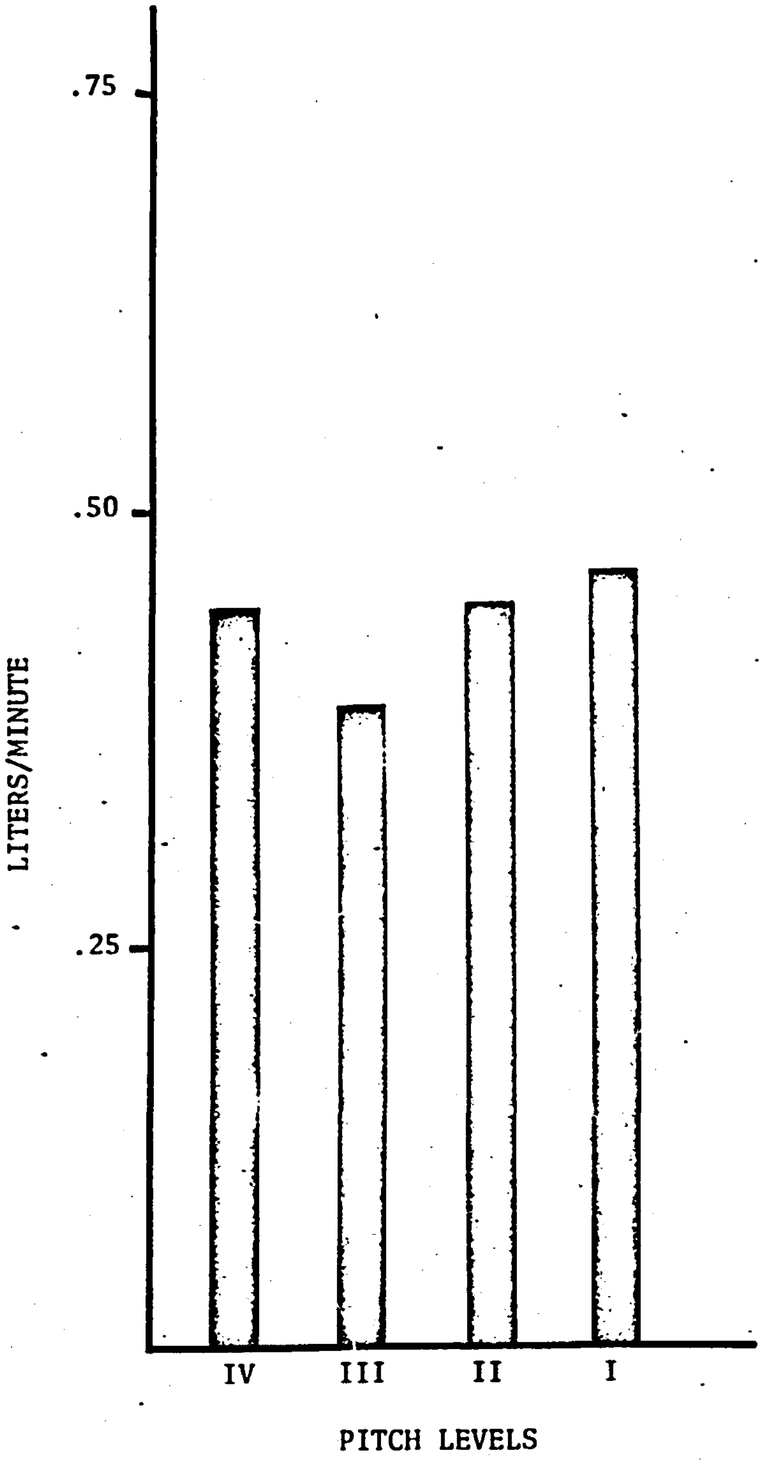

Figure 10.--Nasal air flow means for each of the four vowels produced at each of four pitch levels at each of two intensity levels, for twenty male subjects. The means are averaged over all vowels and intensity levels.

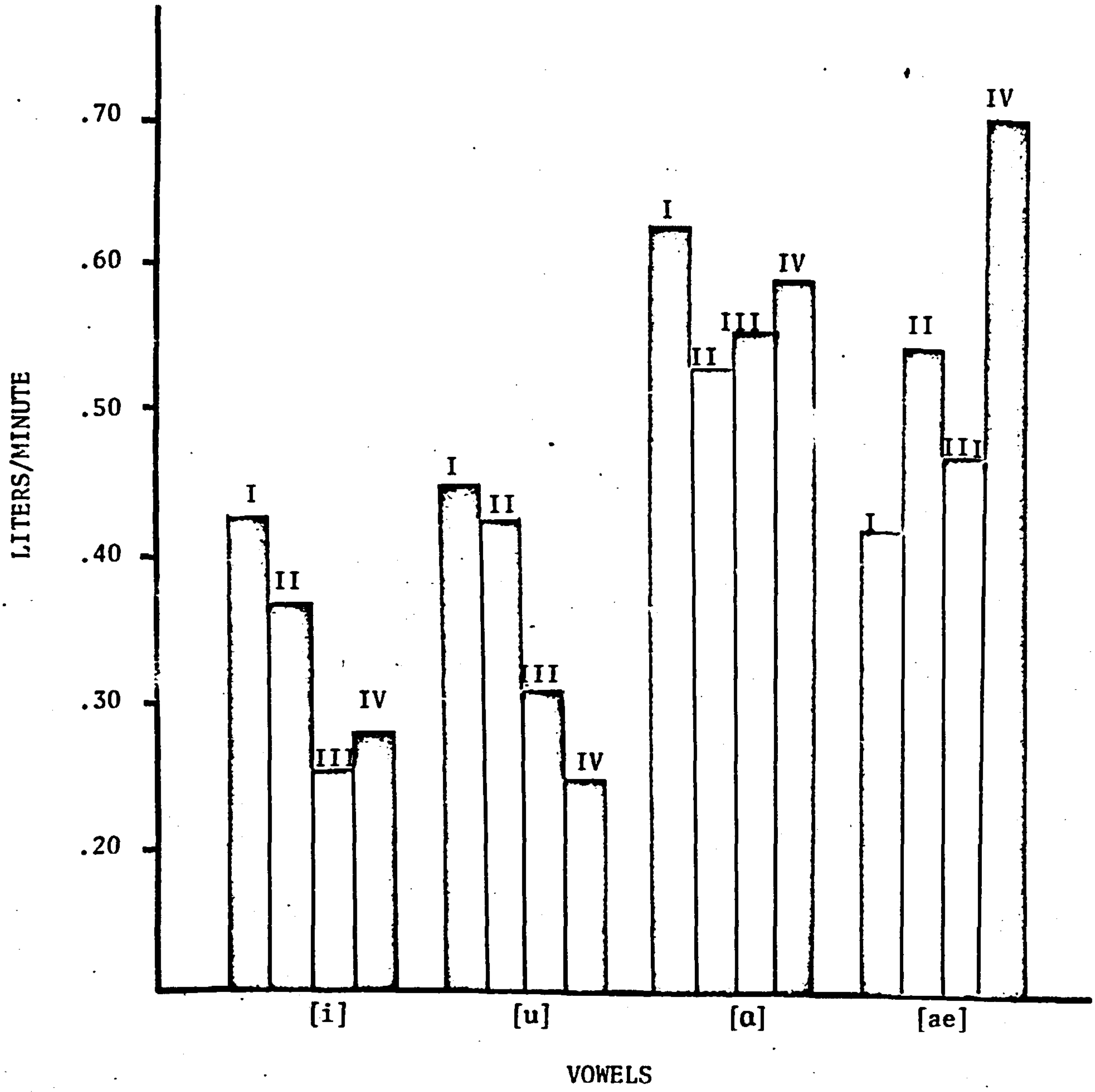

Figure 11.--Nasal air flow means for each of the four vowels produced at each of four pitch levels at each of two intensity levels, for twenty male subjects. The means are averaged over both intensity levels.

