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SOME RELATIONSHIPS BETWEEN SPECTRAL HARMONIC LEVELS AND VOCAL ROUGHNESS FOR VOWELS PRODUCED BY ADULT FEMALES

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SOME RELATIONSHIPS BETWEEN SPECTRAL HARMONIC

LEVELS AND VOCAL ROUGHNESS FOR VOWELS

PRODUCED BY ADULT FEMALES

APPROVED BY

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CHAPTER I

INTRODUCTION

Clinicians commonly include in their evaluations of the vocally abnormal patient a perceptual evaluation of vocal quality. The relationships of perceived quality features to associated acoustic and physiological features in speech have not been fully delineated, however. Systematic, objective, laboratory investigations designed to study further the relationship of perceived quality to associated acoustic speech features are thus among those which are currently needed.

Laboratory studies of vocal quality generally require the explicit identification of the perceived quality investigated. In this regard, it may be noted that descriptions of voice quality in the literature may frustrate rather than aid voice quality identification in research. Few conventions regarding the "appropriate" labeling of voice qualities have been established. Moreover, identifying labels are commonly applied to vocal qualities which are perceived to be abnormal, but seldom to qualities perceived to be within normal limits. The term "hoarseness," for example, is often used in the literature to denote a quality which is sufficiently rough to be regarded as abnormal. Until recently, however, no term was suggested to denote the lesser degree of that same quality which is associated with phonations which are essentially normal.

It has been recommended by some investigators (14, 15, 21, 38, 54, 76) that "vocal roughness" be used as a term which denotes a vocal quality continuum along which both normal and abnormal phonations may be located. Findings reported by these investigators reveal that the roughness continuum concept tends to be accepted as meaningful. Moreover, when speech samples produced by normal-speaking and clinically hoarse subjects are rated for roughness on an equal-appearing intervals scale by a panel of judges, a high degree of intra- and inter-judge agreement regarding the roughness of the samples is generally attained (21). Thus, vocal roughness appears to be an identifiable vocal quality and a claim may be made on the basis of experimental evidence that the concept of a roughness continuum is valid.

It is important in studies of vocal roughness to recognize the constraints which are inherently associated with the measurement of quality perception. It is pertinent, for example, that the perception of vocal quality is an experience unique to the individual and, thus, is contingent in part upon each individual's past experience, present physical and emotional status, and the nature of the environment in which quality evaluations are made. Moreover, an individual's perception of vocal roughness cannot be measured directly. Hirsh (23) observed that "we cannot measure...sensations that are private, but we can measure sensations that are defined in terms of behavior or observable responses." It is possible, therefore, to evaluate indirectly the perception of vocal roughness. It is a common research practice to require a panel of listeners to rate vocal roughness on a defined perceptual scale; thus, it is the listener's response, presumably based upon his perception of vocal roughness, which is actually measured.

Because the perceived quality of phonation appears to relate generally to the spectral structure of the complex acoustic wave of phonation, the delineation of the acoustic features likely to relate meaningfully to quality perception may be achieved with the aid of acoustic spectrography. In studies of the relationship of perceived vocal roughness to acoustic spectral features, the particular approach to spectrographic analysis has varied somewhat across studies. Generally, however, investigators have sought to visualize and to measure the relative level of harmonic and inharmonic acoustic components associated with selected test phonations differing in roughness. On the basis of their spectrographic findings, investigators (14, 15, 21, 38, 54, 76) have proposed recently that the acoustic cues critical to the perception of vowel roughness might be manifested in the relationship between the spectral harmonic and inharmonic components. Specifically, it has been hypothesized that as vowel roughness increases, the level of the low-frequency harmonic components of the acoustic signal will decrease while the level of the inharmonic or noise components will increase across a broad frequency range.

To provide data pertinent to a test of this hypothesis, Emanuel and Whitehead (15) measured the levels of each of the first five harmonics in the narrow-band (3-Hz) acoustic spectra of selected vowels produced normally and with simulated abnormal vocal roughness by twenty normal-speaking adult males. They then related the harmonic level measures to measures of vowel roughness and spectral noise. In general, their findings were consistent with the "trading relationship" hypothesis presented above, but their study has not as yet been verified by replication. Nor has a study been completed investigating vowel spectral harmonic levels and their relationships to vowel spectral noise levels and perceived vowel roughness utilizing the phonations of adult female subjects. Because their voices tend to differ in some respects from those of males, such data for female subjects are relevant to a complete description of the acoustic features of vocal roughness. It was the purpose of this investigation, therefore, to study the harmonic levels associated with normal and simulated abnormally rough vowels produced by adult female subjects, and the relationship of the harmonic level measures to measures of perceived roughness and spectral noise for the vowels.

CHAPTER II

REVIEW OF THE LITERATURE

Investigators have sought to isolate acoustic features which might relate to vocal quality perception. Such studies have provided new information regarding non-phonemic acoustic and perceptual vowel features. Recently, for example, an investigation of the acoustic spectral features of vowels produced by adult males (15) has revealed that the level of low-frequency spectral harmonics tends to decrease while the level of broad-spectrum inharmonic (noise) components tends to increase with increasing vowel roughness. Though potentially useful, a comparable study of the phonations of adult female subjects has not been completed. For the present study, therefore, narrow-band (3-Hz) acoustic spectrography was employed to investigate acoustic features of the roughness perceptually associated with vowels produced by adult females. Specifically, the purpose of this investigation was to study quantitatively spectral harmonic levels associated with normal and simulated abnormally rough vowel productions. Possible relationships between vowel spectral harmonic and noise levels and perceived vowel roughness were also investigated. Literature reviewed as background to this study is reported under the headings: (a) Perceptual Features of Vocal Roughness; (b) Physiological Features of Vocal Roughness; and, (c) Acoustic Features of Vocal Roughness.

Perceptual Features of Vocal Roughness

Voice quality evaluations generally require the precise identification and definition of the vocal quality perceived. Because some of the quality differences delineated by special labels in the literature may not be delineated perceptually by listeners, some authors (1, 46, 63) equate terms used to describe quality disorders of laryngeal origin. Moore and Thompson (43), for example, observed that the "hoarse" vowel samples which they studied were probably comparable in quality to the "harsh" samples studied by others.

There is at least some research support for considering qualities such as "hoarseness" and "harshness" to be perceptually equivalent. Thurman (64), for example, found that sophisticated listeners were able to determine reliably whether an abnormal voice quality was associated with a resonance or with a phonatory disorder, but the same listeners were not able to differentiate reliably among qualities associated with phonatory disorders. Thurman instructed 67 judges to classify each of 129 speech samples as "breathy," "hoarse," "harsh," "strident," or "nasal" in quality. For only 76 of these samples was listener agreement regarding the abnormal quality sufficient to warrant further analysis. Moreover, when the 76 samples were classified independently by two different groups of listeners, only 51% of the samples received a mean classification in the second judgment identical to that obtained in the first judgment. Greatest confusion was noted among the qualities "hoarse," "harsh," "strident," and "breathy," i.e., the "phonatory" qualities.

Kreul and Hecker (30) studied connected speech samples produced by normal-speaking adult males and adult males presenting quality disorders secondary to laryngeal malignancies. Twenty-two naive listeners rated the speech samples separately for "hoarseness," "harshness," and "breathiness." These terms were not defined for the listeners. These investigators found that the judged degrees of "hoarseness," "harshness," and "breathiness" associated with the speech samples tended to vary together. On the basis of their findings, Kreul and Hecker concluded " . . . that either the concepts of nominally different voice qualities overlap in the minds of naive listeners or, at least for the laryngeal disease under consideration, well-defined voice qualities coexist perceptually."

The findings of Thurman and of Kreul and Hecker may be interpreted to support the use of a single descriptive term to refer to voice quality features associated with phonatory phenomena. Investigators have recently defined "vocal roughness" as a perceptually delineated continuum of phonatory quality. "Abnormal vocal roughness" encompasses those qualities which are commonly described as "hoarse" or "harsh." Findings from several studies (14, 15, 21, 38, 54, 76) indicate that listeners can rate reliably the degree of roughness associated with either isolated vowel or connected speech samples. Because neither acoustic nor perceptual differences have been demonstrated among "hoarse," "harsh," and "abnormally rough" qualities, and because it appears that they may be comparable perceptually, at least when isolated vowels are considered, selected literature relating to each of these qualities was reviewed for the present study.

It is pertinent in research to recognize those factors which may affect the perception of roughness and "similar" qualities. Generally, it has been found that tongue height in vowel production tends to influence the degree of roughness perceptually associated with isolated vowels. Sansone and Emanuel (54), for example, studied the roughness associated with isolated, sustained vowels produced normally and with simulated abnormal roughness by adult male subjects. They found that the high vowels /u/ and /i/ tend to be perceived as less rough than the mid vowel /ʌ/ and the low vowels /ɑ/ and /æ/. Similar trends have been reported by others for vowels produced normally and with simulated abnormal roughness by adult females (38) and for vowels produced by subjects presenting clinically hoarse voices (21).

Rees (53) also found that high vowels tended to be judged less harsh than low vowels when the test vowels were produced either in isolation or in CV and CVC syllables by adult males. She found no significant difference, however, in the rated harshness of front and back vowels produced in isolation or in CV and CVC syllables. These findings regarding the effects of tongue height on the harshness of vowels produced in isolation and in syllables appear generally consistent with the findings for vowels in connected speech. Sherman and Linke (56), for example, required subjects presenting clinically harsh voices to read six paragraphs, each of which was "loaded" with a particular vowel type. They found that a paragraph loaded with front vowels did not differ in perceived harshness from a paragraph loaded with back vowels. A paragraph containing low vowels, however, was judged to be significantly more harsh than one containing high vowels, and a paragraph containing tense vowels was judged to be more harsh than one containing lax vowels.

Rees (53) also studied consonant effects on vowel harshness when the test vowels were produced in CV and CVC syllables, and she found that the consonants with which vowels are syllabically combined tend to affect perceived vowel harshness. Specifically, she found that vowels in voiced consonant environments tend to be rated more harsh than those in voiceless consonant environments; and, further, that vowels in fricative environments tend to be rated more harsh than those in plosive environments, regardless of consonant voicing. She also found, however, that vowels produced in isolation did not differ significantly in harshness from those combined with voiced fricative consonants in CV and CVC syllables. Thus, it appears that vowels in isolation tend to be perceived at least as harsh as vowels in CV and CVC syllables. Rees also observed that vowels initiated with the voiceless glottal fricative /h/ tend to be judged less harsh than isolated vowels, but more harsh than vowels in CV or CVC syllables. Further, the harshness of the vowels /ʊ/, /I/, and /ʌ/ was more markedly affected by changes in phonetic environment than that of the vowels /i/, /u/, /ɔ/, /æ/, /ɑ/, or /ɛ/. Comparable findings have been reported by Brubaker and Dolpheide (5) for hoarse vowels in CV and CVC syllables. Rees (52) also investigated relationships between the perceived abruptness of phonatory initiation and the perceived harshness of her test vowels. She found a significant relationship between ratings of abruptness of initiation and harshness only for the vowel /æ/. Both relatively abrupt initiation and relatively severe harshness were associated with /æ/.

To study the effects of the "meaningfulness" of connected speech samples on the perceived harshness of the samples, Sherman (55) required subjects presenting clinically harsh voices to read six paragraphs each of which was "loaded" with a particular vowel type. These paragraphs were recorded and subsequently rated for harshness by a panel of judges both during forward and backward play. Judgments of the harshness of these connected speech samples appeared to be reliable both when the samples were played forward for rating and when they were played backward; however, Sherman reasoned that greater judgment validity may be achieved when connected speech samples are played backward. She thought that the "quality" differences among test passages should be more apparent perceptually and be influenced less by "extraneous factors" when the passages were played backward. Sherman found that a passage loaded with high vowels was rated as the least harsh test passage of the several tested in both backward and forward play. A passage loaded with tense vowels was rated as the most harsh test passage when played forward. Yet when the same samples were played backward, a passage loaded with tense vowels was rated among the least harsh of the test passages. The passage loaded with tense vowels had, in a separate judging, been ranked as "least effective in conveying meaning" and Sherman suggested that this "extraneous factor" may have influenced listeners' perception of the harshness of the passage when it was played forward.

Studies of the perception of synthesized sound stimuli suggest that the fundamental frequency of a complex acoustic signal may affect perceived signal roughness. Coleman (8) used seven-point equal-appearing intervals and direct-magnitude estimation scaling procedures in a study of the roughness of synthesized signals. He found, for complex signals evidencing the same aperiodicity, that stimuli having a relatively low median frequency were rated more rough than those having a relatively high median frequency. These results are of interest in view of reports that high vowels, which tend to have a higher fundamental vocal frequency than low vowels (5, 21, 38, 54, 55, 56), tend to be judged less rough than low vowels.

In summary, the literature reviewed suggests that the fundamental frequency of a signal may influence its perceived roughness. Further, listeners appear able to rate reliably the roughness of both normal and abnormal isolated vowel productions and that associated with synthesized acoustic stimuli. The literature also suggests that the degree of roughness perceptually associated with vowel phonations depends in part on the vowel produced, and, if the vowel is in context, on the phonetic environment in which it is produced. Further, the degree of roughness perceptually associated with normal and with abnormally rough vowel phonations appears to vary according to tongue height in vowel articulation, high vowels tending to evidence less roughness than low vowels. Some characteristics unique to connected speech including "effectiveness in conveying meaning" may affect the degree of roughness perceptually associated with continuous discourse.

Physiological Features of Vocal Roughness

Moore and Thompson (43) have listed two laryngeal vibratory requirements for normal phonation. Within each laryngeal vibratory cycle the opening, closing, and approximated phases of vocal fold movement must be present and the movements of the two vocal folds must be approximately synchronous and equal in amplitude. In addition, normal phonation is characterized by inter-cycle similarity in the pattern of vocal fold movements. The normal larynx, however, is capable of a wide range of vibratory patterns and both random and systematic variations are normal within certain limits (44, 65, 66). Van den Berg (68), experimenting with excised human larynges, observed that anatomical and vibratory asymmetries were common even in larynges which could be induced to produce an essentially "normal" phonatory quality. In contrast to the small inter- and intra-cycle vibratory irregularities associated with normal phonation, vocal fold movements in subjects presenting abnormally rough voices tend to be characterized by marked intra-cycle asymmetries in the movements of the two folds and large inter-cycle variations in vocal fold movements.

Von Leden, Moore, and Timcke (72) studied vocal fold vibratory patterns in subjects presenting laryngeal pathologies. They found essentially normal vocal fold vibratory patterns when the laryngeal lesion presented was small. When the lesion was large, however, markedly abnormal vibratory patterns were found. Asymmetrical vibration of the two vocal folds was noted in all such cases. Moreover, in subjects presenting a unilateral laryngeal disease, the vibratory pattern of the normal fold was often affected by the vibrations of the diseased fold and neither fold functioned normally. It was noted, however, that the fundamental frequency of vibration of the two folds did not differ measurably even when a large lesion was present on only one vocal fold. Moore (41, 42) has observed that normally the two vocal folds are generally comparable with regard to elasticity, mass, length, and compliance; thus, they move similarly during phonation. When these factors affecting vibration are altered by the presence of laryngeal pathology, however, the two folds may then have different vibrational characteristics and such differences may be reflected in perceived vocal quality.

Moore and Thompson (43) studied high-speed laryngeal motion picture films of two adult males, one presenting severe hoarseness and the other presenting moderate hoarseness. The films revealed that cycle-to-cycle variations were more frequent and greater in extent in the vocal fold movements of the subject presenting severe hoarseness than in those of the subject presenting moderate hoarseness. Yanagihara (78) has also reported the presence of marked cycle-to-cycle changes in the shape, amplitude, and periodicity of the glottal area waves of clinically hoarse subjects.

In general, therefore, normal phonation tends to be characterized by synchrony in the movement of the two vocal folds within cycles, and by a similarity in successive cycles of vocal fold movement. Even during normal phonation, however, there are measurable cycle-to-cycle aperiodicities in vocal fold movements. In subjects presenting laryngeal pathologies, vocal fold movements tend to be markedly asynchronous and large cycle-to-cycle variations in the pattern of movement are common. The literature reveals, moreover, that the frequency and magnitude of vocal fold vibratory irregularities tend to be related to the perceived severity of vocal roughness.

Acoustic Features of Vocal Roughness

The supraglottic air column is set into acoustic vibration in phonation by air puffs emitted between the vocal folds when subglottic pressure overcomes the resistance of the folds. The sound wave thus generated is normally complex, but not perfectly periodic (49, 50, 80). On the contrary, it has been reported (1) that sounds synthesized with near perfect periodicity are perceived by listeners to lack a "human" quality. The acoustic waves of vowels produced by the human vocal mechanism are normally characterized by slight cycle-to-cycle variations and are, therefore, "quasi-periodic" (26, 32, 35). While vowel waves are normally quasi-periodic, an abnormal laryngeal mechanism may produce vowel waves which are predominantly aperiodic (3, 4, 36).

Acoustic Wave Features of Vocal Roughness

As noted previously, investigations of vocal fold function have suggested that perceived vocal roughness is associated with marked variations in the vocal fold vibratory pattern. Such physiological variations tend to be reflected in the acoustic wave of phonation. For example, Lieberman (36) studied relationships between acoustic waveform and glottal area wave features in phonation for one normal-speaking adult male subject. He found that aperiodicities in the subject's acoustic voice wave were associated with glottal wave aperiodicities. Moore and Thompson (43) studied the acoustic waveforms and high-speed laryngeal motion picture films of one adult male presenting moderate hoarseness. The films revealed more random variability in vocal fold movements for the severely hoarse than for the moderately hoarse subject. It was also noted that the acoustic waveform of phonations produced by the severely hoarse subject evidenced greater over-all variability among cycles and a lesser number of consecutive cyclic periods of identical length than did the phonations of the subject presenting moderate hoarseness. The magnitude of period variations was also larger for the severely hoarse than for the moderately hoarse phonations.

