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Can phonation types be reliably measured from sound spectra? Some data from Wa and Burmese.

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1. Studying phonation[1] type

Catford (1977:93) defines phonation as "any laryngeal activity of speech that has neither initiatory nor articulatory function," thus including, for example, the laryngeal activity which provides the voicing of vowel sounds, but excluding the articulation of glottal stops or the initiation of a glottalic airstream for ejective plosives. *Voiceless* and *whisper* are also considered to be types of phonation in this analysis. The system allows for a total of twelve types altogether.

This paper is concerned only with those types of phonation defined by Catford (1977: 106) which involve vibration of the vocal folds[2], or, in terms of a source-filter model of speech acoustics, the modification of the glottal source underlying voiced speech. Table 1 outlines the possibilities.

Table 1: Catford's assessment of (non-ventricular) phonation types involving vibration of the vocal folds (adapted from Catford 1977).

type of stricture	location of vocal fold vibration	
	full glottal	*anterior*
free vibration	(modal) voice	tense / sharp voice
low frequency taps	creak	tense creak
wide open + vibrating	breathy voice	-
narrowed + vibrating	whispery voice ('murmur')	tense whispery voice

'Full glottal' vibration entails vibration of the entire length of the vocal folds; 'anterior' vibration indicates that only the part of the vocal folds between the thyroid cartilage and the arytenoid cartilages is vibrating.

More complex analyses of the phonatory capabilities of the larynx do exist (Laver 1980; Sprigg 1978). However, for linguistic phonetic purposes, and for adequate phonological analysis of most languages which make phonological use of phonation type, it is usually necessary to define only three phonation types: modal, creaky and breathy (Ladefoged 1988; Theraphan 1988).

For every instance of phonation in speech, it is possible to describe that phonation in great detail, although in many cases this may be irrelevant in a phonological analysis. Phonation type has tended not to be subjected to the same experimental scrutiny as, for example, pitch or vowel quality for perhaps two reasons. Firstly, relatively few languages use phonation type as the basis of a phonological contrast, so it might in many instances be considered a fringe concern when describing the phonetics of a language. Secondly, the articulatory source of phonation type is the larynx, a speech organ well known for its inaccessibility. Consequently, direct measurement of the larynx is problematic. For linguistic purposes, therefore, phonation type can usually only be measured indirectly. The laryngograph and the pneumotachograph are two instruments which are non-invasive and so suitable for non-clinical linguistic study of laryngeal activity in speech.

However, if, as is often the case, only acoustic data are available, it is important to explore the contribution phonation type makes to the acoustic speech output in order to find out how much that output can tell us about phonation type. Acoustic models of speech production tell us that the speech pressure wave during phonation consists of a glottal source which is modified and shaped by the resonant characteristics of the vocal tract. The study of phonation type is confined primarily to the domain of the glottal source before supralaryngeal modification comes into play, though naturally since the larynx and the vocal tract are connected physiologically, they are not entirely independent of one another. In attempting to decipher information about from phonation type from acoustic data, we are faced with the problem of how to strip away the effects of the supralaryngeal modification to reveal the characteristics of the glottal source underneath. The technique commonly used for reversing the filtering effect of the supralaryngeal vocal tract is inverse filtering, and is not investigated in this paper.

Experimental investigation of phonation type can therefore be approached in two ways, both of which involve a degree of compromise. We can attempt to intercept the speech production process at the larynx to extract information about the glottal source independent of any subsequent shaping by the vocal tract, using techniques such as photoelectric glottography or laryngography (electroglottography). The information obtained using either of these techniques must then be interpreted by relating the data recorded by the instrument to the actual phonatory activity within the larynx. Information thus obtained can only be as reliable as the method used to extract it from the glottal source and the reliability of the method used to interpret the data.

The alternative strategy, in the absence of any but unaltered (ie unfiltered) acoustic data, is to infer information about the glottal source by recording the final speech output outside the mouth and then working backwards. This paper assesses the value of measuring those aspects of an unmodified acoustic recording which can be determined to be attributable to the glottal source. This method obviously brings with it the problem of how to ensure that what is measured is indeed attributable to the glottal source and not to supralaryngeal acoustic shaping.

2. Languages investigated

The languages in this paper make use of phonation type in strikingly different ways.

2.1 Wa

Wa belongs to the Palaungic branch of Northern Mon-Khmer (Diffloth 1980). Wa speakers number roughly one million, and are located in an area which Gérard Diffloth has described as the Waic corridor (Diffloth 1980:5), between the Salween and Mekong rivers in the Shan States of Burma and China's Yunnan province.

The aspect of Wa pronunciation under investigation here is the binary registral phonation type contrast observable in Wa vowels which are not preceded by aspirated consonants:

i) 'creaky'[3] phonation /a̰/

ii) breathy phonation /a̤/

Phonation type is phonologicaly contrastive in Wa, being the basis of minimal pairs of lexical items distinguished by phonation type alone.

The informant was a male Wa speaker roughly 60 years of age, from Anshuai village, Cangyuan county, Yunnan, China. The Wa spoken in this village is considered 'standard' by speakers throughout Wa speaking areas. The Wa wordlist comprised 24 syllables of each phonation type, all containing the same /a/ vowel. Not all of these syllables occur as lexical items in Wa. The use of nonsense syllabes was justified by the fact that this informant is involved in Wa language education and has a good understanding of Wa phonology and of the Chinese-designed writing system (Yan 1983) in which the syllables were presented to him. This writing system was originally based on the speech of the same village. It was felt that the readings could be considered authentic renditions of these sound combinations in Wa.

Table 2: The twelve Wa syllables used in this study. Each is shown in /IPA/ with Wa script underneath.

