A Laryngographic Investigation of Phonation Type and Laryngeal Configurations*

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1.0 INTRODUCTION

Phonetic research into the instrumental characterization of phonation types (Fourcin and Abberton, 1971; Fourcin, 1974; Esling, 1976, 1977, 1978; Roach, 1977; Roach and Hardcastle, 1979) has indicated that the electrical impedance laryngograph provides a useful means of identifying and distinguishing contrasting phonation types. The form of the present investigation follows Esling (1977) in which phonation types are categorized auditorily according to the articulatory phonetic framework established by Laver (1968, 1975, 1976). This framework follows the tradition of the general phonetic theories described by Abercrombie (1967) and the systematic nomenclature for phonation types provided by Catford (1964). Several primary phonation types are analyzed and compared laryngographically to determine the characteristics of ther larynx waveforms. These comparisons suggest a set of relationships between laryngeal configuration and characteristics of the vocal fold vibratory cycle, expressed in terms of contrasting systems of stricture.

Phonation type has several phonetic functions. It may fluctuate rapidly in speech as a feature of segmental contrast, or vary over clausal-length utterances as a feature of voice dynamics denoting shifts in 'register'. More commonly, it constitutes the laryngeal component of voice quality — a speaker's or speakers' habitual,

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quasi-permanent vocal tract setting. It is the description of phonation type as a component of voice quality with which this research is most closely concerned, although the laryngographic characterization of phonation types is applicable to the description of phonatory mechanisms functioning in any linguistic context, whether a part of voice quality, voice dynamics or segmental phonology.

In order to re-examine and test the procedures, hypotheses and conclusions discussed specifically in Esling (1976, 1977), Roach (1977) and Roach and Hardcastle (1979), an analysis of a number of laryngographic waveforms of contrasting phonation types was undertaken. The procedural issues under consideration include (a) how to obtain a permanent, continuous record of the larynx waveform (Lx) in order to make measurements over relatively long stretches of speech and (b) how to measure the various aspects of the Lx waveform period in order to contrast waveforms from one phonation type to another. The hypotheses under examination are:

(1) that contrasting phonation types are distinguishable on the basis of Lx waveform shapes,

(2) that changes in Lx waveform shape are not the result of changes in pitch but the result of changes in phonatory mechanism associated with differing phonation type, and

(3) that characteristics of Lx waveform rise-time and fall-time (or of waveform rise-time and period-time) correspond to differences in mode of phonation.

2.0 PREVIOUS RESEARCH

A considerable amount of research using the electrical impedance laryngograph has been undertaken since its description by Fourcin and Abberton (1971) and Fourcin (1974). Applications have been found in the study of speech disorders (Fourcin and Abberton, 1976; Wechsler, 1976; Wirz and Anthony, 1979) and in the study of language varieties (Thelwall, 1975). A review of this research can be found in Esling (1978).

In Esling (1976, 1977), a number of correspondences are presented between auditorily identified differences in phonation type and quantitative differences in Lx waveform shape, frequency, amplitude, and the relative durations of the rise-time and fall-time of the Lx signal. This signal reflects the changing electrical impedance across the larynx during phonation, by means of a pair of electrodes placed on the throat on either side of the Adam's apple (Fourcin and Abberton, 1971; Fourcin 1974). The rising part of the signal corresponds approximately to the closing of the vocal folds, and the falling part of the signal to the opening of the vocal folds. These relationships between Lx waveform and phonation type are summarized in Esling (1978: 216-272, 311-323), where Lx characteristics are used to describe phonation types in a sociolinguistic survey of speech in an urban community.

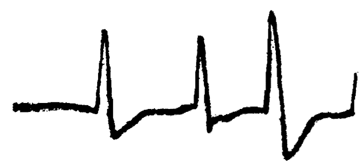
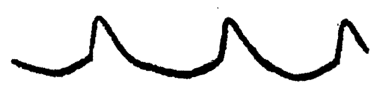
The phonation types under investigation include:

- MV modalvoice (neutral voice for the sensory modality of speech)
- WV whispery voice
- BV breathy voice
- HV harsh voice
- VV ventricular voice
- CV creaky voice
- F falsetto

In an early experiment, summarized in table 1, each distinct phonation type was repeated on the sustained vowel [i] while the Lx signal was photographed from the screen of an oscilloscope. The ratio of rise-time to fall-time was calculated by measuring the duration of the signal from the low point of the trace to the high point of the signal to give rise-time, and from the high point to the low point to give fall-time. This results in a relatively wide range of rise-time to fall-time (RT/FT) ratios, between approximately 3:10 for creaky voice at the one extreme, and 10:1 for breathy voice at the other. The Lx waveforms in question were very preliminary, exhibiting a sharp rise at the bottom of the curve instead of a flat base-line, due to the particular model of laryngograph used in this experiment. In table 1, approximately 40-50 msec. of each signal is represented, with frequency and RT/FT ratio listed for each example.

If we consider a frequency range for any one speaker, that range can be divided into four smaller ranges: low, low-mid, high-mid and high. The range of RT/FT ratios of the Lx signal can also

Table 1. Laryngographic waveforms - characteristic shapes for seven primary phonation types

RT/FT Ratio	Phonation type	Lx waveform
1.44	Modal voice 125 Hz.	
2.50	Whispery voice 100 Hz.	
9.66	Extremely whispery/ Breathy voice 85 Hz.	
0.61	Harsh voice 95 Hz.	
0.35	Ventricular voice 100 Hz.	
0.53	Creaky voice 60 Hz.	
2.00	Falsetto 305 Hz.	