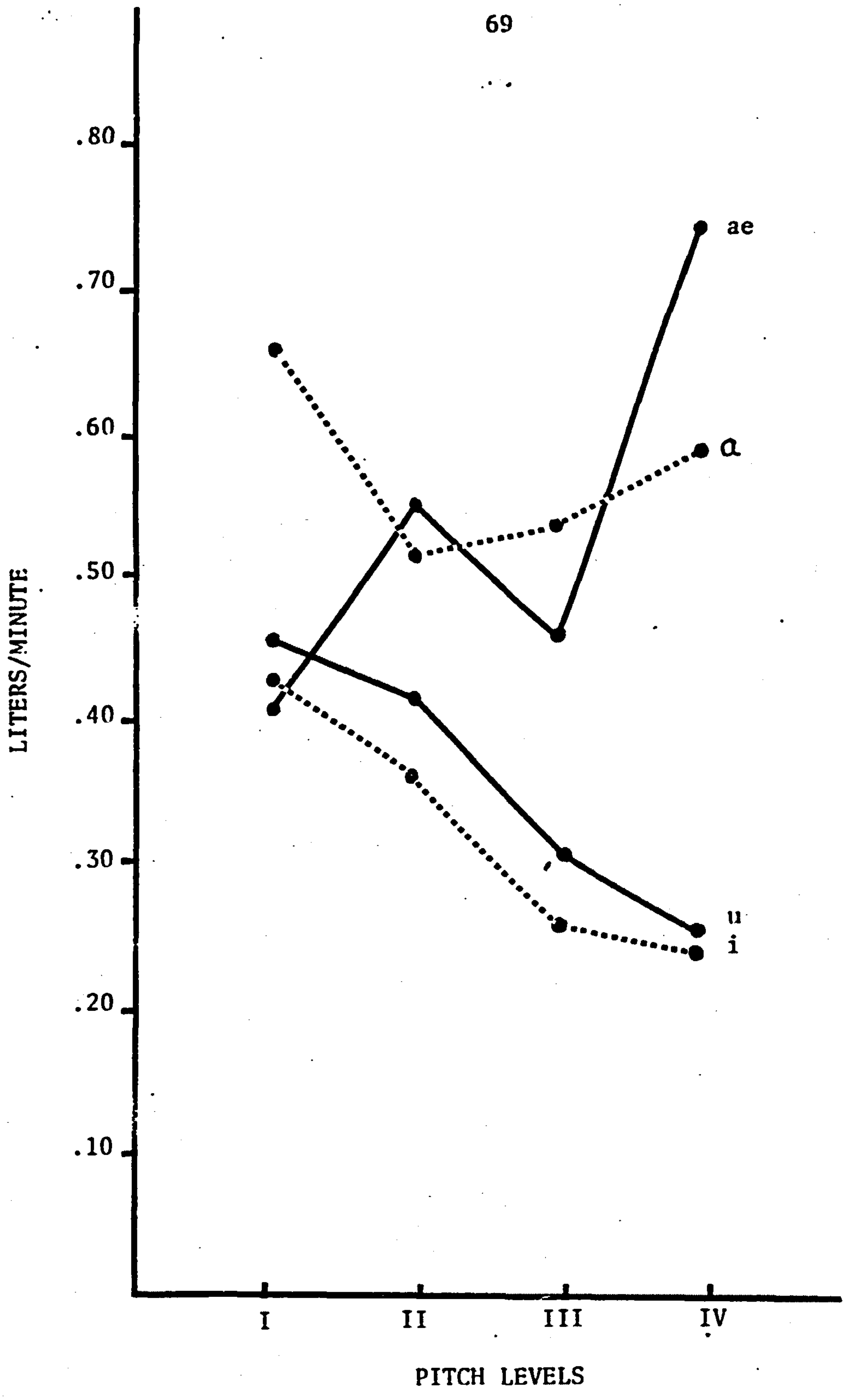

Figure 12.--Nasal air flow means for each of the four vowels produced at each of four pitch levels at each of two intensity levels, for twenty male subjects. The means are averaged over both intensity levels.

and [u] are affected in a similar manner by an increase in the vocal pitch level. The nasal air flow means for these vowels reflect nearly parallel decreases in air flow with an increase in pitch level. The vowel [ɑ], however, exhibits the greatest nasal air flow at Pitch Level I, followed by a decrease at Pitch Level II, and subsequent slight increases in air flow at Pitch Levels III and IV, respectively. At Pitch Level I, the nasal air flow mean for the vowel [ae] is similar to that for the vowels [u] and [i]. At Pitch Level II there is an increase in nasal air flow for [ae], followed by a slight decrease in flow at Pitch Level III, and then a marked increase in nasal air flow for this vowel at Pitch Level IV.

The Duncan Multiple Range Test was employed to locate the significant differences among the vowel means at each pitch level. The results of this analysis are presented in Table 9. Inspection of this table reveals that the mean nasal air flow for the vowel [ae] at Pitch Level IV is significantly greater than the means for the other vowels, regardless of pitch level, with the exception of [ɑ] at all four pitch levels and [ae] at Pitch Level II. The means for [ɑ] at Pitch Level I and IV and [ae] at Pitch Level II are significantly larger than the means for the vowel [i] at Pitch Levels III and IV, and [u] at Pitch Level III. Other differences among the means are not significant. These results suggest that the vowel-by-pitch interaction is primarily due to the differences in nasal air flow means for the vowels [ɑ] and [ae] that result from increases in vocal pitch level. The effect of the vowel-by-pitch interaction on the vowel main-effect will be considered during the discussion of the results regarding vowel nasal air flow, presented in a later section.

TABLE 9.--Duncan Multiple Range Test for differences in nasal air flow means for each of four vowels produced at each of four pitch levels at each of two intensity levels, for twenty male subjects. The means are averaged over both intensity levels.

a) Shortest Significant Ranges

p:	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Rp:	.192	.202	.209	.214	.218	.221	.224

b) Results

Vowel-by-pitch: [i]IV [u]IV [i]III [u]III [i]II [ae]I [u]II

Note: Any two means not underscored by the same line are significantly different at the .05 level.

Any two means underscored by the same line are not significantly different.

TABLE 9.--Continued

(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)
.226	.228	.229	.230	.232	.233	.234	.235

[i]I	[u]I	[ae]III	[ɑ]II	[ɑ]III	[ae]II	[ɑ]IV	[ɑ]I	[ae]IV
.429	.453	.468	.522	.536	.543	.587	.614	.702

Intensity Main Effect

The nasal air flow means for the Comfort and Intense Levels, averaged over the four vowels and four pitch levels, are shown in Figure 13. Inspection of this figure reveals nasal air flow means of .49 and .39 lpm for vowels produced at the Comfort and Intense Levels, respectively. Thus, in contrast to the finding for oral air flow, vowels produced at the Comfort Level exhibited greater nasal air flow than the same vowels produced at the Intense Level. The analysis of variance summary presented in Table 7 indicates that the intensity main effect for nasal air flow is not significant. A consideration of the previously described vowel-by-pitch and of the pitch-by-intensity interaction provides a possible explanation for the absence of a significant intensity main effect for the nasal air flow data.

Pitch-by-Intensity Interaction

The analysis of variance summarized in Table 7 indicates a significant pitch-by-intensity interaction, indicating that the effect of pitch level on nasal air flow is significantly different at the two vocal intensity levels. As previously reported, the significant vowel main effect for nasal air flow is due largely to the influence of increased vocal pitch level on the vowels [ɑ] and [ae]. The significant pitch-by-intensity interaction further indicates that the effect of pitch level on vowel nasal air flow is significantly different at the two vocal intensity levels. The pitch-by-intensity interaction reflects the combined effect of pitch and intensity on the vowel nasal air flow means, when the means are averaged over the four vowels. The means involved in this interaction are presented in Figures 14 and 15. Close inspection of Figure 14 reveals

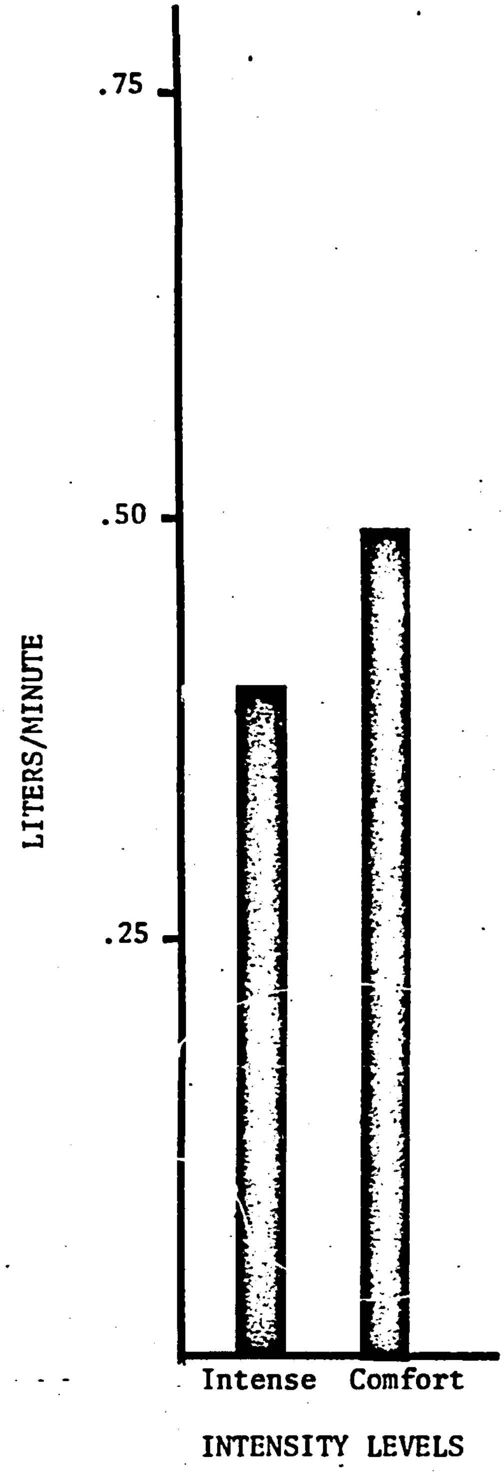

Figure 13.--Nasal air flow means for each of the four vowels produced at each of four pitch levels at each of two intensity levels, for twenty male subjects. The means are averaged over all vowels and pitch levels.

