Production, Perception, and Distribution of Breathy Sonorants in Marathi

KELLY BERKSON, *Indiana University, Bloomington*

ABSTRACT

Breathy sonorants are crosslinguistically rare, and while a small amount of existing work has focused on their acoustic properties much remains to be learned about their perception and their language-internal distribution. Herein, breathy sonorants in Marathi are investigated via instrumental acoustic analysis, a perception experiment, and corpus analysis. Results reveal that breathy sonorants are under-represented language-internally in addition to being typologically rare. The acoustic differences associated with sonorant phonation contrasts are less robust than those in obstruents. They are also prone to more perception errors than obstruents, and breathy sonorants are more heavily restricted phonotactically than breathy obstruents. These data contribute to a more nuanced understanding of breathy sonorants, and lend potential insight into their typology.

1. Introduction

Though phonemic breathy voice is crosslinguistically rare, the breathy obstruents found in Indic phonemic inventories are well-known. What are not so well-known are breathy sonorants. Rare even among Indic languages, these sounds occur in just 1% of the languages in the UCLA Phonological Segment Inventory Database (UPSID). Much about their acoustic properties, perceptual salience, and language-internal distribution remains unknown. Marathi—the state language of Maharashtra—provides an ideal arena in which to investigate these sounds, because it contains multiple breathy sonorants across distinct places and manners of articulation. This study adds to the existing body of knowledge via Marathi data gleaned from a production study, a perception study, and analysis of phonemic frequencies in a Marathi corpus. In the following pages, a brief overview of breathy phonation and Marathi precedes sections devoted to each of the three studies.

1.1 Overview of breathy phonation

Breathy phonation is characterized by greater airflow than modal voice, and by a steep downward spectral slope—namely, strong low-frequency energy and weak higher-frequency energy (Gordon & Ladefoged 2001, Pennington 2005). Numerous scholars have investigated phonemic breathy phonation in vowels (Andruski & Ratliff 2000, Blankenship 2002, Esposito 2006, Khan 2012, Wayland & Jongman 2003) and in Indic obstruents (Alam *et al.* 2008, Berkson 2013, Berkson 2016, Davis 1994, Dutta 2007, Mikuteit & Reetz 2007, Ohala & Ohala 1972). These studies indicate that breathy voice is generally associated with greater values than modal voice in spectral measures like H1-H2 and increased noise as assessed by measures like Cepstral Peak Prominence (CPP). Many of the acoustic correlates of breathy consonants are housed in the following vowel (Berkson 2013, Dutta 2007, Esposito & Khan 2012), and the effect of consonant breathiness can perseverate throughout most or all of the following vowel (Berkson 2013, Dutta 2007). The values associated with breathiness, then—increased spectral values and increased noise in the signal—can be found consonant-externally, in the following vowel.

Work on breathiness in sonorants is limited, though Harris 2009 investigated breathy nasals and laterals in Sumi (Tibeto-Burman) and Traill and Jackson (1988) investigated breathy nasals in Tsonga (Bantu). These studies suggest that sonorant breathiness is associated with the same spectral shape and increased noise associated with vowel/obstruent breathiness. Meanwhile, to the best of my knowledge no work has probed the perception of phonation contrasts in sonorants or perception of phonation contrasts in Marathi in general, so questions about the perceptibility of these contrasts abound. The same can be said of the distribution of breathy sonorants in the Marathi lexicon: anecdotally they seem to occur infrequently, but current data regarding their phonemic frequencies is limited. Many questions about these typologically rare sounds remain open, in other words, both in general and in Marathi in particular.