40 msec.

be divided into four smaller ranges, in order to relate mode of phonation and frequency. For example, creaky voice and ventricular voice were found to have relatively low RT/FT ratios, while whispery voice and breathy voice demonstrated progressively higher RT/FT ratios. These relationships are illustrated in table 2(a), where the seven key or primary phonation types from table 1 are arranged according to increasing frequency, from top to bottom, and increasing RT/FT ratio from left to right. The top letter in each box refers to the shape of the peak of the Lx signal, and the middle letter refers to the shape of the base of Lx: 'p' for peaked, 'dp' for double-peaked, 'r' for rounded and 'f' for flat. The bottom letter in each box refers to the amplitude of the Lx signal: 'L' for low, 'N' for normal. Thus, creaky voice and ventricular voice have similar RT/FT ratios, but usually differ in frequency and the shape of the peak of Lx. Harsh voice has a higher RT/FT ratio than creaky or ventricular voice; the parameter which also distinguishes modal voice from whispery voice. Falsetto, besides its higher frequency, is lower in amplitude. Breathy voice, while in the same frequency range as ventricular and harsh voice, has the highest RT/FT ratio. Table 2(b) illustrates these relationships graphically, showing frequency and RT/FT ranges as target areas.

To summarize briefly:

(1) a relatively short permanent record of electrical impedance across the larynx was obtained by photographing the larynx waveform (Lx) from an oscilloscope screen;

(2) Lx periods were measured between the highest point and the lowest point of the signal to obtain rise-time (RT) and fall-time (FT) and a ratio of RT/FT;

(3) contrasting phonation types were differentiated according to characteristic Lx waveform shapes;

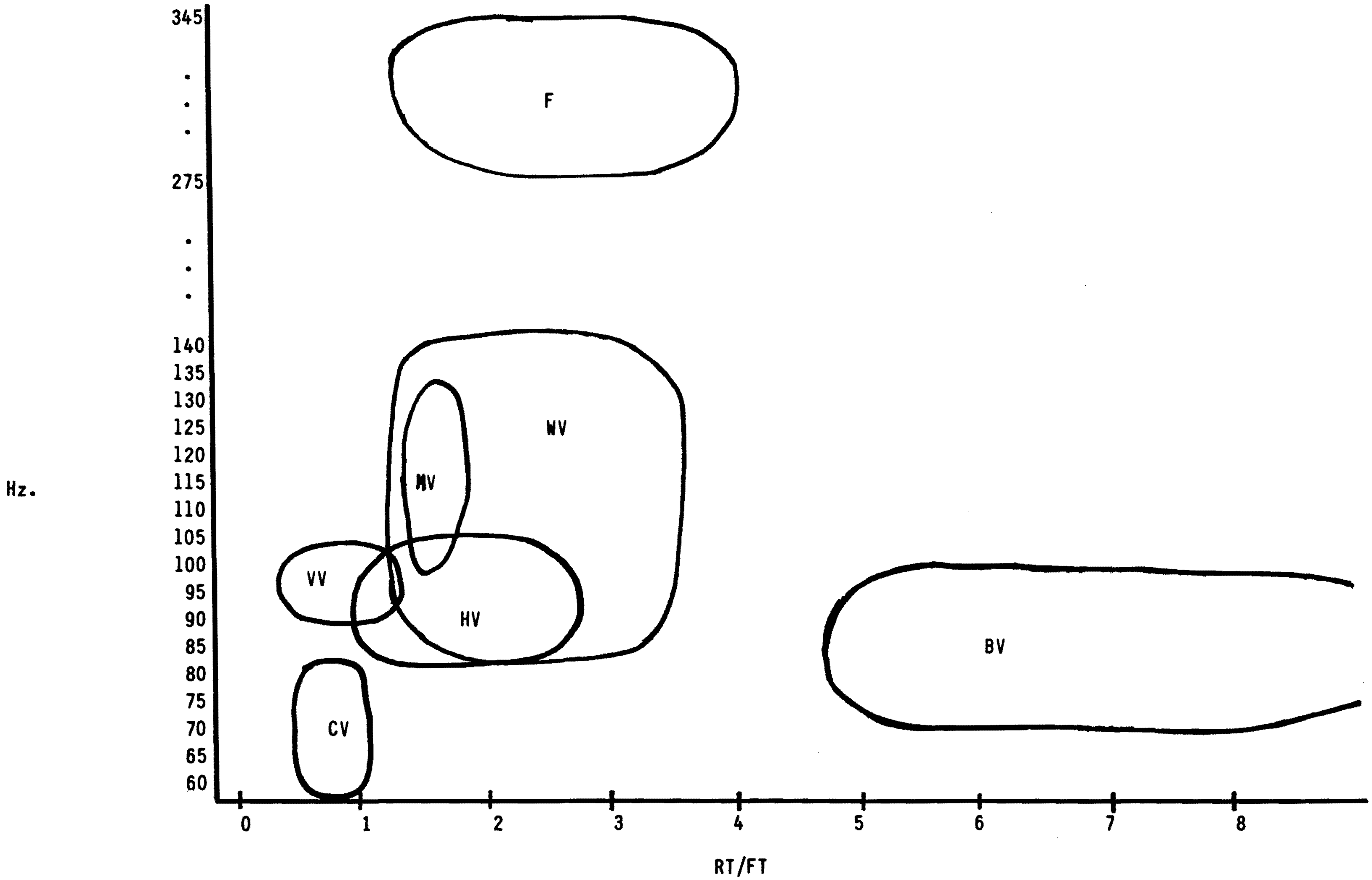
(4) contrasting phonation types were observed to correspond to differences in frequency as well as to other characteristics of Lx, but frequency was not controlled or examined separately;

(5) RT/FT was found to distinguish some phonation types within the same frequency range, but was not independent of frequency in all cases.