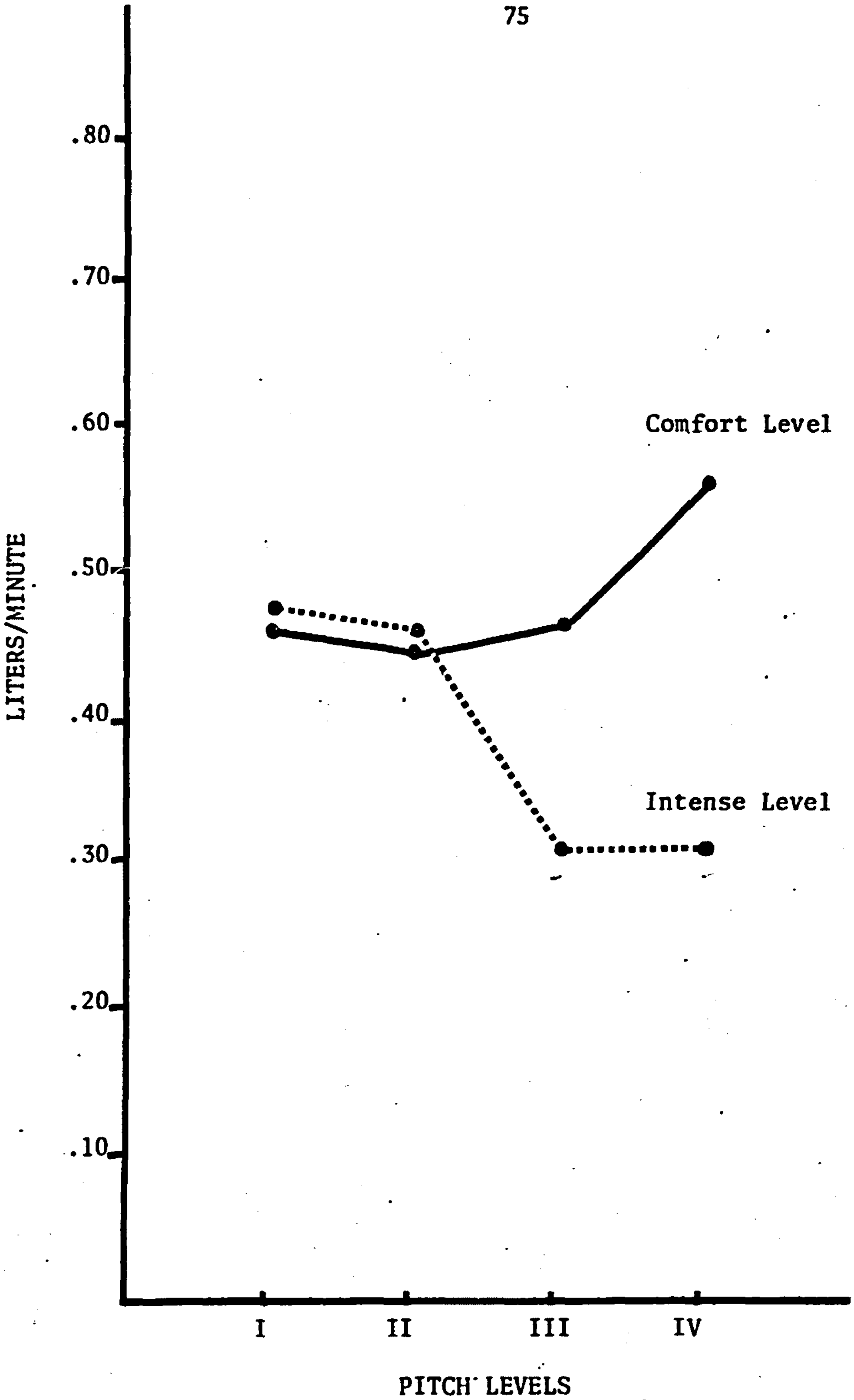

Figure 14.--Nasal air flow means for each of the four vowels produced at each of four pitch levels at each of two intensity levels, for twenty male subjects. The means are averaged over the four vowel sounds.

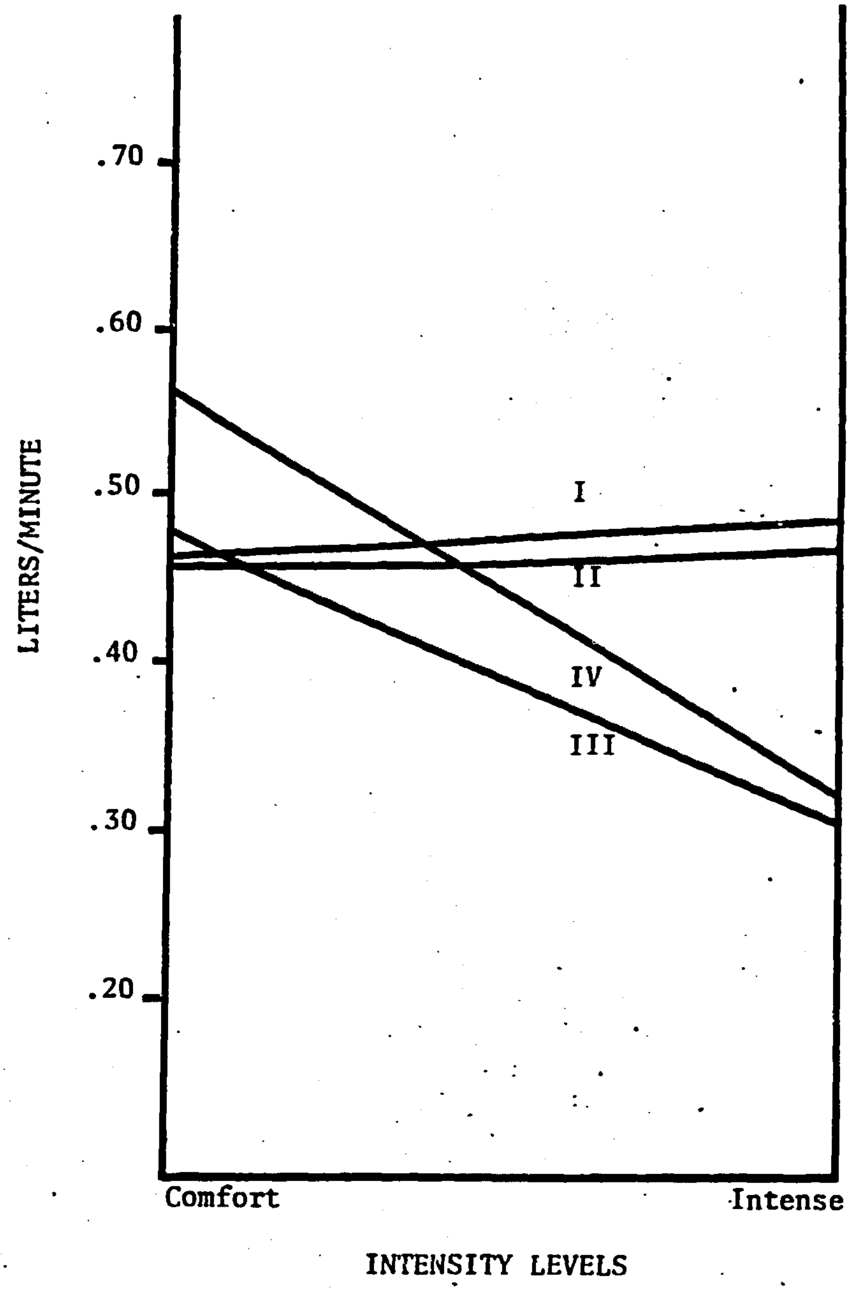

Figure 15.--Nasal air flow means for each of the four vowels produced at each of four pitch levels at each of two intensity levels, for twenty male subjects. The means are averaged over the four vowels.

that at the Comfort Level, nasal air flow remains essentially unchanged for Pitch Levels I, II, and III, followed by an increase in flow of approximately .10 lpm at Pitch Level IV. At the Intense Level, the nasal air flow is essentially equal at Pitch Levels I and II, followed by a sharp decrease of approximately .15 lpm at Pitch Levels III and IV. The laddergram shown in Figure 15 further illustrates the pitch-by-intensity interaction. At Pitch Levels I and II, it may be observed that there is virtually no difference between the nasal air flow means at the Comfort and Intense Levels. At Pitch Levels III and IV, however, decreases in the nasal air flow means are evident at the Intense Level. The Duncan Multiple Range Test was employed to locate the significant differences among the means resulting in the pitch-by-intensity interaction. The results of this analysis are shown in Table 10. Examination of this table reveals significantly smaller nasal air flow means for vowels produced at Pitch Levels III and IV at the Intense Level than for any of the remaining means. All other differences are not significant. These results suggest that the pitch-by-intensity interaction is due primarily to the fact that nasal air flow decreases at Pitch Levels III and IV at the Intense Level, while the flow remains essentially constant for Pitch Levels I and II, regardless of intensity level.