1.2 Overview of Marathi

Marathi is spoken by ~70 million people, mainly in Maharashtra (2001 India Census). As shown in the consonant inventory in Figure (1), it contains both the breathy obstruents for which Indic languages are known and the less common breathy sonorants.[1]

Manner of Articulation	Place of Articulation													
	Labial		Non-retroflex Apical				Retroflex		Alveo-Palatal		Velar		Glottal	
			Dental		Alveolar									
Stop	p pʰ	b bʱ	t tʰ	d dʱ			ʈ ʈʰ	ɖ ɖʱ			k kʰ	g gʱ		
Nasal		m mʱ		n nʱ				ɳ ɳʱ				(ŋ)		
Affricate					ts (tsʰ)	dz (dzʱ)			tʃ tʃʰ	dʒ dʒʱ				
Fricative					s		(ʂ)		ʃ				h	
Approximant		ʋ ʋʱ		l lʱ				ɭ		j				
Rhotic										r rʱ				

Figure (1) Marathi consonant inventory

We can see in Fig. (1) that despite their crosslinguistic rareness, breathy sonorants make up a relatively high proportion of Marathi's consonant inventory. The three experiments described below each address a specific research question, but this program of research also aims to probe the connection between the crosslinguistic trend and the language-internal reality: by studying Marathi, can we learn something about breathy sonorants that sheds light on the typological pattern? This is a question to which we will return.

1.3 Research Questions

Three research questions are addressed herein.

[1] Chart developed with primary reference to Masica (1991), Pandharipande (1997), and Dhongde and Wali (2009). Sounds in parentheses are dubbed 'marginal' by Dhongde and Wali : the retroflex fricative, for instance, appears only in Sanskrit words and is largely produced as an alveo-palatal.

Q1: What are the acoustic characteristics of phonation contrasts in sonorants?
Q2: Are phonation contrasts perceived as well in sonorants as in obstruents?
Q3: How are breathy sonorants distributed language-internally?

Experiments addressing each of these questions are presented in separate sections below.

2. Experiment 1: Production

For a production experiment designed to probe the acoustic correlates of phonation contrasts in Marathi sonorants, ten native Marathi speakers (five female) were recorded producing Marathi words embedded in a carrier sentence. Stimuli featured plain and breathy obstruents and sonorants from the labial, dental, and alveo-palatal places of articulation in word-initial and word-medial positions before the vowels [a] and [e]. Recordings were made in a sound-attenuated booth. Data were analyzed using PRAAT (Boersma & Weenink 2010), VoiceSauce (Shue *et al.* 2011), and *R* (R Core Team, 2012).

Recall that, as outlined in Section 1.1, breathy phonation in vowels and obstruents is associated with increased measures of spectral slope and decreased measures of noise such as CPP. The data collected were subjected to a suite of acoustic analyses (including F0, H1-H2*, H1-A1*, H1-A2*, H1-A3*, and CPP), and the overall trend revealed is that the same holds true for sonorants: breathy voice in both obstruents and sonorants is associated with increased noise and increased spectral values. Consonant breathiness extends far into the subsequent vowel. There is also a theme that emerges in the data, however: acoustic differences triggered by phonation type are more reliably present in obstruent than in sonorant contexts. This is illustrated by the H1-A1* data provided below, which are representative of the larger trend.[2]

An omnibus repeated measures ANOVA was conducted wherein H1-A1* was the dependent variable and the independent variables included Phonation type (modal and breathy), Obstruency (obstruent and sonorant), Place of articulation (labial, dental, alveo-palatal), Vowel context ([a] context and [e] context), Word position (initial and medial), and Speaker sex (male and female). This test revealed a Phonation type by Obstruency by Gender interaction (F (1,6) = 46.36, p = 0.0005). Post hoc tests indicated a significant effect of consonant phonation type for males for vowels after obstruents (F (1,4) = 29.25, p = 0.006) but not after sonorants (F (1,4) = 16.66, p = 0.015). These data are in Fig. (2a). For females, the effect of consonant phonation type on H1-A1* values in vowels was marginal after obstruents (F (1,4) = 19.37, p = 0.011) and was not significant after sonorants (F (1,4) = 1.35, p = 0.31). For both sexes, then, differences are present after obstruents but not after sonorants.

