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THE EFFECTS OF INTENSITY CHANGES ON THE FUNDAMENTAL VOCAL FREQUENCY OF CLEFT PALATE AND NORMAL SPEAKERS

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CHAPTER I

INTRODUCTION

The congenital cleft lip and palate condition produces a profound alteration of the oral-nasal-facial structural complex which, even after surgical repair, may result in disturbances of the dental arches and teeth, partial occlusion of the nasal airway, cosmetic imperfections, hearing loss, and diminished speech efficiency. Although other problems may have a serious impact on the habilitation of the cleft palate person, speech inadequacy is often a primary barrier to his effective function in society. Few conditions affect as many aspects of the speech process. A failure to restore velopharyngeal competency and normal relationships of the anterior oral structures may reduce the ability of the cleft palate speaker to achieve normal oral-nasal resonance and normal precision and placement of the articulators in consonant production. Typically, his voice quality is hypernasal (10, 87) and his articulation, particularly of pressure consonants, may be distorted due to improper tongue placement, escape of impounded oral air through the nose, and weak oral pressure (45, 58, 87). Substitutions of consonants valved at the level of the glottis or oral pharynx are also features of his misarticulations (59, 75). In addition, although they have received less attention, problems of phonation may be associated with the cleft palate condition (58, 92). Since the processes of phonation, resonance, and articulation are intimately interrelated, a disturbance of one is reflected to some degree in another. The interdependence of these processes is clearly seen in cleft palate speech.

In an effort to understand the speech problems of cleft palate persons and to plan more effectively for their habilitation, the speech pathologist has turned increasingly to research. From this effort have emerged detailed descriptions of the articulation and resonance status of cleft palate persons at various age levels (8, 11, 78), the relationships between speech efficiency and velopharyngeal valving (77, 81), and the interrelationships of the resonance and articulation disorders of cleft palate speech studied in a variety of speech samples (4, 5, 6, 7, 90).

Improved research instrumentation has also made it possible to examine more objectively the physiologic and acoustic correlates of nasality. Instruments designed to measure oral or nasal air expenditure in cleft palate speech include the pneumograph designed by Froeschels (26), nasometers (76), and spirometers such as that used by Kantner (46). More recently, the use of the oral manometer (9, 77), the pneumotachograph (42, 55), and the hot-wire anemometer (18, 88) have enhanced research capability in this area. Instrumentation such as the phonelloscope (46), the oscillographic camera (69), and the sound spectrograph (49) have been employed to study changes in the acoustics of nasal voice production, and the probe-tube microphone assembly (6, 82, 90) has been used in the study of nasal sound intensity.

In spite of what amounts to a productive research effort over the past two decades, there has been a paucity of information concerning the phonatory aspects of the cleft palate speech problem. Although clinicians have long recognized the presence of these phonatory problems (1, 58, 92), little data have been presented. For the most part, the data that are available have resulted from subjective clinical impressions and have evolved from treatment considerations. One aspect of phonation, fundamental vocal frequency, is of particular interest, Various clinicians (26, 30, 74) have suggested that fundamental vocal frequency or its subjective correlate, vocal pitch, affects the perceived severity of nasality. Further, some clinicians (27, 37, 74) have recommended that the habitual pitch level of cleft palate speakers be lowered as a means of reducing nasality. Implicit in this recommendation is the assumption that cleft palate speakers may present higher than normal pitch levels. While it has been speculated that some cleft palate persons may raise vocal pitch in an effort to minimize nasality (30), there appears to be no research demonstrating this relationship. Indeed, existing research (30, 54, 74) in this area is contradictory. Although Dickson (15) reported that his experimental subject sample presented a higher fundamental vocal frequency than his normals, Flint (25) reported a tendency for her cleft palate sample to present lower fundamentals than her normal sample. In a study of functionally nasal subjects, Sherman and Goodwin (74) could find no evidence of a relationship between pitch level and perceived severity of nasality.

The absence of consistent data regarding fundamental vocal frequency differences between cleft palate and normal-speaking subjects points to the need for further research. Specifically, there is a need for information concerning the fundamental vocal frequency differences between cleft and normal groups in production of vowels in isolation, in selected consonant contexts, and in connected speech environments. Because of the interrelationships of fundamental vocal frequency and intensity (94) and of vocal intensity and oral-nasal coupling (40), it appears useful to examine vocal frequency data at more than one intensity level. Recent research (40) has indicated that the intensity loss associated with identical degrees of oral-nasal coupling varies for individual vowels. It seems reasonable to expect, therefore, that fundamental vocal frequency relationships among vowels found to obtain for cleft palate and normal speakers at one intensity level may not hold at other levels within the subject's range. Further, in view of known differences in fundamental vocal frequency and intensity between the sexes (24, 63), it is desirable that data be accumulated for males and females separately.

It is the general purpose of this investigation to provide additional information dealing with the relationship of fundamental vocal frequency and vocal intensity in cleft palate and normal speakers.

CHAPTER II

REVIEW OF THE LITERATURE

Through the years, there has been a continuing research interest in the acoustic analysis of speech that is reflected in the wide range of studies dealing with various parameters of the speech signal. Included in these efforts have been studies of formant relationships and such acoustic characteristics as fundamental vocal frequency, intensity, and duration. For the most part, studies have been concerned with normal speech, a trend that emanates from an expanding productivity in the science of communications and experimental phonetics. In spite of the clear need for better definition of the voice quality disorders associated with the various speech pathologies, relatively few acoustic studies have been undertaken. Disturbances of voice quality resulting from the congenital cleft palate condition, for example, have been particularly difficult to define, and available data are often unclear and contradictory.

The purpose of the present investigation was to explore differences that may exist between normal and cleft palate speakers along one parameter of acoustic structure, fundamental vocal frequency. To provide a background for this study, the literature will be reviewed according to three major topics: (a) Fundamental Vocal Frequency of

Normal Speakers, (b) Laryngeal Correlates of Fundamental Vocal Frequency, and (c) Fundamental Vocal Frequency of Cleft Palate Speakers.

Fundamental Vocal Frequency of Normal Speakers

Recent investigations of laryngeal physiology (43, 60, 67, 85, 89) have provided increasing support for the myoelastic-aerodynamic theory of phonation. In its major features, this theory holds that the vocal folds are set into vibration by the air stream emanating from the lungs and trachea. As pressure builds below the vocal folds, the folds are forced apart allowing a puff of air to escape. The emission of air through the glottis creates a negative pressure between the vocal folds which, together with the inherent elasticity of the folds, effects a closure of the glottal opening. This cycle is repeated in rapid succession and the released puffs of air are perceived by the listener as sound.

In normal phonatory activity, a speaker may produce laryngeal tones that vary in their frequency over a range of almost two octaves (24). Zemlin (94, p. 149) states:

> . . . usually, however, the pitches produced are distributed in such a manner that a mode or central tendency is clearly evident . . . . When this mode is expressed in cycles per second it is properly referred to as the fundamental frequency of the sample.

Physiologically, fundamental vocal frequency is determined by the rate of vibration of the vocal folds which corresponds to the number of "puffs" escaping through the glottis per second; acoustically, fundamental frequency is defined as the repetition rate per unit time of a sound wave (38, 51).

Available data indicate that, as expected, substantial differences in fundamental vocal frequency exist between the sexes. Fletcher (24) reports that the average fundamental of adult females is approximately 256 cps and that of males, approximately one octave lower. Pierce and David (63) indicate that the average fundamental of adult males is approximately 120-130 cps and that of females, 250-256 cps. The literature also indicates that a speaker's fundamental vocal frequency cannot be viewed as a static phenomenon, in that it varies according to such factors as type of speech material (38), consonantal environment (39), and vocal intensity level (50).

Research information available suggests that fundamental vocal frequency differences exist among vowels. Taylor (83), utilizing five males and nine females, studied the mean fundamental vocal frequency of each of eight vowels produced in 's_t' environments. For male subjects, the mean fundamental vocal frequencies for the vowels [i], [I], [ɛ], [ae], [ɑ], [ɔ], [ʊ], and [u] were 149, 148, 138, 133, 132, 136, 150, and 152 cps, respectively. For female subjects, the mean fundamental vocal frequencies for the same vowels were 320, 318, 305, 302, 298, 303, 312, and 323 cps, respectively. Peterson and Barney (62) measured the fundamental vocal frequency of these eight vowels produced by 33 male and female subjects in 'h_d' environments. For male subjects, the mean fundamental vocal frequencies of the vowels [i], [I], [ɛ], [ae], [ɑ], [ɔ], [ʊ], and [u] were 136, 135, 130, 127, 124, 129, 137, and 141 cps, respectively. For the females, the mean fundamental vowel frequencies of the same vowels were 235, 232, 223, 210, 212, 216, 232, and 231 cps, respectively. Studies by Black (2) and by House and Fairbanks (39) of the fundamental vocal frequency of vowels produced by male speakers reveal essentially similar relationships among these vowel means.

The following trends are apparent in the results of these studies: (a) high vowels tend to have higher fundamentals than low vowels, (b) tense vowels tend to have higher fundamentals than lax vowels, and (c) closed vowels tend to have higher fundamentals than open vowels. Taylor (83) speculates that the concomitant variation of fundamental vocal frequency with tongue position reflects a "dynamogenetic radiation" of tension from the tongue musculature to the laryngeal muscles. That is, the increase in tongue height of a "high" vowel, in comparison to a "low vowel, is accompanied by a greater increase in tension of the musculature of the tongue. Variations in the degree of tension may be transmitted to the musculature of the larynx creating corresponding variations in vocal fold tension and fundamental vocal frequency.

House and Fairbanks (39) studied the influence of consonant environment on the secondary acoustical characteristics of vowels. Consonant environments of vowels were varied so as to form non-meaningful consonant-vowel-consonant (CVC) syllables consisting of 72 combinations of six vowels and twelve consonants. These syllables were spoken by ten male subjects, and the duration, fundamental vocal frequency, and relative power of each vowel in each context were measured. The authors report that the fundamental vocal frequencies of vowels in voiceless consonant contexts are higher than those in voiced consonant contexts. They also note that the effect of varying the characteristic place of articulation is small. These investigators speculate that, since the natural fundamental vocal frequency of voiced consonants is lower than that of vowels, the effect of placing a vowel in a voiced consonant context is to lower the vowel fundamental. Voiceless consonants, on the other hand, with higher fundamental vocal frequency than voiced consonants seem to elevate the vowel fundamental vocal frequency.

It is also generally acknowledged that a close relationship exists between vocal intensity and fundamental vocal frequency. Zemlin (94, p. 160), for example, states, "It is interesting to note that as intensity is increased there is a tendency for the pitch of phonation to also increase." Black and Moore (3, p. 51) also note the relationship of pitch and intensity:

> . . . pitch tends to rise with increases in loudness. This is not surprising, for certainly the vocal folds become more taut with an increase in muscular tonicity. Indeed physical effort with the hands tends to raise the frequency of the vocal-fold action.

The allusion made by these authors to the relationship of general muscular tonicity and vocal pitch level is similar to the speculations of Taylor (83), described previously.

To understand the research data relating fundamental vocal frequency and vocal intensity, it is useful first to consider findings dealing with the relative intensity of speech sounds. Sacia (70), in an early study, investigated the relative power of eleven vowels that were produced "disconnectedly and without accent" by eight male and eight female normal speakers. Each vowel was placed in a CVC context, the initial consonant in each case being [t]. The data for individual vowels are expressed in terms of "mean power," defined by the investigator as power that would be read by a quickly acting wattmeter and which is proportional to the deflection shown by the ordinary a.c. voltmeter or ammeter. It is further defined as a mean of the maximum ordinates (peaks) that occur in the vowel portion of the syllable. For the male subjects, the greatest power, in microwatts, was found for the vowel [ɑ], 50, followed in order by those for [ae], 44, [ɔ], 37, [ʊ], 33, [o], 33, [i], 33, [ʌ], 29, [u], 27, [ɛ], 26, [I], 25, and [e], 22. For females, the greatest power, in microwatts, occurred for the vowel [ɔ], 50, followed in order by those for [ɑ], 48, [o], 44, [u], 41, [ʊ], 40, [ae], 39, [ʌ], 38, [I], 32, [ɛ], 31, [e], 30, [i], 23. It is interesting to note that differences in the power characteristics of vowels were found between male and female speakers and that these differences varied for individual vowels. Males, for example, displayed greater, acoustic power than females in production of the vowel [i], but the reverse was true in production of the vowel [u]. Further, although greater power was generally associated with open than with closed vowels, mean values for the vowel [ʌ] were similar to those for closed vowels. These data suggested to Sacia that there is a "difference in the resonant structure between male and female voices, which, however, does not affect the higher frequencies enough to alter the vowel characteristics."

It should also be noted that when the maximum ordinate (peak) within each vowel portion of a CVC syllable was considered, males displayed uniformly greater power than females in production of each of the experimental vowels. As in the case of mean power measures, a general trend toward increased power for open vowels vs. closed vowels was evident. It was also found, however, that although the peak power measured during production of [i] and [u] were similar for females, 26 and 28 microwatts, respectively, males exhibited greater peak power for [i], 47 microwatts, than for [u], 26 microwatts.

In a subsequent report, based on the study of the conversational speech of the same sixteen subjects, Sacia and Beck (71) presented the relative mean power of the same eleven vowels. Although the data are not displayed separately for male and female subjects, the trends in relative vowel power are similar to those reported for the same vowels analyzed in CVC contexts. When the differences in mean power among vowels reported by Sacia and Beck are considered in terms of decibels rather than microwatts, a range of 3.2 dB exists between the vowels with greatest and least power.

