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The acoustics of coarticulated non-modal phonation

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Abstract

Despite the growing number of studies on the acoustics of non-modal phonation, little is known about how two distinct non-modal phonations can interact acoustically when coarticulated. This study investigates the acoustics of potential breathy-to-creaky phonation contours from a production study of native speakers of English, White Hmong, and Korean. These languages differ in the nature of the non-modal phonations. In the English corpus, both the breathiness and creakiness are allophonic. In the Hmong corpus, the breathiness is allophonic but the creakiness is phonemic. In the Korean corpus, the breathiness is arguably phonemic, and the creakiness is allophonic.

The contours were analyzed using the three measures of phonation that were found to best differentiate non-modal from modal phonation in these languages: H1*-H2*, H1*-A1*, and Harmonics-to-Noise Ratio. Results from these measures provide support for the presence of breathy-creaky contours in vowels. The duration and differentiation from modal values of the non-modal phonations are largely dependent on whether it is contrastive or allophonic, in support of Blankenship (2002). The limiting of extensive allophonic phonation coarticulation is taken as evidence of a modal feature specification on vowels of English, which lacks contrastive phonation on vowels.[*]

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1 Introduction

This study investigates the acoustics of breathy phonation that is coarticulated with creaky phonation in English, Hmong, and Korean, and finds that the presence of a phonation contrast in a language can account for cross-linguistic differences in the timing of non-modal phonation coarticulation. Little is known about how two distinct non-modal phonations can interact when coarticulated. Studies of non-modal phonation typically focus on experimental (usually acoustic) descriptions of the production of contrastive non-modal phonation, as in Green Mong (Andruski & Ratliff, 2000), White Hmong (Huffman, 1987; Esposito, submitted), Khmer (Wayland & Jongman, 2003), and recently in Chong (DiCanio, 2009) and dialects of Zapotec (Avelino, 2010; Esposito, 2010a). Additionally, there has been some research done on the interaction of phonation and prosody, especially in English (e.g. Epstein, 2002; Huffman, 2005), on the phasing of non-modal phonation (Silverman, 1995), and its duration (Blankenship, 2002). More recently, there has also been research on the perception of contrastive phonation (Abramson, L-Thongkum, & Nye, 2004; Gerfen & Baker, 2005; Esposito, 2010b).

Other research has been directed at non-modal phonation that is allophonic, as in English (Ladefoged, 1983; Löfqvist & McGowan, 1992), Swedish (Gobl & Ní Chasaide, 1999), and Tagalog (Blankenship, 1997), to name a few. The studies of allophonic non-modal phonation have either implicitly or explicitly dealt with phonation coarticulation, because allophonic non-modal phonation is due to coarticulation from adjacent segments, usually glottalized or aspirated ones with modal segments. An example is the allophonic breathiness of English vowels following aspirated stops studied by Löfqvist & McGowan (1992). There is currently little understanding of either the articulation or the acoustics of how one non-modal phonation may be coarticulated with another non-modal phonation. For example, a vowel that begins breathy but ends creaky may have a modal transition between the two non-modal voice qualities, schematized in Figure 1. This schematic is meant to represent the relative durations of each phonation within a vowel, with no claim as to the precise gestures involved. The presence of modal voice would be expected if the glottis was the sole articulator of both breathy and creaky voice, as assumed in the glottal stricture continuum hypothesis (Ladefoged, 1971; Gordon & Ladefoged, 2001). As the glottis transitions from more open (breathy) to more closed (creaky), a portion of the vowel is expected to be modal.

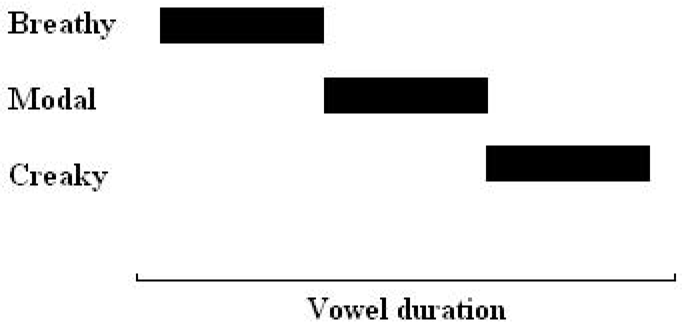


Figure 1. Schematic of breathy-creaky coarticulation with modal transition.

However, non-modal phonation is known to involve other laryngeal and even supralaryngeal postures (Esling & Harris, 2005; Edmondson & Esling, 2006). Given that breathy and creaky voices may be produced by different articulators and therefore independently of one another, there may be no modal transition between them in a breathy-creaky contour. In this case, two scenarios are possible: either the phonation transitions from breathy to creaky with no temporal overlap between them; otherwise, the transition occurs with some degree of overlap. These types of contours are represented in Figure 2:

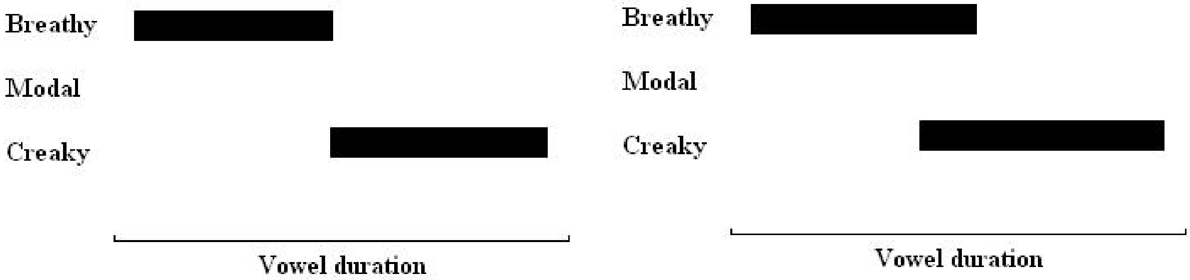


Figure 2. Schematics of breathy-creaky contours with no modal transition. The left panel shows no overlap between the breathy and creaky portions; the right panel shows some amount of overlap.

Another potential interest in studying phonation coarticulation is to investigate the durations of the adjacent voice qualities. Blankenship (2002) found that contrastive non-modal phonation lasts longer and is more differentiated from modal voice than is allophonic (coarticulatory) non-modal phonation. This finding is interesting, because studies of coarticulation of other articulators have shown that coarticulation can span whole segments and even cross segments. For example, Cohn (1990) found that the velum in English begins lowering for a coda nasal early during the preceding vowel. Thus, the allophonic vowel nasalization of English is not substantially shorter than the vowel nasalization of contrastive nasal vowels in French, though the overall amount of nasalization in English may be less than in French. Additionally, the classic study on coarticulation by Öhman (1966) revealed that in VCV sequences, the first vowel already shows effects of the following vowel in English and Swedish. West (1999) also found coarticulatory effects of English /l/ and /r/ on vowels immediately and more distantly preceding the liquid. The coarticulation of some Mandarin tones, which are similar to phonation in that they involve laryngeal articulation, can influence large portions of vowels (Xu, 1997).

Though she studied only coarticulated phonation on modal vowels, Blankenship's findings imply that an interval of allophonic non-modal phonation should be shorter than an interval of contrastive non-modal phonation even when the two are adjacent. However, if two intervals of non-modal phonations that are both allophonic are adjacent in a given segment, then they should have roughly the same duration. These timing differences are schematized for breathy-creaky contours in Figure 3, which ignores the additional question of whether modal voice is present in the transition from breathy to creaky. In both diagrams, the breathiness is allophonic and thus short. In the diagram on the left, the creakiness is phonemic, and thus lasts for much longer than the breathiness. On the other hand, the diagram on the right shows that both the breathy and creaky portions have approximately the same short duration, because both are allophonic:

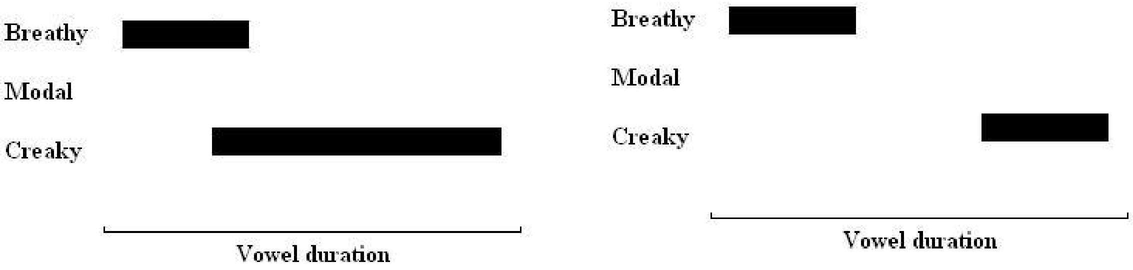


Figure 3. Schematics of the timing of each component of breathy-creaky contours. On the left, allophonic breathiness and phonemic creak; on the right, the creak is also allophonic.

Blankenship did not include in her study allophonic phonation in languages with a phonation contrast. Presumably, allophonic non-modal phonation in these languages should be shorter than the contrastive phonation, but not necessarily shorter than the corresponding allophonic non-modal phonation in a language without phonation contrasts. On the other hand, studies by Manuel & Krakow (1984) and Manuel (1987, 1990) have shown that the system of contrast can limit the extent of coarticulation in a given language. Looking at V-to-V coarticulation, they found that coarticulation was greater in languages with fewer vowel contrasts. They interpret this finding in terms of the presence of output constraints on segments. These constraints are determined in part by the number of contrastive phonemes of the language (in their case, the number of contrastive vowels). Coarticulation is faithful to these constraints, thus being less extensive in languages with many vowels occupying a common space. From the point of view of phonation coarticulation, these studies suggest that having a phonation contrast in a given language should result in less coarticulation of allophonic non-modal phonation. Thus, allophonic non-modal phonation should be less extensive in languages with a phonation contrast, but contrastive phonation should always be extensive. This hypothesis differs from Blankenship's, in that it assumes that the extent of coarticulated (allophonic) non-modal phonation will depend on the presence of phonation contrast in the language, rather than on intrinsic timing differences between phonemic and allophonic phonation.

Thus, the goal of this study is to describe the acoustics of coarticulated non-modal phonation in three languages, and to test whether Blankenship's or Manuel and Krakow's and Manuel's predictions hold true under environments of non-modal coarticulation. The languages investigated all have the potential of showing breathy-creaky contours in vowels, where by "breathy" and "creaky" I make no specific claims about the nature of the articulatory gestures involved in their production. For the purposes of the present study, by "breathy" and "creaky" I mean that the acoustic measures that are known to differentiate phonemic breathy and creaky voice, respectively, show statistically significant differences from modal voice.

In this study, the breathy-creaky contours differ in whether the breathiness and creakiness are contrastive or derived allophonically. Specifically, recordings were made of words with expected breathy-creaky contours in English (for which both the breathiness and creakiness are allophonic), in Hmong (for which the creakiness is phonemic but the breathiness here is allophonic, though it can be phonemic in other environments), and in Korean (for which the creakiness is allophonic but the breathiness, though derived, serves as a major cue to stop contrasts, as will be described below). Keeping with Blankenship (2002), I would predict that the breathiness of Korean should be longer and more differentiated from modal than that of English or Hmong, whose breathiness is purely allophonic. Conversely, the phonemic creakiness of Hmong should be longer and more differentiated from the modal than the allophonic creakiness of English and Korean. If in fact there are output constraints on phonation coarticulation similar to those proposed for vowels by Manuel and Krakow (1984) and Manuel (1987, 1990), then the allophonic breathiness of Hmong should be shorter than that of English, given that the former contrasts three types of phonation while English has no phonation contrast.

2 Phonation types in the languages of study and their acoustic correlates

This section reviews the non-modal phonation found in English, Hmong, and Korean, and outlines which acoustic measures have been used to characterize non-modal phonation in these languages and others.

2.1 Phonation in English, Hmong, and Korean

2.1.1 English

English does not have a phonation contrast, but vowels can show allophonic non-modal phonation in certain prosodic conditions (Kreiman, 1982; Pierrehumbert & Talkin, 1992; Dilley, Shattuck-Hufnagel & Ostendorf, 1996; Redi & Shattuck-Hufnagel, 2001; Epstein, 2002; Huffman, 2005, among others) and adjacent to certain sounds. Vowels following /h/ and aspirated stops are slightly breathy (Ladefoged, 1983; Löfqvist & McGowan, 1992; Epstein, 1999; Gobl & Ní Chasaide, 1999). In addition, glottalized stops (with consequent creakiness on the preceding vowel) often appear as allophones of voiceless stops, especially after sonorants (nasals, liquids, glides or vowels), or before other obstruents and sonorants in coda position(Selkirk, 1972; Westbury & Niimi, 1979; Cohn, 1993; Epstein, 2002; Huffman, 2005).

Allophonic breathiness and creakiness can theoretically co-occur in an English vowel if the environments for both are combined. For example, the vowels in words like *cat* or *hat* should show breathiness at the vowel's onset, because they follow an aspirated stop or /h/. Moreover, the same vowels should show creakiness at the vowel offset, because they are followed by a voiceless stop in coda position. Therefore, my hypothesis is that English words like *cat* or *hat* should show a phonation contour in the vowels, starting from more breathy-like phonation and ending in more creaky-like phonation. Again, by "breathy" and "creaky", I am not committed to the idea that these are necessarily breathy and creaky in the strict sense (described in Section 2.2), but that their phonations are acoustically closer to breathy and creaky voice than to modal. It should matter little, for English as well as for Hmong and Korean, whether in reality these contours are breathy-tense, or lax-creaky, for example, although a more extreme phonation (i.e., a phonation that is more differentiated from modal voice) might in fact be inherently longer in duration. The possibility that cross-linguistic timing differences might be a result of difference in non-modal phonation type will be assessed in the discussion section below.

2.1.2 Hmong

Whereas English only shows non-modal phonation at the allophonic level, Hmong contrasts both breathy and creaky vowels with modal ones. In Hmong, non-modal phonation is associated with certain tones. Vowels may have a phonemic creaky low tone (e.g. /pà̰/ ‘blanket’) or a phonemic breathy falling tone, for example /pâ̤/ ‘pile’. Both the creaky and breathy tones contrast with tones with similar pitch but different phonations. Thus, /pà̰/ ‘blanket’ and /pâ̤/ ‘pile’ contrast mostly in phonation with modal /pà/ ‘stick’ and /pâ/ ‘flower’, respectively, although small differences in the pitch contours exist as well, especially for the creaky tone (Ratliff, 1992; Esposito, submitted).

Hmong distinguishes unaspirated from aspirated stops for voiceless stops at all its places of articulation. The aspirated stops cannot occur before breathy vowels, suggesting that the aspiration noise is perceptually confusable with vowel breathiness. Indeed, both breathy vowels and vowels following aspirated stops show increased breathiness in comparison to modal vowels (Fulop & Golston, 2008).