		Initial consonant			
		unvoiced /p/		*prenasalised voiced* /^{m}b/	
		creaky /a̰/	*breathy* /a̤/	*creaky* /a̰/	*breathy* /a̤/
Final consonant	(none)	/pa̰/ ba	/pa̤/ bā	/^{m}ba̰/ nba	/^{n}ba̤/ nbā
	glottal fricative /h/	/pa̰h/ bah	/pa̤h/ bāh	/^{m}ba̰h/ nbah	/^{m}ba̤h/ nbāh
	glottal stop /ʔ/	/pa̰ʔ/ bax	/pa̤ʔ/ bāx	/^{m}ba̰ʔ/ nbax	/^{m}ba̤ʔ/ nbāx

2.2 Burmese

Burmese is the major language of the Burmic branch of Tibeto-Burman, is spoken natively by upwards of 30 million people in the lower valleys of the Irrawaddy and Chindwin rivers, the central plain of Burma and the Irrawaddy Delta and non-natively by up to another 10 million in the rest of Burma, of which country it is the official language.

Burmese syllables which are not reduced have one of four tones, which are best described in terms of a complex of features, of which phonation type is one. Phonation type is thus only partially responsible for tonal contrasts in Burmese. All the tones, especially the 'low' and 'high' tones, are subject to variation conditioned by morphophonological and intonational effects.

Table 3: Features associated with Burmese tones. This assessment is an amalgam of two published descriptions (Bradley 1982:120 Wheatley 1987:114) and my own observations.

tone	*pitch*	*contour*	*intensity*	*phonation*	*duration*
'low'	low	level	low	normal	fairly long
'high'	fairly high	fall	medium	breathy	very long
'creaky'	high	slight fall	high	creaky	short
'killed'	very high	slight fall	very high	tense	very short

The Burmese data in this study were recorded from two male native speakers of Burmese, one from Rangoon and one from Arakan, aged between 30 and 40. The wordlist comprised 24 words (six on each tone).

Table 4: The 24 Burmese words used in this study. Each is shown in /IPA/ and Burmese script.

IPA	*Burmese*
/paː páː pa̰ paʔ/	på på; p p t\
/maː máː ma̰ maʔ/	ma ma; m m t\
/taː táː ta̰ taʔ/	t a t a; t t t\
/naː náː na̰ naʔ/	na na; n n t\
/kaː káː ka̰ kaʔ/	k a k a; k k t\
/ŋaː ŋáː ŋa̰ ŋaʔ/	cå cå; c c t\

3. Evidence of phonation type in the sound spectrum

3.1 The first and second harmonics

Spectral analysis has previously concentrated on the low-frequency region of the spectrum. The relative amplitudes of the first and second harmonics (H1, H2) have been shown to be an index of phonation type in Wa (Svantesson 1993:103) and in other languages which make phonologically contrastive use of phonation types (Ladefoged et al. 1988, Theraphan 1988), as well as in non-phonological phonation types produced in English words (Ní Chasaide and Gobl 1997:446). It has been suggested that the first and second harmonics effectively serve as an index for the spectral profile of a broader range of frequencies. Figures 1 and 2, derived from recordings of Wa syllables, illustrate the relationship between phonation type and the relative amplitudes of H1 and H2:

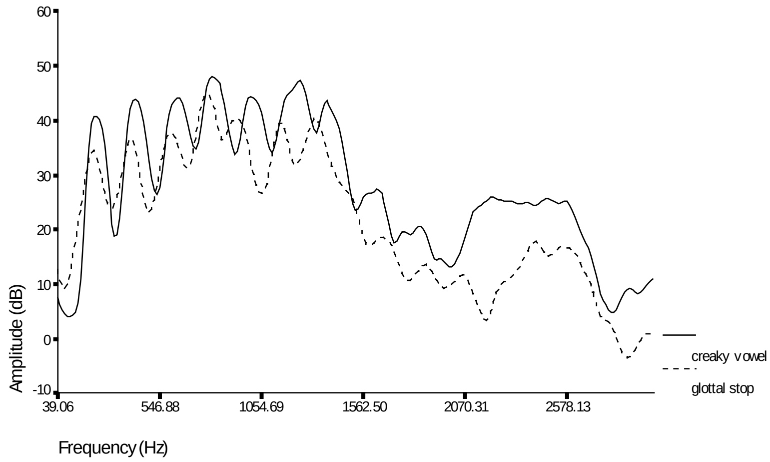

Figure 1: Overlaid spectral profiles (40 Hz b/w, 256-point, 20KHz sample rate, up to 3KHz shown) of Wa syllable-final creaky /a̰/ and of syllable final /ʔ/, realised phonetically as [a̰].

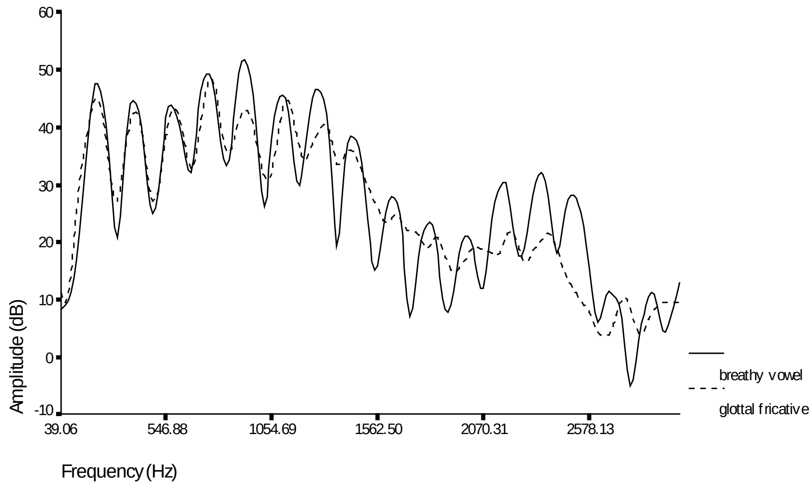

Figure 2: Overlaid spectral profiles (40 Hz b/w, 256-point, 20KHz sample rate, up to 3KHz shown) of Wa syllable-final breathy /a̤/ and of syllable final /h/, realised phonetically as [a̤].

