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1971

SOME WAVEFORM AND SPECTRAL FEATURES

OF VOWEL ROUGHNESS

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PLEASE NOTE:

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SOME WAVEFORM AND SPECTRAL FEATURES OF VOWEL ROUGHNESS

CHAPTER I

INTRODUCTION

Vowel phonemes are apparently differentiated perceptually largely on the basis of quality differences among phonations (15, 19, 30, 43, 44, 49, 50). Two vowel phonations may thus be recognized as different phonemes when the phonations differ with respect to distinctive quality features. Other vowel quality features which are generally non-distinctive with respect to phoneme identification are also perceptible. Vocal roughness, for example, is associated to various degrees with vowels, but does not seem to be an essential cue to phonemic identity in the English language. Even when the intended vowel phoneme is readily identified on the basis of audible cues, however, a non-distinctive quality, e.g., roughness, may be so perceptually intrusive that the production which it accompanies is perceived to be abnormal. Such terms as "hoarse" and "harsh" are among those commonly employed to indicate vocal roughness which exceeds a perceptually defined normal limit.

Not only do listeners commonly differentiate perceptually between normally and abnormally rough vowel phonations, but they may also perceive different degrees of roughness within both normal and abnormal vowel phonations. Listeners may, for example, rate the degree of roughness associated with individual vowel productions by assigning each to a position on a roughness scale. Typically, an equal-appearing intervals scale with five or more scale points is utilized in research to evaluate the relative roughness of vowel phonemes. Such scaling is generally performed with satisfactory intra- and inter-judge agreement (21, 34, 45, 46, 47, 48, 63). It appears, therefore, that the roughness of a vowel phonation may be located perceptually along a vocal quality continuum.

To understand better the auditory stimulus factors which influence roughness perception, investigators have studied the acoustic voice features with which roughness is associated. One major line of investigation has considered roughness-associated acoustic wave features. Attention in such studies has been focused specifically upon the relationship to perceived roughness of random variations in the periods and amplitudes of successive acoustic wave cycles. Commonly, the period variation of interest has been termed "pitch perturbation" (31) or "jitter" (7, 31, 61), while the amplitude variation of interest has been termed "shimer" (61). This line of inquiry has produced meaningful findings of interest to speech pathologists. On the basis of their studies of synthesized complex acoustic waves, for example, Wendahl and his associates (8, 60, 61, 62) observed that perceived signal roughness increases when either the jitter or the shimmer of a quasi-periodic wave is increased. Moore and Thompson (39), Lieberman (32), Coleman (6), and Michel (36) found for human vocalizations that greater jitter was associated with severely hoarse than with mildly hoarse vowel productions. Presently, however, the possible relationship between acoustic shimmer and vowel roughness has apparently not been delineated for human vocalizations.

A second major and productive line of investigation has considered roughness-associated acoustic spectral features. Carhart (5) observed some time ago that an increase in the roughness of model larynx tones was associated with an increase in inharmonic acoustic spectral components (noise). Subsequently, Nessel (41) and, later, Isshiki, Morimoto, and Yanagihara (25) and Yanagihara (66) demonstrated that elevated spectral noise levels were associated with vowels phonated by clinically hoarse subjects. Using a very narrow-band (3-Hz) wave analyzer to produce vowel spectra, Emanuel and his associates (14, 34, 46) have more recently shown that measures of the level of spectral noise associated with vowels phonated at one intensity bear a positive and approximately linear relationship to perceived vowel roughness. Possible relationships between measures of acoustic wave jitter and shimmer and spectral noise levels for vowels representing a range of roughness have apparently not been investigated.

There is a need for further research which delineates the inter-relationships which may exist among several measurable vowel features: perceived roughness, acoustic jitter, acoustic shimmer, and acoustic spectral noise levels. Accordingly, the present study was designed to investigate quantitatively both period and amplitude variations in the acoustic waves of normal and abnormally rough productions of selected vowels. The measures of wave variation were compared to spectral noise level and vocal roughness measures previously obtained for the same vowel samples. It was thought that the findings from this study might be important to the development of improved techniques for the clinical assessment of voice disorders.

CHAPTER II

REVIEW OF THE LITERATURE

In their investigations of acoustic features associated with perceived vocal roughness, researchers have studied the acoustic waves and spectra of vowels. Generally, the wave and the spectral features of vocal roughness have been studied in separate investigations. The wave features studied have included acoustic jitter and shimmer, while the spectral features studied have included harmonic and inharmonic components. The purpose of the present study was to investigate the possible relationship of such wave and spectral features to each other and to the degree of roughness associated with both normal and abnormally rough, e.g., hoarse vowel productions. Literature reviewed as background to this study is reported under two major headings: (a) Acoustic Wave Features and Vocal Roughness, and (b) Acoustic Spectral Features and Vocal Roughness.

Acoustic Wave Features and Vocal Roughness

Investigations of vocal mechanism function during phonation have suggested that normal phonation is associated with minimal vocal fold vibratory aperiodicity, but excessively rough phonation is associated with extreme aperiodicity. A comparable range of disturbance in the phonatory acoustic waves of vowels produced normally and with abnormal vocal roughness has also been observed. Lieberman (32), for example, measured "pitch perturbations," i.e., small, rapid variations in the period of successive cycles, in oscillographically recorded acoustic waves of vowels produced by normal-speaking and by hoarse subjects. He observed that period differences less than 0.5 ms between successive cycles of the voice wave were typical of isolated sustained vowels phonated normally, but period differences greater than 0.5 ms were associated with normal vowels adjacent to consonants in connected speech. Lieberman reported that perturbations exceeding 0.5 ms in magnitude almost never occurred within the steady-state portions of sustained normal vowels, and that perturbations exceeding 1.0 ms in magnitude never occurred in these regions.

In contrast, Lieberman found that pitch perturbations for mildly and moderately hoarse phonations generally exceeded those for normal phonations. To investigate the period variation associated with vowel phonations differing in hoarseness, Lieberman obtained for hoarse and normal phonations a perturbation factor representing for each test vowel the percentage of perturbations equal to or greater than 0.5 ms. When subjects were unable to achieve vocal fold closure during phonation because of laryngeal growths, however, the acoustic wave of their phonations was "filled in," and individual acoustic cycles could not be delineated; thus, the perturbation factor could not be determined. As an additional procedure, connected speech samples produced by Lieberman's clinically hoarse subjects were rated for hoarseness by a panel of listeners. Four categories were utilized in the rating: normal, slightly hoarse, moderately hoarse, and extremely hoarse. Lieberman found that the average ratings for the speech samples did not differentiate the underlying laryngeal pathology presented by the subjects. Moore and Thompson (39), however, subsequently obtained correlation coefficients indicating the relationship between Lieberman's perturbation factors and the hoarseness ratings he obtained for his vowel samples and found a "moderate positive correlation" of the two variables.

Moore and Thompson (39) used high speed laryngeal photography to study the glottal area wave and a phonellograph to visualize the phonatory acoustic wave for a mildly hoarse and a severely hoarse subject. They observed that differences in the periods of consecutive phonatory acoustic cycles were generally greater in severely hoarse than in mildly hoarse phonations. Coleman (6) reported that small random changes in fundamental vocal frequency occurred less frequently in segments of normal phonation than in hoarse segments of comparable duration. Michel (35) utilized motion picture photography to record oscilloscopic acoustic tracings of normal, harsh, and vocal fry phonations of the vowel /ɑ/. He observed that normal voices were characterized by a small degree of random variation around a mean fundamental frequency; harsh voices evidenced greater frequency variation, but the greatest frequency variation was associated with vocal fry phonations.

Vocal roughness has also been investigated by relating the amount of time the acoustic wave of phonation is aperiodic to the total phonation time for the sample. According to Michel (35), a wave is aperiodic when there is a "lack of recognizable repeating wave-forms." Michel investigated the amount of such aperiodicity in standardized passages of connected speech spoken with harsh, vocal fry, and normal vocal qualities. The amount of aperiodicity and the total time for each sample were measured from phonellographic records. It was thus possible for Michel to specify the percentage of time a voice wave was characterized by aperiodicity so extreme that evidence of cyclic vibration could not be discerned. On the basis of his investigation, Michel reported that normal sustained vowel phonation is aperiodic two per cent of the time, while harsh phonation is aperiodic approximately seventeen per cent of the time.

More recently, Hecker and Kreul (22) studied the phonations of subjects presenting laryngeal malignancies and matched normal-speaking subjects. They found that the phonations of their experimental subjects were characterized by larger perturbations than those for the normal-speaking subjects, but that Lieberman's perturbation factor did not distinguish between the two groups. Hecker and Kreul subsequently obtained a second perturbation factor based on the direction rather than the magnitude of changes in the periods of adjacent acoustic wave cycles. This directional perturbation factor was defined as the "percentage of the total number of differences (between adjacent cyclic periods) for which there was a change in algebraic sign." For each matched pair of normal and abnormal phonations, a higher directional perturbation factor was associated with the abnormal than with the normal phonation. In another study, Kreul and Hecker (29) reported that ratings of "hoarseness," "harshness," and "breathiness" for vowels in connected speech were positively correlated with both directional and non-directional types of perturbation factors, but that the magnitude of such correlation was generally low. They concluded that their perceptual measures of vowel quality and their physical measures of vowel wave periodicity were somewhat independent.

Acoustic waveform features associated with perceived signal roughness have been elucidated by examining synthesized speech-like sounds. Wendahl (60), for example, studied the acoustic wave features associated with roughness perception utilizing an electronic laryngeal analog. The analog was used to produce quasi-periodic complex acoustic signals which were computer controlled in both frequency and amplitude. Wendahl found that when signal amplitude was held constant and the period of successive cycles was varied as little as $\pm$ 1 Hz around a median frequency of 100 Hz, the signal was perceived as rough. When the frequency variation was increased, the perceived roughness of the signal also increased. In addition, as the median fundamental frequency of the signal was increased, larger cycle to cycle variations (jitter) were required for the perception of roughness. That is, a 200 $\pm$ 10 Hz signal was judged less rough than a 100 $\pm$ 2 Hz signal. Wendahl suggested, on the basis of these findings, that if male and female voices evidence equal jitter, the male voice would likely be judged more rough. Further, Wendahl (62) observed that synthesized complex acoustic stimuli were perceived as rough when the amplitudes of successive cycles were attenuated randomly around a median amplitude causing the signal to shimmer. He concluded that either jitter or shimmer may cause an acoustic signal to be heard as rough. It appears, therefore, that random variations of the period and amplitude of synthesized speech-like signals tend to be related to perceived signal roughness.

Currently, there is little information available regarding the perceptual effects of amplitude variations in the acoustic waveforms of human phonations. In an early study, Moore and Von Leden (40) noted that amplitude variations in successive cycles of glottal area waves were characteristic of abnormal phonations. Coleman (6) later observed "amplitude breaks," i.e., large amplitude changes occurring on a cycle-to-cycle basis, in the acoustic waves of hoarse subjects' phonations, but similar amplitude breaks were not seen in the waves for normal phonations. The degree of such amplitude variation was not investigated, however, for each sample phonation, nor was a relationship delineated between the amplitude variation and ratings of voice quality. More recently, Koike (28) measured changes in the peak amplitudes of successive cycles in acoustic waveforms of sustained vowels phonated by normal-speaking subjects and by subjects presenting either a laryngeal neoplasm or a unilateral laryngeal paralysis. Serial correlation coefficients were computed and correlograms were made for each vowel sample to investigate the periodicity of amplitude modulation. Koike observed that correlograms for normal phonations evidenced a long-term periodicity in amplitude modulations, while those for the phonations of subjects presenting laryngeal neoplasms tended to evidence shorter periodic amplitude modulations. Subjects presenting vocal fold paralysis did not evidence significant periodicity in amplitude modulations. Koike suggested that acoustic amplitude information may be useful in evaluating laryngeal dysfunction and may aid in the early detection of some laryngeal pathologies. The influence of acoustic voice wave amplitude variations on roughness ratings for human phonations has apparently not been investigated, however.