Sonorants also differ from obstruents in terms of the amount of segment-internal acoustic information they can carry. In this work spectral measures were taken sonorant-internally as well as in vowels, and sonorant-internal measures tend to show a great deal of contextual variation. For example: the omnibus Anova for sonorant-internal H1-A3* values revealed a main effect of phonation type (F (1,7) = 6.59, p = 0.037). Breathy phonation triggers greater segment-internal H1-A3c values. There is also Phonation Type by Place by Vowel context by Window interaction (F (1,7) = 14.73, p = 0.006), however. This type of interaction is difficult to interpret, but Fig. (2b) illustrates the general pattern that presumably underlies the interaction: sonorants before [a]

[2] Additional data are not discussed here due to space constraints, but see Berkson 2013 for in-depth discussion of the acoustic correlates of breathiness in Marathi sonorants.

pattern in the expected direction, with breathy sonorants associated with greater H1-A3c values than their plain counterparts, but the effect disappears in sonorants that occur before [e].[3]

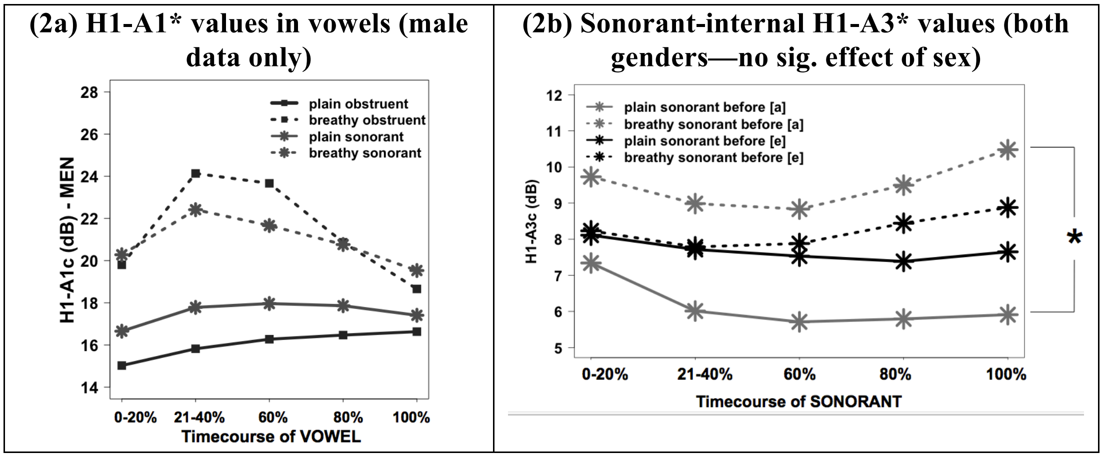

Figure (2) Plots for vowel-internal H1-A1c (2a) and sonorant-internal H1-A3* (2b)

In sum, while the acoustic correlates of breathy sonorants generally align with those found in obstruents/vowels, acoustic differences triggered by sonorants don't always match up: obstruents sometimes trigger differences that sonorants do not (as illustrated in Fig. 2a). And while sonorants can carry more segment-internal cues than obstruents, these are often subject to contextual variation (as illustrated in Fig. 2b).

Given these findings, there is a question raised as to whether the typological pattern observed—that of breathy sonorants being quite rare—arises at least in part because these sounds are poorly differentiated acoustically. To test this proposal, the perception of phonation contrasts in sonorants and obstruents was investigated.

3. Experiment 2: Perception

A perception experiment consisting of a series of ID tasks was conducted next, to determine how well listeners perceive phonation type contrasts in Marathi obstruents and sonorants. Stimuli consisted of CV syllables—dental consonants (/d/~/dʱ/, /n/~/nʱ/, /l/~/lʱ/) paired with [a] and [e]—excised from the real Marathi words recorded in Experiment 1. All 10 talkers from Experiment 1 were used, so stimuli were produced by ten talkers (5 male). Stimuli were presented in consonant-pair blocks (a D block featuring only the /d/~/dʱ/ contrast, an N block, and an L block) in an experiment built in Paradigm (Perception Research Systems 2007).

