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ABSTRACT

A vocal register is a series or range of consecutive frequencies that can be produced with nearly identical voice quality. On the basis of research three fundamental registers can be defined and described: pulse, a low range of phonation; modal, a middle or "normal" range; and loft, a high range, described by some as falsetto. These three principal vocal registers are defined on the basis of four operational criteria. The acoustic characteristics of the registers are that each one occupies different ranges of fundamental frequencies, reveals different magnitudes of vocal intensity, and has a different frequency composition. Perceptually, the three registers can be differentiated and identified on the basis of voice quality. Physiologcally, they differ because of vocal length or thickness and vibratory patterns. Aerodynamic characteristics relate to subglottic pressure, air flow, glottal resistance, and voice intensity. (A list of 55 references is attached to this report.) (RN)

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Preface

The purposes of these progress reports are:

1. To provide other laboratory investigators and professional workers in the field with up-to-date information about our research activities and results,

2. To serve as documentation of our research activities for agencies which provide us with support, and

3. To provide somewhat formal reporting of research activity for our own faculty and students in order to exchange information and encourage collaborative efforts.

These reports are not intended to take the place of publications in recognized journals. Some contributions may be so published subsequently, but others may not. Many of these reports are of projects currently in process or with preliminary or partial findings being already available.

In view of these purposes and the nature of the contributions, no editorial review is exercised. Consequently, these reports should not be quoted unless specific permission to do so is granted by the author.

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ON VOCAL REGISTERS

(Based on an invited paper presented at the Collegium Medicorum Theatri, Buenos Aires, Argentina, August 18, 1971.)

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Abstract

For a considerable length of time, the concept of vocal registers has been subjected to controversy. Various authors have argued that there are as few as one or as many as seven registers and a considerable number of contradictory and confusing names have been used to identify them. Moreover, to date, agreement cannot be obtained even with respect to a reasonable definition of the nature of registers themselves. Accordingly, this paper first provides a definition of vocal registers, viz. a vocal register is a series or range of consecutive voice frequencies which can be produced with nearly identical voice quality; that there will be little overlap in fundamental frequency between adjacent registers, and that the operational definition of a register must depend on supporting perceptual, acoustic, physiologic and aerodynamic evidence. On the basis of this definition, it is postulated that three major registers exist; they are the pulse, modal and loft registers. It is contended that these registers can be experimentally defined and demonstrated and, while other registers could exist (at least for some individuals), they cannot be identified and described at levels approaching the precision and understanding of the three proposed. Perceptual, acoustical, physiological and aerodynamic data are presented to support postulations relevant to these three registers, and to differentiate among them.

Defining Register

A number of definitions of vocal registers have been postulated but no single approach appears to have adequately and operationally defined these rather complex voice phenomena. Further, the actual number of vocal registers associated with phonation by the untrained voice has not been established.[1] Most postulations suggest that there are between three and five registers--although various authors have argued that there are as many as seven or as few as one. In any case, controversy exists in this regard--indeed, to the extent that Morner, Fransesson and Fant (1964) published a paper in which they listed 107 different names which have been used to identify one register or another. While some of the labels they report are simply translations or minor variations of the same name, the number is large even when such duplications are removed.

In an attempt to resolve such confusions, I define a vocal register simply as a series or range of consecutive vocal frequencies which can be produced with nearly identical voice quality and that ordinarily there should be little or no overlap in fundamental frequency (f_o) between adjacent registers. Furthermore, I maintain that, before the existence of a particular vocal register can be established, it must be operationally defined: 1) perceptually, 2) acoustically, 3) physiologically and 4) aerodynamically.

On the basis of my own research and the research of others, I propose that three major vocal registers already have been defined and experimentally described. They are the pulse, modal and loft registers. These three terms probably are unfamiliar to the reader. They were selected in part for this very attribute for, as von Leden (1971) points out, the use of the older and more common terms (as I had been doing) tended to confuse the issues at hand--primarily because these names were used by workers to describe or identify so many different types of phonation. In any case, the three terms listed above were selected in order that the operational definitions provided them would be uncontaminated by any of the concepts lingering in the minds of the phoneticians, laryngologists, voice teachers, speech pathologists or, for that matter, any class of professionals who must deal with the human voice.

The pulse register occupies the lowest range of phonation along the fundamental frequency continuum. The term was selected because its vibratory pattern is pulse-like and because, these perceived pulses usually have relatively low frequencies. Synonyms for the pulse register undoubtedly include such terms as vocal (or glottal) fry, creak and strohbass; a basic postulation of this register has been provided by Hollien, et al (1966).

The modal register is a term I have used for some years; originally, I favored the term "normal" to identify this register. However, as van den Berg (1966) pointed out, the use of the label "normal" would imply that the other registers were abnormal and, of course, his logic is correct. Accordingly, the modal register is so named because it includes the range of fundamental frequencies that are normally used in speaking and singing (i.e., the mode). The modal register is a rather inclusive one and many individuals--especially workers in vocal music--would argue that it actually constitutes a set of registers or sub-registers including either two (chest and head) or three (low, mid and high) separate entities. I concede the tradition of such an approach but, as may be seen, I have yet to find reasonably convincing evidence that such sub-registers do indeed exist.

The loft register is one that phoneticians would recognize (in their terms) as falsetto. However, falsetto is used to describe many different vocal events by different groups of professionals and it appears that the continued use of this label would result in considerable confusion. Hence, a term is used that has little history and yet suggests a higher register than the others--and one with different characteristics. Indeed, the loft register occupies the higher fundamental frequencies of the voice continuum.

It is conceded that these somewhat subjective descriptions alone do not constitute operational definitions. Indeed, they are only postulates and to become established they must be supported by, and consistent with, appropriate research literature. Specifically, if my postulations are reasonable, it should be possible to apply physical, perceptual, physiological and aerodynamic tests in order to determine their validity.

Before proceeding, however, it must be conceded that it is quite possible there are more than three voice registers. For example, observations have been made of a very high-frequency (and relatively rare) "register" which is exhibited by a few women and children; it is usually referred as the "flute," "whistle" or "pipe" register. However, since this register seems to be an unusual one and since little, if any, empirical information is available about it, it obviously has not been established as part of the expected vocal physiology of the normal human larynx. Finally, it should be noted that, although there is practically never any frequency overlap between the pulse and modal registers, many individuals can produce a curious sounding phonation at frequencies which seem to lie between them. These vocalizations appear to be a blend of voice qualities suggesting a mix of both pulse and modal phonation produced simultaneously. However, no experiments have been carried out on this vocal phenomenon either. Hence, even in the light of these various subjective observations, I maintain that only three major registers meet the test criteria cited above.

Acoustical Correlates of Registers

In a paper such as this one, it is not possible (however desirable) to review all of the research and logic that might have a bearing on the postulations made by the author. It is possible, however, to develop and summarize a reasonable position with respect to each of the four areas by which the postulations are to be tested. The first issue, then, is the differentiation of the three specified registers by acoustical means.

Hollien and Michel (1968) investigated the modal, pulse and loft registers in twelve male and eleven female subjects; the data for the males are presented in Figure 1. In this figure, the data for each subject (and for the group means) are provided by the three vertical bars. The lower bar is the extent of the subject's pulse register; the middle, his modal register and the upper, his loft