frequency range \ RT/FT ratio range	1 low	2 low-mid	3 high-mid	4 high
4 high			Falsetto p or r p L	
3 high-mid		Modal voice p p N	Whispery voice p p N	
2 low-mid	Ventricular voice dp p or r L	Harsh voice dp r or f N		Breathy voice p p and f N
1 low	Creaky voice p r L			

RT/FT ratio range

Table 2(a). Lx characteristics of seven phonation types



<u>Table 2(b)</u>. Frequency and RT/FT ratio ranges for seven phonation types

3.0 PROCEDURE

In the present paper, a different technique of recording and measuring the Lx waveform from that described above is reported and evaluated. In this technique, samples of phonation are recorded on an FM data recorder and replayed at slow speed into an oscillograph running at a high paper speed, providing a permanent record of the Lx signal for longer samples of speech than in the earlier experiment. This resembles the technique employed by Roach (1977:51), although the ratios used here to characterize Lx waveforms are obtained by a slightly different method of measuring the periods of Lx.

In the first of two experiments, the subject (JE) produced each of the primary phonation types listed above on the steady-state vowel [a], not controlling specifically for pitch. In the second experiment, each phonation type was produced at four different pitch levels of roughly equal intervals, using the word 'bead' [bi:d]. The output of an electrical impedance laryngograph was recorded at 15 i.p.s. on an FM data recorder and then replayed at one-eighth of that speed into a Mingograf oscillograph running at a paper speed of 1000 mm./sec. The speech signal was recorded for subsequent evaluation of the accuracy and consistency of the subject's performance.

The procedure for measuring the Lx waveform differs from the procedure described above in three respects. First, instead of taking the lowest point of the signal as the base-line, the base-line is drawn to transect the point in each period (A, A_1, ...) at which the rapid rise begins, as shown in figure 1.

The base-line is drawn through point A for two reasons: to compensate for the effects of phase distortion, and because point A represents a reliable indication of the beginning of vocal fold closure. It is possible that the slightly rising slope of the base of the Lx signal may reflect a change in capacitance which is not the direct result of a change in impedance due to vocal fold adduction. The exaggerated slope of this part of the signal in the waveforms in table 1 is the result of a phase distortion introduced in the laryngograph itself as an anticipatory procedure to converting Lx to Fx, which is the running display of fundamental frequency (Fourcin, personal communication). This phase distortion may not necessarily invalidate comparisons between waveforms, as in table 1, if the distortion is uniformly present in all of them. However, excluding

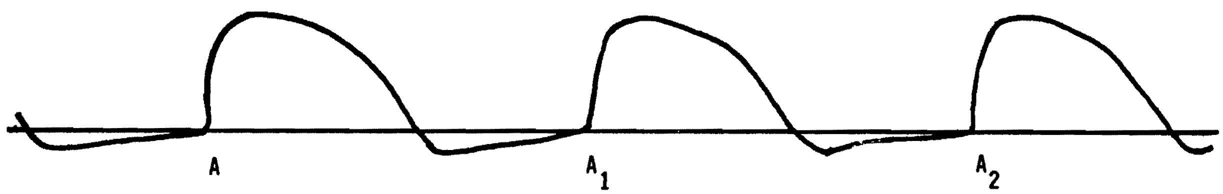


Figure 1. Lx waveform - Base-line

Phonation type	RT/FT	Frequency (Hz.)
Creaky voice (CV)	0.11	75
Modal voice (MV)	0.16	120
Ventricular voice (VV)	0.19	110
Harsh voice (HV)	0.24	100
Whispery voice (WV)	0.4	120
Breathy voice (BV)	0.47	150
Falsetto (F)	0.6	375

Table 3(a). RT/FT for short samples of 7 phonation types it from our calculations may give a truer comparison of rise-time to fall-time (RT/FT) than before.

Furthermore, point A is more reliable because it signals the start of closure.

> Lx provides information about the nature of the closed phase of the vocal fold vibratory cycle. Lx is positive going for increasing closure and its positive peak corresponds to maximum vocal fold contact: *the leading edge of the waveform provides a precise indication of the beginning of the closure phase.* The Lx waveform gives no explicit information about glottal aperture size, however, and it is for this reason that the apparatus has been called a laryngograph rather than a glottograph (Fourcin and Abberton, 1976: 116, my italics).

Taking this point as the start of each cycle, therefore, gives a more reliable measure of the duration of 'closing', taken as roughly equivalent to rise-time (RT), and 'opening', taken as roughly equivalent to fall-time (FT).

The second difference in procedure is that only 80% of the signal is measured. In this procedure, measurements are made from 10% of total amplitude above the base-line, to 10% below the peak of the signal. This accounts for any slight build-up of capacitance or attenuation of the signal not related to the phenomenon being measured.

The third procedural difference in these experiments is that the length of time over which Lx is analyzed is longer than the samples measured in Esling (1977). Here, a minimum of 1250 msec. of Lx waveform traces for each phonation type are included in each calculation, instead of the 40 or 50 msec. obtained previously by photographing the Lx waveform trace. The RT and FT of every third period was measured, and a mean was calculated for each run of each phonation type.