However, creaky vowels may follow aspirated stops in Hmong, for example in /p^{h}à̰/ ‘chubby, fat.’ Such words should show a breathy-creaky phonation contour. However, unlike in English, the creakiness in such contours is phonemic and there is no coda consonant.

2.1.3 Korean

Korean is well-known for showing non-modal phonation in vowels following stops. Accentual phrase-initially, vowels following tense or fortis stops /p*, t*, k*/ show creakier phonation than vowels after a modal sound like /l/. Conversely, vowels following aspirated stops /p^{h}, t^{h}, k^{h}/ or lax (or lenis) ones like /p, t, k/ show breathier phonation (C-W Kim, 1970; Kagaya, 1974; Cho, 1996; Ahn, 1999; Cho, Jun, & Ladefoged, 2002; Kim, Beddor, & Horrocks, 2002; Kang & Guion, 2008). There are reasons for believing that the phonation differences following stops in Korean are on their way towards become contrastive rather than simple coarticulation of adjacent gestures. First, standard Korean is thought to be undergoing tonogenesis as the VOT difference between aspirated and lenis stops decreases in favor of contrastive F0 differences (Silva, 2006), suggesting that aspirated and lenis stops can only be distinguished using vocalic cues like pitch and phonation. Indeed, F0 is known to be favored now over VOT as a cue to stop type in Korean (Cho, 1996; Kim, Beddor, & Horrocks, 2002). Second, non-modal phonation in Korean lasts for at least half of the vowel’s duration (Cho, Jun, & Ladefoged, 2002), which is comparable to the phonemic breathiness found in Mazatec (Blankenship 2002). This study hopes to clarify whether breathiness in Korean behaves like contrastive or allophonic phonation by looking at its timing and differentiation from modal voice.

In Korean, word-final and pre-consonantal coda stops are known to be unreleased (Kim-Renaud, 1974; Ahn, 1998; Choo & O’Grady, 2003). In a pilot study (Garellek, 2010), these stops were found to show some preglottalization, suggesting that breathy-creaky contour could be found in vowels preceded by a lenis or aspirated stop and followed by a coda stop. The following word in the carrier began with a lax /s/ which undergoes tensification following obstruents (Kim-Renaud, 1974). Thus, the preglottalization found before coda stops can either be due to inherent properties of coda obstruents in Korean or to tensification. However, the presence of preglottalization rather than its origin was of importance for the present study, because creaky voice of any type or origin would be used to study breathy-creaky contours.

2.2. Phonation measures

Although phonation is strictly speaking voicing, which is produced by vibrating vocal folds, non-modal phonation is known to sometimes involve other laryngeal and even supralaryngeal postures (Edmondson & Esling, 2006). Moreover, a range of non-modal phonation is possible, even at the level of the vocal folds. For example, breathy phonation can be produced by a wide resting aperture of the vocal folds, by the slower closing and faster opening of the folds, or by maintaining a constant posterior (inter-arytenoid) gap between the folds (Gordon & Ladefoged, 2001). In their laryngeal articulator model, Edmondson and Esling attribute breathy phonation to Valve 1, which involves vocal fold abduction and adduction. Unlike for breathy voice, Edmondson and Esling attribute laryngealized voice – including specifically glottalization before stops – to actions in Valves 1, 2, and 3, which involve not only the vocal folds but also the ventricular folds, arytenoids, and aryepiglottic folds. Additionally, phrase-final creak has been found to involve low sub-glottal pressure (Slifka, 2006), and creaky voice may include additional effects like vocal fry and period doubling (Gerratt & Kreiman, 2001). Owing to this multi-dimensional nature of non-modal phonation, various acoustic measures have been used to distinguish modal phonation from its non-modal counterparts. By far the most common measure is H1-H2, or the difference in the amplitudes of the first and second harmonics. A higher value of H1-H2 is thought and often found to be correlated with greater glottal open quotient (Holmberg, Hillman, Perkell, Guiod, & Goldman, 1995; Stevens & Hanson, 1995; Sundberg, Andersson, & Haltqvist, 1999; DiCanio, 2009; but cf. Kreiman, Iseli, Neubauer, Shue, Gerratt, & Alwan, 2008). Open quotient (OQ) is the proportion of a glottal period during which there is no contact between the vocal folds. H1-H2 as a correlate of OQ should be a good measure for differentiating non-modal phonations from modal, since breathy phonation often has a greater OQ than modal, whereas creaky phonation can involve a more closed glottis. Indeed, for languages with contrastive breathy phonation, H1-H2 (or its formant-corrected counterpart, denoted by asterisks: H1*-H2*) has been shown to be greater in breathy phonation than in modal for a variety of languages (Bickley, 1982, for Gujarati; Huffman, 1986, for Hmong; Blankenship, 1997, for Mazatec; Wayland & Jongman, 2003, for Khmer; Miller, 2005, for Ju|’hoansi; see Esposito, 2010b, for others). For languages that contrast creaky phonation with modal, a lower H1-H2 has also been found for Mazatec (Blankenship, 1997), Green Mong (Andruski & Ratliff, 2000), Ju|’hoansi (Miller, 2005), Chong (DiCanio, 2009), and Santa Ana del Valle Zapotec (Esposito, 2010a) creaky phonation.

In addition to H1-H2, wideband spectral tilt measures comparing H1 to the amplitude of the first formant (A1) or the second or third formants (A2 or A3) have been used. These measures have long been thought to correlate with the abruptness of vocal fold closure (Stevens, 1977). H1-A1 is correlated with the bandwidth of the first formant, which is also thought to reflect posterior glottal opening at the arytenoids (Hanson, Stevens, Kuo, Chen, & Slifka, 2001). Taking these studies into account, higher H1-A1 should be an indication of whispery voice, which is produced by means of air flowing through the arytenoids (Laver, 1980), whereas the higher spectral tilt measures like H1-A2 and H1-A3 should correlate with speed of closure. Blankenship (1997) found that these measures could distinguish modal from laryngealized phonation to some degree. H1-A2 has been shown to be lower after fortis stops than after /l/ in Korean (Cho, Jun, & Ladefoged, 2002). As with H1-H2, these measures are more often used for comparing breathy and modal phonations. For the effectiveness of these measures at distinguishing breathy versus modal phonation in a number of languages, see Esposito 2006. H1-A2 and H1-A3 tend to be used more widely than H1-A1, but Esposito (2010a) showed that the latter was able to distinguish breathy from modal phonation in several languages. If H1-A1 is a correlate of whispery voice, this suggests that some degree of whisper is present in the breathy phonation of some languages, as is claimed in some studies, e.g. by Fulop & Golston (2008). This is not surprising, given that breathy voice often involves incomplete closure of the vocal folds, which could facilitate inter-arytenoid opening as well.

Noise measures have also been used to distinguish breathy or creaky phonation from modal. De Krom (1993) found that the harmonics-to-noise ratio (HNR) decreased almost linearly as the noise in the signal increased. Noise can be due to aspiration, which is a characteristic of breathy voice, or to aperiodicity, which is a characteristic of creaky voice (Gordon & Ladefoged, 2001). Thus, both aspiration and aperiodicity result in lower HNR values. HNR has been used to distinguish breathy from modal phonation in Javanese (Wayland, Gargash, & Jongman, 1994), Ju|’hoansi (Miller, 2005), and White Hmong (Fulop & Golston, 2008). Miller (2005) also found an effect of HNR for glottalized vowels. Blankenship (2002) showed that another, very similar, measure of noise, cepstral peak prominence (Hillenbrand, Cleveland, & Erickson, 1994) distinguished breathy from modal phonation in Mazatec and Chong, as did Esposito (2010a) for a number of languages.

In sum, breathy-creaky contours are likely to be found in English, Hmong, and Korean. The contours may well be manifested by different acoustic measures, given the success of various studies at characterizing phonation differences using a variety of measures.

3 Experiment

This experiment was designed to compare vowels with breathy-creaky contours in English, Hmong, and Korean to modal vowels. In addition, breathy-modal and modal-creaky contours were included for comparison.

3.1 Method

3.1.1 Stimuli

a) English

The stimuli are divided into four groups based on expected phonation pattern. The target group consists of monosyllabic English words with an expected breathy-creaky contour. These words begin with an aspirated stop /p, t, k/ or /h/, have a low vowel /æ/ or /ɑ/, and end in coda /p, t, k/, for example *pat*.

The next group consists of words with an expected breathy-modal contour. These differ from the breathy-creaky words by having a coda-/s/ (or sometimes /st/, /sk/, or /z/) instead of coda-stops, for example *pass*. Although /s/ also involves glottal spreading and therefore in principle could induce some breathiness on the vowel, little breathiness was found. Fricative codas were chosen because a pilot study revealed that voiced stops in coda position still resulted in creak, and sonorants were avoided because they were likely to influence the formant tracker. The voicing difference between /s/ and /z/ in codas was deemed trivial, in that it was unlikely to alter the voice quality of the preceding vowel appreciably. Moreover, the following word from the carrier *Say the words _____ for me* begins with voiceless /f/, thus resulting in the partial devoicing of /z/-codas by assimilation. For complex codas, speakers usually elided the second consonant (either /t/ or /k/), given that the following word began with an obstruent.

The third group of words is comprised of those with an expected modal-creaky contour. These differ from the breathy-creaky words in that they begin with an unaspirated stop /b, d, g/ instead of an aspirated one, for example *bat*.

The last group consists of words with expected modal vowels with little phonation contour. These differ from the modal-creaky words in that they end with /s/ or /z/, for example *boss*. The words ending in fricatives were likely to have some final breathiness, but as shown in the results, such breathiness was minimal.

To increase the likelihood that the word-initial /h/ would be partially voiced, all target words were preceded by a function word ending in a vowel so that /h/ would be intervocalic. Voiced [ɦ] might be more likely to induce breathiness on the following vowel, given that it involves breathy phonation, whereas voiceless [h] involves mostly aspiration noise. Indeed, phonemic breathy vowels can be reflexes of intervocalic /h/, as in Gujarati (Fischer-Jørgensen, 1967) and Mazatec (Silverman, Blankenship, Kirk, & Ladefoged, 1995).

b) Hmong

Hmong has no coda consonants except [ŋ], which was avoided for the effects of nasality on the preceding vowels. Thus, all stimuli are words of shape CV, where the vowel carries a tone, written orthographically as *-m* (low creaky), -g (falling breathy), and the modal tones *–s, -v, -b,* and *–j*, or null. The stimuli are divided into four groups based on expected phonation pattern. The first group consists of words with an expected allophonic breathy-phonemic creaky contour. These words begin with an aspirated stop /p^h, t^h, k^h/ or /h/ and have a low or mid-low creaky vowel /à̰/ or /ɔ̰̀/, for example *pham* /p^hà̰/.

The second group consists of words with an expected allophonic breathy-modal contour. These differ from the previous group in that their tones were modal, either high, mid, or low level tones. The low tone was preferred because its pitch resembles most closely that of the *–m* tone, but if such a word could not be found then other level modal tones were used.

The third and fourth groups consist of words with unaspirated onsets /p, t, k/, but whose tones were creaky and modal, respectively.

As for English, the carrier word preceding the target stimuli in Hmong ended in a vowel, promoting the voicing of /h/ to [ɦ] in targets beginning with that sound. The Hmong carrier was [ʈ̌ɔ haì _____ dua] ‘Repeat _____ again’.

c) Korean

The Korean stimuli consisted of monosyllables with vowel /a/, most of which were non-words. Non-words were used in order to get an evenly distributed sample of targets across categories while controlling for neighboring sounds, which isn’t possible with real words. Given that Korean orthography is transparent with respect to pronunciation, all speakers should pronounce a given target alike. There were four groups of stimuli. The first consisted of syllables with a lenis stop /p, t, k/ in onset position and unreleased /p, t, k/ in coda position. The second group differed from the first in having only /l/ as coda. The coda /l/ was chosen because its effect on the preceding vowel’s phonation is thought to be minimal. Lenis stops were chosen for breathy onsets because they induce breathiness on the vowels (Cho, Jun, & Ladefoged, 2002; Kang & Guion, 2008). Aspirated stops could also have been chosen, since previous work shows they induce breathiness as well. However, this study only studied the effects of lenis stops, because in older studies these were found to induce more breathiness than the aspirated stops (Cho, Jun, & Ladefoged, 2002; but cf. Kang & Guion, 2008). The third group consisted of monosyllables with /l, w/ as onsets and /p, t, k/ in coda position. The fourth group consisted of monosyllables with /l, w/ as onsets and /l/ in coda position. For the latter two groups, the onsets /l, w/ were chosen because they were assumed to be the least likely to have an effect on the following vowel’s phonation. The complete list of stimuli for the three languages can be found in Appendix 1 (Tables 5-7).

3.1.2 Participants

Twelve speakers of North American English were recorded: six women and six men. The English speakers were recorded in a sound-attenuated booth using a Shure SM10A head-mounted microphone, whose signal ran through an XAudioBox pre-amplifier and A-D device. The recording was done using PCQuirerX at a sampling rate of 22,000 Hz. Twelve speakers of Korean, six women and six men, were recorded in Los Angeles. 11 speakers were from Seoul and its environs; one speaker was from Busan. The speakers were recorded as for English.13 speakers of Hmong were recorded: seven women and six men. One of the women was not included in the study because she was a native speaker of Green Mong. Three of the Hmong speakers spoke both White (*Daw*) and Green (*Leng*) natively. The remaining speakers spoke only the White variety. The speakers were recorded in a sound-attenuated room using a CAD u37 USB microphone and a laptop computer and using Audacity at a sampling rate of 22,000 Hz. The fact that the Hmong speakers were recorded in a different environment and with different equipment could theoretically affect the noise measures, presumably with more noise in the Hmong recordings. However, the Harmonics-to-noise measure was actually highest in amplitude for Hmong, indicating that the harmonic amplitudes were well above the noise floor for these recordings.

3.1.3 Test sentences and procedure

Speakers were asked to say the target words in a carrier phrase. They were instructed to repeat each phrase before saying the next one. The English carrier was *Say the words* _____ *for me*, which was chosen because it ensured that the coda-[t] would be unreleased (and thus likely pre-glottalized). The Hmong carrier was [ʈ̌ɔ haì _____ dua] ‘Repeat _____ again’. The Korean carrier was /nega _____ salkʌja/ ‘I will buy _____’. In total, 969 English, 773 Hmong, and 489 Korean tokens were used for the analysis.

3.1.4 Labeling

The target vowel was labeled in Praat (Boersma & Weenink, 2009). The onset and offset of the vowel was taken to be the beginning and end, respectively, of clear first and second formants. All vowels were coded for quality (either /æ/ or /ɑ/ for English; /a/ or /ɔ/ for Hmong, and /a/ for Korean), as well as the preceding and following consonant. In the case of Hmong, the vowel’s tone was also coded.