Acoustic Spectral Features and Vocal Roughness

Some acoustic spectral features associated with synthesized speech-like sounds have been observed. As early as 1941, Carhart (5) studied the spectra of rough and smooth model larynx tones and observed that the perception of greater roughness was associated with tones for which predominantly inharmonic spectra were obtained. Emanuel and Sansone (14) have recently observed that inharmonic components are elevated and harmonic components are diminished in the spectrum of an electronically generated signal when the frequency of the signal is rapidly and randomly varied around a median frequency. They suggested that there may be a relationship between the level of spectral harmonic and inharmonic (noise) components and frequency variations in the human phonatory signal. Apparently, this hypothesis has not been systematically tested.

Efforts have also been made to identify acoustic spectral features related to vocal roughness in human phonation. Thurman (52) utilized a Sonagraph to analyze the spectra of vowels produced by individuals presenting various voice quality disorders. He reported that the differentiation of deviant from normal voice quality on the basis of Sonagraphic analysis was impractical. Although formant bandwidth changes and formant frequency shifts occurred in the vowel spectra for hoarse speakers, patterns typical of hoarseness were not delineated.

Isshiki, Yanagihara, and Morimoto (25) and Yanagihara (66), however, have investigated the spectra of sustained vowels phonated by subjects exhibiting slight, moderate, and severe hoarseness. Sonagrams (45 Hz bandwidth) and amplitude sections were made from tape recordings of the subject's phonations. Four types of hoarseness were differentiated on the basis of the location and intensity of inharmonic components in vowel spectra. Noise components were observed in the high-frequency portion of the spectrum for mildly hoarse phonations and the noise extended into the low-frequency range as hoarseness increased. For severely hoarse vowel samples, noise components in the formant ranges tended to obscure the harmonics. For the most severely hoarse phonations, the harmonics in the main formant ranges were totally obscured or replaced by intensified noise components.

Previous investigations suggest, therefore, that the spectral distribution of acoustic energy is different for vowels produced by subjects presenting abnormal vocal roughness and those produced by subjects presenting normal voice quality. That is, an elevation of spectral inharmonic (noise) components is characteristic of hoarse or abnormally rough vowels. Such general findings have been reported on the basis of investigations utilizing spectrum analyzers with filter bandwidths of 45 Hz or wider. It appears, however, that the level of spectral noise associated with phonations may be evaluated more precisely and accurately utilizing spectrum analyzers with narrow filter bandwidths.

Nessel (41), using a spectrograph of narrow frequency selectivity, compared frequency-by-amplitude spectra of sustained vowels produced by hoarse subjects to similar spectra for vowels produced by normal-speaking subjects. Spectral characteristics of increasing hoarseness included a reduction of harmonic energy below 5000 Hz and an increase in noise throughout the frequency range tested. Nessel indicated that his findings suggested a spectrographic method for defining and differentiating hoarseness.

Sansone and Emanuel (46), using a constant-bandwidth wave analyzer, obtained graphic 3-Hz bandwidth frequency-by-intensity acoustic spectra of each of the five vowels /u/, /i/, /ʌ/, /ɑ/, and /æ/

individually produced by adult males both normally and with simulated abnormal vocal roughness. They found that spectral noise was associated with normal as well as rough vowel productions, but that spectral noise levels for rough vowel productions were elevated with respect to those for normal productions. A high degree of positive linear relationship obtained between spectral noise measures and roughness ratings for the productions of each test vowel. Further, both the rough and the normal test vowels were ranked with respect to increasing spectral noise in the frequency range 100 to 2600 Hz: /u/, /i/, /ʌ/, /ɑ/, and /æ/. In general, therefore, vowels produced with relatively low tongue positions evidenced greater spectral noise levels than those produced with high tongue positions, within normal and within abnormally rough phonatory conditions. Spectral noise levels for individual test vowels tended to increase linearly with an increase in the judged roughness of the productions. Sansone and Emanuel suggested that measures of vowel spectral noise levels might provide a useful index of the roughness of such phonations.

Lively and Emanuel (34) investigated spectral noise levels associated with vowels produced normally and with simulated abnormal vocal roughness by adult females. They also examined relationships between spectral noise measures and ratings of vowel roughness. In general, their findings were consistent with those obtained by Sansone and Emanuel (46) for adult males. Lively and Emanuel found that as the mean spectral noise level of a vowel production increased, its median roughness rating tended to increase. Further, for both normal and rough vowel productions, an increase in spectral noise level appeared to be associated with a decrease in tongue height during vowel production.

Lively and Emanuel also observed that diminished spectral harmonic components as well as elevated noise components were associated with an increase in perceived vowel roughness and hypothesized that the information essential to the perception of vowel roughness may be a relationship between harmonic and inharmonic spectral energy.

Using the acoustic analysis procedure employed by Sansone and Emanuel (46) in their study of males, and by Lively and Emanuel (24) in their study of females, Hanson (21) examined spectral noise levels and roughness severity ratings associated with vowels produced by clinical subjects presenting abnormal larynges. The subjects individually presented one of five different types of laryngeal pathology: vocal cord polyps, laryngeal carcinoma, vocal cord paralysis, benign laryngeal masses, and laryngeal inflammation and edema. A high degree of linear relationship (multiple correlation coefficients $\geq$ .96) was observed between vowel spectral noise levels and listener judgments of vowel roughness. Again, as in the Sansone and Emanuel study (46), vowels were ranked with respect to increasing spectral noise in the frequency range 100 to 2600 Hz: /u/, /i/, /ʌ/, /ɑ/, and /æ/. Regardless of the type of laryngeal pathology presented by the subjects, the high vowels /u/ and /i/ tended to be associated with lower roughness ratings and smaller spectral noise levels than the low vowels /ɑ/ and /æ/ and the mid-vowel /ʌ/. Hanson also investigated possible relationships between spectral noise levels for the test vowels and the perceived roughness of the connected speech samples produced by his subjects. He found, using a suitable multiple regression equation, that the perceived roughness of test sentences produced by his subjects could be predicted from the spectral noise levels associated with the test vowels they produced.

Whitehead (63) subsequently examined spectral noise levels associated with vowels produced normally, with simulated abnormal vocal roughness, and with vocal fry by adult males. He also examined relationships between the vowel spectral noise level measures and ratings of vowel roughness. Whitehead found that spectral noise levels tended to be higher for vocal fry and for abnormally rough phonations than for normal phonations of each test vowel, and that the vowel spectral noise levels for the vocal fry and the abnormally rough vowel productions were similar in magnitude. Within the normal, vocal fry, and simulated abnormally rough modes of phonation, high vowels were generally characterized by lower spectral noise levels than low vowels. High, positive correlation coefficients were obtained when spectral noise levels and listener judgments of vocal roughness for normal, vocal fry, and simulated abnormally rough phonations of each test vowel were related.

Summary

The research literature suggests that a degree of vocal roughness characterizes normal as well as abnormal vocal quality and that the differentiation of normally from abnormally rough phonations may be predicated upon the degree rather than the kind of roughness perceived. Concerning acoustic features associated with vocal roughness, the literature suggests that a greater degree of acoustic jitter tends to be associated with abnormally rough, e.g., hoarse, than with normal phonations. Additionally, for synthesized speech-like sounds, increased variation in the amplitudes of successive acoustic wave cycles tends to be associated with increased signal roughness. The literature also suggests that acoustic spectral noise is associated with normal as well as rough vowel productions, but that spectral noise levels for rough vowel productions are elevated with respect to those for normal productions. A high degree of positive linear relationship generally obtains, moreover, between vowel spectral noise levels and judges' ratings of vowel roughness.

Presently, there is little information available regarding the possible relationship of acoustic period and amplitude variation in the human voice wave to acoustic spectral noise levels (SNLs), or to perceived vocal roughness. The present study was designed to investigate such relationships for selected vowels to provide information pertinent to an understanding of the acoustic features which underlie vocal roughness.

CHAPTER III

DESIGN OF THE INVESTIGATION

Recorded samples of five vowels, each produced at one intensity first normally and then with simulated abnormal vocal roughness by one group of twenty normal-speaking adult males, and at the same intensity by a second group of twenty hoarse adult males, were studied in this investigation. The acoustic wave of each vowel phonation was analyzed to obtain an index of its jitter and shimmer. The obtained indices of jitter and shimmer for each production were subsequently related to previously obtained (21, 46) spectral noise level (SNL) measures and roughness ratings for each production. Details of the plan of the investigation are presented in this chapter.

Research Questions

The research questions investigated for each of five selected vowels were:

1. What is the degree of jitter and shimmer associated with normal and with abnormally rough vowel productions?
2. What relationships can be demonstrated between vowel jitter and vowel SNLs, and between vowel jitter and vowel roughness?
3. What relationships can be demonstrated between vowel shimmer and vowel SNLs, and between vowel shimmer and vowel roughness?

Speech Sample

This investigation made use of magnetic tape recordings of the vowels /u/, /i/, /ʌ/, /ɑ/, and /æ/ produced by two groups of male adults. The samples utilized were originally collected for two previous investigations. For one of the studies, reported previously by Sansone and Emanuel (46), twenty normal-speaking adult male subjects individually sustained each of the five test vowels for seven seconds, first normally and then with simulated abnormal vocal roughness. Two hundred vowel productions were available from this study. For a second study, reported previously by Hanson (21), twenty subjects, each presenting a clinically hoarse voice and a laryngeal pathology, sustained each of the same five test vowels for seven seconds. One hundred vowel samples were available from this study; thus, 300 samples in all were available from the two studies. A single vocal intensity level, 75 dB re .0002 dyne/cm^2 (SPL) at a mouth-to-microphone distance of six inches, was employed in recording the vowel samples for both studies. The recorded vowel samples for the two studies were previously evaluated similarly, but separately, as follows.

To provide an estimate of the perceived roughness of each test vowel production, eleven judges, all graduate students in Communication Disorders, listened to the randomized vowel recordings and independently rated the degree of roughness associated with each production. A five-point equal-appearing intervals scaling procedure in which "1" represented least and "5" most severe vocal roughness was used to obtain the ratings. A median of the eleven individual ratings was obtained as an index of roughness of each test production.

Tape loops, two seconds in duration (tape speed: 15 in./sec.), were then constructed from a central portion of each vowel recording displaying a uniform intensity. The vowel loops were played separately into a wave analyzer which was operated in its 3-Hz bandwidth mode to produce an acoustic spectrum of each production with a frequency range 0 to 8000 Hz. The pre-printed frequency axis of each recorded spectrogram was conveniently divided into 100 Hz sections. For each vowel spectrum, the lowest observable peak level-recorder stylus marking in each 100 Hz spectral section above 100 Hz was measured in dB SPL.

For the present study, the previously obtained spectral noise levels for each vowel production were averaged over the spectral frequency range 100 to 2600 Hz. The mean of the twenty-five SNL measures over this range provided an SNL index for each test phonation. The 100 to 2600 Hz spectral frequency range was of interest because previous investigations (21, 34, 46, 63) suggest that the linear relationship between vowel spectral noise levels and roughness ratings tends to be greater for SNL averages over this than over higher spectral frequency ranges. The vowel loops were also analyzed further in the present study to obtain measurements of the acoustic jitter and shimmer associated with each test phonation.

Instrumentation

Instrumentation used in data collection for this study included a playback system, a filter system, a pulse trigger system, a recording system, and a calibration system. A simplified diagram of the instrumentation is shown in Figure 1.