In summary, it has been shown that the vowel main effect for nasal air flow seems to be due primarily to greater air flow means for [ɑ] and [ae] than for [i] and [u]. Furthermore, the vowel-by-pitch interaction suggests that increases in vocal pitch level affects [ɑ] and [ae] in a different manner than [i] and [u]. Finally, the pitch-by-intensity interaction indicates that the effect of increased pitch on vowel nasal air flow is different at different intensity levels.

TABLE 10.--Duncan Multiple Range Test for differences in nasal air flow means for each of four vowel sounds produced at each of four pitch levels at each of two intensity levels, for twenty male subjects. The means are averaged over the vowels.

a) Shortest Significant Ranges

p:	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Rp:	.136	.143	.148	.151	.154	.156	.158

b) Results

Intensity-by-Pitch:*	I-III	I-IV	C-II	I-II	C-I	C-III	I-I	C-IV
Means:	.308	.323	.457	.470	.471	.481	.486	.566

Note: Any two means not underscored by the same line are significantly different at the .05 level.

Any two means underscored by the same line are not significantly different.

*I=Intense Level and C=Comfort Level.

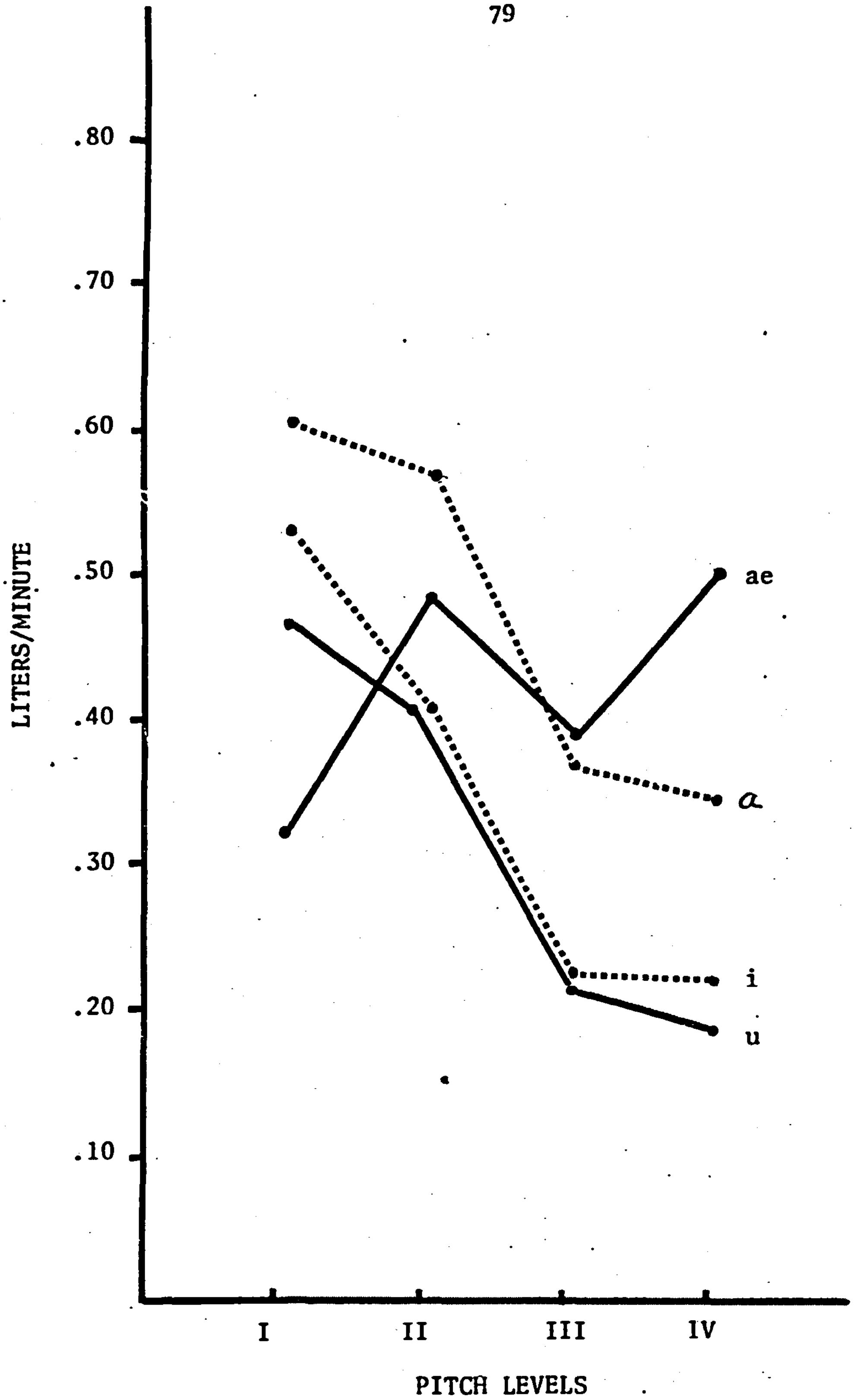

Figure 16.--Nasal air flow means for each of the four vowels produced at each of four pitch levels at the intense level, for twenty male subjects.