3.1.5 Measurements

The acoustic measures for the labeled portions were obtained using VoiceSauce (Shue, Keating, & Vicenik, 2009), which calculates pitch and phonation measures optionally using the correction algorithm from Iseli, Shue, & Alwan (2007). This algorithm is used to correct for the effects of formants on the overall harmonic spectrum, which differ depending on the vowel. VoiceSauce calculates the harmonics by creating a Fast Fourier Transform over three pitch periods. The amplitudes of the harmonics are calculated by searching for peaks around multiples of the fundamental for every pitch period. A variety of measures were initially obtained to determine which ones best distinguish the phonation types. These included F0 using the STRAIGHT algorithm (Kawahara, Masuda-Katsuse, & de Cheveigné, 1999) and corrected amplitudes of the first three formants (A1*, A2*, A3*) with their corresponding spectral tilt measures H1*-A1*, H1*-A2*, and H1*-A3*. The formant frequencies and their amplitudes are calculated using the Snack Sound Toolkit (Sjölander 2004). Harmonics-to-Noise Ratios (HNR) for four frequency ranges (<500 Hz, <1500 Hz, <2500 Hz, <3500 Hz) are calculated using the algorithm in de Krom (1993).

3.2 Results and discussion

The first step in the analysis involved choosing which measures to use in comparing breathy and creaky portions of vowels with a breathy-creaky contour. This was determined by logistic regression analyses. For breathy phonation (in each language), a logistic model with varying intercept by speaker was run at the first ninth of vowels, to compare presumed breathy onsets (breathy-creaky and breathy-modal contours) to vowels with presumed modal onsets (modal-creaky and modal-modal contours). These models were designed to determine which measures best predict presumed breathy vs. modal phonation as categorical outcomes. For creaky phonation for each language, a similar model was run, but at the final ninth. This assumes that breathy and creaky qualities are strongest at the beginning and end of the vowels, respectively, for vowels with expected breathy-creaky contours. The results below will confirm this assumption.

The measures tested in the models were H1*-H2*, H1*-A1*, H1*-A2*, H1*-A3*, H1*, and HNR. Each of these measures has been shown to differentiate non-modal phonation from modal in a variety of languages, including the three languages of this study. Of the four HNR measures, only the HNR under 500 Hz was used, because inclusion of all four measures resulted in a decrease in their significance. This version of HNR was used because its effects on phonation were highest in a pilot version of the regressions. Cepstral peak prominence (CPP) was not used, because its inclusions in the model lowered the significance of HNR, with which it is highly correlated. HNR was chosen over CPP because the former has been shown to differentiate both non-modal phonations from modal, unlike the latter, which was not found to differentiate modal from laryngealized phonation in Mazatec (Blankenship, 2002).

By individually removing each of the measures and comparing the smaller model with the full one (using log likelihood tests), it was possible to determine, for each language, which measures contributed most to the distinction between modal and non-modal phonations. The results for breathy phonation are shown in Table 1. The values for each measure were centered to reduce collinearity. The model fit for each language, calculated using Somers' D_{xy} and the *C* index of concordance, was very good. The results of the models show that the measures contributing most to the breathy-modal distinction are H1*-H2*, H1-A1*, and HNR for the three languages, in the sense that the individual removal of these measures results in the largest decrease of model fit. For English and Korean, H1*-A1* is the biggest contributor to overall model fit; for Hmong it is HNR.

Table 1 ***Significance of the removal of measures from the full model at the first ninth***

Measures	English	Hmong	Korean
H1*-H2*	$\chi^2(1) = 31.91$, $p < 0.001$ ***	$\chi^2(1) = 9.45$, $p < 0.01$ **	$\chi^2(1) =$ $p < 0.001$ ***
H1*-A1*	$\chi^2(1) = 113.91$, $p < 0.001$ ***	$\chi^2(1) = 22.60$, $p < 0.001$ ***	$\chi^2(1) = 17.06$, $p < 0.001$ ***
H1*-A2*	$\chi^2(1) = 0.32$, $p < 0.57$	$\chi^2(1) < 0.01$, $p = 0.99$	$\chi^2(1) < 0.01$, $p = 0.97$
H1*-A3*	$\chi^2(1) = 6.07$, $p < 0.05$ *	$\chi^2(1) = 5.88$, $p < 0.05$ *	$\chi^2(1) = 11.73$, $p < 0.001$ ***
HNR	$\chi^2(1) = 58.83$, $p < 0.001$ ***	$\chi^2(1) = 127.33$, $p < 0.001$ ***	$\chi^2(1) = 16.24$, $p < 0.001$ ***
H1*	$\chi^2(1) = 14.23$, $p < 0.001$ ***	$\chi^2(1) = 0.09$, $p = 0.77$	$\chi^2(1) = 0.01$, $p = 0.92$
Model fit	$D_{xy} = 0.97$ $C = 0.95$	$D_{xy} = 0.95$ $C = 0.90$	$D_{xy} = 0.98$ $C = 0.97$

The results of the regression for the creaky-modal distinction are shown in Table 2. The model fit for each language was very good. The measures which contribute significantly to model fit in all three languages are H1*-H2*, H1*-A1*, HNR, and H1*. For English and Hmong, the biggest contributor is H1*; for Korean, it is H1*-H2*.

Table 2 ***Significance of the removal of measures from the full model at the final ninth***

Measures	English	Hmong	Korean
H1*-H2*	$\chi^2(1) = 10.97$, $p < 0.001$ ***	$\chi^2(1) = 19.37$, $p < 0.001$ ***	$\chi^2(1) = 57.38$ $p < 0.001$ ***

H1*-A1*	$\chi^2(1) = 17.6$, $p < 0.001$ ***	$\chi^2(1) = 20.51$, $p < 0.001$ ***	$\chi^2(1) = 41.27$ $p < 0.001$ ***
H1*-A2*	$\chi^2(1) = 127.29$, $p < 0.001$ ***	$\chi^2(1) = 0.01$, $p = 0.93$	$\chi^2(1) = 4.598$ $p < 0.03$*
H1*-A3*	$\chi^2(1) = 25.2$, $p < 0.001$ ***	$\chi^2(1) = 0.16$, $p = 0.69$	$\chi^2(1) = 0.07$ $p = 0.79$
HNR	$\chi^2(1) = 8.52$, $p < 0.01$ **	$\chi^2(1) = 13.20$, $p < 0.001$ ***	$\chi^2(1) = 49.02$ $p < 0.001$ ***
H1*	$\chi^2(1) = 217.45$, $p < 0.001$ ***	$\chi^2(1) = 256.96$, $p < 0.001$***	$\chi^2(1) = 40.11$ $p < 0.001$ ***
Model fit	$D_{xy} = 0.89$ $C = 0.94$	$D_{xy} = 0.94$ $C = 0.87$	$D_{xy} = 0.98$ $C = 0.95$

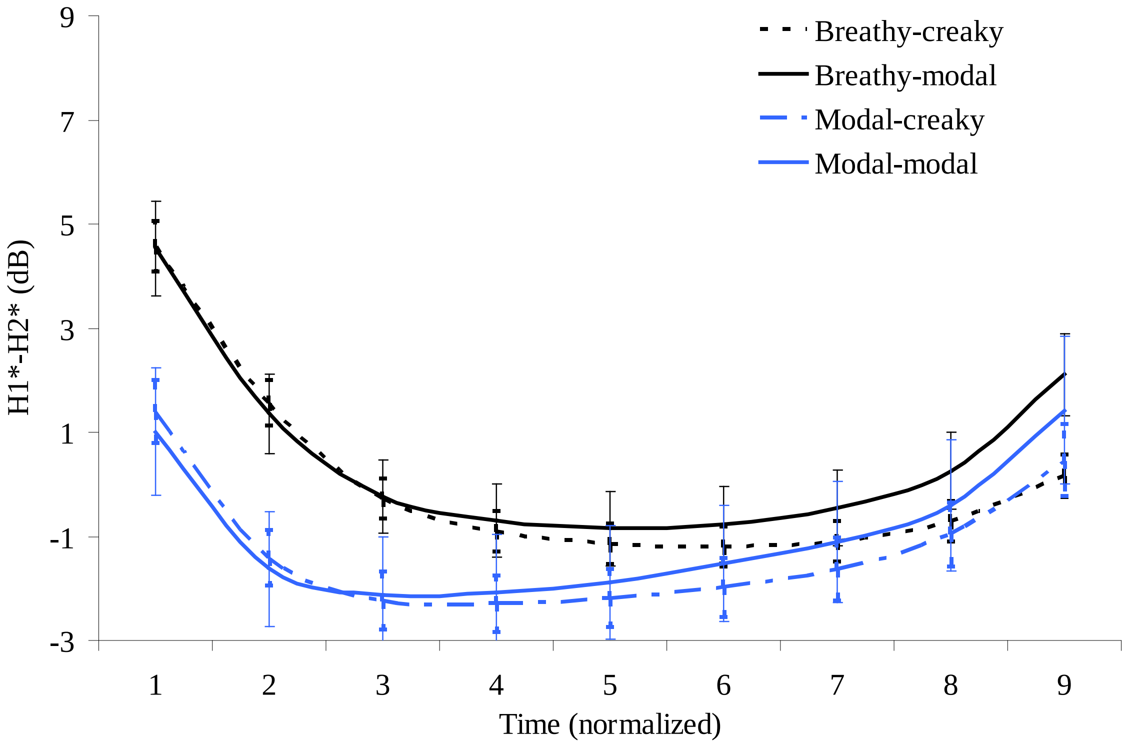
These results indicate that breathy and creaky phonations in the study languages are best distinguished from modal using H1*-H2, H1*-A1*, HNR, and H1*. The subsequent analysis will therefore focus on these measures with the exception of H1*, because it is highly correlated with the spectral tilt measures and HNR, and because it can vary with voice intensity.

The time courses for each measure are plotted in the figures below, organized by measure. For each language plot there are four lines corresponding to the four contours: breathy-creaky, breathy-modal, modal-creaky, and modal-modal. The contours beginning with breathy phonation are in black; those beginning with modal are light. The contours ending in modal phonation have solid lines; those ending in creak are in dotted lines. If a measure differentiates between breathy and modal at the vowel onset and between modal and creaky at the vowel offset, then the figure should show differentiation by line color at the beginning, but differentiation by line texture at the end.

The modal-modal contour was used as the baseline for comparison with the other three contours. At each time point, a linear mixed-effects model was run comparing each contour to the baseline, with the acoustic measure in question as the dependent variable. The largest significant model had both subject and item as random effects. The inclusion of additional fixed or random effects such as vowel quality or onset did not significantly improve model fit. The expected phonation contour and sex were the two fixed effects of the model, in addition to their interaction. The models' fits were generally very good; the correlations between model and data are shown in the appendix. The p-values for the coefficient estimates were obtained using the *pvalues.fnc* function in R (Baayen, Davidson, & Bates, 2008), with 10,000 simulations. Given the large number of tests performed, the p-values were adjusted using the Šidák-Holm correction. *P*-values under 0.0018 were considered statistically significant. The model results can be found in the appendix.

3.2.1 H1*-H2*

The time courses of H1*-H2* are plotted in Figures 4-6 for the three languages. In each figure are plotted four contours: breathy-creaky, breathy-modal, modal-creaky, and modal-modal. The higher the value of H1*-H2*, the breathier the phonation. Conversely, the lower the value of H1*-H2*, the creakier the phonation. Under each figure are the significant differences from the modal-modal (MM) contour for the three non-modal ones (abbreviated as BC, BM, and MC). The results for H1*-H2* for English show that the measure has higher values for breathy phonation than for modal during the first two ninths of the vowel (depicted by both the solid and dotted black lines). H1*-H2* does not differentiate modal from creaky phonation at the vowel offset. That is, there is no difference in values between the solid light line and the others at the vowel offset. Note that for modal-ending contours (the solid lines), the value of H1*-H2* tends to rise towards the end of the vowel. This is likely due to the coda-/s/ in such words, which is [+spread glottis] (Halle & Stevens, 1971).

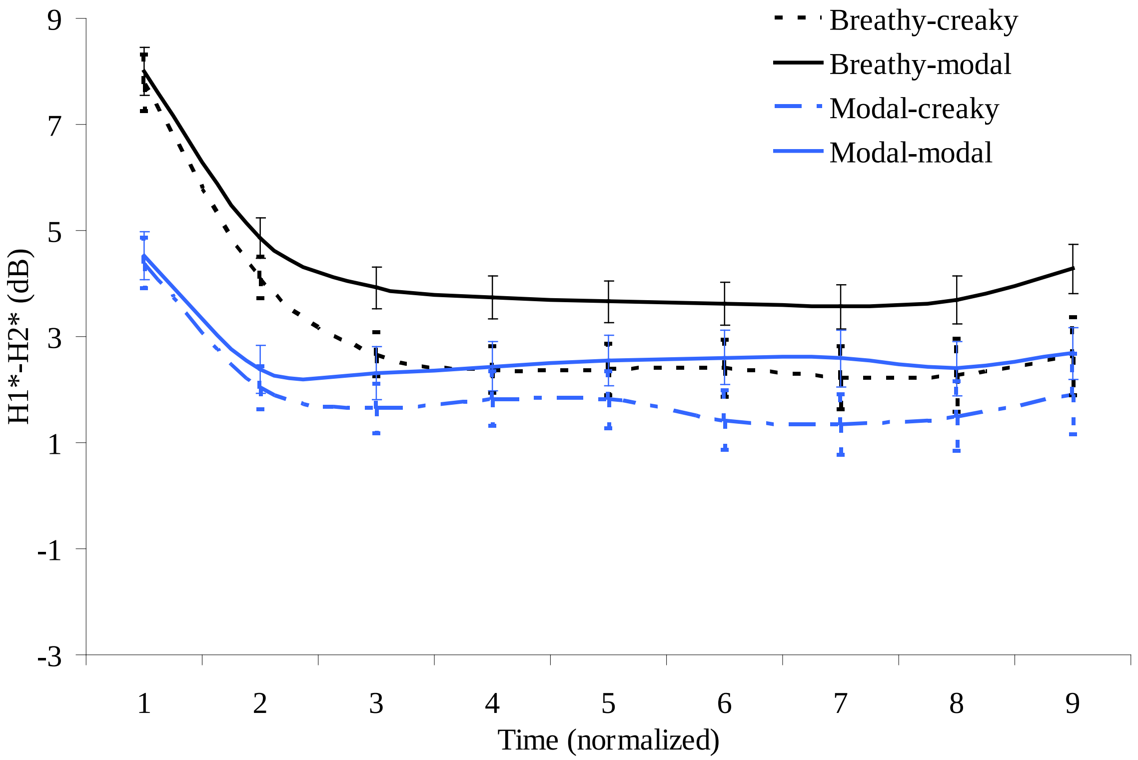


Statistically significant differences at each vowel ninth

Vowel ninth	1	2	3	4	5	6	7	8	9
BC vs. MM	✓	✓							
BM vs. MM	✓	✓							
MC vs. MM									

Figure 4. Time courses of H1*-H2* for English. Breathy-creaky contours are dotted dark lines; breathy modal contours are solid dark lines; modal-creaky are dotted light lines; modal-modal are solid light lines. Different colored lines should be compared at the beginning; different textures at the end.