4.0 RT/FT AND PHONATION TYPE

In the first revised experiment, the seven contrasting phonation types differed both in frequency and in RT/FT ratios. Their

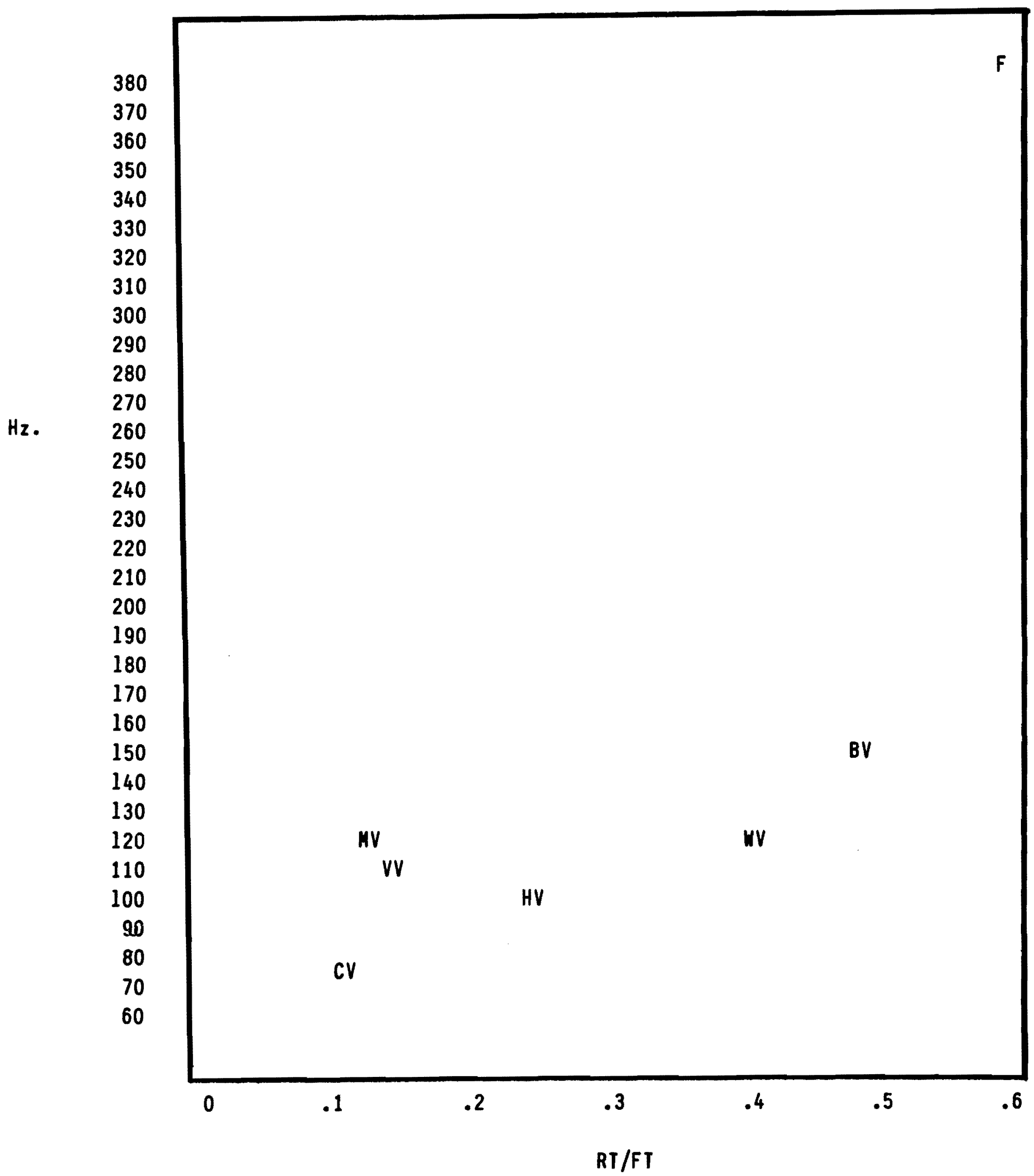


Table 3(b). RT/FT for short samples of 7 phonation types distribution is listed in table 3(a), in order of increasing RT/FT ratio. This information is displayed graphically in table 3(b) to illustrate the relationship between RT/FT and frequency.

The data in table 3 differ in some respects from the data obtained in earlier experiments displayed in table 2, both methodologically and in results. The single tokens in table 3 represent measurements of Lx of up to 0.5 sec. of consecutive waveform periods for each phonation type, whereas the data in table 2 represent several tokens of 40-50 msec. for each phonation type. The figures in table 3 are based on measurements of 80% of total amplitude of the Lx signal, with a corrected base-line, while measurements in table 2 represent RT and FT between the minima and maxima of the Lx signal. For this reason, ratios in the earlier set of data are higher values, often greater than 1, than the ratios in the revised experiments. RT/FT ratios in table 3 are values between 0 and 1, which reflect more accurately the generally accepted model of vocal fold vibration where RT, the closing phase, is always faster than FT, the opening phase of the cycle. Thus, creaky voice, which involves the most antero-posterior laryngeal stricture, has an abrupt closing phase and RT, but a slow opening phase and FT. Ventricular voice, which involves the most transverse laryngeal stricture, also has rapid RT and slow FT. On the other hand, whispery voice and breathy voice, which involve progressively smaller degrees of laryngeal stricture, exhibit progressively slower RT, relative to FT. Reduced transverse stricture, and consequent increased glottal openness during this type of phonation, might explain the long, low rise of the Lx signal for breathy voice as shown in table 1, although the relatively long closing phase (and high RT/FT ratio) *after* base-line correction is the salient feature of whispery voice and breathy voice as shown in table 3.

There are two questions to consider in the light of these results. The first is whether RT/FT is independent of frequency. The results in table 2(b) suggest that RT/FT and frequency are independent, with five of the seven phonation types occurring within the same frequency range, 80 to 120 Hz., while exhibiting a somewhat linear relationship, except perhaps for MV, VV, HV, and WV, which are discriminated by RT/FT within the same frequency range of 100 to 120 Hz. In order to investigate this relationship more closely, it was necessary to conduct a second experiment, described below.