Description

Playback System. The playback system consisted of a tape

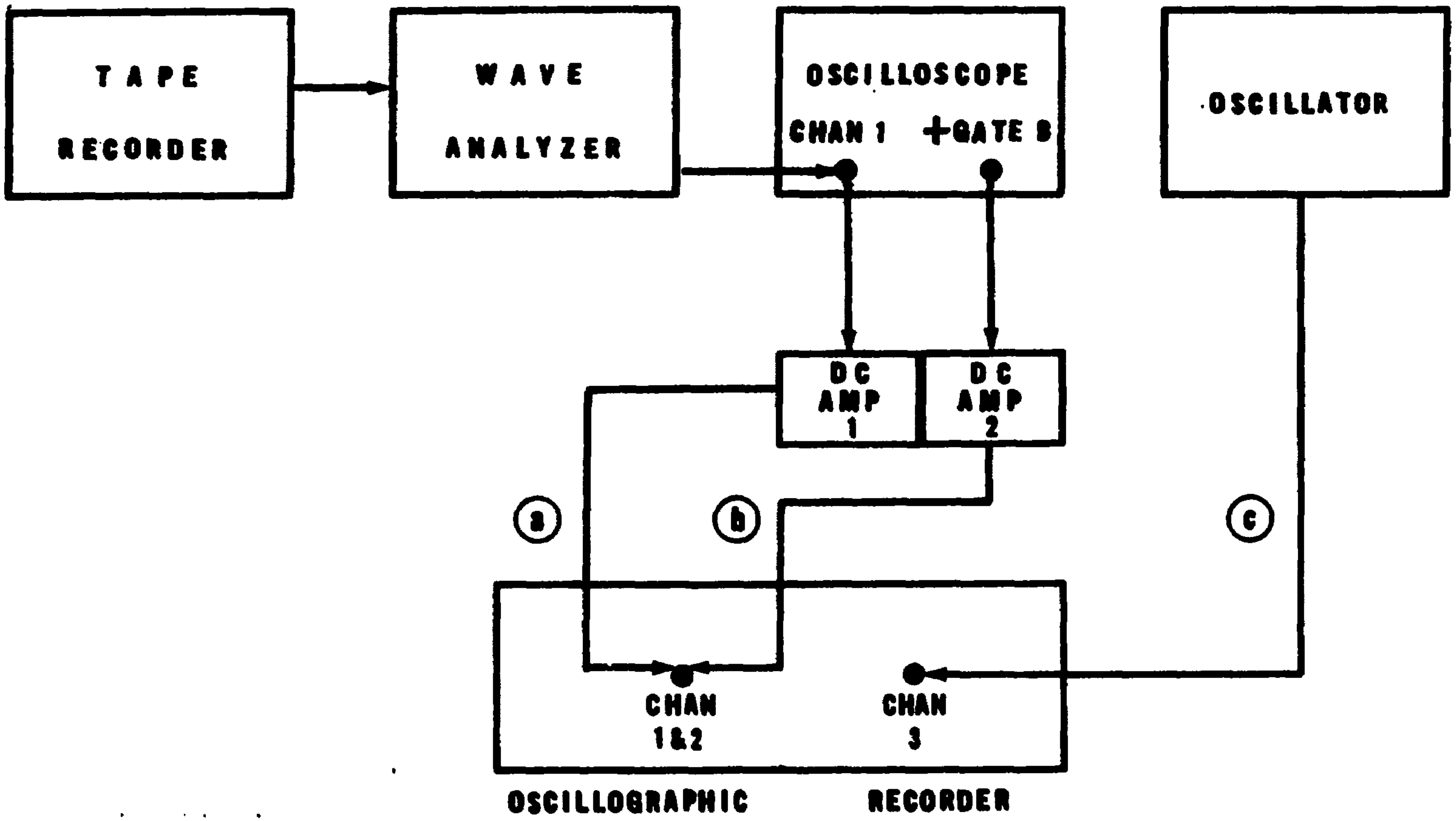

Figure 1.—Simplified diagram of the instrumentation used in data collection. Letters indicate signal inputs to the oscillographic recorder as follows: (a) filtered vowel waveform, (b) zero-crossing pulse, and (c) 1000 Hz reference tone.

recorder (Ampex, Model AG 440).

Filter System. A constant-bandwidth wave analyzer (General Radio, Type 1910-A) was used to bandpass filter each vowel wave. Used in its 10-Hz bandwidth mode, the intensity of frequency components in a complex signal is at least 30 dB down at ± 20 Hz from center frequency, at least 60 dB down at ± 45 Hz, and at least 80 dB down at ± 80 Hz and beyond.

Pulse Trigger System. An oscilloscope (Tektronix, Type 547) was used to produce a recordable voltage pulse for every positive-going zero-crossing of the vowel waveform.

Recording System. The acoustic wave recording system consisted of two DC amplifiers (Honeywell Acudata, Type 104) attached to a multi-channel oscillographic recorder (Honeywell Visicorder, Model 1508). This recorder uses galvanometers to transduce the current variations of an input signal into a photographic record by means of light beam deflection.

Calibration System. A pure tone oscillator (Hewlett-Packard, Model ABR-200), a sound level meter (General Radio, Type 1551-C), and a graphic level recorder (General Radio, Type 1521-B) were used in instrument calibration.

Calibration

Playback System. The tape recorder was aligned and checked for frequency response and proper operation by an audio engineer.

Filter System. The wave analyzer was adjusted to insure accurate frequency and intensity representation on its component graphic level recorder for a controlled input signal.

<u>Pulse Trigger System</u>. The oscilloscope was adjusted to produce a DC voltage pulse at its DC + Gate B output for every positive-going zero-crossing of an input waveform.

<u>Recording System</u>. The amplifying and recording system was calibrated in the following manner. The oscilloscope outputs (Channel 1 and + Gate B) were connected to the two DC amplifiers which were attached to the oscillographic recorder. With the DC amplifiers in the "short" position, the light beams for each amplified channel on the oscillographic recorder were superimposed in the photo-sensitve recording paper and stabilized by means of a screw adjustment of the galvanometers. An external time base input, an oscillator-generated 1000 Hz reference tone, was recorded on the third channel of the oscillographic recorder.

Procedures

The three hundred recorded test vowels were individually filtered to produce measurable oscillographic waveform tracings. Each vowel wave was bandpass filtered through the wave analyzer. To isolate a narrow band of acoustic energy which included the fundamental frequency of each test phonation, the wave analyzer's filter bandwidth was set at 10-Hz, and the center frequency of the band was set to the fundamental frequency of the vowel being filtered. To accomplish this, the wave analyzer output mode was set at "normal," and the analyzer was manually tuned upward in frequency from 0 Hz until a major deflection of its voltmeter indicated that the first harmonic, i.e., the fundamental frequency, of the signal had been located. The analyzer's output mode was then set at "automatic frequency control" (AFC) to lock it to the fundamental frequency. The output voltage of the wave analyzer was then adjusted to peak at .25 R.M.S. volts.

The filtered vowel wave was led from the wave analyzer to the Channel 1 input of the oscilloscope, through DC amplifier 1, to Channel 1 of the oscillographic recorder (Visicorder). The positive-going zero-crossing pulse was obtained at an oscilloscope output (+ Gate B), and was led to Channel 2 of the Visicorder through DC amplifier 2. The 1000 Hz reference tone was led to Channel 3 of the Visicorder through a current-limiting pad. Visicorder paper speed was set at 1000 mm/sec.

The tape loops used in this analysis were constructed from a two-second segment of each recorded vowel phonation. The tape-loop splice was readily observable in the oscillographic tracing of each vowel wave as a brief but extreme diminution of signal amplitude. When the splice effect was observed twice in the same oscillograph, the entire two-second vowel wave had been recorded between the splice indications. Because it appeared possible that some amplitude distortion of the vowel wave occurred adjacent to the splice indication in oscillographic records, a .5 second of each vowel oscillograph (measured medially from the midpoint of each splice indication) was eliminated from analysis. The remaining oscillographically recorded one-second segment of each vowel wave was analyzed for jitter and shimmer.

Individual cycles within the oscillographs of non-filtered vowel waves were not always readily identifiable. When the vowel wave was filtered (10-Hz bandwidth), however, individual cycles of the wave were clearly identifiable and were easily measured. Further, period measures made from one unfiltered vowel wave oscillogram agreed closely with those made from an oscillogram of the same vowel wave filtered

(10-Hz bandwidth). Each vowel wave was filtered, therefore, to assure a measurable presentation of frequency and amplitude variations associated with the wave. A sample oscillographic readout of a vowel filtered in the manner described above is shown in Figure 2.

The peak amplitude of each cycle in the oscillogram of the one-second segment of each test vowel wave was measured in millimeters from the zero baseline to the peak positive excursion of the cycle. Because the galvonometer trace associated with each amplified channel (pulse channel and wave channel) of the Visicorder were superimposed, the vowel wave and the positive-going zero-crossing pulse were superimposed for each vowel waveform. The superimposed pulse provided a convenient guide for period measurements because the elapsed time between two pulses indicated the period of each cycle.

The period of each cycle in each vowel wave was obtained with a digital Data Scaler (Model 400). Each Data Scaler measurement unit was equal to .1 millimeter. Measurements falling between "tenths" were called .05 millimeter. Because the oscillographs of filtered vowels were recorded at a Visicorder paper speed of 1000 mm/sec., .05 mm on the wave oscillographs represented .05 milliseconds. The period measurement accuracy for each vowel wave was thus to the nearest .05 ms. The period of each cycle was also determined by counting the number of peaks of the 1000 Hz reference tone occurring between zero-crossing pulses. This procedure, which provided measurements accurate to the nearest millisecond, was less precise than the Data Scaler method described above, but served as a check on the accuracy of period measurements obtained with the Data Scaler. When the two sets of measurements available for each vowel wave period differed more than expected on the basis of the

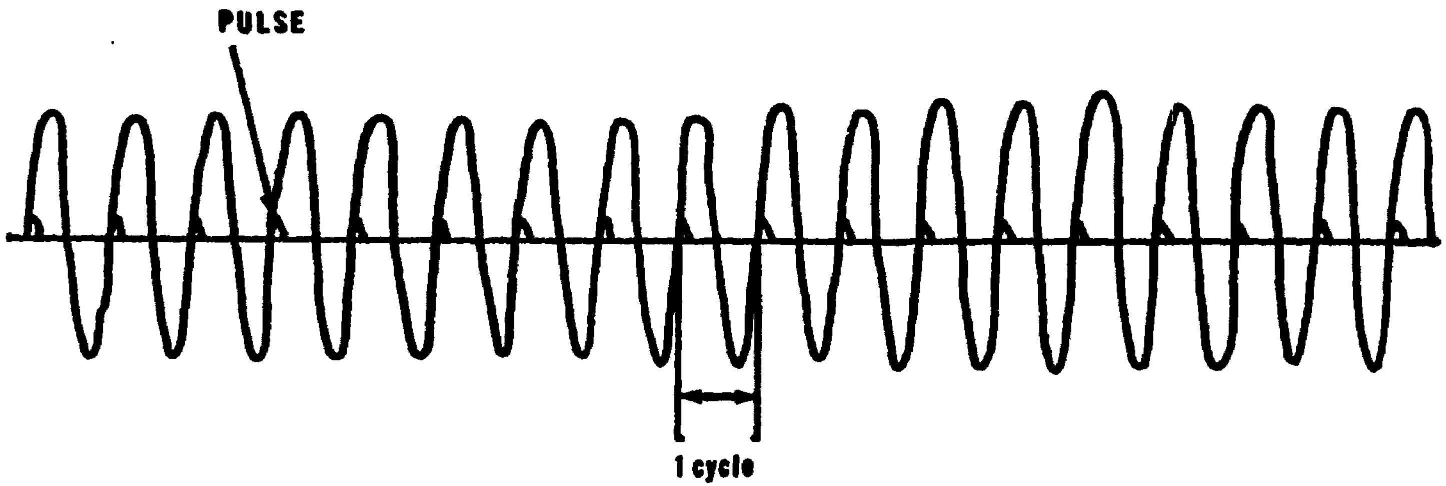

Figure 2.—Oscillogram of a filtered vowel wave. The filter was centered at the fundamental frequency of the vowel and had an effective bandwidth of 10 Hz.

inherent difference in the measurement procedures, a third measurement was made to resolve the difference.