Blocks were randomized. Listeners sat at a computer, heard stimuli presented over headphones, and were asked to identify the consonant they heard by clicking on the appropriate Devanagari character on the screen. Preliminary data from seven native Marathi listeners (four female) reveal that perception of phonation type is more accurate (numerically) for obstruents

[3] Post hoc tests probing the Place and Window interactions are not reported here, but details can be found in Berkson 2013: 168-170. Briefly, the effect size differs across places of articulation and differences are more pronounced later in the sonorant as compared with at the beginning of the sonorant.

(92%) than for sonorants (82%). Overall accuracy rates for the D, L, and N blocks are in Fig. (3a). Listeners identify plain stimuli with about 90% accuracy. Accuracy remains high for breathy obstruents, but drops by about 20% for breathy sonorants. These data are from just seven participants, but they suggest that phonation contrasts are indeed harder to perceive in sonorants than in obstruents, and that accuracy suffers most in breathy sonorants. Note that in any given trial there are two possible options (plain or breathy), so chance is 50%. Listeners are above chance even with breathy sonorants, but with 75% accuracy they're guessing the wrong consonant one out of four times.

We may wonder: are the group means presented in Fig. (3a) representative of the overall response pattern, or is there individual variation in how good listeners are at this task? In Fig. (3b), we can see the individual response patterns for the seven participants' L block trials. The general trend—of greater accuracy with plain stimuli—holds for five out of seven people, with two female participants (W1 and W3) achieving equal accuracy with plain and breathy stimuli.

We may also ask whether response rates vary by producer—or, are stimuli produced by certain speakers easier (or more difficult) for listeners to judge? Fig. (3c) shows L response accuracy plotted by talker—by who produced the stimulus—and these data indicate that the answer to this question is a resounding yes. Response rates vary dramatically based on talker. Participants correctly identified the phonation type of L stimuli produced by male talker m6 with 100% accuracy,

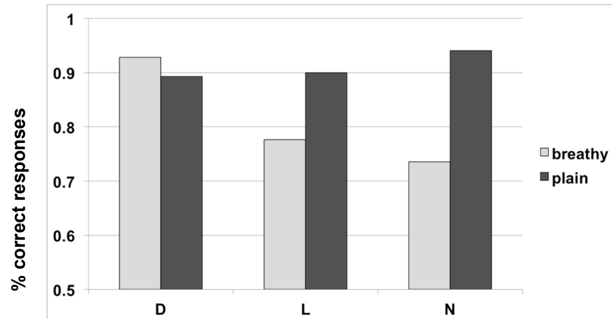

Fig. (3a) Overall response accuracy
Response rates for breathy stimuli are in the light bars and for plain stimuli are in the dark bars.

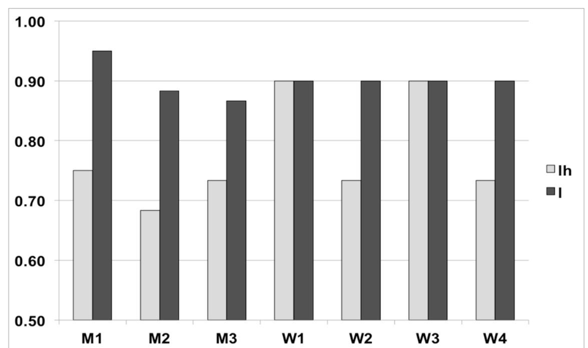

Fig. (3b) Accuracy by listeners – L Block
L results by **listener**—4 males (M1, M2, etc), 3 females. Breathy response accuracy lower, except W1 & W3.

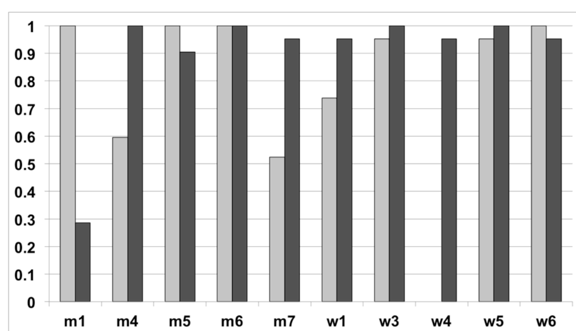

Fig. (3c) Accuracy by Talkers – L Block
L results by the **talker** who produced the tokens. Data for 5 males (m1, m4, etc) & 5 females.