Black (2), in a study of the natural frequency, duration, and intensity of vowels, had 42 males read eleven monosyllabic words, each containing one of eleven vowels, in a 't_p' environment. Vowel intensities were derived by taking the peak vertical displacement of a graphic level recorder stylus as an indication of the peak intensity of the vowel in the words; this presumably represented r.m.s. voltage. These measures were read in decibels directly from the level recorder. Because of faulty pronunciation, the productions of only sixteen subjects were included in the final data analysis. The results of this study indicate that the greatest relative intensity in dB, calculated against the intensity for the vowel [i], occurred for the vowel [o], followed in order by those for [ɑ], [ae], [ɔ], [ɛ], [I], [u], [U], [ʌ], [e], and [i]. The relative intensities of each of these vowels in decibels was 3.71, 3.69, 3.44, 3.22, 3.12, 2.86, 2.56, 2.52, 2.21, 1.77, and 0.00, respectively. Black reports that the means for the vowels [i], [e], and [ɑ] were significantly different. The range of intensities of the vowels studied was 3.7 dB. When means for the vowels [i] and [e] were eliminated from consideration, the range for the vowels was 1.5 dB.

In another study of vowel intensities, Fairbanks, House, and Stevens (21) had ten male subjects phonate 110 monosyllabic words, ten each for the eleven common American vowels. Each monosyllable consisted of a single vowel combined with one of eight voiceless consonants in a CVC arrangement. Through the use of a graphic level recorder, which yielded a graphic record of relative r.m.s. voltage for each word, the level of the vowel maxima in dB above a common arbitrary reference was obtained. Fairbanks, House, and Stevens assumed that the maxima in each monosyllable " . . . had been reached during the vowels and that measurement of them furnished valid basic data concerning the vowels." For each vowel, means were taken over the ten productions of each vowel by the ten subjects. The vowel means were distributed over a range of 4.5 dB, the greatest relative intensity occurring for the vowel [ae], followed in order by those for [ɔ], [ɑ], [o], [e], [ɛ], [ʊ], [ʌ], [i], [u], and [I]. The relative intensities of each of these vowels in decibels above an arbitrary reference was 18.3, 17.6, 17.5, 16.8, 16.7, 16.0, 15.7, 14.9, 14.8, 14.1, and 13.8, respectively. These investigators report significant variations in intensity among productions of the same vowel and suggest that these differences may be the result of consonantal environment.

Lehiste and Peterson (53), also studying differences in the relative intensity of vowels, employed a single male speaker who produced each of ni . isolated vowels and six diphthongs twenty times. Each vowel and diphthong were uttered at a uniform pitch level, 145 cps. The intensity of each speech sample was measured relative to 0.0002 dynes/cm^2. The data obtained for the nine vowels studied reveal that the highest mean sound pressure level occurred for the vowel [ɑ], 85.5 dB, followed in decreasing order by those for [ə], 85.0 dB, [ɔ], 84.8 dB, [ʌ], 83.4 dB, [ae], 83.1 dB, [ɛ], 82.9 dB, [I], 81.4 dB, [u], 80.2 dB, and [i], 80.2 dB. As can be seen from these data, the vowels [ɑ], [ə], [ae], and [ɔ], have greater relative acoustic power than other vowels, a finding supported by the studies of Sacia and Beck (71), Black (2), and Fairbanks, House and Stevens (21).

Differences in experimental design among the various studies might explain some of the data differences that were obtained. A comparison of the studies of Fairbanks, House and Stevens (21) and Black (2), for example, illustrates this point. Both studies utilized the same eleven vowels. The former study, however, employed ten male adults speaking 110 meaningful consonant-vowel-consonant (CVC) monosyllables, involving ten CVC contexts for each vowel. Eight voiceless consonants were utilized. Black, however, had sixteen male subjects speak only eleven words, with each vowel in a 't_p' context. The differences in the number of subjects and types of speech sample may account for the differences between the two investigations. It is also apparent, in light of Sacia's finding that the relative power of vowels differs somewhat for the sexes, that neither of the above investigations, based on male subject samples, can be compared fully with the data of Sacia (70) and Sacia and Beck (71), which are predicated on the study of mixed sex groups. Further, the findings of House and Stevens (40) indicate that consonant environment may have a substantial effect on relative vowel power. The fact that uniform consonant contexts were not employed in the studies here reviewed points to another source of inconsistency in the reported data.

In spite of these limitations, however, certain trends are apparent across studies: (a) females present higher fundamental vocal frequencies than males, (b) high-tense, closed vowels display higher fundamentals than low-lax, open vowels, (c) vowels in voiceless consonant contexts evidence higher fundamentals than vowels in voiced contexts, (d) vocal intensity influences the fundamental vocal frequency of vowels, (e) vowels differ in acoustic power, and (f) vowels with greater acoustic power tend to be associated with lower fundamental vocal frequencies than vowels of weaker intensity.

Laryngeal Correlates of Fundamental Vocal Frequency

In recent years, increasing attention has been focused on those laryngeal structures and functions that regulate the fundamental vocal frequency of the human voice. Research in this area has been greatly abetted by the development of sophisticated instruments that permit visualization and measurement of the laryngeal structures during voice production and of instruments and processes that provide indirect assessment of glottal function through analysis of sub- and supraglottal air pressure and flow patterns and laryngeal muscle potentials. Specifically, the utilization of the high-speed motion picture camera (22), synchronous stroboscopy (32), refined electro-myographic techniques

(19), the pneumotachograph (42), and a variety of sensitive air-flow measuring instruments have enhanced the capability of the researcher in voice.

In a review of the area of research dealing with laryngeal correlates of fundamental vocal frequency, van den Berg (85) cites a number of interdependent factors that determine the rate of vibration of the vocal folds. These include:

> (1) the effective mass of the vibrating part of the vocal folds; (2) the effective tension in the vibrating part of the vocal folds; (3) the effective area of the glottis during the cycle, which determines the effective resistance of the glottis and the effective value of the Bernoulli effect in the glottis; (4) the effective value of the subglottic pressure; (5) the damping of the vocal folds.

A relationship between laryngeal size and vocal pitch has been postulated for some time. It has been recognized (44), on the basis of measures made of cadavers, that male larynges are commonly larger than those of females in superior-inferior, anterior-posterior, and transverse dimensions. Further, the lowered vocal pitch level associated with puberty is associated with a substantial increase in laryngeal size (12). It has also been found that eunuchs, who characteristically present higher than normal vocal pitch levels, display larynges that are similar in size to those of females (44). Hollien (31) measured laryngeal size in four groups of normal adult speakers: low-pitched males, high-pitched males, low-pitched females, and high-pitched females. Each group contained six subjects. Using measures obtained from lateral X-ray films, he confirmed previously suggested sex differences in laryngeal size and also reported that, within sex groups, subjects with high pitch-levels displayed smaller larynges than those with low pitch level. He also notes, however, that the relative magnitude of differences in laryngeal size and differences in vocal pitch among the four subject groups varied, indicating that factors other than laryngeal size also account for differences in pitch level.

The frequency of a vibrator is also related to its mass; that is, the greater the mass, the lower the frequency. According to Gray and Wise (27, p. 99), "Some people's vocal bands are heavier and thicker than those of others and their voices are lower in pitch than those with thinner, lighter bands." Hollien and Curtis (34), utilizing frontal X-ray laminography, investigated the cross-sectional area and thickness of the vocal folds of twelve normal male and twelve normal female subjects. Both sex groups were composed of equal numbers of very high- and very low-pitched subjects. Each subject was required to phonate at pitches that were at levels 10, 25, 50, and 85 per cent above his lowest sustainable tone, representing three pitch levels in the normal range and one in falsetto. These investigators report that the groups with lower pitch levels had significantly greater vocal fold mass, as measured by cross-sectional area, than those groups with high pitch levels. Further, there was a trend toward smaller cross-sectional area for individual subjects with an increase in pitch. Interestingly, the rate of decrease in vocal fold mass tended to be greater in the lower portion of each subject's range than in the upper portion of his range. Discussing the importance of vocal fold mass in the regulation of pitch level, these writers state:

> It was found that there seems to be a general relationship between vocal fold thickness and absolute frequency that transcend differences in laryngeal anatomy between pitch groups. Moreover, this relationship seems to predominate

> over intersex differences including those of general laryngeal size and vocal fold length. The hypothesis that vocal fold cross section is an important correlate of vocal frequency is strongly suggested.

Employing excised larynges and utilizing techniques that afford satisfactory control of air flow, humidity, pressure, and tension, von Leden (89) reports that a dampened or weighted cord retains the same frequency of vibration as the unweighted cord, but that its amplitude is reduced. In addition, this author used ultra-slow motion pictures to demonstrate structural and vibratory changes in the different registers. He reports that, in the chest register, the vibrating margins of the vocal folds are thickened and relaxed; by contrast, in the head register, the vocal margins are thin and tense. Thus, von Leden states, "the mass and tension of the vocal cords determine the pitch of the tone produced."

In agreement with von Leden, van den Berg (85) reports that, in the high-pitched falsetto voice, the vocal margins are thin and tense, whereas in the chest register the margins are thicker, causing the vocal folds to make contact over a depth of several millimeters and resulting in a lower pitch. This author concludes that the amplitude of the vibrations and the effectively vibrating mass of the folds in the chest voice are much larger than in the falsetto voice.

In spite of the contention of Negus (60) that no appreciable lengthening of the vocal folds is possible from an anatomic standpoint, there is reason to believe that changes in fold length are associated with vocal pitch changes. Irwin (41), in an early study (1940), measured vocal fold length from laryngeal photographs of a single subject and reports that there is a slight increase in length with an increase in pitch. This elongation of the folds was seen only in a narrow range of low pitches. Moore (57) in 1947 and Farnsworth (22) in 1940, however, based on their observation of motion pictures of the vocal folds, report a general lengthening of the folds with a rise in vocal pitch.

Recent studies have served to clarify this relationship. Hollien (33) investigated the relationship between vocal pitch changes and vocal fold elongation. He studied four groups composed of six very low-pitched male voices, six very high-pitched male voices, six very low-pitched female voices, and six very high-pitched female voices. Each subject was required to phonate at four pitch levels, three chosen to represent a distribution of levels within the normal pitch register and one within the falsetto register. The pitch levels were specified in relation to each subject's pitch range and were located as proportions of the range above his lowest sustainable tone. Lateral X-ray and laminographic pictures of the vocal folds were taken during phonation by each subject at each pitch level and tracings of the X-ray films were made. To determine the anteroposterior length of the folds, measures were made from a lateral line drawn tangent to the anterior borders of the tubercles formed by the protrusions of the corniculate and arytenoid cartilages. All measurements were corrected for variation in camera-to-fold distance and reported in millimeters. Examination of these data reveals that mean vocal fold length is greatest for low-pitched males, followed in order by high-pitched males, low-pitched females, and high-pitched females. This finding is consistent with other data (12, 31) that indicate a relationship between laryngeal size and vocal pitch. Hollien also reports a systematic lengthening of the vocal folds for all subject groups as pitch level is increased, indicating that increased vocal fold length is associated with a rise in vocal pitch. Using a greater number of pitch levels and refinements in measurement techniques, Hollien and Moore (36) replicated the above experiment. On the basis of their findings, they conclude:

> (a) length of vocal folds increases systematically with increases in vocal pitch for the natural register; (b) vocal folds in abduction are longer than in phonation; (c) no single pattern of elongation or shortening is apparent for pitches in the falsetto register; (d) magnitude of lengthening is no greater in one portion of the pitch range than in any other; (e) there is some evidence of a 'stair step' lengthening function; (f) general vocal fold length appears to bear a moderate relationship to pitch level but does not correlate with the absolute fundamental frequency being phonated.

This finding that vocal fold lengthening is no greater in any one portion of the pitch range than in any other is at variance with the finding of Irwin (41) that changes in fold length are confined to the lower portion of the pitch range. Von Leden (89) measured vocal fold length of "different" subjects phonating at selected pitch levels. His findings confirmed those of Hollien and Moore (36) that the vocal folds elongate with increases in pitch in the different registers. Von Leden concludes: "Any increase in the length of the vocal cords is associated with an increase in pitch."

From the preceding discussion, it is evident that both vocal fold mass and vocal fold length may influence the fundamental frequency of phonation. There is reason to believe, however, that the regulation of vocal pitch in normal speakers is the result of changes in vocal fold tension and that changes in the length and mass of the folds are the result not the cause of this tension. Concerning the role of vocal fold tension in pitch regulation, Zemlin (94, p. 143) writes:

> It is not unreasonable to assume that the increase in tension of the vocal folds may be the sole agent responsible for pitch increases, and that the accompanying changes in length and thickness may simply be the result of the elastic tissue in the vocal folds yielding to the marked increase in tension.

Using the Bell Telephone Laboratories' high-speed films, Farnsworth (22) describes the vibrations of the vocal folds at approximately 120 cps as being characterized by little tension, either in the thyroarytenoid muscle underlying the vocal folds throughout their length or in the muscles which act on the folds by moving the cartilages to which they attach. As the tension in the various muscles increases, he suggests, the folds become firmer due to the contraction of the underlying thyroarytenoid, and they are stretched to a greater length by the action of the other muscles.

In a study of the cricoarytenoid joint, von Leden (89) concluded that the principal motion of this joint is an internal rotation around its longitudinal axis. During this movement, the vocal process rotates from a posterolaterocephalad position at rest to anteromediocaudad direction in phonation. This anatomic observation led the author to conclude that the vocal folds are usually shorter during phonation than in the rest position, a finding experimentally demonstrated by Hollien (33) and Hollien and Moore (36). This observation suggested to von Leden that the vocal folds are both shortened and tensed for phonation. The interdependence of vocal fold length, mass and tension led von Leden to conclude:

> Thus, vocal fold length is apparently not held constant during pitch changes, and since vocal fold mass changes only slightly, except with disease or surgery, it must be concluded that vocal fold tension plays an important role in the pitch regulation mechanism.

In recent years there has been increasing research attention devoted to the role of the breath stream in the regulation of vocal pitch and intensity. Von Leden (89), following extensive research involving anatomical, mechanical, physiological, and clinical data, contends that air flow is an active force in sound production. In his discussion of the aerodynamics of voice production, von Leden states that the explosive release of air from the glottis results in an immediate decrease in subglottal pressure; the elasticity of the vocal fold tissue, plus the Bernoulli effect, causes the folds to return to the adducted position. He posits that high-speed motion pictures of the larynx prove that the vocal folds adduct at the beginning of phonation, and that this adduction can be explained only through an aerodynamic process.

