Phonation types: a cross-linguistic overview

Matthew Gordon
University of California, Santa Barbara

Peter Ladefoged
University of California, Los Angeles

1. Introduction

Cross-linguistic phonetic studies have yielded several insights into the possible states of the glottis. People can control the glottis so that they produce speech sounds with not only regular voicing vibrations at a range of different pitches, but also harsh, soft, creaky, breathy and a variety of other phonation types. These are controllable variations in the actions of the glottis, not just personal idiosyncratic possibilities or involuntary pathological actions. What appears to be an uncontrollable pathological voice quality for one person might be a necessary part of the set of phonological contrasts for someone else. For example, some American English speakers may have a very breathy voice that is considered to be pathological, while Gujarati speakers need a similar voice quality to distinguish the word /ba̤ɾ/ meaning ‘outside’ from the word /baɾ/ meaning ‘twelve’ (Pandit 1957, Ladefoged 1971). Likewise, an American English speaker may have a very creaky voice quality similar to the one employed by speakers of Jalapa Mazatec to distinguish the word /já̰/ meaning ‘he wears’ from the word /já/ meaning ‘tree’ (Kirk et al. 1993). As was noted some time ago, one person's voice disorder might be another person's phoneme (Ladefoged 1983).

2. The cross-linguistic distribution of phonation contrasts

Ladefoged (1971) suggested that there might be a continuum of phonation types, defined in terms of the aperture between the arytenoid cartilages, ranging from voiceless (furthest apart), through breathy voiced, to regular, modal voicing, and then on through creaky voice to glottal closure (closest together). This continuum is depicted schematically in Figure 1.

	Most open ◄			►	**Most closed**
Phonation type	Voiceless	Breathy	Modal	Creaky	Glottal closure

Figure 1. Continuum of phonation types (after Ladefoged 1971)

Although this is somewhat of an oversimplification, there nevertheless appears to be a linguistic continuum that can be characterized using these terms as an ordered set. Sections 2.1-2.4 explore some of the ways in which languages exploit this phonation continuum. Throughout the discussion, a number of languages with different types of phonation contrasts will be mentioned. The names of all of these languages are summarized in an Appendix, along with some additional basic information about each language: genetic affiliation, where spoken, references, and type of phonations contrasted.

2.1. Voiced vs. voiceless contrasts

The majority of languages employ two points along the phonation continuum in making contrasts: voiced and voiceless sounds. This contrast is particularly common among stop consonants and is exploited in a number of widely-spoken languages, such as English, Japanese, Arabic and Russian. The minimal pair *wrangle* with a voiced /g/ vs. *rankle* with a voiceless /k/ illustrates the contrast between voiced and voiceless stops in English. In a smaller set of languages, the voiced vs. voiceless contrast is found in sonorants. For example, Burmese, Hmong, Klamath, and Angami have a voiced vs. voiceless contrast among the nasals. Sample words illustrating this contrast in Burmese are given in Table 1.

Table 1. Voiced and voiceless nasals in Burmese (from Ladefoged and Maddieson 1996:111)

	Voiced		Voiceless	
Bilabial	mă	‘hard’	m̥ă	‘notice’
Alveolar	nă	‘pain’	n̥ă	‘nose’
Palatal	≠ă	‘right’	≠̥ă	‘considerate’
Velar	ŋă	‘fish’	ŋ̊ă	‘borrow’
Labialized alveolar	nʷă	‘cow’	n̥ʷă	‘peel’

No language appears to make a clear voicing distinction in vowels, though it is common, as in Japanese, for phonologically voiced vowels to devoice in certain contexts such as in final position and when adjacent to voiceless consonants (see Gordon 1998 for a cross-linguistic survey of vowel devoicing).

2.2. Breathy voice

Another point on the phonation continuum exploited by certain languages (far fewer in number than languages which have voiceless sounds) is breathy voice. Breathy phonation is characterized by vocal cords that are fairly abducted (relative to modal and creaky voice) and have little longitudinal tension (see Ladefoged 1971, Laver 1980, and Ní Chasaide and Gobl 1995 for discusson of the articulatory settings characteristic of breathy phonation); this results in some turbulent airflow through the glottis and the auditory impression of “voice mixed in with breath” (Catford 1977:99). Certain languages contrast breathy voiced and regular modal voiced sounds. Some of these languages, e.g. Hindi, Newar, Tsonga, make this contrast among their nasals. Words illustrating the breathy vs. modal voiced contrast in Newar appear in Table 2.

Table 2. Modal voiced and breathy voiced nasals in Newar

Modal voiced		Breathy voiced	
maː	‘garland’	m̤aː	‘be unwilling’
naː	‘it melts’	n̤aː	‘knead’

Waveforms and spectrograms illustrating the breathy vs. modal voiced contrast for two of these Newar words (uttered in isolation) appear in Figure 2, with the modal voiced nasal on the left and the breathy voiced one on the right. The waveforms are excerpted sections from the modal voiced and breathy voiced nasals, respectively, with the time of the excerpt labeled on the x-axis of the waveforms.

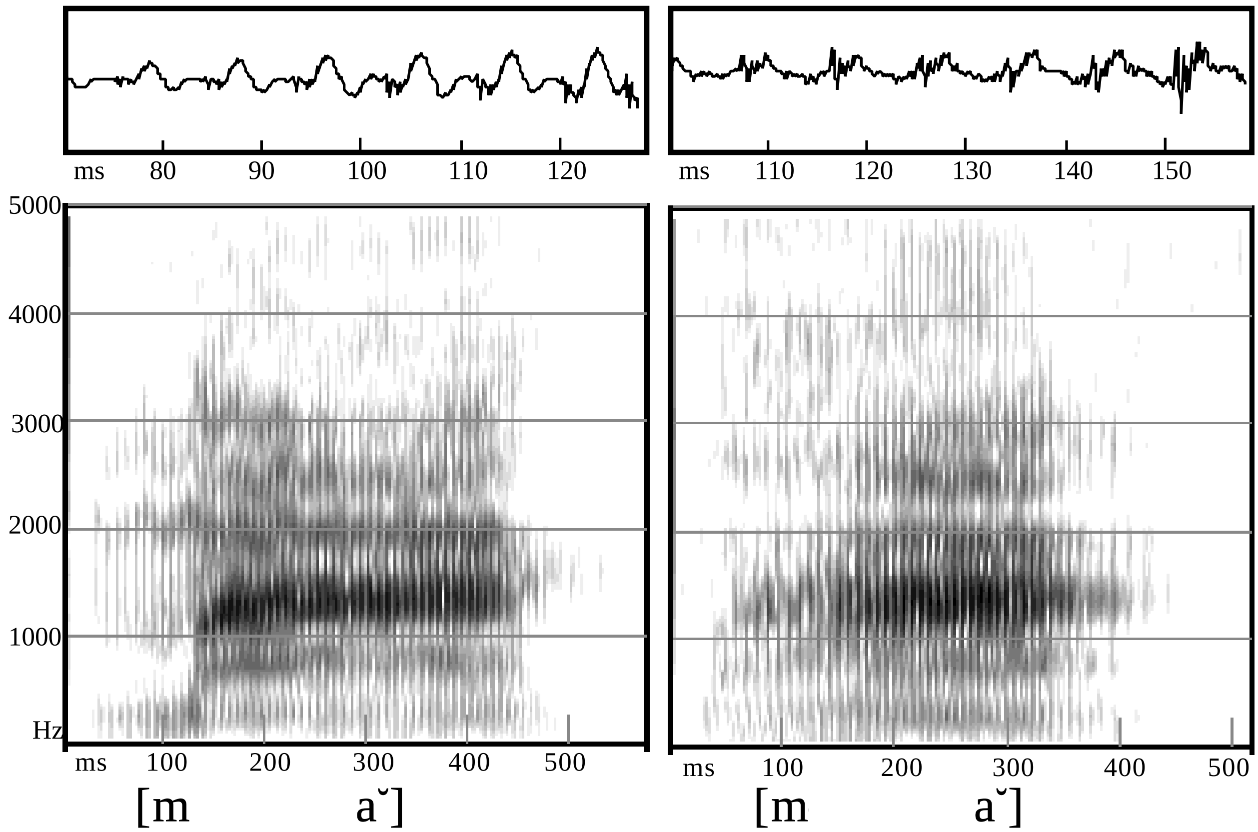

Figure 2. Spectrograms of modal and breathy voiced nasals in the Newar words /maː/ ‘garland’ and /m̤aː/ ‘be unwilling’ (male speaker)

The waveform for the breathy voiced nasal is characterized by a fair amount of noisy energy which contributes a relatively jagged appearance to the waveform and diminishes the clarity of individual pitch pulses. In comparison, the modal voiced nasal is not marked by this turbulence and has relatively well-defined pitch pulses. One of the more salient features differentiating modal and breathy voiced nasals in the spectrograms is the visually well-defined nasal-to-vowel transition characteristic of the modal voiced nasal (at about 130 milliseconds) but not the breathy voiced nasal (at about 150 milliseconds). In fact, breathiness persists throughout the vowel following the breathy voiced nasal, resulting in increased formant bandwidths relative to the modal voiced vowel in the spectrogram on the left. In addition, the breathy voiced nasal has some high frequency noise not present in the modal voiced nasal. The aperiodic energy characteristic of breathy nasals in Newar, as seen in the waveform and, to a lesser extent, in the spectrogram, in Figure 2, is a general feature of breathiness in other languages discussed below (see also the discussion of the acoustic correlates of breathiness in section 5).