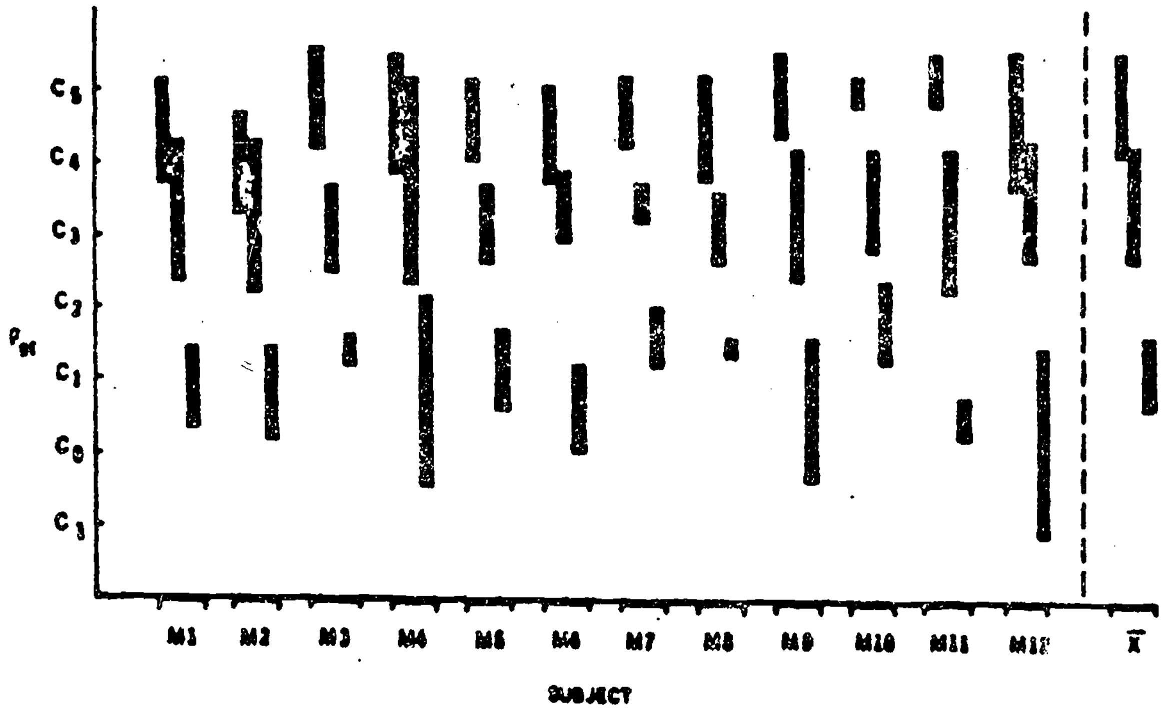


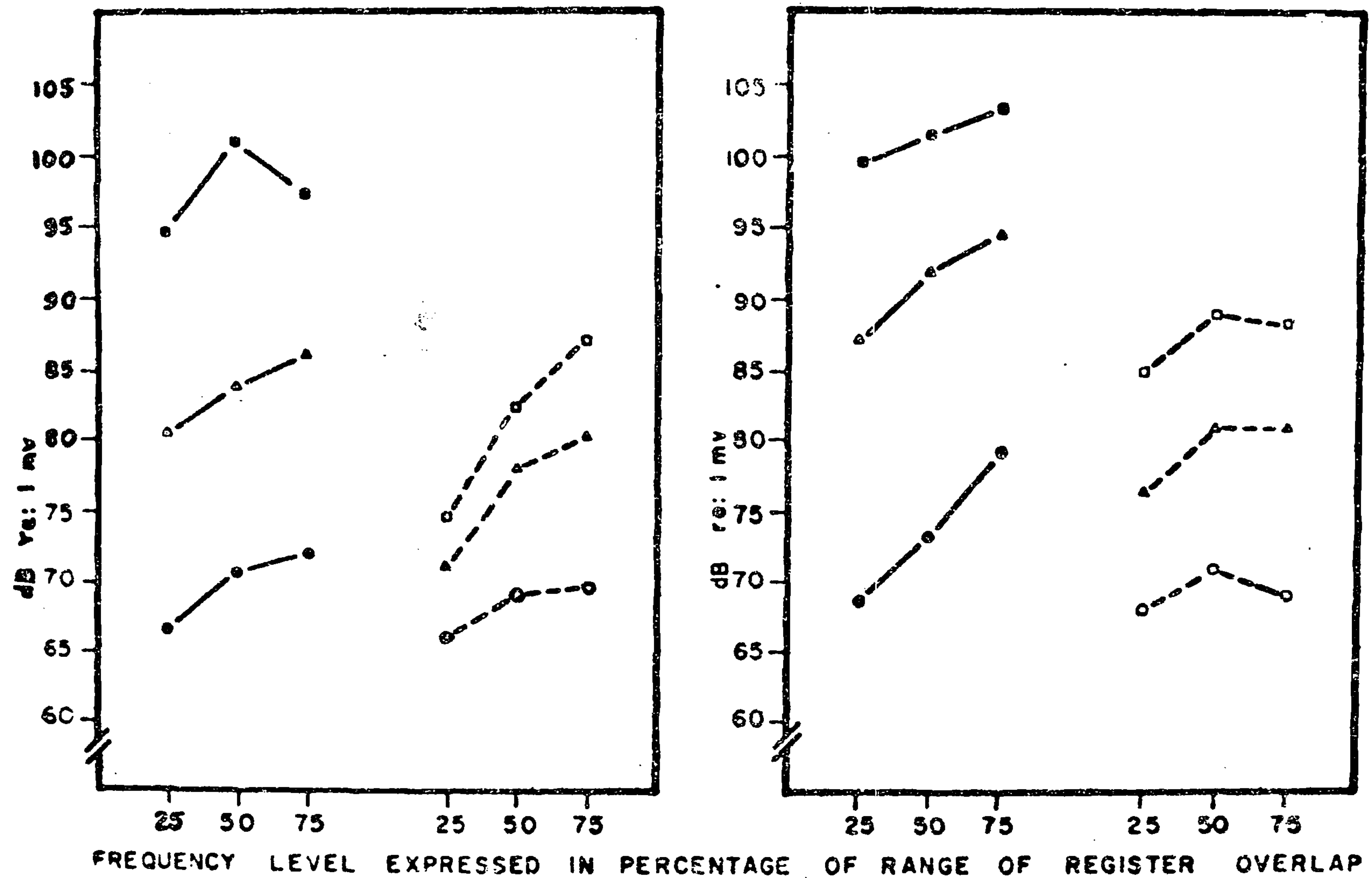
Figure 1. Phonatory frequency ranges of 12 male subjects. For each subject, the lowest bar provides the extent of the pulse register, the middle bar the range for the modal register and the upper bar, that for the loft register (from Hollien and Michel, 1968).

register. When comparing the registers, it was noted that fundamental frequency for the pulse register exhibited a maximum range of 7-78 Hz; for the modal register, 71-561 Hz and 156-795 Hz for loft. Incidentally, the data for the female subjects were very similar excepting the maximum ranges for the modal and loft registers were between three and four tones higher than were those for the males (i.e., modal: 122-798 Hz; loft: 210-1729 Hz). Surprisingly, the pulse register range was almost identical for both sexes (males: 7-78 Hz; females: 2-78 Hz). Other reported data are more or less in agreement with these observations at least for the upper two registers (see, for example, Nadoleczny, 1925; Preissler, 1939; Hollien, Dew and Beatty, 1971; and Colton and Hollien, 1972). In any case, their data suggest that the mean phonational frequency range (i.e., the modal and loft registers combined) is approximately three octaves, and varies between about 27 and 54 semitones, both for males and females, and for singers and nonsingers.[2] Further, from the data at hand, it would appear that the average pulse and loft ranges of nonsingers each exceed one octave whereas a range of 1.5-2.0 octaves can be expected for the modal register.

A number of workers (see, particularly, Stout, 1944; Ruth, 1963; Vennard, 1967 and Colton, 1972) have indicated that the intensity of phonations produced in one vocal register may be greater or less than the intensity of phonations produced in another register--both with respect to spontaneously produced vocalizations and with attempts to produce a dynamic intensity range. Unfortunately, vocal intensity comparisons between two or more registers are difficult to establish primarily because of the difficulty in producing them at the same frequencies; hence, there is a limited amount of experimental data available in this regard. However, some research has been completed; for example, Colton (1972) has reported that, for both singers and nonsingers, the minimum and "comfortable" intensity levels for the loft and modal registers were not particularly dissimilar but that all individuals could produce much greater intensities in the modal register than they could in loft. A review of Figure 2 will provide evidence of both the greater dynamic range for modal as well as its more substantial maxima. With respect to the pulse register, Murry and Brown (1970) found that the intensities which accompany such phonations were lower in overall magnitude than the intensities of phonation produced in the modal register. They further report that very little, if any, variation in intensity was possible in the pulse register--at least by their subjects.

The relationship of the voice spectrum to voice register is not clear at the present time, primarily because currently available electronic/acoustical analysis equipment is not adequate to provide much appropriate information. However, there are some data available, and both Large (1968) and Colton (1969) have been able to demonstrate that there are a greater number of partials exhibiting significant energy in the modal register than there are in loft register phonations. Figure 3 illustrates the spectral differences between the two registers; indeed, such differences in the higher harmonic partials (overtones) have long been suspected to exist--especially by workers in vocal music and speech pathology.

To summarize this section on the acoustic correlates of phonational registers, it may be said that the pulse, modal and loft registers tend to 1) occupy different ranges of fundamental frequencies, 2) exhibit somewhat different magnitudes of



LEGEND

MODAL	INTENSITY CONDITION	FALSETTO
	Minimum	
	Most Comfortable	
	Maximum	

Figure 2.