Considering the two overlaid spectra of a Wa vowel with modal phonation and of a Wa glottal stop shown in Figure 1, we see that the first peak, representing the first harmonic (H1), is higher than the second peak, indicating that the amplitude of H1 is greater than H2. The reverse is true in Figure 2, which depicts the spectral profiles of a vowel with breathy phonation and of a glottal fricative. The overall formant structure of all four spectra in these illustrations is similar because they are all associated with an /a/ vowel produced by the same speaker.

A general word of caution must be voiced whenever measurements of formant and harmonic amplitudes are made for the purpose of investigating phonation type: it is vital to ensure as far as possible that the amplitude of H1 or of H2 is not boosted artificially by a formant peak in the same frequency range. Such a situation might arise with a high-pitched voice with a high F0 or with a close vowel with a low F1.

3.2 Formant amplitude and spectral tilt

This paper focuses some attention on the higher formants, examining the possibility of a degree of correlation of phonation type with formant amplitudes beyond the frequency range of H1, H2 and F1. Ní

Chasaide and Gobl (1997:448) show that average sound spectra do vary with phonation type. The spectral differences detected in this study are neither extreme, nor necessarily consistently observable in all the data.

Attempts to obtain objective measures of spectral tilt have met with difficulties (Jackson et al. 1985, 1986). Both this study, which fitted linear regression lines to source spectra, and another method tried in Ní Chasaide and Gobl (1997:449) made use of source spectra obtained by inverse filtering, which was not possible in the present paper.

Misinterpretation of the spectrum is often a possible pitfall since some of the features observable on the sound spectrum are potentially ambiguous. For instance, skewness of the glottal source waveform is known to correlate with spectral profile, particularly the amplitude of the lower harmonics, with the depth of the notches between formant peaks, as well as with the strength of laryngeal excitation (Ní Chasaide and Gobl 1997:441, Titze 1990), i.e. the overall effort put into phonation, which boosts the amplitude of the spectrum as a whole. When it comes to reading the glottal spectrum, care must be taken to ensure exactly what effects are being measured, since skewness of the glottal pulse as measured by a laryngograph is also an index of phonation type (Watkins 1997).

4 Experimental procedure and measurements

256-point, 40Hz bandwidth average spectra were generated using PCLx Laryngograph Analyser software. The spectra were calculated from a window of 100ms near the middle of each vowel in an attempt to avoid as much as possible the effects on the spectrum of formant transitions from initial consonants and, in the case of Wa and Burmese, the effects on phonation of final glottal consonants.

Just as the wordlists were designed to minimise the influence on the spectrum of factors other than phonation type, great care was taken to ensure that procedural variables were kept maximally constant within each body of data which was pooled. Means were only calculated for speech material which was collected in a single recording session, and data collected from different speakers was kept separate.

The Burmese killed tone is associated with a different set of vowels from the other three tones. The different formant structure of the killed tone /a/ had to be borne in mind throughout the study.

Determining the frequency of fifth formant peak for the /a/ vowels in Wa and Burmese (in the region 4 - 4.5 kHz for all these voices) presented great problems. This formant peak was often impossible to pinpoint, since its proximity to F4 often caused it to fuse indistinguishably with the F4 peak in the great majority of the data from all three languages. What is measured as F5 in the measurements presented below is true F6, which features prominently in all the spectra, while F4 would more properly be described as F4', a fusion of F4 and F5, located in the region of 3.5 - 4 kHz).

4.1 Frequency and amplitude of formants

4.1.1 Wa

The means of all the spectra for each of the two Wa phonation types of the Wa speaker are shown in Figure 3 below, with tabulated calculations of the mean frequency and amplitude of the first five formants in Table 5 underneath it. (See §4 above about measurements of F5.)

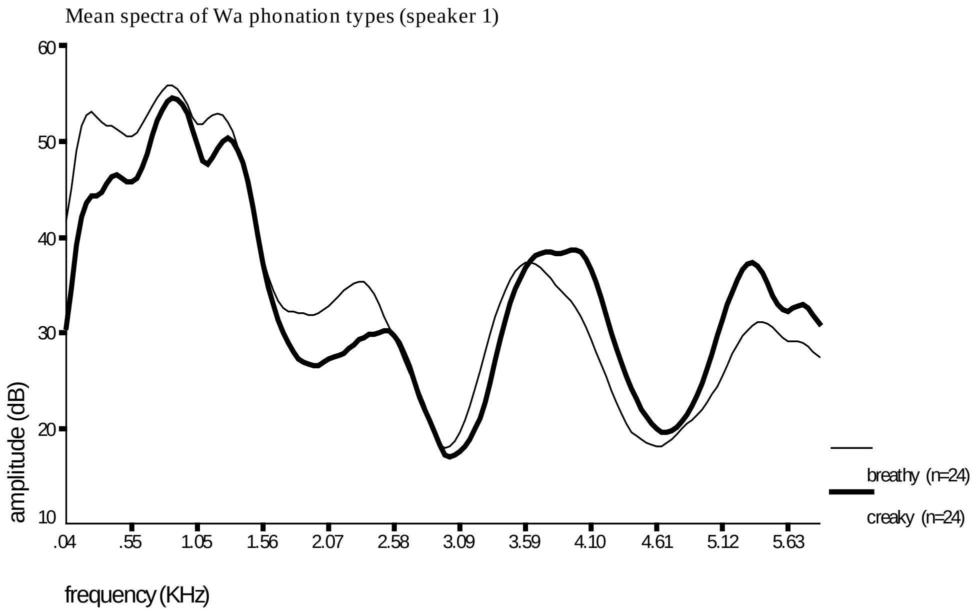

Figure 3: Mean (n=24) spectra of Wa vowel /a/ with breathy and creaky phonation types.