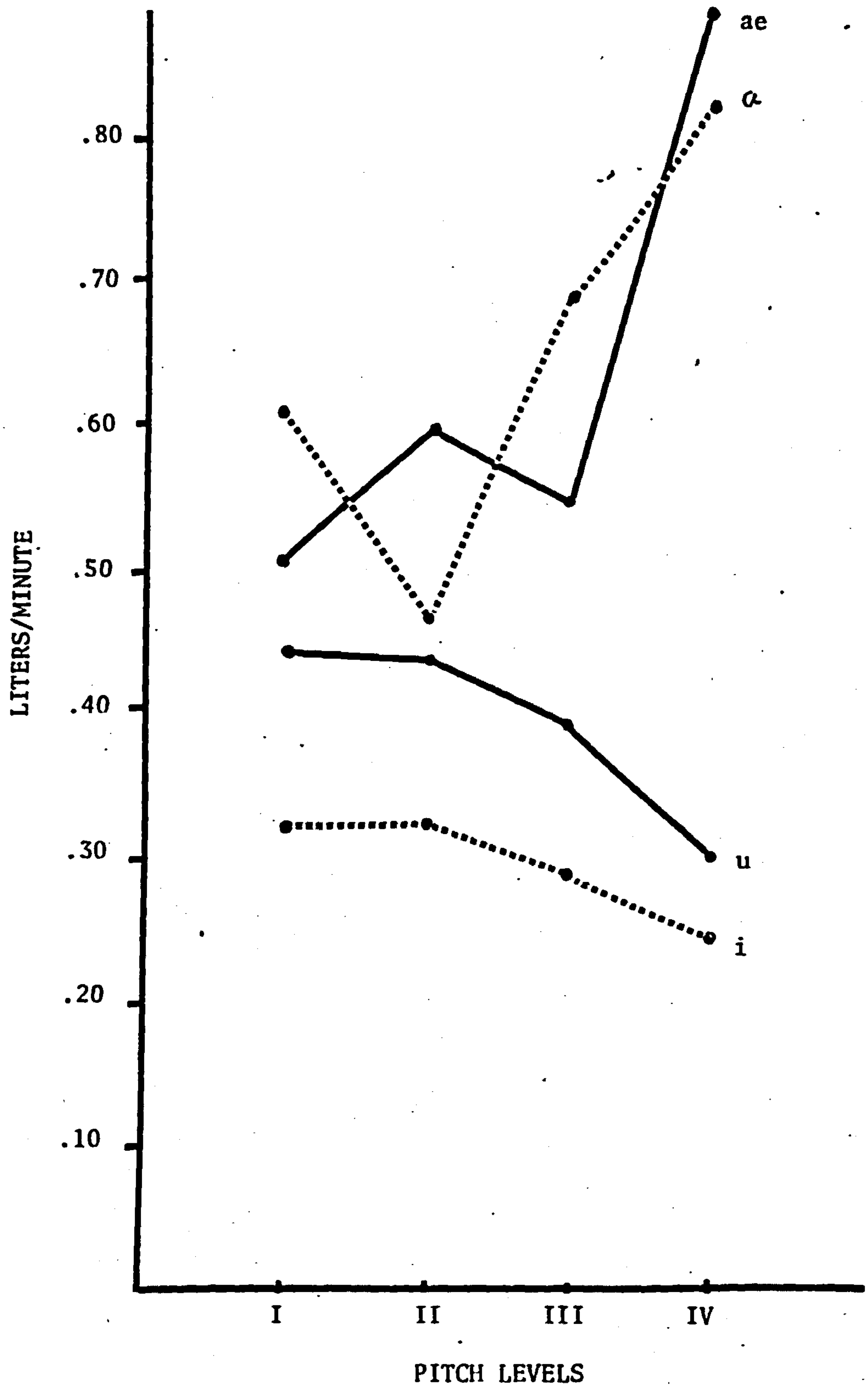

Figure 17.--Nasal air flow means for each of the four vowels produced at each of four pitch levels at the comfort level, for twenty male subjects.

To facilitate an interpretation of these relationships, the vowel nasal air flow means are plotted for each of the four pitch levels at the intense and comfort levels, respectively, in Figures 16 and 17. Inspection of these figures reveals that the vowels [ɑ] and [ae] involve greater air flow than [u] and [i] at all four pitch levels at both intensity levels with the exception of [ae] at Pitch Level I at the Intense Level. Further, the vowels [i] and [u] exhibit a pattern of decreasing nasal air flow with increased pitch. At the Comfort Level, this decrease is small in magnitude and is gradual. At the Intense Level, the decrease is relatively large with a sharp drop in flow from Pitch Level I to Pitch Level III. At the Intense Level, the vowel [ɑ] follows a pattern similar to that noted above for [i] and [u], i.e., a sharp decrease in nasal air flow with increased pitch. At the Comfort Level, however, after a decrease in air flow from Pitch Level I to Pitch Level II, the vowel [ɑ] shows a sharp increase in nasal air flow at Pitch Levels III and IV. For the vowel [ae], there is substantially greater nasal air flow at each pitch level at the Comfort Level than at the Intense Level. It is also interesting to note that at both intensity levels, there is a decrease in nasal air flow at Pitch Level III.

Discussion of Vowel Nasal Air Flow Results

The lack of information in the literature pertaining to vowel nasal air flow limits direct comparison of the present findings with previous research data. However, an interpretation of the results of this study may be made on the basis of related investigations of vowel sounds. First, the present findings indicate that the vowels which cinefluorographic and static x-ray studies have demonstrated to be produced with greater velopharyngeal opening are also characterized by greater nasal air flow. The present finding of greater nasal air flow for [ɑ] and [ae] than for [i] and [u] may also be considered in relation to the previously discussed concept of vowel power. It will be recalled that the present study employed a uniform reference intensity level for all vowel productions. Since the [ɑ] and [ae] are inherently more powerful than [i] and [u], it is conceivable that the subjects employed a greater oral-nasal coupling during production of the former sounds to compensate for their greater inherent power. Oral-nasal coupling, as noted by Cotton (7) and House and Stevens (20), results in a loss of acoustic power. Thus, by utilizing greater coupling, the subjects would be able to reduce the power of [ɑ] and [ae] and maintain the uniform intensity levels. In accord with this interpretation, it would follow that the coupling would be more pronounced at the Comfort Level productions of [ɑ] and [ae] than for productions of these vowels at the Intense Level. The effect of differences in vowel power would be expected to be somewhat minimized at the Intense Level, since a more nearly maximum effort would be required for all vowel productions. At the Comfort Level, however, a relatively greater coupling would be anticipated for [ɑ] and [ae] to compensate for their greater acoustic power. Following the same line of reasoning, the observed decrease in oral-nasal coupling for the relatively weak vowels [i] and [u] could be interpreted as an effort to achieve increased vocal intensity.

On the basis of related research information the greater coupling for the Comfort Level production of [ɑ] and [ae] might be expected to be more pronounced at the higher pitch levels. The results of a number of studies (28, 35, 40) have suggested an increase in sound pressure level with increases in pitch. Therefore, to maintain a uniform intensity level among the four vowels at the higher pitch levels, greater coupling would be expected for [ɑ] and [ae], especially at the Comfort Level. Thus, the present findings regarding nasal air flow for [ɑ] and [ae] may be an artifact of the intensity levels employed in this study. The tendency toward decreased nasal air flow for [i] and [u] at both intensity levels and [ɑ] and [ae] at the Intense Level may be interpreted as resulting from the increased vocal effort associated with phonation at increased pitch and intensity levels. Accordingly, had a more intense production of the vowel [ae] been required, it is possible that a similar tendency would be evident.

Comparison of Oral and Nasal Air Flow Findings

The present section is devoted to a discussion of apparent relationships between the oral and nasal air flow data. The comparisons are not based on statistical analyses and are presented only to point out interesting trends in the data.

The first comparison of interest is the relationship between the mean oral and nasal air flow rates for the four test vowels. When the oral air flow means are averaged over all pitch and intensity levels, the vowel [u] exhibits the greatest oral air flow, followed in order of decreasing flow by [ɑ], [i], and [ae]. The analysis of the oral air flow data indicates that the means for [i], [u], and [ɑ] do not differ significantly. Further, the means for [ae] and [ɑ] are not significantly different but the mean for [ae] is significantly smaller than the means of either [ɑ] or [u]. The nasal air flow means, averaged over all pitch and intensity levels, indicate that the [ɑ] exhibits the greatest nasal air flow, followed closely by [ae] and then by [u] and [i], which show substantially less nasal air flow. The analysis of the nasal air flow data indicates that the means for [ɑ] and [ae] are not significantly different, nor are the means for [i] and [u]. However, the means for the [ɑ] and [ae] are significantly greater than the means for [u] and [i].

These results suggest that the oral and nasal air flow means vary in a different manner for the four vowels. It is of interest to note that the smallest oral air flow mean is evident for the vowel [ae], which is considered the most powerful vowel acoustically. The nasal air flow mean for this vowel is relatively large. Conversely, the vowel [u], which is a much weaker vowel acoustically, exhibits a large oral air flow mean but a negligible nasal air flow mean. This comparison again suggests the possibility of a systematic variation in oral-nasal coupling which is related to the acoustic power of the vowel being produced.

The second comparison of interest is between the oral and nasal air flow means at the four pitch levels studied. When the oral air flow means are averaged over the four vowels and two intensity levels, Pitch Level IV exhibits the largest mean air flow followed by Pitch Level III, II, and I, in order of decreasing flow. The analysis of the oral air flow data indicates a significant difference among the air flow means for all pitch levels, revealing a progressive increase in oral air flow as pitch level is increased. The absence of a vowel-by-pitch interaction indicates that the increase in oral air flow with increases in pitch is evident regardless of the vowel being produced or the intensity level employed. The nasal air flow means, averaged over all vowels and both intensity levels, are essentially equal at Pitch Levels I, II, and IV, with a slight decrease in mean flow at Pitch Level III. Analysis of the nasal air flow data indicates that the differences in means at the various pitch levels is not significant. However, the presence of a significant vowel-by-pitch interaction indicates that the four vowels are not similarly affected by pitch changes. The vowel-by-pitch interaction indicates that the nasal air flow means for [i] and [u] are similar, reflecting nearly parallel decreases in air flow with increases in pitch level. The vowel [ɑ] exhibits the greatest nasal air flow at Pitch Level I, followed by decreased flow at Pitch Level II, and subsequent slight increases in flow at Pitch Levels III and IV, respectively. The nasal air flow mean for [ae] is similar to the means of [u] and [i] at Pitch Level I. At Pitch Level II, there is an increase in flow, followed by a slight decrease in flow at Pitch Level III, and then a marked increase in nasal air flow for [ae] at Pitch Level IV.

The results reveal that, while there is a progressive increase in oral air flow for all the test vowels as pitch level is increased, the nasal air flow means at the four pitch levels vary according to the vowel being produced. Thus, the vowels [i] and [u] exhibit a progressive decrease in nasal air flow as the pitch level is increased. The nasal air flow means for the vowels [ɑ] and [ae] tend generally to increase with an increase in pitch level although this trend is not consistent at all pitch levels.