Bowler (3, 4) studied the fundamental frequency of phonations produced by subjects presenting clinically harsh voices. Oscillographic recordings were obtained of connected speech samples in which harsh and non-harsh portions had been identified by judges. The harsh portions of the speech samples were characterized either by extremely aperiodic waveforms or by "frequency breaks." These frequency breaks or abrupt changes in the periods of successive cycles were commonly as large as one octave and occurred in both upward and downward directions from the median frequency. Such breaks were not seen, on the other hand, in the non-harsh portions of the speech samples. Coleman (7), however, did not find any large frequency breaks in the sustained vowel productions of clinically hoarse female subjects, but he did observe cycle-to-cycle frequency variations of less than an octave in their phonations. Further, he found the number of such variations per unit time to be closely associated with the perceived severity of the subjects' hoarseness. He observed that the median value of the deviations of individual acoustic cycles from the mean fundamental vocal frequency for each test phonation was not markedly different for normal and hoarse phonations; however, the range of such deviations was considerably greater for the hoarse than for the normal phonations.

In an investigation of normal-speaking and hoarse adult subjects, Lieberman (36) measured small, cycle-to-cycle period variations, which he termed "pitch perturbations," in oscillographic acoustic wave records of isolated vowels and vowels in sentences produced with varying inflections, e.g., question, statement. Lieberman noted, for normal-speaking subjects, that perturbations $\geq$ 0.5 msec usually occurred at formant transitions, but seldom during the steady-state portions of a vowel in connected speech. The steady-state portions of vowels sustained by the normal-speaking subjects contained no perturbations greater than 0.5 msec. Relatively large perturbations were generally associated with acoustic wave cycles of relatively long duration in the phonations of both normal-speaking and hoarse subjects.

Lieberman obtained a "perturbation factor" which he defined as the percentage of occurrence of perturbations $\geq$ 0.5 msec in a timed segment of phonation. He found that larger perturbation factors were associated with hoarse than with normal phonations. Perturbation factors obtained for the phonations of subjects presenting small masses on their vocal folds tended to be smaller than those for the phonations of subjects presenting large laryngeal masses, but essentially the same as those for the phonations of subjects with normal larynges. Lieberman's findings regarding the perturbation factor were subsequently confirmed by Smith and Lieberman (57, 58) in follow-up studies.

Hecker and Kreul (22) studied the phonations of subjects presenting laryngeal malignancies and matched normal-speaking subjects. The phonations of their experimental subjects appeared to be characterized by larger perturbations than those for the control subjects, but it was found that Lieberman's perturbation factor did not distinguish between the two groups. Hecker and Kreul subsequently obtained a "directional perturbation factor." This factor was based on the direction rather than the magnitude of changes in the periods of adjacent acoustic wave cycles and was defined as the "percentage of the total number of differences for which there is a change in sign." For each matched pair of normal and abnormal phonations, a significantly higher directional perturbation factor was associated with the phonation of the experimental subject than with that of the control subject. In another study, Kreul and Hecker (30) reported that the severity ratings of "hoarseness," "harshness," and "breathiness" were correlated with both directional and non-directional types of perturbation factors.

Wendahl (73, 75) utilized an electrical laryngeal analog (LADIC) to study acoustic features associated with the perception of roughness. A complex synthesized acoustic signal, computer controlled in both frequency and amplitude, was produced by LADIC. LADIC could be programmed to produce variations both in the period (jitter) and in the amplitude (shimmer) of successive cycles of the signal. When the periods of each cycle of a synthesized wave were varied around a median frequency, it was found that period variations as small as $\pm$ 1 Hz around the median frequency caused the signal to be perceived as rough. Further, the greater the jitter around the median frequency, the more severe the judged roughness. Coleman and Wendahl (9) subsequently confirmed in another study the finding that the amount of jitter in a synthesized complex acoustic signal is related to perceived signal roughness.

Wendahl's findings also revealed, when the amount of jitter was held constant, that the roughness perceptually associated with a signal was greater at relatively low median frequencies. Coleman (8) also used LADIC to generate stimuli at five median frequency and four jitter levels. He found that stimuli having relatively low median frequencies tended to be rated by listeners as more rough than those having relatively high median frequencies. At each median frequency tested, signals with greater jitter were judged to be more rough.

Cycle-to-cycle variations in acoustic waveform amplitude have also been associated with vocal roughness. Coleman (7) observed "amplitude breaks," i.e., large amplitude changes occurring on a cycle-to-cycle basis, in the acoustic waves of vowels produced by clinically hoarse female subjects, but similar amplitude breaks were not seen in the waves for normal phonations. Koike (28) has reported that period and amplitude fluctuations (jitter and shimmer) are present in normal as well as in hoarse phonation and are more marked at the initiation of phonation than during steady-state portions of phonation.

Wendahl (74) also studied the perceptual effects of acoustic shimmer using his laryngeal analog LADIC. His judges rated the roughness of jitter, shimmer, and jitter-shimmer programs using the method of paired comparisons. Wendahl found that increased jitter was associated with increased roughness when the jittered signal was inflected as well as when it was produced with a constant median frequency. It appeared, however, that equal signal variations were associated with less roughness at the high-frequency than at the low-frequency end of the inflection. The judges also perceived increased signal roughness when signal shimmer was increased but jitter was not increased. The roughness perceptually associated with shimmer did not seem to differ perceptually from that associated with jitter. Wendahl thus concluded that either jitter or shimmer, or both, might underlie the roughness associated with a given stimulus.

Koike (29) and von Leden and Koike (71) have recently investigated acoustic features of perceived vocal roughness by means of serial correlation (autocorrelation) of the peak amplitudes of thirty consecutive cycles in the phonatory acoustic wave. Their findings are displayed in correlograms which are graphic representations of the autocorrelations obtained. Von Leden and Koike (71) undertook such an analysis of the phonations of normal-speaking subjects and subjects presenting laryngeal pathologies. For their study, the vowel /a/ was sustained by each subject for several seconds at habitual pitch and comfortable loudness levels. Von Leden and Koike described four basic types of correlograms which were obtained for the test phonations. The first type of correlogram was typical of the phonations of normal-speaking subjects and subjects presenting small laryngeal lesions. This correlogram indicated a high positive correlation between the amplitudes of adjacent acoustic wave periods and an increasing negative correlation as the cycles considered were more widely spaced. A high positive correlation between adjacent acoustic wave cycles was also seen in the second type of correlogram; however, aperiodicities appeared among more widely spaced cycles. The second type of correlogram was usually obtained for the phonations of patients presenting benign lesions of the vibrating margins of the vocal folds. Correlograms of the third type indicated variable irregularities in acoustic cycles and were typically associated with the phonations of subjects whose vocal folds did not approximate. Correlograms of the fourth type were characterized by marked alternating positive and negative correlations when adjacent cycles and then increasingly widely spaced cycles were considered. Though von Leden and Koike report this type of a correlogram only for the phonations of patients with large, often malignant, lesions of the vocal folds, Koike (59) had noted previously that such correlograms were obtained for the phonations of two of twenty normal-speaking subjects and, thus, could not be considered pathognomonic.

To summarize, the literature reviewed suggests that aperiodicities in vocal fold vibration during phonation are reflected in both period and amplitude variations in successive cycles of the acoustic waveform. Studies of the acoustic waveforms of synthesized complex acoustic signals and human phonations reveal that increased roughness is associated with an increase in the number and magnitude of these waveform aperiodicities.

Spectral Features of Vocal Roughness

In 1941, Carhart (6) noted the presence of both harmonic and inharmonic acoustic components in acoustic spectra of model larynx tones derived with a heterodyne wave analyzer. He suggested that harmonic and inharmonic partials in such spectra may be lawfully related. He observed further that the perceived roughness of model larynx tones with elevated inharmonic components was similar to that heard in hoarse human voices, but he speculated, apparently incorrectly, that inharmonic spectral partials should be expected only in abnormal vocalizations.

Nessel (45) later employed a spectrograph of narrow frequency selectivity to produce frequency-by-amplitude acoustic spectra of sustained vowels produced by hoarse and normal-speaking subjects. He found that increased hoarseness was characterized spectrographically by a reduction of harmonic components below 5000 Hz and by an increase in the level of inharmonic or noise components in both the high-formant frequency ranges and above 5000 Hz.

An automatic acoustic analyzer commonly known as the Kay Sonagraph has been employed frequently in investigations of the spectral characteristics of complex acoustic stimuli. This instrument is particularly useful in studies investigating the vowel formants and their relationships to vowel identification (10, 13, 27, 34). Thurman (64) used the sonagraph in a study designed to delineate acoustic spectral features related to hoarseness, harshness, stridency, breathiness, and nasality. He was not able, however, to differentiate the abnormal vocal qualities or to determine the degree of their severity on the basis of a sonagraphic analysis of test phonations. Although deviations from normal in the locations of formant frequencies were observed for abnormal phonations, such deviations were not consistently associated with any one type of abnormal voice quality. Further, he found no relation between the amount and direction of formant shifts and the perceived severity of a voice quality disorder. Thurman also reported that the presence or absence of inharmonic partials in hoarse voices could not be determined from the sonagrams.

Yanagihara (78), however, has reported that the elevation of spectral noise in the sonagraphic spectra of hoarse phonations is related to cycle-to-cycle changes in the shape, amplitude, and periodicity of the hoarse subjects' glottal area waves as plotted from high-speed laryngeal motion picture films. Yanagihara and others (25, 70, 77, 78, 79) have also studied the relationships between vowel harmonic and noise components using a narrow-band (45-Hz) sonagraphic analysis procedure. On the basis of their analyses, they have delineated four "types" of hoarseness sonagraphically. They report that the noise components in sonagrams of slightly hoarse voices tend to be confined primarily to the frequency ranges of the second and third formants. As the severity of hoarseness increases somewhat, the noise components dominate the harmonic components in the region of the second formant, and noise components begin to appear above 3000 Hz in the sonagram. With an additional increase in the severity of hoarseness, high frequency noise components increase with respect to both their intensity and frequency range, and there is an additional increase in noise in the second formant frequency range. For the most severe hoarseness, the harmonic structures of the second and third formants are replaced by noise and the high-frequency noise components are further intensified and expanded in their frequency range.

Yanagihara (79) investigated relationships between the four sonagraphically delineated "types" of hoarseness and the perceived severity of hoarseness. Vowels produced by 167 hoarse subjects at comfortable pitch and intensity levels were rated as slightly, moderately, or severely hoarse by three otolaryngologists. Thirty vowels, ten of which the judges unanimously agreed were representative of each of the three degrees of hoarseness, were then selected for further analysis. For these thirty vowels, a correlation coefficient of .65 was obtained between the sonagraphic "type" and the judged degree of hoarseness.

Yanagihara (79) also synthesized hoarse vowels by mixing a vowel produced by a normal-speaking adult male and band-pass filtered noise. Six otolaryngologists rated the "hoarseness" associated with the obtained samples. When noise components were introduced into the range of the first formant, only slight hoarseness was perceived. The addition of noise in the second formant region resulted in an increase in the perceived severity of hoarseness; even more severe hoarseness was perceived when the second formant was obscured by noise. Loss of the harmonic structure in the high frequencies due to an elevation of spectral noise also resulted in the perception of increased hoarseness, and the most severe hoarseness was associated with an expanded frequency range of high-frequency noise.

The narrowest sonagraph filter bandwidth generally available at present is 45 Hz. Because a filter as wide as 45 Hz may not provide an optimum display of spectral noise, some investigators (14, 15, 21, 38, 54, 76) have recently utilized a constant bandwidth analyzer to obtain graphic 3-Hz bandwidth frequency-by-amplitude acoustic spectra. Sansone and Emanuel (54), for example, analyzed vowels sustained at one intensity with normal and simulated abnormally rough phonatory qualities by twenty normal-speaking adult males. Narrow-band (3-Hz) acoustic spectra of the individual vowel productions were then analyzed to determine the spectral noise level associated with each production. It was observed that noise components were present in the spectra for both normal and abnormally rough productions, but were elevated in those for the rough productions. Spectral noise levels were higher for the abnormally rough than for the normal productions of each test vowel regardless of the spectral frequency range considered. The spectral noise level difference between normal and rough productions did not vary greatly for any of the vowels across the frequency range analyzed (100–8000 Hz). Generally, the high vowel /u/ evidenced the lowest and the low vowel /æ/ the highest spectral noise level for both normal and rough productions. When the spectral noise level for the vowel productions was averaged from 100 to 2600 Hz, both normal and abnormally rough vowels could be ranked in order of increasing mean spectral noise levels: /u/, /i/, /ʌ/, /ɑ/, and /æ/.

Sansone and Emanuel also related the spectral noise levels to the roughness ratings obtained for the productions of each test vowel. The spectral noise levels, averaged separately over the frequency ranges 100 to 2600 Hz, 2600 to 5100 Hz, and 5100 to 8100 Hz for the productions of each vowel, were highly and positively correlated with the vowel median roughness ratings. The largest coefficients were obtained when the noise level, averaged over the range from 100 to 2600 Hz, was related to vocal roughness. Further, a multiple-regression analysis revealed for all vowels a high degree of linear relationship between spectral noise levels in each 100 Hz spectral section from 100 to 2600 Hz and the median roughness ratings. Comparable findings have been reported by Emanuel and Sansone (14) and Whitehead (76), for males producing normal and simulated abnormally rough vowels; Lively and Emanuel (38), for females producing normal and simulated abnormally rough vowels; and by Hanson (21), for subjects presenting clinically hoarse voices.

Emanuel and Whitehead (15) measured the level of each of the first five harmonics of normal and simulated abnormally rough vowels produced by twenty adult male subjects. The vowels tested were /u/, /i/, /ʌ/, /ɑ/, and /æ/. The roughness of each vowel was also rated by trained judges. A general tendency was found for harmonic levels to decrease with an increase in vowel roughness. For all test vowels, the greatest such decrease was associated with the second harmonic. A reversal in this trend was noted, however, for the fourth and fifth harmonics of /u/ and for the fifth harmonic of /i/. Greater differences were found between the harmonic level means for the normal and rough productions when harmonic levels were averaged over the first three harmonics than when they were averaged over the first five harmonics. For all test vowels, the differences between harmonic level means for normal and rough productions were significant when the three-harmonic means were considered. When the five-harmonic means were considered, significant differences between normal and rough productions were found for /ʌ/, /ɑ/, and /æ/; the rough-normal difference for /i/ was small but significant, and that for /u/ was not significant. Correlations between the second harmonic and the median roughness ratings and between the three-harmonic means and the median roughness ratings were significant for all test vowels. When the five-harmonic means and roughness ratings were related, the obtained coefficients were moderately high and significant for /ʌ/, /ɑ/, and /æ/. The coefficient for /i/ was considerably smaller, but significant, and the coefficient for /u/ was very small and not significant.

Ratios of the five-harmonic means to the noise level over a comparable frequency range were smaller for the rough productions than for the normal productions for all test vowels, but the normal-rough differences tended to be greater for the high than for the mid and low vowels. Differences between the five-harmonic means and the noise level over a comparable frequency range tended to be smaller for the rough than for the normal vowel productions. When these ratio and difference measures were correlated with the roughness rating for each test vowel, all the obtained coefficients were negative, moderately high, and significant. There was no clear tendency for either ratio or difference measures to yield consistently higher coefficients.

To generalize, the literature reviewed reveals that both harmonic and inharmonic (noise) components are present in the acoustic spectra of normal and abnormally rough phonations. Spectrographic analyses of phonation suggest that increases in vocal roughness are associated with increased inharmonic component levels and decreased harmonic component levels. It appears that narrow-band (3-Hz) acoustic spectrography may offer advantages with respect to obtaining measures of spectral harmonic and noise levels.

Summary

The term "roughness" refers to a perceived quality which is associated to different degrees with both normal and abnormal voices; thus, it refers to a perceptually delineated quality continuum. Generally, the concept of a roughness continuum appears meaningful and listeners appear able to rate reliably the degree of roughness associated with normal and with abnormal voices. Vocal roughness appears to be related to physiological variations in vocal fold movements. Such variations associated with abnormally rough phonations tend to be extreme in their frequency and magnitude, but are associated to a lesser extent with normal phonations as well. The individual cycles of the acoustic waveforms of normal phonations also evidence aperiodicities which, though smaller in magnitude, are similar in kind to the more extreme wave aperiodicities associated with abnormally rough phonation.

Recent studies have revealed that acoustic spectral inharmonic or noise components are associated with the roughness of normal as well as abnormally rough vowel productions, and that an increase in vowel roughness is associated with an increase in acoustic spectral noise levels. Additionally, data for adult males has been presented suggesting that the level of the spectral harmonics tends to decrease as vowel roughness is increased, but comparable data is not presently available for adult females. A study designed to investigate the harmonic levels associated with the vowel phonations of adult female subjects and the relationships of the harmonic levels to spectral noise levels and perceived vowel roughness appears to be needed. This study was designed to obtain such data for adult female subjects.

CHAPTER III

DESIGN OF THE INVESTIGATION

This study was designed to investigate quantitatively the level of spectral harmonics associated with normal and with simulated abnormally rough vowel phonations. Possible relationships between vowel spectral harmonic levels and perceived vowel roughness, and between vowel spectral harmonic and noise levels were studied. Additionally, some possible relationships of vowel spectral harmonic and noise level differences and ratios to judged vowel roughness were investigated.

To provide the data of interest, the present study made use of vowel samples obtained for a study reported by Lively and Emanuel (38) investigating the relationship of vowel spectral noise levels to vowel roughness. For the previous study, twenty normal-speaking adult females individually phonated each of five vowels first normally and then with simulated abnormal vocal roughness at one intensity. Each test vowel production was recorded on magnetic tape, and the recordings were subsequently analyzed individually to produce a narrow-band (3-Hz) acoustic spectrum of each test phonation. The spectral noise level in successive 100-Hz spectral sections from 100 to 8000 Hz was measured for each phonation and these measures were related to vowel roughness. To quantify the roughness perceptually associated with the vowels, the randomized vowel samples were played individually to eleven judges who rated each for roughness on a five-point equal-appearing intervals scale. An obtained median of the judges' ratings provided an index of the roughness of each vowel sample.