Hz.	CV	MV	VV	HV	WV	BV	F
515							0.81
435							1.01*
410							0.55
390							0.7
.							
.							
.							
		0.36					
220				0.51*			
					0.44		
210							
200							
190		0.45					
180						0.56	
	0.31**						
170			0.35				
160						0.37	
					0.47		
150				0.28			
		0.35					
140							
130			0.21		0.52	0.41	
	0.18						
120				0.25			
		0.39					
110			1.1*				
	0.17						
100					0.44		
90				0.6*		0.58	
80							
70	0.17		0.29				

CV MV VV HV WV BV F

Phonation types

Table 4. RT/FT ratios at 4 frequencies for each phonation type

The second question to consider is whether another technique of measuring the Lx signal would produce similar results. Roach's (1977:54) calculation of rise-time over period-time (base-to-peak over time, BT/T) differs from the calculation of RT/FT used here, but results in low ratios for *creaky voice* and *tense voice* (around 0.3) with progressively higher ratios for *creak*, *normal voice*, *lax voice*, *murmur*, and *breathy voice* (approaching 0.7). If we suppose that tense voice corresponds auditorily to harsh voice or ventricular voice, and that lax voice is similar to whispery voice or breathy voice, then the distribution of RT/FT in tables 2 and 3 confirms Roach's findings for the measure BP/T. This supports the conclusion that RT, representing closing of the vocal folds, becomes slower as phonation becomes more whispery or breathy, and less creaky or harsh.

5.0 RT/FT AND FREQUENCY

In the second experiment, the subject produced the same primary phonation types as before, but this time controlling for frequency by rendering each type four times, increasing pitch each time. Lx was recorded on the FM data recorder and replayed as before into the oscillograph. At least ¼ sec. of each token was measured from the paper trace to obtain RT/FT.

Table 4 lists the RT/FT ratios for each of the four tokens of each phonation type, in the same order as in table 3, with frequency increasing from bottom to top. If RT/FT increased as frequency increased, we would expect to see an increase in the value of RT/FT for each phonation type as pitch increases. This, however, is not the case. For this relatively small sample of 28 tokens, there does not appear to be any tendency for RT/FT to increase as frequency increases. For creaky voice, for example, the first three tokens are practically the same over a range of 55 Hz. The fourth token at 175 Hz.** was evaluated auditorily from the tape-recording as diplophonic, a combination of two competing regular vibratory patterns resulting in a secondary peak in the waveform. Auditorily, this token was described as harsh creaky voice, a combination of creaky voice and harshness. Laryngographically, this token has a higher RT/FT ratio as well as the double-peak associated above with harsh voice and ventricular voice. This type of waveform has been observed before for creaky voice (Fourcin, personal communication) and I suspect that the explanation is that the phonation type being observed was in fact a slightly harsh variety of creaky voice.