The results for Hmong in Figure 5 show that H1*-H2* is higher for breathy than for modal phonation during the first two ninths of the vowel for breathy-creaky words, but for the whole duration for breathy-modal ones. That is, words that start with an aspirated stop and have a modal vowel (represented by a dark solid line) are breathier that those with unaspirated onsets (represented by a light solid line) for the entire duration, at least for this measure. Unlike for English, H1*-H2* for Hmong *does* differentiate modal from creaky phonation at the vowel offset, but only during the sixth and seventh ninths for modal-creaky words (represented by the dotted light line).

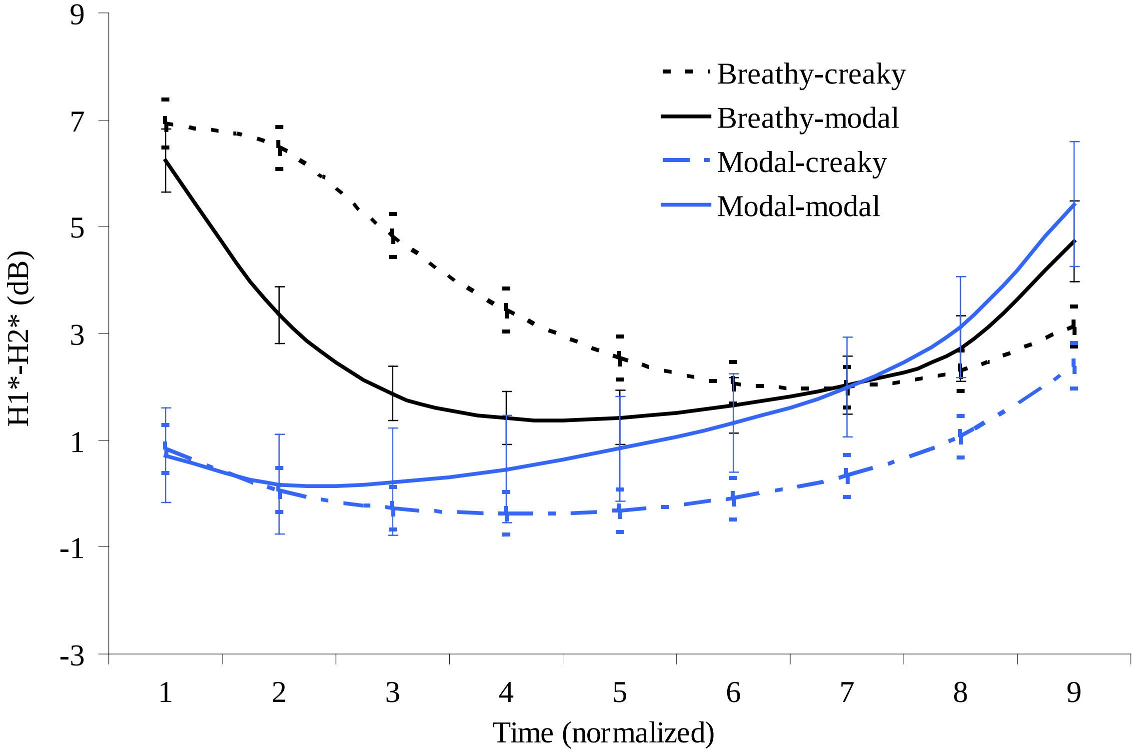


Statistically significant differences at each vowel ninth									
Vowel ninth	1	2	3	4	5	6	7	8	9
BC vs. MM	✓	✓							
BM vs. MM	✓	✓	✓	✓	✓	✓	✓	✓	✓
MC vs. MM						✓	✓		

Figure 5. Time courses of H1*-H2* for Hmong. Breathy-creaky contours are dotted dark lines; breathy modal contours are solid dark lines; modal-creaky are dotted light lines; modal-modal are solid light lines. Different colored lines should be compared at the beginning; different textures at the end.

H1*-H2* for Korean (Figure 6) is higher in breathy-initial contours derived from preceding lenis stops. For words with breathy onsets that end in preglottalized stops (the dotted dark line), H1*-H2* is higher than for modal-modal vowels (the solid light line) for the first third. For breathy-modal contours, represented by a solid dark line, H1*-H2* shows statistically significant differences from modal in the initial ninth only. At first glance, this could suggest a possible dissimilation effect, whereby vowels following lenis stops are breathier when coda-preglottalization will occur. However, the breathy-modal contours were significantly longer than the breathy-creaky ones, and this apparent effect was found to be a by-product of the time normalization.

As shown in Experiment 1, H1*-H2* for Korean differentiates modal-modal (solid light line) from modal-creaky contours (dotted light line), with the latter showing lower values for the measure beginning halfway into the vowel. This contrasts with the results from English and Hmong, which show poor differentiation of modal from creaky phonation, suggesting that creak in those languages is articulatorily different from the preglottalization in Korean.

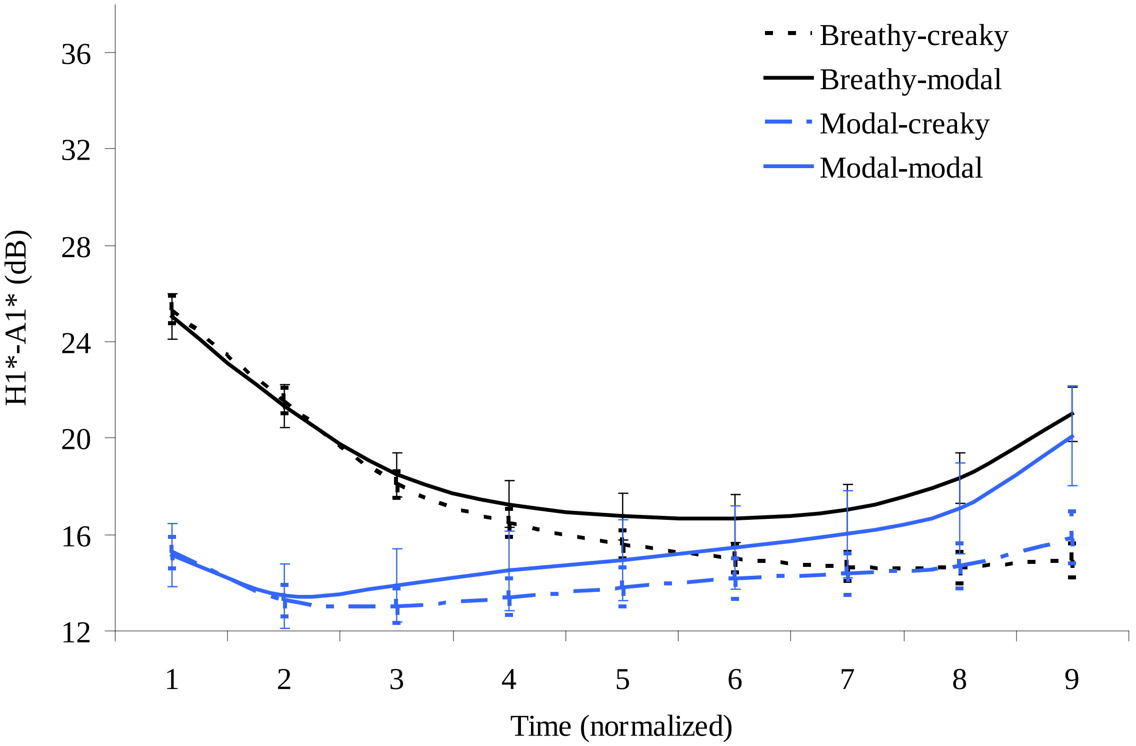


Statistically significant differences at each vowel ninth									
Vowel ninth	1	2	3	4	5	6	7	8	9
BC vs. MM	✓	✓	✓				✓	✓	✓
BM vs. MM	✓								
MC vs. MM					✓	✓	✓	✓	✓

Figure 6. Time courses of H1*-H2* for Korean. Breathy-creaky contours are dotted dark lines; breathy modal contours are solid dark lines; modal-creaky are dotted light lines; modal-modal are solid light lines. Different colored lines should be compared at the beginning; different textures at the end.

3.2.2 H1*-A1*

The results for H1*-A1* for English in Figure 7 show that this measure differentiates between breathy and modal phonation during the first third of the vowel. For breathy onsets, H1*-A1* is higher, as expected. As with H1*-H2*, H1*-A1* does not significantly differentiate modal from creaky phonation at the vowel offset, although the trend is in the expected direction, with lower values for creaky offsets.

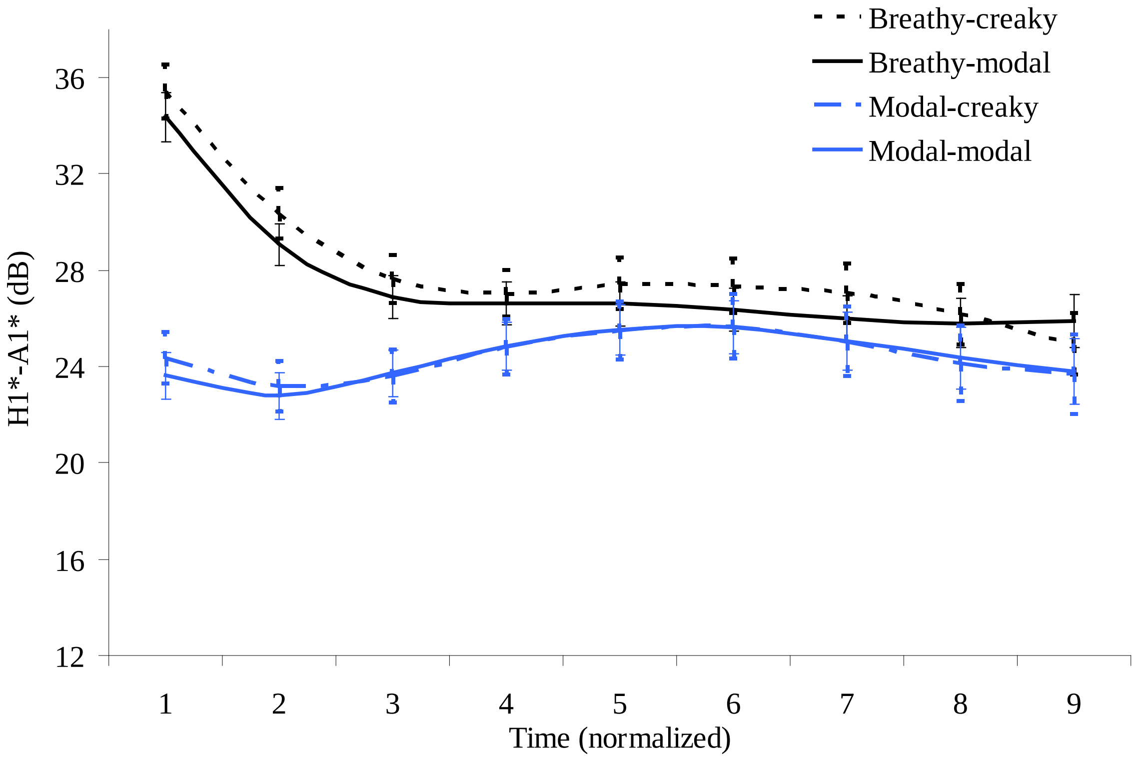


Statistically significant differences at each vowel ninth

Vowel ninth	1	2	3	4	5	6	7	8	9
BC vs. MM	✓	✓	✓						
BM vs. MM	✓	✓	✓						
MC vs. MM									

Figure 7. Time courses of H1*-A1* for English. Breathy-creaky contours are dotted dark lines; breathy modal contours are solid dark lines; modal-creaky are dotted light lines; modal-modal are solid light lines. Different colored lines should be compared at the beginning; different textures at the end.

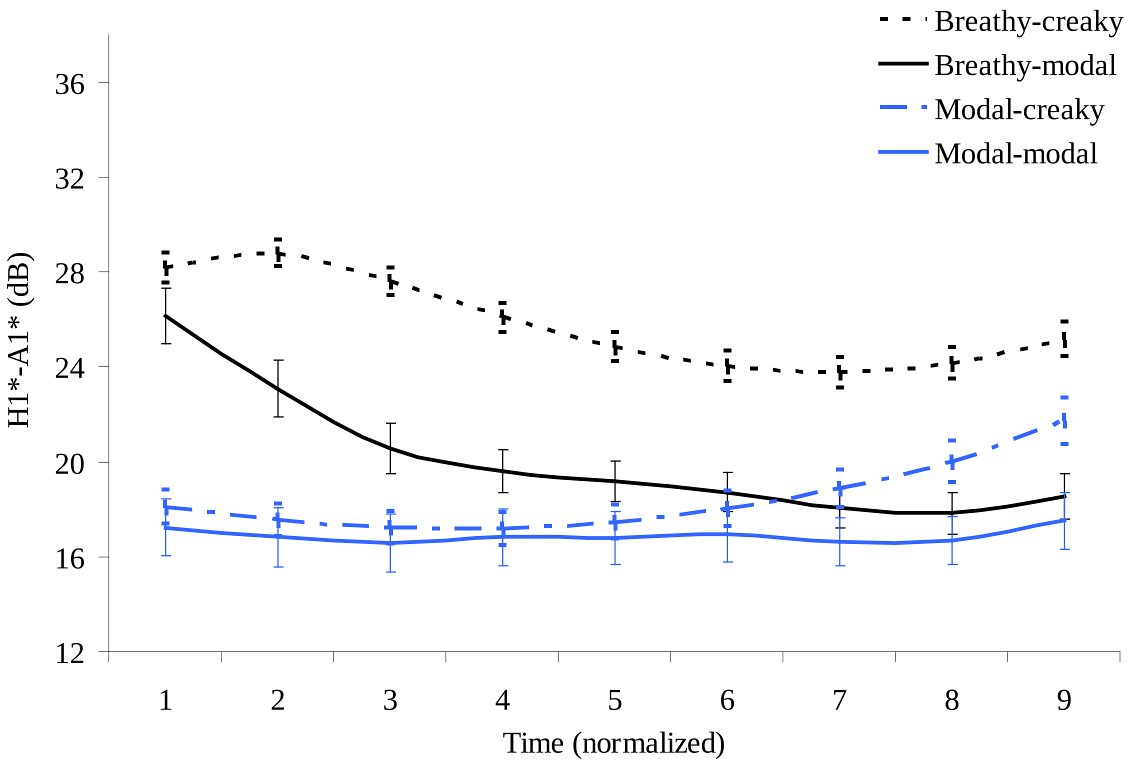
For Hmong, H1*-A1* (in Figure 8) differentiates between breathy and modal phonation for over two-thirds of the vowel for breathy-creaky words, and for nearly the whole duration for breathy-modal ones. This finding is similar to that of H1*-H2*, lending further support that words that start with an aspirated stop and have a modal vowel are breathier that those with unaspirated onsets for the entire duration, at least for this measure.