The spectra obtained by Lively and Emanuel provided an accurate presentation of vowel spectral noise levels, but did not always indicate harmonic levels accurately because the wave analyzer attenuation utilized was not appropriate for displaying the level of all harmonics. To obtain a suitable vowel harmonic level display for this study, the recorded vowel samples described above were re-analyzed to produce a narrow-band (3-Hz) acoustic spectrum in which harmonic levels were accurately delineated. The level of each of the first five harmonics was then measured in each vowel spectrum. These harmonic level measures, together with vowel roughness and vowel spectral noise level measures obtained previously, were then examined with respect to specific research questions. The research questions for this study and the methods employed to investigate them are discussed in detail in the following sections.

Research Questions

The following research questions concerning selected vowels produced both normally and with simulated abnormal vocal roughness by adult female subjects were investigated.

1. What are the harmonic levels associated with normal and simulated abnormally rough productions of each vowel?

2. What relationships obtain between the harmonic levels and the judged roughness of the productions of each vowel?

3. What relationships obtain between the harmonic levels and the spectral noise levels for the productions of each vowel?

4. What relationships obtain between selected indices of harmonic and noise level relationship, and the roughness perceptually associated with the productions of each vowel?

Collection and Preliminary Analysis of Vowel Samples

The procedure employed in collection and preliminary analysis of the vowel samples investigated in this study have been reported in detail elsewhere (38). Briefly, twenty adult females, each presenting normal speech and voice quality as determined by a trained speech pathologist, served as subjects. Subjects ranged in age from twenty-two to thirty-one years; thus, they had undergone adolescent voice change, but did not present the voice changes associated with advanced age.

Five vowels, /u/, /i/, /ʌ/, /ɑ/, and /æ/ comprised the speech sample. This selection of vowels permitted investigation of possible phonetic effects on the judged roughness and spectral characteristics of the samples.

An audio recording system was utilized to obtain magnetic tape recordings of the test vowels. This system consisted of a sound level meter (General Radio, Type 1551-C) the output of which was connected directly to the input of a magnetic tape recorder (Ampex, Model AG 440). The recorder's output served as input to a monitoring amplifier (Bruel and Kjaer, Type 2603). The amplifier functioned as a vocal-intensity indicator; its voltmeter was calibrated to indicate when subjects were phonating at the required intensity.

To obtain the vowel recordings, each subject was initially familiarized with the experimental procedures and was then seated in an examination chair. The sound level meter's microphone was placed at a

70° angle of incidence to and six inches in front of the subject's mouth. To eliminate from normal productions the possible effect of vocal abuse associated with roughness simulation, each subject phonated the test vowels first normally and then with simulated abnormal roughness. Each vowel production was carefully monitored by the investigator. If the subject did not produce the appropriate vowel, did not maintain the required intensity, or did not suitably effect vowel roughness, the trial was repeated until an acceptable performance was achieved. The intensity of each test phonation was controlled at 75 dB (± 1 dB) SPL, and each was sustained for seven seconds.

To provide an estimate of the roughness of each sample, the two hundred recordings of rough and normal productions were randomized by means of tape dubbing for presentation to judges for rating. Eleven judges, all graduate students in speech pathology, independently evaluated each sample. The judges were instructed to listen to each vowel phonation and to rate its roughness on a five-point scale of equal-appearing intervals on which "1" represented least severe and "5" represented most severe roughness. A median of the judges' ratings for each vowel production was obtained as an index of the roughness of each test phonation.

To evaluate the spectral noise level associated with each vowel phonation, tape loops were constructed from the magnetic tape recordings of each normal and rough vowel production. Each loop was constructed from a two-second central portion of the original seven-second vowel production having a uniform intensity of 75 dB (± 1 dB) SPL. Thus, initial and terminal vowel inflections were eliminated from the loops.

The loop of each test vowel phonation was replayed and the recorder's output was led to a graphic wave analyzer (General Radio, Type 1910-A). The analyzer was operated in its 3-Hz bandwidth mode to produce a graphic spectrum of each vowel sample analyzed. For this initial study, a wave analyzer attenuator setting was selected which would insure that the obtained vowel spectra would clearly present spectral noise levels, but would cause the level of some spectral harmonics to exceed the dynamic range of the level recorder. Hence, for some vowel productions the recording of harmonic levels was inaccurate.

To quantify the noise level in each spectrum, the lowest observable peak graphic level recorder stylus marking in each 100-Hz section of each vowel spectrum was measured in dB SPL. Seventy-nine measures were obtained in this manner from the spectrum of each vowel, one for each successive 100-Hz spectral section from 100 to 8000 Hz. Measures of noise in the first 100 Hz section of each spectrum were omitted because system noise was greater in that than in any higher spectral frequency range.

Evaluation of Vowel Harmonic Levels

Instrumentation

Instrumentation used in the present investigation included a wave analyzing system, a fundamental vocal frequency analyzing system, and a calibration system.

Wave analyzing system. The previously obtained tape loops for the productions of each test vowel were individually played and the recorder's (Ampex, Model AG 440) output was introduced as a complex electrical signal into a graphic wave analyzer (General Radio, Type 1910-A) to obtain acoustic vowel spectra. The analyzer's frequency accuracy to

50,000 Hz was ± 0.5% of the frequency-dial reading, plus 5 Hz. When used in its 3-Hz bandwidth mode, the instrument functioned as a continuously tunable narrow-band filter with the intensity of the frequency components in a complex signal at least 30 dB down at ± 6 Hz, and at least 60 dB down at ± 15 Hz, from center frequency. The analyzer's signal-to-noise ratio was at least 75 dB.

An electric motor drive system mechanically tuned the wave analyzer through its frequency range and coupled the analyzer to a component graphic level recorder to permit automatic recording of the level of frequencies in the complex signal under analysis. The movement of the recorder's chart paper was synchronized with the wave analyzer's frequency-tuning dial. The voltage output of the wave analyzer was proportional to the intensity of the frequency components in a 3-Hz band of the complex signal under analysis and served as an electrical input to the graphic level recorder. The recorder was equipped with an 80 dB input potentiometer designed for accuracy within ± 1% of full scale decibel value. The level recorder's output was proportional to the logarithm of changes in its input and, hence, was linear in decibels. A simplified diagram of the wave analyzing system is presented in Figure 1.

Fundamental vocal frequency analyzing system. The system used to determine the fundamental vocal frequency of each test vowel sample consisted of a magnetic tape recorder (Ampex, Model AG 440), a wave analyzer (General Radio, Type 1910-A), and a universal counter (TSI, Model 361). A simplified diagram of this system is presented in Figure 2.

Calibration. Before each use, the graphic wave analyzer was adjusted for minimal carrier frequency intensity at low frequencies and aligned for frequency analysis accuracy within design specifications.

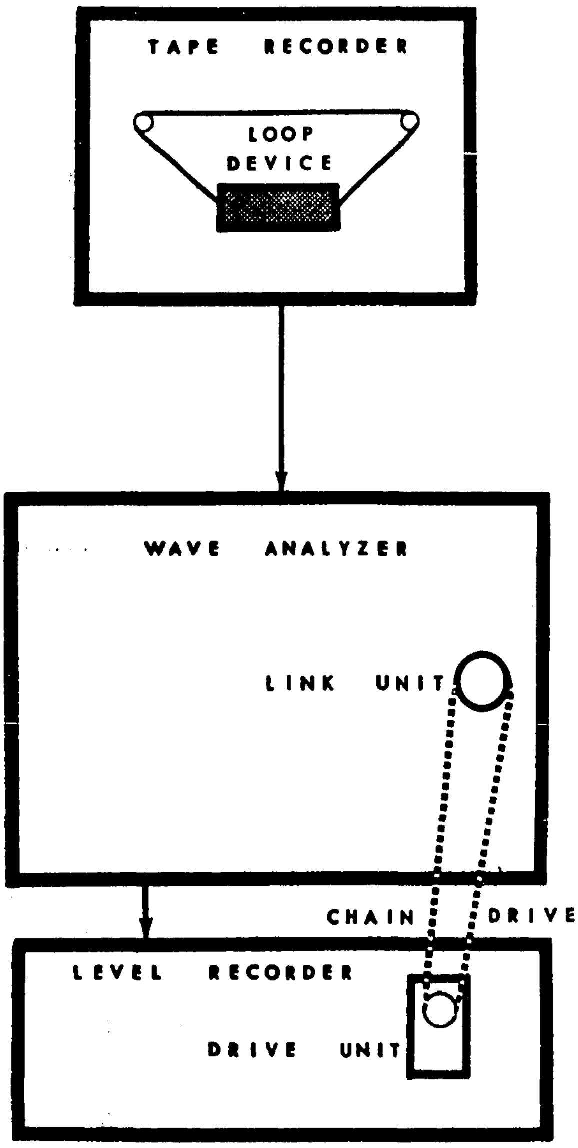

Figure 1.—Simplified diagram of the wave analyzing system.

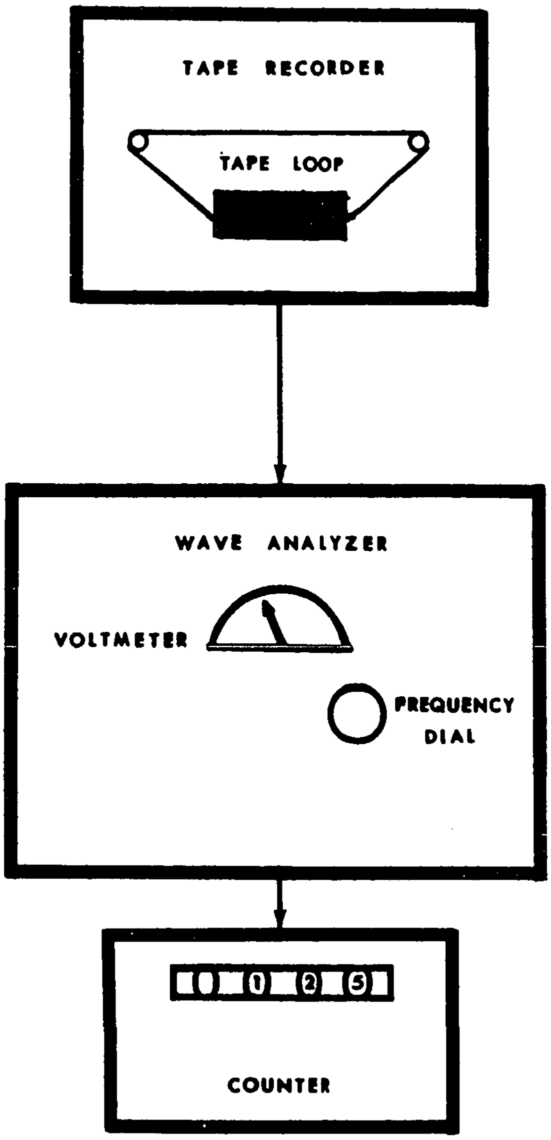

Figure 2.—Simplified diagram of the fundamental vocal frequency analyzing system.

After this initial adjustment, intensity calibration was effected by introducing a recorded 75 dB SPL 1000-Hz reference tone into the wave analyzer. The gain of the analyzer and the pen excursion of the graphic level recorder were then adjusted for a 75 dB indication on the graph paper.

Calibration of the fundamental vocal frequency analyzing system was effected by introducing a tone produced by a pure tone oscillator (Hewlett-Packard, Model ABR 200) directly into the universal counter and the frequency of the oscillator tone was then read from the universal counter. The same pure tone was then led to the graphic wave analyzer which was operated with a 3-Hz bandwidth in its tracking generator mode. The frequency dial of the analyzer was hand-tuned upward in frequency from 0 Hz until a large deflection of the analyzer's voltmeter indicated that the frequency of the pure tone had been located. The output from the wave analyzer's tracking generator was then introduced into the universal counter from which the frequency of the tracking generator output was read. This procedure was repeated at 50 Hz intervals from 100 to 400 Hz. The frequency reading on the universal counter was consistently 3 Hz higher when the fundamental was obtained from the analyzer's tracking generator output than when obtained directly from the pure tone oscillator; therefore, a 3 Hz correction factor was applied to all fundamental frequencies obtained from the tracking generator output.

Procedures

The experimental procedures in this study included analyzing the recorded productions of each test vowel to obtain their fundamental vocal frequencies and their frequency-by-amplitude acoustic spectra.

Fundamental vocal frequency analysis. The vowel tape loops previously described were used in determining the fundamental vocal frequency of the normal and rough productions. The vowel loops were played individually into the graphic wave analyzer which was operated with a 3-Hz bandwidth in its tracking generator mode. The frequency dial of the analyzer was then hand-tuned until a large deflection of the analyzer's voltmeter indicated that the fundamental vocal frequency of the signal had been located. The analyzer's tracking generator output was then coupled to the TSI universal counter which displayed digitally the fundamental vocal frequency of the vowel production being analyzed.

Spectral analysis. The vowel tape loops were also re-analyzed in the present investigation to obtain measurements of the level of harmonics associated with each test phonation. Each vowel loop was played on the tape-recorder used in data collection and the output of the recorder was led to the wave analyzer. The analyzer was operated at a paper speed of 0.5 inches per minute and a writing speed of 20 inches per second to produce the vowel spectra. For this analysis, a wave-analyzer attenuator setting of 80 dB was selected to insure that the level of the harmonics would not exceed the dynamic range of the analyzer's component graphic level recorder. The dynamic range of the level recorder at these settings was from 10 to 90 dB.

Examples of acoustic spectra for normal and abnormally rough productions of the vowel /ɑ/ by Subject 18 are presented in Figures 3 and 4. In general, the spectral features observed in these examples are typical of those observed for all productions. Figure 3 shows that the spectrum for the normal phonation is characterized by identifiable

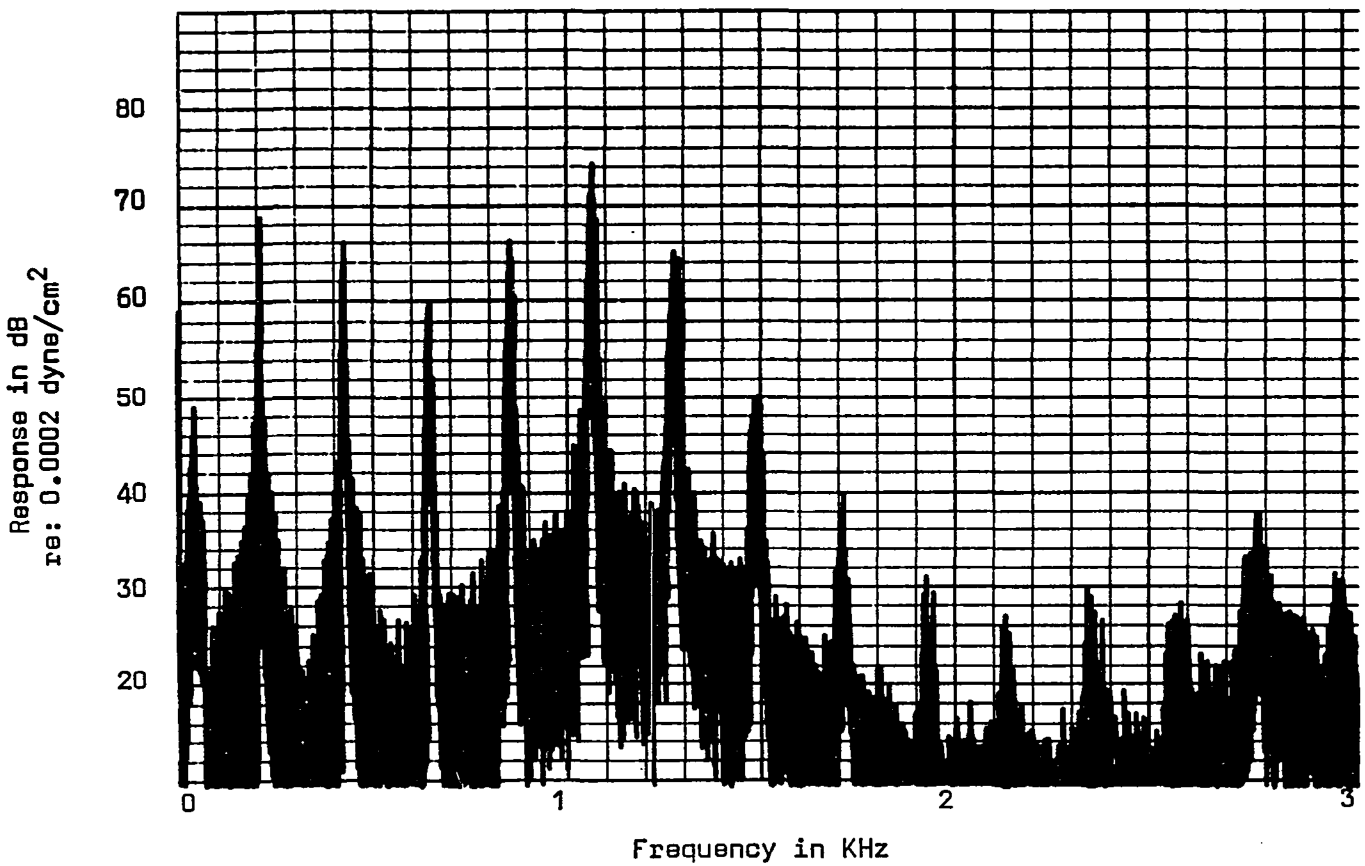

Figure 3.—Spectrum of a normal /ɑ/ produced by Subject 18.