As it turns out, Newar also makes a breathy vs. modal voiced contrast in their stops. Languages with contrastively breathy voiced obstruents are relatively rare cross-linguistically, although they are common in Indo-Aryan and other languages spoken in Asia, e.g. Hindi, Maithili, Telugu, in addition to Newar (see Ladefoged and Maddieson 1996 for further examples).

Some languages contrast breathy and modal voicing in their vowels rather than consonants. Gujarati, which was mentioned earlier in the introduction, is one such language. Representative pairs illustrating this contrast appear in Table 3. (We will see waveforms and spectrograms illustrating breathy voiced vowels in the discussion of Jalapa Mazatec and San Lucas Quiaviní Zapotec in section 2.3)

Table 3. Modal and breathy voiced vowels in Gujarati

Modal voiced		Breathy voiced	
bar	‘twelve’	ba̤r	‘outside’
pɔr	‘last year’	pɔ̤r	‘dawn’
kan	‘ear’	ka̤n	‘Krishna’
mɛl	‘dirt’	mɛ̤l	‘palace’

2.3. Creaky voice

Another type of phonation along the continuum in figure 1 is creaky voice, which contrasts with modal voice in many languages and with both modal voice and breathy voice in other languages. Creaky phonation (also termed vocal fry) is typically associated with vocal folds that are tightly adducted but open enough along a portion of their length to allow for voicing (Ladefoged 1971, Laver 1980, Ní Chasaide and Gobl 1995). The acoustic result of this laryngeal setting is a series of irregularly spaced vocal pulses that give the auditory impression of a “rapid series of taps, like a stick being run along a railing” (Catford 1964:32). Like the contrast between breathy and modal voiced among obstruents, contrasts between creaky and modal voice are also relatively rare in obstruents, though Hausa and certain other Chadic languages make such a contrast for stops. The creaky stops in these languages are implosives and involve larynx lowering as well as a creaky voice quality (see Ladefoged and Maddieson 1996 for discussion).

Some languages contrast creaky and modal voicing among their sonorants. This type of contrast is particularly common in Northwest American Indian languages, e.g. Kwakw’ala, Montana Salish, Hupa, and Kashaya Pomo, among many others. Representative words illustrating the creaky vs. modal voiced contrast among nasals in Kwakw’ala (Boas 1947) appear in Table 4.

Table 4. Modal and creaky nasals in Kwakw’ala

Modal voiced		Creaky voiced	
nəm	‘one’	n̰an̰əm̰a	‘nine’
naka	‘drinking’	n̰ala	‘day’

Figure 3 contains (in the top figure) a waveform and spectrogram for a word (uttered in isolation) with three creaky voiced nasals in Kwakw’ala: one occurs word-initially and the others after vowels. The waveform is excerpted from the transition from the vowel preceding the creaky /m̰/ into the nasal itself. The waveform and spectrogram on the bottom illustrate for comparative purposes modal voiced nasals occurring in the same language; the waveform is from the modal voiced /m/. Differences in phonation type are indicated in the phonetic transcription below the spectrograms in Figure 3 (and in subsequent spectrograms throughout the paper).

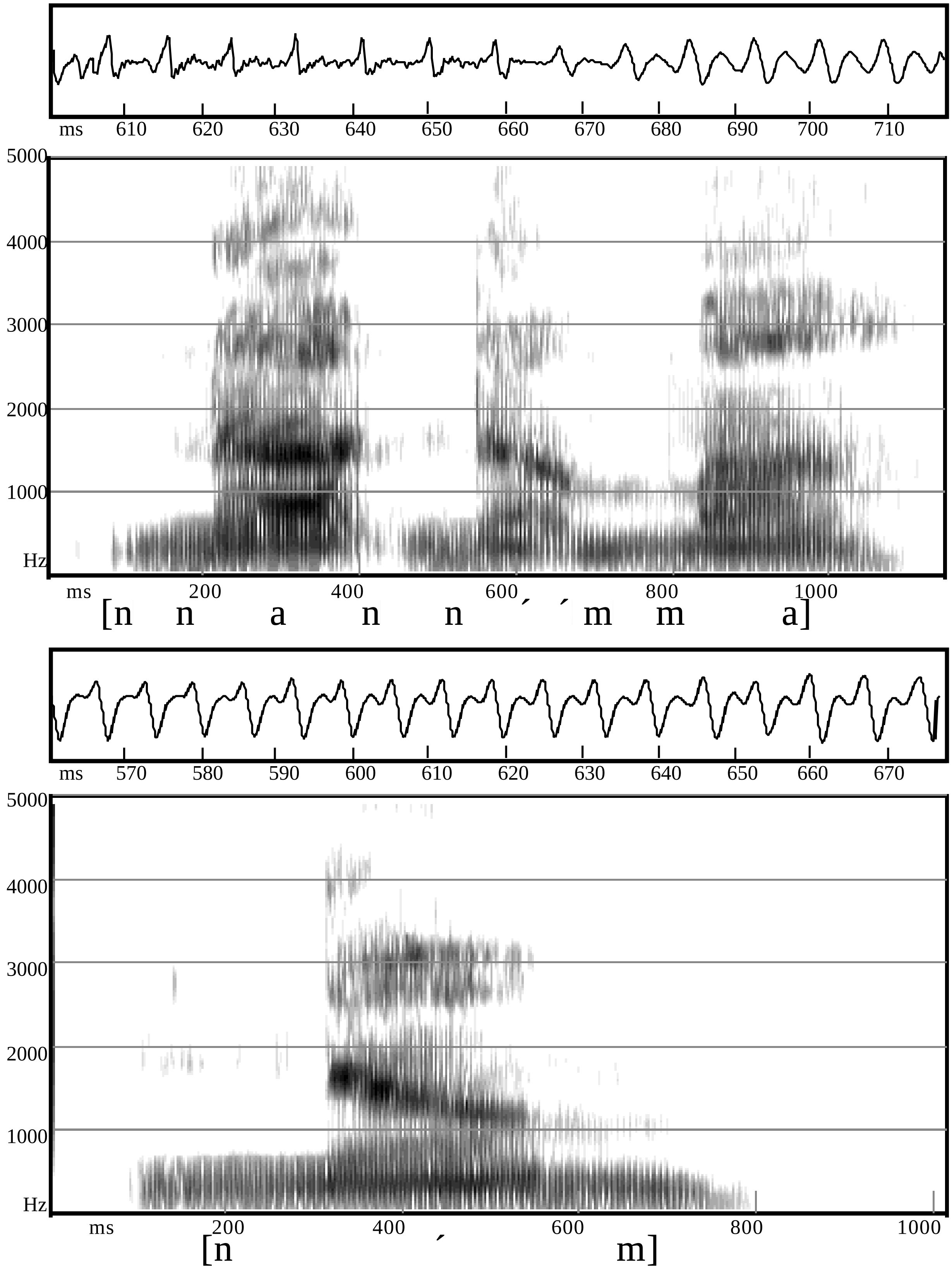

Figure 3. Spectrograms of creaky and modal voiced nasals in the Kwakw’ala words /n̰an̰əm̰a/ ‘nine’ and /nəm/ ‘one’ (female speaker)

Looking at the waveforms, the creaky phonation is characterized by irregularly spaced pitch periods and decreased acoustic intensity relative to modal phonation. Furthermore, there are fewer pitch periods per second in the creaky token than in the modal one (particularly at the beginning of the waveform up to 660 milliseconds when creak is strongest), indicating a lowered fundamental frequency for the creaky nasal. These properties differentiating creaky and modal voice are discussed further in section 5. The spectrogram on the left indicates that creak is realized primarily at the beginning of the creaky voiced nasals, visually reflected in increased distance between the vertical striations reflecting pitch pulses, before modal voicing commences in the latter portion of the nasals (indicated by modal voiced nasals in the transcription below the spectrogram). The localization of creak to the beginning of sonorants is a common timing pattern in languages with creaky voiced sonorants (see section 4.2 for further discussion of the timing issues involved in the realization of creaky voicing associated with sonorants.) Of particular interest in figure 3 are the creaky voiced pitch periods at the beginning of the word-initial nasal in the spectrogram on the left, as word-initial creaky nasals are comparatively rare in languages of the world (see section 4.2 for discussion).