The final comparison of interest is between the oral and nasal air flow means at the two vocal intensity levels. When the oral air flow means are averaged over the four vowels and four pitch levels, the Intense Level productions show the greater mean. The analysis of the oral air flow data indicates that the greater air flow mean at the Intense Level is significant. However, this result must be interpreted in relation to a significant vowel-by-intensity interaction. An analysis of the data involved in this interaction reveals that the mean for the Intense Level produccion of the vowel [u] is significantly greater than the means for the other vowels, regardless of intensity level. Further, the means for the Intense Level productions of [i] and [ɑ] were significantly greater than the means for all vowels produced at the Comfort Level and the mean for [ae] produced at the Intense Level. Thus, the oral air flow means for the vowels [u], [ɑ], and [i] appear to be significantly affected by increased vocal intensity, while the vowel [ae] is not.

Analysis of the nasal air flow means reveal that the difference between the flow at the Comfort Level and the flow at the Intense Level is not significant. However, the presence of a significant pitch-by-intensity interaction indicates that the effect of intensity level on nasal air flow differs according to the pitch level. Analysis of the data involved in the interaction reveals that at Pitch Levels I and II there is virtually no difference between the nasal air flow means at the Comfort and Intense Levels. At Pitch Levels III and IV, however, there is a significant decrease in nasal air flow at the Intense Level.

CHAPTER V

SUMMARY AND CONCLUSIONS

The purpose of this study was to investigate the volume rates of oral and nasal air flow expended during the production of four vowel sounds and to determine the effects of increased vocal pitch and intensity on these flow rates. Twenty normal-speaking adult males with fundamental vocal frequencies of approximately 145 cps, as determined by spectrographic analysis, served as subjects. Since the experimental task required the ability to sing an ascending musical scale while maintaining a relatively constant vocal intensity, it was necessary to select trained singers or persons who had received voice training. To avoid possible air flow variations due to physiological factors associated with age, young adults were chosen. Moreover, testing was deferred for persons presenting current upper respiratory infections, allergy conditions, or similar disorders which could interfere with normal air flow during speech.

Each subject sang an ascending musical scale using each of four test vowels, [i], [u], [ae], and [ɑ], at both a predetermined comfort level and at a level approximately 6 db more intense. The subject was instructed to begin phonation of each vowel at his natural pitch level. Each vowel production was sustained for approximately three seconds, as monitored by means of a signal light, and the subject took a breath following each vowel production. The instruction to breathe between each vowel production was used to avoid a possible difference in air flow at successive pitch levels that might result from diminished breath supply. To insure that the subjects achieved the desired pitch levels, all productions were tape recorded simultaneously with the recording of the air flow measurements. These tape recorded vowel productions were subsequently analyzed spectrographically for determination of fundamental vocal frequency. The sound spectrograph was also employed to control for vocal intensity. Each subject monitored the intensity of his phonation by maintaining the VU-meter needle of the sound spectrograph at a zero reading. The spectrograph attenuator was preset to deflect to a zero reading at a predetermined reference intensity level. To minimize any order effect that might occur as a result of having all subjects begin phonation at the same intensity level, the intensity level order was counterbalanced among subjects. Similarly, the order of the vowel presentations was randomized.

All data were collected with the subjects seated in a standard dental examination chair which could be adjusted to individual differences in sitting height. A pneumoanemometer assembly consisting of two pneumoanemometer units and an associated face mask was utilized in data collection. The pneumoanemometer measures volume rate of air flow by recording voltage changes in an electrically heated sensing wire. The anemometer sensing elements are contained in an open-ended metal tube which projects from the mask. This tube and the face mask are separated by a horizontal partition which serves to direct the oral air flow past one sensing element and the nasal air flow past another. Each sensing element was connected to a different pneumoanemometer unit, permitting separate and simultaneous transduction of oral and nasal air flow into continuous voltage analogs. These analogs were recorded by means of a dual-channel chart recorder and provided a graphic record of the oral and nasal air flow for each test vowel at the various pitch and intensity levels employed. Oral and nasal air flow measurements were obtained for each test vowel, [i], [u], [ae], and [ɑ], at pitch levels corresponding (± 5 cps) to fundamental vocal frequencies of 145, 175, 220, and 260 cps, at each of two intensity levels employed in the study. The measurements were made in terms of millimeters of stylus deflection at the beginning, middle, and end of the middle .75-second segment of each three-second vowel record. These measurements were processed by an electronic computer which was programed to convert from millimeters of stylus deflection to pneumo-anemometer voltage equivalents and then to mean volume rates of oral and nasal air flow in accordance with a previously described mathematical calibration curve for each unit.

The data were analyzed by means of an analysis of variance with a factorial arrangement of treatments. The alpha level was set at .05. To locate significant differences revealed by the analysis of variance, the Duncan Multiple Range Test was employed.

In the presentation of findings, the predetermined uniform intensity level that was found to be comfortable for all subjects was referred to as the "Comfort Level" and the level which was approximately six decibels more intense as the "Intense Level". Also, the pitch levels corresponding to the fundamental vocal frequencies 145, 175, 220, and 260 were referred to as Pitch Levels I, II, III, IV, respectively.

Oral and Nasal Air Flow Differences Among the Four Vowels

The initial research question posed in the present study was: How do the vowels [i], [u], [ae], and [ɑ] differ with respect to mean volume rates of oral air flow and simultaneously measured mean volume rates of nasal air flow? The statistical analyses relevant to this question were the vowel main effects and the associated Duncan Multiple Range Tests.

With regard to oral air flow, when the means were averaged over the four pitch levels and both intensity levels, the vowel [u] exhibited the greatest air flow, followed in order of decreasing flow by [ɑ], [i], and [ae]. The analysis of the vowel main effect revealed that the oral air flow means for the vowels [u], [ɑ], and [i] did not differ significantly. The means for [ae] and [i] were not significantly different, but the mean for the vowel [ae] was smaller than the means for either [ɑ] or [u]. A possible explanation for the relatively small mean oral air flow associated with the vowel [ae] could be related to the acoustic power of this phoneme. Since [ae] is the most powerful vowel acoustically, it may be that less physiological effort is required in production and that, consequently, less air flow is expended.

With regard to nasal air flow, when the means were averaged over the four pitch levels and both intensity levels, the vowel [ɑ] exhibited the greatest nasal air flow, followed in order of decreasing flow by [ae], [u], and [i]. The analysis of the vowel main effect revealed that the nasal air flow means for the vowels [ɑ] and [ae] were not significantly different, nor were the means for the vowels [i] and [u]. However, the means for the [ɑ] and [ae] were significantly greater than the means for

[i] and [u]. Hence, the vowels which are inherently more powerful acoustically and which cinefluorographic and static X—ray studies have shown to exhibit greater oral-nasal coupling also involved greater nasal air flow. It was suggested that the subjects may have used greater oral-nasal coupling to compensate for the greater acoustic power of [ɑ] and [ae]. The result of increased coupling, as demonstrated by House and Stevens (20), is a loss of acoustic power. Since the present study utilized a uniform intensity level for all vowel productions, it is possible that the subjects utilized greater oral-nasal coupling in production of [ɑ] and [ae] to maintain the intensity levels used in this experiment.

These results indicated that the oral and nasal air flow means varied in a different manner for the four test vowels. On the basis of a comparison of the oral and nasal air flow means for each of the vowels studied, it was suggested that a possible systematic variation in oral-nasal coupling occurred during production of the vowels which may, in part, be related to the acoustic power of the vowel being produced. Thus, for the vowel [ae] the smallest oral air flow was evident, whereas, the nasal air flow mean for this vowel was large. Conversely, the vowel [u] exhibited a large oral air flow mean but a negligible nasal air flow mean.

Effect of Increased Vocal Pitch on Vowel Oral and Nasal Air Flow

The second research question posed in the present study was: What is the effect of increased vocal pitch on the mean volume rates of oral air flow and simultaneously measured mean volume rates of nasal air flow for the vowels? The statistical analyses relevant to this question were the pitch main effect, the vowel-by-pitch interaction, and the associated Duncan Multiple Range Tests.

With regard to oral air flow, when the means were averaged over the four vowels and two intensity levels, Pitch Level IV exhibited the largest air flow mean followed by Pitch Levels III, II, and I, in order of decreasing flow. The analysis of the pitch main effect revealed a significant difference among the air flow means for all pitch levels, thus indicating a progressive increase in oral air flow as pitch level was increased. Moreover, the absence of a vowel-by-pitch interaction indicated that the increase in oral air flow with increases in vocal pitch was present irrespective of the vowel being produced.