Tiffin, Saetveit, and Snidecor (84) report that, during vibration of the vocal folds, the pressure immediately beneath the glottis is in direct proportion to the area between the vocal folds. They comment that, in order for the folds to vibrate, there must be a difference between the pressure in the lungs and the atmospheric pressure, the former being greater if phonation occurs on exhalation. This difference in pressure, they contend, is accomplished by the vocal folds closing, or nearly closing, the air passage.

It is commonly held in laryngeal physiology that vocal pitch rises when subglottic air pressure and air flow are increased, all other parameters, including intensity, being held constant. During the past few years, however, some disagreement has arisen. Piquet, et al (64) introduced a cannula into the trachea of a human cadaver and noted that increasing air flow caused the resulting sound to be louder, but not higher in pitch. The same observation was made by Fessard and Vallencien (23), and Dunker and Schlosshauer (17) using anesthetized dogs whose larynges were artificially stimulated. In these studies, varying air flow within physiologic limits did not alter pitch. However, Hast (28) and Isshiki (43), in studies of living dogs, report a rise in pitch, as judged by the experimenter, with increased air flow. Rubin (67), using an anesthetized dog, reports that vocal intensity may be raised by increasing air flow at constant pitch and/or increasing cordal resistance (pitch) at constant air flow.

Ladefoged and McKinney (52) employed one speaker and 30 listeners to explore the interrelationship of subglottal pressure, effective sound pressure in front of the speaker, and judgements of loudness. Words were spoken at a number of different intensities with no restrictions on pitch level. These investigators found no quantifiable relationship between the subglottal pressure, air volume velocity, and fundamental frequency of the vocal folds. They did find, however, that there is a relatively high air volume velocity when a high pitch is produced with a comparatively small subglottal pressure. Draper, Ladefoged, and Whitteridge (16) report that, during an utterance which a speaker considered to be a constant "loudness" level, the mean pressure below the vocal folds remains stable.

In a study of eleven male and eleven female subjects, Isshiki (42) required each subject to sustain the vowel [ɑ] at low, medium, and high pitch levels over a two-octave range. He notes that the variation in air flow as a function of intensity is generally greater at high pitch levels than at low pitch levels. Although individuals varied considerably, this finding suggests that glottal resistance is more important in varying intensity at low pitch than at high pitch levels.

The foregoing review of the literature suggests that (a) speakers with larger larynges tend to display lower fundamental vocal frequencies than speakers with smaller larynges, (b) laryngeal size is not the sole nor the most important factor to be considered in the regulation of vocal pitch, and (c) vocal fold mass, length, tension, subglottal pressure, and glottal air flow are complexly interrelated variables that are active in the regulation of fundamental vocal frequency.

Fundamental Vocal Frequency of Cleft Palate Speakers

The presence of phonatory concomitants of "nasality" has led some writers (58, 92) to conclude that at least part of the voice quality differences of cleft palate speakers may be unrelated to alterations of the acoustic signal that result from excessive coupling of the oral and nasal cavities. McDonald and Koepp-Baker (58), commenting on this relationship, state:

> We believe that an important part of the quality of cleft palate speech is the result of faulty phonation . . . . it can best be described as an ineffective use of air which adds to the over-all quality a feature similar to breathiness.

A similar view is presented by Westlake (92):

> Phonation is also important. If the balance of resonance is in the direction of nasality rather than orality, reducing nasality is not the only way of establishing proper balance. Often the child needs routine voice improvement drills in addition to the special techniques for cleft palate patients.

In addition to breathiness, hoarseness (1) and harshness (87) have at various times been described as part of cleft palate voice quality. These voice quality deviations have been variously ascribed to chronic inflammation and edema of the vocal folds (1), habitual use of the vocal folds as an articulator (72), a tendency toward ventricular phonation (1), "faulty" phonation (92), and the spread of tension to pharyngeal and laryngeal muscles that occurs with glottal articulation (1).

Although there is little direct evidence that cleft palate speakers present fundamental vocal frequencies, or vocal pitch levels, that differ from normal, there is reason to suspect that this may be true. Since vocal pitch differences have been found in association with hoarse, harsh, and breathy voice qualities (20, 61, 68, 91, 93), and since these qualities have been observed in cleft palate speakers, it might be assumed that vocal pitch differences are a feature of cleft palate speech. Moreover, the susceptibility of cleft palate persons to upper respiratory infections (58), with resultant vocal fold edema, could be expected to change vocal fold mass and affect pitch level.

It has been speculated (1) that phonatory disturbances add acoustic features to the over-all voice quality that prevent cleft palate speakers from producing sounds with wider acoustic spectra. Curtis (14) compared the wave composition of several vowels produced by two normal speakers simulating nasality and by three pathologically nasal speakers. He found nasalizations similar in regard to the great relative energy in the low frequencies and marked attenuation of the high frequency components. McDonald and Koepp-Baker (58) speculate that this attenuation may be related to faulty phonation rather than to the damping effects of certain resonators. These authors also comment that the tendency to employ glottal valving for fricatives and other consonants, typical of cleft palate speakers, is alien to the usual phonatory process. They also cite direct and indirect laryngoscopic findings that show hyperemia and hyperplasia of the vocal folds to be common among cleft palate speakers. In addition, they speculate that the physiology of the nasal and pharyngeal mucosa may be severely disturbed. Hoarseness, therefore, may result from tissue pathology alone or from the aberrant use of the vocal folds as "articulators."

In their discussion of cleft palate speech, Berry and Eisenson (1) also note the occurrence of hoarse, ventricular speech in persons with cleft palate. They point out that this vocal characteristic is not seen in the very young cleft palate child, but is fairly common after the age of nine years. Etiologic factors, according to these authors, may include chronic inflammation of the nasal and pharyngeal mucosa and excessive tension in voice production which may result in hyperemia, nodules, and other types of vocal fold pathology. Curry (13) suggests that the "rebound" of pharyngeal resonance upon the larynx could result in injury to the vocal folds. The literature suggests that any one or combination of these factors may produce tissue alterations in the vocal folds which could account for the faulty phonation seen in cleft palate speech.

The contention of some clinicians that nasal voice quality and vocal pitch are closely related has led to recommendations that the habitual pitch level of cleft palate speakers be lowered as a way of reducing nasality (37, 87). Implicit in this recommendation are the assumptions that (a) the pitch level of cleft palate speakers may differ from that of normal speakers, and (b) this difference affects the degree of nasality perceived by the listener. Available research designed to explore these differences and relationships has been, for the most part, equivocal and the problems posed remain essentially unanswered.

Van Riper (87) discussing techniques for reducing nasality, advocates that, as a preliminary to articulation retraining, cleft palate speakers use low pitches while blending vowels. Although he does not discuss the rationale for this procedure, it is implied that higher-than-normal pitch levels may be employed by cleft palate speakers. This observation is consistent with those of Holmes (37) and Gray and Wise (27), who also suggest that the perception of nasality decreases at low pitch levels. Froeschels (26), however, observes that the degree of nasality diminishes with a raise in vocal pitch.

In a study of the relationship between vocal pitch and functional nasality, Kelly (47) evaluated nasality ratings assigned to each of three vowels, [o], [a], and [e], produced at "low," "middle" and "high" pitch levels. Significant differences, in terms of judged duration of nasal resonance, were found only for the vowel [a] between the "low" and "high" pitch levels. He concludes:

> These findings do not necessarily deny that the unpleasant quality of nasal voices may not be improved by lowering the pitch; it merely points out the amount of nasalized phonation is not appreciably related to pitch.

Testing the effect of pitch level on the degree of perceived nasality, Sherman and Goodwin (74) utilized both male and female functionally nasal speakers. Each subject was required to read a paragraph aloud at his habitual pitch level and at one level above and one below his habitual pitch level. Judgements of the degree of nasality of the speech samples were made by trained listeners. When the speech samples were played forward, significant differences were found among the means for males, but not for females. For males, less nasality was evident at the low than at the habitual or high pitch levels. When the samples were judged in the backward play condition, no significant differences in nasality ratings were found for either sex. On the basis of their findings, the authors contend that the routine lowering of pitch as a means of decreasing nasality is not warranted.

Interrelationships of pitch, intensity, and nasal voice quality were investigated by Hess (30). In this study, fifteen male cleft palate speakers were asked to phonate each of six vowels at each of two pitch levels, habitual pitch in cycles per second and a pitch level 1.4 times higher, and two intensity levels, 75 and 85 dB SPL. His findings indicate that the mean nasality rating of the cleft palate group is significantly lower at the higher pitch level than at the habitual pitch level. This relationship was obtained at both of the intensity levels employed. Discussing the implications of his research for therapy with cleft palate persons, he writes:

> Speech therapists may profitably experiment with judiciously elevated pitch and increased intensity as therapeutic adjuncts to enable the cleft palate speaker to reduce at least some of his perceptually disturbing voice quality, particularly nasality.

While the preceding research findings suggest that the vocal pitch level of cleft palate speakers affects the extent to which they are perceived as nasal, relatively few studies have concerned themselves with direct comparisons of the fundamental frequency of cleft palate and normal groups. This is somewhat surprising in view of the lively clinical interest in the use of pitch changes as a technique in the treatment of nasality.

As a part of a study designed to investigate spectrographic differences among nasal and normal speakers, Dickson (15) obtained fundamental vocal frequency measures for twenty normal speakers, ten functionally-nasal speakers, and ten cleft palate speakers; all subjects were males. He reports that the most severely nasal subjects in both the cleft palate and functionally-nasal groups displayed higher fundamental vocal frequencies than the normal-speaking group. Flint (25), however, studying isolated vowels produced by thirteen male and seven female cleft palate speakers and a group of normal speakers, matched to them in age and sex, could find no evidence of higher fundamental vocal frequencies for the cleft palate group. Female cleft palate subjects displayed significantly lower fundamentals than female normal speakers; male cleft palate subjects averaged slightly lower fundamentals than male normal speakers, but the difference between means of the two groups was not significant. Interestingly, Flint reports very low correlations between fundamental vocal frequency and degree of nasality for both the male and female cleft palate groups.

The difference in findings between the Dickson (15) and Flint (25) studies may reflect differences in the composition of their subject samples. Dickson, for example, studied only male subjects and his conclusions are necessarily limited to males. Flint reports essentially similar fundamental vocal frequencies for her cleft palate and normal males and notes that significant differences occurred only between her cleft palate and normal female groups. It is possible that cleft palate females display different adjustments to increased oral-nasal coupling than males and that these adjustments caused a lowered fundamental vocal frequency of phonation. It should also be noted that the two studies differed in terms of the speech sample employed; Dickson studied vowels in 'b_t' consonant environments whereas Flint studied vowels produced in isolation. Conceivably, the direction and extent of differences in fundamental frequency between the cleft palate and normal groups might be altered when vowels are examined in consonant contexts.

The important interrelationships that exist between fundamental vocal frequency and vocal intensity make difficult any statement about one of these variables without due reference to the other. It is generally accepted that the abnormal coupling of the oral and nasal cavities in cases of velar insufficiency has a notable effect on the over-all output of the vocal tract. It appears reasonable, therefore, to assume that such changes in over-all level could influence the fundamental frequency of phonation.

The resonance characteristics of the vocal tract are determined by its length and configuration. As the velum is raised or lowered during speech, the size and shape of this tract is modified; consequently, the resonance characteristics of the system are altered. The coupling efficiency of the vocal tract is determined by the proportion of sound energy generated at the larynx that reaches the outer air. An excessive coupling of the nasal cavity, which is seen in many cleft palate speakers, results in a reduction of coupling efficiency.

Stevens and House (80) state that nasal coupling adds to vowel production a source of additional acoustic loss by increasing the damping effect on the laryngeal sound source. House and Stevens (40) point out that, "By virtue of its smaller size and greater damping, the nose radiates much less sound energy than the mouth when nasalized vowels are produced."

In a study of the effect of varying degrees of oral-nasal coupling on the acoustic output of the vocal tract, House and Stevens (40) employed an electrical analog that simulated the damping characteristics of the oral and nasal cavities. Almost without exception, their tabulated data reveal that the over-all level of artificial vowels decreases as coupling is increased. It was also observed that individual vowels respond differently to changes in the degree of nasal coupling. The high vowels [i] and [u] were consistently weakest in over-all level in all coupling conditions; the low vowels [ɑ], [ae], and [ɔ], however, evidenced a relatively greater loss of acoustic power as nasal coupling was increased. The role of the nasal cavity as a damping channel, particularly for high frequency components of the speech signal, has been more recently defined by Hattori, Yamamoto, and Fujimura (29).

That the nasal cavity acts as a damping rather than a resonant chamber was speculated in an early study by Russell and Cotton (69). These investigators report that coupling the oral and nasal cavities, without changing the type of voice production, causes a "loss of vocal efficiency rather than an improvement due to nasal resonance." They utilized two enclosed microphones and an oscillograph to determine the relative intensities of the oral and nasal components in nasalized and non-nasalized vowels. One tube from the microphone box led to a nostril; the other led to a mouthpiece. Oscillograms were made of vowels sustained on a single breath, and the results were plotted to show variations in the nasal and oral intensities of the individual vowels at eight different pitch levels. Their results indicate that there is a 20- to 30-dB loss in sound transmission through the velum at different pitch levels. With the exception of [u] and [i], the nasal component averaged about 30 dB less intense than the oral component in non-nasal speech. For the vowel [i], the average difference was approximately 17 dB. On the basis of their findings, they conclude that nasal resonance is negligible so long as the velum was raised. In nasalized phonation, the oral and nasal intensities were approximately equal, indicating a relatively greater strength of the nasal component of the speech signal in nasal than in non-nasal speech. No evidence of greater nasal resonance was found at any of the pitch levels studied.