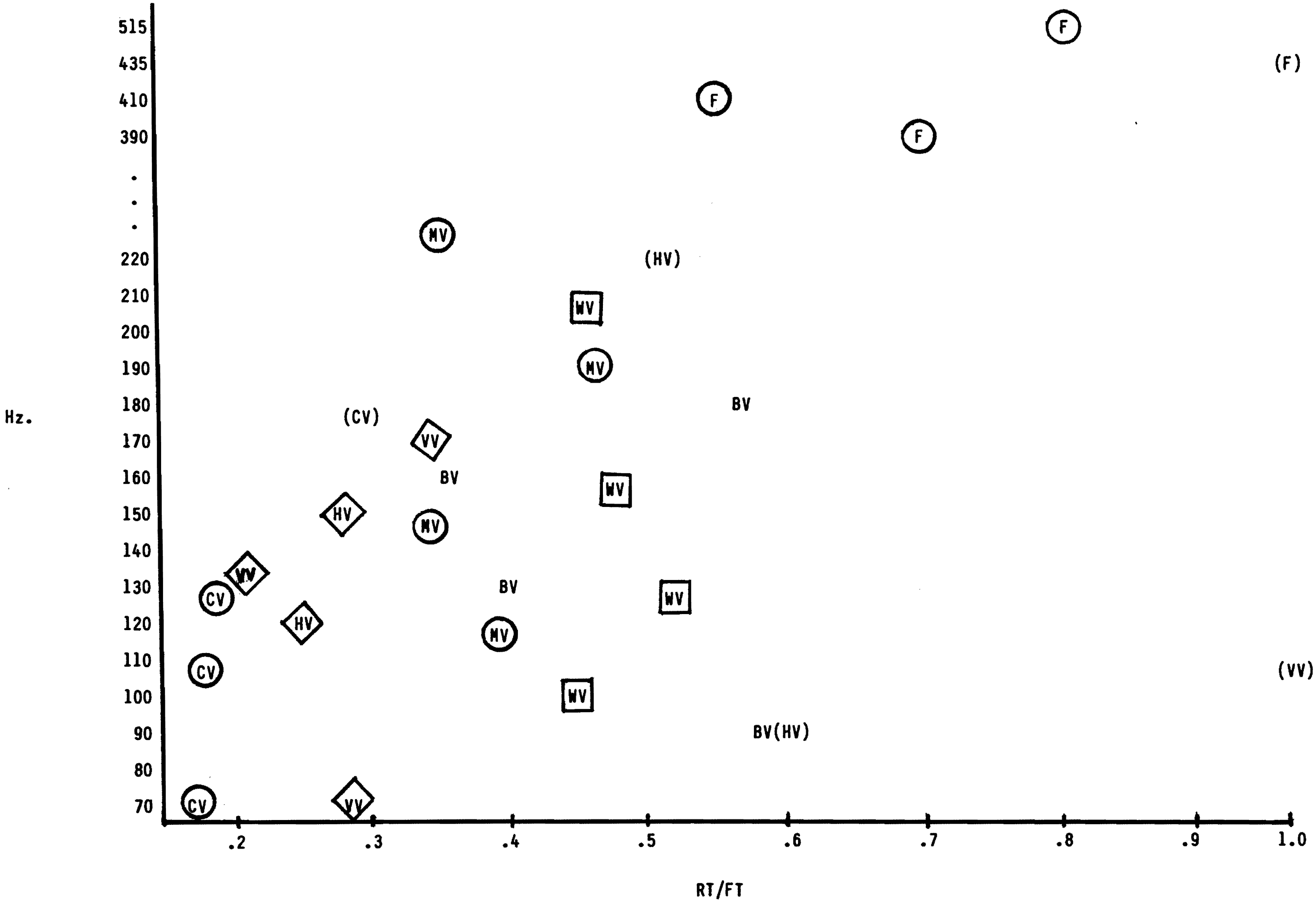


Table 5. RT/FT by frequency for 7 primary phonation types

The phase duration relationships for modal voice are also relatively constant over a 110 Hz. range. The single exceptional token of ventricular voice* exhibited a secondary peak *before* the principal peak of the waveform, which is not inconsistent with the shape expected for this signal but yields an inordinately long RT. The RT/FT ratios for harsh voice are almost the same as for ventricular voice, and the two exceptionally high values* also exhibit secondary peaks before the principal peak of the waveform. In any case, this phenomenon is clearly not due to frequency, because it occurred at both extremes of the frequency range for this phonation type. Whispery voice has consistent phase duration ratios over a 105 Hz. range. While breathy voice is less consistent, the RT/FT ratio at the bottom of the frequency range is practically the same as the ratio 90 Hz. higher. Falsetto, varying in frequency over 125 Hz., has a high RT/FT ratio at both ends of the frequency range; the exceptional token* having the pre-peak and exhibiting the auditory harshness characteristic of the abnormally high tokens of harsh voice and ventricular voice.

The consistency of RT/FT values up and down the vertical axis of table 4 presents a strong argument, therefore, that increasing frequency of vibration does not necessarily entail higher RT/FT ratios, that is, that the closing phase of the vibratory cycle does not necessarily become relatively longer. These results support hypothesis 1, that contrasting phonation types are distinguishable on the basis of laryngographic waveform shape, and support hypothesis 2, that changes in Lx waveform shape are not the result of changes in pitch.

6.0 RT/FT AND MODE OF PHONATION

Table 5 shows the distribution of phonation types in the second experiment, with frequency increasing vertically, and RT/FT increasing from left to right. The RT/FT values are those presented in table 4, with each token of each phonation type represented by an abbreviation, with exceptional values in parentheses. As in table 4, it is evident that tokens of the same phonation type fall within the same general range of RT/FT ratios, whether low-pitched or high-pitched. CV, MV, and F are circled for easy reference. VV and HV are enclosed in diagonals, and WV is boxed in. Creaky voice has a consistently low ratio up and down the frequency scale, 0.17 or 0.18, except for the single token of harsh creaky voice. Ventricular voice and harsh voice have slightly higher ratios, 0.2 to 0.35, with three exceptions, distinguishable by their double-peaked waveform shape. Modal voice shows ratios between 0.35 and 0.45, overlapping somewhat with lower ratios of breathy voice or whispery voice. RT/FT ratios for breathy voice are split between near 0.4 and near 0.6, although results from earlier experiments, shown in table 2, suggest that the correct RT/FT relationship for this 'most open' type of phonation is the higher value, with a longer RT. Ratios for whispery voice are concentrated between 0.44 and 0.52, with little variation for frequency, and a fairly distinct target area especially at lower frequencies. Below 100 Hz., there is a clear distinction in RT/FT ratio between creaky voice, below 0.2; ventricular voice, near 0.3; whispery voice, near 0.45; and breathy voice, near 0.6. In the frequency range 115-130 Hz., near normal pitch for the subject in this case, creaky voice remains below 0.2; ventricular voice and harsh voice are both in the range between 0.2 and 0.3; modal voice is close to 0.4, as is breathy voice for this particular token; and whispery voice is near 0.5, higher than breathy voice at this frequency. Falsetto, always higher in frequency, ranges from near 0.6 to 0.8, higher than the RT/FT ratios of the other six primary phonation types.

7.0 CONCLUSIONS

Two separate systems of increasing laryngeal stricture are proposed to account for these results:

(A) a continuum of antero-posterior stricture for changing pitch, and

(B) a continuum of transverse stricture for glottal openness.

(A)	(B)
1. falsetto	1. breathy voice
	2. whispery voice
2. modal voice	3. modal voice
	4. harsh voice
3. creaky voice	5. ventricular voice

Because the laryngograph measures impedance and not glottal opening, these hierarchies describe laryngeal stricture or posture, not glottal aperture. Glottal aperture size, except as an effect of the laryngeal configuration in question, is not considered here.

The physiological basis for the laryngeal postures that characterize these phonation types is discussed in a fibre-optic study by Esling (1978:272-305).