Table 5: Mean (n=24) formant frequencies (Hz) and amplitudes (dB, in brackets4) of Wa syllables with breathy and creaky phonation types.

	F1	*F2*	*F3*	*F4*	*F5*
creaky phonation	833 (33.00)	1266 (30.17)	2390 (11.67)	3756 (16.67)	5378 (15.50)
breathy phonation	799 (35.17)	1219 (32.25)	2348 (15.00)	3688 (16.17)	5449 (11.58)

Figures 4 and 5 below illustrate the degree of variation of the means in the above table. In the upper diagram, only frequency is shown to scale; in the lower, only amplitude.

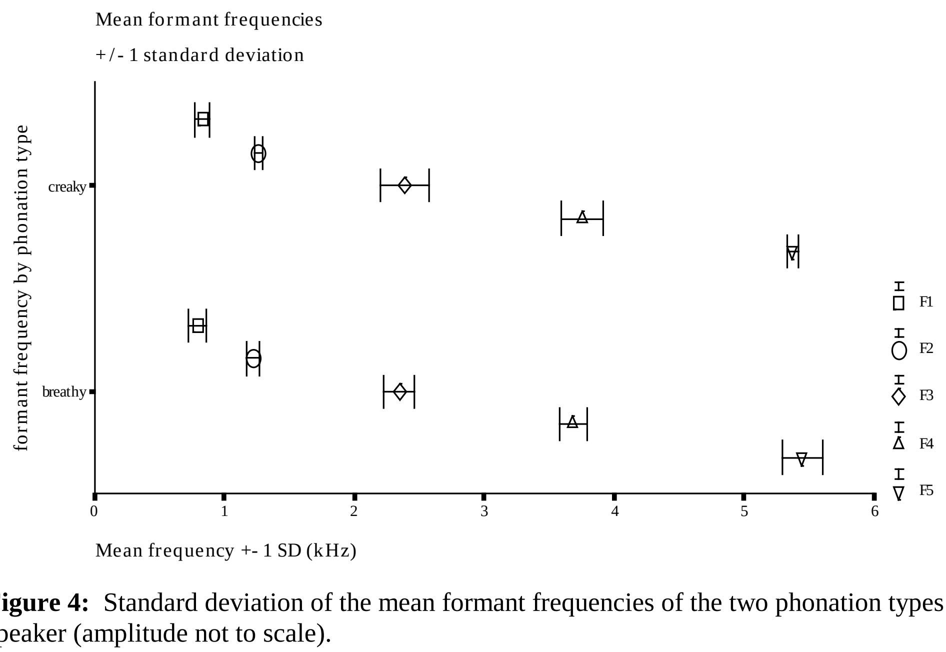

Figure 4: Standard deviation of the mean formant frequencies of the two phonation types of the Wa speaker (amplitude not to scale).

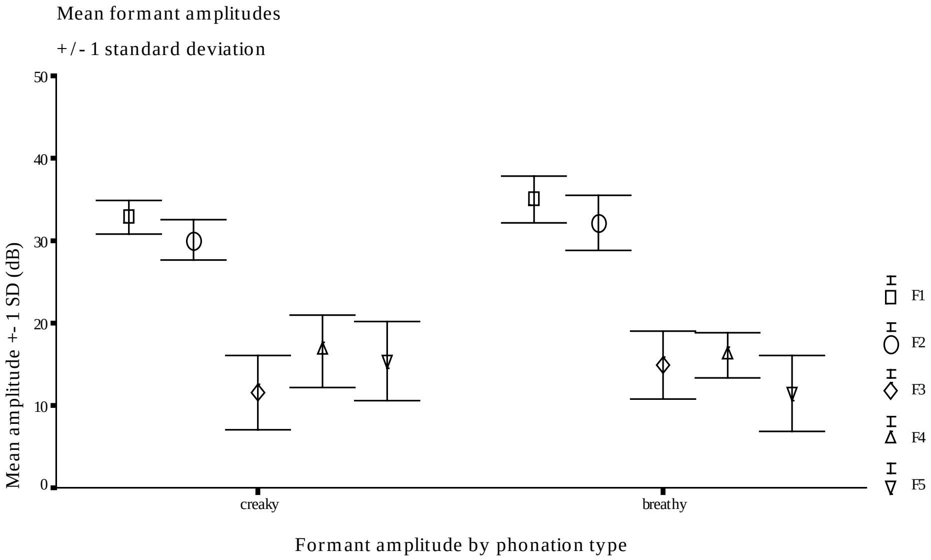

Figure 5: Standard deviation of the mean amplitude levels of the two phonation types of the Wa speaker (frequency not to scale).

4.1.2 Burmese

The means of all the spectra for each of the four Burmese tones of one of the Burmese speakers are shown in Figure 6 below, with tabulated calculations of the mean frequency and amplitude of the first five formants in Table 6 underneath. (See §4 above about measurements of F5.)