Statistically significant differences at each vowel ninth									
Vowel ninth	1	2	3	4	5	6	7	8	9
BC vs. MM	✓	✓	✓	✓	✓	✓	✓		
BM vs. MM	✓	✓	✓	✓	✓	✓		✓	✓
MC vs. MM									

Figure 8. Time courses of H1*-A1* for Hmong. Breathy-creaky contours are dotted dark lines; breathy modal contours are solid dark lines; modal-creaky are dotted light lines; modal-modal are solid light lines. Different colored lines should be compared at the beginning; different textures at the end.

For Korean, H1*-A1* is higher for the entire duration of breathy-creaky vowels than for modal-modal ones, which is similar to the results for Hmong (see Figure 8). For breathy-modal vowels, the values are higher than modal-modal during the initial third, after which no difference is found. Modal-creaky vowels do not differ significantly from the modal-modal ones, although on this measure they show a tendency to rise at the offset, which is unexpected if H1*-A1* should be lower for creaky phonation.

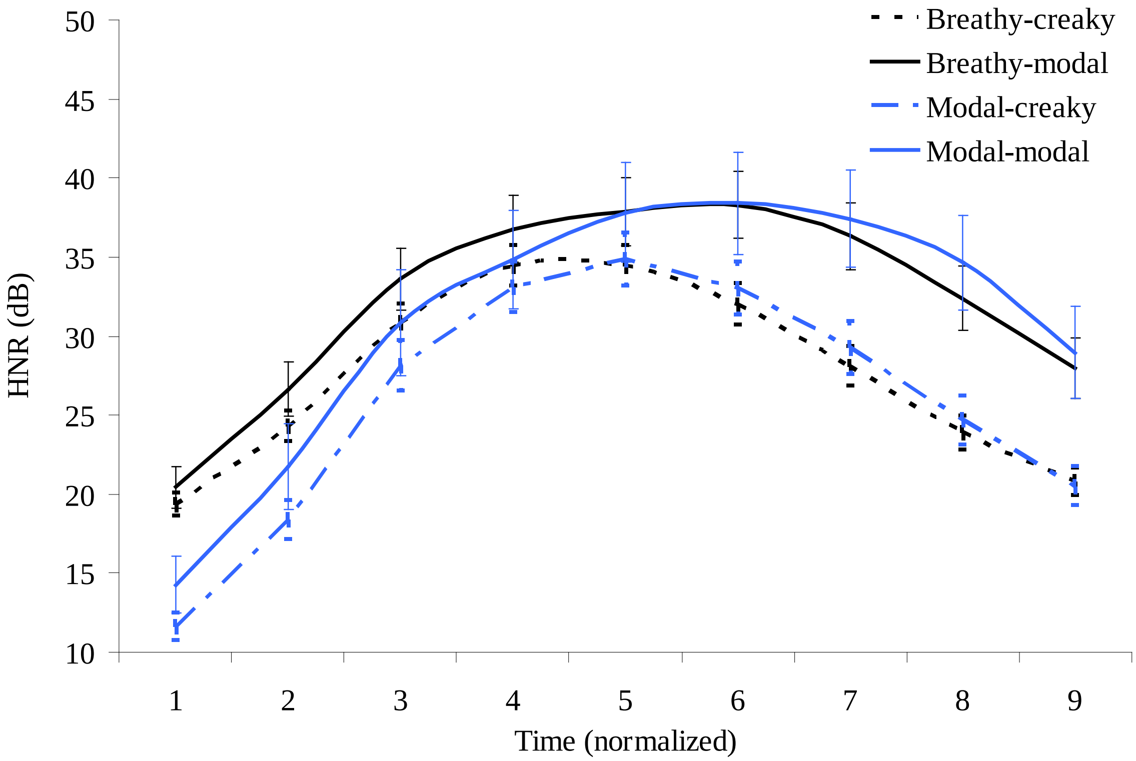


Statistically significant differences at each vowel ninth									
Vowel ninth	1	2	3	4	5	6	7	8	9
BC vs. MM	✓	✓	✓	✓	✓	✓	✓	✓	✓
BM vs. MM	✓	✓	✓						
MC vs. MM									

Figure 9. Time courses of H1*-A1* for Korean. Breathy-creaky contours are dotted dark lines; breathy modal contours are solid dark lines; modal-creaky are dotted light lines; modal-modal are solid light lines. Different colored lines should be compared at the beginning; different textures at the end.

3.2.3 Harmonics-to-Noise Ratio

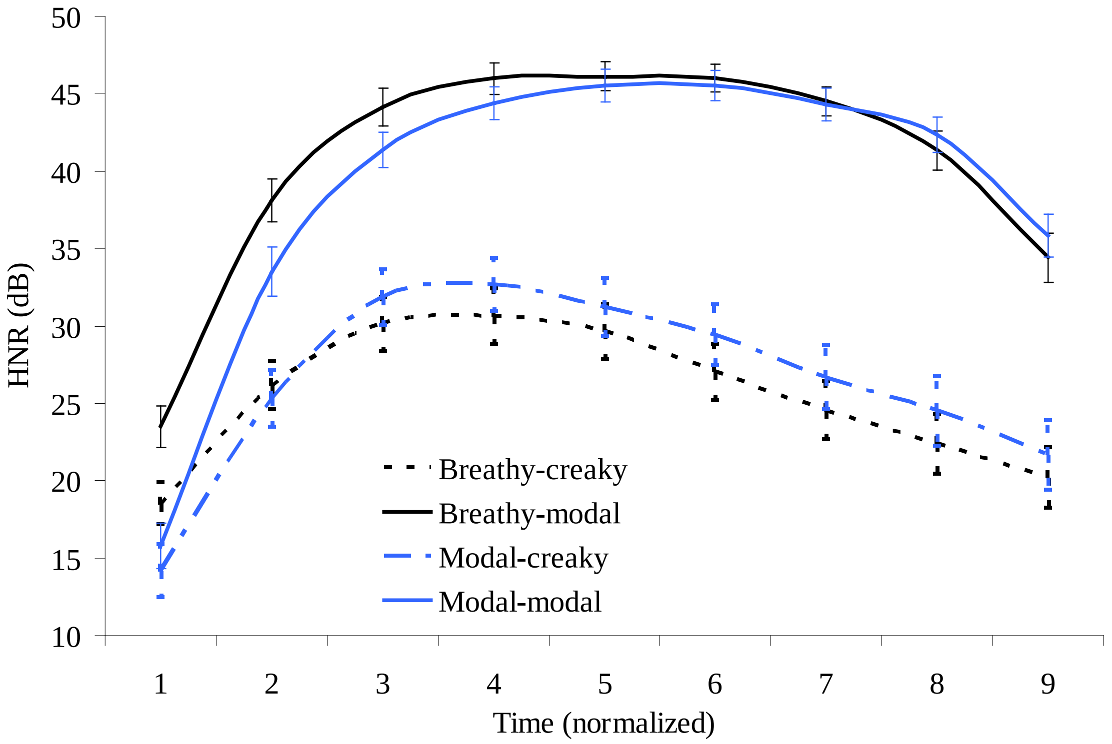
HNR is expected to be lower for breathy and creaky portions, because noise is sensitive to both aspiration and aperiodicity. The results for HNR for English in Figure 10 show that the measure differentiates between breathy and modal phonation during the first ninth for breathy-modal, though in the opposite direction than expected, with breathy onsets having a higher HNR. However, this was not found for breathy-creaky contours. For both contours ending in creaky voice, HNR is lower in creaky phonation than in modal phonation in the final two ninths. For breathy-creaky, the measure differentiates creaky from the modal for the latter third. The differentiation between modal and creaky phonation is in the predicted direction, with creaky values having lower HNR values, presumably due to decreased periodicity.



Statistically significant differences at each vowel ninth									
Vowel ninth	1	2	3	4	5	6	7	8	9
BC vs. MM							✓	✓	✓
BM vs. MM	✓								
MC vs. MM								✓	✓

Figure 10. Time courses of HNR for English. Breathy-creaky contours are dotted dark lines; breathy modal contours are solid dark lines; modal-creaky are dotted light lines; modal-modal are solid light lines. Different colored lines should be compared at the beginning; different textures at the end.

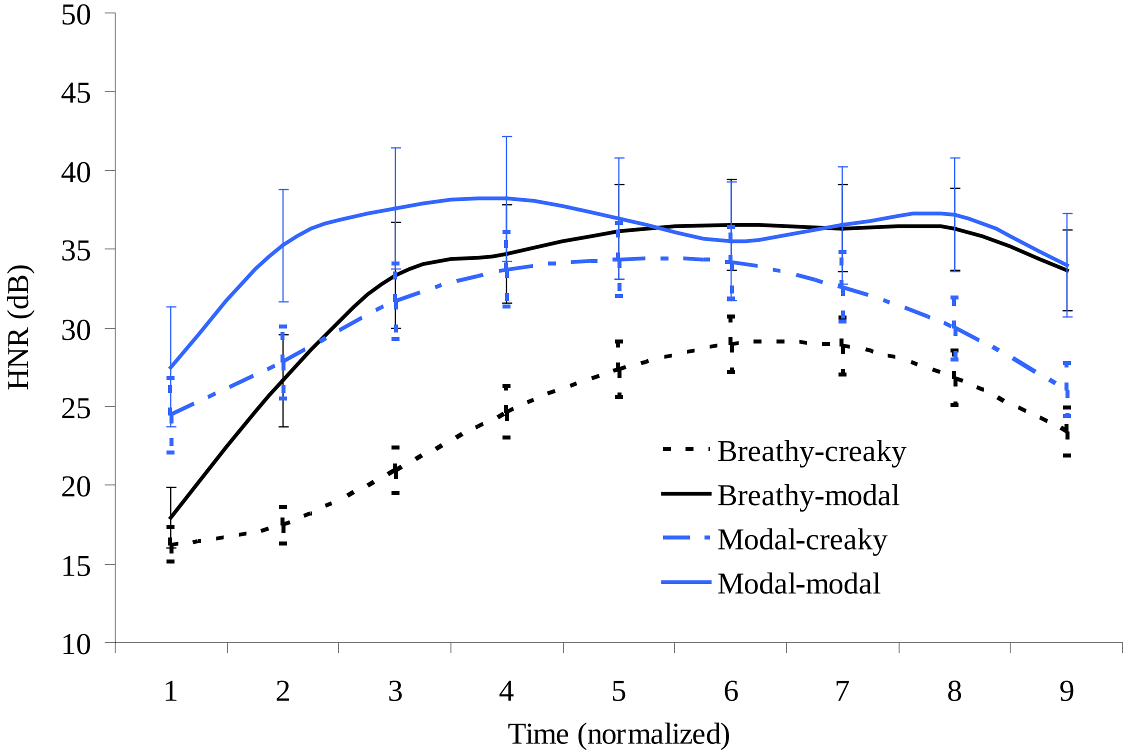
The results for HNR for Hmong in Figure 11 indicate that this measure differentiates between breathy and modal phonation during the first ninth for breathy-modal, but not for breathy-creaky. This is similar to the findings for the same measure in English. For both contours ending in creaky voice, HNR has lower values for creaky phonation for nearly the whole duration. This suggests that HNR in Hmong is reflecting mostly the noise due to creaky voice rather than that of breathy phonation. Interestingly, it is the breathy onsets that have the higher HNR values at the first ninth for English and Hmong, suggesting that modal onsets are less periodic. This suggests that the breathy vibration at the vowel onset for English and Hmong is very periodic.



Statistically significant differences at each vowel ninth									
Vowel ninth	1	2	3	4	5	6	7	8	9
BC vs. MM							✓	✓	✓
BM vs. MM	✓								
MC vs. MM								✓	✓

Figure 11. Time courses of HNR for Hmong. Breathy-creaky contours are dotted dark lines; breathy modal contours are solid dark lines; modal-creaky are dotted light lines; modal-modal are solid light lines. Different colored lines should be compared at the beginning; different textures at the end.

For Korean, HNR has lower values, i.e. greater noise or faster f0 change, in breathy-creaky vowels than in modal-modal ones for the entire duration (see Figure 12). For breathy-modal vowels, a lower value for HNR is reported only during the first two ninths. For modal-creaky, the differentiation from modal is found only at the final two ninths. This suggests that the measure is reacting to both breathy and creaky phonations additively, such that breathy-creaky always has HNR values lower than those of breathy-modal and modal-creaky contours. This is likely to occur if the measure is sensitive to both aspiration noise and aperiodicity of the glottal source, but it is interesting that the same effect is not found for English and Hmong.



Statistically significant differences at each vowel ninth

Vowel ninth	1	2	3	4	5	6	7	8	9
BC vs. MM	✓	✓	✓	✓	✓	✓	✓	✓	✓
BM vs. MM	✓	✓							
MC vs. MM		✓						✓	✓

Figure 12. Time courses of HNR for Korean. Breathy-creaky contours are dotted dark lines; breathy modal contours are solid dark lines; modal-creaky are dotted light lines; modal-modal are solid light lines. Different colored lines should be compared at the beginning; different textures at the end.

3.4 Spatial differentiation

As mentioned earlier, Blankenship (2002) also found that contrastive non-modal phonation is more differentiated from modal than allophonic non-modal phonation. Since I found non-modal phonation to be most differentiated from modal at the onsets and offsets of the vowel, this claim was tested for breathy-modal contours at the first ninth, and for modal-creaky ones at the final ninth, compared to the modal-modal results. Differences in the level of breathiness were assessed using the best measures found for differentiating breathy from modal phonation in the three languages, H1*-H2* and H1*-A1*. Differences in the level of creakiness were assessed using HNR, which was found to be significant in differentiating modal from creaky phonation in the three languages.

Table 3 ***Absolute differences (in dB) in measures of breathiness (H1*-H2* and H1*-A1*) between breathy-modal and modal-modal contours at the first ninth***

	H1*-H2*	H1*-A1*
English – *allophonic breathiness*	3.53	9.93
Hmong – *allophonic breathiness*	3.46	10.74
Korean – *contrastive-like breathiness*	5.52	9.00

Table 4 ***Absolute differences (in dB) in HNR between modal-creaky and modal-modal contours at the final ninth***

	HNR
English – *allophonic creakiness*	8.45
Hmong – *contrastive creakiness*	14.18
Korean – *allophonic creakiness*	7.95

The higher H1*-H2* difference for Korean lends additional support to the claim that breathiness acts as if it is contrastive in the language (although H1*-A1* is comparable across languages). The HNR difference for Hmong modal versus creaky is much higher than for English and Korean. These results confirm that non-modal phonation, when contrastive, is more differentiated from modal.