Figure (3) Perception Accuracy Rates

for instance, while no listener ever correctly identified one of female talker w4's breathy L stimuli. This was surprising: acoustic analysis of her stimuli reveal that she does produce breathy Ls, which differ along the expected spectral and noise parameters. These acoustic differences do not translate into a perceptually salient difference for listeners, however. They do not identify her breathy L as breathy.

Considering these data together, then, what can we say about the perception of phonation contrasts in Marathi? One point that is made is clear is that the variability is ubiquitous: accuracy varies across sonorant and obstruent contexts, listeners vary in terms of how much their accuracy declines from plain to breathy sonorant contexts, and speakers vary in terms of how perceptibly breathy their breathy sounds are. The indication, though, is that phonation contrasts in sonorants are "vulnerable" in a way that those in obstruents are not—response accuracy declines when the stimuli being judged are breathy sonorants.

If the acoustic cues for phonation contrasts are more variable in sonorants, and perception of breathy sonorants is more vulnerable as well, might there be diachronic consequences? If so, we may expect these sounds to be under-represented in Marathi. We turn now to Experiment 3, which assessed phonemic frequencies in a Marathi corpus to address exactly this question.

4. Experiment 3: Distribution of Breathy Sonorants in a Marathi Corpus

To investigate the distribution of breathy consonants in the Marathi lexicon, the final experiment investigated phonotactic frequencies in the 2.2 million-word Marathi portion of the EMILLE (Enabling Minority Language Engineering)/CIIL (Central Institute of Indian Languages) corpus. This is a collection of South Asian language corpora totaling 97 million words.[4] The Marathi portion is a written corpus pulled from multiple types of sources (newspapers, magazines, novels, etc.). No spoken corpus of Marathi of comparable size is currently available, and analysis of a written corpus as a first step towards identifying general phonotactic patterns in the language is suitable given that Devanagari is relatively phonetic in nature. Token frequency of consonants (the sheer number of times the phone of interest appears) and type frequency of bigrams (the number of words that contain the targeted bigram) are reported.

The most basic finding, shown in the mosaic plot in Figure (4a), is consonant token frequency: 59% of the consonants in the corpus are obstruents, and 41% are sonorants. Breathy sounds are underrepresented in general: 8% of the consonants in the corpus are breathy, but upwards of 90% of these are obstruents. Just 0.63% of the consonants in the corpus are breathy sonorants.

Recall, too, that not all vowel contexts are created equal: this was evident in Fig. (2b), where sonorant-internal H1-A3* values differed before [a] but not before [e]. Anecdotally, when culling through dictionaries and working with speakers to generate stimuli for Experiment 1, lexical items containing breathy sonorants before [a] or schwa were the easiest to find. To rigorous probe the question of whether there is a bias towards breathy sonorant-lower vowel sequences in the corpus, type frequency of CV bigrams—meaning the number of words that contain the targeted bigram—was calculated. Data for CV syllables containing monophthongs are in Fig. (4b), and show that breathy sonorants do not co-occur with all monophthongs evenly.

[4] Details about the corpus—and to fair and appropriate use thereof—can be found at http://catalog.elra.info/product_info.php?products_id=696.

Rather, they co-occur with [a] more than 60% of the time. Co-occurrence with back rounded [o] and [u] is heavily restricted.