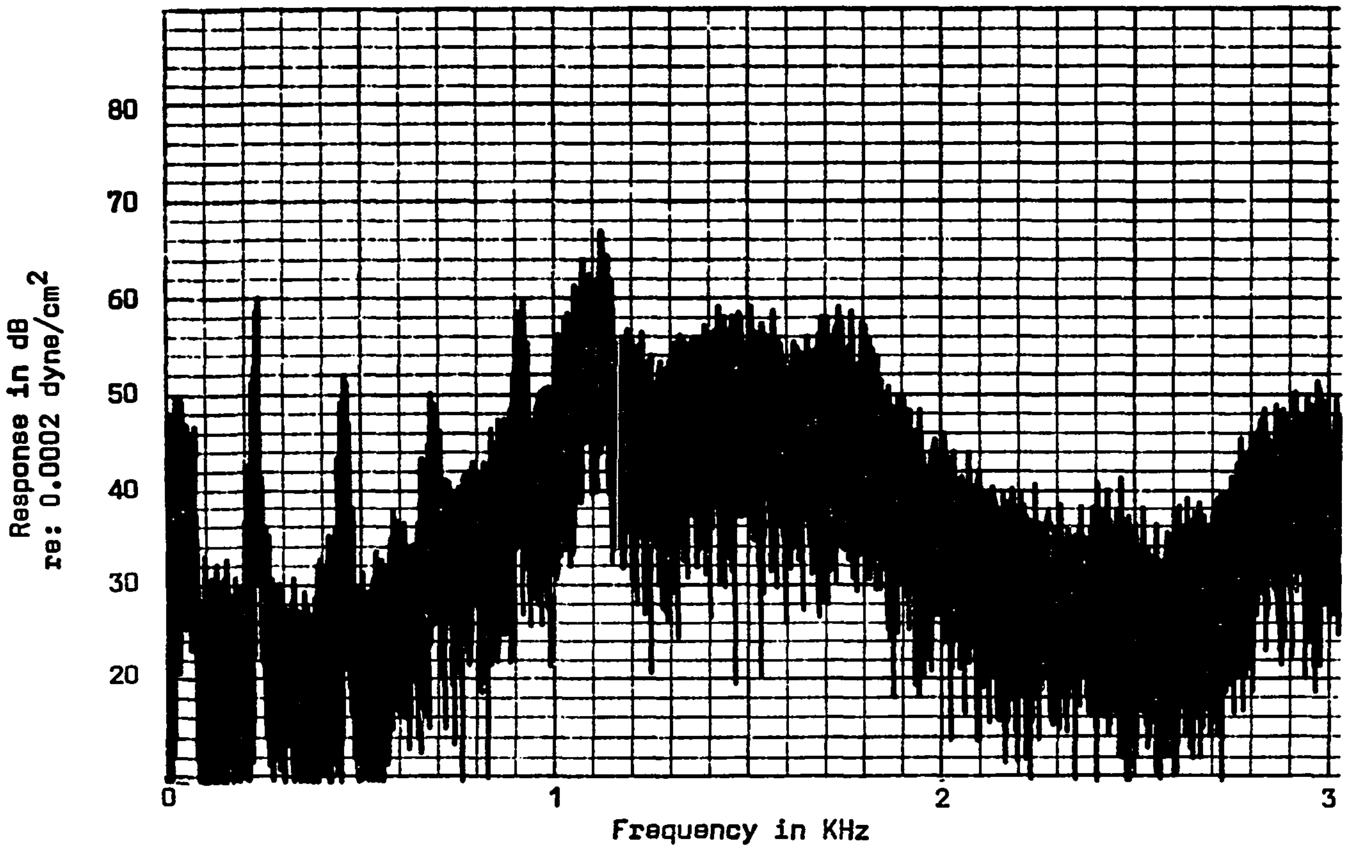

Figure 4.—Spectrum of a rough /ɑ/ produced by Subject 18.

harmonics throughout the frequency range displayed. Noise components may be seen between the harmonics. In contrast, Figure 4 shows that in the spectrum for a simulated abnormally rough vowel produced by the same subject, noise components are generally elevated and the harmonics are obscured by the noise except in the low-frequency spectral range. Each of the first five harmonics in the spectrum of the rough production are diminished in amplitude with respect to those in the spectrum of the normal production.

Inspection of the spectra obtained for productions representing a range of roughness revealed that harmonic components were discernable in a low-frequency range for all vowels, but high-frequency harmonics were commonly obscured by elevated spectral noise levels. This was particularly true in the spectra for abnormally rough productions. A decision was made, therefore, to limit this investigation to measurement of the level of only the first five harmonics in each spectrum; that is, to the harmonic lowest in frequency which represented the fundamental vocal frequency, and to the next four higher harmonics. The peak level of each of the five harmonics was measured in dB SPL to the nearest 0.5 dB. Each measurement was repeated on a separate occasion and a third measurement was made to resolve differences in the first two.

To evaluate the reliability of the spectral delineation of vowel harmonics, two consecutive spectra were obtained from one vowel loop chosen randomly from the productions of each subject. The mean difference between the harmonic levels obtained for the first and second spectra was $\pm$ .88 dB. Thus, the harmonic level analysis procedure appeared to be sufficiently reliable for this study.

For this investigation, it was of interest to obtain an index of vowel spectral noise associated with each test vowel production in a frequency range comparable to that considered for the harmonics. To provide this index, the following procedures were employed. First, the frequency of the first harmonic or fundamental frequency was determined for each production. The frequency locations of the second, third, fourth, and fifth harmonics were then calculated and verified by inspection of the spectra. It was then possible to delineate a specific 100-Hz spectral section in which each of the first five harmonics of a production was located. Next, the previously obtained noise level measures in each 100-Hz spectral section from 100 to 2600 Hz were recorded for each vowel production. This frequency range was of interest because it has been reported previously (38) that the level of noise in this range tends to be positively and linearly related to the judged roughness of vowels. Finally, the spectral noise measures for each production were averaged over the following frequency ranges:

1. From 100 to 2600 Hz. Means over this frequency range have been termed the S-1 means in previous studies and, for consistency, were termed S_1N in this investigation.

2. From 100 Hz through the spectral section in which the second harmonic of the production appeared. This noise level mean was termed 2N.

3. From 100 Hz through the spectral section in which the third harmonic of the production appeared. This noise level mean was termed 3N.

4. From 100 Hz through the spectral section in which the fifth harmonic of the production appeared. This noise level mean was termed 5N.

In obtaining the means described above, except the S_1N, the actual number of spectral sections over which noise was averaged varied slightly from one spectrum to another depending on the frequency location of the individual harmonics. In spite of this variation, the noise level means obtained provided data pertinent to a consideration of spectral harmonic levels relative to spectral noise levels in a comparable frequency range.

CHAPTER IV

RESULTS AND DISCUSSION

Results

This study was designed to investigate the relationship of vowel spectral harmonic levels to vowel spectral noise levels and perceived vowel roughness. Tape recordings were studied of each of the five vowels /u/, /i/, /ʌ/, /ɑ/, and /æ/ phonated by each of twenty adult female subjects first normally and then with simulated abnormal roughness at one intensity. For a previous investigation (38), the vowel samples were individually rated for roughness on a five-point equal-appearing intervals scale by eleven judges. A median of the judges' ratings was obtained as an index of the roughness of each sample. A narrow-band (3-Hz) acoustic spectrum indicating the spectral noise level associated with each test phonation was also obtained, and the noise level in successive 100-Hz spectral sections from 100 to 8000 Hz was measured.

For the present investigation, the recorded vowel samples were analyzed further to provide data pertinent to the research questions. A 3-Hz acoustic spectrum indicating the level of spectral harmonics was obtained for each test phonation. The level of each of the first five spectral harmonics of each vowel production was then measured and these measurements were related to the spectral noise level measures and median roughness ratings obtained previously for the phonations. Additionally, the fundamental vocal frequency of each test phonation was measured.

Fundamental Vocal Frequency

Table 1 presents the fundamental vocal frequency (FVF) obtained for each production of each test vowel and, separately for normal and for simulated abnormally rough productions, the range of fundamentals associated with each test vowel. The difference between the fundamentals for the normal and the rough productions of each test vowel is also shown for each of the twenty subjects.

Inspection of the range of fundamentals for the normal and the rough productions of each test vowel in Table 1 reveals that the lowest FVF, 160 Hz, was associated with a normal /ʌ/ produced by Subject 14, and the highest, 346 Hz, was associated with a simulated abnormally rough /u/ produced by Subject 11. Regarding the fundamentals for normal productions of each test vowel, Table 1 reveals that Subject 13 evidenced the highest fundamental for all five test vowels.

Examination of the differences between the FVF for the normal and the simulated abnormally rough production of each test vowel reveals that individual subjects tended to behave somewhat differently with respect to FVF changes associated with a change in phonation from normal to simulated abnormally rough. Subject 1, for example, elevated her fundamental 4 Hz over that associated with her normal productions in simulating abnormally rough /u/ and /ɑ/ productions, but lowered her fundamental with respect to that for her normal productions in simulating abnormally rough /i/, /ʌ/, and /æ/ productions. The rough-normal

TABLE 1.--The fundamental vocal frequency in Hz for each normal (N) and simulated abnormally rough (R) production of each of five test vowels, and the rough-normal difference (d) in the fundamentals. The range of the fundamentals for rough and for normal productions is also presented for each vowel.

	/u/			/i/			/ʌ/			/ɑ/			/æ/		
Subject	N	R	d	N	R	d	N	R	d	N	R	d	N	R	d
1	211	215	4	214	209	-5	190	169	-21	186	190	4	195	182	-13
2	214	264	50	217	254	37	207	259	52	199	256	57	205	225	20
3	206	256	50	213	248	35	203	220	17	204	201	-3	208	239	31
4	202	244	42	199	242	43	190	234	44	194	232	38	193	239	46
5	241	273	32	237	269	32	233	237	4	216	260	44	221	266	45
6	189	235	46	188	261	73	199	190	-9	183	176	-7	185	191	6
7	229	274	45	231	272	41	227	273	46	221	253	32	228	266	38
8	203	229	26	204	249	45	197	227	30	198	237	39	201	242	41
9	232	244	12	231	248	17	228	242	14	225	216	-9	229	259	30
10	178	221	43	181	217	36	172	222	50	171	207	36	174	210	36
11	228	346	118	235	332	97	224	295	71	226	270	44	232	279	47
12	220	247	27	227	265	38	214	238	24	219	240	21	222	224	2
13	265	278	13	262	228	26	254	273	19	253	268	15	258	267	9
14	161	251	90	182	269	87	179	233	54	160	171	11	188	237	49
15	180	266	86	179	254	75	176	236	60	179	220	41	186	218	32
16	245	254	9	246	261	15	239	261	22	245	243	-2	239	252	13
17	221	313	92	232	326	94	216	278	62	215	290	75	228	260	32
18	211	249	38	208	237	29	212	228	16	212	224	12	211	229	18
19	216	269	53	226	260	34	225	246	21	219	203	-16	224	224	00
20	210	213	3	217	213	-4	208	212	4	202	217	15	207	223	16
Range:															
Low	161	213		179	209		172	169		160	171		174	182	
High	265	346		262	332		254	295		253	290		258	279	

difference in fundamentals for /ʌ/ produced by Subject 1 was -21 Hz, the largest such negative difference obtained.

In contrast, for all five test vowels, Subject 11 evidenced a FVF for simulated rough productions which exceed that evidenced by the other nineteen subjects and, in simulating abnormally rough productions of each test vowel, Subject 11 generally tended to elevate her FVF markedly above that for her normal productions. The rough-normal difference in FVF between her normal and rough /u/ productions was 118 Hz, the largest such positive difference observed in this study. The preponderance of positive rough-normal FVF differences in Table 1 suggests that the subjects for this study generally tended to elevate their FVF somewhat when they simulated abnormally rough phonations. It may be noted, however, that for each test vowel there were at least two subjects who evidenced as little as 5 Hz or less difference in their fundamentals for normal and rough productions.

Table 2 presents separately for normal and for simulated abnormally rough productions an average over the twenty subjects of the fundamental vocal frequencies obtained for each vowel, and the standard deviation associated with each mean fundamental. The difference between the means for the rough and normal productions and the ratio of means for rough and normal productions is also presented for each vowel. Table 2 shows that the FVF means for both normal and rough productions tended to be higher for the high vowels /u/ and /i/ than for the mid vowel /ʌ/ or the low vowels /ɑ/ and /æ/. It is also apparent that higher FVF means tended to be associated with the rough than with the normal phonations of each test vowel. Though the magnitude of the rough-normal difference in FVF means tended to be somewhat larger for

TABLE 2.--The fundamental vocal frequency (FVF) in Hz averaged over the twenty subjects for normal and for simulated abnormally rough productions of each test vowel, the standard deviation associated with each mean, the rough-normal difference between means for each vowel, and the rough-normal ratio of means for each vowel.

Vowel		FVF Mean	SD
/u/	Normal	213.10	24.45
	Rough	257.05	31.73
	Difference	43.95[b]	
	Ratio	1.20	
/i/	Normal	216.45	22.70
	Rough	258.70	31.30
	Difference	42.25[b]	
	Ratio	1.19	
/ʌ/	Normal	209.65	21.89
	Rough	238.65	29.85
	Difference	29.00[b]	
	Ratio	1.14	
/ɑ/	Normal	206.35	23.56
	Rough	228.70	32.15
	Difference	22.35[b]	
	Ratio	1.11	
/æ/	Normal	211.70	21.34
	Rough	236.60	25.74
	Difference	24.90[b]	
	Ratio	1.12	

[b]($p < 0.01$): A two-tailed Wilcoxon matched-pairs signed-ranks test was utilized to test the significance of the difference between normal and rough productions.

/u/ and /i/ than for the other test vowels, Table 2 shows that the obtained differences were significant ($p < 0.05$) for all five vowels. Moreover, Table 2 shows that the ratios of rough to normal means tended to be similar across the vowel tested, ranging from 1.11 for /ɑ/ to 1.20 for /u/.

Harmonic Levels

Table 3 presents separately for normal and for simulated rough productions of each test vowel the level of each of the first five harmonics averaged over the twenty subjects. The difference between harmonic level means for normal and rough productions is also shown for each vowel. The individual subject data regarding the level of each of the first five harmonics for normal and for rough productions of each test vowel, and differences in harmonic levels for rough and normal productions are presented in Appendix A.

Regarding the vowels /ʌ/, /ɑ/, and /æ/, Table 3 reveals a general tendency for the mean for each of the five harmonics to be larger for normal than for rough productions. A similar trend is evident for the first and second harmonics of /u/ and /i/, but the means for the third, fourth, and fifth harmonics of /u/ and /i/ tended to be larger for rough than for normal productions. It may also be noted in Table 3 that the means for the third, fourth, and fifth harmonics of normal /u/ and /i/ productions tended to be small in comparison to those for normal /ʌ/, /ɑ/, and /æ/ productions.

When the harmonics are considered individually, Table 3 shows that the normal-rough differences in mean harmonic levels for the first, third, and fifth harmonics were not significant for all test vowels, but

TABLE 3.—Harmonic level means in dB SPL and standard deviations for the first five harmonics of each of five test vowels produced normally and with simulated abnormal vocal roughness by each of twenty adult female subjects. Each mean is over the twenty subjects.

Vowel		Harmonic 1	SD	Harmonic 2	SD	Harmonic 3	SD	Harmonic 4	SD	Harmonic 5	SD
/u/	Normal	73.12	2.02	73.72	2.06	49.82	9.14	46.10	6.74	43.52	6.15
	Rough	71.72	2.98	69.70	4.92	56.30	6.52	53.82	5.67	49.90	7.63
	Difference	1.40		4.02[b]		-6.48[b]		-7.72[b]		-6.38[b]	
/i/	Normal	75.30	2.15	71.42	3.25	48.08	6.04	41.25	4.60	36.52	4.64
	Rough	72.95	2.36	66.85	4.41	50.50	5.59	45.70	4.28	40.10	5.61
	Difference	2.35[b]		4.57[b]		-2.42		-4.45[b]		-3.58	
/ʌ/	Normal	71.38	1.85	68.60	3.28	68.90	2.99	68.62	3.08	60.90	4.62
	Rough	68.45	4.59	62.80	4.45	64.50	5.82	65.78	3.56	60.22	4.38
	Difference	2.93[a]		5.80[b]		4.40[b]		2.84[b]		.68	
/ɑ/	Normal	70.12	2.50	66.18	2.47	65.75	3.47	68.30	3.27	67.05	4.17
	Rough	66.60	4.74	59.45	6.28	60.72	6.57	63.82	5.14	65.52	5.07
	Difference	3.52[b]		6.73[b]		5.03[b]		4.48[b]		1.53	
/æ/	Normal	71.85	2.10	67.50	2.71	66.62	2.63	69.55	3.33	63.12	5.24
	Rough	67.52	4.36	59.53	6.21	59.18	5.34	63.48	5.77	59.08	5.73
	Difference	4.33[b]		7.97[b]		7.44[b]		6.07[b]		4.04	

[a]($p < 0.05$); [b]($p < 0.01$): a two-tailed Wilcoxon matched-pairs signed-ranks test was utilized to test the significance of the difference between normal and rough productions.

those for the second and fourth harmonics were significant ($p < 0.01$) for all five vowels. The mean for the second harmonic of normal productions always exceeded that for rough productions, regardless of the test vowel considered. In contrast, for /ʌ/, /ɑ/, and /æ/ the mean for the fourth harmonic of normal productions exceeded that for rough productions, but for /u/ and /i/ the mean for the fourth harmonic of rough productions exceeded that for normal productions.

Table 4 presents separately for normal and for rough vowel productions, the harmonic levels averaged over all subjects and over the first two harmonics (2H), the first three harmonics (3H), and the first five harmonics (5H) of each test vowel. When the 2H means are considered, it may be seen that significantly ($p < 0.01$) larger harmonic level means were associated with the normal than with the rough productions of all five vowels. Similarly, for /ʌ/, /ɑ/, and /æ/, significantly ($p < 0.01$) larger 3H and 5H harmonic level means were associated with normal than with rough productions. For /u/ and /i/, the differences between the 3H means were not significant. Regarding the 5H means for /u/ and /i/, it may be noted that the means for rough productions tended to exceed those for normal productions, and that this difference was significant ($p < 0.01$) for /u/ but not for /i/.