3.5 Summary of results

The results show that breathy is differentiated from modal phonation mostly by H1*-H2* and H1*-A1*. For English and Hmong, breathiness lasts for the initial third of the vowel, though for Hmong H1*-A1* is higher than modal for most of the duration, suggesting that a posterior glottal opening may persist throughout the vowel for those words beginning with an aspirated stop. Strictly speaking, a higher H1-A1 does not indicate breathy phonation caused by a large open quotient, and may even be found during glottalization if the arytenoids are spread apart, as the modal-creaky contour for Korean seems to indicate. For Korean, H1*-H2* is higher for breathy onsets, but quickly approaches the level of modal vowels. However, H1*-A1* for the Korean breathy-creaky contour is higher than modal throughout the vowel, which is likely a result of breathiness (due to whispery voice) rather than to the creakiness of the offset. This is because HNR, which best distinguishes creaky phonation from modal, shows only late glottalization in breathy-creaky Korean contours, as does H1*-H2*. In sum, breathiness lasts longer for Korean than for English and Hmong. HNR values show that for English and Korean, the difference between modal-creaky and modal-modal vowels is made at the vowel offset, mostly in the latter third of the vowel. For Hmong, however, creakiness starts after the first third.

4 General discussion

4.1 The acoustic measures

Many acoustic studies of voice quality use several measures to characterize non-modal phonation. The use of multiple cues rests on the assumption that phonation is multi-dimensional in its articulation (Gordon & Ladefoged, 2001; Edmondson & Esling,

2006) and in its perception (Gerfen & Baker, 2005; Esposito, 2006, 2010a), as well as from cross-linguistic work like that of Esposito (2006, 2010a), which showed that listeners of different languages rely on different cues to perceive phonation differences.

This study provides further evidence for the need to use multiple cues to characterize perceived non-modal phonation. Both breathy and creaky phonations can be characterized by a combination of measures thought to reflect such independent properties as ligamental glottal opening and closing, posterior glottal opening, and noise levels. Although the values for each measure differ across the languages, they all show significant deviations in non-modal phonation from the modal.

As mentioned earlier, acoustic measures of phonation are thought to reflect various articulatory postures from which non-modal voice arises. Therefore, the articulatory origins of the acoustic results found in this study may be speculated. First, the major contribution of H1*-A1* to the “breathy” category of the contours in the three languages suggests that aspiration noise in English and Hmong, as well as breathy voice from lenis stops in Korean, contain strong whispery components in addition to incomplete closure of the folds, which is arguably reflected in H1*-H2*. In English, H1*-A1* contributed most to the difference between breathy and modal voices, but all three languages used it to some degree. The results of the logistic regression analysis on Korean breathy voice showed that H1*-H2*, H1*-A1*, H1*-A3*, and HNR were all major contributors to the breathy-modal distinction, suggesting that in Korean a combination of spread vocal folds, spread arytenoids, slow vocal fold closure, and noise is used to create the breathiness of lenis stops.

Creakiness in English and Hmong were best differentiated from modal voice by the Harmonics-to-Noise Ratio measure. HNR also decreases throughout the creaky portions of English and Hmong, which is understandable, because many creaky tokens would eventually end with infrequent and very irregular glottal pulses.

The results indicate that in Korean, the voice quality of vowels preceding coda-stops is more glottalized than for vowels preceding [l]. I believe that this effect is true glottalization without creak, given that H1*-H2* was very sensitive to the changes. In languages that use slight glottalization or laryngealization (e.g. Mazatec, Chong), H1*-H2* is good at distinguishing it from modal voice (Blankenship, 2002; DiCanio, 2009). On the other hand, for English and Hmong, the languages that showed heavy creak, H1*-H2* did not show many statistically significant differences from modal voice.

To my knowledge, this preglottalization has not been shown before for Korean, but it strongly suggests that coda effects on vowel phonation should be carefully assessed and accounted for in studies of voice quality. If the preglottalization was due to inherent properties of coda stops in Korean (rather than to tensification of obstruents before lenis /s/), then the findings for Korean have important implications. Many other languages possess unreleased stops that are likely to influence the quality of adjacent vowels. Lacking the burst cues, unreleased stops are likely to make use of glottalization to enhance the spectral cues leading in to them. Glottalization results in the amplification of higher frequencies in the spectrum, thereby amplifying the cues to the place of articulation. Although further research regarding the prevalence of voice quality effects due to coda-stops is needed, studies on vowel phonation should be prepared to deal with neighboring consonant effects.

4.2 The timing of coarticulated non-modal phonation

The results indicate that breathy-creaky contours are observable in English, Hmong, and Korean. Thus, it is not the case that the presence of one non-modal phonation type on a vowel precludes the presence of some other, even opposing phonation, at least for the languages studied here. In fact, different phonation types are known to co-occur on a single vowel in Chong (DiCanio, 2009) and in some Zapotecan languages (Monro, Lopez, Méndez, Garcia, & Galant, 1999). Although both breathy and creaky portions surface in contours here, the three languages differ in their timing. The results concerning the timing of phonation are largely in accordance with those of Blankenship (2002), in that the allophonic breathiness of Hmong is shorter than the creakiness. In contrast, English allophonic breathiness and creakiness both last for about a third of the vowel's duration. The Korean data suggest that breathiness following lax stops is in fact contrastively used, given its long duration and strong differentiation from modal. Thus, this study indicates that, when two non-modal phonations are juxtaposed, a contrastive one will last longer than an allophonic type.

Can these timing differences be due to inherent timing disparities across differing types of non-modal phonation? This is unlikely, given that the "creakiness" in English and Korean was shorter, despite that the former was mostly characterized by noise (HNR) while the latter could be characterized by both noise and a smaller OQ (H1*-H2*). The longer "breathiness" of Korean was also characterized by both H1*-H2* and a larger H1*-A1*, as was the shorter variety of Hmong and English. The fact that the same measures show differences in timing for contrastive versus allophonic phonation suggests that timing differences are not solely due to different non-modal phonation types.

The presence of modal voice in the breathy-creaky contours is also of interest. In English, the vowels start off breathy, then become modal, and finally end creaky. The breathiness and creakiness both last for about a third of the vowel's duration. Therefore, English's breathy-creaky contours can be schematized as in Figure 13:

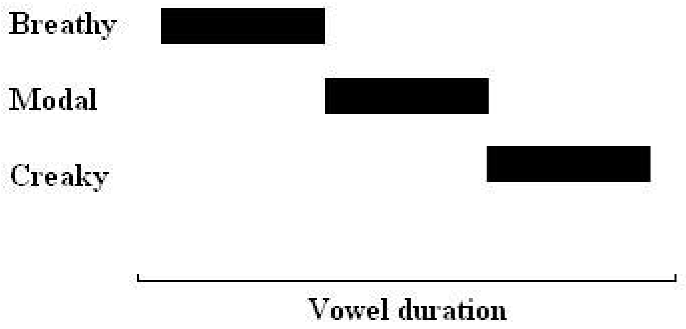


Figure 13. Schematic of breathy-creaky contours in English.

On the other hand, breathy-creaky contours in Hmong are dominated by creak, which lasts for most of the vowel and co-occurs with breathiness. In Hmong, no modal portions appear in these contours.

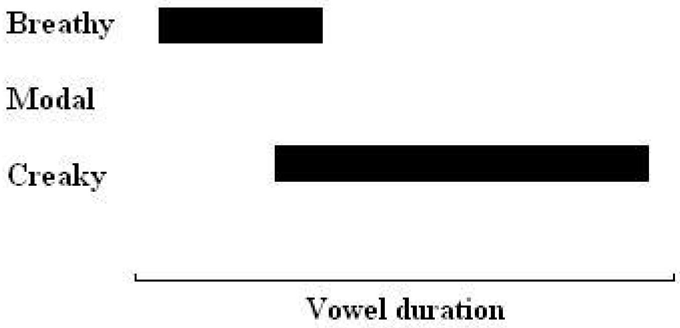


Figure 14. Schematic of breathy-creaky contours in Hmong.

Korean shows a different picture, with the vowels in such contours dominated by the breathiness of the lax stop. In Korean as in Hmong, the vowel does not appear to be modal at any point, at least not in the way the vowel of forms like *lal* or *wal* are.

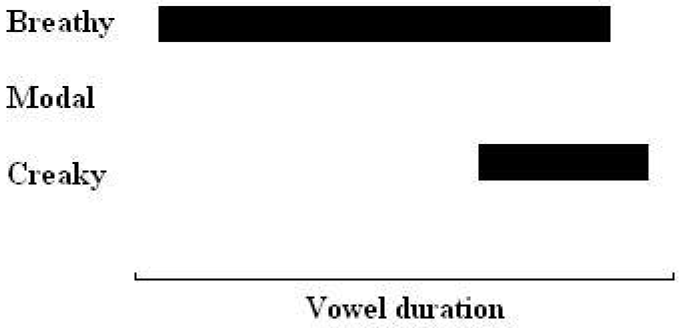


Figure 15. Schematic of breathy-creaky contours in Korean.

In Hmong and Korean, the acoustic cues of breathy and creaky phonation appear simultaneously at some points in the vowel. The simultaneity of breathy and creaky voices runs counter to the basic model of phonation involving only the glottal opening (e.g. in Ladefoged, 1971; Gordon & Ladefoged, 2001), given that the glottis cannot be both open and closed at once. The findings do lend support, however, to models of phonation involving either the vocal folds as a whole (e.g. Laver, 1980; Hanson, Stevens, Kuo, Chen, & Slifka, 2001), or the entire laryngeal system, such as the Laryngeal Articulator Model (Esling, 2005; Edmondson & Esling, 2006). Nevertheless, it should be noted that these acoustic findings are merely presumed to be correlated with aerodynamic or articulatory postures, so future articulatory research would be needed to confirm both the simultaneity of breathy and creaky phonation as well as the nature of these voice qualities for the languages at hand.

4.3 Contrast and allophony in phonation coarticulation

As mentioned above, this study confirms the findings of Blankenship (2002) from other languages that contrastive non-modal phonation is more pronounced and lasts longer than allophonic non-modal phonation. Since contrastive features require that they be perceptually salient in order to distinguish words of a language, it is not surprising that they should last long and be well-differentiated. What is puzzling, however, is that allophonic non-modal phonation, which results from coarticulation, should consistently be found to be shorter in duration. Coarticulation effects are not always found to be short-lived. According to Manuel and Krakow (1984) and Manuel (1987, 1990), coarticulation can be strongly influenced by the number of contrasts in a language. Assuming that languages do have output constraints on coarticulation that are derived from the number of contrasts to be maintained, a language should not have to limit its allophonic coarticulation of a certain feature, if that feature is not contrastive. It is therefore interesting that English should have such limited allophonic non-modal phonation. In Hmong, the breathiness derived from coarticulated aspiration is short in duration perhaps because the language must contrast modal, creaky, and breathy vowels. For English, such an explanation would not hold, because the language does not contrast phonation. Even in the breathy-modal contours, which for English ended with slight breathiness due to the coda-/s/, breathiness derived from the aspirated stop drops after a third of the vowel's duration, only to rise again for the /s/. This seems to imply that English vowels are featurally specified for modal voice. The allophonic breathy phonation in English behaves similarly to the allophonic breathiness of Tagalog and Navaho, which also showed rapid onsets and offsets (Blankenship, 1997). To account for this, Blankenship hypothesized that in these languages vowels are featurally specified for modal voice. Indeed, Cohn (1990, 1993) found that gestural coarticulation for nasality typically shows a sharp decline when the language has a feature specification corresponding to the gesture, but not when there is underspecification. Under a windows model of coarticulation (Keating, 1988a, 1990), this would be a result of narrow windows for specified features causing sharp declines and onsets of a gesture. If modal phonation is specified in the English grammar, then the language would still have just one phonation specification, unlike Hmong's three. Thus, according to Manuel and Krakow (1984) and Manuel (1987, 1990), English would still be likely to show more coarticulated breathiness than Hmong.

Unlike in English, the Korean data show that breathiness derived from lenis stops can be strongly coarticulated on the following vowel, showing large differentiation from modal phonation and lasting for much of the vowel in breathy-creaky contours. In this way, Korean breathiness behaves as if it were contrastive. The fact that Korean must maintain a three-way voiceless stop distinction word-initially implies that not only would these stops resist coarticulation, but that their features would likely spread onto following vowels. If Korean vowels are specified for modal voice as in English, then the features of the lenis stop (low F0, breathy, and high VOT) must spread on to the vowel at the expense of this modal specification.

These findings are relevant to theories of the phonetics-phonology interface, which often assume that the phonological component of the grammar manipulates features and has access to information about contrasts, either directly (from a phoneme inventory) or indirectly (e.g. through constraint ranking). On the other hand, it is often claimed that the phonetics only has access to the output of the phonological component, and not directly to underlying representations which would bear information of contrast (e.g. Keating, 1988b; Keating 1990, though see Kingston, 2007 for a survey of alternative accounts). Thus, if phonetic coarticulation is allowed to override the feature specification of another segment in order to enhance a contrast, then the phonetic component of the grammar must somehow have access to the contrasts of the language, either directly or indirectly by way of the phonological output.

However, I argue that the differences found between Korean and English breathiness coarticulation can be explained phonologically, assuming that the feature specification of English vowels differs from that of Korean vowels. I claim that Korean has a phonological rule of obstruent feature spreading onto following vowels, similar to the nasal spreading rule posited by Cohn (1990) for Sundanese. In English, however, vowels would always be assigned features resulting in modal voice, regardless of the neighboring sounds. This begs the question of when in the derivation vowels would be assigned such features. In Hmong, it makes sense that vowels would underlyingly bear features resulting in phonemic creaky voice, given that creaky voice is contrastive in the language. For English and Korean, on the other hand, there is no contrastive phonation on vowels (although Korean may be developing such a contrast, as mentioned in Section 2.1.3). Assuming that the phonological component of the grammar has two levels. In the first level, the vowels in both English and Korean are unspecified for laryngeal features, due to the absence of a phonological contrast. At a later level, English gets assigned a feature configuration for modal voice, whereas Korean has a rule stating that the vowels must inherit the laryngeal features of the preceding onset, the appropriate phonological output could be obtained. Supposing for simplicity that the features responsible for breathy, modal, and creaky voices are [breathy], [modal] and [creaky], respectively, then in the output of the phonology, an English word like /hæt/ and a Korean word like /pat/ would have the following features assigned to each segment:

	English			**Korean**		
Underlying representation:		/hæt/			/pat/	
Underlying segments:	/h/	/æ/	/t/	/p/	/a/	/t/
Underlying feature assignment:	[breathy]	Unspec.	[creaky]	[breathy]	Unspec.	[creaky]

Feature spreading rule in Korean: [breathy] [breathy] [creaky]

English modal vowel default rule: [breathy] [modal] [creaky]

Figure 16. Hypothetical phonological feature output for English and Korean breathy-creaky words with vowel feature assignment at a later stage

According to this hypothesis, the phonetic component would again be responsible for the coarticulation in voice quality between each of the laryngeal features, but differences between English and Korean in the duration of breathy voice would be accounted for by the different laryngeal specifications on the vowels. This hypothesis (as in Fig. 16) would work well with Blankenship's assumption that allophonic phonation is shorter than contrastive phonation, because allophonic phonation would always be the result of coarticulation of the laryngeal mechanism transitioning to or from a non-modal configuration. These phonological issues warrant further study, because they can increase our understanding of the nature and assignment of laryngeal features.