Both an amplitude variability index and a period variability index were computed for each filtered vowel waveform using the statistic $[1/n \ \Sigma (X_i - \overline{X})^2]/\overline{X}^2$, where n was the total number of period or amplitude measures made for a given vowel production, X_i was any individual period or amplitude measure within a given vowel production, and $\overline{X}$ was the mean of the period or amplitude measures for a given vowel production. It may be noted that the computation of the above statistic also provided an estimate of the fundamental frequency of each vowel sample when the reciprocal of the mean of the period measures for each one-second sample was obtained. A more detailed discussion of this statistic is presented in Appendix A. Because the magnitude of these computed indices were uniformly quite small for all vowel samples, each index was multiplied by a constant, 10^3, to provide a more convenient decimal notation.

Preliminary data processing suggested that the degree of demonstrable linear relationship between roughness severity ratings and Log_{10} amplitude variability index would be greater than that between roughness severity ratings and amplitude variability index. Moreover, previous investigations (21, 34, 46, 63) have demonstrated a consistently high degree of positive linear relationship between roughness severity ratings for vowels and vowel spectral noise levels measured in dB SPL (also a logarithmic measure). It was decided, therefore, to utilize Log_{10} of the amplitude variability index as the index of wave amplitude variation for this study and to call it "AVI." Similarly, the period variability index was termed the "PVI."

The reliability with which the AVIs and PVIs could be obtained was estimated by two, measure-remeasure procedures. To evaluate both instrumentation and measurement reliability on separate readouts from the same tape loop, ten vowel oscillographs evidencing varying degrees of jitter and shimmer were replicated. A Pearson $\underline{r}$ of .96 was obtained when the original and replicate AVIs for these vowel productions were related. When the original and replicate PVIs were related, A Pearson $\underline{r}$ of .98 was obtained. To evaluate measurement reliability further, three vowel oscillographs were selected from the above ten replicates and remeasured after a one-week period. For the AVIs, the differences observed between the two measurements ranged from .0006 to .0238, while PVI differences ranged from .0210 to .0241. Instrumentation and measurement reliability, therefore, appeared adequate.

CHAPTER IV

RESULTS AND DISCUSSION

Results

For this investigation, a further study was made of vowel phonations originally collected for two previous investigations. For both of the previous investigations, magnetic tape recordings were made of each of the five vowels /u/, /i/, /ʌ/, /ɑ/, and /æ/ phonated at one intensity (75 dB SPL: mouth-to-microphone distance six inches) by adult male subjects. For the first of the previous studies (46), twenty normal-speaking subjects produced each test vowel first normally and then with simulated abnormal vocal roughness; thus, two hundred vowel productions were available from the first study. For the second of the previous studies (21), twenty clinically hoarse subjects, each presenting a medically diagnosed laryngeal pathology, produced each of the five test vowels; thus, one hundred vowel productions were available from the second study. For both of the previous studies, measures of the acoustic spectral noise levels associated with each test vowel phonation were obtained. Additionally, the roughness of each test phonation was rated on a five-point equal-appearing intervals scale by eleven judges. A median of the judges' ratings was obtained in both studies as an index of the roughness of each test phonation.

For the present study, each recorded vowel production was filtered to isolate acoustic energy in a 10-Hz band centered at the fundamental vocal frequency of the production. The peak amplitude and the period of each acoustic cycle within a one-second segment of each filtered vowel wave was measured in an oscillographic recording of the wave. The period and amplitude measures for each test phonation were then treated statistically to obtain an amplitude variability index (AVI) and a period variability index (PVI) each of which was essentially independent of the mean ampiitude and mean period respectively of the vowel wave. Finally, the vowel AVIs and PVIs obtained for the present study were related to the spectral noise levels and median roughness ratings for the test phonations obtained previously.

Period Variation Indices

Possible differences in acoustic wave period variation associated with normal, simulated abnormally rough (SR), and clinically hoarse (CH) vowel phonations were considered. The PVIs and fundamental vocal frequencies obtained for the individual productions for each test vowel are presented in Appendix B. Table 1 presents, for each of the five test vowels, the obtained PVIs averaged separately over normal, SR, and CH test phonations. Table 1 shows that the observed PVI means were larger for both SR and CH productions than for normal productions of each test vowel. Utilizing an analysis of variance appropriate for a 2 x 5 factorial arrangement of treatments with repeated measures on the second factor (vowels), these observed differences were tested for significance with an alpha level chosen as .05. The initial analysis of variance and the test on simple effects of vowels within each mode of phonation (i.e., normal, SR, or CH) and modes of phonation within each

TABLE 1

PVI MEANS FOR NORMAL, SIMULATED ABNORMALLY ROUGH, AND CLINICALLY HOARSE PRODUCTIONS OF EACH TEST VOWEL

Vowel	PVI mean (N) n=20	PVI mean (SR) n=20	PVI mean (CH) n=20
/u/	.4454	.7143[a]	.7815[a]
/i/	.4898	.6394	.9427[a]
/ʌ/	.4916	.7159[a]	1.0100[a]
/ɑ/	.4712	.7129[a]	.6770
/æ/	.4953	.6031	.7360[a]
Overall mean	.4807	.6771[a]	.8295[a]

[a]Significantly different from normal at the .05 level as determined by analysis of variance.

vowel were made in accordance with the procedures given by Winer (64). The same procedure was used for the comparison of CH to normal and for SR to normal. Clearly these two analyses are not independent since the same set of data for the normal phonations was used in both. Therefore, the alpha level of .05 is appropriate for consideration of each analysis individually, but the probability level associated with joint consideration is not necessarily the product of the two alpha levels (.0025). Summaries of these analyses are presented in Appendix C.

Table 1 shows that the overall PVI mean was significantly larger for SR and CH than for normal vowel productions. Regarding the SR and the normal productions of the individual test vowels, Table 1 shows that for /u/, /ʌ/, and /ɑ/ the PVI means for SR productions were significantly larger than those for the normal productions, but for /i/ and /æ/ the means for SR and the normal productions were not significantly different. Regarding the CH and the normal productions of the individual test vowels, Table 1 shows that for /u/, /i/, /ʌ/ and /æ/ the PVI means for the CH productions were significantly larger than those for normal productions. For /ɑ/, however, the PVI means for the CH and normal productions were not significantly different. With the exception of those for SR /i/ and /æ/ productions and CH /ɑ/ productions, therefore, the PVI means were significantly larger for both SR and CH productions than for normal productions of each test vowel.

It was also of interest to consider the relationship of the PVIs to the median roughness ratings and to the SNLs for each test vowel. On the basis of an inspection of scatter plots, it appeared appropriate to consider the degree of linear relationship between these variables. Because the spectral noise and roughness rating data for

CH phonations and for normal and simulated abnormally rough (N-SR) phonations were obtained in separate previous studies, the present findings regarding the PVI versus roughness rating and PVI versus spectral noise level relationships are presented separately for the two previous studies.

To explore the degree of linear relationship between the PVIs and the median roughness ratings for each test vowel, correlation coefficients (Pearson r) were obtained. Table 2, presenting the coefficients for each test vowel, shows that those obtained for the CH productions ranged from .03 for /æ/ to .69 for /ɑ/, while those for the N-SR productions ranged from .29 for /æ/ to .52 for /i/. Regarding CH and N-SR phonations, the coefficients obtained for each of the vowels /u/, /i/, /ʌ/, and /ɑ/ were significant, but the coefficients for /æ/ were not significant. With the exception of the vowel /æ/, therefore, the obtained coefficients indicated a positive, significant, relationship between the PVIs and roughness ratings for both CH and N-SR test vowel phonations.

To explore the degree of linear relationship between the PVIs and the SNLs (averaged over the frequency range 100 to 2600 Hz) for each test vowel, correlation coefficients (Pearson r) were obtained. Table 3, presenting the coefficients for each test vowel, shows that those obtained for the CH productions ranged from .11 for /æ/ to .68 for /ɑ/, while those for the N-SR productions ranged from .29 for /æ/ to .54 for /ɑ/. Regarding CH and N-SR phonations, the coefficients obtained for each of the vowels /u/, /i/, /ʌ/, and /ɑ/ were significant, but the coefficients for /æ/ were not significant. With the exception of the vowel /æ/, therefore, the coefficients obtained for each test vowel

TABLE 2

THE CORRELATION BETWEEN THE PERIOD VARIABILITY INDICES AND THE ROUGHNESS SEVERITY RATINGS OBTAINED FOR THE PRODUCTIONS OF EACH TEST VOWEL

	Correlation Coefficients	
	Normal-Simulated Abnormally Rough	Clinically Hoarse
Vowel	n=40	n=20
/u/	.39[a]	.47[a]
/i/	.52[a]	.46[a]
/ʌ/	.47[a]	.52[a]
/ɑ/	.51[a]	.69[a]
/æ/	.29	.03

[a]Significant at the .05 level as determined by analysis of variance.

TABLE 3

THE CORRELATION BETWEEN THE PERIOD VARIABILITY INDICES AND THE SPECTRAL NOISE LEVEL MEANS OBTAINED FOR THE PRODUCTIONS OF EACH TEST VOWEL

	Correlation Coefficients	
	Normal-Simulated Abnormally Rough	Clinically Hoarse
Vowel	n=40	n=20
/u/	.36[a]	.48[a]
/i/	.52[a]	.45[a]
/ʌ/	.41[a]	.67[a]
/ɑ/	.54[a]	.68[a]
/æ/	.29	.11

[a]Significant at the .05 level as determined by analysis of variance.

indicated a positive, significant, relationship between PVIs and SNLs for both CH and N-SR test vowel phonations.

Amplitude Variation Indices

Possible differences in acoustic wave amplitude variation associated with normal, SR, and CH vowel phonations were also considered. The AVIs for the individual productions for each test vowel are presented in Appendix B. Table 4 presents, for each of the five test vowels, the obtained AVIs averaged separately over normal, SR, and CH phonations. Table 4 shows that the observed AVI means were larger for both SR and CH productions than for normal productions of each test vowel. For this set of data, the same statistical techniques were employed as for the analyses of the PVI data. Hence, the same reservations concerning joint consideration apply to the AVI analyses. Summaries of these analyses are presented in Appendix C.

Table 4 shows that the overall AVI mean was significantly larger for SR and CH than for normal productions. It is pertinent, however, that the vowel by mode-of-phonation interaction was significant for normal and CH phonations (see Appendix C), but was not significant for normal and SR phonations. The significant interaction for normal and CH phonations was attributable to a greater difference between normal and CH vowel AVIs for the high vowels /u/, /i/, and the mid-vowel /ʌ/ than for the low vowels /ɑ/ and /æ/. Regarding the SR and the normal productions, Table 4 shows for all five test vowels that the AVI means for SR productions were significantly larger than those for the normal productions, Table 4 shows for /u/, /i/, and /ʌ/ that the AVI means for the CH productions were significantly larger than those for

TABLE 4

AVI MEANS FOR NORMAL, SIMULATED ABNORMALLY ROUGH, AND CLINICALLY HOARSE PRODUCTIONS OF EACH TEST VOWEL

Vowel	AVI mean (N) n=20	AVI mean (SR) n=20	AVI mean (CH) n=20
/u/	-.1287	.6052[a]	.4142[a]
/i/	-.1330	.5410[a]	.5706[a]
/ʌ/	-.0389	.4498[a]	.5977[a]
/ɑ/	-.0619	.7491[a]	.2163
/æ/	-.0216	.6038[a]	.1550
Overall mean	-.0768	.5898[a]	.3908[a]

[a]Significantly different from normal at the .05 level as determined by analysis of variance.

normal productions, but for /ɑ/ and /æ/ the means for CH and normal productions were not significantly different. With the exception of those for CH /ɑ/ and /æ/ productions, therefore, the AVI means were significantly larger for both SR and CH productions than for normal productions of each test vowel.