Creaky voicing is also found among vowels in certain languages, including some languages which also use breathy voice to create a three-way phonation contrast. Table 4 contains words illustrating the three-way contrast between modal voiced, breathy voiced, and creaky voiced vowels in Jalapa Mazatec. Spectrograms illustrating each of the three vowel types in Jalapa Mazatec (from words uttered in isolation) appear in Figure 4.

Table 4. Modal, breathy, and creaky voiced vowels in Jalapa Mazatec (from Ladefoged and Maddieson 1996: 317)

Modal voiced		Breathy voiced		Creaky voiced	
já	‘tree’	já̤	‘he wears’	já̰	‘he carries’
ntʰǽ	‘seed’	ndǽ̤	‘horse’	ndǽ̰	‘buttocks’

Both the breathy voiced and the creaky voiced vowel are characterized by decreased intensity in the waveform, as well as a lowered fundamental frequency relative to the modal voiced vowel. In addition, the breathy voiced vowel is marked by substantial turbulent energy which makes it difficult to discern individual pitch pulses. As Silverman (1997) points out, creakiness and breathiness tend not to be co-extensive with entire vowels in Jalapa Mazatec. It is thus apparent from the spectrograms that the breathy phase of the breathy vowel is largely localized to the first portion of the vowel. In the breathy token in figure 4, there is even a short portion of the vowel during which phonation temporarily ceases as the larynx opens too wide for vocal fold vibration to continue. In the creaky voiced vowel, creakiness is most pronounced during the middle of the vowel, as reflected in the widely spaced vertical striations reflecting lowered fundamental frequency (210 to 260 milliseconds). It is also interesting to note that both the breathy and creaky vowels have greater overall duration than their modal voiced counterparts. This additional length associated with non-modal vowels in Jalapa Mazatec is shared with other languages (see section 5 for discussion).

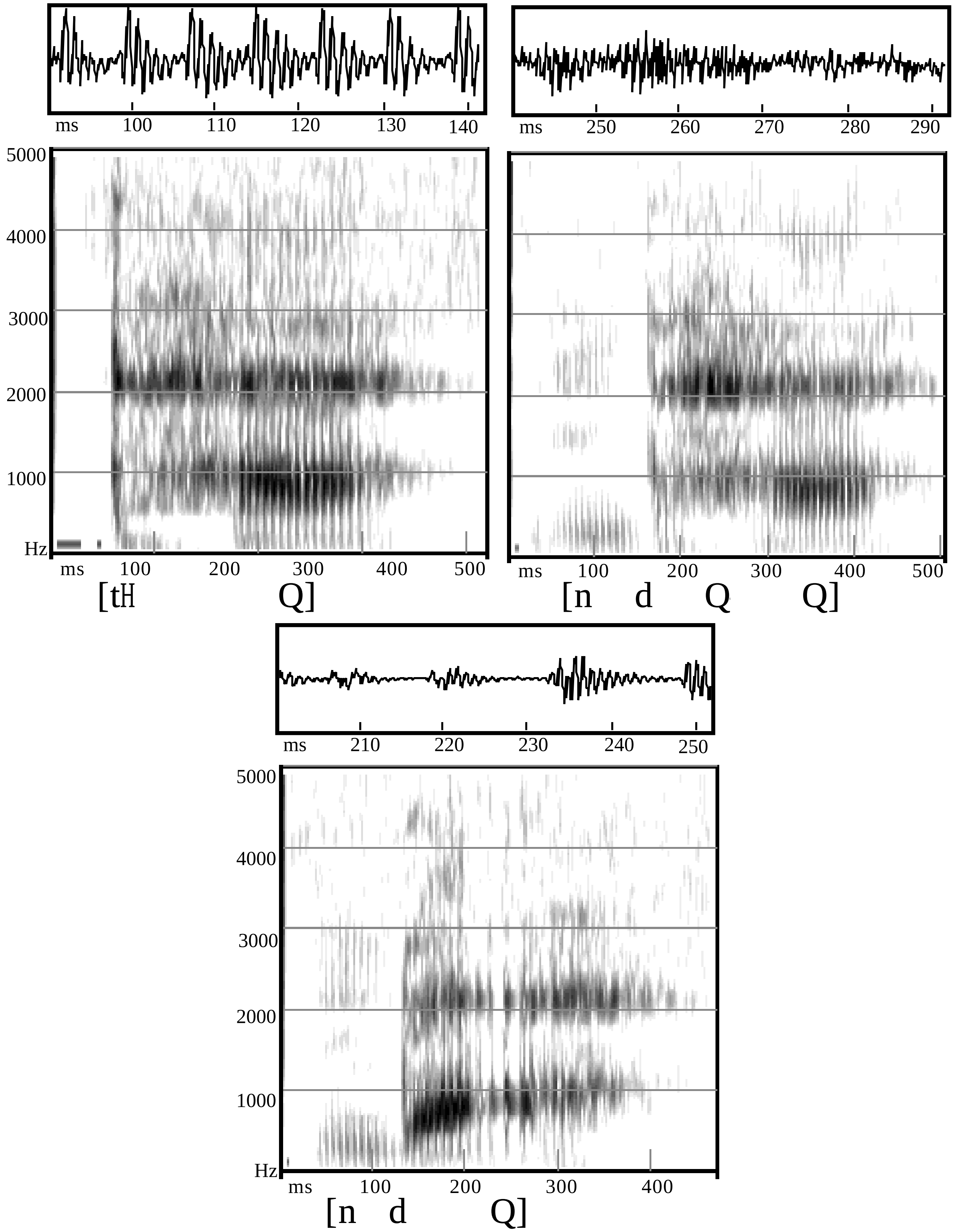

Figure 4. Spectrograms of modal, breathy, and creaky voiced vowels in the Jalapa Mazatec words /nt^{h}ǽ/ ‘seed’, /ndǽ̤/ ‘horse’, and /ndǽ̰/ ‘buttocks’(female speaker)

A similar three way contrast between modal, breathy voiced, and creaky voiced vowels is also found in San Lucas Quiaviní Zapotec (Munro and Lopez 1999). Words (uttered in isolation) illustrating the modal vs. breathy vs. creaky contrast in this language appear in Table 5.

Table 5. Modal, breathy, and creaky vowels in San Lucas Quiaviní Zapotec

Modal voiced		Breathy voiced		Creaky voiced	
laː	is named	na̤ː	‘hard, strong’	mna̰ːʔ	woman
daː	‘Soledad’	kilda̤	‘forehead’	ɾda̰ːʔ	‘lets go of’
ndiː	‘right’	bi̤ː	‘air’	bdḭːʔ	‘gate’
ʒiː	‘tomorrow’	nʒi̤ː	‘salty’	ɾʒḭːʔ	‘gets milked’

Representative waveforms and spectrograms of some of these words as uttered by a female speaker appear in Figure 5.