Harmonic Level and Roughness Rating Relationships

Table 5 presents the correlation (Spearman $\underline{r}_s$) observed between the median roughness ratings for the productions of each vowel and the level of each of the first five harmonics of those productions. Table 5 shows that the coefficients obtained for /ʌ/, /ɑ/, and /æ/ were negative, regardless of the harmonic considered. For /u/ and /i/, negative

TABLE 4.--Harmonic level means in dB SPL and standard deviations for each of five test vowels produced normally and with simulated abnormal vocal roughness by each of twenty adult female subjects. Each mean is over the twenty subjects and, respectively, over the first two (2H), first three (3H), and first five (5H) harmonics of each vowel.

Vowel		2H	SD	3H	SD	5H	SD
/u/	Normal	73.42	.95	65.56	3.03	57.26	3.26
	Rough	70.71	2.09	65.91	3.04	60.29	3.38
	Difference	2.71[b]		-0.35		-3.03[b]	
/i/	Normal	73.36	1.03	64.93	2.31	54.52	2.61
	Rough	69.90	2.21	63.43	2.01	55.22	2.30
	Difference	3.46[b]		1.50		-0.70	
/ʌ/	Normal	69.99	2.13	69.62	1.75	67.68	.87
	Rough	65.62	3.92	65.25	3.13	64.35	1.62
	Difference	4.37[b]		4.37[b]		3.33[b]	
/ɑ/	Normal	68.15	1.97	67.35	1.64	67.48	1.28
	Rough	63.02	4.38	62.26	3.90	63.23	3.71
	Difference	5.13[b]		5.09[b]		4.25[b]	
/æ/	Normal	69.68	1.53	68.66	1.17	67.73	.66
	Rough	63.52	4.21	62.07	3.58	61.76	3.20
	Difference	6.16[b]		6.59[b]		5.97[b]	

[b]($p < 0.01$): a two-tailed Wilcoxon matched-pairs signed-ranks test was utilized to test the significance of the difference between normal and rough productions (see Appendix C).

TABLE 5.--Spearman rank correlation coefficients ($\underline{r}_s$) indicating the relationship between the median roughness ratings (MRR) and the level of each of the first five harmonics of each test vowel.

Vowel	Harmonic 1 vs MRR	Harmonic 2 vs MRR	Harmonic 3 vs MRR	Harmonic 4 vs MRR	Harmonic 5 vs MRR
/u/	−.24	−.64[b]	.40[a]	.53[b]	.38[a]
/i/	−.50[b]	−.54[b]	.18	.42[b]	.24
/ʌ/	−.33[a]	−.48[b]	−.40[a]	−.40[a]	−.13
/ɑ/	−.28	−.52[b]	−.48[b]	−.44[b]	−.30
/æ/	−.40[a]	−.65[b]	−.58[b]	−.59[b]	−.40[a]

[a]($p < 0.05$); [b]($p < 0.01$): a two-tailed $\underline{t}$ test was utilized to test the significance of the correlations.

coefficients were obtained when the levels of either the first or the second harmonics were related to roughness ratings for those vowels, but positive coefficients were obtained when the levels of the third, fourth, or fifth harmonic were related to the roughness ratings. The coefficients for all five test vowels were significant ($p < 0.05$) only when the second and the fourth harmonics were considered. The coefficients for at least one of the five test vowels failed to reach significance when coefficients for the first, third, and fifth harmonics were considered across vowels. The coefficients associated with the second harmonic were negative for all test vowels and ranged from - .48 for /ʌ/ to - .65 for /æ/. Those associated with fourth harmonic were negative for /ʌ/, /ɑ/, and /æ/, but positive for /u/ and /i/. The negative coefficients associated with the fourth harmonic ranged from - .40 for /ʌ/ to - .59 for /æ/, while the positive coefficients ranged from .42 for /i/ to .53 for /u/.

Table 6 presents the correlation (Spearman $\underline{r}_s$) observed between the median roughness ratings and the harmonic level means (c.f. Table 4) averaged over the first two (2H), first three (3H), and first five (5H) harmonics of the productions of each vowel. The coefficients presented in Table 6 are all significant ($p < 0.05$) except two. A nonsignificant ($p > 0.05$) relationship was found between the median roughness ratings and the 5H means for /i/, and between the median roughness ratings and the 3H means for /u/. Table 6 shows that the largest coefficients for /ʌ/, /ɑ/, and /æ/ were obtained when vowel roughness ratings were related to the 5H means and that these relatively large coefficients ranged from - .69 for /ɑ/ to - .78 for /æ/. For the high vowels /u/ and /i/, however, the largest coefficients were obtained when the roughness

TABLE 6.--Spearman rank correlation coefficients (r_s) indicating the relationship between the median roughness rating (MRR) and the mean for the first two (2H), first three (3H), and first five (5H) harmonics of the productions of each test vowel.

Vowel	2H vs MRR	3H vs MRR	5H vs MRR
/u/	$-.74^b$	.01	$.41^b$
/i/	$-.76^b$	$-.40^a$	.00
/ʌ/	$-.49^b$	$-.58^b$	$-.76^b$
/ɑ/	$-.57^b$	$-.67^b$	$-.69^b$
/æ/	$-.68^b$	$-.73^b$	$-.78^b$

$^a(p < 0.05)$; $^b(p < 0.01)$: a two-tailed *t* test was utilized to test the significance of the correlations (see Appendix C).

ratings were related to the 2H means. These coefficients ranged from - .74 for /u/ to - .76 for /i/.

Harmonic Level and Spectral Noise Level Relationships

Table 7 presents the correlation (Spearman $\underline{r}_s$) observed between the levels of each of the first five harmonics and the average of the spectral noise levels from 100 to 2600 Hz (S_1N) for the productions of each test vowel. Table 7 shows that the coefficients obtained for /ɑ/ and /æ/ were negative, regardless of the harmonic considered. For /ʌ/, the coefficients associated with all harmonics except the fifth were negative. For /u/ and /i/, negative coefficients were obtained when the levels of either the first or the second harmonic were related to the S_1N for the productions of those vowels, but positive coefficients were obtained when the levels of the third, fourth, or fifth harmonic were related to the S_1N. Table 7 shows that the coefficients for all five test vowels were significant ($p < 0.05$) only when the levels of the second, third, or fourth harmonic were related to the S_1N. The coefficients associated with the second harmonic were negative for all vowels and ranged from - .47 for /i/ and /u/ to - .74 for /æ/. Those associated with the third and the fourth harmonic were negative for /ʌ/, /ɑ/, and /æ/, but positive for /u/ and /i/. The negative coefficients associated with the third and the fourth harmonic ranged from - .44 for /ʌ/ and /ɑ/ (third harmonic) to - .68 for /æ/ (third harmonic), while the positive coefficients ranged from .38 for /i/ (third harmonic) to .63 for /i/ (fourth harmonic).

Table 8 presents the correlation (Spearman $\underline{r}_s$) observed between the 5H means and the spectral noise levels averaged over the frequency range of the first five harmonics (5N), the 3H means and the spectral

TABLE 7.—Spearman rank correlation coefficients (r_s) indicating the relationship between the level of each of the first five harmonics and the 100 to 2600 Hz (S_1N) spectral noise level means for the productions of each test vowel.

Vowel	Harmonic 1 vs S_1N	Harmonic 2 vs S_1N	Harmonic 3 vs S_1N	Harmonic 4 vs S_1N	Harmonic 5 vs S_1N
/u/	-.28	-.47[b]	.54[b]	.53[b]	.36[a]
/i/	-.55[b]	-.47[b]	.38[a]	.63[b]	.46[b]
/ʌ/	-.41[b]	-.56[b]	-.51[b]	-.44[b]	.04
/ɑ/	-.19	-.58[b]	-.48[b]	-.44[b]	-.28
/æ/	-.44[b]	-.74[b]	-.68[b]	-.65[b]	-.26

[a]($p < 0.05$); [b]($p < 0.01$): a two-tailed *t* test was utilized to test the significance of the correlations (see Appendix C).

TABLE 8.--Spearman rank correlation coefficients (r_s) indicating the relationship between the means for the first two (2H), first three (3H), and first five (5H) harmonics and the spectral noise averaged over the frequency range of the first two (2N), first three (3N), and first five (5N) harmonics, respectively; and, between the 2H, 3H, and 5H means and the 100 to 2600 Hz (S_1N) spectral noise level means for the productions of each test vowel.

Vowel	2H vs 2N	2H vs S_1N	3H vs 3N	3H vs S_1N	5H vs 5N	5H vs S_1N
/u/	-.52[b]	-.59[b]	.21	.23	.52[b]	.48[b]
/i/	-.61[b]	-.71[b]	-.16	-.21	.18	.29
/ʌ/	-.01	-.56[b]	-.42[b]	-.70[b]	-.68[b]	-.77[b]
/ɑ/	-.20	-.54[b]	-.53[b]	-.65[b]	-.62[b]	-.67[b]
/æ/	-.28	-.77[b]	-.50[b]	-.84[b]	-.84[b]	-.84[b]

[b]($p < 0.01$): a two-tailed *t* test was utilized to test the significance of the correlations (see Appendix C).

noise levels averaged over the frequency range of the first three harmonics (3N), and 2H means and the spectral noise levels averaged over the frequency range of the first two harmonics (2N); and, between the 5H, 3H, and 2H means and the spectral noise levels averaged over the 100 to 2600 Hz range (S_1N) for the rough and normal productions of each vowel. Table 8 reveals that the coefficients associated with /ʌ/, /ɑ/, and /æ/ were all negative but were small and nonsignificant ($p > 0.05$) when the 2H means were related to the 2N means for those vowels. The coefficients for /i/ were negative except when the 5H means were related to either the 5N means or the S_1N means. The coefficients for /u/ were negative only when the 2H means were related to the 2N means or the S_1N means. The coefficients presented in Table 8 were significant ($p < 0.05$) for all five test vowels only when the 2H means were related to the S_1N means. These negative coefficients ranged from − .54 for /ɑ/ to − .77 for /æ/.

Harmonic and Noise Level Ratios and Differences

The correlations between judged vowel roughness and selected indices of harmonic and noise level relationship for the productions of each vowel were also investigated. The indices of harmonic and noise level relationship of interest were obtained in the following ways. First, ratio measures were obtained for each vowel production. The ratios obtained were: 2H/2N, 3H/3N, 5H/5N, 2H/S_1N, 3H/S_1N, and 5H/S_1N. Second, difference measures were obtained for each vowel production. The differences obtained were: 2H−2N, 3H−3N, 5H−5N, 2H−S_1N, 3H−S_1N, and 5H−S_1N.

Table 9 presents the 2H/2N, 3H/3N, and 5H/5N ratios, and the

TABLE 9.—Means over the twenty subjects and standard deviations of the harmonic/noise level ratios and harmonic-noise level differences for normal and for simulated abnormally rough productions of each test vowel. Both ratios and differences are presented for the means of the first two (2H), first three (3H), and first five (5H) harmonics and, respectively, the spectral noise levels averaged over the frequency range of the first two (2N), first three (3N), and first five (5N) harmonics.

	Ratios						Differences					
Vowel	2H/2N	SD	3H/3N	SD	5H/5N	SD	2H-2N	SD	3H-3N	SD	5H-5N	SD
/u/												
Normal	2.62	.35	2.71	.31	3.04	.32	44.96	3.70	41.03	3.21	38.20	2.42
Rough	1.96	.34	1.86	.32	1.75	.29	33.63	6.79	29.50	6.70	25.11	6.12
Difference	.66[b]		.85[b]		1.29[b]		11.33[b]		11.53[b]		13.09[b]	
/i/												
Normal	2.44	.23	2.61	.23	3.29	.36	43.03	3.14	39.92	2.71	37.78	2.73
Rough	1.97	.33	1.94	.35	1.91	.35	33.62	6.62	29.92	6.25	25.39	5.74
Difference	.47[b]		.67[b]		1.38[b]		9.41[b]		10.00[b]		12.39[b]	
/ʌ/												
Normal	2.72	.47	2.60	.28	2.40	.19	43.68	3.18	42.64	2.60	39.36	2.00
Rough	2.14	.28	1.97	.23	1.69	.15	34.52	4.94	31.74	4.60	26.06	3.86
Difference	.58[b]		.63[b]		.71[b]		9.16[b]		10.90[b]		13.30[b]	
/ɑ/												
Normal	2.70	.30	2.70	.27	2.48	.21	42.62	2.71	42.20	2.68	40.02	2.38
Rough	2.25	.38	2.08	.32	1.81	.27	34.36	6.77	31.91	6.22	27.75	6.35
Difference	.45[b]		.62[b]		.67[b]		8.26[b]		10.29[b]		12.27[b]	
/æ/												
Normal	2.71	.41	2.65	.32	2.43	.22	43.43	3.57	42.44	3.00	39.65	2.68
Rough	2.11	.32	1.97	.30	1.71	.22	32.86	5.81	30.03	5.78	25.17	5.61
Difference	.60[b]		.68[b]		.72[b]		10.57[b]		12.41[b]		14.48[b]	

[b]($p < 0.01$): a two-tailed Wilcoxon matched-pairs signed-ranks test was utilized to test the significance of the difference between normal and rough productions (see Appendix C).

2H-2N, 3H-3N, and 5H-5N differences for rough and normal productions of each test vowel, averaged over the twenty subjects. Also shown in Table 9 is the standard deviation associated with each mean, and the difference between the ratio means and between the difference means for rough and normal productions of each vowel. Table 9 shows that the difference in the ratio means for normal and for rough productions of each test vowel tended to be largest for 5H/5N ratios, and progressively smaller for 3H/3N and 2H/2N ratios. The differences between the ratio means for normal and abnormally rough productions of each vowel were all significant ($p < 0.01$) regardless of whether 2H/2N, 3H/3N, or 5H/5N ratios were considered. Thus, for each vowel tested and each relationship considered, the mean ratio associated with normal productions significantly exceeded that associated with rough productions.

Table 9 also shows that the difference between the mean harmonic level and noise level differences for normal and for rough productions of each test vowel tended to be largest for the 5H-5N differences, and progressively smaller for the 3H-3N and 2H-2N differences. The differences between the mean harmonic level and noise level differences for normal and rough productions of each vowel presented in Table 9 were all significant ($p < 0.01$), however, regardless of whether 2H-2N, 3H-3N, or 5H-5N differences were considered. Thus, for each vowel tested and each relationship considered, the mean harmonic level and noise level difference associated with normal productions significantly exceeded that associated with rough productions.

As a further procedure, the $5H/S_1N$, $3H/S_1N$, and $2H/S_1N$ ratios and the $5H-S_1N$, $3H-S_1N$, and $2H-2_1N$ differences were obtained for rough and normal productions of each vowel. Table 10 presents the average of

TABLE 10.--Means over the twenty subjects and standard deviations of the harmonic/noise level ratios and harmonic-noise level differences for normal and for simulated abnormally rough productions of each test vowel. Both ratios and differences are presented for the 2H, 3H, and 5H and the S_1N means.

	Ratios						Differences					
Vowel	$2H/S_1N$	SD	$3H/S_1N$	SD	$5H/S_1N$	SD	$2H-S_1N$	SD	$3H-S_1N$	SD	$5H-S_1N$	SD
/u/												
Normal	6.03	1.79	5.36	1.49	4.69	1.39	60.40	3.26	52.53	3.54	44.24	4.10
Rough	2.32	.50	2.15	.42	1.97	.39	39.07	6.22	34.27	5.56	28.65	5.93
Difference	3.71[b]		3.21[b]		2.72[b]		21.33[b]		18.26[b]		15.59[b]	
/i/												
Normal	7.52	2.36	6.65	2.05	5.56	1.65	62.74	2.98	54.31	3.20	43.90	2.78
Rough	2.74	.63	2.48	.53	2.15	.45	43.26	6.86	36.79	5.85	28.58	5.39
Difference	4.78[b]		4.17[b]		3.41[b]		19.48[b]		17.52[b]		15.32[b]	
/ʌ/												
Normal	2.84	.31	2.83	.32	2.75	.28	45.08	3.36	44.72	3.49	42.78	2.74
Rough	1.72	.19	1.71	.17	1.69	.16	27.34	5.45	29.96	4.94	26.06	4.00
Difference	1.12[b]		1.12[b]		1.06[b]		17.74[b]		14.76[b]		16.72[b]	
/ɑ/												
Normal	3.03	.39	3.00	.39	3.00	.39	45.36	2.68	44.57	2.56	44.72	2.57
Rough	1.81	.44	1.79	.44	1.82	.44	27.10	8.50	26.33	8.33	27.30	8.18
Difference	1.22[b]		1.21[b]		1.18[b]		18.26[b]		18.24[b]		17.42[b]	
/æ/												
Normal	2.52	.22	2.51	.23	2.47	.20	41.85	2.96	40.82	2.79	40.15	2.35
Rough	1.64	.22	1.60	.21	1.59	.21	24.37	6.27	22.92	6.08	22.60	5.87
Difference	.88[b]		.91[b]		.88[b]		17.48[b]		17.90[b]		17.55[b]	

[b]($p < 0.01$): a two-tailed Wilcoxon matched-pairs signed-ranks test was utilized to test the significance of the difference between normal and rough productions (see Appendix C).

these ratios over the twenty subjects for rough and for normal productions of each test vowel, and the standard deviation associated with each mean. The difference between the harmonic level and noise level ratio means and between the harmonic and noise level difference means for rough and normal productions are also shown for each test vowel. Table 10 shows that the obtained harmonic level and noise level ratio means tended to be larger for the normal than for the rough productions of each test vowel. There is also an evident tendency for the differences between the ratio means for normal and rough productions to be larger for the high vowels /u/ and /i/ than for the other test vowels. Such differences were significant ($p < 0.01$) for all five test vowels regardless of the number of harmonics averaged to obtain the harmonic level means.

Table 10 also shows that there was a tendency for the difference between harmonic level and noise level difference means for rough and for normal productions to be larger for the high vowels /u/ and /i/ than for the other test vowels when 5H-S_1N differences were considered, but an opposite trend obtained when 2H-S_1N differences were considered. The differences in harmonic level and noise level difference means were significant ($p < 0.01$), however, regardless of the number of harmonics averaged to obtain the harmonic level means.