A consideration of the linear relationship between the AVIs and both the median roughness ratings and the SNLs for each test vowel also appeared appropriate from an inspection of scatter plots of the variables. Findings regarding such relationships are presented separately for CH and N-SR phonations below. To explore the degree of linear relationship between the AVIs and the median roughness ratings for each test vowel, correlation coefficients (Pearson r) were obtained. Table 5, presenting the coefficients for each test vowel, shows that those obtained for the CH productions ranged from .48 for /æ/ to .75 for /ʌ/, while those for the N-SR productions ranged from .54 for /ʌ/ to .70 for /i/ and /ɑ/. For both CH and N-SR phonations the coefficients for all five test vowels were significant. The obtained coefficients indicated, therefore, a positive, significant relationship between the AVIs and the roughness ratings for both CH and N-SR test vowel phonations.

To explore the degree of linear relationship between the AVIs and the SNLs for each test vowel, correlation coefficients (Pearson r) were obtained. Table 6, presenting the coefficients for each test vowel, shows that those for the CH productions ranged from .41 for /u/ to .80 for /ʌ/, while those for the N-SR productions ranged from .49 for /ʌ/ to .72 for /ɑ/. Regarding CH phonations, the coefficient for each of the vowels /ʌ/, /ɑ/, and /æ/ was significant, but the

TABLE 5

THE CORRELATION BETWEEN THE AMPLITUDE VARIABILITY INDICES AND THE ROUGHNESS SEVERITY RATINGS OBTAINED FOR THE PRODUCTIONS OF EACH TEST VOWEL

	Correlation Coefficients	
	Normal-Simulated Abnormally Rough	Clinically Hoarse
Vowel	n=40	n=20
/u/	.68[a]	.54[a]
/i/	.70[a]	.62[a]
/ʌ/	.54[a]	.75[a]
/ɑ/	.70[a]	.62[a]
/æ/	.65[a]	.48[a]

[a]Significant at the .05 level as determined by analysis of variance.

TABLE 6

THE CORRELATION BETWEEN THE AMPLITUDE VARIABILITY INDICES AND THE SPECTRAL NOISE LEVEL MEANS OBTAINED FOR THE PRODUCTIONS OF EACH TEST VOWEL

Vowel	Correlation Coefficients Normal-Simulated Abnormally Rough n=40	Clinically Hoarse n=20
/u/	.53[a]	.42
/i/	.66[a]	.41
/ʌ/	.49[a]	.80[a]
/ɑ/	.72[a]	.61[a]
/æ/	.66[a]	.65[a]

[a]Significant at the .05 level as determined by analysis of variance.

coefficient for /u/ and for /i/ was not significant. Regarding the N-SR phonations, the coefficient for each of the five test vowels was significant. With the exception of those for CH /u/ and /i/ productions, therefore, the obtained coefficients indicated a positive, significant, relationship between the AVIs and SNLs for both CH and N-SR test vowel phonations.

Combined Indices

To explore further the relationships among AVIs, PVIs, SNLs, and median roughness ratings for the test vowels, a multiple regression procedure was employed. The AVI and PVI indices were related in combination first to the roughness ratings and then to the mean spectral noise levels for each test vowel.

Table 7 presents for each test vowel the multiple correlation coefficients indicating the degree of linear relationship observed for AVIs and PVIs versus median roughness ratings. Table 7 shows that coefficients for the CH productions ranged from .50 for /æ/ to .75 for /ʌ/, while those for N-SR productions ranged from .54 for /ʌ/ to .71 for /i/. Regarding CH phonations, the coefficient for each of the vowels /i/, /ʌ/, and /ɑ/ was significant, but the coefficient for /u/ and for /æ/ was not significant. Regarding the N-SR phonations, the coefficient for each of the five test vowels was significant. With the exception of those for CH /u/ and /æ/ productions, therefore, the coefficients obtained for each test vowel indicated a positive, significant relationship between AVIs and PVIs considered together and roughness ratings for both CH and N-SR test vowel phonations.

Table 8 presents for each test vowel the multiple correlation

TABLE 7

THE MULTIPLE CORRELATION FOR THE AMPLITUDE VARIABILITY INDICES AND THE PERIOD VARIABILITY INDICES VERSUS THE ROUGHNESS SEVERITY RATINGS OBTAINED FOR THE PRODUCTIONS OF EACH TEST VOWEL

	Correlation Coefficients	
	Normal-Simulated Abnormally Rough	Clinically Hoarse
Vowel	n=40	n=20
/u/	.69[a]	.54
/i/	.71[a]	.63[a]
/ʌ/	.54[a]	.75[a]
/ɑ/	.70[a]	.69[a]
/æ/	.65[a]	.50

[a]Significant at the .05 level as determined by analysis of variance.

TABLE 8

THE MULTIPLE CORRELATION FOR THE AMPLITUDE VARIABILITY INDICES AND THE PERIOD VARIABILITY INDICES VERSUS THE SPECTRAL NOISE LEVEL MEANS OBTAINED FOR THE PRODUCTIONS OF EACH TEST VOWEL

	Correlation Coefficients	
	Normal-Simulated Abnormally Rough	Clinically Hoarse
Vowel	n=40	n=20
/u/	.53[a]	.48
/i/	.66[a]	.46
/ʌ/	.49[a]	.81[a]
/ɑ/	.72[a]	.68[a]
/æ/	.67[a]	.65[a]

[a]Significant at the .05 level as determined by analysis of variance.

coefficients indicating the degree of linear relationship observed for AVIs and PVIs versus SNLs. Table 8 shows that the coefficients for the CH productions ranged from .46 for /i/ to .81 for /ʌ/, while those for the N-SR productions ranged from .49 for /ʌ/ to .72 for /ɑ/. Regarding the CH phonations, the coefficient for each of the vowels /ʌ/, /ɑ/, and /æ/ was significant, but the coefficient for /u/ and for /i/ was not significant. Regarding the N-SR phonations, the coefficient for each of the five test vowels was significant. With the exception of those for CH /u/ and /i/ productions, therefore, the coefficients obtained for each test vowel indicated a positive, significant relationship between AVIs and PVIs considered together and SNLs for both CH and N-SR test vowel phonations.

To explore the degree of linear relationship between AVIs and PVIs for each test vowel, correlation coefficients (Pearson $\underline{r}$) were obtained. Table 9, presenting the coefficients for each test vowel, shows that those for the CH productions ranged from .32 for /æ/ to .86 for /u/, while those for the N-SR productions ranged from .54 for /æ/ to .84 for /ʌ/. Regarding N-SR phonations, the coefficient for each of the five test vowels was significant. With the exception of that for CH /æ/ productions, therefore, the obtained coefficients indicated a positive, significant relationship between the AVIs and PVIs for both CH and N-SR test vowel phonations.

Possible differences in PVIs and AVIs associated with normal phonations and with CH phonations classified according to the type of laryngeal pathology presented by the hoarse subjects were also considered. Table 10 presents separately for normal-speaking subjects and subjects presenting each of five types of laryngeal pathology (vocal

TABLE 9

THE CORRELATION BETWEEN THE PERIOD VARIABILITY INDICES AND THE AMPLITUDE VARIABILITY INDICES OBTAINED FOR THE PRODUCTIONS OF EACH TEST VOWEL

	Correlation Coefficients	
	Normal-Simulated Abnormally Rough	Clinically Hoarse
Vowel	n=40	n=20
/u/	.66[a]	.86[a]
/i/	.82[a]	.79[a]
/ʌ/	.84[a]	.74[a]
/ɑ/	.75[a]	.85[a]
/æ/	.54[a]	.32

[a]Significant at the .05 level as determined by analysis of variance.

TABLE 10

MEAN AMPLITUDE VARIABILITY INDEX AND PERIOD VARIABILITY INDEX AVERAGED OVER FIVE VOWELS FOR NORMAL-SPEAKING SUBJECTS AND FOR SUBJECTS PRESENTING FIVE TYPES OF LARYNGEAL PATHOLOGY

		PVI mean	AVI mean
NORMAL	(n=20)	.4807	-.0768
PATHOLOGY TYPE			
Polyps	(n=4)	.9706	.7374
Carcinoma	(n=6)	.7631	.1541
Paralysis	(n=3)	.9075	.8192
Benign Mass	(n=3)	.7113	.4136
Inflammation/Edema	(n=4)	.8042	.0575

cord polyps, laryngeal carcinoma, vocal cord paralysis, benign laryngeal masses, and laryngeal inflammation and/or edema) the obtained AVIs and PVIs averaged over all subjects in each group and over all five test vowels. Table 10 shows that both AVI and PVI means tended to be larger for hoarse than for normal vowel phonations regardless of the type of laryngeal pathology presented by the hoarse subjects. The PVI mean for normal phonations was .4807, while the PVI means for hoarse phonations ranged from .7113 for subjects presenting benign laryngeal masses to .9706 for subjects presenting vocal cord polyps. The AVI mean for normal phonations was -.0768, while the AVI means for hoarse phonations ranged from .0575 for subjects presenting vocal cord inflammation and/or edema to .8192 for subjects presenting vocal cord paralysis.

It was of interest to compare the correlation coefficients presented in Tables 2, 5, and 7. Table 2 presents the coefficients (Pearson $\underline{r}$) indicating the correlation between the PVIs and the median roughness ratings for each test vowel; Table 5 presents the coefficient (Pearson $\underline{r}$) indicating the correlation between the AVIs and the median roughness ratings for each test vowel; while Table 7 presents coefficients indicating the multiple correlation for the AVIs and PVIs versus the median roughness ratings for each test vowel. It appears that the magnitude of the multiple correlation coefficient obtained for each test vowel (Table 7) was generally similar to the higher of the PVI versus median roughness rating (Table 2) and AVI versus median roughness rating (Table 5) coefficients obtained for each test vowel. Similarly, when Tables 3, 6, and 8 are compared, it may be seen that the magnitude of the multiple correlation coefficient indicating the degree of linear relationship for the AVIs and PVIs versus SNLs for each test vowel (Table 8) was generally similar to the higher of the PVI versus SNL (Table 3) and AVI versus SNL (Table 6) coefficients obtained for each test vowel.

Discussion

The findings indicated that the AVIs and the PVIs for all five test vowels were positively and significantly correlated when N-SR phonations were considered. Positive relationships obtained between the AVIs and PVIs for CH phonations (though the coefficient for /æ/ was not significant). These findings for the subject groups tested suggest that the vowel waves which were characterized by a relatively large degree of peak cyclic amplitude variation also tended to be characterized by a relatively large degree of period variation. This finding may be attributable to the fact that the PVI and the AVI were both indices of wave variability. The finding that the correlation coefficients indicating the AVI versus PVI relationship were not always large, ranging from .32 for /æ/ (CH phonations) to .86 for /u/ (CH phonations), suggests, however, that the amplitude and the period variation in vowel waves tended to occur somewhat independently. This observation appears consistent with the fact that the frequency and the intensity of vowel phonations may be varied with some degree of independence. In general, the findings suggest that the AVI and PVI measures were to some extent overlapping and to some extent independent measures of vowel wave variability.