5 Conclusions

The goals of this study were twofold. The first was to show that breathy-creaky contours in vowels can be found in the world's languages, even those like English that lack contrastive phonation. These contours can be described using common measures of phonation. Measures of spectral tilt like H1*-H2* and H1*-A1*, as well as noise measures like HNR, are good at distinguishing either the breathy or creaky portions of such contours, or in some case both types of non-modal phonation.

The second goal was to account for cross-linguistic differences in the timing of the contours using previous work on phonation timing and theories of coarticulation. The findings of this study support the findings of Blankenship (1997, 2002) that contrastive non-modal phonation is longer and more differentiated from modal than allophonic non-modal phonation. The contrastive Hmong creak is longer and more pronounced than the allophonic forms in English and Korean, and the perhaps contrastive Korean breathiness is longer and stronger than the allophonic varieties in English and Hmong. The shorter duration and lesser differentiation of allophonic non-modal phonations compared to modal are attributed to phonation feature specification of vowels, even in languages like English and Korean, for which these features are redundant. However, the Korean results suggest that non-modal phonation can be more extensive on the vowel if it helps distinguish a contrast.

This study adds to our understanding of the production of phonation by showing that codas can alter a vowel's phonation significantly, as in Korean, that rapid changes in phonation within vowels are possible and likely more common than assumed, and that breathiness can be found to co-occur simultaneously with creakiness in vowels. It also raises important issues in phonological theory regarding laryngeal specification for vowel phonation.

Appendix A: Stimuli

Table 5 ***List of English stimuli***

Breathy-creaky	Breathy-modal	Modal-creaky	Modal-modal
a pat	a pass	a bat	a boss
a tat	a task	a dot	a gas
a cat	a cask	I got	a gauze
a hat	he has	a bop	
a pot	a pause	a dop	
a tot	a toss	I gap	
a cot	a cost	a back	
a hot		to balk	
a pop		a gack	
a tap		to gawk	
a cap		a dock	
a hop			
a top			
a cop			
a pack			
a tack			
a pock			
a hack			
a hawk			

Table 6 ***List of Hmong stimuli***

Breathy-creaky	Breathy-modal	Modal-creaky	Modal-modal	Phonemic breathy
pʰà̰	pʰa	pà̰	pà	pâ̤
pʰɔ̰̀	pʰɔ̀	pɔ̰̀	pɔ̀	pɔ̤̂
tʰà̰	tʰa	tà̰	tà	tâ̤
tʰɔ̰̀	tʰɔ	tɔ̰̀	tɔ̀	tɔ̤̂
kʰɔ̰̀	tʰɔ̀	kà̰	kà	kâ̤
hà̰	kʰá	kɔ̰̀	kɔ̀	
hɔ̰̀	kʰɔ			
	ha			
	hɔ			

Table 7 ***List of Korean stimuli***

Lenis-coda stop	Lenis-coda [l]	Modal-coda stop	Modal-coda [l]
pap˺	pal	lap˺	lal
pat˺	tal	lat˺	wal
pak˺	kal	lak˺	
tap˺		wap˺	
tat˺		wat˺	
tak˺		wak˺	
kap˺			
kat˺			
kak˺			

Appendix B: Results from linear regression analyses at selected time intervals

English H1*-H2*

First 9th	**Estimate**	**95% CI**		**Pr(>|t|)**
(Intercept)	-0.2324	-3.007	2.3374	0.8851
Sex - male	-4.4461	-8.191	-0.8001	0.0453
Breathy-creaky	3.0056	1.526	4.6195	**0.0002 *****
Breathy-modal	3.3835	1.627	5.0805	**0.0002 *****
Modal-creaky	0.0903	-1.535	1.7281	0.9146
Random effects	**Standard Deviation**	**95% CI**		
Item (intercept)	0.6158	0.0000	0.8744	
Speaker (intercept)	3.4909	1.8764	3.8320	
Residuals	3.9332	3.7839	4.1467	
R^2=0.5053341				

Third 9th	**Estimate**	**95% CI**		**Pr(>|t|)**
(Intercept)	1.3164	-0.6933	3.3874	0.2926
Sex - male	-5.0315	-7.8949	-2.1881	0.0045
Breathy-creaky	1.1705	-0.0030	2.2926	0.0381
Breathy-modal	1.6147	0.3001	2.9040	0.0105
Modal-creaky	-0.8786	-2.0918	0.3092	0.1391
Random effects	**Standard Deviation**	**95% CI**		
Item (intercept)	0.0000	0.0000	0.4854	
Speaker (intercept)	2.7796	1.4469	2.9675	
Residuals	3.1510	3.0148	3.3042	
R^2=0.5313496				

Sixth 9th	**Estimate**	**95% CI**		**Pr(>|t|)**
(Intercept)	2.5948	0.5745	4.4765	0.0359
Sex - male	-5.5311	-8.1048	-2.7161	**0.0016*****
Breathy-creaky	-0.2522	-1.2874	0.7879	0.6235
Breathy-modal	0.6992	-0.5614	1.7941	0.2236
Modal-creaky	-1.1384	-2.2670	-0.0620	0.0356
Random effects	Standard Deviation	95% CI		
Item (intercept)	0.0000	0.0000	0.4233	
Speaker (intercept)	2.7888	1.4645	2.7445	
Residuals	2.8718	2.7533	3.0130	
R^2= .5953311				

Final 9th	**Estimate**	**95% CI**		**Pr(>|t|)**

(Intercept)	3.2479	0.6739	6.0407	0.0213
Sex - male	-4.9722	-8.0585	-1.5375	0.0036
Breathy-creaky	-1.8888	-3.9172	0.2027	0.0714
Breathy-modal	0.4900	-1.7145	2.8646	0.6745
Modal-creaky	-2.0843	-4.3027	0.0731	0.0589
Random effects	**Standard Deviation**	**95% CI**		
Item (intercept)	1.4714	0.9073	1.6523	
Speaker (intercept)	2.9578	1.5978	3.2704	
Residuals	3.8908	3.5791	3.9226	
R^2= 0.4714627				

English H1*-A1*

First 9th	**Estimate**	**95% CI**		**Pr(>|t|)**
(Intercept)	-4.7180	-7.639	-1.724	0.0135
Sex - male	-4.0046	-7.955	0.045	0.1258
Breathy-creaky	9.9313	8.196	11.643	**0.0000 *****
Breathy-modal	10.2656	8.305	12.197	**0.0000 *****
Modal-creaky	-0.3925	-2.247	1.395	0.6762
Random effects	**Standard Deviation**	**95% CI**		
Item (intercept)	0.8127	0.3375	1.1596	
Speaker (intercept)	4.2029	2.1107	3.9067	
Residuals	4.1216	3.9626	4.3466	
R^2=0.7087843				

Third 9th	**Estimate**	**95% CI**		**Pr(>|t|)**
(Intercept)	0.696	-2.1082 0.6112	3.224	0.7341
Sex - male	-6.576	-10.2573	-2.886	0.0210
Breathy-creaky	2.862	1.4735	4.334	**0.0001*****
Breathy-modal	3.780	2.1806	5.344	**0.0000*****
Modal-creaky	-2.086	-3.6863	-0.656	0.0080
Random effects	Standard Deviation	95% CI		
Item (intercept)	0.6717	0.2308	0.9623	
Speaker (intercept)	4.7217	2.1093	3.6800	
Residuals	3.4582	3.3365	3.6628	
R^2=0.7130082				

Sixth 9th	**Estimate**	**95% CI**		**Pr(>|t|)**
(Intercept)	4.5931	1.7240	7.4263	0.0354
Sex - male	-8.4226	-12.1804	- 4.2889	0.0056
Breathy-creaky	-2.1088	-3.5928	-0.5961	0.0068
Breathy-modal	0.1644	-1.5749	1.8054	0.8499
Modal-creaky	-2.4234	-4.0359	-0.8891	0.0032
Random effects	**Standard**	**95% CI**		

	Deviation			
Item (intercept)	0.6761	0.1630	1.0294	
Speaker (intercept)	5.0367	2.3275	3.8555	
Residuals	3.6651	3.5530	3.8986	
R^2= 0.6989929				

Final 9th	**Estimate**	**95% CI**		**Pr(>|t|)**
(Intercept)	6.7450	1.8247	11.676	0.0380
Sex - male	-6.4801	-11.4048	-1.774	0.0246
Breathy-creaky	-6.8935	-11.1478	-2.548	0.0161
Breathy-modal	0.0084	-4.6938	5.012	0.9979
Modal-creaky	-5.7749	-10.2296	-1.055	0.0559
Random effects	**Standard Deviation**	**95% CI**		
Item (intercept)	4.3800	2.6939	3.9014	
Speaker (intercept)	4.5121	2.4922	4.8146	
Residuals	5.2052	5.0623	5.5516	
R^2= 0.6196829				

English HNR

First 9th	**Estimate**	**95% CI**		**Pr(>|t|)**
(Intercept)	2.5832	-1.3505	6.1741	0.2414
Sex - male	-10.8653	-15.1022	-6.8577	**0.0000*****
Breathy-creaky	4.3832	1.3905	7.4448	0.0096
Breathy-modal	6.6542	3.3040	10.0404	**0.0004*****
Modal-creaky	-3.5969	-6.8189	-0.3902	0.0435
Random effects	**Standard Deviation**	**95% CI**		
Item (intercept)	2.3902	1.5910	2.5805	
Speaker (intercept)	3.7719	2.1019	4.2616	
Residuals	4.5749	4.4148	4.8391	
R^2=0.7229706				

Third 9th	**Estimate**	**95% CI**		**Pr(>|t|)**
(Intercept)	5.1118	-0.6240	11.138	0.1420
Sex - male	-9.8260	-17.8245	-1.684	0.0460
Breathy-creaky	0.8005	-2.6585	4.170	0.6264
Breathy-modal	4.3362	0.4764	8.082	0.0185
Modal-creaky	-1.1231	-4.5051	2.633	0.5166
Random effects	**Standard Deviation**	**95% CI**		
Item (intercept)	0.0000	0.0000	1.5607	
Speaker (intercept)	7.6513	4.1266	8.3226	
Residuals	9.1916	8.7844	9.6286	

R^2=0.5193957

Sixth 9th	**Estimate**	**95% CI**		**Pr(>|t|)**
(Intercept)	7.200	0.3703	14.4452	0.0946
Sex - male	-5.246	-15.2171	4.4018	0.3889
Breathy-creaky	-5.005	-8.7207	-1.0346	0.0060
Breathy-modal	2.269	-1.8644	6.5764	0.2643
Modal-creaky	-4.133	-8.1985	-0.1592	0.0311
Random effects	**Standard Deviation**	**95% CI**		
Item (intercept)	0.0000	0.0000	1.8859	
Speaker (intercept)	9.6918	5.0465	10.0017	
Residuals	10.1626	9.7282	10.6745	
R^2= 0.5019769				

Final 9th	**Estimate**	**95% CI**		**Pr(>|t|)**
(Intercept)	14.7561	9.861	19.923	**0.0000*** **
Sex - male	-16.6761	-22.822	-10.688	**0.0000*** **
Breathy-creaky	-11.6548	-15.420	-7.875	**0.0000*** **
Breathy-modal	-0.8523	-5.125	3.401	0.7054
Modal-creaky	-12.1193	-16.148	-8.084	**0.0000*** **
Random effects	**Standard Deviation**	**95% CI**		
Item (intercept)	2.5524	1.6737	3.0409	
Speaker (intercept)	5.1093	2.8557	5.9360	
Residuals	7.0767	6.8071	7.4676	
R^2= 0.593465				

Hmong H1*-H2*

First 9th	**Estimate**	**95% CI**		**Pr(>|t|)**
(Intercept)	-1.8085	-3.3989	-0.1133	0.1081
Sex - male	-0.4503	-2.6274	1.8206	0.7734
Breathy-creaky	4.6887	3.8018	5.5268	**0.0000*** **
Breathy-modal	4.4908	3.6566	5.3371	**0.0000*** **
Modal-creaky	0.5614	-0.3391	1.4997	0.2355
Random effects	**Standard Deviation**	**95% CI**		
Item (intercept)	0.5078	0.1979	0.7514	
Speaker (intercept)	2.6340	1.3023	2.4490	
Residuals	2.3306	2.2366	2.4792	
R^2=0.6288675				

Third 9th	**Estimate**	**95% CI**		**Pr(>|t|)**
(Intercept)	-0.3105	-1.4590	0.9039	0.8079
Sex - male	-0.3028	-1.9489	1.3554	0.8665

Breathy-creaky	0.7319	0.2581	1.2438	0.0039
Breathy-modal	2.0544	1.5681	2.5131	0.0000***
Modal-creaky	-0.5350	-1.0713	-0.0235	0.0483
Random effects	**Standard Deviation**	**95% CI**		
Item (intercept)	0.2209	0.0000	0.3382	
Speaker (intercept)	3.0937	1.1430	1.6887	
Residuals	1.4985	1.4699	1.6317	
R^2=0.7805406				

Sixth 9th	**Estimate**	**95% CI**		**Pr(>|t|)**
(Intercept)	0.2322	-1.3657	1.9086	0.8546
Sex - male	-0.4359	-2.6602	1.8717	0.8073
Breathy-creaky	-0.0191	-0.7079	0.6913	0.9574
Breathy-modal	1.6183	0.9340	2.3007	0.0000***
Modal-creaky	-1.4642	-2.2197	-0.7049	0.0001***
Random effects	**Standard Deviation**	**95% CI**		
Item (intercept)	0.2315	0.0000	0.4274	
Speaker (intercept)	3.0342	1.3807	2.4564	
Residuals	2.2642	2.1743	2.4116	
R^2= 0.6052655				