Roughness Rating Relationships to Harmonic and Noise Level Ratios and Differences

To obtain data illustrating the relationship of the vowel median roughness ratings to the indices of vowel harmonic level and noise level relationship, the median roughness ratings for the productions of each vowel were related to the harmonic level and noise level ratios and to the harmonic level and noise level differences. Initially, the 5H/5N, 3H/3N, and 2H/2N ratios, and the 5H-5N, 3H-3N, and 2H-2N differences were related to the median roughness ratings. Table 11 presents the correlation (Spearman $\underline{r}_s$) observed when those relationships were studied.

All the coefficients presented in Table 11 are negative and significant ($p < 0.01$) indicating a tendency for the vowel median roughness ratings to vary inversely with the ratio and with the difference measures. For all test vowels, a trend is evident in Table 11 for the roughness ratings to be more highly correlated with the harmonic level and noise level ratios and differences associated with the 3H means than with those associated with the 2H means. The largest negative coefficients were obtained, however, when the roughness ratings for the productions of each vowel are related to the harmonic level and noise level ratios and differences associated with the 5H means. When all test vowels are considered, Table 11 reveals no clear difference in the magnitude of the coefficients associated with either the harmonic level and noise level ratios or the harmonic level and noise level differences. There was, however, a trend toward slightly larger coefficients for the 2H-2N differences than for the 2H/2N ratios than those associated with the 5H-5N differences, for all test vowels except /ʌ/.

As a further procedure, the 5H/S_1N, 3H/S_1N, and 2H/S_1N ratios and the 5H-S_1N, 3H-S_1N, and 2H-S_1N differences were related to the median roughness ratings for each test vowel. Table 12 presents the correlation (Spearman $\underline{r}_s$) observed when these relationships were studied. All the coefficients presented in Table 12 are negative and

TABLE 11.—Spearman rank correlation coefficients ($\underline{r}_s$) indicating the relationship between the median roughness ratings (MRR) and both the 2H/2N, 3H/3N, and 5H/5N harmonic/noise level ratios and the 2H-2N, 3H-3N, and 5H-5N harmonic-noise level differences for the productions of each test vowel.

	Ratios			Differences		
Vowel	2H/2N vs MRR	3H/3N vs MRR	5H/5N vs MRR	2H-2N vs MRR	3H-3N vs MRR	5H-5N vs MRR
/u/	-.69[b]	-.81[b]	-.84[b]	-.71[b]	-.78[b]	-.82[b]
/i/	-.84[b]	-.86[b]	-.91[b]	-.86[b]	-.88[b]	-.89[b]
/ʌ/	-.74[b]	-.83[b]	-.85[b]	-.79[b]	-.83[b]	-.86[b]
/ɑ/	-.71[b]	-.84[b]	-.89[b]	-.72[b]	-.83[b]	-.88[b]
/æ/	-.72[b]	-.80[b]	-.85[b]	-.75[b]	-.82[b]	-.84[b]

[b]($p < 0.01$): a two-tailed $\underline{t}$ test was utilized to test the significance of the correlation (see Appendix C).

TABLE 12.—Spearman rank correlation coefficients ($\underline{r}_s$) indicating the relationship between the median roughness ratings (MRR) and both the $2H/S_1N$, $3H/S_1N$, and $5H/S_1N$ harmonic/noise level ratios and the $2H-S_1N$, $3H-S_1N$, and $5H-S_1N$ harmonic-noise level differences for the productions of each test vowel.

	Ratios			Differences		
Vowel	$2H/S_1N$ vs MRR	$3H/S_1N$ vs MRR	$5H/S_1N$ vs MRR	$2H-S_1N$ vs MRR	$3H-S_1N$ vs MRR	$5H-S_1N$ vs MRR
/u/	$-.85^b$	$-.84^b$	$-.84^b$	$-.86^b$	$-.84^b$	$-.83^b$
/i/	$-.84^b$	$-.84^b$	$-.85^b$	$-.85^b$	$-.86^b$	$-.87^b$
/ʌ/	$-.82^b$	$-.82^b$	$-.83^b$	$-.77^b$	$-.79^b$	$-.83^b$
/ɑ/	$-.90^b$	$-.92^b$	$-.92^b$	$-.86^b$	$-.88^b$	$-.89^b$
/æ/	$-.83^b$	$-.83^b$	$-.88^b$	$-.80^b$	$-.83^b$	$-.87^b$

[b]($p < 0.01$): a two-tailed $\underline{t}$ test was utilized to test the significance of the correlation (see Appendix C).

significant ($p < 0.01$), indicating a tendency for the vowel median roughness ratings to vary inversely with the ratio and with the difference measures regardless of the number of harmonics averaged to obtain the harmonic level means. When the ratio measures are considered, the coefficients associated with the vowels /u/, /i/, /ʌ/, or /ɑ/ tend to be similar for the three measures. For /æ/, however, the negative coefficient obtained when the $5H/S_1N$ ratios were related to the median roughness ratings tended to be larger than that obtained when the $3H/S_1N$ or $2H/S_1N$ ratios were related to ratings. When the difference measures are considered, it may be seen that the largest coefficients for /æ/, /ʌ/, /ɑ/, and /i/ were obtained when the $5H-S_1N$ differences were related to the median roughness rating, but only the coefficient for /æ/ was substantially larger than those associated with the other difference measures. The highest coefficient for /u/ was obtained when the $2H-S_1N$ differences were related to the median roughness ratings. When all test vowels are considered, Table 12 reveals no clear difference in the magnitude of the coefficients associated with either the harmonic-noise level ratios or the harmonic-noise level differences.

Discussion

To aid in understanding the present findings, it appears pertinent to discuss a number of variables which may influence vowel harmonic levels. It is of interest, for example, to consider the effect of the fundamental vocal frequency (FVF) employed in vowel production on the frequency location of vowel spectral harmonics. Because by definition (20, 26, 32, 39, 40, 51) the harmonic vowel components occur at spectral frequencies which are simple integral multiples of the FVF

(H_1 = 1 x FVF, H_2 = 2 x FVF,...H_n = n x FVF), the harmonics of vowels produced with a relatively high FVF are further apart on the spectral frequency scale than those for vowels produced with a relatively low FVF. This spectral spacing of harmonics is apparently uninfluenced by supraglottic vocal tract resonator effects except as physiological adjustments employed to effect vocal resonance changes may also affect the FVF (12, 32, 36, 60, 61). As will be seen when vocal tract resonator effects are discussed below, however, the frequency location of vowel spectral harmonics relative to vocal tract resonant frequencies does affect vowel harmonic levels.

Modern theories of phonation suggest that the glottal volume-velocity wave resembles a pulsating direct current wave, and that successive cycles of the volume-velocity wave tend to be approximately triangular in shape during vowel phonation (12, 17, 18, 60, 61). Thus, the harmonics of that wave diminish approximately 12 dB per octave from low to high spectral frequencies. This "source function" effect, i.e., the effect of the shape of the glottal volume-velocity wave on harmonic levels, is modified, however, by effects imposed by the supraglottic resonators (12, 18, 19, 32, 47, 48, 60, 61). These resonance effects are often termed vocal tract "filter function" effects. It is well known that the frequency locations and bandwidths of vocal tract resonances and antiresonances have a marked effect on the relative level of individual vowel harmonics. Should the frequency at which an individual harmonic occurs be one at which the vocal tract tends to be resonant, that harmonic will be relatively high in level with respect to adjacent harmonics, but the same harmonic will be relatively low in level with respect to adjacent harmonics should it occur at a vocal tract antiresonant frequency. Because different vowel phonemes tend to differ with respect to their characteristic resonant and antiresonant frequencies, resonance or filter function effects on vowel harmonic levels tend to be different for different vowels.

An additional modification of vowel harmonic levels occurs when vowel acoustic energy is transferred from the vocal tract to the external environment. This "radiation" or "transfer function" effect diminishes the level of the low-frequency spectral harmonics with respect to the level of high-frequency harmonics by approximately 6 dB per octave (12, 16, 18, 60, 61, 70). The aforementioned source function, filter function, and transfer function effects on vowel harmonic levels are often described as the major determinants of the acoustic spectral envelope of vowels and, thus, of the vowel formants (16, 32, 47, 48, 60).

It is germane to an interpretation of the present findings to note that the test vowels studied were expected to differ, not only with respect to the frequency location of their major formants, i.e., regions of spectral energy prominance, but also with respect to formant bandwidths and amplitudes. Further, they were expected to evidence different degrees of harmonic diminution in interformant frequency regions. Such expectations appeared reasonable in view of findings from previous studies (12, 16, 33, 47, 48, 60) of vowel formant features. Thus, it was expected that the levels of specific harmonics, i.e., H_1, H_2,...H_n, would tend to vary across test vowels in part because of formant differences characteristic of different vowel phonemes.

Two additional factors which appear to affect vowel harmonic levels in spectra comparable to those obtained for the present study are also of interest. Those factors are acoustic wave periodicity effects, and effects of the interaction of signal and noise in vowel spectra. Regarding acoustic wave periodicity effects on harmonic levels, the following observations appear pertinent. It is understood, in general, that the more nearly a complex acoustic wave approaches periodicity the more the wave energy will tend to be concentrated spectrographically in components which are simple integral multiples of the fundamental frequency of the wave, i.e., in the spectral harmonics (26, 32, 39, 40). Thus, in the theoretical extreme case of a complex acoustic wave which is of infinite duration and perfectly periodic, acoustic components of the wave would be evidenced spectrographically only at a fundamental frequency and its higher harmonics. Conversely, the less periodic an acoustic wave is, i.e., the more aperiodic, the more its spectral energy will be distributed broadly over spectral frequencies (32, 49, 50). Thus, for a theoretical complex acoustic wave which is perfectly aperiodic, a continuous noise spectrum indicating an equal acoustic intensity at all spectral frequencies should be obtained. Vowel acoustic waves, however, are neither perfectly periodic nor perfectly aperiodic, but vary between those extremes. Moreover, waves of equal duration and intensity for repeated productions of the same vowel phoneme may vary in their periodicity. It is pertinent to note in this regard that vowel waves are functions of time; thus, for successive productions of the same vowel which are of equal duration and intensity, an increase in acoustic wave aperiodicity is accompanied by a decrease in wave periodicity, and vice versa.

Generally, the acoustic waves of normal vowel productions are more periodic than aperiodic; hence, such waves are said to be "quasi-periodic" (16, 32, 49, 50, 80). On the other hand, the acoustic waves of hoarse or abnormally rough vowels tend to be more aperiodic than periodic, and the waves for extremely rough or hoarse vowel phonations may lack visually discernable periodicity (34, 35, 36). The acoustic spectra of normal vowel productions tend to be characterized by visually prominent harmonic components over a wide range of spectral frequencies, and by relatively low spectral noise levels. The spectra for hoarse or abnormally rough vowels, on the other hand, tend to be characterized by diminished harmonic levels and by elevated spectral noise levels (14, 15, 21, 25, 54, 70, 76, 77, 78, 79). Thus, it appears that increased vowel roughness and accompanying wave aperiodicity should tend to have the effect of diminishing vowel harmonic levels. It also appears that this aperiodicity effect should obtain independently of the previously discussed source, filter, and transfer function effects on vowel harmonic levels.

On the basis of acoustic theory, it may be concluded that there is a significant interactive relationship between acoustic wave noise and signal components at spectral harmonic frequencies, and that this relationship is dependent upon the level of the signal component relative to the level of the noise component at the frequency of interest (15, 23, 32). The above generalization that vowel harmonic levels should diminish with increasing vowel roughness must be qualified, therefore, to take into account the effects of signal and noise interactions in vowel spectra. To understand such interactive effects in the spectra obtained for this study, it is useful to recall that vowel waves are never perfectly periodic but are, to various degrees, somewhat aperiodic. It is also useful to recall that while the vowel wave periodicity (signal) contributes to a concentration of energy only at the spectral harmonic frequencies, wave aperiodicity (noise) contributes to spectral noise levels over a broad range of frequencies, including the frequencies which are in harmonic relationship to the fundamental frequency. It may be seen, therefore, that the apparent level of each vowel spectral harmonic must be determined in part by the periodicity (signal) and in part by the aperiodicity (noise) present in the vowel wave, while the level of spectral inharmonics or noise must be determined by the wave aperiodicity (noise) alone (possible artifactual noise effects are neglected in this presentation).

It may be noted further that the vowel spectral harmonic and noise levels obtained for this study were measured in decibels (SPL). Thus, the combined effect of acoustic wave periodicity (signal) and aperiodicity (noise) upon the apparent level of a particular spectral harmonic would not be a simple sum of the noise and signal levels expressed in decibels. To differentiate and to quantify the contribution of the signal and noise within a vowel wave to the decibel level of a particular harmonic, it appears necessary to obtain independent measures of the sound intensity attributable to wave periodicity (signal) at the harmonic frequency, and the sound intensity at that frequency attributable to wave aperiodicity (noise). Such independent intensity measures for signal and noise within an acoustic wave are not readily obtained at present. It may be suggested, however, that the primary acoustic energy component of a particular vowel harmonic, as it appears spectrographically, may be either signal or noise, depending on the harmonic of interest and on the extent to which the vowel wave is periodic rather than aperiodic.

Generally, it appears that wave periodicity or signal effects would tend to be greatest on the observed level of vowel harmonics which are relatively low in frequency, while wave aperiodicity or noise effects would tend to be greatest on the level of harmonics which are relatively high in frequency. This conclusion is predicated mainly on theoretical concepts regarding vowel spectral features. It was noted earlier in this discussion, for example, that theoretical "source function" effects diminish vowel harmonic levels by about 12 dB per octave from low to high spectral frequencies. Because the foregoing description of source function effects generally assumes the glottal volume-velocity wave to be essentially periodic in vowel production (12, 17, 18, 60, 61), it appears somewhat more meaningful in the present context to suggest that the source function effect is to diminish the signal level at harmonic frequencies by about 12 dB per octave. Thus, the signal level contribution to harmonic levels tends to become asymptotic to zero at higher spectral frequencies. That is, the contribution of signal to harmonic levels tends to be greatly diminished at relatively high spectral frequencies, but tends to be relatively large at low spectral frequencies. Modern acoustic theories (23, 32) and empirical findings (14, 15, 21, 38, 54, 76) both suggest that vowel spectral noise levels tend to increase uniformly across spectral frequencies with increasing vowel roughness. It follows, therefore, that relative to signal levels at harmonic frequencies, noise levels should be higher at high than at low harmonic frequencies.

It appears, moreover, that as vowel wave periodicity diminishes with increasing vocal roughness, the absolute signal contribution to harmonic levels should tend to diminish proportionately. Concurrently, the absolute level of noise should increase over a broad band of spectral frequencies, including harmonic frequencies. Thus, the apparent level of an harmonic can reflect mainly either the level of the signal or the noise, depending on which is more intense at the harmonic frequency of interest. Further, because the signal contribution to harmonic levels tends to diminish from low to high spectral frequencies, the noise contribution should tend to predominate at higher harmonic frequencies while the signal contribution should tend to predominate at lower harmonic frequencies. With increasing vocal roughness in vowel production, the noise contribution should tend to predominate over the signal contribution at successively lower harmonic frequencies.

These observations suggest that vowel low-frequency harmonics should decrease in level with increasing vowel roughness because the apparent level of those harmonics is mainly attributable to the signal level, and because the signal contribution to the harmonic level diminishes with increasing roughness. They also suggest that higher vowel harmonics may increase in level with increasing roughness because wave aperiodicity or noise increases with vocal roughness and because the contribution of such noise to harmonic levels tends to be relatively large with respect to the signal contribution at higher harmonic frequencies. In such instances, the apparent harmonic level mainly reflects noise levels. When vowel phoneme differences in filter function effects upon the signal level at harmonic frequencies are taken into account, it may also be seen that the relationship of signal and noise at a specific harmonic, i.e., H_1, H_2,...H_n, would tend to be different for different vowels.

In summary, the foregoing discussion provides a conceptual paradigm regarding factors which may affect vowel harmonic levels on the basis of which the present findings may be interpreted. In general, it was noted that the major factors which may influence harmonic levels in vowel spectra include source, filter, and transfer function effects which are commonly described. Wave periodicity and signal and noise interaction effects on vowel harmonic levels were also discussed. All of the described effects appear important to an interpretation of acoustic spectra for vowel productions differing in roughness.

It may be noted that the spectral differences between normal and abnormally rough vowel phonations observed in the present study do not appear to be attributable simply to a difference in the FVF of normal and rough productions. Although there was a tendency for rough productions to evidence a FVF which was somewhat higher than that for normal productions, in several instances the FVFs for normal and rough productions of the same vowel produced by individual subjects were essentially the same, or the FVF for the normal production exceeded that for the rough production. Trends evident in the spectra of vowels produced by subjects who did not increase their FVF from normal to rough productions were generally similar to those obtained for the total subject group.

Generally, the level of the harmonics of the test vowels for this study tended to diminish from low to high spectral frequencies. This commonly reported (2, 6, 31, 59, 62) spectral feature of vowels appears to be mainly attributable to the source function effects on vowel spectra discussed earlier. It was also found, however, that the third, fourth, and fifth harmonics of the high vowels /u/ and /i/ tended to be more markedly diminished in level than those of the mid vowel /ʌ/ or the low vowels /ɑ/ and /æ/. Similar findings have been reported previously

(15) for vowels produced by adult male subjects. This difference among vowels appears to be mainly attributable to differences in vocal tract filter function effects associated with different vowel phonemes. The higher harmonics of the high vowels /u/ and /i/ produced by female subjects tend to occur in an interformant frequency range, while the low-frequency harmonics of these vowels tend to occur near or within a formant (47). Thus, because of the formant features of the higher vowels, the higher harmonics of /u/ and /i/ tend to be greatly diminished in level with respect to their lower harmonics. In contrast, for the mid vowel /ʌ/ and the low vowels /ɑ/ and /æ/ produced by females, the third, fourth, and fifth harmonics tend to occur near or within the first formant. Thus, for the mid vowel and the low vowels tested, the level of the higher harmonics (of the five harmonics studied) tends to be relatively high with respect to that of the lower harmonics for those test vowels.