With regard to nasal air flow, when the means were averaged over the four vowels and two intensity levels, the nasal air flow means at the four pitch levels were essentially equal. The analysis of the pitch main effect revealed that the differences among the means at the four pitch levels were not significant. The presence of a significant vowel-by-pitch interaction, however, indicated that the four vowels were not similarly affected by increased pitch. The analysis of the vowel-by-pitch interaction revealed that the nasal air flow means for the vowels [i] and [u] reflected nearly parallel decreases in air flow with increased pitch. The vowel [ɑ] exhibited its greatest nasal air flow mean at Pitch Level I, followed by a marked decrease at Pitch Level II and subsequent small increases at Pitch Levels III and IV. The most divergent nasal air flow means were evident for the vowel [ae]. At Pitch Level I the mean air flow for this vowel was not significantly different from the means for the vowels [i] and [u]. At Pitch Level II there was an increase in nasal air flow, followed by a small decrease in flow at Pitch Level III, and then a marked increase in flow at Pitch Level IV.

These results indicated that, while there was a progressive increase in oral air flow for all test vowels as pitch level was increased, the nasal air flow means at the four pitch levels varied according to the vowel being produced. Thus the vowels [i] and [u] exhibited a progressive decrease in nasal air flow as pitch was increased, whereas, the vowels [ɑ] and [ae] revealed divergent patterns.

Effect of Increased Vocal Intensity on Vowel Oral and Nasal Air Flow

The third research question posed in the present study was: What is the effect of increased vocal intensity on the mean volume rates of oral air flow and simultaneously measured mean volume rates of nasal air flow for the vowels? The statistical analyses relevant to this question were the intensity main effect, the vowel-by-intensity interaction, and the associated Duncan Multiple Range Tests.

With respect to oral air flow, the presence of a significant intensity main effect indicated that when the oral air flow means were averaged over the four vowel sounds and the four pitch levels, the mean for the Intense Level production was significantly larger than the mean for the Comfort Level production.

The presence of a significant vowel-by-intensity interaction indicated that the effect of intensity level on oral air flow varied according to the vowel being produced. Analysis of the data for the vowel-by-intensity interaction revealed that the oral air flow means for the vowel [u] at the Intense Level were significantly greater than the means for the other vowels, regardless of intensity level. The means for the vowels [i] and [ɑ] at the Intense Level were significantly greater than the means for all vowel productions at the Comfort Level and greater than the mean for [ae] at the Intense Level. Other differences among the vowel means were not significant. These results indicated that the oral air flow means for the vowels [u], [ɑ], and [i] are significantly affected by increased vocal intensity, while the mean for [ae] is not. The vowel-by-intensity interaction was viewed in relation to the previously mentioned concept of vowel power. It was noted that, when the four vowel sounds were ranked on the basis of the difference in mean air flow between the Comfort Level productions and the Intense Level productions, the rank order was nearly opposite that which would obtain if the same vowels were ranked according to their inherent acoustic power. Thus, the smallest difference in oral air flow between the Comfort and Intense Level productions was observed for the vowel [ae], which is the most powerful vowel acoustically. Conversely, the greatest difference in air flow between the Comfort and Intense Level productions occurred for the vowel [u], the weakest vowel used in this study. A possible explanation of this finding is that the subjects could increase the intensity level of [ae] with relatively less physiological effort than would accompany a similar increase for [u]. Consequently, greater air expenditure might be expected to occur during the production of [u] at a given intensity level than for [ae] at the same level.

With regard to nasal air flow, the intensity main effect was not significant. Therefore, this experiment did not demonstrate that increased intensity, per se, differentially affected nasal air flow for the four vowels as a group. Moreover, the absence of a significant vowel-by-intensity interaction indicated that the differences between the individual vowel means at the Comfort and Intense Levels were similar. The presence of a significant pitch-by-intensity interaction, however, indicated that the effect of pitch level on nasal air flow is significantly different at the two vocal intensity levels. This interaction was analyzed in the final research question posed in this study.

Combined Effect of Increased Vocal Pitch and Intensity on Vowel Oral and Nasal Air Flow

The final research question posed in the present study was: What is the combined effect of increased vocal pitch and intensity on the mean volume rates of oral air flow and simultaneously measured mean volume rates of nasal air flow for the vowels? The statistical analyses relevant to this question consisted of the pitch-by-intensity interaction and the associated Duncan Multiple Range Tests.

The pitch-by-intensity interaction reflects the combined effect of pitch and intensity on air flow, when the means are averaged over the four vowel sounds. With regard to oral air flow, this interaction was not significant. This indicated that the effect of increased vocal pitch on oral air flow was similar at the Comfort and Intense Levels, or, that oral air flow at the Comfort and Intense Levels was affected in a similar manner by increases in vocal pitch level. Thus, the previously discussed tendency toward a progressive increase in oral air flow with increases in vocal pitch was evident at both the Comfort and Intense Levels.

With respect to nasal air flow, the presence of a significant pitch-by-intensity interaction indicated that the effect of increased pitch on nasal air flow was significantly different at the two vocal intensity levels. Analysis of the data involved in the interaction revealed that at Pitch Levels I and II there was virtually no difference between the nasal air flow means at the Comfort and Intense Levels. At Pitch

Levels III and IV, the air flow for the Comfort Level productions did not change significantly; however, at the Intense Level there was a significant decrease in nasal air flow at these pitch levels. All other differences were not significant, indicating that the pitch-by-intensity interaction was due primarily to the decrease in nasal air flow at Pitch Levels III and IV at the Intense Level.

Within the limitations of the design of the experiment, the present findings appear to warrant the following conclusions:

1. When oral air flow means are averaged over the four pitch and two intensity levels employed in the present study, significantly smaller flow occurs for the vowel [ae] than for the vowels [i] and [ɑ].

2. When nasal air flow means are averaged over the four pitch and two intensity levels employed in the present study, significantly greater nasal air flow occurs for the vowels [ɑ] and [ae] than for [i] and [u].

3. When oral air flow means are averaged over all vowels and the two intensity levels used in this study, there is a progressive and significant increase in flow with an increase in pitch level.

4. When nasal air flow means are averaged over all vowels and the two intensity levels studied, there is not a significant difference in air flow at the four pitch levels.

5. When oral air flow means are averaged over the four pitch levels, there is a significantly greater flow for the vowels [i], [u], and [ɑ] at the Intense Level than at the Comfort Level. Oral air flows for the vowel [ae] at the Intense and Comfort Levels are not significantly different.

6. When nasal air flow means are averaged over the four pitch levels, there is not a significant difference among the flows for the vowels studied at the Comfort and Intense Levels.

7. The effect of increased pitch on oral air flow is similar for the two intensity levels employed. A tendency toward progressive increased oral air flow with increased pitch is evident at both the Comfort and Intense Levels.

8. The effect of increased pitch on nasal air flow is significantly different at the two intensity levels. This difference is evidenced in a significant decrease in flow for Pitch Levels III and IV at the Intense Level.

Possible Sources of Error

Certain possible sources of experimental error should be considered in the interpretation of the present findings. One of these is related to the calibration procedure. It is possible that a discrepancy existed between the temperature of the air used in calibrating the pneumo-anemometer and the air expended during the experimental condition. Since the anemometer is a temperature sensitive instrument, the extent of the error would be related directly to the difference in air temperature for the two conditions. The air flow readings would be in error by one per cent for each six degrees of error in the temperature difference. It should be noted, however, that the present measurements are in close agreement with pneumotachographic measurements of air flow obtained recently by Isshiki (22). Moreover, such an error would have been constant and if the measurements obtained did not reflect accurately the absolute volume of air expended, they would reflect valid relative measurements. Also, errors associated with reading the air volume meter utilized in the calibration procedure were possible. Since readings were made with the meter indicator in motion, precise measurements were not assured. However, the similarity between calibration readings obtained before, during, and at the conclusion of the experiment suggest that this error was not great.

A second possible source of experimental error was associated with data collection. First, since the face mask could not be adjusted to fit individual facial contours, it was difficult to insure that small quantities of air did not escape around the rim of the face mask during data collection. However, extreme care was taken in adjusting the face mask and varying facial contours were closely approximated by means of the inflatable pneumatic rubber rim. Also, the fact that the face mask was stabilized during data collection minimized the possibility of developing air leaks due to changes in head positioning. Another problem associated with the face mask was the pressure exerted upon the upper lip by the oral-nasal partition. To insure an airtight seal between the oral and nasal sections of the mask, appreciable force was exerted at the juncture of the upper lip and the floor of the nose. It is possible that this pressure adversely affected the ability of the subjects to produce sounds in a "normal" manner.