The presence of a relationship between vocal intensity level and perceived nasality has also been postulated by Weiss (90), House and Stevens (40), and Hess (30). Weiss reports a high negative correlation between the mean over-all intensity levels of connected speech samples and nasality ratings of these samples. He speculates that less nasality is perceived in samples that are "louder," i.e., are more intense, than in samples that are weaker in intensity. House and Stevens also report that the vowels characterized by least acoustic power, i.e., [i] and [u], are perceived to be most nasal by trained judges. Hess studied the relative nasality of each of six vowels produced at two intensity levels, 75 and 85 dB SPL. Each of the experimental vowels, [i], [u], [e], [o], [ae], and [ɑ], was perceived to be less nasal at the more intense level. These findings are consistent with those of Williamson (92) and of Cotton (10).

The foregoing review of studies concerned with fundamental vocal frequency differences between normal and cleft palate speakers suggests that: (a) chronic vocal fold inflammation and edema may result in lower fundamental vocal frequencies for cleft palate than for normal speakers; (b) the greater frequency of ventricular phonation, glottal articulation, and other phonatory disturbances may result in a lower fundamental vocal frequency for cleft palate speakers; (c) nasal speakers, as a group, may display different fundamental vocal frequencies than non-nasal speakers; and (d) the loss of acoustic power associated with excessive oral-nasal coupling can be expected to effect the fundamental vocal frequency employed by cleft palate speakers.

It may also be seen from this review of pertinent studies that disparate observations and research findings exist concerning the relationship between fundamental vocal frequency and nasality and the presence of fundamental vocal frequency differences between cleft palate and normal subjects. In view of the reported interrelationships of vocal intensity, fundamental vocal frequency, and perceived nasality, it is possible that at least some of the reported differences in findings may reflect a lack of uniformity in experimental control of these variables. It is also apparent that findings based on limited subject samples cannot logically be extrapolated to the total population of nasal speakers. Further, the fact that individual vowels have been shown to respond differently to coupling of the oral and nasal cavities suggests that any attempt to generalize findings based on the study of selected vowels to "nasal speech" may be hazardous. In light of the need for additional data dealing with the fundamental vocal frequency differences between normal and nasal cleft palate speakers, the present study is formulated.

CHAPTER III

DESIGN OF THE INVESTIGATION

The present study was designed to investigate the differences in and the relationships among fundamental vocal frequencies of selected vowels produced at four different intensity levels by groups of normal-speaking persons and by cleft palate subjects with velar incompetency.

Specifically, the following research questions were formulated:

1. What differences in fundamental vocal frequency exist between the normal-speaking and cleft palate groups in production of each of the vowels: [i], [u], [ae], and [ɑ]?

2. What differences in the fundamental vocal frequency of these vowels exist between the normal-speaking and cleft palate groups when the data are analyzed according to the sex of the subjects?

3. Are these differences in fundamental vocal frequency, if present, similar at each of the four intensity levels employed in this study?

Subjects

An experimental group of twenty cleft palate persons, ten male and ten female, were selected to serve as subjects in this investigation. The subjects ranged in age from 15.5 to 53 years, with a mean age of 26.4 years. No limitations were imposed with respect to extent or type of cleft or manner of repair. Consistent with the purposes of the investigation, all experimental subjects were required to present velopharyngeal incompetency. To assess velopharyngeal competency, breath-pressure ratios were obtained for all cleft palate subjects using an oral manometer (Hunter, Model 360), following the procedure described by Spriestersbach and Powers (77). The use of breath-pressure ratios as an index of velar competency was dictated by the finding (77) that these ratios correlate well ($r = -.69$) with X-ray measures of velopharyngeal opening in pressure-sound production. Although Shelton, Bankson, and Brooks (73) have recently questioned the use of breath-pressure ratios as a measure of velopharyngeal opening, their data suggest that the ratios are useful in identifying subjects with poor velar closure. While some subjects with evident velar incompetency attained spuriously high breath-pressure ratios, there was little evidence to suggest that subjects with competent velar mechanisms attained low breath-pressure ratios. No subject with a palatopharyngeal gap of one millimeter or less, as determined by measures of lateral X-ray films, obtained a breath-pressure ratio less than .80. Since the present study was concerned with identifying velar inadequacy and was not concerned with discriminating degrees of velar opening, the use of the breath-pressure ratio appeared justified.

Each experimental subject was required to present a mean breath-pressure ratio less than .75. This ratio was selected in light of the finding (73) that persons with essentially normal velar closure may achieve mean ratios as low as .80. The mean manometric ratio for the present cleft palate group was .61; the standard deviation, .13.

All subjects were required to have sufficient intelligence to perform the experimental task, that is, to produce and sustain each of four isolated vowels for a four-second period at specified intensities as monitored on a sound-pressure-level meter. No subject exhibited a hearing loss greater than 20 dB hearing level at the frequencies 500, 1000, and 2000 cps in the better ear. Control subjects, selected from normal speakers locally available, were matched to the cleft palate speakers with respect to age and sex. Each normal-speaking subject was within one year the age of the cleft palate subject to whom he was matched.

Apparatus

The apparatus employed in this investigation included: (a) a signal system to guide the subjects in the experimental task; (b) an audio-recording system; (c) a fundamental-vocal-frequency analyzing system; and (d) an intensity-analyzing system. A simplified block diagram of the apparatus, excluding the signal system, is shown in Figure 1.

Description

Signal system. This system, utilized to signal subjects when to initiate and terminate vowel phonation, consisted of a cam timer which, when activated by the experimenter, illuminated one of two signal lights in the test room. The signal system was designed so that an amber light flashed for a one-second period followed by a red light that flashed for a four-second period.

Audio-recording system. The audio-recording system consisted

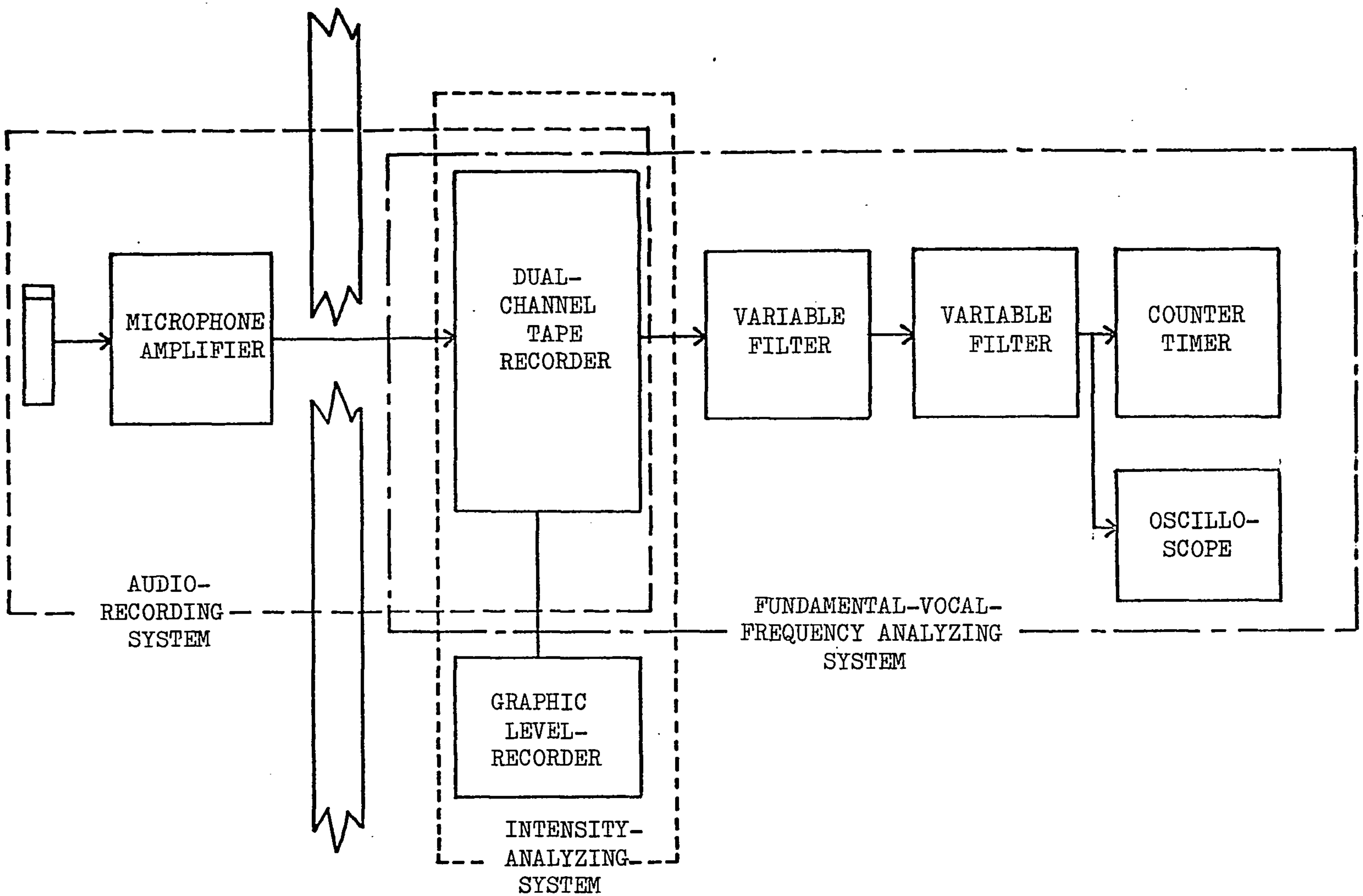

Figure 1.--Simplified block diagram of the research apparatus.

of: (a) a one-half-inch condenser microphone cartridge, (Bruel and Kjaer, Type 4134); (b) a cathode-follower (Bruel and Kjaer, Type 2615); (c) a microphone amplifier (Bruel and Kjaer, Type 2603); and (d) a dual-channel, magnetic tape recorder (Ampex, Model 354-C).

The condenser microphone cartridge, as calibrated by the manufacturer, had a flat frequency response within ± 2 dB from 20-20,000 cps in a sound field. According to the manufacturer's specifications, the protective grid covering the microphone cartridge had no effect on frequencies below 10,000 cps when the microphone was placed at a 90° angle of incidence to the sound source. The cathode-follower was designed specifically for use with the Bruel and Kjaer condenser microphone. This component transformed the high source impedance of the microphone to the relative low output impedence required for the succeeding microphone amplifier.

Designed to amplify the voltages of small alternating currents, the microphone amplifier had a potential gain of 100 dB and an essentially flat frequency response, ± 2 dB, from 2-40,000 cps. This amplifier served as a sound pressure level meter when used with the Bruel and Kjaer condenser microphone, according to the manufacturer's specifications, indicating sound pressure in decibels re .0002 dyne/cm^2 on its volt meter.

At a tape speed of 7.5 inches per second, the dual-channel tape recorder had a flat frequency response, ± 2 dB, from 40-12,000 cps, and was matched in impedance with the microphone amplifier.

<u>Fundamental-vocal-frequency analyzing system.</u> Instrumentation used to determine vowel fundamentals for the experimental and control

subjects consisted of: (a) a filter network employing two variable electronic filters (Spencer-Kennedy Laboratories, Model 300), (b) a cathode-ray oscilloscope (Tektronix, Type 532), and (c) a counter-timer (Transistor Specialities Incorporated, Model 361).

The filter network was made up of the two variable electronic filters arranged in series. Each band of each filter had a rejection rate of 18 dB per octave beyond the cut-off frequency; since the filters were arranged in series, a 36-dB per octave rejection rate was possible. Maximum attenuation for each filter was greater than 90 dB, and each had an insertion loss of 0 dB, ± 1 dB for cut-off frequencies from 20-20,000 cps. Over-all harmonic distortion was not greater than 0.5% (predominantly second harmonic) with an input voltage of four volts r.m.s. and with the fundamental component and distortion products within the pass band.

The oscilloscope employed in this investigation was equipped with an output preamplifier (Tektronix, Type CA, Plug-in). The vertical deflection system of the oscilloscope had a frequency response of dc-5 mc and a rise time of .06 cm. With a frequency response of dc-300 kc., the horizontal input-deflection was continuously variable from .2 volts/cm to 20 volts/cm.

The counter-timer was a dual-channel instrument that utilized an in-line Nixie-tube digital readout. Its time base had eight ranges, a display time that was continuously variable from 0.2-10 seconds, a range of 0.1 cycle-1 mc/second, and a resolution, with minimum spacing between successive input pulses, of one microsecond. Either channel could be triggered by signal slopes of positive or negative polarity;

the trigger levels were continuously variable with a sensitivity of ten millivolts.

Intensity-analyzing system. A graphic level recorder (Bruel and Kjaer, Type 2304) was employed to assure that the vowel productions closely approximated the four intensity levels used in this investigation. This instrument produces a continuous, permanent record of voltage excursions as a function of time within the frequency range 20-20,000 cps. Its 50-dB potentiometer is accurate within ± .5 dB, according to the manufacturer. A level-recorder chart paper speed of 30 mm/second and a stylus-writing speed of 200 mm/second were used throughout data collection. White-waxed calibrated chart paper (Bruel and Kjaer, QP 2350) ruled in ten equal intervals, each of which represented five decibels, was employed.

Calibration

Audio-recording system. Utilizing a noise generator (Grason-Stadler, Model E5539A) which supplied white noise to the condenser microphone through an amplifier-speaker (Ampex, Model 620), the audio-recording system was calibrated prior to the tape-recording of the vowel samples. The condenser microphone was placed at a 90° angle of incidence to and at a distance of one inch in front of the amplifier-speaker in the test room. The intensity of the white noise was adjusted until it produced an 85 dB SPL deflection on the volt meter of the microphone amplifier and this signal was introduced into the tape recorder. The "record" and "reproduce" potentiometer settings of the tape recorder were adjusted to this reference signal prior to the recording of each subject. Prior to playing the recorded vowel samples into the fundamental-vocal-frequency and intensity-analyzing system, it was necessary to adjust the tape recorder's "reproduce" level to correspond to its "record" level, which was initially adjusted in the manner described above. With the reference noise present, the "reproduce" potentiometer was adjusted until the output signal was equal in intensity to the output signal from the "record" head.