With respect to vowel wave period variability, the findings revealed a general tendency for the PVIs associated with the SR and CH vowel phonations to be larger than those associated with the normal phonations of each test vowel. This difference obtained for all five test vowels, but was not significance for all five vowels. For only two of the test vowels, /u/ and /ʌ/, did the PVI associated both with SR and with CH phonations significantly exceed that associated with normal phonations. Inspection of the individual subject data for N-SR productions indicated, moreover, that for /u/ and /ʌ/, as well as for the other test vowels, there were instances in which the PVI obtained for a subject's normal phonation was greater than that for his SR phonation of the same vowel. Similarly, PVIs obtained for normal phonations sometimes exceeded those for CH phonations of the same vowel. It appears, therefore, that the PVI measures alone would not always differentiate normal and CH vowel phonations. The clinical usefulness of such measures for isolated sustained vowels may thus be limited. It does not follow that such measures could have no clinical usefulness. A "markedly larger" vowel PVI than normal would suggest abnormal vowel roughness, while the meaning of PVIs within "normal limits" may be equivocal.

The present findings revealed a tendency for PVIs and roughness ratings for each of the five test vowels to be positively related. Generally, the correlation coefficients indicating the degree of such linear relationship for both N-SR and CH phonations were moderately large (ranging from .39 to .69) and significant for four of the five test vowels (/u/, /i/, /ʌ/, and /ɑ/). For the vowel /æ/, however, relatively small and non-significant positive coefficients were associated with both N-SR and CH productions. The fact that the magnitude of these coefficients was not large for any of the test vowels may be attributable in part to the limited amount of the vowel wave sampled to obtain the PVI measures (the PVIs were obtained by analyzing one-second samples of filtered vowel waves) relative to the amount of vowel wave rated for roughness (a seven-second unfiltered sample of the vowel wave was rated). It also may be that period variability tends to be related only incidentally to the perceived roughness of vowels. Possibly, the vowel roughness percept, at least for some vowels, tends to be predicated primarily on acoustic wave variability other than period variability. Said differently, period variability may be a more important cue to the roughness of some vowels than others.

The findings also indicated that the degree of linear relationship observed between PVIs and SNLs was similar to that observed between PVIs and roughness ratings for each test vowel. This finding appears consistent with previous findings (21, 34, 46, 63) indicating high degree of positive, linear relationship between vowel median roughness ratings and vowel SNLs. The fact that the magnitude of the present correlation coefficients indicating the relationship between PVIs and SNLs was not large, however, was of interest. Previously presented (14, 21, 34, 46, 63, 66) theoretical concepts regarding the relationship of acoustic wave features to perceived vowel roughness and vowel SNLs suggest that a high degree of positive linear relationship should be expected between vowel wave aperiodicity and vowel SNLs. The present findings regarding the PVIs may be regarded as consistent with the theory when it is considered that vowel wave period variation might account for no more than a part of the noise observed in vowel spectra and for only a part of the acoustice wave aperiodicity of importance to vowel roughness perception.

With respect to vowel wave amplitude variability, the findings revealed a general tendency for the AVIs associated with the abnormal

(SR and CH) vowel phonations to be larger than those associated with the normal phonations of each test vowel. This trend held for all five test vowels. For only three of the test vowels, /u/, /i/, and /ʌ/, however, did the AVI associated both with SR and with CH phonations significantly exceed that associated with normal phonations. Inspection of the individual subject data for N-SR productions indicated that for /u/, /i/, and /ʌ/, as well as for the other test vowels, there were instances in which the AVI obtained for a subject's normal phonation was greater than that for his SR phonation of the same vowel. Similarly, AVIs obtained for normal phonations sometimes exceeded those for CH phonations of the same vowel. It appears, therefore, that the AVI measures alone might not always differentiate normal and CH vowel phonations. The implied constraints regarding the clinical usefulness of such measures thus appear similar to those associated with PVIs.

The findings indicated a moderate, positive, linear relationship between AVIs and median roughness ratings for all five test vowels for both N-SR and CH phonations. The fact that the magnitude of the correlation coefficients indicating the degree of such relationship was not large (ranging from .48 to .75) may be in part attributable to the limited amount of the vowel wave sampled to obtain the AVI measures relative to the amount of vowel wave rated for roughness. It may also reflect the fact that the variation of only one measure of wave amplitude (the peak amplitude of each cycle) was considered. The variation associated with the instantaneous amplitudes of each cycle other than the peak amplitude was not sampled. The AVI versus median roughness rating correlation coefficients obtained for all five test vowels were significant both for N-SR and for CH phonations. With the exception of that for CH /ɑ/ productions, the magnitude of the AVI versus median roughness rating coefficients tended to be somewhat larger than those obtained when vowel PVIs and median roughness ratings were related. This tendency was especially apparent when /æ/ productions were considered. It appears, therefore, that acoustic wave cyclic peak amplitude variation may provide a better index than period variation of the roughness of some vowels. Depending on which provides the better estimate of the total acoustic wave variability, it may be that measures of either the amplitude or the period variation of the vowel wave could provide the better index of vowel roughness.

The findings also indicated that the degree of linear relationship observed between AVIs and SNLs was generally comparable to that observed between AVIs and roughness ratings for the test vowels. This finding appears consistent with previous findings (<u>21</u>, <u>34</u>, <u>46</u>, <u>63</u>) indicating a high degree of positive, linear relationship between vowel median roughness ratings and vowel SNLs. The fact that the magnitude of present coefficients for AVIs versus SNLs was not large suggests that the variation observed in the amplitude of cyclic peaks may account for only a part of the acoustic noise observed in vowel spectra.

The findings revealed that AVIs and PVIs considered together and roughness ratings for each of the five test vowels were positively correlated. Generally, the coefficients indicating the degree of such linear relationship for both N-SR and CH phonations were moderately large (ranging from .54 to .75) and significant for N-SR productions of each of the five test vowels. For CH /u/ and /æ/ productions, however, non-significant coefficients (.54 and .50 respectively) were obtained. Generally, the magnitude of the multiple correlation coefficient obtained for each test vowel was similar to the higher of the PVI versus median roughness rating and AVI versus median roughness rating coefficients obtained for each test vowel. To interpret this finding, it is pertinent to note that the amplitude variation and period variation indices for the N-SR and the CH productions of each test vowel were related positively, but not perfectly, to each other. Thus, in general, the multiple correlation coefficient for each vowel might be expected to resemble either the AVI or the PVI versus roughness rating coefficient which evidenced the higher degree of relationship to vowel roughness.

The findings also revealed, for each of the five test vowels, that AVIs and PVIs considered together were moderately and positively correlated with SNLs. The correlation coefficients indicating the strength of such relationship were significant (ranging from .49 to .81) for all vowel phonations except CH /u/ and /i/ productions (.48 and .46 respectively). The magnitude of the multiple correlation coefficient obtained for each test vowel was generally similar to the higher of the PVI versus SNL and AVI versus SNL coefficients obtained for each test vowel.

It appears pertinent to an interpretation of these relationships that the variability associated with instantaneous amplitudes other than the cyclic peaks were not considered in the computation of the AVI. Neither the AVIs nor the PVIs, nor the two indices considered together, therefore, reflected all of the wave aperiodicity associated with a vowel phonation. Thus, it does not seem surprising that these multiple correlation coefficients were not of greater magnitude when it is considered that the vowel SNLs may well reflect total vowel wave aperiodicity somewhat more completely than the direct measures of wave variation obtained for this study. It is also germane that the PVIs and AVIs for each test vowel tended to be moderately and positively correlated; that is, they were apparently overlapping measures of wave variability. Thus, the multiple correlation of AVIs and PVIs versus SNLs should not exceed greatly the correlation of SNLs with AVIs or PVIs considered separately.

With regard both to amplitude and to period variation associated with types of laryngeal pathology, the present findings suggested that for each of the five pathology types presented by subjects in the CH group, AVIs and PVIs averaged across all test vowel phonations tended to be larger than the comparable AVI and PVI means respectively for normal test vowel phonations. The small number of subjects presenting each pathology type precluded generalizations regarding these findings, but in view of findings reported by Koike (28), it was of interest that the test phonations of subjects presenting vocal cord polyps and vocal cord paralysis tended to evidence the greatest amount of amplitude variation. Koike observed that serial correlograms for normal phonations evidenced a long-term periodicity in amplitude modulations, while those for the phonations of subjects presenting laryngeal neoplasms tended to evidence shorter periodic amplitude modulations. Koike's subjects presenting vocal fold paralysis did not evidence significant periodicity in amplitude modulations.

In some instances, the correlation coefficients associated with the N-SR productions in this study were statistically significant while comparable coefficients of similar magnitude for CH productions were not significant. Such instances appear to be related to the number of phonations of each test vowel obtained from each experimental subject group. That is, for the N-SR group forty phonations (twenty normal and twenty simulated rough) of each test vowel were available, while for the CH group twenty phonations of each test vowel were available. This difference in number of phonations per test vowel for the experimental groups could influence the significance associated with each correlation coefficient. Further, on the basis of listening to all of the test vowel recordings, it appeared to the investigator that the N-SR vowel productions represented a greater range of vowel roughness than the CH vowel productions. A greater range of roughness associated with N-SR phonations might tend to enhance the strength of the correlation between the indices of wave variability and the roughness associated with those productions.

With respect to vowel AVI means, the findings revealed that the vowel by mode-of-phonation interaction was significant for normal and CH phonations, but was not significant for normal and SR phonations. This significant interaction suggests that laryngeal pathology may increase the amplitude variation of high vowels more than that of low vowels. On the other hand, the lack of a significant interaction for normal and SR productions suggests that simulated abnormal roughness affects the amplitude variation of high and low vowels similarly.

In general, the present findings appear consistent with an hypothesis that vowel acoustic wave periodicity tends to diminish as vowel roughness and spectral noise levels increase. The findings suggest, moreover, that the decrease in wave periodicity, as estimated by the indices of the variation of vowel acoustic wave periods (PVI) and peak cyclic amplitudes (AVI), is related both to increases in the roughness and to the spectral noise levels associated with the test vowels. The degree of such relationship was not sufficiently high or reliable (when individual subject data was considered), however, to conclude that either of the obtained indices of wave variability would serve alone or in combination as an entirely satisfactory clinical indicant of abnormally rough (hoarse) vocal quality.

Previous investigations (21, 34, 46, 63) have revealed that a reliable, high, positive, linear relationship generally obtains between vowel SNLs and vowel median roughness ratings. Clinically useful estimates of vowel roughness from vowel SNLs thus appear possible. Hanson's findings (21) for clinically hoarse subjects suggest, moreover, that the roughness of a subject's connected discourse may be predictable from the SNLs associated with his isolated vowel productions. It appears, therefore, that measures of spectral noise in isolated sustained vowels might provide a more reliable and clinically useful indicant of vocal roughness than the indices of amplitude and/or period variation of filtered vowel waves obtained for this study.

Further investigations of vowel wave variability are needed, however. The present findings suggest that measures of vowel wave variation which reflect total wave aperiodicity more completely than the AVIs and PVIs for this study might be profitably developed and applied in future studies. Such indices might help to delineate better the relationship of acoustic wave variation to vowel SNLs and vowel roughness. Because the magnitude of the correlation coefficients indicating the degree of linear relationship between vowel AVIs and roughness ratings was generally higher than that between PVIs and roughness ratings, it may be that a more complete sampling of vowel wave cyclic amplitude variation would be particularly useful. Finally, the manual procedure for measuring the cyclic periods and amplitudes of vowel waves employed in the present study might be profitably modified in future studies. To effect time savings, it would seem desirable to automate such measures more completely than was feasible in this investigation.