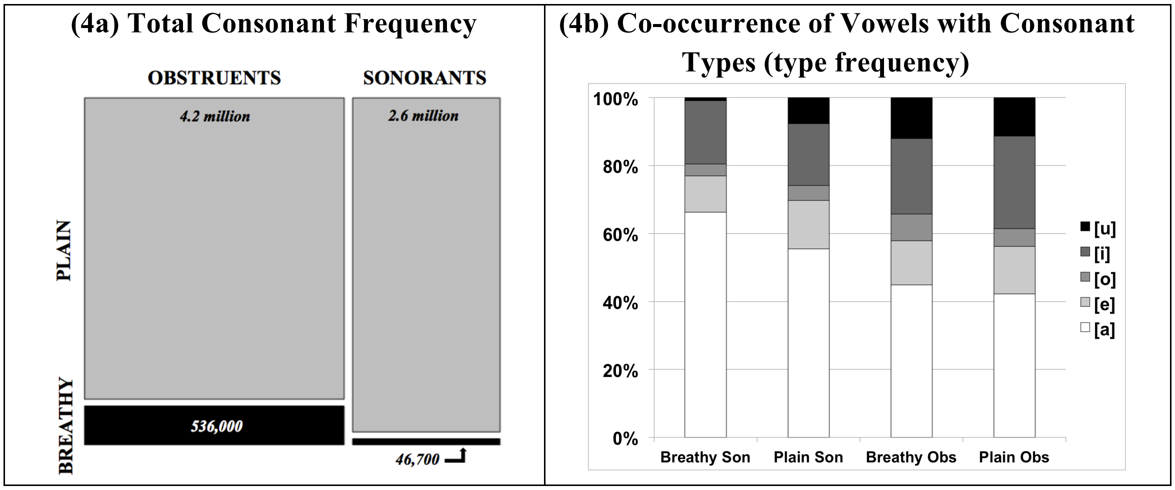

Figure (4) Total consonant frequency (4a) and CV bigram type frequency (4b)

It is important to note that the pattern seen in breathy sonorants does not diverge completely from the pattern evident in the remaining consonant types: the back rounded vowels are infrequent overall, and [a] accounts for a large proportion of CV syllables regardless of consonant type. Nevertheless, [a] dominates the breathy sonorant syllables.

These data represent only an initial foray into understanding the phonotactic frequencies of Marathi. More remains to be examined in the existing corpus—for instance, due to space restrictions only data related to the major groupings of plain obstruent, breathy obstruent, plain sonorant, and breathy sonorant have been reported. No individual consonant data are shown here. Bigram frequencies shared here are limited to those involving monophthongs, but Marathi contains diphthongs, as well. There is also the question of corpus type: future work on a spoken corpus would enhance the generalizability of findings. These provide exciting directions for future work, which can build on the basic picture established here. The present data add to our understanding of breathy sonorants, however, by allowing us to understand their basic distribution within a language which contains them. These sounds, which are typologically rare, are rare in Marathi as well. They are underattested both cross-linguistically and language-internally.

5. Discussion

This work focused on phonation type contrasts in sonorants: though crosslinguistically rare, there are a number of breathy voiced sonorant phonemes in Marathi. Three experiments were conducted: one probed the acoustic properties of these sounds, the second the perception of these sounds by native Marathi listeners, and the third their phonotactic frequencies in a Marathi corpus. Each addressed one of the three specific questions laid out in Section 1.3.

The first question asked, **What are the acoustic characteristics of phonation contrasts in sonorants?** The production task confirmed that breathy sonorants are associated with the same sorts of acoustic patterns found in breathy obstruents and vowels—increased spectral measures and increased noise—but that differences are not triggered as reliably by sonorants as by obstruents. H1-A1* values in subsequent vowels differ based on obstruent phonation type, for instance, but not based on sonorant phonation type. Furthermore, sonorants can carry segment-internal cues, but these are often subject to contextual variation: recall that sonorant-internal H1-A3* values differed before [a] but not before [e].

The second question asked, **Are phonation contrasts perceived as well in sonorants as in obstruents?** Preliminary data suggests that the answer is no. Listeners identified obstruent phonation-type with 92% accuracy and sonorant phonation-type with 82% accuracy, and the decrement in sonorants is mainly in the breathy category: plain sonorants are identified more accurately than breathy sonorants, where identification accuracy is around 75%. Importantly, the by-speaker analysis shown in Fig. (3c) indicates a tremendous amount of variation across individual stimuli: while some breathy tokens appear to be easy for listeners to correctly identify, others are tremendously difficult. For one of the talkers who produced stimuli for this experiment, in fact, no breathy stimulus was ever identified correctly. This suggests that breathy voiced sonorants can be produced quite differently, with some productions lending themselves to accurate identification and some being quite confusable with plain sonorants.