4.2 Spectral profile in the low-frequency range

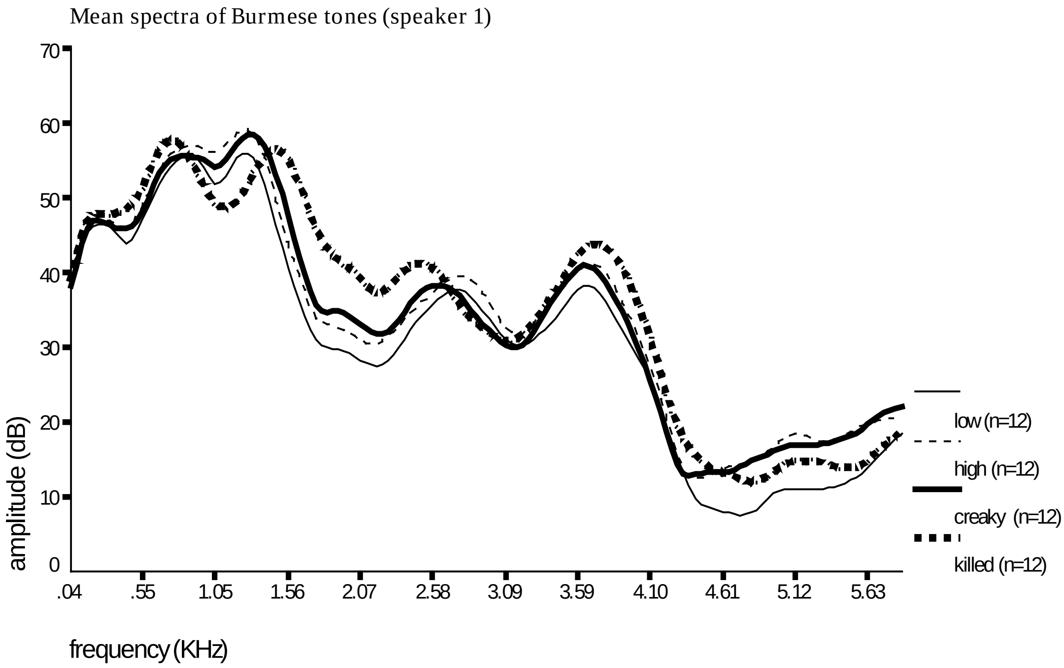

Figure 6: Mean (n=12) spectra of Burmese vowel /a/ on four tones: low, high, creaky and killed (Speaker 1).

Table 6: Mean (n=12) formant frequencies (Hz) and amplitudes (dB, in brackets) of Burmese syllables on four tones: low, high, creaky and killed. (speaker 1).

	F1	*F2*	*F3*	*F4*	*F5*
low tone	827 (35.83)	1219 (35.67)	2762 (19.33)	3661 (17.33)	5839 (11.50)
high tone	760 (35.83)	1241 (38.33)	2725 (22.50)	3707 (22.00)	5584 (21.50)
creaky tone	752 (34.33)	1270 (39.17)	2641 (21.17)	3481 (22.67)	5567 (11.83)
killed tone	685 (37.00)	1508 (36.67)	2524 (22.17)	3611 (26.17)	5325 (11.83)

Figures 7 and 8 below illustrate the degree of variation of the means in the above table. In the upper diagram, only frequency is shown to scale; in the lower, only amplitude.

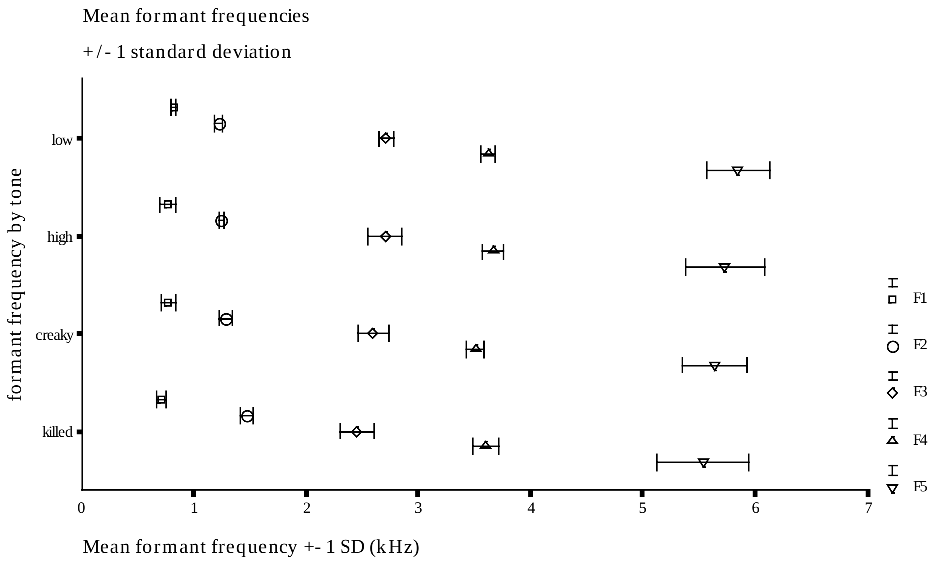

Figure 7: Standard deviation of the mean formant frequencies of the four tones of the first Burmese speaker (amplitude not to scale).

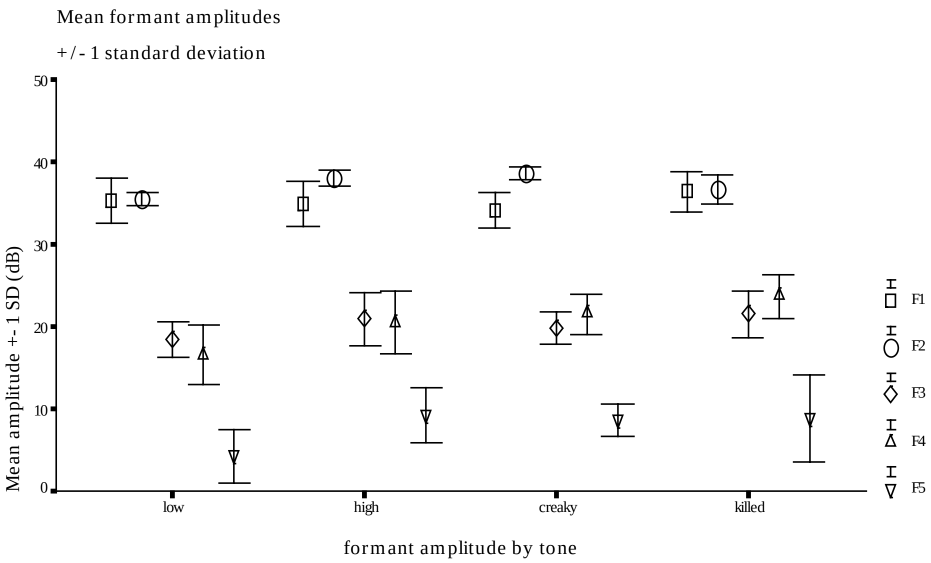

Figure 8: Standard deviation of the mean amplitude levels of the four tones of the first Burmese speaker (frequency not to scale).