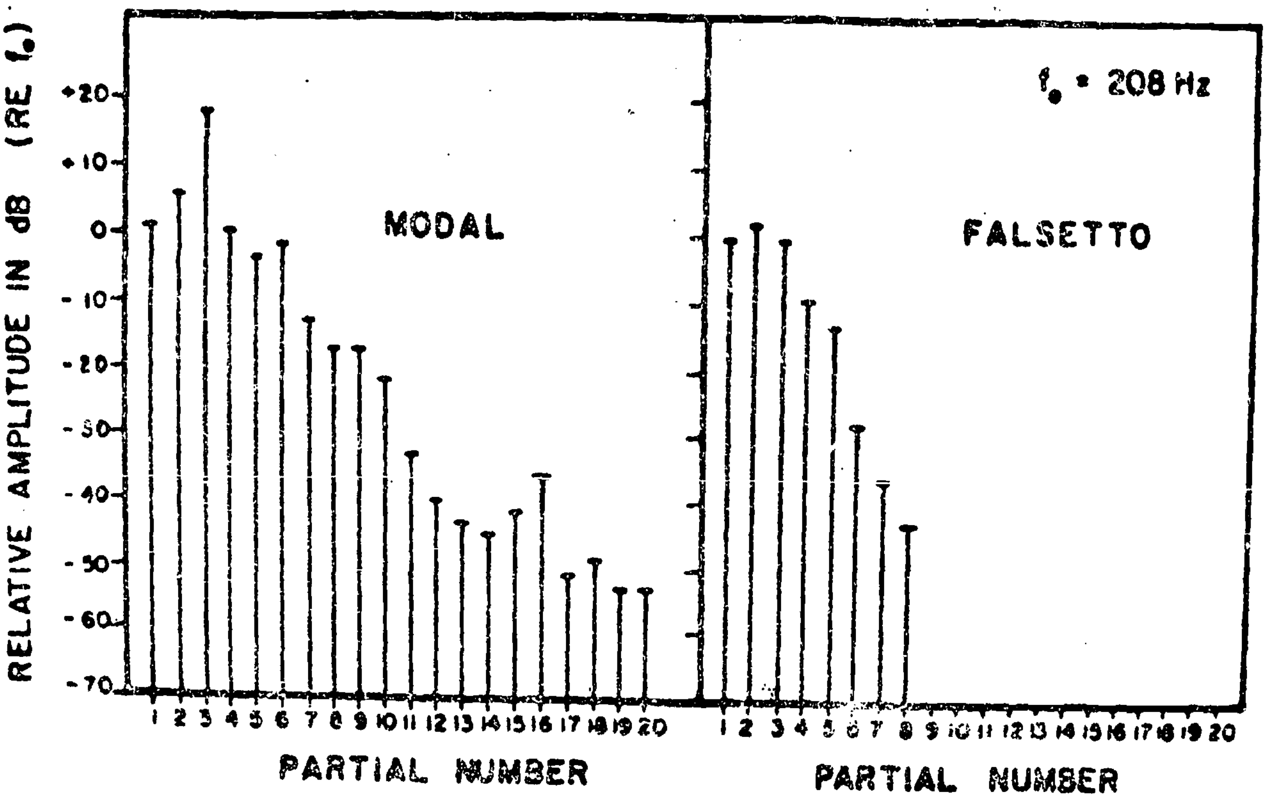


Figure 3. Example of a harmonic partial spectrum display for phonations produced in the modal and falsetto registers by a single subject at 208 Hz (from Colton, 1969). Very similar spectrum differences between the registers were found for all subject/frequency conditions. In the case of this research, the term falsetto is analogous to loft.

vocal intensity and 3) show differences in frequency composition. Table 1 presents a summary of these characteristics as they relate to each of the registers and differentiate among them.

Table 1. Summary table of the acoustic characteristics that serve to differentiate among the pulse, modal and loft voice registers.

	Acoustic Characteristic		
Register	Fundamental Frequency (f_o)	Vocal Intensity (I)	Voice Spectrum
<u>Pulse</u>			
Level within register	Low f_o	Low I	Pulse train
Variation within: males females	1-70 Hz* 1-70 Hz	Very small dynamic range	Single or double pulses
Relation to Modal	Lower f_o	Lower I	More partials
<u>Modal</u>			
Relation to Pulse	Higher f_o	Higher I	Fewer partials
Level within register	Mid f_o	Greatest I	Sawtooth wave
Variation within: males females	75-500 Hz 130-750 Hz	Greatest dynamic range	Changes with changes in f_o and I
Relation to Loft	Lower f_o	Higher I	More partials
<u>Loft</u>			
Relation to Modal	Higher f_o	Lower I	Fewer partials
Level within Register	High f_o	Medium I	Flat/broad wave
Variation within: males females	150-750 Hz 220-1700 Hz	Moderate dynamic range	--

*Frequency data are based on probable extremes
-- no data

Perceptual Correlates of Registers

With respect to the perceptual correlates of vocal registers, it is contended that all three registers can be reliably differentiated (and/or identified) perceptually on the basis of voice quality alone. However, only a small number of studies have been completed in this area and the position stated above is based primarily on the work of Luchsinger and Arnold (1965), Michel and Hollien (1968), Hollien and Wendahl (1968) and Colton and Hollien (1970). Perhaps more experiments of this nature would be carried out were it not for the exacting and time-consuming procedures necessary to insure that valid and reliable data are obtained.

Colton and Hollien (1972) report a series of experiments in which they attempted to directly compare perceived quality differences between the loft and modal registers. First, they selected a group of individuals (with subgroups of singers and nonsingers) who could produce phonation in both registers at several of the same frequencies. Specifically, these individuals were asked to phonate first in loft and then in the modal register at three separate frequencies within their f_o overlap; recordings of these phonations were adjusted so that vocal intensity was reasonably well controlled. In one of several experiments, when the stimuli (grouped by frequency) were presented to both trained and untrained listeners, the observers made correct identifications nearly two-thirds (64%) of the time. In another experiment, all of the phonations from the two registers were evaluated by a paired comparison technique and, in this case, the several groups of judges correctly differentiated between the two registers over 93% of the time. These studies provide evidence that phonations in the modal and loft registers are sufficiently different with respect to voice quality that they can be perceptually differentiated by that characteristic alone--at least under controlled conditions.

Since the modal and pulse registers do not overlap at all, studies of the nature described above cannot be carried out. However, to test the perceptual uniqueness of the pulse register, Hollien and Wendahl (1968) asked eight males to match the pitch of pre-recorded steady-state pulse register samples. The procedure, typical of many of these perceptual studies may be seen schematized in Figure 4. In any case, examination of Table 2 will demonstrate that the judges could make appropriate matches within a very small tolerance. Even though these data do not provide primary evidence about the voice quality of the pulse register, the inference can be made that subjects' success with the task suggests the existence of a vocal quality that is readily identifiable. Moreover, in 1968, Michel and Hollien demonstrated both perceptually and acoustically that (clinically) harsh phonation was distinctly different from pulse phonation; the psychophysical experiments utilized were very similar to those cited above. In any case, they requested several groups of variously trained listeners to sort ten recorded samples of pulse register phonations and ten samples of clinical harshness (produced by males) into two sets.[3] The listeners averaged well over 90% correct identification for 0.5-sec. vowel stimuli and 100% correct responses for four-word utterances. In summary, all of the evidence to date suggests that the three proposed registers can be contrasted perceptually; in any case, Table 3 provides an embarkation point for consideration of the known and suspected perceptual differentiations among the registers.

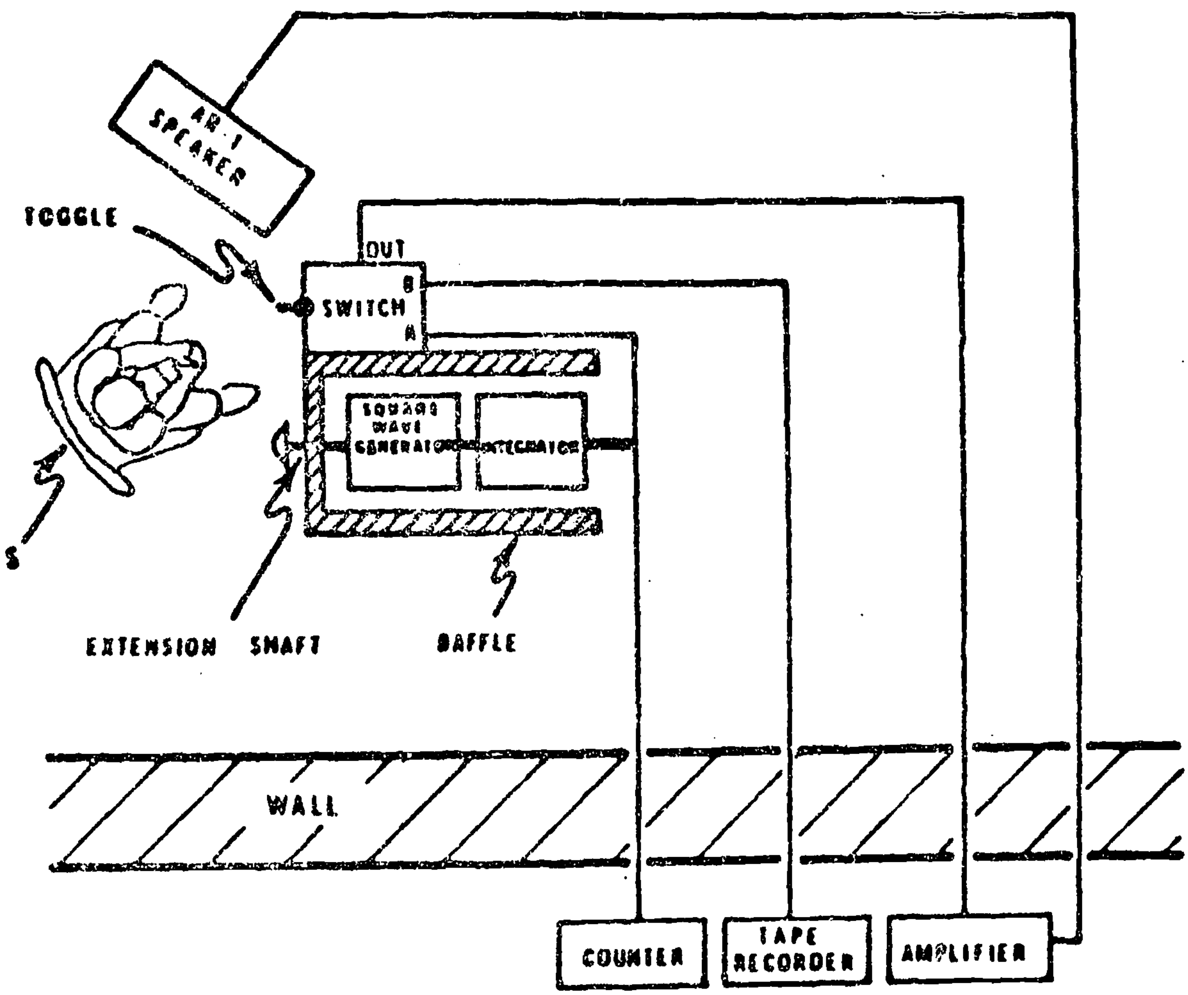


Figure 4. Typical arrangement of equipment by means of which listeners are able to carry out perceptual voice studies. In this case, observers compared pulse-train repetition rates with pulse register samples. In other studies, the equipment would be modified to permit different types of comparisons (from Hollien and Wendahl, 1968).