The third question asked, **How are breathy sonorants distributed language-internally?** Analysis of a written corpus revealed that breathy sonorants occur infrequently, making up <1% of the consonants in the corpus. They also co-occur with the low vowel [a] more often than with the remaining monophthongs, and co-occur with the back rounded vowels [o] and [u] quite infrequently indeed.

To tie all of these results together, we can again consider the broader point that this research aims to probe: namely, the connection between the crosslinguistic trend and the language-internal reality. By studying Marathi, can we learn something about breathy sonorants that sheds light on the typological pattern? I posit that the answer is yes. Consider the following quote, from Wright (2004):

> In an ideal setting, there is no background noise or distractions, and the listener is so riveted by what the talker is saying that he/she gives the signal undivided attention. Under normal conditions it is rare for speech to occur in the absence of at least some form of environmental masking. What this means for speech is that a robustly encoded phonological contrast is more likely to survive signal degradation or interference in reception…. (Wright 2004:42)

We have seen that phonation type contrasts are better differentiated acoustically in obstruent than in sonorant contrasts, and that such contrasts in sonorants are subject to contextual variation. Whether as a direct result of that or due to other factors, phonation contrasts are also perceived more accurately in obstruents than in sonorants. And finally, we have seen underrepresentation of breathy sonorants in a Marathi lexicon. With Wright's quote in mind, we can hypothesize the following: phonation type contrasts in sonorants are phonemic in Marathi, but the sounds themselves are not robustly encoded. The contrasts are vulnerable to the kind of signal degradation that occurs in normal, every day language use. Over time, they are subject to confusability and misperception. The cumulative result of such forces does not benefit breathy sonorants, either language-internally or cross-linguistically. Perhaps they are not likely to become phonologized in the first place: if they do, they may—for many reasons—be winnowed out of the language over time.

It's important to note that breathy sonorants are not only phonemic in Marathi, but are also included in some very high-frequency function words— [am^{ɦ}i] *'we'* and [tum^{ɦ}i] *'y'all'*. Given such items, breathy sonorants are unlikely to disappear from Marathi. Their functional load, however, is not heavy. The forms for *we* and *y'all,* for instance—along with morphologically-related terms—represent the majority of instances of [m^{ɦ}] found in the EMILLE corpus. As with any high-frequency items, we may wonder about the acoustic characteristics of these function words in running speech. Is the nasal truly produced with breathiness? Does it look different in casual than in careful speech?

This remains an open question. Other open questions have to do with whether the data presented here are representative: what do breathy sonorants look like in other languages? Are the acoustic, perceptual, and distributional patterns found in Marathi unique, or are they indicative of a larger trend? Similar investigation of breathy sonorants in other languages will shed additional light on the typology of these sounds, and help test the hypothesis supported by the Marathi data presented herein: namely, that phonation type contrasts in sonorants are uncommon because they are not robust.

References

Alam, Firoj, S.M. Murtoza Habib, and Mumit Khan. (2008). Acoustic analysis of Bangla consonants. Avail. at http://dspace.bracu.ac.bd/xmlui/bitstream/handle/10361/669/ACOUSTIC%20ANALYSIS%20OF%20BANGLA%20CONSONANTS.pdf?sequence=1

Andruski, Jean E., and Martha. Ratliff. (2000). Phonation types in production of phonological tone: The case of Green Mong. *Journal of the International Phonetic Assoc.*, 30:37-61.

Berkson, Kelly. (2013). *Phonation Types in Marathi: An Acoustic Investigation.* PhD diss., University of Kansas.

Berkson, Kelly. (2016). Durational properties of Marathi obstruents. *Indian Linguistics* Vol. 76, Nos. 3-4: pps 7-25.

Blankenship, Barbara. (2002). The timing of nonmodal phonation in vowels. *Journal of Phonetics*, 30: 163-191.