Although RT/FT and frequency were shown not to be directly related for some phonation types, creaky voice, modal voice, and falsetto exhibit a linear relationship between RT/FT and frequency in a manner consistent with increasing antero-posterior stretching of the vocal folds for increasing pitch. Creaky voice is always lower in RT/FT ratio than any other phonation type, which suggests that fast RT, or rapid closing and slow opening of the vocal folds is associated with the antero-posterior shortening and slack vocal folds of creaky voice. Modal voice continues up the frequency scale where creaky voice stops, and the RT/FT ratio doubles, to about 1:3 or 1:2. Falsetto, high frequency, is highest in RT/FT, approaching a 1:1 ratio. The antero-posterior stretching and lengthening of the glottis for falsetto is assumed here to entail slow RT, or slower closing of the vocal folds, relative to FT. The thin, stretched vocal folds of falsetto open and shut in almost equal phases, where closing is only slightly faster than opening. Thus, in continuum A there is a relationship between frequency and RT/FT which conforms to a theory of three principal vocal 'registers' (Hollien, 1972) or phonation types. Table 6 shows the target areas in this linear relationship.

The second continuum of laryngeal stricture which accounts for the data reported here begins with breathy voice, with the least transverse laryngeal stricture, presumably equivalent to low medial compression, and consequently greatest glottal openness of vocal fold vibration. RT/FT ratios for breathy voice are nearly as high as for falsetto, while frequency is of course much lower, suggesting that frequency is not responsible for slow RT in this continuum. Instead, it may be that the antero-posterior length of the vocal folds during breathy voice is similar to their length for falsetto, keeping closing relatively slow (see Esling, 1978:286). For creaky voice, on the other hand, the antero-posterior bunching of the vocal folds may induce the rapid snapping shut indicated by the fast RT. This conforms with Catford's description of breathy voice where the vocal folds 'flap in the breeze' (1964:32), and with Roach's finding of a high BP/T ratio for breathy voice (1977:51-52). Whispery voice, the next step on the continuum, involves more stricture and slightly faster RT or closing. Modal (neutral) voice is in the middle of both continua, with the same ratio (0.4) found by Roach (1977:54)and Roach and Hardcastle (1979:207). If Roach's