Table 2. Listener judgments of pulse register repetition (frequency) rates. The ranges for the pulse register samples are based on the period of the longest and shortest waves measured within the sample; the range for the judgments, the highest and lowest frequency match. (from Hollien and Wendahl, 1968).

Sample Number	Pulse Samples Mean	Range	Mean	Range
1	31.6	28.7-35.4	31.2	26.0-33.5
2	31.8	29.2-35.4	33.8	30.5-36.5
3	33.9	29.0-37.2	34.9	32.5-38.0
4	47.7	40.3-54.9	48.2	37.5-55.5
5	49.4	43.0-57.7	47.7	41.5-53.0
6	49.8	45.5-54.3	49.4	47.0-53.0
7	50.8	43.3-59.4	49.1	43.5-52.0
8	69.1	61.6-73.4	66.6	60.0-69.5

Table 3. The relationship of perceived voice characteristics to vocal registers and differentiation among them. By-and-large, the comments here tend to be more speculative than for the other three summary tables.

Register	Pitch	Loudness	Quality
<u>Pulse</u>			
Level within register	Low	Softest	Systematic pulsing or popping sound
Variation within	Yes	No variation	No
Relation to Modal	Lower	Softer	Rougher
<u>Modal</u>			
Relation with Pulse	Higher	Louder	--
Level within register	Mid	Loud	NA
Variation within	Largest range	Greatest range	Great variation
Relation to Loft	Lower	Louder	--
<u>Loft</u>			
Relation to Modal	Higher	Softer	Smoother, sometimes slight breathy qualit
Level within register	High	Medium	NA
Variation within	Yes	Moderate variation	Minor

NA - not applicable.

Physiologic Correlates of Registers

Many of the physiological correlates of the modal register have been established; considerable data are available on the other two registers also. Obviously, an exhaustive review of all of the appropriate information in this area would involve a discussion too lengthy for a paper of this nature. Moreover, many of the techniques developed, or being developed, to study the physiology of laryngeal function have provided data only on one register (usually the modal); hence, available information is so sparse, and the relationships so incomplete, that reasonable comparisons among the registers (using these techniques) are nearly impossible. Included among the research methodologies that appear to have a high potential for the future study of vocal registers but which have not, as yet, provided much useful information to differentiate among them are: electro-myography (EMG) of the laryngeal muscles, photosensor monitoring (photo-electric glottography) of vocal fold vibratory patterns, ultrasonic approaches to laryngeal function and fiber optic techniques. On the other hand, indirect laryngoscopy and x-ray approaches have proved to be successful in the physiological study of voice registers and various of the specific techniques related to these general methodologies have provided rather substantial data on vocal fold: 1) length, 2)thickness (per-unit mass) and 3) vibratory patterns. Further, data from the first two areas permit empirical estimations of actual vocal fold mass to be made--and the physical vocal fold attributes of mass and stiffness are of extreme importance to phonatory theory. Unfortunately for the understanding of general laryngeal function (and theory development), no data are available that relate directly to vocal fold stiffness, the second major physical characteristic relating directly to oscillation by the folds. Perhaps, in the future, such information can be deduced from EMG studies. Finally, it is obvious that the obtained data on the vibratory patterns of the vocal folds provide substantial insight into a wide variety of vocal events. In any case, as with the other two physiological areas (vocal fold length and thickness), data on vibratory patterns permit a rather specific differentiation among the three registers postulated in this paper.

Vocal Fold Length

Vocal fold length measures may be obtained by means of indirect laryngoscopy and photography systems. This approach provides prints of the folds and measurements can be made as per Figure 5. Lateral (or spot) x-ray techniques also are useful in studying the issue of vocal fold length; Figure 6 provides a schematic drawing of such a system as well as the associated equipment used to control the subject's fundamental frequency and vocal intensity. Naturally, the vocal fold length measurement procedures are different for x-ray studies than they are for vocal fold photography; Figure 7 provides a typical approach to such x-ray measurements.

By means of both the photographic and x-ray techniques, it has been demonstrated that the length of the vocal folds increases systematically with corresponding increases in fundamental frequency of phonation in the modal register (Sonninen, 1954; Hollien, 1960; Hollien and Moore, 1960; Pfau, 1961; Wendler, 1964, and Hollien, Brown and Hollien, 1969). Figure 8 provides an example of such data. Note the increase in vocal fold length with rising frequency in the modal register; indeed, the mean length change within the modal register (for the several studies cited above) is about 5 mm. Moreover, some individuals show variations of nearly 10 mm in magnitude.

With respect to the pulse register, Hollien, Damste, and Murry (1970) report that no observable vocal fold length changes occur as a function of variation in fundamental frequency; nor do systematic lengthening and shortening patterns seem to relate to frequency change in the loft register (Hollien and Moore, 1960 and Hollien, Brown and Hollien, 1971). Indeed, since both lengthening and shortening patterns are observable for loft, no specific relationships can be postulated at all. In summary, the differences in vocal fold length and lengthening patterns for the three registers are readily discernable; these relationships may be seen in Table 4.

Table 4. Some physiological bases of vocal register and the factors that serve to differentiate among them. Data are related to frequency as the relationships of these characteristics to intensify and/or spectra are incomplete or not relevant.

Register	Vocal Fold Length	Vocal Fold Thickness	Vibratory Patterns
<u>Pulse</u>			
Level within register	Relatively short	Ventricular folds load true folds	Sharp, short pulse, very long closed time
Variation within	Do not vary	No systematic variation	Little to none
Relation to Modal	Same as low f_o modal	Thicker	Open time much shorter
<u>Modal</u>			
Relation to pulse	Same to longer	Same to much thinner	Open time much longer
Level within register	Systematic variation	Systematic variation	Generally triangular opening and closing; short to no closed time
Variation within	From very short to very long	From very thick to very thin	Variation in wave shape and closed time as function of f_o, I and spectra.
Relation to Loft	Same to shorter	Same to much thicker	Better defined wave shape
<u>Loft</u>			
Relation to Modal	Similar to high f_o modal	Same as for high f_o	Opening and closing slopes more gradu
Level within register	Relatively long	Thin	Low amplitude, litt or no closed time
iation within	Unpatterned variation	No variation	Little variation

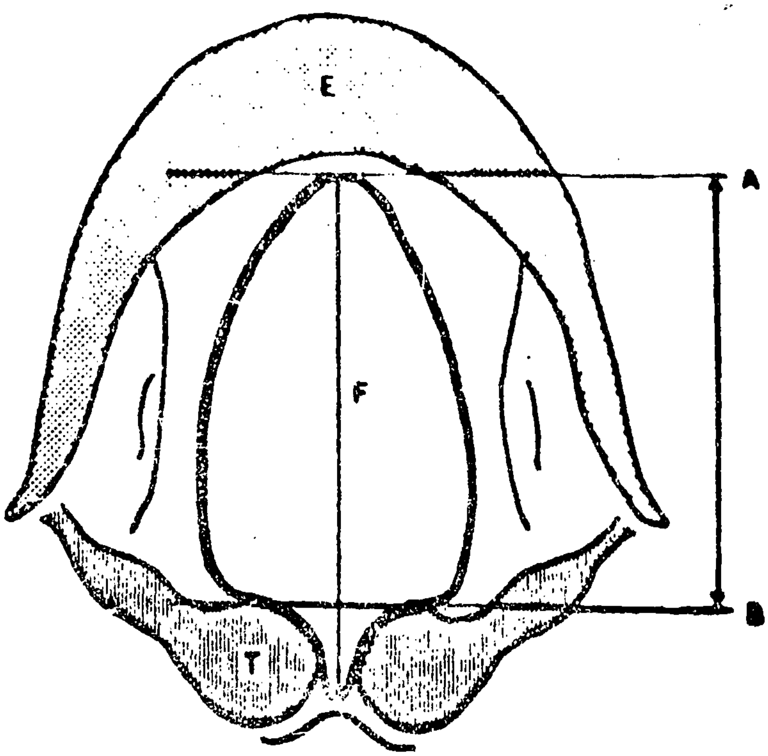


Figure 5. A schematic drawing of the vocal folds with landmarks used in vocal fold length measurements. E is the epiglottis; F, the vocal folds; and T, the tubercles formed by the corniculate and arytenoid cartilages. Line A is drawn tangent to the most anterior extent of the vocal folds and line B tangent to the tubercles (adapted from Hollien and Moore, 1960).