Intensity-analyzing system. The intensity-analyzing system was calibrated by pre-recording white noise at an intensity level of 85 dB re .0002 dyne/cm^2 through the audio-recording system as described above. The white noise produced by the noise generator was transduced by the amplifier-speaker, received by the microphone, amplified by the microphone amplifier, and recorded on tape. Introduction of this signal into the graphic-level recorder from the magnetic tape recorder produced a tracing on the chart paper, and the input potentiometer of the level recorder was adjusted so the tracing corresponded to a designated reference line on the chart paper. The intensity level represented by this line in the chart recordings of each vowel sample was equal to 85 dB. Periodic calibrations of the intensity-analyzing system were made throughout the study. The microphone amplifier was calibrated periodically by comparing its response to that of a sound pressure level meter (General Radio, Type 1551-C), and to that of another microphone amplifier identical to that utilized in this study. In addition, the microphone amplifier had internal calibration controls which were used to determine the response of the unit prior to each data-taking session. These calibrations indicated that the intensity-analyzing system remained in calibration throughout data collection.

Fundamental vocal frequency analyzing system. Utilizing a beat-frequency oscillator (Bruel and Kjaer, Type 1014) and a frequency range of 50-10,000 cps, the two electronic filters were calibrated by introducing pure tones at 100-cps intervals. The filters were arranged to low-pass and high-pass the range of frequencies between 50-10,000 cps at 100-cps intervals and the results recorded on the graphic-level recorder. This was done to assure that the filters were passing the appropriate bands at the rejection rate of 36 dB per octave. Analyses of these calibration data revealed that the filters remained in calibration throughout the experiment.

The counter-timer was equipped with internal oscillators which were employed in calibration of this unit prior to its use. By using the internal oscillators, the frequency calibration of the counter-timer was found to be accurate, ± 1 count, throughout the data collection.

Speech Sample

The speech sample employed in this study consisted of four vowels: [i], [u], [ae], and [ɑ] sustained in isolation for four seconds. These four vowels were chosen because they differ in degree of velar valving (56), fundamental vocal frequency (2), relative acoustic power (21), and tongue height during production (71). These factors were deemed important in that the presence of abnormal oral-nasal coupling might be expected to have a different effect on the fundamental vocal frequency of individual vowels according to their acoustic and physiologic requirements.

The four intensity levels, 70, 75, 80, and 85 dB re .0002

$dyne/cm^2$ were chosen because they represent a range of intensities from "normal" to "very loud" speech (24). A mouth-to-microphone distance of eight inches was employed in this investigation to afford comparison of the present findings with those of other investigations (6, 66) recently completed at the University of Oklahoma Medical Center.

Procedure

Data collection took place at the University of Oklahoma Medical Center's Speech and Hearing Center in an acoustically-isolated suite consisting of a test room and a control room. The ambient noise level of this suite, measured on the C-scale of a sound level meter (General Radio, Model 1551-C), was approximately 30 dB.

The test room was equipped with an adjustable dental chair, a table on which were placed the microphone amplifier and signal lights, and an adjustable stand holding the condenser microphone and the cathode follower. The variable electronic filters, the cam-timer which controlled the signal lights, the oscilloscope, and the counter-timer were situated in the control room.

Each subject was first instructed in the use of the signal lights and the volt meter of the microphone amplifier that was used to monitor vocal intensity level. As previously noted, the microphone amplifier, when used in conjunction with its associated condenser microphone and cathode follower, served as a sound pressure level meter. The subject was then seated in the dental chair that was adjusted to provide a suitable and comfortable posture. To minimize movement, the subject's head was positioned against a head-rest by means of a rubber strap. The equipment was arranged so that the subject could readily see the sound pressure level meter, signal lights, and speech materials without head movement. The microphone was placed at a 90° angle of incidence to and approximately eight inches from the speaker's mouth. Situated directly above the microphone amplifier, the signal lights were used to indicate the initiation and termination of vowel phonation. A one-second amber light was used to indicate that the subject should prepare to phonate; a four-second red light, immediately following, signaled the duration of phonation. All vowels, written phonically, were presented on four-by-six cards to the subject; the experimenter also presented each vowel orally to the subject to assure correct production.

After the subject was positioned, he was instructed to monitor his vocal intensity so that it remained constant at the experimental intensity levels during phonation of each of the four vowels studied. A practice session preceded the tape recording of each vowel at each intensity. In collection of the experimental data, the order of presentation of the vowels and intensity levels were randomized for each subject.

Measurement of fundamental vocal frequency. The instrument most frequently utilized in determining fundamental vocal frequency is the sound spectrograph. In spectrographic analysis, the fundamental of a vowel may be determined according to the procedure recommended by Koenig, Dunn, and Lacy (48), Kopp and Green (49), Peterson and Barney (62), and Potter (65). In this procedure, the number of vertical striations per second along the horizontal axis of the spectrogram may be used to measure the speaker's fundamental vocal frequency in cycles per second. While spectrographic analysis is a useful method for determining fundamental vocal frequency, it has certain disadvantages. First, to obtain the fundamental, the number of vertical striations must be counted per one second display or calculated on the basis of measures made in shorter display times. Second, the reliability of the experimenter in counting the vertical striations and in computing the fundamental is a variable affecting the accuracy of measures. Further, the display of vertical striations on the voice bar may lack sufficient definition for accurate measurement, and the time required for recording and measurement of the spectrograms can be extensive.

The method used to determine fundamental vocal frequency in this study was designed to provide an immediate digital readout of the fundamental of each subject's tape-recorded vowel phonations. Two variable electronic filters, arranged in series to provide a 36 dB per octave rejection-rate beyond selected cut-off frequencies, were employed. Since various studies (24, 63) have shown that the mean fundamental vocal frequency for normal-speaking males and females ranges from 120-130 cps and from 250-256 cps, respectively, two filter sections were set to high-pass frequencies above 80 cps in order not to filter the fundamental of low-pitched males. The settings for the two low-pass sections of the filters varied somewhat for each subject in that, for some subjects, the first harmonic was band-passed and contaminated the measure of fundamental vocal frequency. The filters, under these circumstances, were adjusted to eliminate the first and successive harmonics by decreasing the frequency cut-off of the low-pass filter sections. When the first and remaining harmonics were filtered from the signal, fundamental vocal frequency was displayed digitally by the counter-timer.

The oscilloscope served a dual purpose, that is, as a monitoring device for the experimenter to observe the waveform following filtering and to provide a means of identifying the best locations on the waveform for the trigger setting of the counter-timer. Since the input signal was known to be fundamental vocal frequency, which has a uniform repetition waveform and since the waveform could be visually monitored on the oscilloscope, the shape, amplitude, and frequency of the input waveform could be observed. The trigger-level control adjustment of the counter-timer was used to select a point on the waveform that was uncluttered and associated with maximum rate of change. This control setting varied somewhat from subject to subject. The trigger-slope control was set to activate the counter-timer only on positive-going voltage excursions. Adjustments of the sensitivity-control were made at the lowest setting that produced reliable counting (+100) and this setting remained constant throughout data collection. The time-interval control established precisely the interval during which measurements of the input signal were performed and was set at one second in this experiment. The display-time control was set to provide time for accurate readings of fundamental vocal frequency.

Subjects in this study phonated each vowel at each of the four intensity levels for a period of four seconds, and these phonations were tape-recorded in the manner previously described. To eliminate the frequency changes that may be associated with the initiation and termination of phonation, the initial and final one-half second of each vowel recording for each subject at each intensity level were erased; only the steady-state portions of the vowels were analyzed.

A pilot study was conducted to determine if the above method of determining fundamental vocal frequency would yield results similar to those attained by spectrographic analysis. Three male and three female cleft palate subjects and six normal speakers matched to them according to sex phonated the four vowels utilized in this study. These vowel samples were tape-recorded and spectrograms were made using the sound spectrograph (Kay Sonograph, Model 661-A). Measurements of fundamental vocal frequency were then derived using the method suggested by Potter (65) and Kopp and Green (49). The vowel recordings were then introduced into the fundamental-vocal-frequency analyzing system used in this study. The differences in fundamental vocal frequency using the two methods did not exceed ± 4 cps for any vowel sample. Thus, the present method of determining fundamental vocal frequency appeared to correlate well with spectrographic analysis.

Intensity analysis. Visual tracings of the intensity of the vowels were obtained by introducing the tape-recorded vowel samples into the graphic level recorder. The level-recorder was calibrated in the manner previously described, and the tracings provided a means of measuring the intensity of each vowel phonation.

Since vowel intensity was a critical variable in this investigation and since subjects varied slightly in their ability to sustain vowels at the experimental intensities, a mean sound pressure level for each vowel was computed by taking the average of measures at 20-mm intervals during the steady-state portion of each vowel phonations. In this manner, the mean intensity level for each vowel produced by each subject was calculated.

Because intensity was an important control in the present investigation, every attempt was made to assure that each subject matched the experimental intensity levels as closely as possible. This required, in almost all cases, several attempts on the subject's part before an acceptable production was attained. Analysis of the intensity data revealed that the maximum deviation from the experimental intensity levels that occurred for any subject in the production of any speech sample was no greater than $\pm$ 2 dB. This variation is within the error of the instruments used in the intensity-analyzing system. To determine the reliability of the experimenter in measuring vowel intensity from the level recorder traces, fifteen per cent of the samples were re-measured by a person familiar with the experimental procedure. No measure made by these individuals differed by more than one decibel, a level of agreement believed satisfactory for purposes of the present study. The results of the study and a discussion of the findings are presented in the following section.

CHAPTER IV

RESULTS AND DISCUSSION

This study was designed to investigate differences in and relationships among fundamental vocal frequencies of selected isolated vowels produced at four different intensity levels by a group of normal speakers and by a group of cleft palate speakers with suspected velar incompetency. Twenty cleft palate subjects, both male and female, and twenty normal speaking subjects matched to them with respect to age and sex, sustained the vowels [i], [u], [ae], and [ɑ] at intensity levels of approximately 70, 75, 80, and 85 dB SPL at a mouth-to-microphone distance of eight inches. Each vowel sample was recorded by means of a high-fidelity recording system and introduced into an instrumental assembly, previously described, which measured the average fundamental vocal frequency of the stable mid-portion of each vowel sample. The quantitative data of this study, therefore, consisted of the average fundamental vocal frequency of each vowel sample at each of the experimental intensity levels for each subject.

In order to answer the research questions stated in Chapter III, the data were analyzed by means of a split-plot analysis of variance with a factorial arrangement of treatments (79).[1] Main effects in the analysis were groups, sexes, vowels, and intensities. The alpha level was set at .05.

The results of an analysis of variance of the fundamental vocal frequency data are summarized in Table 1. Examination of this table reveals that the vowel, sex, and intensity main effects and the group-by-vowel, vowel-by-intensity, sex-by-intensity, and group-by-sex-by-vowel interactions are significant. All other main effects and interactions are not significant at the confidence level set for this experiment. For purposes of organization and discussion, the findings of the study will be presented in two sections: (a) findings related to intensity levels, including discussion of the vowel and sex main effects and appropriate vowel and sex interactions; and (b) findings related to groups, including discussion of appropriate interactions involving vowels and sexes.

Intensity Levels

One of the purposes of the present investigation was to explore the effect of changes in vocal intensity level on the fundamental vocal frequency of vowels produced by male and female cleft palate and normal speakers. Inspection of Table 1 indicates that none of the interactions involving groups and intensity levels is significant, suggesting that

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[1] The statistic employed is a partially-nested hierarchical design with subjects nested within groups and sexes. In this analysis subjects may be viewed as plots in which split-plot treatments are a combination of vowels and intensity levels. Thus, the analysis reflects that portion of the analysis of variance which is obtained from data measures on sub-plots. No whole-plot treatment was applied to the subjects.

TABLE 1

SUMMARY OF THE ANALYSIS OF VARIANCE

Source	df	ms	F
Groups (A)	1	9060.10	1.069
Sex (B)	1	2250079.23	2653.588[a]
AB	1	5118.91	.604
Subjects (C)/AB	36	8479.38	
Vowels (D)	3	6976.61	26.514[a]
AD	3	1258.92	4.784[a]
BD	3	396.74	1.507
ABD	3	683.12	2.596[a]
CD/AB	108	263.12	
Intensity (E)	3	41330.81	115.917[a]
AE	3	185.70	.521
BE	3	1538.26	43.142[a]
ABE	3	784.18	2.199
CE/AB	108	356.55	
DE	9	741.55	5.181[a]
ADE	9	52.82	.037
BDE	9	177.78	.124
ABDE	9	239.01	1.670
CDE/AB	324	143.10	

[a]P = $<$ .05

the relationships between fundamental vocal frequencies of the cleft palate and normal-speaking subjects were similar at the various vocal intensity levels. To understand the effect of changes in vocal intensity on both subject groups, therefore, it is necessary to consider the significant main effects and interactions involving vowels, sex, and intensity levels.