The present findings also revealed a tendency for the level of the first five harmonics of the mid vowel /ʌ/ and the low vowels /ɑ/ and /æ/ and the first two harmonics of the high vowels /u/ and /i/ to be lower for the simulated abnormally rough than for the normal productions. This finding is consistent with findings reported previously by Emanuel and Whitehead (15) for vowels produced by males. It was also found in the present study that the level of the third, fourth, and fifth harmonics of the high vowels /u/ and /i/ tended to be higher for the rough than for the normal vowel productions. This finding is also consistent with previous findings for male subjects (15). Such findings for the higher harmonics of /u/ and /i/ appear to be attributable both to filter function and to signal and noise interaction effects on spectral harmonic levels. That is, because the third, fourth, and fifth harmonics of the vowels /u/ and /i/ produced by adult females tend to occur at vocal tract antiresonant frequencies (47), the signal component of those spectral harmonics for /u/ and /i/ tends to be diminished more than that for the corresponding harmonics of /ʌ/, /ɑ/, and /æ/. Thus, the level of the signal at the frequency of the third, fourth, and fifth harmonics of both rough and normal /u/ and /i/ productions tends to be relatively low with respect to the level of the noise at those frequencies. This diminution of the signal component should be more marked for the abnormally rough than for normal productions because of the elevated spectral noise levels associated with the rough phonations. In such instances, it appears that the vowel wave aperiodicity or noise is a more important determinant of the observed harmonic level than is the wave periodicity or signal. The higher spectral noise levels associated with the rough than with the normal /u/ and /i/ productions may thus account for the elevation of the third, fourth, and fifth harmonics of those vowels which is associated with increased vowel roughness.

When vowel harmonic levels were averaged over selected harmonics, the present findings indicated that the 2H, 3H, and 5H means were all greater for the normal than for the rough productions of the mid vowel /ʌ/ and the low vowels /ɑ/ and /æ/. For the high vowels /u/ and /i/, however, only the 2H means evidenced a similar trend. The levels of the 3H and 5H means for /u/ and /i/ were greater for the rough than for the normal productions. Moreover, these findings regarding the harmonic level means for the present study are generally similar to comparable findings for the vowel productions of adult males (15).

The present findings revealed that both the median roughness ratings and spectral noise level measures for the test vowels tended to be linearly and negatively related to the levels of each of the five measured harmonics of the mid vowel /ʌ/ and the low vowels /ɑ/ and /æ/. The median roughness ratings and spectral noise level measures for /u/ and /i/ also tended to be linearly and negatively related to the obtained levels of the first and second harmonics of those test vowels. This finding is consistent with an hypothesis of a trading relationship trend between spectral harmonic and noise levels for the harmonics indicated. The aforementioned negative relationships did not hold, however, when the levels of the third, fourth, and fifth harmonics of /u/ and /i/ were related to the median roughness ratings and spectral noise levels for those vowels. Similar findings have been reported by Emanuel and Whitehead (15) for vowels produced by adult males. These exceptions to the generally obtained negative, linear-relationship trend between spectral harmonic and noise levels and harmonic levels and vowel roughness were found only for specific harmonics of individual vowels. The exceptions occurred when the level of the harmonics considered tended to be low relative to noise levels and, as was discussed earlier, it appeared that the observed level of the harmonics may have been determined mainly by noise rather than by signal levels.

The present findings also indicated that the harmonic noise level ratios and harmonic-noise level differences for the test vowels tended to be larger for the normal than for the simulated abnormally rough productions. This finding is also consistent with an hypothesis that diminished harmonic levels tend to be associated with elevated vowel spectral noise levels and increased vowel roughness. When the harmonic/noise level ratios and harmonic-noise level differences were related to the vowel median roughness ratings, moderately large, negative correlation coefficients (Spearman $\underline{r}_s$) ranging from - .69 to - .92 were obtained. Generally, these negative coefficients were larger than those obtained when vowel median roughness ratings were related to individual harmonic levels or to levels averaged over selected harmonics of each vowel production. These negative coefficients associated with the ratio and difference measures tended to be slightly smaller, however, than the positive coefficients (Pearson $\underline{r}$) obtained previously (38) when spectral noise levels alone were related to the median roughness ratings for the vowels. Similar findings have been reported for adult male subjects (15).

Except for the sex of the subjects, the present study was designed to replicate, in most respects, the study reported by Emanuel and Whitehead (15) for the vowel productions of adult males. With similar data available for the two sexes, it was possible to confirm that many of the findings reported for males tend to obtain also for females. There were, however, differences in the findings for males and females which are of interest. In Appendix B, tables are presented which compare certain of the present findings with those from the Emanuel and Whitehead study and illustrate differences of interest between the studies.

When the levels of the first two harmonics of each test vowel produced by adult males and by adult females were compared across sexes (see Table 18, Appendix B), there was little evident sex difference in the harmonic levels obtained either for normal or for simulated abnormally rough vowel productions. When the levels obtained for the third and fourth harmonics of the test vowels were compared across sexes, however, the levels obtained for the productions of the females were found to be substantially lower than those for the males, both for rough and for normal productions of the high vowels /u/ and /i/. This sex-difference trend tended to be smaller for the fourth harmonic of /u/ and /i/ than for the third. A comparable sex-difference trend was not evident, however, for the third and fourth harmonics of the mid vowel /ʌ/ and the low vowels /ɑ/ and /æ/, or for the fifth harmonic of any of the five test vowels. These observed sex-difference trends associated with the third and fourth harmonics of /u/ and /i/ may be largely attributable to differences in the FVF of vowels produced by the two sexes. It may be noted that the vowel FVF differences between sex groups were considerably larger than the FVF differences between normal and rough productions within sex groups. The harmonics of vowels produced by females tend to be more widely spaced and, thus, to occur at higher frequencies on the spectral scale than those for vowels produced by males. It appears, therefore, that harmonics of the vowels /u/ and /i/ are more likely to be within an interformant range when the vowels are produced by females than when they are produced by males. This interpretation appears reasonable even though there is a tendency for the location of the formants for /u/ and /i/ to be slightly higher on the frequency scale when the vowels are produced by females than when they are produced by males (33, 47, 48, 60, 61). The sex differences in formant locations for /u/ and /i/ tend to be relatively small with respect to the sex-related harmonic-spacing differences.

The absence of a similar sex-difference trend for the other test vowels is also of interest. It would appear that effects of sex differences in the FVF of the mid vowel /ʌ/ and the low vowels /ɑ/ and /æ/ on the harmonic spacing for those test vowels tends to be compensated for in some manner. Previous studies (33, 47, 48, 60, 61) of the formant features of vowels suggest that the formants of the mid vowel /ʌ/ and the low vowels /ɑ/ and /æ/ tend to shift their frequency locations more with a change in FVF than do those for the high vowels /u/ and /i/. It may be, therefore, that formant frequency shifts associated with sex differences in FVFs tend to offset the sex-related harmonic spacing differences for the mid and low vowels.

It is also of interest to consider briefly some possible research implications of the present findings. It is pertinent to note in this regard that recent investigations have demonstrated a high degree of linear relationship between the perceived vowel roughness and vowel spectral noise levels when vowels are produced at a uniform intensity level. Lively and Emanuel (38), for example, obtained correlation coefficients (Pearson r) ranging from .91 to .94 for the five test vowels when median roughness ratings and spectral noise levels for normal and simulated abnormally rough vowels produced by female subjects were related. Generally, relationships demonstrated between vowel roughness and harmonic and noise level ratios and differences in the present study did not appear to be as large as those reported by Lively and Emanuel (38). For vowels produced at a uniform intensity, therefore, it may be that spectral noise level measures would provide a more useful quantitative index of vowel roughness than measures of vowel spectral harmonic levels or harmonic and noise level relationship.

It appears possible, however, that a change in vowel intensity (FVF constant) may be accompanied by a proportional change in both vowel harmonic and noise levels without a proportional change in vowel roughness. Thus, for vowels produced at different intensities, spectral noise level measures alone may not provide a meaningful index of vowel roughness. When vowel intensity is not controlled, therefore, a more useful index of vowel roughness might be a measure of harmonic and noise level relationship. This hypothesis may be profitably tested in a further investigation.

CHAPTER V

SUMMARY

The purpose of this study was to investigate spectral harmonic levels in narrow-band (3-Hz) acoustic spectra of normal and simulated abnormally rough vowels produced by adult female subjects. The relationship of the obtained spectral harmonic levels to spectral noise levels and roughness ratings for the vowel productions was also investigated. This study was designed to replicate, in most respects, a similar study of vowels produced by adult males which was reported by Emanuel and Whitehead (15). In general, the findings for males tended to support an hypothesis of a trading relationship between broad-band spectral noise levels and low-frequency spectral harmonic levels for normal and simulated abnormally rough vowel productions. It was of interest in the present study to investigate the possibility that similar findings would obtain for adult females.

The test vowel samples investigated in the present study were originally obtained for a previous study (38) in which twenty normal-speaking adult female subjects individually produced the vowels /u/, /i/, /ʌ/, /ɑ/, and /æ/, first normally and then with simulated abnormal roughness. Each vowel production was sustained for seven seconds at a uniform intensity level of 75 dB (± 1 dB) at a mouth-to-microphone distance of six inches. The vowel productions were recorded on magnetic tape, randomized, and rated for roughness on a five-point equal-appearing intervals scale by eleven judges. A median of the judges' ratings served as an index of the roughness of each vowel sample. A two-second tape-loop constructed from a central portion of the recording of each vowel production was also analyzed to produce a narrow-band (3-Hz) frequency-by-amplitude acoustic vowel spectrum.

For the present investigation, the vowel recordings were reanalyzed spectrographically to provide an accurate display of vowel harmonic levels. Because individual harmonics were discernable in the vowel spectra at low but not always at high spectral frequencies, the levels of only the first five harmonics of each normal and abnormally rough vowel production were measured. For the Lively and Emanuel study, measures of the lowest observable peak of spectral energy in successive 100-Hz spectral sections from 100 to 8000 Hz were obtained for each test phonation. For the present investigation, spectral noise level means were obtained for each test vowel over a frequency range comparable to that spanned by the first two, first three, and first five vowel harmonics (2N, 3N, and 5N, respectively), and over the frequency range from 100 to 2600 Hz (S_1N). Finally, the fundamental vocal frequency (FVF) of each test production was obtained.

The present findings revealed that the FVFs were generally higher for the rough than for the normal vowel productions. Further, there was a general tendency for the harmonic levels for normal productions to be higher than those for simulated abnormally rough productions, when the first five harmonics of the mid vowel /ʌ/ and the low vowels /ɑ/ and /æ/, and the first two harmonics of the high vowels /u/ and /i/ were considered. This difference was significant ($p < 0.01$) for all test vowels, however, only when the second harmonic of each vowel was considered. Levels of the third, fourth, and fifth harmonics of /u/ and /i/ tended to be higher for the rough than for the normal vowel productions, however. Trends associated with the harmonic level means obtained by averaging levels over the first two harmonics (2H), the first three harmonics (3H), and the first five harmonics (5H) of each test phonation were generally consistent with those observed for the individual harmonics.

When the levels of each of the first five harmonics were related separately to the spectral noise levels and to the median roughness ratings for the test vowels, negative correlations were obtained for the mid vowel /ʌ/ and the low vowels /ɑ/ and /æ/, regardless of the harmonic considered. When the high vowels /u/ and /i/ were considered, however, both the spectral noise levels and the median roughness ratings were found to be negatively correlated with the levels of the first and the second harmonics, but positively correlated with the levels of the third, fourth, and fifth harmonics. The observed negative relationships between harmonic levels and the noise levels and between harmonic levels and the median roughness ratings were significant ($p < 0.01$) for all vowels only when the second harmonic was considered. Similar findings were also obtained when the 2H, 3H, and 5H harmonic level means were related to the spectral noise levels and the median roughness ratings for each test vowel.

As a further procedure, selected indices of the relationship between harmonic and noise levels were obtained for each test phonation. Specifically, harmonic/noise level ratios and harmonic-noise level differences were obtained for: the 2H, 3H, and 5H means and the 2N, 3N, and 5N means, respectively; and, the 2H, 3H, and 5H means and the S_1N means. For both the ratio and difference measures, the means over subjects were significantly ($p < 0.01$) larger for the normal than for the rough productions for all five test vowels.

When the harmonic/noise level ratios and harmonic-noise level differences were related to the median roughness ratings for the test vowels, moderately large, negative correlation coefficients (Spearman $\underline{r}_s$) ranging from - .69 to - .92 were obtained. Thus, there was a tendency for the vowel roughness ratings to vary inversely with both the ratio and the difference measures regardless of the spectral index considered. There was no clear tendency for higher coefficients to be associated with either the harmonic/noise level ratios or the harmonic-noise level differences. In general, however, larger negative correlation coefficients were obtained when the vowel median roughness ratings were related to the indices of harmonic and noise level relationship than when they were related either to individual harmonic levels or to harmonic level means.

The present findings appear generally consistent with an hypothesis of a trading relationship between low-frequency spectral harmonic levels and broad-band spectral noise levels for vowels produced at uniform intensity. Exceptions to this generalization were found only for the third, fourth, and fifth harmonics of the high vowels /u/ and /i/, which tended to increase in level with increasing vowel spectral noise levels. Such exceptions appeared to be consistent with concepts of wave periodicity and signal and noise interaction effects on vowel harmonic levels. On the basis of the present findings it was suggested that harmonic/noise level ratios and harmonic-noise level differences might provide clinically useful indices of the roughness of vowels produced at different intensities. Additional investigations are needed, however, to provide data regarding the effects of intensity changes on vowel spectral harmonic and noise levels.

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APPENDIX A

Harmonic Levels for Each Normal and Simulated Abnormally Rough Vowel Production

TABLE 13.—Levels in dB SPL of each of the first five harmonics of the vowel /u/ produced by twenty adult female subjects both normally (N) and with simulated abnormal vocal roughness (R). The normal-rough difference (d) in levels for each harmonic are also presented for each subject.

	Harmonic 1			Harmonic 2			Harmonic 3			Harmonic 4			Harmonic 5		
Subject	N	R	d	N	R	d	N	R	d	N	R	d	N	R	d
1	72.0	71.0	1.0	74.5	63.5	11.0	43.5	58.5	-15.0	39.0	54.5	-15.5	41.5	49.5	- 8.0
2	75.5	69.0	6.5	74.0	68.5	5.5	44.0	55.5	-11.5	41.5	55.0	-13.5	46.5	58.5	-12.0
3	70.5	70.5	.0	74.0	70.5	3.5	38.5	53.5	-15.0	33.5	41.5	- 8.0	30.5	38.5	- 8.0
4	72.5	69.0	3.5	75.5	70.5	5.0	55.5	49.5	6.0	43.0	51.5	- 8.5	37.5	50.5	-13.0
5	74.5	74.5	.0	73.5	64.5	9.0	53.0	59.5	- 6.5	47.5	50.5	- 3.0	41.5	44.0	- 2.5
6	73.0	67.5	5.5	73.5	70.0	3.5	62.5	57.5	5.0	47.0	54.0	- 7.0	44.5	59.5	-15.0
7	77.0	77.0	.0	69.5	56.5	13.0	37.5	45.5	- 8.0	53.5	55.5	- 2.0	48.5	38.5	10.0
8	71.5	70.0	1.5	73.0	73.5	- .5	54.5	42.5	12.0	50.5	38.0	12.5	38.5	38.0	.5
9	73.5	69.5	4.0	73.5	72.5	1.0	46.0	60.5	-14.5	50.0	61.5	-11.5	49.5	49.5	.0
10	70.5	69.5	1.0	77.5	74.5	3.0	59.5	58.5	1.0	53.0	56.0	- 3.0	53.5	62.5	- 9.0
11	72.0	76.5	-4.5	75.5	60.5	15.0	48.5	51.0	- 2.5	49.0	58.5	- 9.5	44.5	52.0	- 7.5
12	74.5	66.0	8.5	72.5	73.5	-1.0	41.5	46.5	- 5.0	48.0	53.5	- 5.5	49.5	58.5	- 9.0
13	75.5	73.0	2.5	69.0	70.0	-1.0	51.5	60.5	- 9.0	50.5	57.5	- 7.0	49.0	47.0	2.0
14	73.0	74.0	-1.0	72.5	71.0	1.5	74.0	69.0	5.0	54.5	58.5	- 4.0	37.5	52.5	-15.0
15	77.0	74.0	3.0	74.0	70.0	4.0	49.5	60.5	-11.0	33.5	56.5	-23.0	35.5	41.0	- 5.5
16	70.0	74.5	-4.5	75.5	72.5	3.0	56.5	63.5	- 7.0	49.5	59.5	-10.0	48.0	50.0	- 2.0
17	73.0	70.0	3.0	75.5	70.5	5.0	50.5	59.5	- 9.0	49.5	52.5	- 3.0	42.0	55.0	-13.0
18	73.0	74.0	-1.0	74.5	72.5	2.0	41.5	58.5	-17.0	34.0	51.0	-17.0	40.5	44.5	- 4.0
19	71.5	73.0	-1.5	71.5	72.5	-1.0	50.0	60.5	-10.5	52.5	58.0	- 5.5	53.0	60.5	- 7.5
20	72.5	72.0	.5	72.5	76.5	-1.0	38.5	55.5	-17.0	42.5	53.0	-10.5	39.0	48.0	- 9.0

TABLE 14.--Levels in dB SPL of each of the first five harmonics of the vowel /i/ produced by twenty adult female subjects both normally (N) and with simulated abnormal vocal roughness (R). The normal-rough difference (d) in levels for each harmonic are also presented for each subject.