Boersma, Paul. & David Weenink. (2010). Praat: doing phonetics by computer [Computer program]. Version 5.1.32. Available at www.praat.org.

Census of India. (2001). *Statement 1: Abstract of speakers' strength of languages and mother tongues.* Available at http://censusindia.gov.in/Census_Data_2001/Census_Data_Online /Language/Statement1.htm

Davis, Katharine. (1994). Stop voicing in Hindi. *Journal of Phonetics*, 22.2: 177-193.

Dhongde, Ramesh Vaman & Kashi. Wali. (2009). *Marathi.* John Benjamins Publishing Co.: Amsterdam.

Dutta, Indranil. (2007). Four-way stop contrasts in Hindi: An acoustic study of voicing, fundamental frequency and spectral tilt. Ph.D. diss., U. Illinois at Urbana-Champaign.

EMILLE/CIIL. Enabling Minority Language Engineering project (Lancaster/Sheffield Universities, UK & Central Institute of Indian Languages, Mysore). Information at http://www.lancaster.ac.uk /fass/projects/corpus/emille/.

Esposito, Christina M. (2006). *The Effects of Linguistic Experience on the Perception of Phonation.* Ph.D. dissertation, University of California Los Angeles.

Esposito, Christina M., & Sameer ud Dowla Khan. (2012). Contrastive breathiness across consonants and vowels: A comparative study of Gujarati and White Hmong. *Journal of the International Phonetic Association 42*(2), 123-143.

Gordon, Matthew, and Peter Ladefoged. (2001). Phonation types: a cross-linguistic overview. *Journal of Phonetics*, 29: 383-406.

Harris, Thomas Christopher. (2009). *An acoustic and articulatory study of sonorant phonation in Sumi.* Thesis; Univ. of Melbourne School of Languages & Linguistics. Melbourne, Australia.

Khan, Sameer ud Dowla. (2012). The phonetics of contrastive phonation in Gujarati. *Journal of Phonetics,* 40: 780-795

Masica, Colin P. (1991). *The Indo-Aryan languages.* Cambridge Univ. Press: Cambridge, UK.

Mikuteit, Simone and Henning Reetz. (2007). Caught in the ACT: The timing of aspiration and voicing in Bengali. *Language and Speech,* 50.2: 247-277.

Ohala, Manjari and John Ohala. (1972). The problem of aspiration in Hindi phonetics. *Annual Bulletin of the Research Institute of Logopedics and Phoniatrics, Faculty of Medicine, University of Tokyo, Japan.* No. 6: 39-46.

Pandharipande, Rajeshwari. (1997). *Marathi.* Routledge: London, UK.

Pennington, Mark. (2005). *The phonetics and phonology of glottal manner features*. PhD dissertation, Indiana University.

Perception Research Systems. 2007. Paradigm Stimulus Presentation, Retrieved from http://www.paradigmexperiments.com

R Core Team. (2012). *R: A Language and Environment for Statistical Computing*. R Foundation for Statistical Computing. Vienna, Austria. *available at* http://www.R-project.org.

Shue, Yen-Liang, Patricia Keating, Chad Vicenik, & Kristine Yu. (2011). VoiceSauce: A Program for Voice Analysis. *available at* http://www.ee.ucla.edu/~spapl/voicesauce/.

Traill, Anthony and Michel. Jackson. (1988). Speaker variation and phonation type in Tsonga nasals. *Journal of Phonetics,* 16.4: 385-400.

UCLA Phonological Segment Inventory Database. http://web.phonetik.uni-frankfurt.de/cgi-bin/upsid_sounds.cgi.

Wayland, Ratree and Allard Jongman. (2003). Acoustic correlates of breathy & clear vowels: The case of Khmer. *Journal of Phonetics* 31:181-201.

Wright, Richard. (2004). A review of perceptual cues and cue robustness. In Hayes B., R. Kirchner, & D. Steriade eds., *Phonetically Based Phonology*, 34-57. Cambridge University Press, New York.