For the second Burmese speaker, the mean formant frequencies and amplitudes are shown in Table 7 below. These means are illustrated with their standard deviations in Figures 9 and 10 which follow it:

Table 7: Mean (n=12) formant frequencies (Hz) and amplitudes (dB, in brackets) of Burmese syllables on four tones (speaker 2).

formant	F1	F2	F3	F4	F5
low tone	808 (29.67)	1352 (24.58)	2758 (11.17)	3573 (3.50)	5195 (-.75)
high tone	785 (23.50)	1341 (23.25)	2842 (9.75)	3565 (7.17)	5122 (21.50)
creaky tone	927 (25.00)	1458 (21.50)	2656 (13.25)	3391 (10.92)	5093 (-.50)
killed tone	817 (26.75)	1550 (23.83)	2731 (12.33)	3488 (9.83)	5153 (-.58)

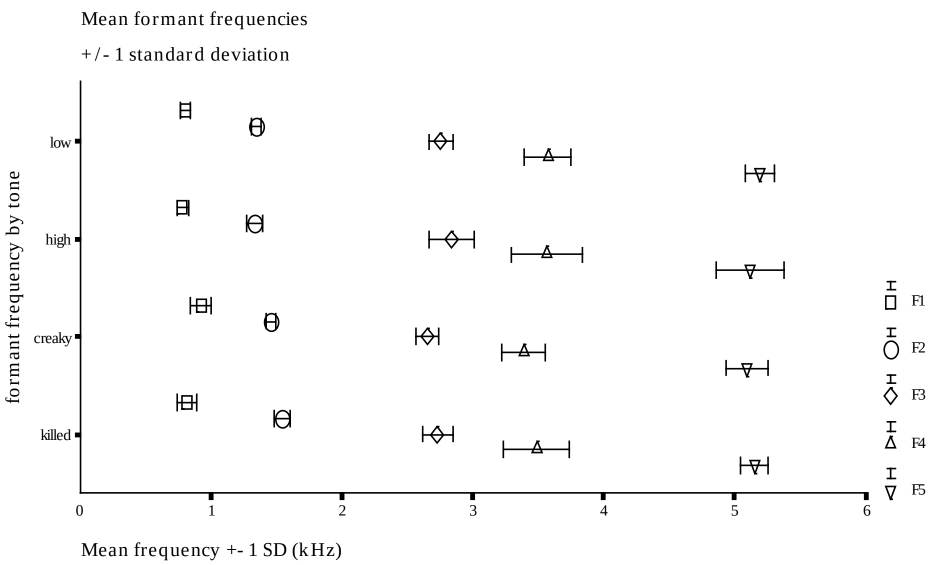

Figure 9: Standard deviation of the mean formant frequencies of the four tones of the second Burmese

speaker (frequency not to scale).

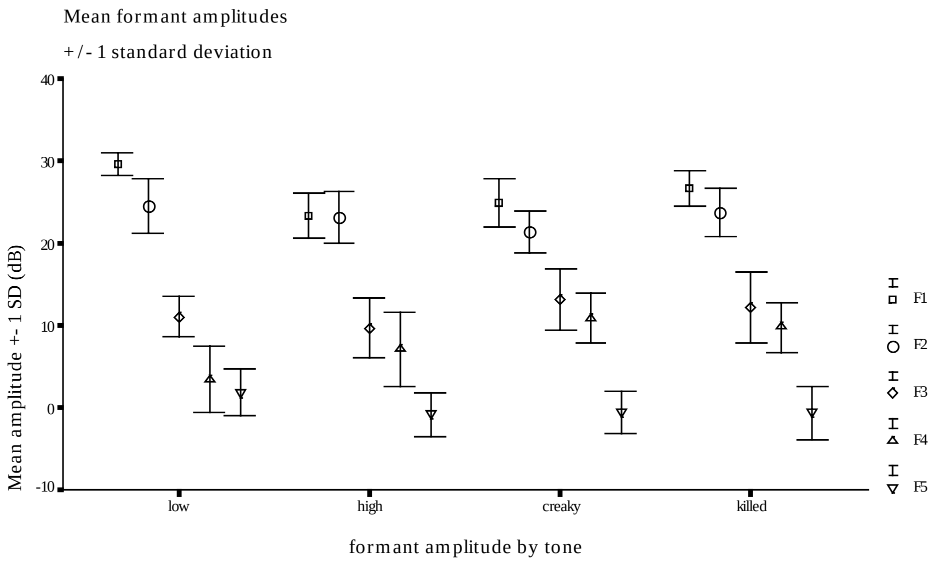

Figure 10: Standard deviation of the mean amplitude levels of the four tones of the second Burmese speaker (frequency not to scale).

The amplitudes of H1, H2, F1 and F2 from the Wa data and Burmese speaker 1 were compared to make the following measurements. Burmese speaker 2 was omitted from this leg of the study.

4.2.1 Wa

Set out in Figures 12 and 13 below are the mean amplitudes of H1, H2, F1 and F2 for both phonation types in Wa and mean amplitudes of H2, F1 and F2 relative to H1.