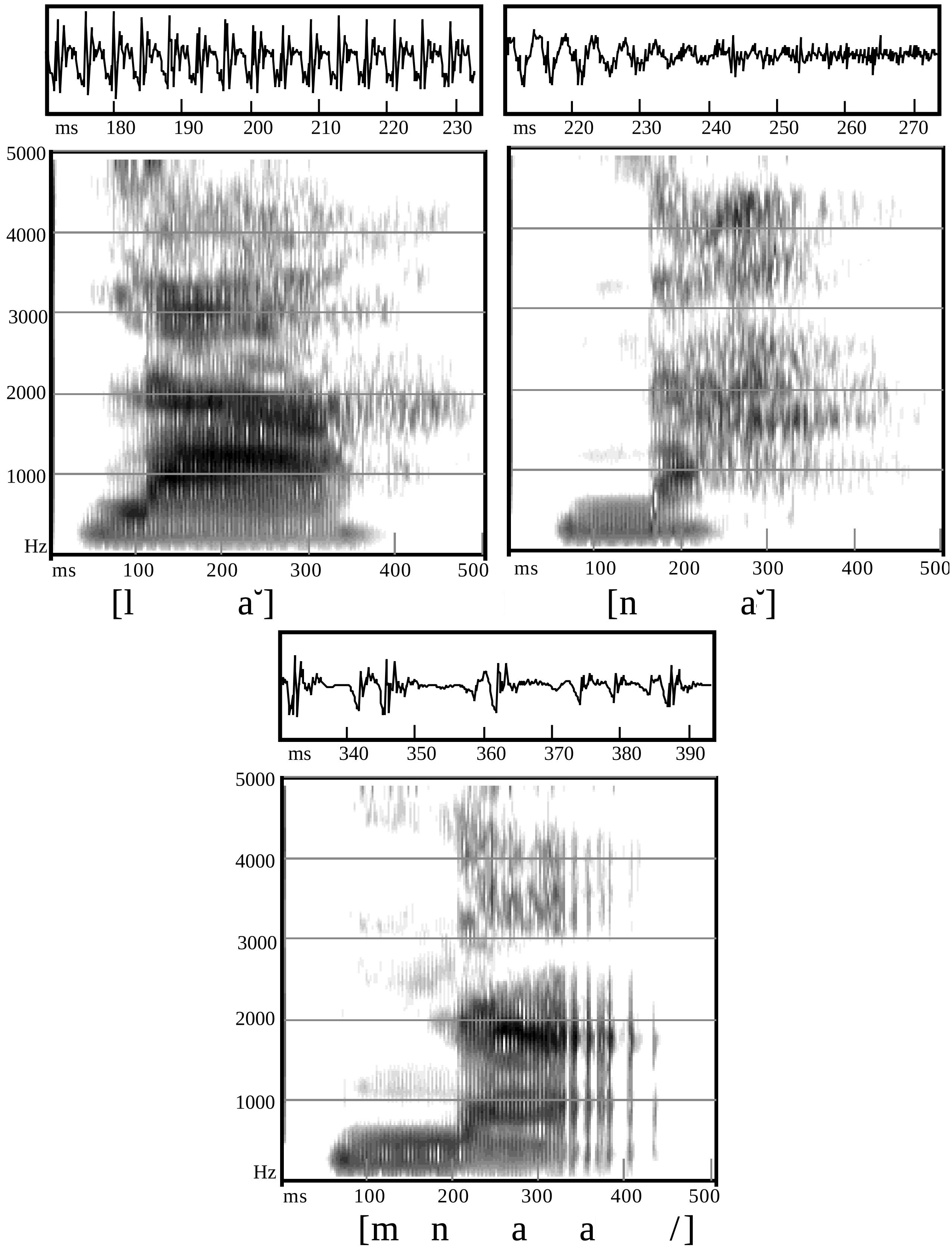

Figure 5. Spectrograms of modal, breathy, and creaky voiced vowels in the San Lucas Quiaviní Zapotec words /laː/ ‘is named’, /na̤ː/ ‘hard, strong’, and /mna̰ːʔ/ ‘woman’ (female speaker)

The waveform for breathy voice shows the same noisiness and reduced intensity characteristic of breathy voice in Newar (figure 2) and Jalapa Mazatec (figure 4). Creakiness is associated with less frequent pitch periods which are very irregular in their duration. From the spectrogram it is clear that the breathy exemplar becomes progressively more breathy and thus noisier throughout the vowel culminating in a completely voiceless offset. Note that the modal vowel also ends somewhat breathy, most likely because the words were said in isolation where the vowel is in utterance-final position, a common environment for allophonic breathiness (see section 3). Like the breathy vowel, the creaky vowel starts off fairly modal before non-modal phonation commences. In the spectrogram for the creaky vowel, the irregular pitch periods indicative of creak are particularly noticeable at the end of the vowel, which culminates in a glottal stop. It is interesting to note that another speaker of San Lucas Quiaviní Zapotec from whom data have been collected, a male, sustains creaky phonation throughout the entire duration of the phonemically creaky vowel, rather than localizing the creakiness to the latter portion of the vowel. Conversely, the female speaker whose spectrograms appear in figure 5 tends to have noticeably breathier vowels than the male speaker. Gender dependent differences of this sort, particularly increased breathiness for female speakers, have also been observed in languages with allophonic rather than contrastive non-modal phonation, including English (e.g. Henton and Bladon 1985, Klatt and Klatt 1990, Hanson and Chuang 1999).

Certain languages employ voice qualities which resemble creaky voice in involving increased constriction in the laryngeal area, but which do not neatly fall under the rubric of creaky voice. For example, Mpi has a tense phonation type which clearly differs from creaky phonation in other languages, though it shares certain properties with creaky voice (such as increased spectral tilt; see section 5 for discussion of phonetic correlates of phonation differences). Furthermore, Bruu has contrasts that might be described as involving stiff vs. slack vocal folds. But the stiffness is not the same as that in creaky voice of the kind used in Jalapa Mazatec, nor does the slackness sound like breathy voice in Gujarati. The stiffness seems to include not only some compression of the glottis, but also increased tension of the pharyngeal walls. This could be classified as a creaky voice, with a 'helping feature' (Stevens, Keyser & Kawasaki, 1986). In addition, certain vowels in !Xóõ employ a voice quality which is typically referred to as "strident" in the literature (Ladefoged and Maddieson 1996). Traill (1985) has given a good description of this voice quality, including x-ray pictures of his own pronunciation of the sound. (His language consultants attest to the high quality of his pronunciation.) It has a narrowing above the glottis that involves the aryeppiglottic fold that affects the vibration of the true vocal folds. Strident vowels are associated with irregular noisy vibrations and higher first and second formant values due to the pharyngeal constrictions associated with the movement of the aryeppiglottic fold and backing of the epiglottis (Ladefoged and Maddieson 1996).

2.4. Glottal stop

Before concluding discussion of the nature of linguistic phonation contrasts, a few words about the fifth step along Ladefoged's continuum of phonation types are in order. This fifth step, complete glottal closure, entails an absence of vocal fold vibration, as occurs in the middle of the English interjection *uh-oh*. Glottal stops like the one occurring in this English example are quite common in languages of the world often contrasting with oral stops, unlike in English where glottal stop is non-contrastive. Often phonemic glottal stops are realized as creaky phonation on neighboring sounds rather than with complete glottal closure (Ladefoged and Maddieson 1996: 75).

3. Allophonic non-modal phonation

Thus far, we have only considered languages in which phonation differences are used contrastively. Non-modal phonation types also commonly arise as allophonic variants of modal phonation in certain contexts. Segmentally conditioned allophonic non-modal phonation on vowels is extremely common in the vicinity of consonants that are not produced with modal phonation. For example, allophonic breathiness is characteristically found on vowels adjacent to /h/ and allophonic creak is often associated with vowels adjacent to glottal stop, with languages differing in the duration of this allophonic non-modal phonation (see Blankenship 1997). Final voiceless stops in certain varieties of English also trigger a short creaky phase on the end of the immediately preceding vowel. In many languages, particularly those of the Pacific Northwest, e.g. Hupa, Quileute, Yana, Takelma (Sapir 1912), allophonic non-modal phonation occurs on vowels preceding stops (subject to certain prosodic restrictions in some languages; see section 4.1), breathiness before voiceless stops and creak before ejectives. In Chitimacha (Swadesh 1934), underlying glottalized stops are realized as preglottalized stops in syllable-final position.

Non-modal phonation, especially creaky voice, is commonly used cross-linguistically as a marker of prosodic boundaries, either initially and/or finally, as, for example, in Swedish (Fant and Kruckenberg 1989), English (Lehiste 1979, Kreiman 1982, Dilley et al. 1996), Finnish (Lehiste 1965), Czech (Lehiste 1965), and Serbo-Croatian (Lehiste 1965). Vowel-initial words frequently have a creaky onset in many languages, where creakiness is more common at the beginning of larger prosodic units than smaller ones (Pierrehumbert and Talkin 1992, Dilley et al. 1996) and more frequent in accented than unaccented syllables (Pierrehumbert 1995, Dilley et al. 1996). There are numerous other factors in addition to accent and constituency, e.g. grammatical category, frequency of occurrence, segmental context, etc., which influence the likelihood of non-modal phonation occurring (see Dilley et al. 1996 for an overview of some of the relevant literature on prosodically conditioned glottalization).