Although Table 1 shows that the vowel, sex, and intensity main effects are significant, the presence of significant interactions among these main effects limits the meaningfulness of the main effects and indicates that the effect of vocal intensity changes on fundamental vocal frequency differs for the sexes and for individual vowels. This is illustrated by the significant vowel-by-intensity interaction presented graphically in Figure 2. Inspection of the plot of means involved in this interaction reveals that the mean fundamental vocal frequency for [i], derived over both groups and sexes, is 174 cps at Intensity Level I, 186 cps at Intensity Level II, 199 cps at Intensity Level III, and 224 cps at Intensity Level IV. The mean fundamental vocal frequencies for [u], arranged from the lowest to the highest intensity levels are 176 cps, 186 cps, 199 cps, and 216 cps; for [ae], 173 cps, 179 cps, 188 cps, and 202 cps; and for [ɑ], 168 cps, 177 cps, 186 cps, and 198 cps. Evaluation of the trends within these data suggests that the mean fundamental vocal frequency of each experimental vowel increases as intensity level is increased. It is evident, however, that the amount of increase in mean fundamental vocal frequency associated with each 5 dB increment in intensity varies among individual vowels. The increase in fundamental from Intensity Level I to Intensity Level II is greater

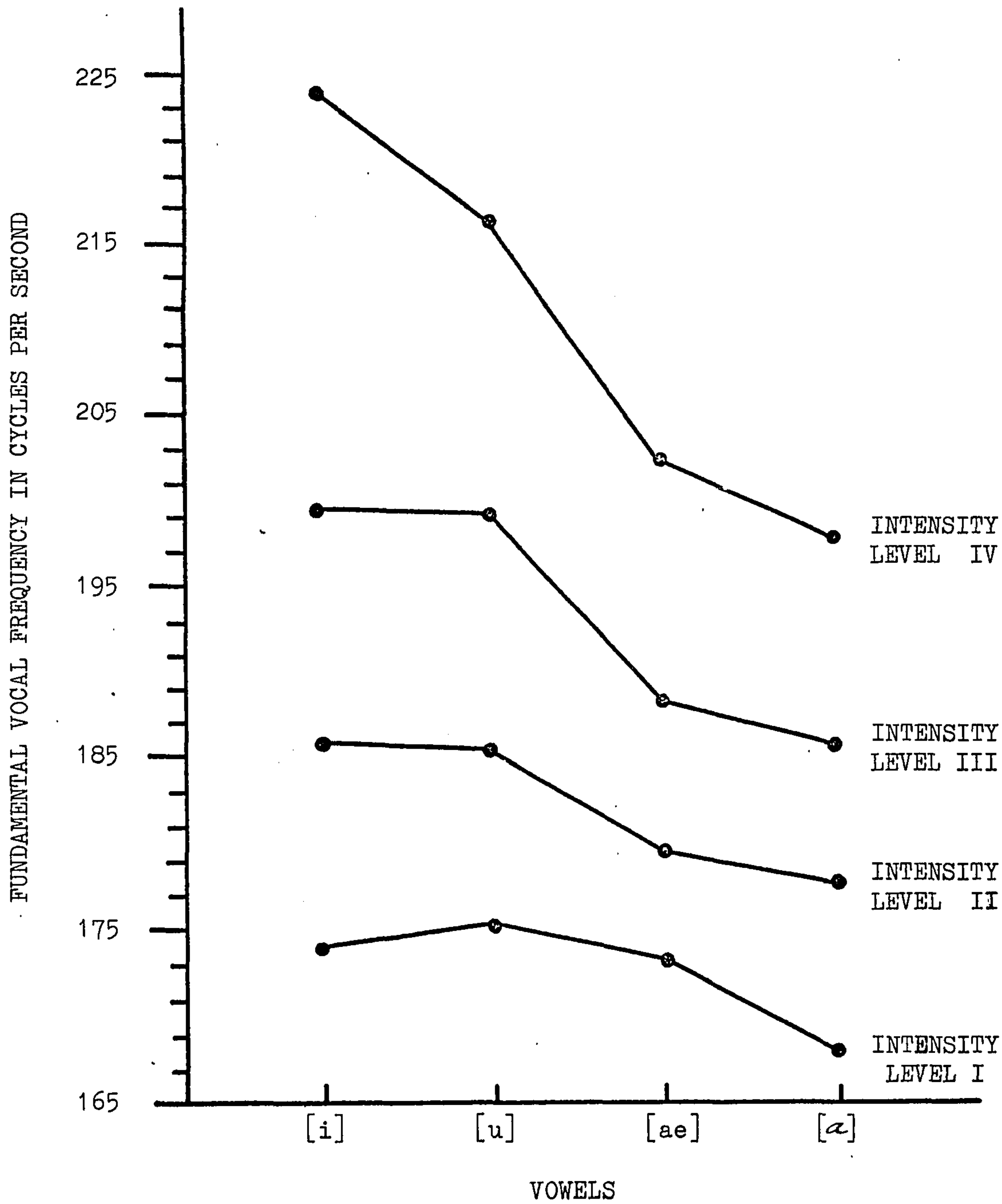

Figure 2.--Fundamental vocal frequency means for each of four vowels at each of four intensity levels. The means are derived over all groups and sexes.

for both [i] and [u] than that for [ae] and greater than that for both [ae] and [a] from Intensity Levels II to III to IV. This pattern results in a progressively greater difference between the vowel group [i] and [u] and the vowel group [ae] and [a] as intensity level is increased. These data also show that, although the means for [i] and [u] are almost identical at the three lowest intensity levels, the mean for [i] exceeds that for [u] at the highest intensity level. It may also be seen that the increase in mean fundamental vocal frequency is greatest for all vowels between Intensity Levels III and IV.

It is interesting to note that the relationship among the vowel fundamentals at the three highest intensity levels, 75, 80, and 85 dB are compatible with their differences in intrinsic amplitude as reported by Black (2), Fairbanks, House and Stevens (21), and Lehiste and Peterson (53). The work of Lehiste and Peterson is especially pertinent to the present findings since their data are concerned with the relative amplitude of isolated sustained vowels. These investigators report that the vowel [a] is approximately 5 dB more intense than the vowels [i] and [u] when vocal pitch was held constant at 145 cps. The vowel [ae] was approximately 3 dB more intense than [i] and [u] under these conditions. In the present investigation, each experimental vowel was produced at the same intensity at each of four specified intensity levels, so that relative power difference among vowels were obscured. This procedure presumably demanded greater effort for vowels with less intrinsic power at each of the intensity levels studied.

The relationships between vocal intensity and fundamental vocal frequency of vowels, displayed in Figure 2, are consistent with correlative research that has attempted to relate subglottal pressure, vocal intensity, and fundamental vocal frequency. The word of Ladefoged and McKinney (52) and Isshike (42) supports the existence of a strong relationship between subglottal pressure and vocal intensity. Isshiki's data indicate that vocal intensity is approximately proportional to subglottic pressure $^{3.3 \pm 0.7}$, and that this relationship applies to the entire pitch range. If an increase in subglottic pressure is associated with increased vocal intensity, it is reasonable to assume that differences in the intrinsic amplitude of vowels may be explained on the basis of the differences in subglottal pressure associated with their production. This assumption is supported by Ladefoged's findings that the vowel [ɑ] is approximately 5 dB more intense than the vowels [i] and [u] when each vowel is produced with the same subglottal pressure. It may be reasoned from these data that, were all vowels produced at the same intensity level, differences in subglottal pressure would be evident.

There is reason to believe that subglottal pressure is also related to fundamental vocal frequency. Ladefoged and McKinney (52) present data which indicate that increases in subglottal pressure are associated with proportional increases in fundamental vocal frequency. If it is assumed that subglottal pressure is proportional to both vocal intensity and fundamental vocal frequency, it may be reasoned that differences or changes in subglottal pressure should affect both of these acoustic parameters in a lawful way. It also seems reasonable to conclude that when vowels with relatively strong and relatively weak intrinsic amplitude are produced at a uniform intensity level, differences in subglottal pressure exist between vowels that are reflected in fundamental vocal frequency differences.

Inspection of Figure 2 reveals that the mean fundamental vocal frequency for [i] and [u] at each of the three lowest intensity levels is similar to that for [ɑ] at the next highest intensity level, i.e., at a level 5 dB more intense. Assuming that [ɑ] has greater intrinsic amplitude than [i] and [u] (approximately 5 dB, when each vowel is produced with the same subglottal pressure), it can be speculated that the differences in fundamental vocal frequency among these vowels are an artifact of their differences in intrinsic amplitude. To obtain a condition in which the three vowels are produced with a similar subglottal pressure in the present study, it is necessary to compare [i] and [u] at a given intensity level with [ɑ] at the next highest level. When this is done, the differences among these vowels means appear to be minimal. This line of reasoning is consistent with that of Lehiste and Peterson (52) who state:

> We have been considering the hypothesis that phonetic variations in pitch level are due, to a considerable degree, to the intrinsic relative amplitude of the vowel to which the pitch is applied . . . . It appears very probable that this phonetic variation in the pitch level associated with certain phonetic stress may be influenced to a considerable extent by the intrinsic amplitude of the nucleus of the syllable carrying the stress, higher pitch compensating for lower intrinsic amplitude.

The significant sex-by-intensity interaction, displayed in Figure 3, indicates that, when means are derived over all vowels and groups, the mean fundamental vocal frequency of females substantially exceeds that of males at each of the experimental intensity levels. Inspection of the means making up this interaction indicates that the

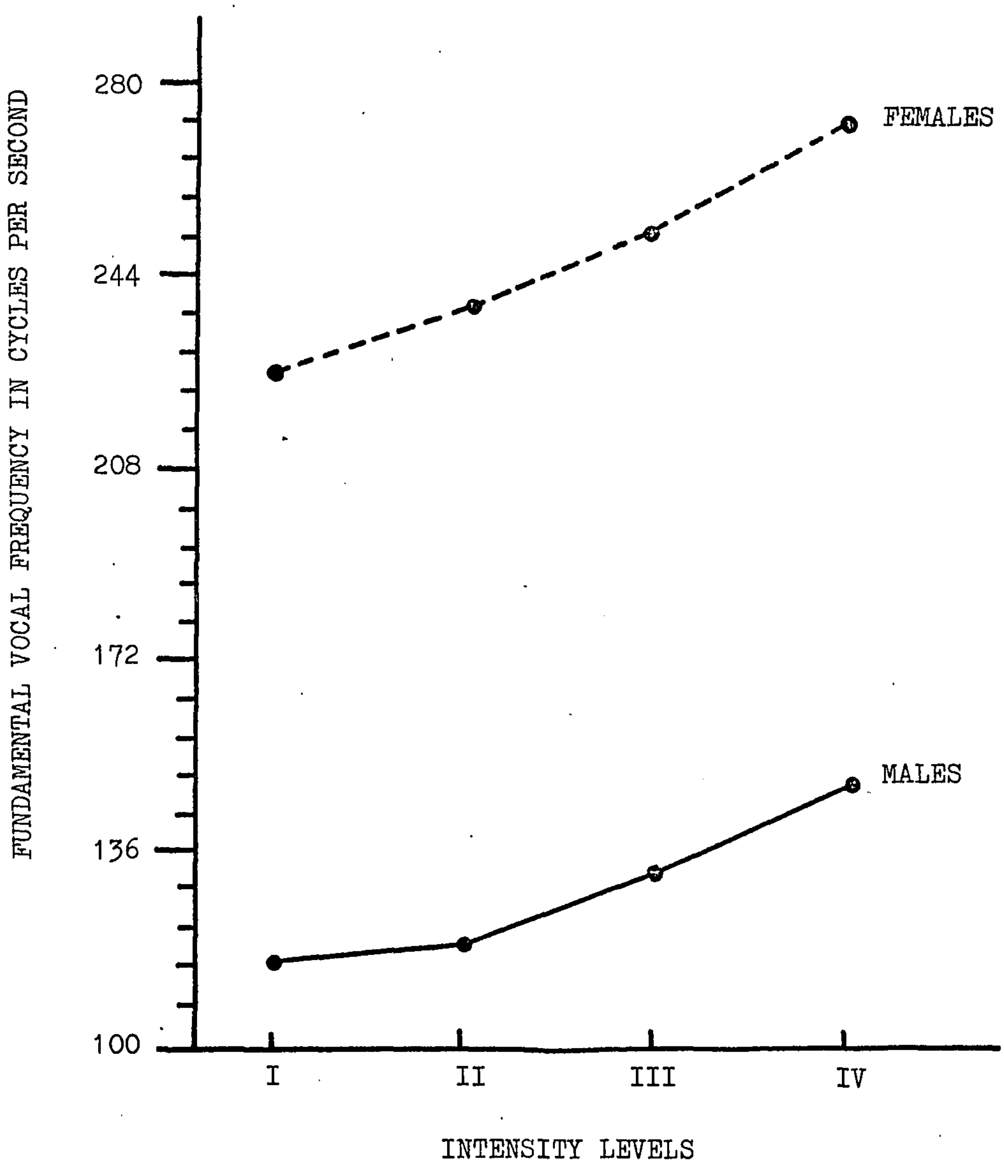

Figure 3.--Fundamental vocal frequency means for each of four intensity levels for male and female subjects. The means are derived over all vowels and groups.

mean fundamental vocal frequency of females at Intensity Level I is 229 cps; at Intensity Level II, 241 cps; at Intensity Level III, 253 cps; and at Intensity Level IV, 274 cps. The mean for males at Intensity Level I is 117 cps; at Intensity Level II, 123 cps; at Intensity Level III, 133 cps; and at Intensity Level IV, 147 cps. Examination of trends within the data plotted in Figure 3, suggests that consistent differences between the means for males and females exist at each intensity level. These differences, approximating one-octave, are compatible with the findings of other studies dealing with sex differences in fundamental vocal frequency (62). Although both sexes evidence an increase in fundamental vocal frequency with increased vocal intensity, the data show that the amount of increase in mean fundamental vocal frequency associated with the 5 dB increments in intensity is dissimilar for the sexes. Female subjects, for example, manifest an increase in mean fundamental vocal frequency of 12 cps from Intensity Level I to II and from Intensity Level II to III. From Intensity Level III to IV, however, this increase amounts to 21 cps. Male subjects evidence an increase in mean fundamental vocal frequency of 6cps from Intensity Level I to II; 10 cps, from Intensity Level II to III; and 14 cps, from Intensity Level III to IV. These differences in the differences among the means are the likely source of the significant sex-by-intensity interaction.