Final 9th	**Estimate**	**95% CI**		**Pr(>|t|)**
(Intercept)	-0.1324	-2.2179	1.8462	0.9086
Sex - male	-0.3890	-3.1827	2.4300	0.8111
Breathy-creaky	0.8494	-0.2474	1.9224	0.1174
Breathy-modal	2.9174	1.8910	3.9559	0.0000***
Modal-creaky	-1.1662	-2.4150	-0.0636	0.0458
Random effects	**Standard Deviation**	**95% CI**		
Item (intercept)	0.2120	0.0000	0.6014	
Speaker (intercept)	2.6486	1.4836	3.1175	
Residuals	3.5841	3.4133	3.7794	
R^2=0.353398				

Hmong H1*-A1*

First 9th	**Estimate**	**95% CI**		**Pr(>|t|)**
(Intercept)	-8.7068	-12.214	-5.106	0.0001***
Sex - male	3.5456	-1.288	8.581	0.2575
Breathy-creaky	16.0809	14.105	18.013	0.0000***
Breathy-modal	14.4134	12.566	16.263	0.0000***
Modal-creaky	0.9934	-1.067	3.014	0.3505
Random effects	**Standard Deviation**	**95% CI**		

Item (intercept)	1.0015	0.0000	1.4800	
Speaker (intercept)	5.2052	2.7125	5.4634	
Residuals	5.6076	5.3691	5.9519	
R^2=0.6263861				

Third 9th	**Estimate**	**95% CI**		**Pr(>|t|)**
(Intercept)	-3.7101	-6.6895	-0.9628	0.1793
Sex - male	3.0659	-0.4584	7.1555	0.4246
Breathy-creaky	6.0184	4.4212	7.7159	**0.0000*****
Breathy-modal	5.4044	3.8207	6.9854	**0.0000*****
Modal-creaky	-0.0956	-1.7076	1.7670	0.9162
Random effects	**Standard Deviation**	**95% CI**		
Item (intercept)	1.2381	0.7465	1.6052	
Speaker (intercept)	6.5807	2.5434	3.8103	
Residuals	3.5172	3.4356	3.8158	
R^2=0.7577858				

Sixth 9th	**Estimate**	**95% CI**		**Pr(>|t|)**
(Intercept)	-2.0526	-5.573	1.3597	0.4964
Sex - male	2.6610	-1.950	7.4171	0.5253
Breathy-creaky	3.7929	1.891	5.8271	**0.0002*****
Breathy-modal	3.1700	1.251	5.0311	**0.0013*****
Modal-creaky	0.7708	-1.296	2.8521	0.4769
Random effects	**Standard Deviation**	**95% CI**		
Item (intercept)	1.4256	0.8651	1.8463	
Speaker (intercept)	7.1545	2.9878	4.9699	
Residuals	4.4203	4.2835	4.7589	
R^2= 0.6809525				

Final 9th	**Estimate**	**95% CI**		**Pr(>|t|)**
(Intercept)	-3.6982	-7.9771	0.7736	0.1981
Sex - male	5.8418	0.0304	12.2208	0.1508
Breathy-creaky	2.5735	0.3551	4.6787	0.0109
Breathy-modal	5.0030	2.9143	7.0371	**0.0000*****
Modal-creaky	-0.9183	-3.2284	1.4358	0.3984
Random effects	**Standard Deviation**	**95% CI**		
Item (intercept)	0.0000	0.0000	1.3490	
Speaker (intercept)	6.7923	3.5554	6.6633	
Residuals	6.8352	6.4996	7.1965	
R^2= 0.4680329				

Hmong HNR

First 9th	**Estimate**	**95% CI**		**Pr(>|t|)**
(Intercept)	-3.1168	-6.7562	0.8281	0.4685
Sex - male	1.0730	-4.1194	6.1142	0.8586
Breathy-creaky	2.4179	0.4103	4.4657	0.0209
Breathy-modal	7.5092	5.5326	9.4159	**0.0000*****
Modal-creaky	-3.0295	-5.1857	-0.8540	0.0064
Random effects	**Standard Deviation**	**95% CI**		
Item (intercept)	1.4356	0.8233	1.9427	
Speaker (intercept)	10.3549	3.5586	5.1292	
Residuals	4.6185	4.5390	5.0467	
R^2=0.8179566				

Third 9th	**Estimate**	**95% CI**		**Pr(>|t|)**
(Intercept)	6.8297	2.3882	11.4861	0.0383
Sex - male	-5.0015	-11.2559	0.9615	0.2735
Breathy-creaky	-9.0029	-11.5884	-6.6206	**0.0000*****
Breathy-modal	2.9509	0.5067	5.3280	0.0178
Modal-creaky	-6.0981	-8.7388	-3.4119	**0.0000*****
Random effects	**Standard Deviation**	**95% CI**		
Item (intercept)	1.5955	0.7747	2.2814	
Speaker (intercept)	7.7142	3.7013	6.5614	
Residuals	6.4311	6.1851	6.8534	
R^2=0.7169754				

Sixth 9th	**Estimate**	**95% CI**		**Pr(>|t|)**
(Intercept)	8.9570	4.312	13.692	0.0029
Sex - male	-0.6541	-7.266	5.736	0.8765
Breathy-creaky	-22.3158	-24.651	-20.000	**0.0000*****
Breathy-modal	0.2733	-1.913	2.608	0.8120
Modal-creaky	-21.5687	-24.078	-19.016	**0.0000*****
Random effects	**Standard Deviation**	**95% CI**		
Item (intercept)	0.8882	0.0000	1.5075	
Speaker (intercept)	7.0115	3.7523	7.0617	
Residuals	7.3928	7.0624	7.8314	
R^2= 0.7019673				

Final 9th	**Estimate**	**95% CI**		**Pr(>|t|)**
(Intercept)	9.043	3.3082	14.755	0.0300
Sex - male	-1.635	-9.9197	6.436	0.7812
Breathy-creaky	-20.713	-23.2119	-18.097	**0.0000*****

Breathy-modal	-3.655	-6.1133	-1.131	0.0027
Modal-creaky	-21.455	-24.2550	-18.706	**0.0000*** **
Random effects	**Standard Deviation**	**95% CI**		
Item (intercept)	0.0001	0.0000	1.1125	
Speaker (intercept)	9.9298	4.8355	8.7827	
Residuals	8.5801	8.2153	9.0980	
R^2= 0.6543379				

Korean H1*-H2*

First 9th	**Estimate**	**95% CI**		**Pr(>|t|)**
(Intercept)	-1.6605	-3.0213	-0.2299	0.0188
Sex - male	-4.0390	-5.9255	-2.2101	**0.0000*** **
Breathy-creaky	5.8085	4.6552	6.9143	**0.0000*** **
Breathy-modal	5.1238	3.7639	6.4013	**0.0000*** **
Modal-creaky	-0.2058	-1.3859	0.9818	0.7308
Random effects	**Standard Deviation**	**95% CI**		
Item (intercept)	0.3092	0.0000	0.5666	
Speaker (intercept)	1.1716	0.6799	1.6457	
Residuals	2.3421	2.2066	2.5090	
R^2=0.69538				

Third 9th	**Estimate**	**95% CI**		**Pr(>|t|)**
(Intercept)	0.1884	-1.2586	1.5237	0.8026
Sex - male	-4.8639	-6.6975	-2.9787	**0.0000*** **
Breathy-creaky	2.9985	1.8698	4.0372	**0.0000*** **
Breathy-modal	0.1146	-1.1504	1.3506	0.8580
Modal-creaky	-1.2136	-2.3426	-0.1139	0.0349
Random effects	**Standard Deviation**	**95% CI**		
Item (intercept)	0.3683	0.0000	0.5972	
Speaker (intercept)	1.3889	0.7737	1.7683	
Residuals	2.1138	1.9884	2.2681	
R^2=0.6626272				

Sixth 9th	**Estimate**	**95% CI**		**Pr(>|t|)**
(Intercept)	2.1055	0.7994	3.5441	0.0067
Sex - male	-4.2539	-6.1033	-2.3419	**0.0001*** **
Breathy-creaky	-0.9646	-1.9060	0.0687	0.0516
Breathy-modal	-0.3591	-1.4679	0.8260	0.5348
Modal-creaky	-2.0187	-2.9962	-0.9614	**0.0001*** **
Random effects	**Standard Deviation**	**95% CI**		

Item (intercept)	0.2804	0.0000	0.4928	
Speaker (intercept)	1.5478	0.8537	1.7799	
Residuals	2.0028	1.8911	2.1554	
R^2= 0.5229947				

Final 9th	**Estimate**	**95% CI**		**Pr(>|t|)**
(Intercept)	5.120	3.7015	6.6293	**0.0000*****
Sex - male	-6.295	-8.1539	-4.2223	**0.0000*****
Breathy-creaky	-5.058	-6.2181	-3.8409	**0.0000*****
Breathy-modal	-1.486	-2.9019	-0.1427	0.0380
Modal-creaky	-5.444	-6.6809	-4.1957	**0.0000*****
Random effects	**Standard Deviation**	**95% CI**		
Item (intercept)	0.4035	0.0000	0.6522	
Speaker (intercept)	1.3384	0.7348	1.7812	
Residuals	2.3733	2.2436	2.5545	
R^2=0.4437377				

Korean H1*-A1*

First 9th	**Estimate**	**95% CI**		**Pr(>|t|)**
(Intercept)	-5.2556	-8.024	-2.5475	**0.0003*****
Sex - male	-2.5202	-5.816	0.9516	0.1551
Breathy-creaky	10.5232	8.277	12.8882	**0.0000*****
Breathy-modal	9.6184	6.800	12.2091	**0.0000*****
Modal-creaky	1.3728	-0.938	3.8692	0.2682
Random effects	**Standard Deviation**	**95% CI**		
Item (intercept)	1.0909	0.4860	1.5475	
Speaker (intercept)	2.4308	1.3593	3.0551	
Residuals	3.7680	3.5637	4.0574	
R^2=0.681699				

Third 9th	**Estimate**	**95% CI**		**Pr(>|t|)**
(Intercept)	-4.2992	-6.5583	-2.0274	**0.0012*****
Sex - male	-3.0034	-5.9905	0.2314	0.1038
Breathy-creaky	10.5587	9.0418	12.0207	**0.0000*****
Breathy-modal	3.4986	1.6169	5.1858	**0.0001*****
Modal-creaky	1.2644	-0.3640	2.8002	0.1103
Random effects	**Standard Deviation**	**95% CI**		
Item (intercept)	0.3457	0.0000	0.6976	
Speaker (intercept)	2.7740	1.4828	3.0384	
Residuals	3.1906	3.0048	3.4269	
R^2=0.7583133				

Sixth 9th	**Estimate**	**95% CI**		**Pr(>|t|)**

(Intercept)	-2.6300	-5.1797	-0.2170	0.0824
Sex - male	-2.5386	-5.7481	0.7483	0.2154
Breathy-creaky	6.1326	4.4435	7.9799	**0.0000*** **
Breathy-modal	1.7038	-0.4265	3.5869	0.0971
Modal-creaky	1.9275	0.1190	3.7306	0.0366
Random effects	**Standard Deviation**	**95% CI**		
Item (intercept)	0.6368	0.0000	0.9968	
Speaker (intercept)	3.1487	1.6035	3.1603	
Residuals	3.2854	3.1202	3.5584	
R^2= 0.6396107				

Final 9th	**Estimate**	**95% CI**		**Pr(>|t|)**
(Intercept)	-3.9505	-7.419	-0.6559	0.0430
Sex - male	-1.3530	-5.198	2.4802	0.5505
Breathy-creaky	6.6771	3.781	9.5643	**0.0000*****
Breathy-modal	0.0690	-3.197	3.5239	0.9692
Modal-creaky	4.3538	1.360	7.4539	0.0075
Random effects	**Standard Deviation**	**95% CI**		
Item (intercept)	1.6250	0.8677	2.1032	
Speaker (intercept)	3.3225	1.7595	3.7510	
Residuals	4.2008	3.9816	4.5326	
R^2= 0.5365936				

Korean HNR

First 9th	**Estimate**	**95% CI**		**Pr(>|t|)**
(Intercept)	15.216	9.277	21.073	**0.0000*** **
Sex - male	-16.868	-22.608	-11.177	**0.0000*** **
Breathy-creaky	-14.332	-19.937	-8.574	**0.0000*** **
Breathy-modal	-11.595	-17.936	-4.846	**0.0018*** **
Modal-creaky	-2.037	-8.271	3.714	0.5490
Random effects	**Standard Deviation**	**95% CI**		
Item (intercept)	3.8354	2.2421	4.3485	
Speaker (intercept)	4.0496	2.3337	5.2497	
Residuals	6.8083	6.4653	7.3630	
R^2=0.6683383				

Third 9th	**Estimate**	**95% CI**		**Pr(>|t|)**
(Intercept)	21.9472	17.270	26.649	**0.0000*** **
Sex - male	-24.4033	-30.587	-18.048	**0.0000*** **
Breathy-creaky	-22.9007	-26.116	-19.451	**0.0000*** **
Breathy-modal	-5.5371	-9.393	-1.572	0.0048
Modal-creaky	-5.3423	-8.890	-1.877	0.0023

Random effects	**Standard Deviation**	**95% CI**	
Item (intercept)	0.9357	0.0000	1.6616
Speaker (intercept)	5.3942	2.8469	5.9961
Residuals	6.7896	6.4269	7.3051
R^2=0.7749755			

Sixth 9th	**Estimate**	**95% CI**		**Pr(>|t|)**
(Intercept)	14.5252	9.7079	19.095	**0.0000*****
Sex - male	-22.8120	-29.4384	-16.408	**0.0000*****
Breathy-creaky	-8.9619	-11.9465	-5.812	**0.0000*****
Breathy-modal	-0.5069	-4.1183	3.108	0.7735
Modal-creaky	-0.7308	-3.9140	2.501	0.6407
Random effects	**Standard Deviation**	**95% CI**		
Item (intercept)	0.0000	0.0000	1.2457	
Speaker (intercept)	5.8593	3.0922	6.3159	
Residuals	6.7601	6.3644	7.2395	
R^2=	0.762035			

Final 9th	**Estimate**	**95% CI**		**Pr(>|t|)**
(Intercept)	16.7012	12.541	20.895	**0.0000*****
Sex - male	-19.1594	-25.220	-13.530	**0.0000*****
Breathy-creaky	-12.5870	-15.961	-9.554	**0.0000*****
Breathy-modal	-0.8551	-4.398	3.052	0.6439
Modal-creaky	-10.6211	-13.851	-7.288	**0.0000*****
Random effects	**Standard Deviation**	**95% CI**		
Item (intercept)	0.5211	0.0000	1.3560	
Speaker (intercept)	4.2480	2.3998	5.5557	
Residuals	6.8708	6.4579	7.3475	
R^2= 0.6649445				

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