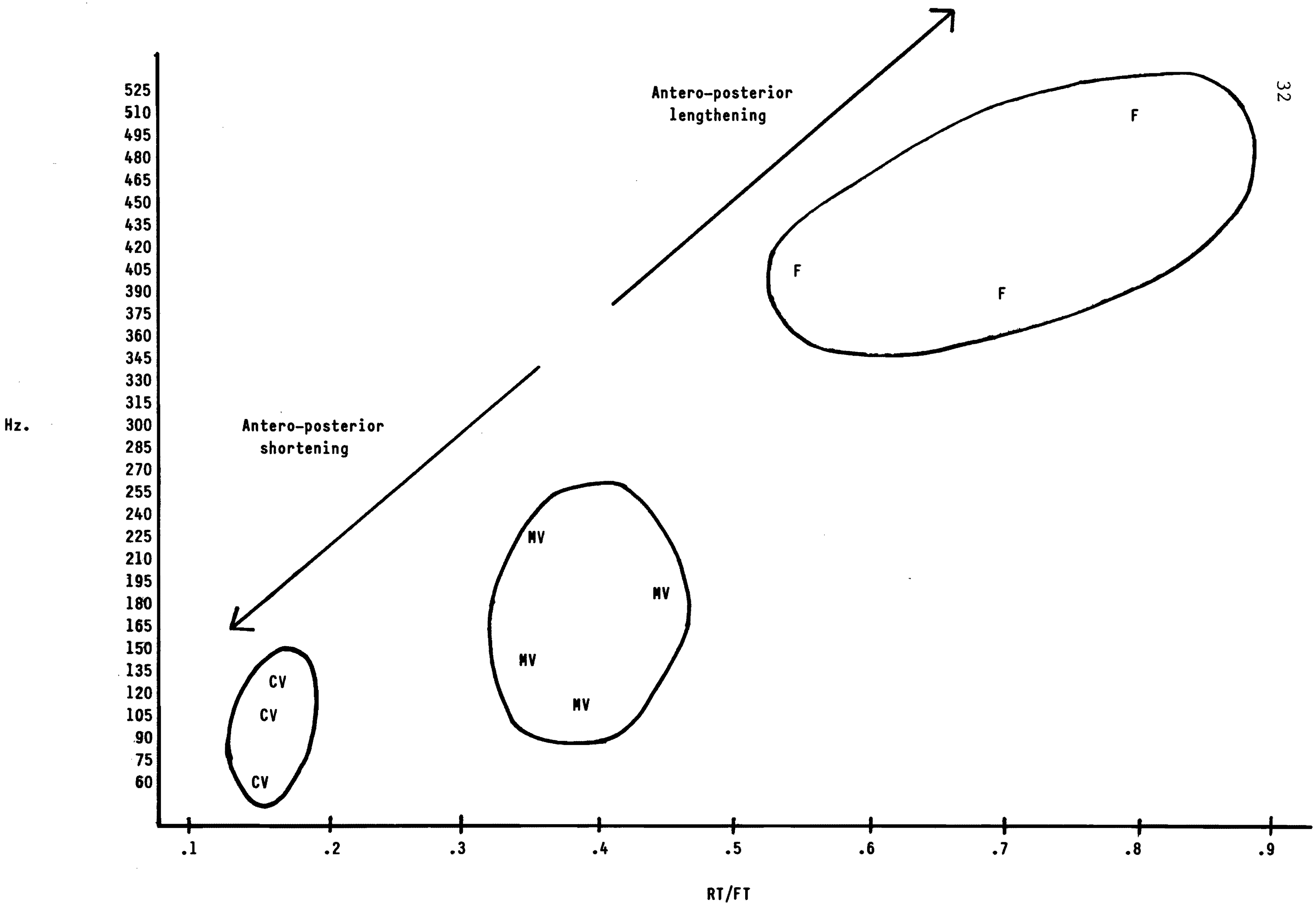


Table 6. Continuum A - Falsetto, Modal voice, Creaky voice

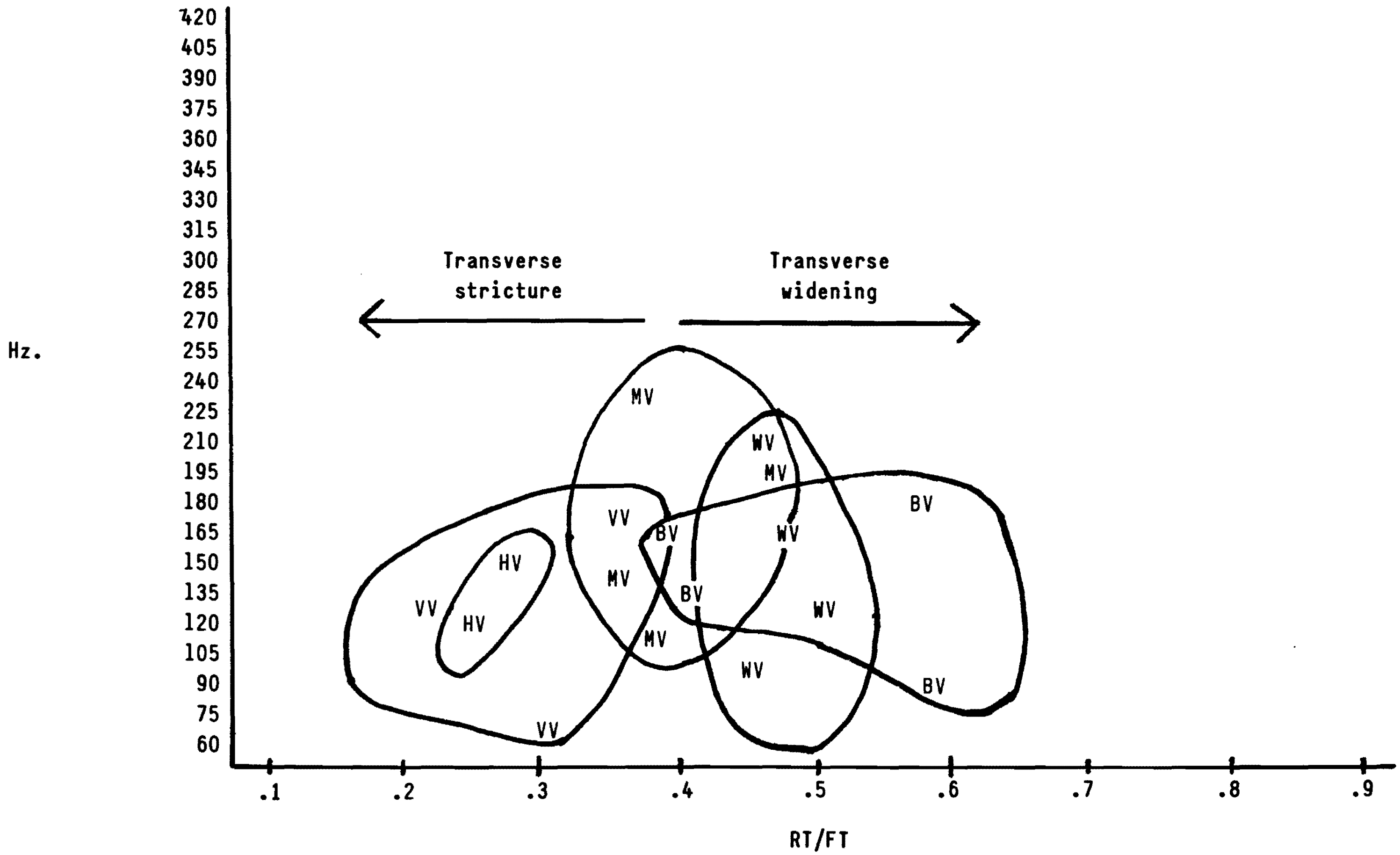


Table 7. Continuum B - Breathy voice, Whispery voice, Modal voice, Harsh voice, Ventricular voice

performance of breathy voice, murmur, lax voice, and normal voice reflect similar degrees of progressive laryngeal stricture to breathy voice, whispery voice, and modal voice as performed in this study, then these results corroborate Roach's findings.

Greater transverse laryngeal stricture along continuum B for harsh voice and ventricular voice tends to reduce RT almost to the speed of RT for creaky voice. This might be explained by the increased tension introduced over the glottis by the transverse stricture introduced in these phonation types, as described by Esling (1978:293-294). The direction of strictures is different from that which produces creaky voice, but the effect on vocal fold vibration seems to be similar, although never as profound as in the case of creaky voice. We are led to suspect similar muscular participation, such as the contraction of the vocalis, for both phonation types. Table 7 shows the horizontal, non-linear relationship of RT/FT ratios along the continuum of transverse narrowing and widening.

Despite the similarity of RT/FT ratios at the lower (most constricted) end of each continuum, the stricture appears to be of two different sorts, the product of different laryngeal configurations. Furthermore, creaky voice maintains consistently lower RT/FT values than harsh voice or ventricular voice, tending to confirm Roach's original hypothesis and hypothesis 3 of this study, that characteristics of Lx waveform rise-time and fall-time correspond to differences in mode of phonation, and that such a measure as RT/FT is useful in discriminating among phonation types produced with greater degrees of laryngeal stricture. The two configurational continua proposed here account for the data obtained using electrical impedance measurements, and demonstrate the usefulness of combining information on laryngeal structure with laryngographic information.

Equipment:

Electrical Impedance Laryngograph (University College, London)
T3000 Thermionic 4-channel FM tape-recorder
Siemens-Elema Mingograf 803
Oscilloscope

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