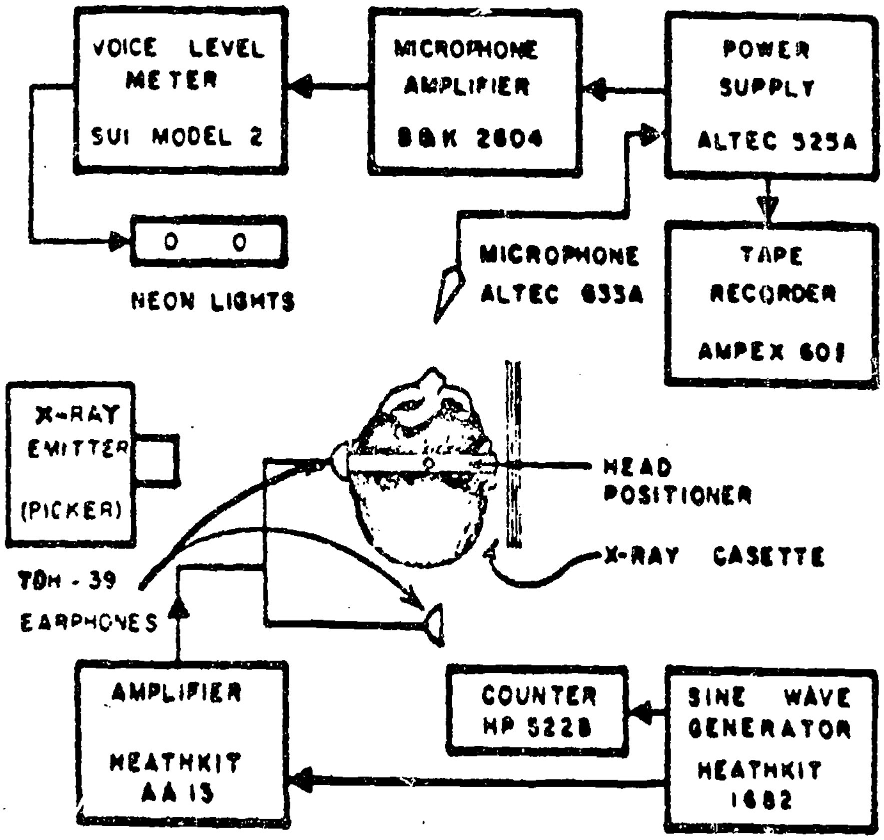


Figure 6. Block diagram of equipment utilized in obtaining x-rays of the vocal folds. The apparatus permitted the experimenter to control, monitor and record the phonatory events. The ray emitter and cassette were at the level of the larynx (from Damste, Hollien, Moore and Murry, 1968).

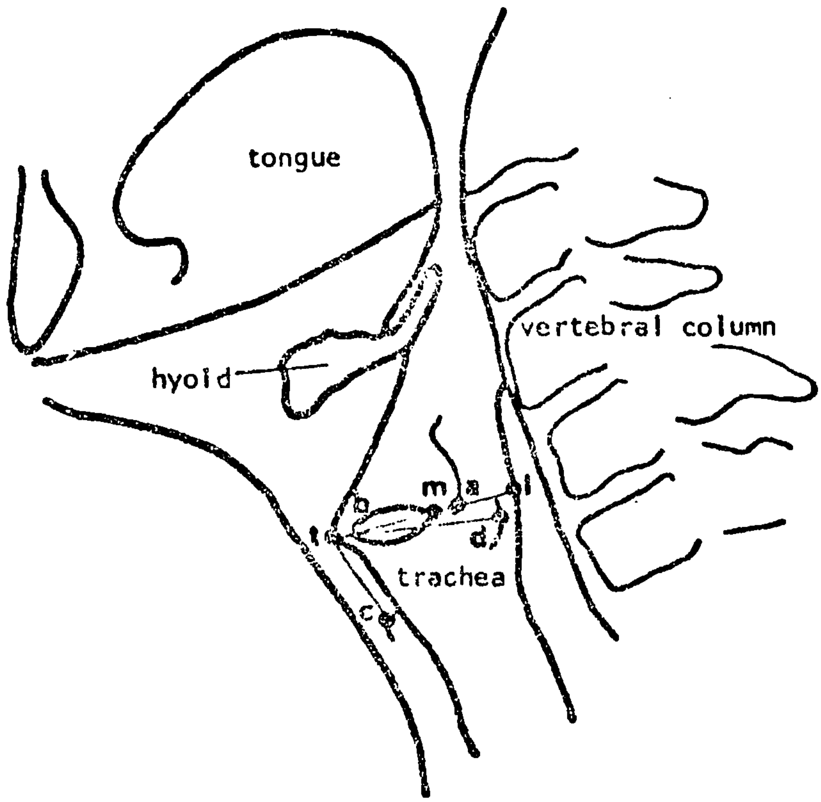
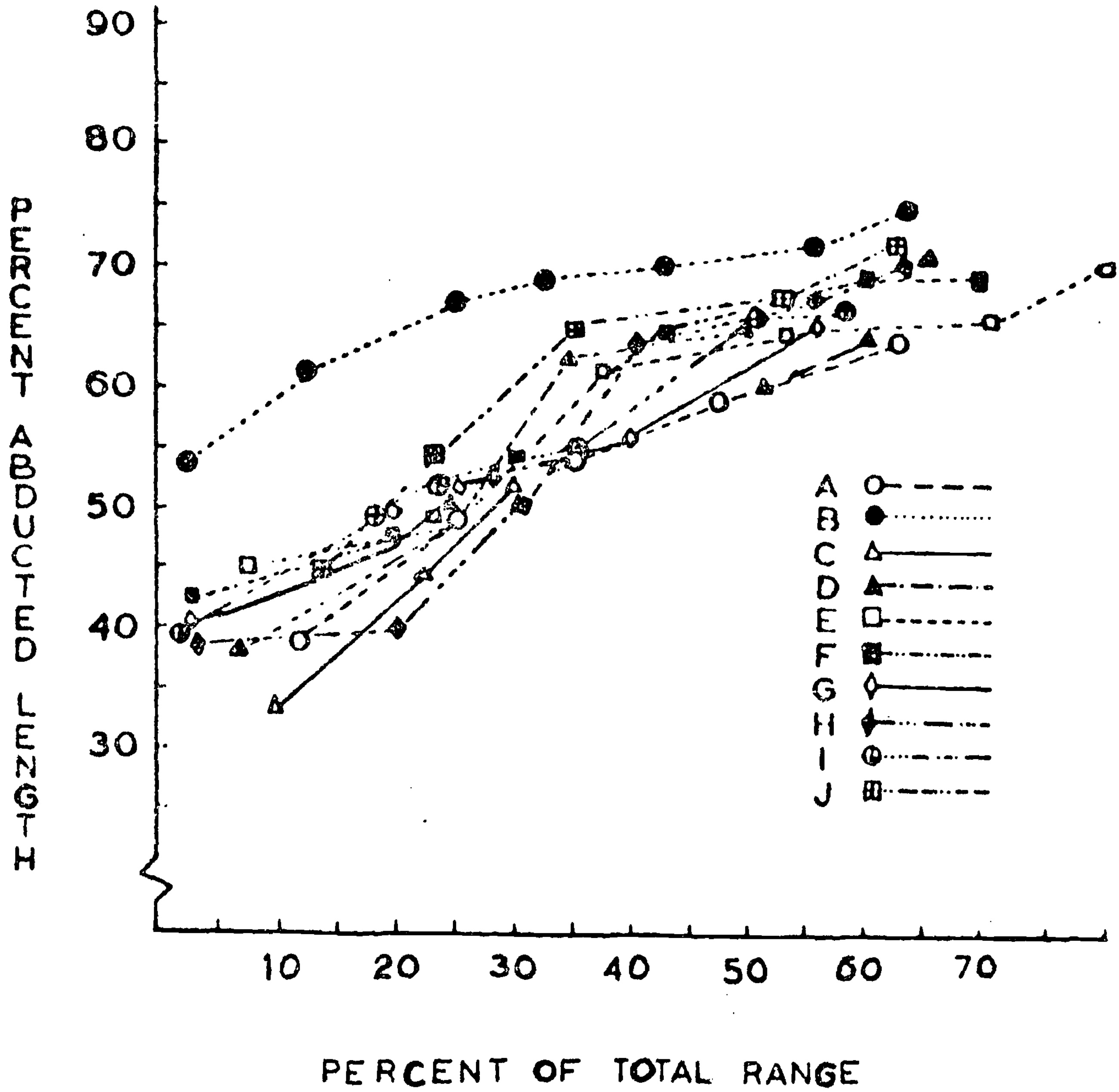


Figure 7. Sketch of a lateral x-ray of the larynx showing reference points and lines used to obtain five estimates of vocal fold length and one of crico-thyroid relationship (from Damste, Hollien, Moore and Murry, 1968).