4. Issues in the timing of non-modal phonation

Thus far in our discussion of segmental phonation contrasts, we have not talked about the timing of phonation events. In many cases, sounds which are described as being realized with non-modal phonation do not extend their non-modal phonation over an entire segment. Rather, non-modal phonation is often confined to a portion of the sound and/or spills over onto an adjacent sound. An especially common timing feature of non-modal phonation is its confinement to contexts in which its potentially detrimental effects on other perceptually important properties are minimized.

4.1. Timing of non-modal phonation in vowels

Among contrastively non-modal voiced vowels, creakiness and breathiness are localized to a portion of the vowel in Jalapa Mazatec (see spectrograms in Figure 4; also, Silverman et al. 1995, Blankenship 1997). Silverman (1995, 1997) suggests a link between the confinement of non-modal phonation to a portion of vowels and the use of contrastive tone in Jalapa Mazatec. He hypothesizes, and then corroborates for breathy phonation in later experimental work (Silverman to appear) that, because non-modal phonation influences fundamental frequency (see discussion in section 5), it adversely affects the ability of vowels to support tonal contrasts. By preserving modal phonation on a portion of the vowel, there is sufficient space remaining on which to realize tonal contrasts effectively, particularly since the overall duration of non-modal vowels is substantially longer than that of modal vowels. Thus, preservation of non-modal phonation on a portion of the vowel does not come at the expense of rendering information about voice quality less salient.

Confinement of non-modal phonation to portions of vowels is not only a feature of languages that use tone contrastively. In Hupa (Golla 1970, 1977, Gordon 1998), which does not have contrastive tone, creaky voice and breathy voice spread from syllable-final ejectives and voiceless obstruents, respectively, onto only the latter half of a preceding long vowel and not onto short vowels at all. By asymmetrically spreading non-modal phonation in this way, there is always a portion of the vowel which is characterized by modal phonation, the entire vowel in the case of short vowels and the first half of long vowels. A similar spreading asymmetry conditioned by vowel length is found in Quileute (Powell and Woodruff 1976), with the added restriction that non-modal phonation does not spread onto unstressed long vowels. It is thus only those vowels that are presumably longest, namely the stressed long vowels, that support non-modal phonation in Quileute and only for a portion of their duration. One might hypothesize that the Hupa and Quileute patterns stem from a detrimental effect of non-modal phonation on not only the ability to realize tonal information, as shown by

Silverman (to appear), but also on the ability to realize place information in vowels. In support of this hypothesis, non-modal phonation types often alter formant structure (see section 5). The additional length associated with breathy vowels in languages like Kedang (Samely 1991) could also reflect an attempt to enhance the overall salience of place information in the face of the reduced salience at any one point in time due to non-modal phonation.

4.2. Timing of non-modal phonation in consonants

Non-modal phonation realized on consonants displays interesting timing patterns. We discuss here some of the timing properties characteristic of the most common type of non-modally voiced consonants: creaky voiced sonorants. Creaky voiced sonorants, also termed “glottalized” sonorants, show an overwhelming cross-linguistic tendency to realize their creak early in the sonorant, often sharing it with the immediately preceding vowel, an as yet poorly understood timing preference presumably driven by auditory considerations (see Kingston 1985, Silverman 1995, Steriade 1999). These “pre-creaked” sonorants are reported in a number of North American Indian languages, including Montana Salish (Flemming et al. 1994), Klamath (Barker 1964, Blevins 1993), Yokuts (Newman 1944), Coast Tsimshian (Dunn 1979), Nuuchahnulth (Shank and Wilson 2000), Nez Perce (Aoki 1970a), Kalispel (Vogt 1940), Heiltsuk (Rath 1981), Ineseño Chumash (Applegate 1972), Squamish (Kuipers 1967). In Figure 3, we saw examples of pre-creaked sonorants in Kwakw’ala.

In a number of other languages, the location of the creak is dependent on the context in which the creaky voiced sonorant occurs. In the most typical case, glottalized sonorants realize their creak primarily at the beginning (often shared with the preceding vowel) in prevocalic position, but shift their creak towards the end when they do not precede a vowel. This timing asymmetry is found, for example, in Caddo (Chafe 1976), Shuswap (Kuipers 1974), Chitimacha (Swadesh 1934), Bella Coola (Nater 1984). In Kashaya Pomo (Buckley 1990, 1992), glottalized sonorants are restricted to preconsonantal and final (i.e. coda), positions, where their creak is realized near the end. This timing pattern is consistent with the tendency for glottalized sonorants in many languages to realize their creak at the beginning in positions that are not prevocalic. Typically, context-dependent timing differences of the type just discussed are implicitly described in primary sources with reference to isolated words; it is conceivable that investigation of words in phrasal contexts could reveal further interesting timing properties.

Hupa (Golla 1970, 1977, Gordon 1996) has turned what once was a predictable timing asymmetry between preglottalized nasals in prevocalic position and postglottalized nasals in preconsonantal and final position into a morphologically contrastive timing difference due to a chronologically later apocope process (loss of word-final vowels) affecting final short vowels. Thus, preglottalized sonorants appear in root-final position of stems which historically ended in a short vowel (which still surfaces before consonant-initial clitics), while postglottalized nasals occur in consonant-final stems. Because of final vowel loss, we thus find pairs of words differing in whether they end in a pre- or post-glottalized nasal. In practice, this contrast typically does not rely solely on the timing of glottalization, since nasals originally occurring before a vowel are alveolar whereas those not followed by a vowel are velar. However, place assimilation affecting final nasals can turn a velar nasal to an alveolar one, thereby eliminating the place difference between pre and postglottalized nasals. Figure 6 contains spectrograms (from words uttered in isolation) illustrating pre- (on the left) and post- (on the right) glottalized nasals in Hupa (with an accompanying place difference).

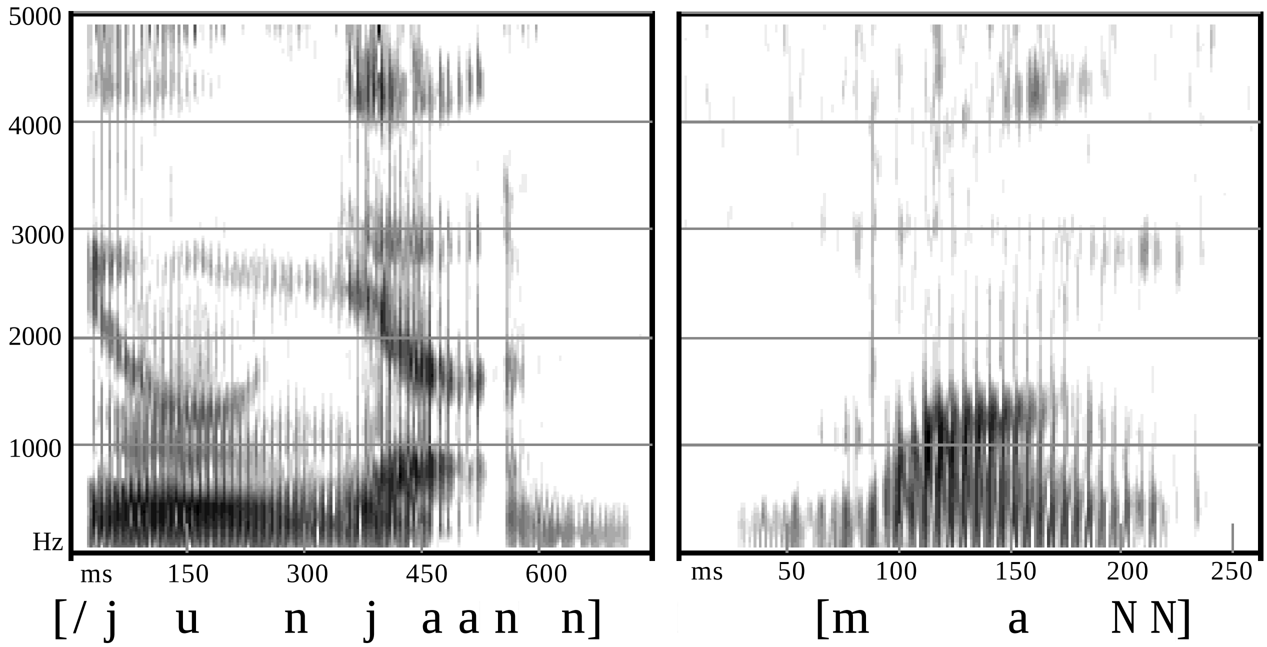

Figure 6. Spectrograms of a pre- and post-glottalized sonorants in the Hupa words /kʲ’unjaːŋ̰/ (in this token, phonetically [ʔjunjaːŋ̰]) ‘acorn’ and /maŋ̰/ ‘fly’ (female speaker)

In the case of the preglottalized nasal on the left, creak is realized primarily on the end of the preceding vowel (450 to 550 milliseconds). In the postglottalized nasal at the end of the word on the right, creak is realized at the end of the velar nasal (210 to 230 milliseconds).