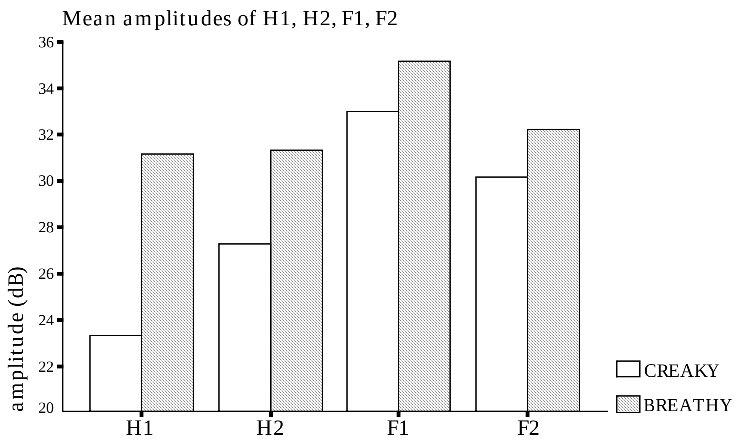

Figure 11: Mean (n=24) amplitudes of H1, H2, F1 and F2 for both Wa phonation types.

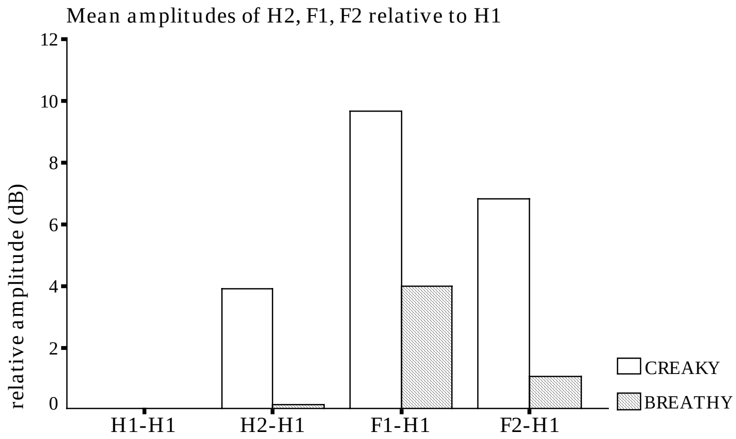

Figure 12: Mean (n=24) amplitudes of H2, F1 and F2 relative to H1 for both Wa phonation types.

4.2.2 Burmese

Set out in Figures 14 and 15 below are the mean amplitudes of H1, H2, F1 and F2 for each of the four tones in Burmese and mean amplitudes of H2, F1 and F2 relative to H1.

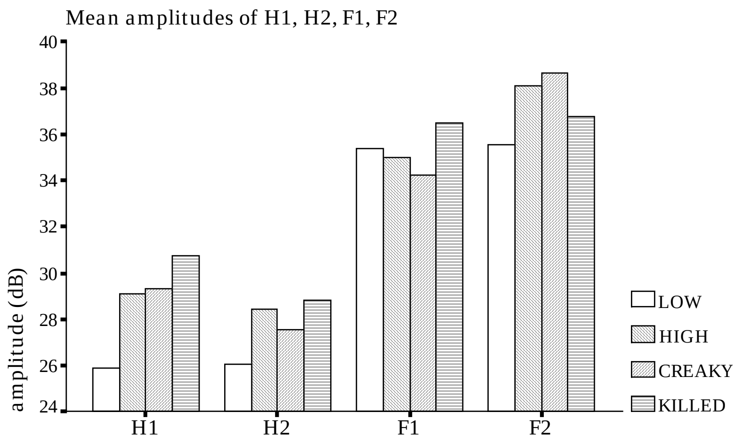

Figure 13: Mean (n=12) amplitudes of H1, H2, F1 and F2 for each tone in Burmese (speaker 1 only).

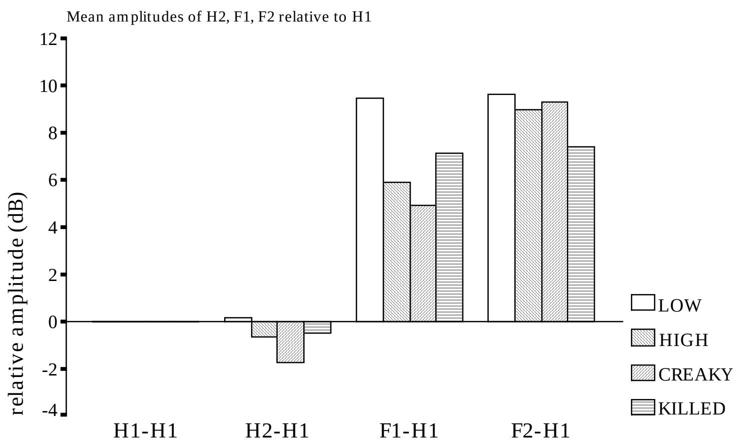

Figure 14: Mean (n=12) amplitudes of H2, F1and F2 relative to H1 for each tone in Burmese (speaker 1 only).

5. Statistical tests and summary of findings

In the tables which follow, 'significance' is defined at the $p<0.05$ level and is indicated by means of an asterisk.

Anova tests were carried out to ascertain whether the various mean measurements presented in section 4 above were significantly different from each other across phonation types in Wa. Mean frequency and amplitude of the five formants, mean amplitude of H1 and H2 and mean amplitudes of H2, F1 and F2 relative to H1 were tested. The frequencies of H1 and H2 were not measured and so were not included in the tests. Tables 9, 10 and 11 below show the results of the tests in each language category.

Table 9: Wa data

	F1	*F2*	*F3*	*F4*	*F5*	*H1*	*H2*
frequency		*				-	-
amplitude	*				*	*	*

H1-H2	*H1-F1*	*H1-F2*
*	*	*

Summary *of Anova test:*

F2 frequency higher in creaky than in breathy;
F1, F5, H1 and H2 all greater amplitude in breathy than creaky.
Difference between H2, F1 and F2 and H1 greater in creaky than breathy.