Although the significance of the sex-by-intensity interaction suggests that the increases in mean fundamental vocal frequency associated with increments in the experimental intensity levels differ for the sexes, a closer inspection of the means in Figure 3 indicates that such mean fundamental vocal frequency of females at Intensity Level I is 229 cps; at Intensity Level II, 241 cps; at Intensity Level III, 253 cps; and at Intensity Level IV, 274 cps. The mean for males at Intensity Level I is 117 cps; at Intensity Level II, 123 cps; at Intensity Level III, 133 cps; and at Intensity Level IV, 147 cps. Examination of trends within the data plotted in Figure 3, suggests that consistent differences between the means for males and females exist at each intensity level. These differences, approximating one-octave, are compatible with the findings of other studies dealing with sex differences in fundamental vocal frequency (62). Although both sexes evidence an increase in fundamental vocal frequency with increased vocal intensity, the data show that the amount of increase in mean fundamental vocal frequency associated with the 5-dB increments in intensity is dissimilar for the sexes. Female subjects, for example, manifest an increase in mean fundamental vocal frequency of 12 cps from Intensity Level I to II and from Intensity Level II to III. From Intensity Level III to IV, however, this increase amounts to 21 cps. Male subjects evidence an increase in mean fundamental vocal frequency of 6 cps from Intensity Level I to II; 10 cps, from Intensity Level II to III; and 14 cps, from Intensity Level III to IV. These differences in the differences among the means are the likely source of the significant sex-by-intensity interaction.

Although the significance of the sex-by-intensity interaction suggests that the increases in mean fundamental vocal frequency associated with increments in the experimental intensity levels differ for the sexes, a closer inspection of the means in Figure 3 indicates that such a conclusion may be misleading. Examination of the differences between the means for the sexes at each intensity level reveal that the differences are similar in proportion at each level. For example, if the mean fundamental vocal frequency for males is expressed as a proportion of the mean for females at each intensity level, the proportions obtained are .51, .51, .53, and .54 at Intensity Levels I, II, III, and IV, respectively. These data suggest that the mean fundamental vocal frequency for males bears a reasonably constant relationship to that of the females at each intensity level. Further, if the mean fundamental vocal frequency at each intensity for each sex is expressed as a proportion of a reference frequency one octave above the fundamental for that sex at the lowest intensity level, the increments in fundamental frequency between intensity levels seem to be similar for the sexes. For the male group, these proportions are .50, .53, .57, and .63 at Intensity Levels I, II, III, and IV, respectively. For females, these proportions are .50, .53, .55, and .60, respectively. From these data, it is possible to conclude that both male and female groups display a similar proportional increase in fundamental vocal frequency with each increase in experimental intensity level.

Groups

Inspection of Table 1 shows that the group main effect is not significant. The presence of significant interactions involving groups, sex, and vowels, however, suggests that differences in the mean fundamentals of individual vowels exist between the cleft palate and normal groups and that these differences vary for the sexes within each group. Although the significance of differences among individual means is not revealed by the present statistic, a discussion of the trends within the data is useful.

Of primary interest in this analysis is the group-by-sex-by-vowel interaction displayed graphically in Figures 4 and 5. Inspection of Figure 4 reveals, that, for normal female subjects, the highest mean fundamental vocal frequency occurs for [i], 269 cps, followed in order by those for [u], 264 cps, [ae], 247 cps, and [ɑ], 242 cps. For cleft palate females, the highest mean fundamental is seen for [u], 247 cps, followed in order by those for [i], 243 cps, [ae], 242 cps, and [ɑ], 236 cps. Each of these means are derived over all intensity levels. It may be noted that the largest differences between means for the same vowel produced by the two groups are those for [i], 26 cps, and [u], 17 cps; differences between the group means for [ae], 5 cps, and [ɑ], 6 cps, are relatively small. The range of vowel means within each subject group is also substantially different. For normal females, the difference between the highest and lowest vowel means amounts to 27 cps; for cleft palate females, this difference is 11 cps.

Figure 5 shows that, for normal male subjects, the highest mean fundamental vocal frequency occurs for [i], 138 cps, followed by those for [u], 135 cps, [ae], 127 cps, and [ɑ], 125 cps. For cleft palate males, the highest mean fundamental is seen for [i], 134 cps, followed by those for [u], 131 cps, [ae], 127 cps, and [ɑ], 125 cps. Unlike the differences between normal and cleft palate females, it can be seen that the differences in mean fundamental vocal frequency between cleft palate and normal males are uniformly small. The greatest differences between means for the same vowels produced by the two groups, 4

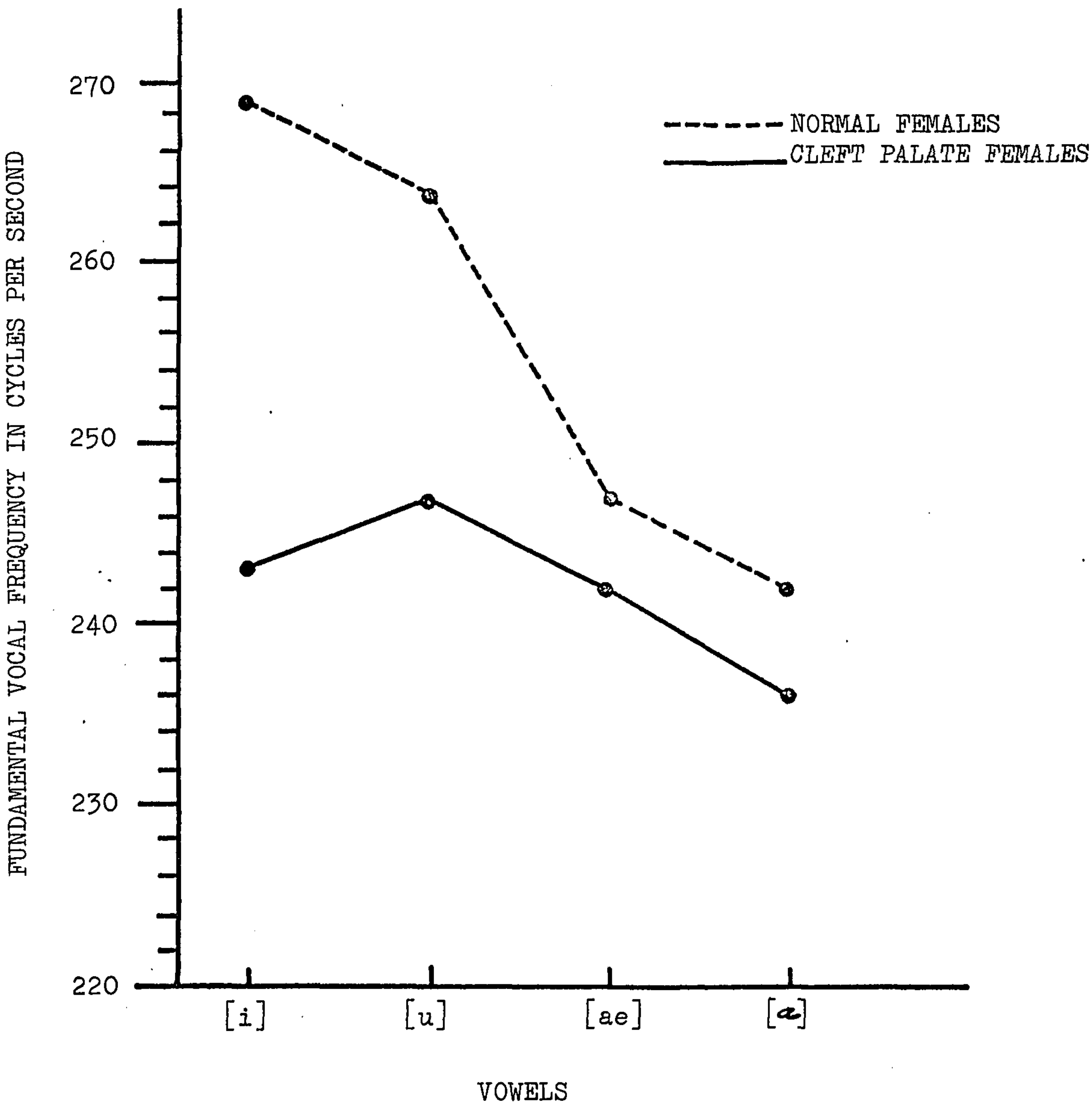

Figure 4.--Fundamental vocal frequency means for each of four vowels for cleft palate and normal-speaking female subjects. The means are derived over all intensity levels.

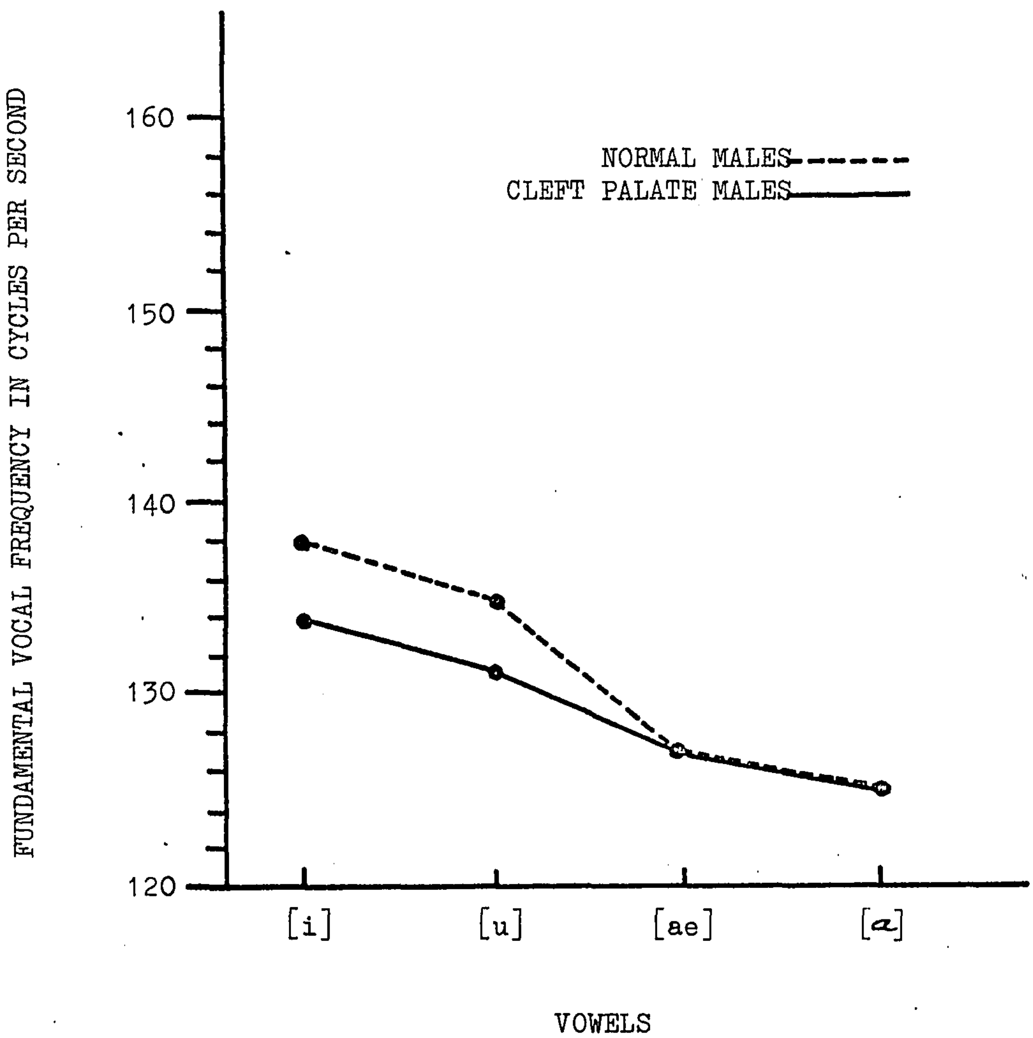

Figure 5.--Fundamental vocal frequency means for each of four vowels for cleft palate and normal-speaking male subjects. The means are derived over all intensity levels.

cps, are seen for [i] and [u]. The range of vowel means within each group is also similar. For cleft palate males, this range is 9 cps; for normal males, the range amounts to 13 cps.

These data suggest that the differences between the cleft palate and normal groups seen in the group-by-vowel interaction are primarily attributable to the lower fundamentals for [i] and [u] for cleft palate females, or, conversely, the higher means for those vowels for normal females. The differences between means for the same vowels produced by cleft palate and normal males are small and would seen not to be a major factor in this interaction.

Examination of the relationships among the vowel means displayed in Figures 4 and 5 suggests that the lesser differences among the means for vowels produced by cleft palate females may be critical to an understanding of this interaction. If the mean fundamental vocal frequency for each vowel for each of the four subject groups is expressed as a proportion of the lowest vowel mean for that group, [ɑ], the relative fundamental vocal frequency of the vowels is more clearly seen. For normal males, the proportion for [i] is 1.10, followed in order by those for [u], 1.08, [ae], 1.00, and [ɑ], 1.00. For normal females, the proportion for [i] is 1.11, for [u], 1.09, [ae], 1.00, and [ɑ], 1.00. For cleft palate males, the proportion for [i] is 1.07; for [u], 1.05, [ae], 1.00, and [ɑ], 1.00. For cleft palate females, the proportion for [i] is 1.03, for [u], 1.05, for [ae], 1.02; and for [ɑ], 1.00.

From these data, it is apparent that the relationship among the mean fundamental vocal frequencies of the four vowels is similar for normal males and females and for cleft palate males. The proportions shown for cleft palate females suggest that there are proportionally smaller differences among the vowel means for these subjects than for the other subject groups. Although there is no cogent explanation of this finding, it is possible that oral-nasal coupling may have a differential effect upon the amplitude of individual vowels, altering their relative intensity. Such an interpretation is consistent with the findings of House and Stevens (40) who studied the over-all level of vowels under various oral-nasal coupling conditions by means of an electronic analog. Their data indicate that the loss in over-all level with increased nasal coupling varies for individual vowels, ranging from a loss of 5 dB for [i] to a loss of 9.5 dB for [ɔ]. It is possible, therefore, that increased nasal coupling may reduce the differences in relative amplitude among vowels. If differences in the fundamental vocal frequency of vowels are related to their differences in amplitude (53), such an effect would minimize the fundamental vocal frequency differences among vowels.