4.3. Auditory motivations for timing of non-modal phonation

A unifying feature of languages which asymmetrically realize creak at the beginning of prevocalic sonorants and at the end of sonorants in other positions is their avoidance of creaky voice on transitions from the sonorant into the following vowel. Shifting non-modal phonation away from the CV transition is plausibly driven by considerations similar to those hypothesized above to account for the dispreference for non-modal phonation to be coextensive with entire vowels. Transitions from consonants into an adjacent vowel, particularly those into a following vowel, provide important information about place and manner of the consonant (see experimental data in Malécot 1956, 1958, Recasens 1983, Kurowski and Blumstein 1984, Manuel 1991, inter alia, and its implications for phonological neutralization patterns in Jun 1995, 1996). By realizing non-modal phonation at the beginning of a prevocalic sonorant, the transitions into a following vowel, which are perceptually most valuable, remain modal voiced and thus clearer from an auditory standpoint. In positions that are not prevocalic, i.e. in final or preconsonantal position, sonorants are adjacent to a vowel on only one side, the left side. By shifting the glottalization to the end of the sonorant in these contexts, the sole consonant-vowel transition is realized with modal voicing and thus retains maximal perceptual salience.

Other languages display asymmetries in the timing of glottalized sonorants based on vowel length and stress in ways that fit in with the hypothesis that non-modal phonation adversely affects the perception of place information. In Saanich (Montler 1986), creaky voiced sonorants share their creak with a preceding vowel if it is stressed, otherwise with the following vowel. In Cowichan (Bianco 1999), glottalized sonorants in intervocalic position realize their glottalization at the beginning if the preceding vowel is full, i.e. long, otherwise at the end. (In preconsonantal and final position, glottalization is consistently realized at the end of the sonorant, a pattern similar to one reported above for Caddo, Shuswap, Chitimacha, Bella Coola, Hupa, and Kashaya Pomo.) Similarly, creak migrates onto stressed vowels in Shuswap (Kuipers 1974). These timing patterns are amenable to the same explanation claimed earlier to drive the timing patterns seen in non-modal vowels: non-modal phonation is realized in environments where its effect on other perceptually significant properties is minimized.

Clearly, however, it is not only the realization of information about place and manner which is relevant in accounting for timing patterns associated with non-modal phonation. In many languages, e.g. Nez Perce (Aoki 1970b), Hupa (Golla 1970), Thompson Salish (Thompson and Thompson 1992), Yokuts (Newman 1944), glottalized sonorants either do not occur or are rare in word-initial position or after another consonant. As Steriade (1999) suggests, this phonological restriction likely results from the rigid language-specific phonetic preference for realizing creaky voice at the beginning of sonorants, combined with a requirement that creak be realized at least partially on an adjacent vowel, thereby enhancing the salience of the creaky phonation. Because a sonorant in word-initial or postconsonantal position has no preceding vowel on which to realize its creak, creaky sonorants are banned in these positions in many languages.

In contrast to languages that restrict glottalized sonorants in word-initial and postconsonantal position, Nuuchahnulth (Shank and Wilson 2000) restricts word-final and preconsonantal glottalized sonorants. This phonological restriction is presumably also driven from a combination of auditorily-driven requirements on timing, albeit a slightly different combination than is responsible for the restriction against word-final and postconsonantal sonorants seen in other languages. In Nuuchahnulth, glottalized sonorants must realize their creak at the beginning, while simultaneously preserving modal voiced transitions into at least one adjacent vowel. In final and preconsonantal positions, both requirements cannot be satisfied; the result is a phonological ban on glottalized sonorants in these positions.

As this section's preliminary hypotheses suggest, cross-linguistic exploration of phonation timing patterns is in its relative infancy. As a greater amount of phonetic and phonological data on the distribution and realization of phonation contrasts comes to light, we will be in a better position to describe and explain the rich set of timing patterns observed in languages of the world.

5. Phonetic properties associated with phonation types

Ladefoged and Traill (1980) and Ladefoged (1983), following suggestions from Ken Stevens (p.c.), showed that phonation differences can be quantified through a number of phonetic measurements, even if certain physiological or auditory properties defining these phonation types are harder to define. Much work on linguistic voice quality (e.g. Fischer-Jørgensen 1967, Bickley 1982, Maddieson and Ladefoged 1985, Huffman 1987, Traill and Jackson 1988, Ladefoged et al. 1988, Thongkum 1988, Kirk et al. 1993, Blankenship 1997, etc.) has focused on discovering these phonetic dimensions along which contrasts in phonation type are realized. This body of work has revealed a number of cross-linguistic similarities in the realization of phonation differences, but has also indicated some differences. Some of the properties used to describe phonation differences have been discussed in the context of the examples in section 2. We summarize here some of these results, focusing on differences between modal voice and the two most common non-modal phonation types, breathy voice and creaky voice.

There are a number of acoustic, articulatory, and aerodynamic properties that potentially distinguish creaky and breathy phonation (as well as other non-modal phonation types) from each other and from modal phonation. Languages differ in the precise set of properties used to distinguish these phonation types, though there is generally some agreement between languages in how phonation contrasts are signaled. We focus here on some acoustic and aerodynamic characteristics defining phonation differences in naturally occurring non-pathologic speech (see Gerratt and Kreiman this volume for discussion of phonation differences in vocal pathologies). These include periodicity (section 5.1), intensity (section 5.2), spectral tilt (section 5.3), fundamental frequency (section 5.4), formant frequencies (section 5.5), duration (section 5.6), and airflow (section 5.7).

Further discussion of the physiological characteristics of various laryngeal settings can be found in Catford (1964), Ladefoged (1971), Laver (1980), Hirose (1995), and Ní Chasaide and Gobl (1995).

5.1. Periodicity

Creaky phonation is characteristically associated with aperiodic glottal pulses. This feature of creak was evident in the waveforms and spectrograms of creak in figures in section 2. The degree of aperiodicity in the glottal source can be quantified by measuring the "jitter", the variation in the duration of successive fundamental frequency cycles. Jitter values are higher during creaky phonation than other phonation types, as found for Burmese by Javkin and Maddieson (1985) and Jalapa Mazatec (Kirk et al. 1993). Breathiness is characterized by increased spectral noise, particularly at higher frequencies, as we saw earlier in waveforms and spectrograms of breathy sounds in Newar, Jalapa Mazatec, and San Lucas Quiaviní Zapotec. This noise reflects the presence of substantial random noise during breathy vowels (particularly at high frequencies) due to the persistent leakage of air through the glottis (see Ladefoged et al. 1988 for !Xóõ and Blankenship 1997 for Jalapa Mazatec and Chong).

5.2. Acoustic intensity

Breathy phonation is associated with a decrease in overall acoustic intensity in many languages, e.g. Gujarati (Fischer-Jørgensen 1967), Kui and Chong (Thongkum 1988), Tsonga (Traill and Jackson 1988), Hupa (Gordon 1998). Creakiness also triggers a reduction in intensity (relative to modal phonation) in certain languages, e.g. Chong (Thongkum 1988) and Hupa (Gordon 1998). The reduction in intensity characteristic of both creaky and breathy vowels relative to modal ones was evident in the waveforms and spectrograms in section 2.