An asterisk in the Anova tables for the Burmese data indicates that some statistically significant difference between means across tones was detected. The nature of such the differences is explored by means of Scheffé tests. If the means of each variable in the Burmese data are ranked by tone, the Scheffé test makes it possible to show which tones are significantly different from which others. This information is set out below such that each subset of tones within which the means are *not* significantly different from each other is bracketed together in the ranking lists. A mean which not included in any subset may be considered to be significantly different from the other three.

Table 10: Burmese data
(Speaker 1)

	F1	*F2*	*F3*	*F4*	*F5*	*H1*	*H2*
frequency	*	*	*	*		-	-
amplitude		*		*		*	

H1-H2	*H1-F1*	*H1-F2*
	*	

Summary of Anova and Scheffé tests: Means of each variable by tone are ranked greatest to least. Brackets (or [indicate subsets of means which are not significantly different from each other at the p<0.05 level.

	F1	*F2*	*F3*	*F4*	*F5*	*H1*	*H2*
frequency	(low ([creaky ([high [killed	killed (creaky (high (low	(low (high ([creaky [killed	(high ([low ([killed [creaky		-	-
amplitude		(creaky (high ([killed [low		(killed ([creaky ([high [low		(killed ([creaky ([high [low	

H1-H2	*H1-F1*	*H1-F2*
	(killed	
	([creaky	
	([high	
	[low	

(Speaker 2)

	F1	*F2*	*F3*	*F4*	*F5*
frequency	*	*			
amplitude	*			*	

Summary of Anova and Scheffé tests: Means of each variable by tone are ranked greatest to least. Brackets (or [indicate subsets of means which are not *significantly different from each other at the p<0.05 level.*

	F1	*F2*	*F3*	*F4*	*F5*
frequency	creaky	killed			
	(killed	(creaky			
	(high	(low			
	(low	(high			
amplitude	(low			killed	
	([killed			creaky	
	[creaky			(low	
	[high			(high	

6. Discussion

6.1 Wa

The results from the Wa data show that the low frequency H1-based tests for phonation type are readily applicable, despite the fact mentioned in section 2.1 above that the phonation types of both registers in Wa can stray close to modal phonation type. The statistical test results in Table 9 above confirm the visual impression given in Figure 12 that H2, F1 and F2 are all more energetic than H1 to a greater degree in creaky phonation than in breathy, though this is due in part to the significantly dominant H1 in breathy phonation, seen in Figure 11 and confirmed in Table 9.

One of the primary aims of this paper was to attempt to broaden the palette of technique available for measuring phonation type beyond the tried and tested measures which focus on the low-frequency end of the spectrum and the relative amplitudes of H1, H2, F1 and F2. One piece of statistically significant evidence in this study which may succeed in this regard, namely the greater amplitude of F5 in creaky register in Wa. According to Ní Chasaide and Gobl (1997:451), sharpness of formant peaks and narrow formant bandwidth are attributable to a long closed phase in the glottal source, though they do not refer specifically to a dominant peak at F5 which shows up consistently in their average spectra of tense and creaky phonation types.

6.2 Burmese

The more fronted variety of /a/ in the Burmese killed tone has a predictably different formant structure, specifically a higher F2. This is borne out by the results: the amplitude of F2 in the killed tone can be singled out as significantly greater than the other three tones for both speakers.

A look at Table 3, in which various phonetic features associated with the Burmese tones are set out, reminds us that we might expect the killed and high tones to show evidence of tense or creaky phonation. The methods in this study are too crude to tell these two phonation types apart, but they are sufficient to identify the cruder three-way categorisation of phonation types (modal, creaky and breathy), which, it has been suggested, is sufficient to give a satisfactory account of phonologically contrastive phonation type for most purposes.

This limitation notwithstanding, the amplitude of F4 is significantly greater in the killed and creaky tones than in the low and high tones for Speaker 2, and a similar observation can be made for Speaker 1, though with only partially statistical significance, as illustrated in Figure 6. This constitutes evidence that increased amplitude in the region of F4 in the killed and creaky tones is indeed diagnostic of creakier phonation, and corroborates the evidence provided by the prominent F5 in creaky phonation in Wa.

In the context of this study, though, this unexpected finding is perversely encouraging, since it forces us to take more seriously the evidence in the higher frequency region of the spectrum.

7. Further research

It is hoped that further research may be undertaken to address how phonation type affects the bandwidth of formants and the notches between them, since formant damping is clearly an important part of the relationship between phonation type and spectral profile. Spectral analysis combined with more direct measurement of the glottal source, such as laryngography or measurement of airflow data, might lead to a better understanding of the way glottal activity influences the higher frequency region of the spectrum. Another line of inquiry which might assert further the relevance of studying spectral profile as a measure phonation type would be a test of the role of spectral profile as an acoustic cue in languages, such as Burmese or Wa, in which phonation type is phonologically contrastive.

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Notes

[1] This paper avoids the term *voice quality* (cf Laver, 1980), since it may be used to describe laryngeal activity and supra-laryngeal articulatory settings.

[2] i.e. excluding ventricular phonation.

[3] The term 'creaky' is applied to Wa with some hesitation, since for many speakers the phonation type of this register could be more accurately labelled as tense, pressed or modal. It is convenient to think in terms of a binary phonological contrast between 'creaky' and breathy, and for this reason the term 'creaky' is used throughout this paper.

[4] The measurements of formant frequency and amplitude in the table were made independently of the graph in Figure 3 and so do not tally exactly with that illustration. The dB values are measured relative to a different reference amplitude, but are, of course, still accurate relative to each other. The same discrepancy applies to Figure 4 and the table underneath it.