PERCENT ABDUCTED LENGTH
90
80
70
60
50
40
30
10
20
30
40
50
60
70
PERCENT OF TOTAL RANGE
A
B
C
D
E
F
G
H
I
J

Figure 8.

Vocal Fold Thickness

Data on vocal fold thickness serve to differentiate among the registers also. Systems such as that described in Hollien, Curtis and Coleman, 1968, provide x-ray plates from which measurements can be made according to the protocols exhibited by Figure 9. Generally, for the modal register, the thickness of the vocal folds is systematically decreased as fundamental frequency of phonation is increased (Hollien and Curtis, 1960; Hollien, 1962; Hollien and Coleman, 1970; Hollien and Colton, 1969); an example of this relationship may be observed in Figure 10. Note especially that for a specific fundamental frequency, the vocal folds appear to be of about the same thickness no matter what type voice (for example, bass, baritone, tenor) subjects exhibit--or whether they are male or female. Indeed, for the modal register, vocal fold thickness (or per-unit mass) appears to correlate more closely to the f_0 produced than does any other phonatory attribute. On the other hand, Hollien and Colton (1969) have demonstrated that the vocal folds are thinner for the loft register than for modal and that thickness does not vary as a function of fundamental frequency for this register. Recently Allen and Hollien (1972) found a similar lack of systematic variation with respect to this parameter for pulse register phonations. Further, the vocal fold configuration for pulse register phonation is different than for the other two registers. Specifically, for this type of phonation, the vocal folds are very thick and the ventricular folds appear to come in contact with (or load) the true vocal folds. Finally, it should be noted that, by combining the data from vocal fold length with those from the vocal fold thickness research, reasonably good estimates of the actual mass of the vocal folds should be obtainable. In any case, the data on the relationships between vocal fold thickness and voice register may be found summarized in Table 4.

Vibratory Patterns

Another major approach to the physiological study of vocal registers is the investigation of the vibratory patterns of vocal fold movement. This glottal amplitude-by-time analysis--obtained by ultra-high speed photography--has been used in laryngeal research for over thirty years. The equipment and techniques involved are similar to those described under Vocal Fold Length above; they are nicely described by Moore, von Leden and White (1962). A typical plot of the opening and closing of the vocal folds within the duty cycle of a full vibratory event may be seen in Figure 11. For the pulse register, this type of plot yields a rapidly opening and closing motion of the vocal folds and a very long closed period (Moore and von Leden, 1958 and Wendahl, Moore and Hollien, 1963); physically (and perceptually) this pulse decays to zero before the succeeding pulse is initiated. In the modal register, on the other hand, the generalized pattern is one best characterized by those displays seen in the published reports of such workers as Timke, von Leden and Moore (1958). Here the glottal pulse (see again Figure 6) is characterized by a relatively rapid onset followed by a brief open period with a longer period of closing and a short closed time. Of course, these several parameters of the glottal waveform all vary as a function of the vocal frequencies and/or intensities produced. Nevertheless, the typical pattern for the modal register is markedly different than those observed for the other two registers. Finally, both Baisler (1950) and Rubin and Hirt (1960) have measured the area of the glottis for the loft register. These data shed at least some light on loft vibratory patterns as it is reported that for this register 1) there is a reduction in the glottal area during phonation, 2) the

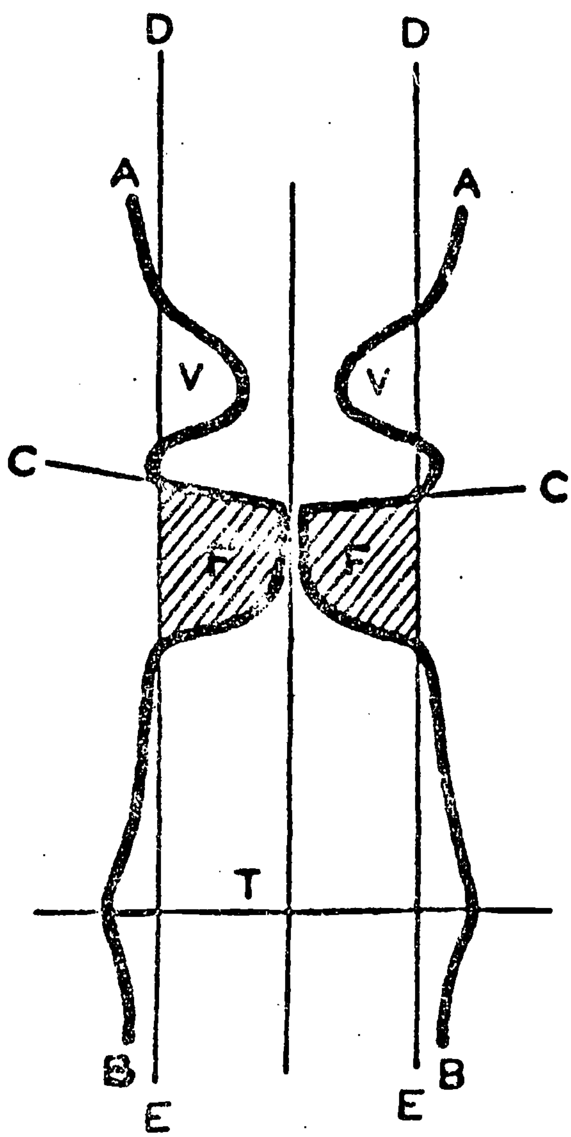


Figure 9. A tracing of a laminagram of the vocal folds showing the reference lines used to obtain area and thickness measurements. F identifies the vocal folds, V the ventricular folds and T the trachea; lines A-B define the mesial borders of the laryngeal tract, line C the superior surface of the vocal folds, and lines D-E constitute the standard reference lines (parallel to the mid line) established to close the area of the folds laterally (from Hollien, 1962).

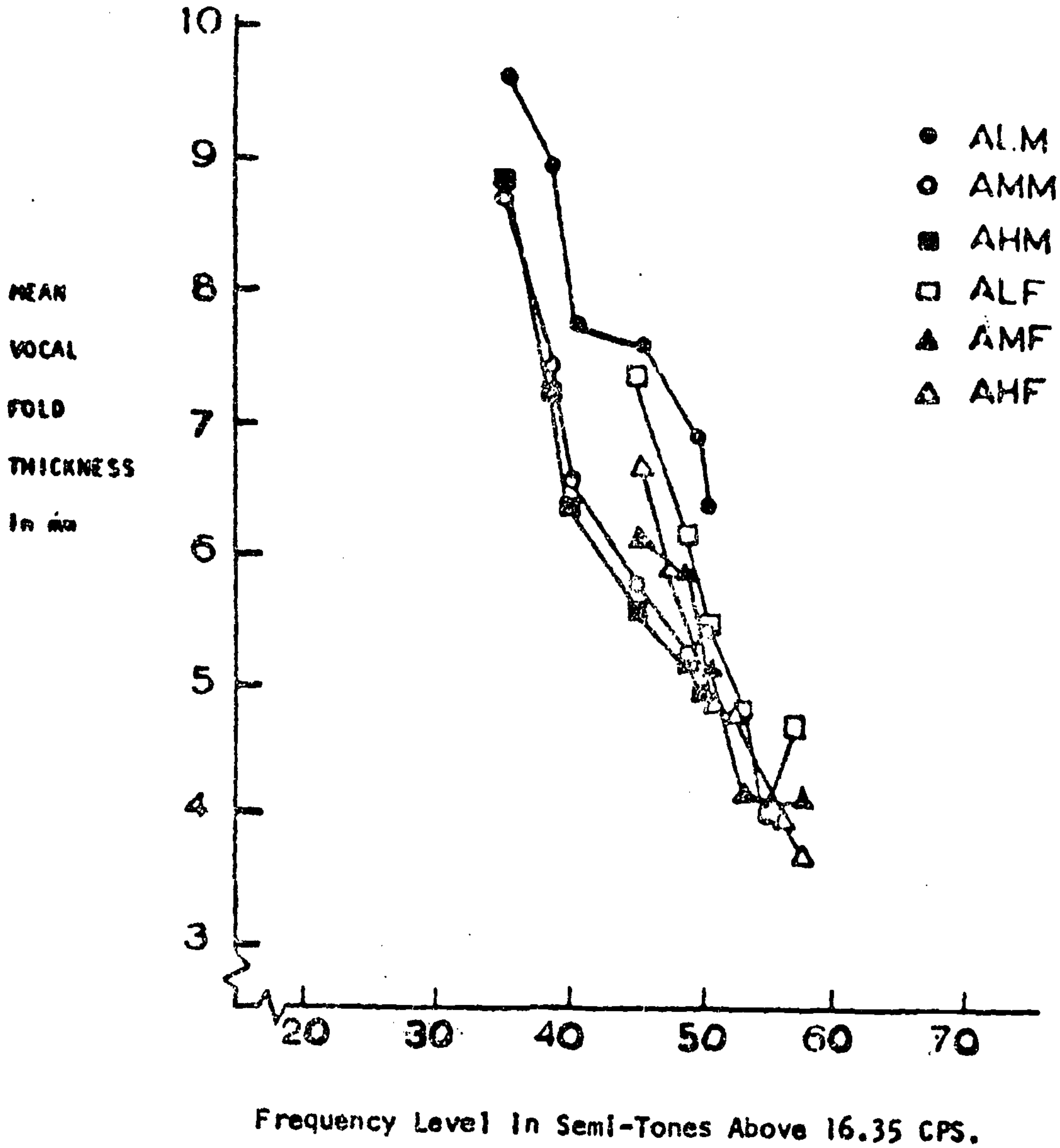

MEAN
VOCAL
FOLD
THICKNESS
In mm
10
9
8
7
6
5
4
3
20
30
40
50
60
70
ALM
AMM
AHM
ALF
AMF
AHF
Frequency Level In Semi-Tones Above 16.35 CPS.