It should also be pointed out that a difference existed between the angle of admission of the nasal air flow to the sensing wire under the calibration and experimental conditions. In the calibration procedure, air entered the oral and nasal sections of the tube containing the sensing units at a 0° angle of incidence. Under the experimental condition, the air flow from the nose was directed downward and presumably entered the nasal section of the tube at an angle. It would be anticipated that this may result in unusual air currents within the sensing tube. The effect of such currents on the accuracy of nasal air flow measurements is unknown.

BIBLIOGRAPHY

1. Benson, A. F. "Respirometric Study of the Effect of Postural Changes on Lung Function and Air Flow During Speech of Eight-Year-Old Boys." Unpublished Master's thesis, University of Iowa, 1961.

2. Benson, J. "An Experimental Study of the Relationship Between the Amount of Nasal Emission of Air and Judged Nasality." Unpublished Master's thesis, West Virginia University, 1951.

3. Black, J. W. The Pressure Component in the Production of Consonants. JSHD, 1950, 15.

4. Bullen, A. Nasality: Cause and Remedy of Our American Blight. Quarterly Journal of Speech, 1942, 28.

5. Bzoch, K. R. "An Investigation of the Speech of Preschool Cleft Palate Children." PhD dissertation, Northwestern University, 1956.

6. Carrell, J. A Cinefluorographic Technique for the Study of Velopharyngeal Closure. JSHD, 1952, 17.

7. Cotton, J. C. A Study of Certain Phoniatric Resonance Phenomena. JSD, 1940, 5.

8. Counihan, D. T. "A Clinical Study of the Speech Efficiency and Structural Adequacy of Operated Adolescent and Adult Cleft Palate Persons." PhD dissertation, Northwestern University, 1956.

9. Curry, R. O. L. The Mechanism of the Human Voice. New York: Longmans, Green and Co., 1940.

10. Fairbanks, G. A. A Physiological Correlative of Vowel Intensity. Speech Monogr., 1950, 17.

11. Fairbanks, G. A., House, A. B., and Stevens, E. L. An Experimental Study of Vowel Intensities. JASA, 1950, 22.

12. Farnsworth, D. W. High-Speed Motion Pictures of the Human Vocal Cords. Bell Labs. Rec., 1940, 18.

13. Flanagan, J. L. Some Properties of the Glottal Sound Source. JSHR, 1958, 1.

14. Fletcher, W. [illegible]. "A Study of Internal Laryngeal Activity in Relation to Vocal Intensity." PhD dissertation, Northwestern Univ., 1950.

15. Goddard, L. A. 'Normative Study of Oral Breath Pressure in Children." Unpublished Master's thesis, Univ., of Iowa, 1959.

16. Gray, G. W. Studies in Experimental Phonetics. Baton Rouge: Lousiana State Univ. Press, 1936.

17. Gray, G. W. and Wise, C. M. The Basis of Speech. 3rd ed. New York: Harper and Brothers, 1959.

18. Gutzmann, H. Physiologie der Stimme und Sprache. Braunschweig: Vieweg und Sohn, 1909.

19. Hardy, J. C. Intraoral Breath Pressure In Cerebral Palsy. JSHD. 1961, 26.

20. House, A. S. and Stevens, K. N. Analog Studies of the Nasalization of Vowels. JSHD, 1956, 21.

21. Idol, H. R. A Statistical Study of Respiration in Relation to Speech Characteristics. Studies in Experimental Phonetics. Edited by G. W. Gray. Baton Rouge: Lousiana State Univ. Press, 1936.

22. Isshiki, N. Regulatory Mechanism of Voice Intensity Variation. JSHR, 1964, 7.

23. Johnson, W., Darley, F. L. and Spriestersbach, D. C. Diagnostic Manual in Speech Correction. New York: Harper, 1952.

24. Judson, L. S. and Weaver, A. T. Voice Science. New York: F. S. Crofts and Company, 1942.

25. Kantner, C. E. Four Devices in the Treatment of Rhinolalia Aperta. JSD, 1937, 2.

26. Kelly, J. P. Studies in Nasality. Archives of Speech, 1934, 1.

27. Lintz, L. B. and Sherman, D. Phonetic Elements and Perception of Nasality. JSHR, 1961, 4.

28. Luchsinger, R. Phonetics and Pathology. Manual of Phonetics. edited by L. Kaiser. Amsterdam: North Holland Publishing Company, 1957.

29. McIntosh, C. W. "An Auditory Study of Nasality." Unpublished Master's thesis, State University of Iowa, 1937.

30. Moll, K. L. Cinefluorographic Techniques in Speech Research. JSHR, 1960, 3.

31. ______________________ Velopharyngeal Closure on Vowels. JSHR, 1962, 5.

32. Nusbaum, E. A., Foley, L., and Wells, C. Experimental Studies of the Firmness of Velopharyngeal Occlusion During the Production of English Vowels. Speech Monographs, 1935, 2.

33. Potter, R. K., et. al. Visible Speech. New York: D. Van Nostrand Company, Inc., 1947.

34. Roudet, L. De La Despence D' Air Dans La Parole Et De Ses Consequences Phonetiques. La Parole, 1900, 2.

35. Russell, G. O. and Cotton, J. C. Causes of Good and Bad Voices. National Research Foundation, undated.

36. Sallee, W. H. An Objective Study of Respiration in Relation to Audibility in Connected Speech. Studies in Experimental Phonetics. Edited by G. W. Gray. Baton Rouge: La. State Univ. Press, 1936.

37. Spriestersbach, D. C., and Powers, G. R. Articulation Skills, Velopharyngeal Closure, and Oral Breath Pressure of Children with Cleft Palates. JSHR, 1959, 2.

38. ________________________________ Nasality in Isolated Vowels and Connected Speech of Cleft Palate Speakers. JSHR, 1959, 2.

39. Starr, C. B. "A Study of Some Characteristics of the Speech and Speech Mechanisms of a Group of Cleft Palate Children." PhD dissertation, Northwestern Univ., 1956.

40. Van den Berg, J. W. Direct and Indirect Determination of the Mean Subglottic Pressure. Folia Phoniatr., 1956, 8.

41. Van Hattum, R. J. "A Study of Air Use by Cleft Palate and Normal Speaking Subjects." Unpublished Master's thesis, Penn. State Univ., 1952.

42. Van Riper, C. and Irwin, J. W. Voice and Articulation. Englewood Cliffs, N. J.: Prentice-Hall, Inc., 1958.

43. Wiksell, W. A. An Experimental Analysis of Respiration in Relation to the Intensity of Vocal Tones in Speech. Studies in Experimental Phonetics. Edited by G. W. Gray. Baton Rouge: La. State Univ., 1936.

44. Williams, R. L. "A Serial Radiographic Study of Velopharyngeal Closure and Tongue Position in Certain Vowel Sounds." In Northwestern University Dental School Bulletin, 1952.

APPENDIX

TABLE 11.--Results of the calibration procedures performed before and after collection of experimental data

Initial Calibration Data				Final Calibration Data			
Oral		Nasal		Oral		Nasal	
V	AF	V	AF	V	AF	V	AF
.04	.20	.04	.29	.04	.20	.04	.30
.08	.45	.08	.65	.08	.47	.08	.70
.12	.89	.12	1.05	.12	.90	.12	1.00
.16	1.15	.16	1.25	.16	1.10	.16	1.30
.20	1.50	.20	1.70	.20	1.45	.20	1.75
.24	2.40	.24	2.10	.24	2.30	.24	2.20
.28	3.30	.28	3.20	.28	3.30	.28	3.15
.32	3.60	.32	4.50	.32	3.50	.32	4.70
.36	5.60	.36	5.50	.36	5.50	.36	5.55
.40	7.10	.40	6.40	.40	7.00	.40	6.45
.44	8.25	.44	7.95	.44	8.10	.44	7.90
.48	11.00	.48	9.60	.48	11.10	.48	9.70
.52	13.50	.52	11.60	.52	12.90	.52	11.40
.56	15.50	.56	13.30	.56	16.00	.56	13.20
.60	18.35	.60	15.80	.60	18.10	.60	16.10
.64	22.70	.64	18.80	.64	22.50	.64	18.50
.68	27.20	.68	21.70	.68	26.80	.68	21.50
.72	32.10	.72	25.50	.72	32.30	.72	25.00
.76	36.00	.76	28.80	.76	36.00	.76	28.50
.80	40.00	.80	33.70	.80	41.00	.80	33.30
.84	46.10	.84	38.80	.84	46.00	.84	39.50
.88	54.00	.88	43.90	.88	54.50	.88	43.50
.92	61.00	.92	50.20	.92	61.60	.92	53.00
.96	70.00	.96	55.10	.96	71.00	.96	56.50
1.00	84.00	1.00	61.30	1.00	84.00	1.00	60.50

V=Voltage Reading AF=Air Flow