5.3. Spectral tilt

One of the major acoustic parameters that reliably differentiates phonation types in many languages is spectral tilt, i.e. the degree to which intensity drops off as frequency increases. Spectral tilt can be quantified by comparing the amplitude of the fundamental to that of higher frequency harmonics, e.g. the second harmonic, the harmonic closest to the first formant, or the harmonic closest to the second formant. Spectral tilt is characteristically most steeply positive for creaky vowels and most steeply negative for breathy vowels. In other words, the fall off in energy at higher frequencies is least for creaky voice and most for breathy voice. Subtracting the amplitude of the fundamental from the amplitude of higher harmonics thus yields the greatest values for creaky vowels and the smallest values for breathy vowels, with intermediate values for modal vowels. Spectral tilt reliably differentiates phonation types in a number of languages, including Jalapa Mazatec (Kirk et al. 1993, Silverman et al. 1995), which contrasts creaky, breathy, and modal vowels, !Xóõ (Bickley 1982, Ladefoged 1983, Jackson et al. 1988), which distinguishes between breathy and modal vowels (as well as a third type of phonation, strident, discussed in section 2.3), Gujarati (Fischer-Jørgensen 1967), which contrasts breathy and modal vowels, Kedang (Samely 1991), which contrasts modal and breathy vowels, Hmong (Huffman 1987), which distinguishes breathy and modal vowels, Tsonga (Traill and Jackson 1988), which contrasts breathy and modal nasals, some minority languages of China (Jingpho, Haoni, Wa, Yi) examined by Maddieson and Ladefoged (1985), which contrast a "tense" phonation somewhat different from creaky phonation with a more modal phonation type, and, finally, Mpi, which also contrasts tense and non-tense (or "lax") phonation.

Different measures of spectral tilt do not always behave uniformly in differentiating phonation types in a single language. In Mpi, which uses tone contrastively, Blankenship (1997) found interactions between tone level and measurements of spectral tilt. The amplitude difference between the fundamental and the second harmonic was a more reliable indicator of phonation type for high tone than for either mid or low tone, whereas the amplitude difference between the fundamental and the harmonic closest to the second formant was more useful for differentiating phonation contrasts in mid and low tone vowels than in high tone vowels.

Differences in spectral tilt between creaky, breathy, and modal vowels in San Lucas Quiaviní Zapotec are illustrated in Figure 7 by means of FFT spectra from a male speaker.

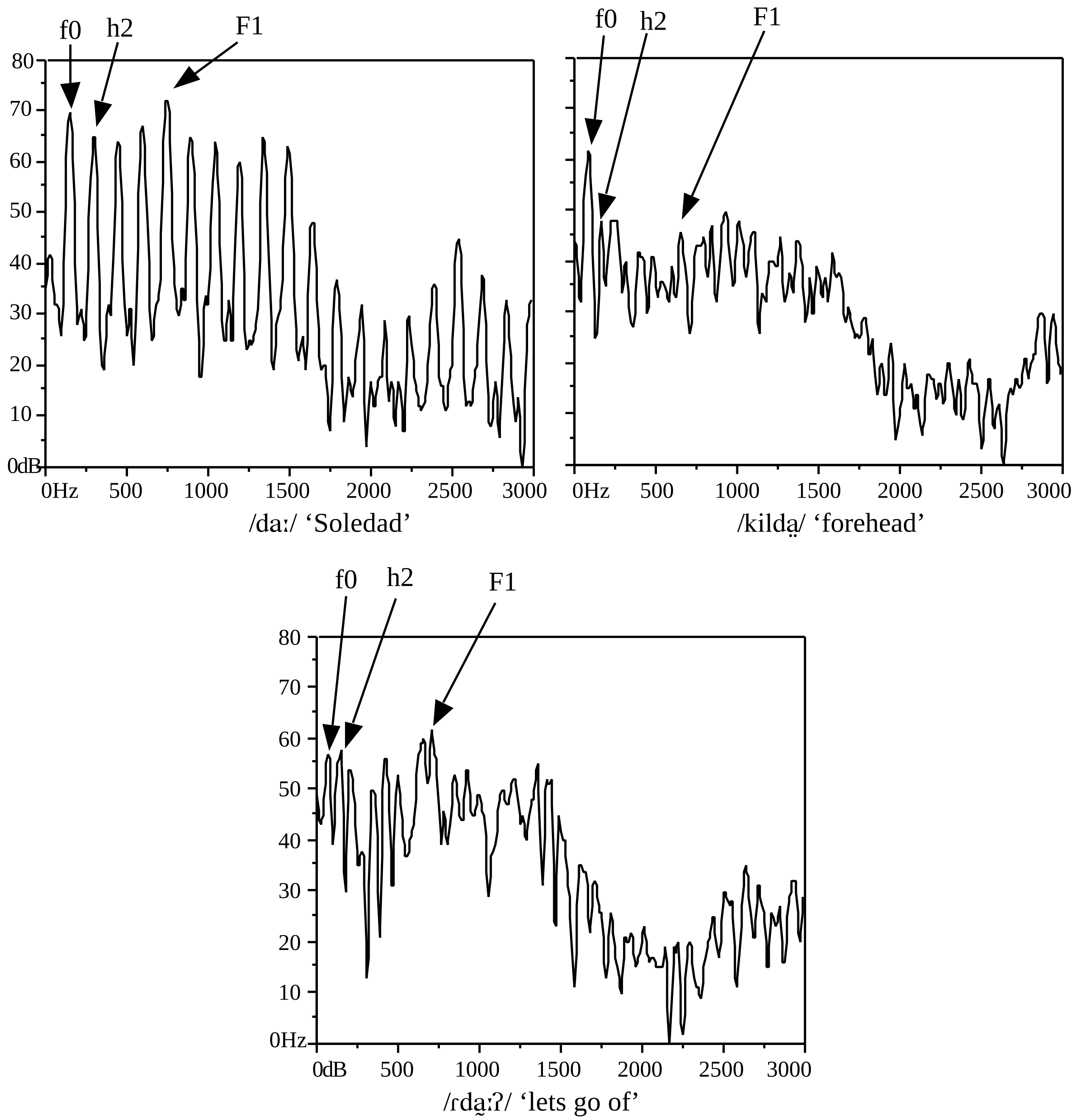

Figure 7. FFT spectra of modal, breathy, and creaky /a/ in the San Lucas Quiaviní Zapotec words /daː/ ‘Soledad’, /kilda̤/ ‘forehead’, and /ɾda̰ːʔ/ ‘lets go of’ (male speaker)

In the creaky vowel, the amplitude of the second harmonic is slightly greater than that of the fundamental. At the other extreme, in the breathy vowel, the amplitude of the second harmonic is considerably less than that of the fundamental. The modal vowel occupies middle ground between the creaky and breathy vowels: its second harmonic has slightly less amplitude than the fundamental. Similar differences between phonation types can be seen by comparing the amplitude of the harmonic closest to the first formant relative to that of the fundamental. In the breathy vowel, the harmonic closest to the first formant has much lower amplitude than the fundamental. In the creaky vowel, on the other hand, the harmonic closest to the first formant has much greater amplitude than the fundamental. The modal vowel is intermediate, characterized by very similar amplitude values for the fundamental and the first formant. Spectral tilt values, as defined by two measurements, h2-f0 and F1-f0, thus form a continuum differentiating the three phonation types of San Lucas Quiaviní Zapotec: breathy vowels have the greatest drop off (or smallest increase depending on the particular measure) in energy as frequency increases, while creaky vowels display the largest boost in energy as frequency is increased.

Spectral tilt has been associated with various physiological characteristics. Holmberg et al. (1995) found that intensity differences between the fundamental and the second harmonic correlate with the percentage of the glottal cycle during which the glottis is open (the open quotient): the less the amplitude of the second harmonic relative to that of the fundamental, the greater the open quotient. Stevens (1977) has suggested that a general measure of spectral slope, quantified in terms of amplitude differences between the fundamental and higher harmonics, correlates with the abruptness (or gradualness) of vocal fold closure: the less the amplitude of higher harmonics relative to that of the fundamental, the less abrupt the glottal closing gesture. Both an increased open quotient and a less abrupt glottal closing gesture are physiological correlates of breathiness (see Huffman 1987 on breathiness in Hmong). Conversely, a decreased open quotient and a more precipitous closing gesture are potentially associated with creakiness (see Javkin and Maddieson 1985 on creak in Burmese). Consequently, it is not surprising that both measures of spectral tilt (h2-f0 and F1-f0) often pattern together in languages.

5.4. Fundamental frequency

Non-modal phonation types are commonly associated with lowering of fundamental frequency, a tendency which was evident in earlier waveforms in section 2 and in the spectra in figure 7. Creaky voice is associated with lowered fundamental frequency values (relative to modal phonation) in many languages, synchronically or diachronically, e.g. Mam (England 1983), Northern Iroquoian languages such as Mohawk, Cayuga, and Oneida (Chafe 1977, Michelson 1983, Doherty 1993). It should, however, be noted that this lowering effect is not universal, as certain languages have developed high tone as a reflex of glottal constriction (see Hombert et al. 1979 for discussion). The historical development of Athabaskan languages from proto-Athabaskan provides a nice example of how glottalization can be associated with high tone in some languages but with low tone in closely related languages (Leer 1979). Breathy phonation appears to be more consistently associated with lowered tone in the majority of languages (see Hombert et al. 1979 for an overview).