CHAPTER V

SUMMARY AND CONCLUSIONS

For this study, quantitative indices of the jitter and shimmer in the acoustic waves of selected normal, simulated abnormally rough (SR), and clinically hoarse (CH) vowel productions were obtained. The study was designed to investigate the relationship of the jitter and the shimmer indices to spectral noise levels (SNLs) and roughness ratings for the vowels.

To provide data for this investigation, a further study was made of vowel phonations originally collected for two previous investigations. For both of the previous investigations, magnetic tape recordings were made of each of the five vowels /u/, /i/, /ʌ/, /ɑ/, and /æ/ phonated at one intensity (75 dB SPL: mouth-to-microphone distance six inches) by adult male subjects. For the first of the previous studies (46), twenty normal-speaking subjects produced each test vowel first normally and then with simulated abnormal vocal roughness. For the second of the previous studies (21), twenty clinically hoarse subjects, each presenting a medically diagnosed laryngeal pathology, produced each of the five test vowels. For both of the previous studies, measures of the acoustic spectral noise levels associated with each test vowel phonation were obtained. Additionally, the roughness of each test phonation was rated on a five-point equal-appearing intervals scale by eleven judges. A median of the judges' ratings was obtained in both studies as an index of the roughness of each test phonation.

For the present study, each recorded vowel production was filtered to isolate acoustic energy in a 10 Hz band centered at the fundamental vocal frequency of the production. The peak amplitude and the period of each acoustic cycle within a one-second segment of each filtered vowel wave was measured in an oscillographic recording of the wave. The period and amplitude measures for each test phonation were then treated statistically to obtain an amplitude variability index (AVI) and a period variability index (PVI), each of which was essentially independent of the mean amplitude and the mean period respectively of the vowel wave. Finally, the vowel AVIs and PVIs obtained for the present study were related to the spectral noise levels and median roughness ratings for the test phonations obtained previously.

The findings revealed, for all five test vowels, that both the PVIs and the AVIs associated with SR and CH phonations were larger than those associated with normal phonations. A significant vowel by mode-of-phonation AVI interaction was observed, however, for normal and CH but was not for normal and SR vowel productions. This finding suggested that laryngeal pathology may tend to increase the amplitude variation of high vowels more than that of low vowels, whereas the simulation of abnormal vocal roughness may tend to affect the amplitude variation of high and low vowels similarly. The differences between AVI and PVI means for normal and SR and for normal and CH phonations were not significant for all of the five test vowels. Instances were noted, moreover, in which the PVI and/or the AVI for an individual subject's normal vowel phonation was greater than that for his SR phonation of the same vowel. It was also observed that PVIs and AVIs obtained for normal phonations sometimes exceeded those for CH phonations of the same vowel. These findings suggested that the PVIs or the AVIs might not always differentiate normal and abnormally rough vowel phonations, but an "extremely large" vowel PVI or AVI would tend to suggest abnormal vowel roughness.

The findings also revealed for each test vowel that both PVIs and AVIs tended to be positively correlated with vowel roughness ratings. Generally, the degree of such linear relationship observed between AVIs and roughness ratings was only moderate but stronger than that between PVIs and roughness ratings. Additionally, a positive relationship between the AVI and PVI indices and vowel SNLs was observed which was generally similar in strength to that observed between the variation indices and vowel roughness ratings.

A tendency was also observed for AVIs and PVIs considered together to be positively and linearly related to the roughness ratings for each of the five test vowels. The magnitude of the multiple correlation coefficient indicating the degree of such relationship for each test vowel was similar to the higher of the separately obtained PVI versus median roughness rating and AVI versus median roughness rating coefficients for each test vowel. There was also a tendency for AVIs and PVIs considered together and SNLs for each of the five test vowels to be positively correlated. The magnitude of the multiple correlation coefficient indicating the degree of such relationship for each test vowel was similar to the higher of the separately obtained PVI versus SNL and AVI versus SNL coefficients for each vowel.

With respect to the relationship between AVIs and PVIs for each test vowel, the findings suggested, in general, that vowel waves which tended to evidence a relatively large degree of peak cyclic amplitude variation also tended to evidence relatively large period variations. The magnitude of the correlation coefficients indicating the linear relationship of AVIs to PVIs for each test vowel suggested that these indices tended to be to some extent overlapping and to some extent independent measures of wave variability.

Finally, the results of this investigation suggested that further investigations of vowel wave variability are needed which utilize measures of vowel wave variation reflecting total wave aperiodicity more completely than the AVIs and PVIs obtained for this study. It was suggested that a more complete sampling of the variation of instantaneous vowel wave cyclic amplitudes might aid in delineating better the relationship of acoustic wave variation to vowel SNLs and vowel roughness.

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APPENDIX A

Description of the Index of Variability

Description of the Index of Variability

The index of variability for the amplitudes (AVI), as well as for the periods (PVI), was based on the coefficient of variation (10) for the reason that this measure is independent of the scale of the measurements. That is, if measurements in an experiment were scaled to be some constant times the same measurements, the two sets of measurements would have the same coefficient of variation. Or, if it is questionable whether two sets of data are measures to the same scale, then this approach alleviates this concern.

In particular, it is important that even though controls were devised to insure a reasonably constant overall intensity level of the acoustic waves analyzed, the amplitude level for an individual fundamental frequency may be considerably higher in one sample than in another, and it is desired to have an index of variability which is not prominently influenced by this difference in levels. A similar concern is that the fundamental frequency of test phonations was not controlled from one subject to another even for productions of the same vowel. Moreover, it is basic in the science of hearing that logarithms of intensity levels are the measurements proportional to human judgments of loudness. For the amplitude variability index, therefore, a number was chosen to be conveniently proportional to the logarithm of the coefficient of variation.

It should be noted that, from a statistical viewpoint, the amplitude variability and period variability indices were used in the analyses of variance simply as scientific measurements of the phenomena being studied, as opposed to being used in a stochastic process analysis of the individual wave characteristics.

APPENDIX B

Fundamental Frequencies, PVIs, and AVIs, for Each Test Vowel Production

TABLE 11

FUNDAMENTAL VOCAL FREQUENCIES, PVIs, AND AVIs OF THE VOWEL /u/ PRODUCED BY TWENTY ADULT MALE SUBJECTS BOTH NORMALLY AND WITH SIMULATED ABNORMAL VOCAL ROUGHNESS AND BY TWENTY CLINICALLY HOARSE ADULT MALE SUBJECTS

MODES OF PHONATION											
NORMAL				SIMULATED ABNORMALLY ROUGH				CLINICALLY HOARSE			
Subject	FVF	PVI	AVI	Subject	FVF	PVI	AVI	Subject	FVF	PVI	AVI
1	102.3	.3052	-.33894	1	139.5	.8430	1.20276	1	131.1	.5734	.17580
2	121.2	.3480	-.38320	2	136.9	.3744	.45009	2	168.3	.8947	.98542
3	113.8	.2675	-.20648	3	113.0	.2628	.00043	3	84.7	.7625	.25115
4	101.6	.4200	-.09832	4	93.2	.4725	.29424	4	131.6	1.2210	1.33945
5	112.0	.4289	-.24557	5	160.7	.4720	.70859	5	124.1	.4381	-.20439
6	117.0	.7394	.07881	6	128.3	.5007	.64738	6	94.8	.9977	.81597
7	115.0	.3824	.10105	7	126.9	.5535	-.24848	7	90.2	.5280	.07335
8	111.9	.4817	-.35144	8	119.2	.4726	.21245	8	135.3	.5428	.06107
9	93.9	.3896	-.71466	9	112.9	.7317	.75936	9	117.8	.5642	.26810
10	108.4	.4784	-.03203	10	100.9	.8532	1.89696	10	102.6	.8588	.51890
11	111.2	.6280	-.03226	11	124.9	.5399	.37383	11	138.8	.9292	.75974
12	128.2	.5098	.08098	12	121.2	.6392	.18412	12	122.6	1.4986	1.12613
13	100.7	.4675	.05880	13	138.9	1.2944	1.44498	13	91.7	1.1299	.56098
14	108.8	.3388	.08849	14	138.2	.4440	.05537	14	146.7	.9327	.84260
15	138.9	.4702	.18752	15	149.7	.4293	.31555	15	133.8	.3573	-.70553
16	113.2	.4550	-.28525	16	115.2	1.0436	.59988	16	134.4	.7951	.52478
17	115.7	.6269	.12450	17	122.8	1.1001	1.73495	17	116.0	.8063	.12936
18	112.4	.4767	-.32440	18	109.1	.4626	.09482	18	139.2	1.0598	1.81980
19	117.1	.5619	.06781	19	121.6	.5318	.20384	19	111.6	.3611	-.48678
20	85.2	.3310	-.35095	20	82.0	2.2640	1.17464	20	78.7	.3793	-.57137

TABLE 12

FUNDAMENTAL VOCAL FREQUENCIES, PVIs, AND AVIs OF THE VOWEL /i/ PRODUCED BY TWENTY ADULT MALE SUBJECTS BOTH NORMALLY AND WITH SIMULATED ABNORMAL VOCAL ROUGHNESS AND BY TWENTY CLINICALLY HOARSE ADULT MALE SUBJECTS

MODES OF PHONATION											
NORMAL				SIMULATED ABNORMALLY ROUGH				CLINICALLY HOARSE			
Subject	FVF	PVI	AVI	Subject	FVF	PVI	AVI	Subject	FVF	PVI	AVI
1	101.6	.3596	-.12912	1	129.3	.4522	.97831	1	107.9	2.0856	1.63477
2	120.5	.3852	-.93033	2	126.0	.7488	.79239	2	199.6	1.4038	2.02160
3	108.5	.2491	-.89859	3	110.5	.4969	-.14892	3	83.8	1.8234	1.60303
4	97.1	.6052	.31701	4	94.5	.4155	.10957	4	118.5	.6468	.27323
5	112.1	.3905	-.23784	5	143.9	.5348	.54728	5	125.6	.5223	-.42504
6	115.5	.4630	-.07535	6	127.2	.7734	.68654	6	93.9	2.3941	1.73343
7	117.0	.5179	.23829	7	127.3	.7094	.48529	7	109.9	.4602	-.09151
8	111.8	.3928	-.51812	8	123.5	.3431	-.64111	8	131.8	.5117	.65098
9	94.5	.4576	-.21410	9	109.6	.7590	.64107	9	118.9	.5947	.08564
10	108.1	.4970	-.16108	10	103.5	.6341	.85618	10	109.0	1.1414	.85672
11	111.8	.4263	.09691	11	120.9	.6092	.38703	11	114.4	.6543	.08529
12	119.8	.6064	.59162	12	120.0	.5081	.27669	12	117.8	1.3350	.90211
13	100.3	.7800	.36116	13	142.2	.7179	1.27253	13	101.2	.9450	.52465
14	110.5	.4004	.13798	14	143.1	.7572	.83154	14	145.4	.5983	.04688
15	129.1	.6296	-.47134	15	149.4	.4855	.04296	15	141.6	.6677	-.27679
16	113.8	.5144	-.22541	16	112.8	.9018	.83097	16	110.0	.7235	1.47334
17	113.4	.4386	-.39437	17	117.6	1.4149	2.15259	17	117.6	.4094	-.54363
18	112.9	.5324	.00173	18	118.4	.5125	.08813	18	170.2	1.0751	1.82717
19	116.2	.7248	.35869	19	121.3	.4988	.45939	19	114.7	.4510	-.72792
20	89.3	.4255	-.46017	20	88.4	.5145	.17318	20	89.6	.4115	-.24131