Figure 10.

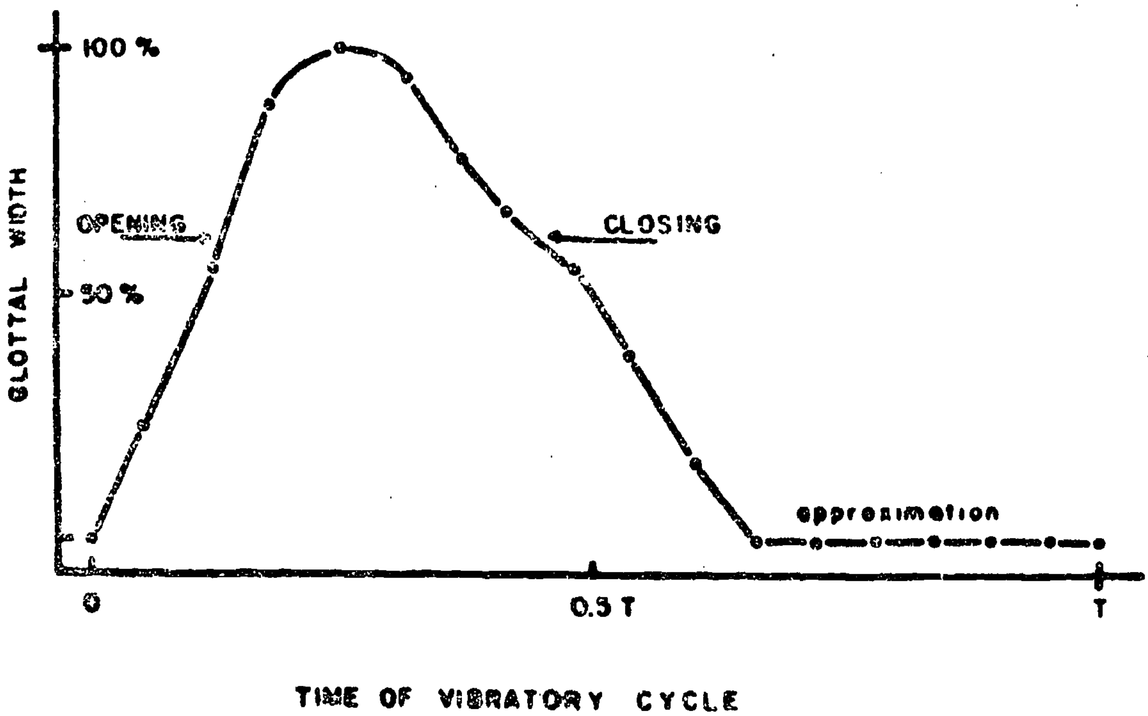


Figure 11. Graphic illustration of a single vibratory cycle. The vertical axis represents the lateral excursion of a vocal fold as a percentage of maximal opening; the horizontal axis, time. The rising section of the curve depicts the opening phase, the declining section the closing phase, and the horizontal section the period of approximation (from Timke, von Leden and Moore, 1958).

amplitude of vocal fold vibration is reduced and/or 3) the folds do not completely adduct during the closed phase. However, great subject variability may be observed among these factors when the loft register is produced.

In summary, it is obvious that the three registers show markedly different modes of operation with respect to vocal fold vibratory patterns. Most notable among these differences are 1) closed time: longest for pulse and shortest (if indeed it occurs at all) for loft and 2) length of open time within the duty cycle: extremely short for pulse and extremely long for loft. In any case, these differences may be seen contrasted in Table 4.

Aerodynamic Correlates of Registers

Of course, aerodynamic parameters are fundamental to phonation as without air flow there would be no voice. Moreover, there are a number of characteristics linked to aerodynamics that can be studied and related to voice registers. These include: subglottic pressure (via intra-esophageal balloon or intra-tracheal puncture), air flow, glottal resistance and voice intensity. Of these four, the first two provide the most complete sets of data with respect to differentiation among the vocal registers and will be reviewed below. Incidentally, the schematics that may be seen in Figure 12 are taken from Murry (1969); they illustrate a typical system whereby measures of subglottic pressure and air flow may be obtained simultaneously. Many such systems are currently available to the voice scientist who wishes to study the aerodynamic features of phonation.

Typical methodological approaches to the study of laryngeal air flow include various types of respirometers and pneumotachographs. By utilization of such procedures, a number of studies have been carried out investigating air flow/frequency relationships within the modal register. These studies reveal little, if any, relationship throughout the modal range (van den Berg, 1956; Kunze, 1962); nor does any such relationship appear to exist if only the lower part of this register is considered (Yanagihara and Koike, 1967; Rubin, LeCover and Vennard, 1967 and Perkins and Yanagihara, 1968). On the other hand, Issihiki (1964, 1965) and Yanagihara and Koike (1967) found a slight tendency for air flow to increase with increasing fundamental frequency for the upper portion of the modal register--however, this relationship was not confirmed by Perkins and Yanagihara (1968). Consequently, it must be stated that there appears to be very little, if any, relationship between air flow and f_o throughout the modal register. When comparing the pulse register with the modal register, McGlone (1967), Murry (1969) and McGlone and Shipp (1972) (see Table 5) found substantially lower overall magnitudes of air flow for pulse. Moreover, the data reported by these authors show no systematic relationship between air flow and frequency change within the pulse register. Finally, while there appears to be little difference in the level of air flow between the modal and loft registers (Kunze, (1962), there are differences of opinion concerning the relationship between air flow and f_o change within the loft register. That is, Kunze (1962) reports a slight tendency for air flow to decrease as fundamental frequency was increased in loft whereas van den Berg (1956) and Faaborg-Anderson, Yanagihara and von Leden (1967) report first a decrease, then something of an increase and, finally, McGlone (1970) reports an initial decrease in air flow as a function of increasing frequency followed by no change. In all these cases, however, the small number of subjects studied makes interpretation of the results difficult.

In summary, overall air flow is considerably lower for the pulse register than it is for the other two registers and it seems not to correlate with changes in f_o within any of the three registers--except possibly loft. A summary of these data may be seen in Table 6.

Table 5. Mean fundamental frequency, air flow and subglottal air pressure produced by seven subjects phonating in the pulse and modal registers (from McGlone and Shipp, 1972).

Condition	Pulse Register	Modal Register
Fundamental Frequency (Hz)		
Mean	31.6	99.1
Range	18.0-50.0	87-117
Air Flow (cc/sec)		
Mean	44.1	145.1
Range	14.5-100.0	66.3-275.0
Subglottic Pressure (cmH_2O)		
Mean	4.8	4.6
Range	2.1-7.0	1.0-7.0

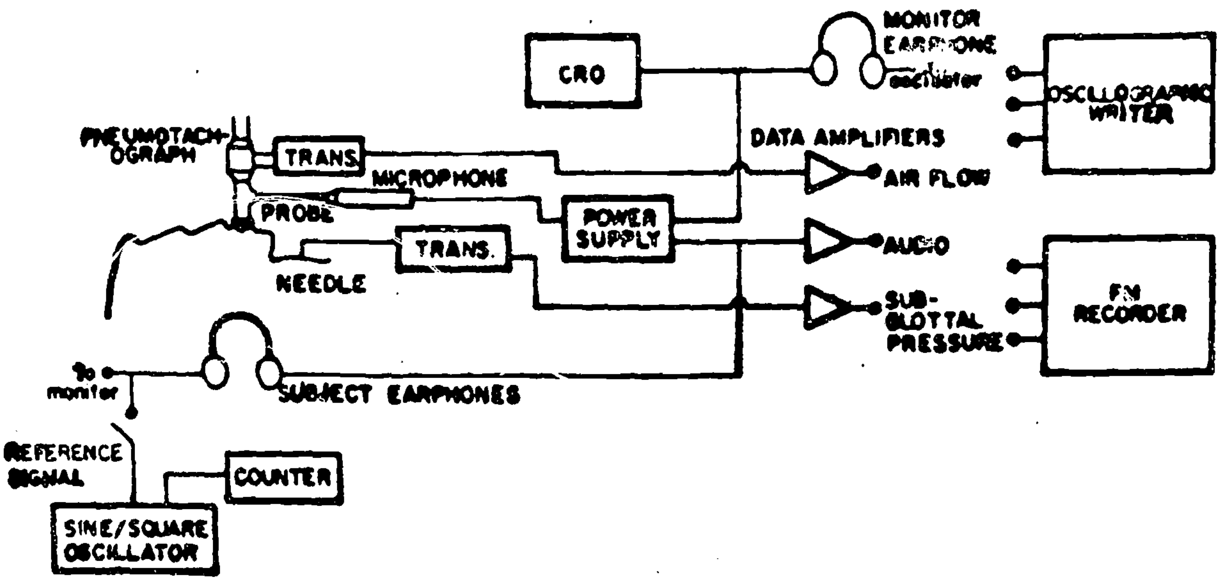


Figure 12. Block diagram of a system that can be utilized to obtain and record subjects' subglottic air pressure, air flow rate and acoustic output (from Murry, 1969).