5.5. Formant frequencies

Formant frequencies may also vary as a function of phonation type. For example, Kirk et al. (1993) observe that frequency values for the first formant are higher during creaky phonation than either breathy or modal phonation in Jalapa Mazatec, which they speculate is due to a raising of the larynx and concomitant shortening of the vocal tract during creaky voice. Maddieson and Ladefoged (1985) also report raised first formant values for tense vowels in Haoni. Conversely, Thongkum (1988) reports that breathiness is associated with a lowering of the first formant in Chong, though she does not observe this difference in the related languages Nyah Kur and Kui. Based on observations of other scholars (Henderson 1952, Gregerson 1976), Thongkum suggests that the lowering of the first formant during breathy phonation in Chong might be attributed to larynx lowering; this explanation would fit in with the suggestion of Kirk et al. (1993) that the opposite effect, the raising of the first formant during creaky phonation, is an acoustic correlate of larynx raising. Samely (1991) also found that breathy vowels have lower first and second formant values than modal vowels in Kedang, though it should be pointed out that breathy vowels in this language are associated with increased pharyngeal width which could contribute to the observed formant differences.

5.6. Duration

Non-modal phonation types are in some languages, though not all, associated with increased duration. This is not true of Hmong (Huffman 1987) and is not true of the San Lucas Quiaviní Zapotec data in figure 5. Breathy vowels are substantially longer than modal vowels, however, in Kedang (Samely 1991) and Jalapa Mazatec (Kirk et al. 1993, Silverman et al. 1995), and creaky vowels are longer than modal vowels in Jalapa Mazatec (Kirk et al. 1993, Silverman et al. 1995). A related observation in keeping with the greater duration characteristic of non-modal phonation types is that non-modal phonation may occur on phonemic long vowels but not on phonemic short vowels in Hupa (Golla 1970, 1977, Gordon 1998). Quileute (Powell and Woodruff 1976) displays a similar restriction, with the added proviso that the long vowels must be stressed to support non-modal phonation (see section 4 for further discussion of duration and timing issues relevant for non-modal phonation).

5.7. Aerodynamic properties

Phonation contrasts also appear to be associated with aerodynamic differences, at least as far as the limited amount of relevant data show. Ladefoged and Maddieson's (1985) study of four minority languages of China (Jingpho, Wa, Yi, Haoni) shows that the tense vowels in the four languages are generally associated with less airflow for a given subglottal pressure than the lax vowels, suggesting that the tense vowels are associated with a more constricted glottis that allows less air flow.

6. Conclusions

In summary, investigation of phonation differences is an important area of research, as many languages employ distinctions which rely solely on differences in voice quality. As we have seen, these distinctions may involve two or more different phonation types and may affect consonants, vowels, or both consonants and vowels. In addition, many other languages regularly use non-modal phonation types as variants of modal voice in certain prosodic contexts. Languages also differ in their timing of non-modal phonation relative to other articulatory events in interesting ways, although there are certain recurrent timing patterns and distributional restrictions which warrant explanation.

Differences in phonation type can be signaled by a large number of quantifiable phonetic properties in the acoustic, aerodynamic, and articulatory domains, the last of which has been relatively unstudied due to the invasive measurement techniques required. It is unlikely, however, that future research will yield many truly universal observations about the range and realization of phonation types in languages of the world. We can never know whether some language in the past had or in the future will have a novel method of using the vocal folds to make a linguistic contrast. The occurrence of phonetic rarities such as the strident voice quality that occurs in !Xóõ (section 2.3) and a few neighboring languages shows that we can use the glottis in totally unexpected ways. If the Xóõ did not exist, and someone had suggested that a sound of this kind could be used in a language, scholars would probably have said that this was a ridiculous notion. !Xóõ is an endangered language, and we are lucky to have been able to hear these sounds. But who knows what other phonation types could occur in a language?

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Appendix: Languages discussed in the text with phonation contrasts

Language	Non-modal phonation	Genetic Affiliation[1]	Area	References
!Xóõ	strident	Khoisan	Botswana	Traill (1985), Ladefoged and Antoñanzas-Barroso (1985), Ladefoged et al. (1988)
Bella Coola	creaky	Salishan	British Columbia Canada	Nater (1984)
Bruu	stiff	Austro-Asiatic	Thailand, Laos	Ladefoged (fieldwork)
Burmese	breathy, creaky	Sino-Tibetan	Myanmar	Javkin and Maddieson (1985)
Caddo	creaky	Caddoan	Oklahoma, USA	Chafe (1976)
Chitimacha	creaky	Gulf	Louisiana, USA	Swadesh (1934)
Chong	breathy, creaky	Austro-Asiatic	Thailand	Thongkum (1988)
Coast Tsimshian	creaky	Penutian	British Columbia Canada	Dunn (1979)
Cowichan	creaky	Salishan	British Columbia Canada	Bianco (1999)
Gujarati	breathy	Indo-European	India	Pandit (1957), Fischer-Jørgensen (1967)
Haoni	tense	Sino-Tibetan	China	Ladefoged and Maddieson (1985)
Hausa	creaky	Afro-Asiatic	Nigeria	Ladefoged and Maddieson (1996)
Heiltsuk	creaky	Wakashan	British Columbia Canada	Rath (1981)
Hindi	breathy	Indo-European	India	Kagaya and Hirose (1975), Benguerel and Bhatia (1980), Dixit (1989)
Hmong	breathy	Hmong-Mien	Laos	Huffman (1987)
Hupa	creaky	Na Dene	California, USA	Gordon (1996)
Ineseño Chumash	creaky	Chumash	California, USA	Applegate (1972)
Jalapa Mazatec	breathy, creaky	Otomanguean	Mexico	Kirk et al. (1993), Silverman et al. (1995), Silverman (1997)
Jingpho	tense	Sino-Tibetan	China	Ladefoged and Maddieson (1985)
Kalispel	creaky	Salishan	Washington, Montana, USA	Vogt (1940)
Kashaya Pomo	creaky	Hokan	California, USA	Buckley (1990, 1992)
Kedang	breathy	Austronesian	Indonesia	Samely (1991)
Klamath	creaky	Penutian	Oregon, USA	Barker (1964), Blevins (1993)
Kui	breathy	Dravidian	Thailand	Thongkum (1988)
Kwakw'ala	creaky	Wakashan	British Columbia, Canada	Boas (1947)

[1] Genetic affiliations are according to the 14^{th} edition of the SIL Ethnologue (CD-ROM version, 2000, edited by Barbara Grimes).

Maithili	breathy	Indo-European	India	Yadav (1984)
Montana Salish	creaky	Salishan	Washington, Montana, USA	Flemming et al. (1994)
Mpi	tense	Sino-Tibetan	Thailand	Blankenship (1997)
Newar	breathy	Sino-Tibetan	Nepal	Ladefoged (1983)
Nez Perce	creaky	Penutian	Idaho, USA	Aoki (1970a, b)
Nuuchahnulth	creaky	Wakashan	British Columbia Canada	Shank and Wilson (2000)
Nyah Kur	breathy	Austro-Asiatic	Thailand	Thongkum (1988)
Quileute	creaky	Chimakuan	Washington, USA	Powell and Woodruff (1976)
Saanich	creaky	Salishan	British Columbia Canada	Montler (1986)
San Lucas Quiaviní Zapotec	breathy, creaky	Oto-Manguean	Mexico	Munro and Lopez (1999)
Shuswap	creaky	Salishan	British Columbia Canada	Kuipers (1974)
Squamish	creaky	Salishan	British Columbia Canada	Kuipers (1967)
Takelma	creaky	Penutian	Oregon, USA	Sapir (1912)
Telugu	breathy	Dravidian	India	Ladefoged and Maddieson (1996)
Thompson Salish	creaky	Salishan	British Columbia Canada	Thompson and Thompson (1992)
Tsonga	breathy	Niger-Congo	Mozambique	Traill and Jackson (1988)
Wa	tense	Austro-Asiatic	China	Ladefoged and Maddieson (1985)
Yana	creaky	Hokan	California, USA	Sapir and Swadesh (1960)
Yi	tense	Sino-Tibetan	China	Ladefoged and Maddieson (1985)
Yokuts	creaky	Penutian	California, USA	Newman (1944)