	Harmonic 1			Harmonic 2			Harmonic 3			Harmonic 4			Harmonic 5		
Subject	N	R	d	N	R	d	N	R	d	N	R	d	N	R	d
1	75.5	67.0	8.5	72.0	72.0	.0	48.5	47.5	1.0	42.0	40.5	1.5	38.5	36.0	2.5
2	78.0	69.5	8.5	69.5	68.0	1.5	47.0	54.5	- 7.5	38.5	45.5	- 7.0	32.5	47.5	-15.0
3	73.5	70.5	3.0	74.5	65.5	9.0	44.0	56.5	-12.5	38.5	46.5	- 8.0	35.5	33.5	2.0
4	76.0	74.5	1.5	72.0	66.0	6.0	58.0	41.0	17.0	40.5	42.0	- 1.5	40.0	36.0	4.0
5	75.5	75.5	.0	66.5	66.5	.0	40.5	50.0	- 9.5	40.5	42.0	- 1.5	31.0	27.5	3.5
6	74.0	69.0	5.0	69.5	70.0	- .5	48.0	54.5	- 6.5	31.5	47.5	-16.0	38.5	41.5	- 3.0
7	78.0	75.0	3.0	66.5	59.0	7.5	39.0	50.5	-11.5	40.0	48.5	- 8.5	33.0	40.5	- 7.5
8	74.0	71.5	2.5	74.5	73.5	1.0	47.5	42.5	5.0	41.0	42.0	- 1.0	35.5	35.5	.0
9	78.5	74.5	4.0	66.5	73.5	- 7.0	46.5	41.5	5.0	37.5	44.5	- 7.0	30.0	35.0	- 5.0
10	72.0	75.0	-3.0	75.0	71.0	4.0	58.5	49.5	9.0	40.5	44.5	- 4.0	40.0	43.5	- 3.5
11	75.5	72.0	3.5	72.5	62.0	10.5	45.0	47.0	- 2.0	40.0	49.0	- 9.0	40.5	38.5	2.0
12	78.5	73.5	5.0	67.5	63.5	4.0	49.0	49.5	- .5	43.5	38.5	5.0	30.5	43.5	-13.0
13	75.5	75.0	.5	68.0	66.5	1.5	47.0	49.0	- 2.0	49.5	43.0	6.5	44.0	37.5	6.5
14	74.5	74.5	.0	74.0	68.5	5.5	54.5	56.5	- 2.0	40.5	57.5	-17.0	40.5	46.0	- 5.5
15	77.0	75.0	2.0	69.0	59.5	9.5	44.0	60.0	-16.0	38.0	47.5	- 9.5	30.5	49.0	-18.5
16	72.0	73.0	-1.0	75.5	62.0	13.5	62.0	46.0	16.0	53.5	49.5	4.0	46.0	40.5	5.5
17	75.5	72.5	3.0	73.5	62.5	11.0	43.5	49.5	- 6.0	39.5	46.5	- 7.0	38.0	43.5	- 5.5
18	71.0	73.5	-2.5	75.5	68.0	7.5	46.0	58.8	-12.8	45.0	42.0	3.0	36.5	49.0	-12.5
19	76.5	73.5	3.0	72.0	67.5	4.5	50.5	57.5	- 7.0	45.5	46.5	- 1.0	32.0	42.0	-10.0
20	75.0	74.5	.5	74.5	72.0	2.5	42.5	48.5	- 6.0	39.5	50.5	-11.0	37.5	36.0	1.5

TABLE 15.—Levels in dB SPL of each of the first five harmonics of the vowel /ʌ/ produced by twenty adult female subjects both normally (N) and with simulated abnormal vocal roughness (R). The normal-rough difference (d) in levels for each harmonic are also presented for each subject.

	Harmonic 1			Harmonic 2			Harmonic 3			Harmonic 4			Harmonic 5		
Subject	N	R	d	N	R	d	N	R	d	N	R	d	N	R	d
1	73.0	58.5	14.5	66.5	61.0	5.5	67.0	67.0	.0	63.5	67.0	-3.5	68.5	67.5	1.0
2	71.5	66.0	5.5	71.5	65.0	6.5	72.5	67.5	5.0	68.5	66.5	2.0	57.0	56.5	.5
3	68.5	65.0	3.5	69.5	65.5	4.0	68.0	58.0	10.0	68.5	64.5	4.0	57.5	55.5	2.0
4	71.5	70.5	1.0	66.5	63.0	3.5	72.0	58.5	13.5	72.5	66.5	6.0	59.5	60.5	-1.0
5	72.5	70.0	2.5	66.5	68.0	-1.5	68.5	68.0	.5	69.5	67.5	2.0	58.0	54.0	4.0
6	73.0	58.5	14.5	65.0	52.0	13.0	72.0	63.5	8.5	70.0	66.0	4.0	56.5	69.5	-13.0
7	74.5	69.5	5.0	69.0	56.5	12.5	66.5	64.5	2.0	69.5	62.5	7.0	60.0	58.5	1.5
8	70.5	69.0	1.5	67.5	61.0	6.5	66.0	66.0	.0	68.5	69.5	-1.0	65.0	59.5	5.5
9	70.5	71.5	-1.0	73.0	62.0	11.0	72.5	64.5	8.0	66.5	68.5	-2.0	61.5	54.5	7.0
10	69.0	70.0	-1.0	59.5	70.5	-11.0	65.5	65.0	.5	67.5	66.0	1.5	72.5	60.5	12.0
11	73.5	69.5	4.0	73.5	61.5	12.0	66.5	70.5	-4.0	64.5	57.5	7.0	56.5	67.5	-11.0
12	72.5	71.5	1.0	71.0	62.5	8.5	67.0	71.5	-4.5	69.0	68.0	1.0	63.0	56.5	6.5
13	72.0	73.5	-1.5	70.5	62.5	8.0	70.5	65.5	5.0	69.5	66.5	3.0	58.0	55.5	2.5
14	71.5	73.0	-1.5	67.5	66.0	1.5	64.5	52.5	12.0	73.0	60.5	12.5	67.5	62.0	5.5
15	72.5	69.5	3.0	69.5	56.5	13.0	66.5	69.5	-3.0	61.5	60.5	1.0	60.0	64.0	-4.0
16	66.5	70.5	-4.0	65.5	63.5	2.0	75.0	70.5	4.5	67.5	65.5	2.0	56.5	59.0	-2.5
17	72.0	75.5	-3.5	70.5	69.5	1.0	70.0	66.5	3.5	67.5	63.0	4.5	62.0	60.5	1.5
18	70.5	63.5	7.0	67.5	61.0	6.5	66.5	54.0	12.5	73.0	68.5	4.5	63.5	60.0	3.5
19	71.5	63.5	8.0	72.5	62.0	10.5	72.5	71.5	1.0	69.5	68.0	1.5	55.0	62.5	-7.5
20	70.5	70.5	.0	69.5	66.5	3.0	68.5	55.5	13.0	73.0	73.0	.0	60.0	60.5	-.5

TABLE 16.--Levels in dB SPL of each of the first five harmonics of the vowel /ɑ/ produced by twenty adult female subjects both normally (N) and with simulated abnormal vocal roughness (R). The normal-rough difference (d) in levels for each harmonic are also presented for each subject.

	Harmonic 1			Harmonic 2			Harmonic 3			Harmonic 4			Harmonic 5		
Subject	N	R	d	N	R	d	N	R	d	N	R	d	N	R	d
1	73.5	57.5	16.0	66.0	54.5	11.5	67.5	53.5	14.0	66.5	51.0	15.5	67.5	50.5	17.0
2	68.5	64.5	4.0	66.5	64.5	2.0	68.5	73.5	- 5.0	72.0	69.5	2.5	62.5	63.0	- .5
3	69.0	63.5	5.5	67.5	60.5	7.0	65.5	52.5	13.0	67.0	58.0	9.0	67.5	65.0	2.5
4	72.5	70.0	2.5	64.0	66.0	- 2.0	68.0	58.5	9.5	71.0	67.0	4.0	65.5	64.5	1.0
5	72.0	72.0	.0	66.5	50.0	16.5	64.5	60.5	4.0	70.0	62.0	8.0	69.5	60.5	9.0
6	74.5	59.5	15.0	66.5	52.5	14.0	65.5	58.5	7.0	64.0	56.5	7.5	68.5	68.0	.5
7	72.5	67.5	5.0	63.5	57.5	6.0	67.5	70.5	- 3.0	66.5	64.0	2.5	61.5	69.5	- 8.0
8	68.5	67.0	1.5	67.0	58.0	9.0	66.5	66.0	.5	70.0	67.0	3.0	71.5	66.5	5.0
9	70.5	70.5	.0	67.5	66.5	1.0	63.0	62.0	1.0	68.5	66.5	2.0	68.5	72.5	- 4.0
10	67.0	73.0	- 6.0	61.5	66.5	- 5.0	62.5	60.5	2.0	60.5	64.0	- 3.5	70.5	68.0	2.5
11	70.5	69.5	1.0	71.5	67.0	4.5	64.5	52.0	12.5	70.0	66.5	3.5	66.0	64.5	1.5
12	69.5	69.5	.0	67.5	56.5	11.0	62.5	61.5	1.0	69.5	72.0	- 2.5	71.5	60.5	11.0
13	71.0	73.0	- 2.0	66.5	61.5	5.0	68.5	52.0	16.5	72.5	66.0	6.5	66.5	69.5	- 3.0
14	68.5	60.5	8.0	65.0	62.5	2.5	58.5	57.5	1.0	67.5	58.5	9.0	63.5	70.5	- 7.0
15	74.5	68.5	6.0	66.5	48.0	18.5	63.0	60.5	2.5	64.5	62.0	2.5	68.0	67.0	1.0
16	66.0	64.5	1.5	61.5	56.5	5.0	74.0	70.0	4.0	68.5	67.0	1.5	61.0	68.5	- 7.5
17	70.0	70.5	- .5	69.0	54.5	14.5	66.5	63.5	3.0	70.5	68.0	2.5	68.0	58.5	9.5
18	67.5	59.0	8.5	66.0	52.0	14.0	61.5	51.5	10.0	64.5	58.0	6.5	73.5	65.5	8.0
19	69.5	64.5	5.0	69.5	67.5	2.0	70.5	61.5	9.0	74.0	66.5	7.5	57.5	69.5	-12.0
20	67.0	67.5	- .5	64.0	66.5	- 2.5	66.5	68.5	- 2.0	68.5	66.5	2.0	72.5	68.5	4.0

TABLE 17.--Levels in dB SPL of each of the first five harmonics of the vowel /æ/ produced by twenty adult female subjects both normally (N) and with simulated abnormal vocal roughness (R). The normal-rough difference (d) in levels for each harmonic are also presented for each subject.

	Harmonic 1			Harmonic 2			Harmonic 3			Harmonic 4			Harmonic 5		
Subject	N	R	d	N	R	d	N	R	d	N	R	d	N	R	d
1	71.5	62.5	9.0	68.5	57.5	11.0	66.0	52.5	13.5	65.0	48.5	16.5	69.5	50.5	19.0
2	71.5	57.0	14.5	70.5	59.0	11.5	66.5	58.5	8.0	73.5	66.5	7.0	57.5	55.0	2.5
3	71.0	68.5	2.5	68.5	59.0	9.5	66.5	55.5	11.0	69.0	59.0	10.0	64.0	57.0	7.0
4	73.5	66.5	7.0	61.5	58.0	3.5	69.5	54.5	15.0	73.0	68.5	4.5	66.5	53.5	13.0
5	72.5	74.0	- 1.5	69.0	56.5	12.5	63.5	67.0	- 3.5	72.5	65.5	7.0	65.0	50.5	14.5
6	76.5	61.5	15.0	66.5	45.0	21.5	63.0	60.0	3.0	65.0	55.5	9.5	64.5	68.5	- 4.0
7	73.5	66.5	7.0	66.0	57.5	8.5	66.5	60.5	6.0	66.5	66.5	.0	61.5	57.5	4.0
8	72.5	71.5	1.0	66.5	61.5	5.0	66.0	67.5	- 1.5	73.5	60.5	13.0	65.5	48.5	17.0
9	72.0	71.5	.5	73.5	72.0	1.5	67.5	59.5	8.0	66.5	70.5	- 4.0	58.5	61.0	- 2.5
10	70.5	71.5	- 1.0	64.5	61.5	3.0	66.0	55.5	10.5	65.0	60.0	5.0	74.5	66.5	8.0
11	70.5	64.5	6.0	72.0	64.0	8.0	69.5	56.5	13.0	69.5	67.0	2.5	58.5	58.0	.5
12	72.0	67.5	4.5	68.5	66.5	2.0	65.5	62.0	3.5	74.5	71.5	3.0	57.5	63.0	- 5.5
13	73.5	73.5	.0	65.5	54.5	11.0	71.5	57.5	14.0	69.5	62.5	7.0	61.0	61.0	.0
14	72.5	72.0	.5	64.5	66.5	- 2.0	64.0	54.5	9.5	66.5	62.5	4.0	67.5	63.0	4.5
15	75.0	69.5	5.5	66.5	55.0	11.5	62.5	50.5	12.0	66.5	56.5	10.0	61.5	63.5	- 2.0
16	67.5	64.5	3.0	66.0	61.5	4.5	71.5	69.5	2.0	72.5	67.0	5.5	57.5	64.5	- 7.0
17	72.5	65.5	7.0	68.5	54.5	14.0	68.0	53.5	14.5	69.5	62.5	7.0	59.5	57.5	2.0
18	69.5	66.5	3.0	67.0	51.5	15.5	63.5	61.5	2.0	67.5	61.5	6.0	70.5	57.5	13.0
19	70.5	65.5	5.0	69.0	68.5	.5	69.0	66.5	2.5	73.5	70.5	3.0	54.5	57.5	- 3.0
20	68.5	70.5	- 2.0	67.5	60.5	7.0	66.5	60.5	6.0	72.0	67.0	5.0	67.5	67.5	.0

APPENDIX B

Comparisons of the Harmonic Levels for Vowels Produced by Female Subjects in the Present Study and Those Reported by Emanuel and Whitehead (15) for Vowels Produced by Male Subjects

TABLE 18.—Harmonic level means in dB SPL for each of the first five harmonics of each of five test vowels produced normally and with simulated abnormal vocal roughness by each of twenty adult male and twenty adult female subjects. The means are over the twenty subjects of each sex. Sex differences between the means for each harmonic are also shown for the rough and normal productions of each test vowel.

Vowel	Harmonic 1	Harmonic 2	Harmonic 3	Harmonic 4	Harmonic 5
/u/ Normal					
Male	72.50	71.45	71.50	58.40	45.45
Female	73.12	73.72	49.82	46.10	43.52
Difference	- .62	- 2.27	21.68	12.30	1.93
Rough					
Male	69.20	63.80	66.75	62.35	53.30
Female	71.72	69.70	56.30	53.82	49.90
Difference	- 2.52	- 5.90	10.45	8.53	3.40
/i/ Normal					
Male	72.35	72.80	69.15	57.75	42.90
Female	75.30	71.42	48.08	41.25	36.52
Difference	- 2.95	1.38	21.07	16.50	6.38
Rough					
Male	70.10	65.30	66.65	57.20	47.45
Female	72.95	66.85	50.50	45.70	40.10
Difference	- 2.85	- 1.55	16.15	11.50	7.35
/ʌ/ Normal					
Male	72.15	68.70	64.55	65.55	66.90
Female	71.38	68.60	68.90	68.62	60.90
Difference	.77	.10	- 4.35	- 3.07	6.00
Rough					
Male	69.50	62.40	59.60	61.55	61.65
Female	68.45	62.80	64.50	65.78	60.22
Difference	1.05	- .40	- 4.90	- 4.23	1.43
/ɑ/ Normal					
Male	72.15	68.25	64.00	62.20	63.60
Female	70.12	66.18	65.75	68.30	67.05
Difference	2.03	2.07	- 1.75	- 6.10	- 3.45
Rough					
Male	66.95	59.95	60.05	57.20	59.25
Female	66.60	59.45	60.72	63.82	65.52
Difference	.35	.50	- .67	- 6.62	- 6.27

TABLE 18.--Continued.

	Harmonic 1	Harmonic 2	Harmonic 3	Harmonic 4	Harmonic 5
/æ/ Normal					
Male	72.50	69.45	64.05	63.50	64.65
Female	71.85	67.50	66.62	69.55	63.12
Difference	.65	1.95	- 2.57	- 6.05	1.53
Rough					
Male	67.30	61.30	59.70	58.80	60.65
Female	67.52	59.53	59.18	63.48	59.08
Difference	- .22	1.77	.52	- 4.68	1.57

TABLE 19.--Harmonic level means in dB SPL for the first three (3H) and the first five (5H) harmonics of each of five test vowels produced normally and with simulated abnormal roughness by each of twenty adult male and twenty adult female subjects. The means are over the twenty subjects of each sex. Sex differences between the means are also shown for the rough and normal productions of each test vowel.

Vowel	3H	5H
/u/ Normal		
Male	71.83	63.86
Female	65.56	57.26
Difference	6.27	6.60
Rough		
Male	66.57	63.09
Female	65.91	60.29
Difference	.66	2.80
/i/ Normal		
Male	71.43	62.99
Female	64.93	54.52
Difference	6.50	8.47
Rough		
Male	67.85	61.34
Female	63.43	55.22
Difference	4.42	6.12
/ʌ/ Normal		
Male	68.48	67.57
Female	69.62	67.68
Difference	- 1.14	- .11
Rough		
Male	63.82	62.94
Female	65.25	64.35
Difference	- 1.43	- 1.41
/ɑ/ Normal		
Male	68.13	66.04
Female	67.35	67.48
Difference	.78	- 1.44
Rough		
Male	62.32	60.66
Female	62.26	63.23
Difference	.06	- 2.57

TABLE 19.--Continued.

	Vowel	3H	5H
/æ/	Normal		
	Male	68.67	66.83
	Female	68.66	67.73
	Difference	.01	- .90
	Rough		
	Male	62.77	61.55
	Female	62.07	61.76
	Difference	.70	- .21

APPENDIX C

Comment on the Statistical Analysis

Comment on the Statistical Analysis

When tests of significance are applied to data considered in more than one context, the alpha level associated with the joint consideration of such tests is not equal to the product of the individual alpha levels. In the present study the same data were sometimes considered in more than one context. For example, differences between normal and simulated abnormally rough vowel productions were tested for significance considering levels both of individual harmonics and averages over harmonics (2H, 3H, 5H). In such instances, the above constraint regarding joint consideration of the statistical tests is applicable.