It is apparent, however, that if the hypothesis posed above is valid, the effect of oral-nasal coupling on relative vowel amplitude must differ for the sexes. To be consistent, the hypothesis requires that, for females, nasal coupling reduces the amplitude of the vowels [ɑ] and [ae] to a greater extent than [i] and [u]; for males, it must be assumed that the amplitude of all vowels is reduced to a similar degree. Since differences in the intrinsic amplitude of vowels, measured at a certain point outside the mouth, are influenced by such factors as the shape of the vocal tract (44) and the area of mouth opening (47), it is possible that differences in the physiology and acoustics of vowel production between cleft palate male and female subjects account for differences in the relative amplitude of vowels produced by the two groups. This difference in relative vowel amplitude might account, then, for the differences in the relative fundamental frequency of vowels displayed by the two groups. On the basis of these data, further investigation of physiologic and acoustic differences in vowel production that may exist between cleft palate male and female subjects would seem useful. The existence of sex-related differences in the acoustic structure of vowels has been suggested by Sacia (70), who writes:

> These results suggest a difference in the resonant structure between the male and female voices, which, however, does not effect the higher frequencies enough to alter the vowel characteristics.

It is also possible that the present findings may not reflect accurately the differences in fundamental vocal frequency that exist between the cleft palate and normal-speaking groups and this, in large part, may be due to the design of the present experiment. Research dealing with the effect of oral-nasal coupling on the over-all level of vowels indicates that there is a loss of acoustic power when the nasal and oral cavities are coupled. In light of this finding, the effect of requiring cleft palate and normal speakers to produce vowels at a uniform intensity level is to eliminate the differences in over-all level that obtain between the groups. Presumably, cleft palate persons utilize greater vocal effort at each intensity level in an attempt to compensate for the power loss imposed by excessive nasal coupling, resulting in an increased fundamental vocal frequency. It may be, therefore, that wider differences in fundamental vocal frequency would exist between the two groups were it possible to compare them under conditions of equal vocal effort.

The findings of the present study are in agreement with those reported by Flint (25) who studied fundamental vocal frequency differences between cleft palate and normal-speaking subjects in production of isolated sustained vowels at a single intensity level (75 dB SPL). Flint reports a significantly lower mean fundamental vocal frequency for her cleft palate than for her normal female subjects. Significant differences did not obtain between the cleft palate and normal-speaking male groups. It should be noted, however, that the means for Flint's cleft palate female group for each of the vowels [i], [u], [ae], and [a] are more than 20 cps lower than the means reported for cleft palate females in the present investigation. The means for the normal female groups are similar in the two studies.

Dickson (15), who studied fundamental vocal frequency differences among groups of normal, functionally nasal, and nasal cleft palate speakers, reports findings that differ somewhat from those of the present investigation. Dickson studied the vowels [i] and [u] in CVC contexts produced by male speakers. In his study, the vowel samples produced by subjects in each of the three experimental groups were rated in nasality and, on the basis of this rating, all subjects were reassigned to three groups: a "least nasal group," a "mid-group," and a "most-nasal group." Comparisons of the fundamental vocal frequency of subjects in each of the three groups indicated that subjects with greater nasality display higher fundamental vocal frequency than subjects with less nasality.

It is apparent, however, that differences in the design of the present study and that of Dickson preclude a direct comparison of results. This is true for several reasons. First, since comparisons in the Dickson study are made among subjects grouped according to degree of nasality, comparisons between the "least nasal" group and the "mid" and "most nasal" groups inevitably involve comparisons between normal speakers and a mixed group of functionally nasal and cleft palate subjects. Direct comparisons, therefore, between normal and cleft palate speakers are not implied. Second, differences in fundamental vocal frequency between nasality groups were determined by counting the number of subjects in each group with fundamental vocal frequencies above 130 cps. Differences between the mean fundamental vocal frequencies of the groups, therefore, are not available for comparison with the present data. Last, it is possible that the differences in fundamental vocal frequency that exist between cleft palate and normal speakers in isolated vowels may be altered both in direction and extent when they are examined in consonant contexts. This latter possibility deserves further investigation.

CHAPTER V

SUMMARY AND CONCLUSIONS

The purpose of the present study was to explore the relationships and differences among the fundamental vocal frequencies of four vowels produced at each of four intensity levels by groups of normal-speaking and cleft palate subjects. Twenty adolescent and adult cleft palate persons, ten male and ten female, and twenty normal speakers, matched to them according to age and sex, served as subjects. To obtain a cleft palate sample with velopharyngeal incompetency, all cleft palate subjects were required to present oral breath-pressure ratios less than .75.

Each subject sustained each of the vowels [i], [u], [ae], and [a] in isolation at each of four intensity levels: 70, 75, 80, and 85 dB SPL at a mouth-to-microphone distance of eight inches. Each vowel was sustained for approximately four seconds. The vowel samples were tape-recorded and subsequently analyzed by instrumentation that provided a measure of fundamental vocal frequency. Fundamental vocal frequency measures were made only of the stable mid-portion of each vowel sample.

The intensity of each vowel production was monitored by the subject who maintained a constant, predetermined needle deflection on the dial of a sound pressure level meter. No instructions were given to the subject with respect to vocal pitch. The actual intensity at which each vowel sample was produced was verified using a graphic level recorder; no vowel production accepted for inclusion in the study varied by more than one decibel from the reference intensity levels used in this investigation. Analysis of the data was accomplished using a split-plot analysis of variance with a factorial arrangement of treatments. The confidence level was set at .05.

Effect of Vocal Intensity Changes in Fundamental Vocal Frequency

One of the major purposes of the present study was to examine the effect of changes in vocal intensity level on the fundamental vocal frequency of vowels produced by groups of male and female cleft palate and normal speakers. The findings of the present investigation indicated that none of the interactions involving groups and intensity levels was significant at the experimental confidence level. On this basis, it was possible to conclude that, although cleft palate and normal speakers may display differences in mean fundamental vocal frequency, the differences can be assumed to exist to a similar degree at each of the intensity levels studied. To understand the effect of vocal intensity changes on the fundamental vocal frequency of both subject groups, therefore, it was necessary to examine the significant interactions involving vowels, sex, and intensity.

Evaluation of the significant vowel-by-intensity interaction disclosed that the mean fundamental vocal frequencies of the vowels [i] and [u] were consistently higher than that for [ɑ] at all intensity levels and higher than that for [ae] at the three highest intensity levels. At the lowest intensity level, the means for [i], [u], and

[ae] were similar. Although the mean fundamental vocal frequency of each vowel showed an increase with each increase in intensity, it was apparent that the magnitude of the differences between the vowel group [i] and [u] and the vowel group [ae] and [ɑ] increased as vocal intensity increased. This finding suggested that, as vocal intensity was increased, a greater increase in fundamental vocal frequency occurred for the vowels [i] and [u] than for the vowels [ae] and [ɑ].

It was speculated that the differences in fundamental vocal frequency of the four vowels might be related to the differences in intrinsic amplitude, i.e., intrinsically weaker vowels require a greater increase in fundamental vocal frequency than vowels that are intrinsically more intense. Inspection of the relationships between the vowel group [i] and [u] and the vowel group [ae] and [ɑ] revealed that the means for the latter group at each of the three highest intensity levels corresponded closely to the means for the former vowel group at the next lowest intensity level. This relationship appeared to support the contention of Lehiste and Peterson (53) that differences in the natural frequency of vowels may be influenced to a considerable extent by differences in their intrinsic amplitude. It was also found that the greatest increase in fundamental vocal frequency occurred, for all vowels, between the two highest intensity levels, 80 and 85 dB SPL.

Evaluation of the significant sex-by-intensity interaction revealed that, as expected, females evidenced mean fundamental vocal frequencies that were approximately one octave higher than those for males. Examination of the proportions between the fundamental vocal frequencies of males and females at each intensity level indicated that the differences between the sex groups was generally similar at each intensity level. Although the female group evidenced a greater absolute increase in fundamental vocal frequency as vocal intensity was increased, the proportional increase in fundamental vocal frequency was similar for the sexes. In this analysis, the mean fundamental vocal frequency for each sex at each intensity was expressed as a proportion of a reference frequency that was one octave above the fundamental for that sex at the lowest intensity level. These data suggested that the male and female groups employed a similar proportional adjustment of fundamental vocal frequency as they increased intensity in these 5-dB steps.

Differences in the Fundamental Frequency of Vowels Between the Cleft Palate and Normal-Speaking Groups

Although the group main effect was not significant, evaluation of the significant group-by-sex-by-vowel interaction suggested that differences in the mean fundamental vocal frequencies of individual vowels existed between the cleft palate and normal speaking groups and that these differences varied for the sexes within each subject group. Evaluation of this interaction revealed that the difference between the mean fundamental vocal frequency of each experimental vowel produced by cleft palate and normal male sub-groups was small, amounting at maximum to 4 cps. Differences between the cleft palate and normal female sub-groups in production of the vowels [ae] and [ɑ] were also relatively small, amounting at maximum to 6 cps. Substantial differences, however, existed between the means for cleft palate and normal sub-groups in production of the vowels [i] and [u], 26 cps and 17 cps, respectively. These differences between the means for cleft palate and normal female sub-groups appeared to constitute the primary source of the group-by-sex-by-vowel interaction.

When the mean fundamental vocal frequency of each of the four vowels for each of the sub-groups was expressed as a proportion of the lowest vowel mean for that group, it was found that smaller differences among the vowel means existed for the cleft palate female group than for any other group. The proportional difference among the means for the four vowels used in this experiment was essentially similar for normal males and females and cleft palate males. This finding suggested that some factor was operating to reduce the normal differences in fundamental vocal frequency among these vowels in the cleft palate female group. It was hypothesized that the differences in the natural frequency of vowels may be an artifact of their differences in relative intensity and that alterations in the relative intensity of vowels occur to a greater extent for cleft palate females than for cleft palate males, resulting in smaller differences among the mean fundamental vocal frequencies of the vowels.

Since differences in the intrinsic amplitude of vowels, measured at a certain point outside the mouth, are influenced by such factors as the shape of the vocal tract (44) and the area of mouth opening (47), it is also possible that differences in the physiology and acoustics of vowel production between cleft palate male and female subjects account for differences in the relative amplitude of vowels produced by the two groups. Such differences in relative vowel amplitude could account for the differences in the relative fundamental vocal frequency of vowels displayed by the two groups. On the basis of these data, further investigation of physiologic and acoustic differences in vowel production that may exist between cleft palate male and female subjects would seem useful.

Within the limitations of the present experiment, the following conclusions appear warranted:

1. Differences in mean fundamental vocal frequency exist among the vowels [i], [u], [ae] and [ɑ], when means are derived over all groups, sexes, and intensity levels.

2. When means are derived over both groups and sexes, differences among the mean fundamental vocal frequencies of these vowels are compatible with their differences in intrinsic amplitude. When produced at the same intensity level, vowels with lower intrinsic amplitude are characterized by higher fundamental vocal frequency than vowels with greater relative intensity.

3. When means are derived over both groups and sexes, the mean fundamental vocal frequency of each experimental vowel increases with each 5-dB increment in intensity from 70 to 85 dB SPL.

4. When means are derived over both groups and sexes, the mean fundamental vocal frequencies of the vowels [i] and [u] are increased to a greater extent than those for [ae] and [ɑ] with each 5-dB increment in intensity from 70 to 85 dB SPL.

5. When means are derived over both groups and sexes, the greatest increase in mean fundamental vocal frequency occurs, for all vowels between the two highest intensity levels, 80 and 85 dB SPL.

6. When means are derived over both groups and all vowels,

female subjects evidence a greater absolute increase in fundamental vocal frequency between the experimental intensity levels than do males. The increases, however, are similar for both sexes when they are viewed as proportions of a reference frequency one octave above the fundamental for each sex at the lowest intensity level, 70 dB SPL.

7. When means are derived over both groups and all vowels, the mean fundamental vocal frequency for males bears a similar relationship to that of the females at each intensity level.

8. When means are derived over all intensity levels, the cleft palate and normal male groups display similar mean fundamental vocal frequencies for each of the experimental vowels. Significant differences in mean fundamental vocal frequency in production of the vowels [i] and [u] occur between the cleft palate and normal female groups. The cleft palate female group evidences lower fundamentals for these vowels than the normal female group.

Limitations of the Present Study

The experimental design of the present study might be altered profitably in future studies of the relationship of vocal intensity and fundamental vocal frequency in cleft palate and normal speakers. First, since a major purpose of the present investigation was to explore the differences that may exist between groups of male and female cleft palate and normal speakers, no attempt was made to control the selection of subjects on the basis of fundamental vocal frequency. The range of fundamental vocal frequency within each subject sub-group, as might be expected, was wide. Although this distribution of subjects allowed the study of intergroup differences in fundamental vocal frequency, it may have obscured the different effects of intensity changes on the fundamental vocal frequency of individual subjects within each group. It is possible, for example, that low-pitched subjects in each subgroup may have made different adjustments in fundamental vocal frequency with the same change in vocal intensity level than high-pitched subjects. If such were the case, the present study would not show it.

Second, although a range of intensity levels was employed in this study, it might be useful to obtain fundamental vocal frequency data for vowels produced at intensity levels above and below those used. An examination of the fundamental vocal frequency differences between cleft palate and normal speakers at the upper and lower limits of their intensity range might serve to define further relationships that are suggested by the present data.

Third, although an attempt was made to identify cleft palate subjects with velopharyngeal incompetency, using oral breath-pressure ratios, the study would have been enhanced if the degree of oral-nasal coupling of each subject could have been specified more accurately. If this had been done, the effect of specific degrees of nasal coupling on fundamental vocal frequency could have been determined.

Last, many unresolved questions posed by the present findings might have been answered if concomitant subglottal pressure and oral-nasal air flow data had been obtained with the measures of vocal intensity and fundamental vocal frequency. It seems increasingly apparent that an understanding of the physiologic events underlying acoustic changes is necessary if the acoustic end-product of speech is to be fully understood. Attempts to derive an understanding of these physiologic processes through analysis of the acoustic signal alone would appear to have serious limitations.

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