TABLE 13

FUNDAMENTAL VOCAL FREQUENCIES, PVIs, AND AVIs OF THE VOWEL /ʌ/ PRODUCED BY TWENTY ADULT MALE SUBJECTS BOTH NORMALLY AND WITH SIMULATED ABNORMAL VOCAL ROUGHNESS AND BY TWENTY CLINICALLY HOARSE ADULT MALE SUBJECTS

MODES OF PHONATION											
NORMAL				SIMULATED ABNORMALLY ROUGH				CLINICALLY HOARSE			
Subject	FVF	PVI	AVI	Subject	FVF	PVI	AVI	Subject	FVF	PVI	AVI
1	104.8	.5344	.21298	1	127.6	.4557	.16554	1	119.5	.5129	.02734
2	117.4	.5216	-.41318	2	137.1	.7596	.75732	2	168.8	1.7400	1.93871
3	107.9	.3296	-.28760	3	100.3	.4130	.02448	3	84.3	.9486	1.81123
4	86.6	.5177	.23628	4	89.3	.4795	.09166	4	114.2	.7253	.05422
5	106.3	.4072	-.41850	5	146.2	.6706	.38738	5	123.8	.5245	-.22907
6	117.4	.3931	.12742	6	105.3	.4645	-.20114	6	88.7	1.4460	1.05422
7	115.7	.5419	.08849	7	124.3	1.1620	.93348	7	98.3	1.4276	.22454
8	108.6	.3769	-.51513	8	118.8	.3774	-.15316	8	115.5	.3996	.24551
9	95.3	.3872	.06445	9	109.3	.6436	.94507	9	105.4	.3883	-.29593
10	95.9	.5586	.32366	10	91.7	.7152	.50677	10	88.7	.6598	.50215
11	108.4	.6415	.01367	11	111.9	.3812	.00475	11	116.0	1.0112	.40140
12	123.9	.4532	-.16089	12	115.9	.7248	.69583	12	112.6	.9488	1.00086
13	98.2	.5492	.09968	13	105.3	.6975	.24402	13	100.9	1.1623	1.66511
14	111.6	.6630	.10311	14	140.9	.7421	.81130	14	151.9	.4488	-.01161
15	129.5	.4948	-.13300	15	140.0	.3779	.18269	15	131.3	.4857	-.46737
16	110.2	.4775	.01452	16	109.3	2.0810	1.84198	16	115.0	3.6088	2.49331
17	120.4	.6586	.13987	17	118.0	1.1920	1.00902	17	114.5	.9686	.61246
18	101.4	.5324	-.09701	18	104.9	.3872	.03502	18	133.9	.8233	1.13924
19	118.7	.4090	.15228	19	117.5	.6646	.41647	19	104.6	.4971	-.33301
20	83.9	.3844	-.33059	20	82.5	.9295	.29797	20	85.3	1.4752	.12254

TABLE 14

FUNDAMENTAL VOCAL FREQUENCIES, PVIs, AND AVIs OF THE VOWEL /a/ PRODUCED BY TWENTY ADULT MALE SUBJECTS BOTH NORMALLY AND WITH SIMULATED ABNORMAL VOCAL ROUGHNESS AND BY TWENTY CLINICALLY HOARSE ADULT MALE SUBJECTS

MODES OF PHONATION											
NORMAL				SIMULATED ABNORMALLY ROUGH				CLINICALLY HOARSE			
Subject	FVF	PVI	AVI	Subject	FVF	PVI	AVI	Subject	FVF	PVI	AVI
1	104.8	.3385	-.06854	1	136.6	.9547	.90939	1	121.8	.6595	.12287
2	116.2	.5379	.06855	2	123.0	.5262	.59593	2	161.8	.6910	.64256
3	101.5	.2416	-1.48945	3	99.1	.5114	.87702	3	84.8	1.3457	1.05115
4	82.5	.4109	-.20655	4	82.8	1.4540	1.22349	4	111.6	.4841	-.15440
5	102.9	.3054	-.35183	5	139.4	.6705	.7663	5	128.1	.5763	.01745
6	118.3	.3810	-.08286	6	102.3	.5613	.44310	6	85.2	.8427	-.11992
7	115.0	.5479	.21537	7	110.8	.7905	1.31513	7	101.8	.4306	.49540
8	108.4	.2655	-.14050	8	121.8	.4249	-.11345	8	113.3	.6414	.50406
9	91.2	.4594	.38934	9	104.6	.5480	.69152	9	92.4	.4709	-.02747
10	102.8	.6120	-.09788	10	88.9	.8548	.95041	10	85.2	.3705	-.44684
11	107.2	.6623	-.08008	11	109.8	.6563	.55906	11	113.5	.4992	-.23395
12	123.0	.5116	-.09296	12	119.3	.8416	1.29885	12	97.9	.7370	.64884
13	96.4	.7191	.44185	13	103.3	.8456	1.26268	13	113.5	1.4034	1.95760
14	102.8	.3973	.21245	14	131.8	.8415	.74873	14	139.8	.5037	.22814
15	128.5	.4432	-.14333	15	137.9	.4453	.26030	15	126.6	.5484	-.02287
16	108.8	.4893	.20330	16	112.4	.5417	.47304	16	111.3	1.1106	.58950
17	113.6	.8580	.36660	17	123.4	.7195	.21801	17	106.9	.3565	-.65266
18	98.4	.5194	-.01295	18	100.9	.6554	.42781	18	108.7	1.0780	.82665
19	108.5	.4596	-.07360	19	117.8	.7929	1.27323	19	111.2	.3337	-.56655
20	85.8	.2647	-.29183	20	71.9	.6228	.80119	20	76.9	.4576	-.53165

TABLE 15

FUNDAMENTAL VOCAL FREQUENCIES, PVIs, AND AVIs OF THE VOWEL /æ/ PRODUCED BY TWENTY ADULT MALE SUBJECTS BOTH NORMALLY AND WITH SIMULATED ABNORMAL VOCAL ROUGHNESS AND BY TWENTY CLINICALLY HOARSE ADULT MALE SUBJECTS

MODES OF PHONATION											
NORMAL				SIMULATED ABNORMALLY ROUGH				CLINICALLY HOARSE			
Subject	FVF	PVI	AVI	Subject	FVF	PVI	AVI	Subject	FVF	PVI	AVI
1	102.6	.4485	.03462	1	128.0	.5144	1.00518	1	118.9	.5969	.28148
2	120.4	.6912	-.65130	2	139.8	.4456	.00000	2	167.2	.7021	-.01867
3	100.7	.3458	-.44177	3	101.3	.5075	.60390	3	83.8	.7330	.35140
4	90.1	.4491	.17347	4	78.5	.4820	.42618	4	92.3	.5466	.04414
5	106.9	.3727	-.17619	5	145.1	.5668	.63083	5	121.3	.6403	.00560
6	109.8	.4901	.26552	6	108.3	.6921	.42078	6	85.2	.8079	.25430
7	114.4	.3959	-.12796	7	114.5	.7735	.90249	7	94.9	.8158	.21431
8	108.8	.4137	.01994	8	119.0	.4077	-.02993	8	117.2	.3608	-.03531
9	90.5	.4415	.40483	9	99.6	.5893	1.10720	9	101.5	.5593	.34772
10	96.1	.4216	.09061	10	92.5	.7544	1.69775	10	86.8	.6559	.06445
11	109.7	.7896	.01029	11	126.7	.7344	.94016	11	115.5	.5030	-.25924
12	114.8	.6357	.28578	12	110.6	.5983	.27485	12	104.9	1.1167	.72205
13	100.7	.4376	.08671	13	103.4	.7417	.86528	13	96.1	1.7134	1.87840
14	106.2	.4878	.25115	14	132.4	.4790	.47596	14	143.1	.4791	.40500
15	125.1	.4139	-.08286	15	140.5	.5248	.63052	15	132.2	.3935	-.50891
16	111.5	.5947	-.09474	16	115.0	.8337	.62190	16	121.2	.6182	.84577
17	112.2	.5350	-.10468	17	124.0	.7122	.42537	17	112.9	.4379	-.64801
18	103.7	.6245	.09131	18	106.2	.8609	.90003	18	119.3	.5475	.35179
19	115.2	.4038	-.06484	19	109.5	.4833	.42275	19	106.9	.4185	-.65364
20	82.6	.5141	-.34553	20	72.4	.3600	-.24458	20	78.7	2.0735	-.61065

APPENDIX C

Summaries of Analyses of Variance

TABLE 16

SUMMARY OF AN ANALYSIS OF VARIANCE TO COMPARE OVERALL PVI VOWEL MEANS FOR NORMAL AND SIMULATED ABNORMALLY ROUGH MODES OF PHONATION

Source of Variation	Analysis of Variance df	ss	ms	F
Modes of Phonation	1	192.98	192.98	18.66[a]
Subjects within Modes	38	393.09	10.34	

[a]($p < .05$)

TABLE 17

SIMPLE EFFECTS OF MODES OF PHONATION (N AND SR) WITHIN EACH VOWEL

Source of Variation	df	ms	F
/u/	1	67.04	11.64[a]
/i/	1	22.37	3.88
/ʌ/	1	50.33	8.74[a]
/ɑ/	1	58.43	10.14[a]
/æ/	1	11.61	2.01

[a]($p < .05$) Critical F value found as $F(1, 38)$.

TABLE 18

SUMMARY OF AN ANALYSIS OF VARIANCE TO COMPARE OVERALL PVI VOWEL MEANS FOR NORMAL AND CLINICALLY HOARSE MODES OF PHONATION

	Analysis of Variance			
Source of Variation	df	ss	ms	F
Modes of Phonation	1	608.40	608.40	24.94[a]
Subjects within Modes	38	927.09	24.40	

[a]($p < .05$)

TABLE 19

SIMPLE EFFECTS OF MODES OF PHONATION (N AND CH) WITHIN EACH VOWEL

Source of Variation	df	ms	F
/u/	1	106.39	7.85[a]
/i/	1	205.14	15.15[a]
/ʌ/	1	268.86	19.85[a]
/ɑ/	1	42.36	3.12
/æ/	1	57.94	4.27[a]

[a]($p < .05$) Critical F value found as $F(1, 38)$

TABLE 20

SUMMARY OF AN ANALYSIS OF VARIANCE TO COMPARE OVERALL AVI VOWEL MEANS FOR NORMAL AND SIMULATED ABNORMALLY ROUGH MODES OF PHONATION

	Analysis of Variance			
Source of Variation	df	ss	ms	F
Modes of Phonation	1	22.22	22.22	57.66[a]
Subjects within Modes	38	14.65	.38	

[a]($p < .05$)

TABLE 21

SIMPLE EFFECTS OF MODES OF PHONATION (N AND SR) WITHIN EACH VOWEL

Source of Variation	df	ms	F
/u/	1	5.39	29.76[a]
/i/	1	4.54	25.10[a]
/ʌ/	1	2.39	13.20[a]
/ɑ/	1	6.58	36.34[a]
/æ/	1	3.91	21.61[a]

[a]($p < .05$) Critical F value found as $F(1, 38)$

TABLE 22

SUMMARY OF AN ANALYSIS OF VARIANCE TO COMPARE OVERALL AVI VOWEL MEANS FOR NORMAL AND CLINICALLY HOARSE MODES OF PHONATION

Source of Variation	Analysis of Variance df	ss	ms	F
Modes of Phonation	1	10.94	10.94	11.23[a]
Subjects within Modes	38	36.99	.97	

[a]($p < .05$)

TABLE 23

SIMPLE EFFECTS OF MODES OF PHONATION (N AND CH) WITHIN EACH VOWEL

Source of Variation	df	ms	F
/u/	1	2.95	9.24[a]
/i/	1	4.95	15.53[a]
/ʌ/	1	4.05	12.71[a]
/ɑ/	1	.77	2.42
/æ/	1	.31	.97

[a]($p < .05$) Critical F value found as $F(1,38)$