Table 6. Summary table of some of the aerodynamic factors that would appear to differentiate among the pulse, modal and loft registers. These data are related primarily to frequency change as the relationship of these factors to vocal intensity and spectra are in many cases incomplete or not relevant.

Register	Air Flow	Subglottic Pressure
<u>Pulse</u>		
Level within register	Very low	Possibly highest
Variation within	Little or no change	No systematic variation
Relation to Modal	Much lower	Slightly higher
<u>Modal</u>		
Relation to Pulse	Much higher	Slightly lower
Level within register	Moderately high	High
Variation within	Some variations in upper part of register	Increases with increase in f_o
Relation to Loft	Same	Higher
<u>Loft</u>		
Relation to Modal	Same	Lower
Level within register	Moderately high	Lowest
Variation within	Probably decreases with increase in f_o	Possible slight increase with increase in f_o

Subglottic pressure (P_s), on the other hand, correlates with certain of the acoustic characteristics of voice[4]--as well as with registers. Data on pressure are usually obtained by means of an intra-esophageal balloon or an intra-tracheal needle or catheter coupled to some type of a manometer or pressure transducer--and, of course, to an output device (see again Figure 12). Since the data obtained from the intra-esophageal balloon appears to vary as a function of

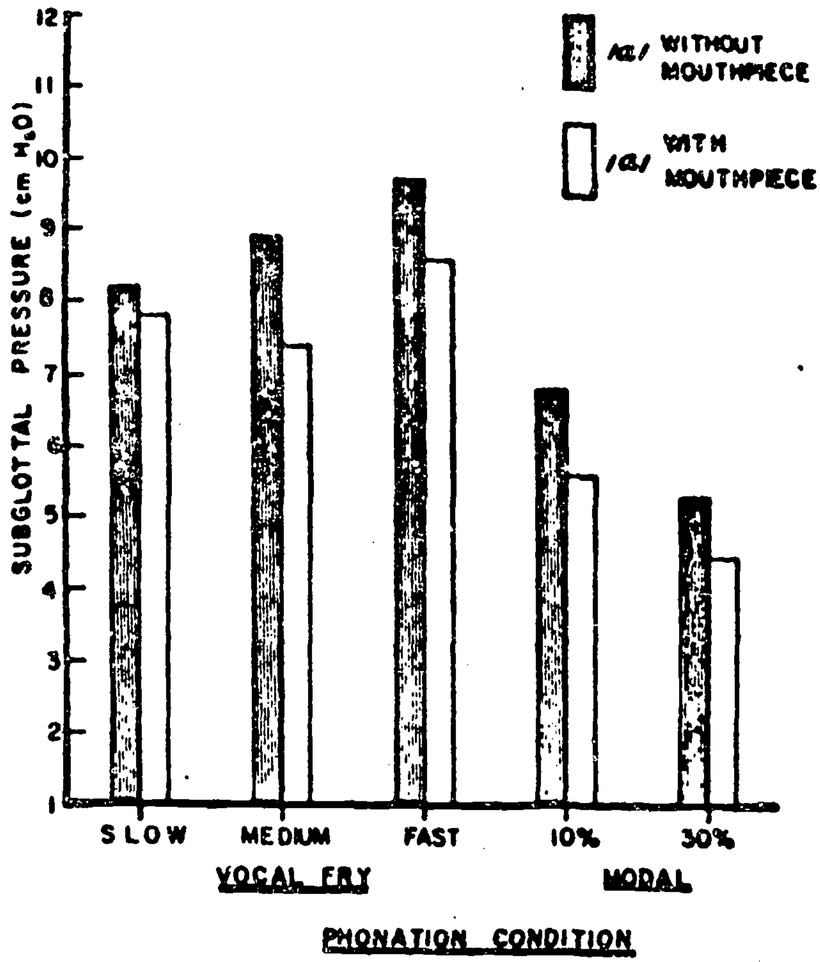


Figure 13. Mean subglottic air pressure (cm H_2) for phonation of the vowel /a/--with and without apparatus for measuring air flow--at two modal register and three pulse register phonatory conditions (from Murry, 1969).

lung volume, it can be argued that the intra-tracheal approach is the more valid of the two (Kunze, 1964). In any case, most data on subglottic pressure accompanying phonations produced in the modal register reveal that P_s increases as f_o is increased (van den Berg, 1956; Ladefoged, 1962 and Kunze, 1962). With respect to the pulse register, Hollien, et al (1966) predicted lower overall magnitudes of subglottic air pressure than for the other two registers. This prediction appears to be in error as Murry (1971) reports fairly large magnitudes--and larger than for modal in any case--of intra-tracheal air pressure associated with the pulse register and McGlone and Shipp (1972) found the overall pressure levels to be about the same for the modal and pulse registers (see again, Table 5). Finally, Kunze (1962) reported the subglottic pressures that accompany modal register phonation are greater than are the pressures associated with the loft register--even when the phonations in both of these registers were produced at the same fundamental frequency. In summary, overall subglottic pressure seem to be lowest for the loft register and higher for the other two registers--and possibly highest of all for pulse. A summary of these relationships may be seen in Table 6.

Discussion

From the above presentation, it should be possible to make some simplified summary statements concerning the three vocal registers postulated and relate them somehow (if even only speculatively) to theories of phonation. With regard to the first issue, the available evidence suggests not only that the three registers can be perceptually differentiated one from another but also that each can be said to reside in its own unique acoustical domain. Moreover, it can be argued that laryngeal function also is register dependent with respect to the mass and (at least by inference) stiffness of the vocal folds as well as to the measurable aerodynamic correlates of voice. Indeed, while any one factor or relationship may serve only to partially differentiate among the registers, the evidence taken as a whole is quite powerful.

It is not just the static differences between the registers that permits their identification; the patterns of change within registers also provide important information concerning register-linked differences in laryngeal operation. For the modal register, frequency change appears to be mediated by a combination of changes in the mass and stiffness of the vocal folds which, hence offer variable resistance to air flow. In the loft register, on the other hand, there appears to be no variation in mass (as estimated from measures of thickness and length) related to changes in f_o. It can be speculated, however, that the stiffness of the folds continues to be a factor here and stiffness coupled with aerodynamic factors could account for f_o variation in this register. Moreover, pulse register production appears to be most closely linked to the mass of the vocal folds. That is, the ventricular folds load the true folds in pulse and this loading may create a damping mechanism which can ultimately account for this unique type of phonation. Finally, aerodynamic factors clearly operate in the control of vocal intensity for all registers.

Further relationships can be noted among the statements in the above discussion and these relationships utilized to integrate vocal registers into phonatory theory. First, even though the aerodynamics of voice (especially the Bernoulli effect) are important to all phonation, they do not account for registers any more than they (alone) account for phonation in general. Physiologic factors are of substantial importance also. Inductively, such logic demands a myoelastic/aerodynamic theory of phonation. On the other hand, differences among the registers (remember registers are more powerfully linked to frequency than to intensity) permit such a theory to be differentially applied to these several modes of phonation. Hence, the reduced role aerodynamics play in the pulse register suggests that the myoelastic aspects of the basic theory are more dominant for this register. On the other hand, the physiological measurements that have been made while the loft register is being produced show little in the way of systematic patterns; hence, it can be speculated that the aerodynamic aspects of the general theory are more dominant for loft. For modal there appears to be no particular dominance. Accordingly, it is suggested that within the myoelastic/aerodynamic theory of phonation, the myoelastic aspects are more dominant for the pulse register, they are about equal for the modal register and the aerodynamic relationships best account for the loft register.

In conclusion, it should be noted that this paper had two basic purposes. The first was to establish a system of vocal registers--and to provide reasonable evidence for it--in order that practitioners of all types might have a rational model of this set of vocal operations in order to support their attempts to modify the human voice. The second purpose was to provide the community of voice scientists with an organized structure of voice registers--one which can be efficiently tested and modified. It is hoped that this effort contributed to these purposes.

Notes

1. It is my understanding that there are some differences of opinion among teachers of singing concerning whether the trained voice should exhibit one or more registers. In this regard, I agree with those individuals who maintain that, in most cases, the "premier" singer will exhibit only a single register when performing. However, it is quite possible that this elimination of noticeable register changes in the singing voice is the result of training and, physiologically, even singers retain their original set of registers.

2. It is conceded, however, that the comparisons between singers and nonsingers may not be wholly valid as I suspect the ranges produced by nonsingers were their physiological ranges while those produced by singers were their "singing" ranges.

3. Listeners were not even told that the heard stimuli were produced by human voices much less that they represented specific types of vocal production.

4. The relationship between subglottic pressure and vocal intensity, within a register, does not seem germane to this paper and will not be discussed here.

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