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Managing the distinctiveness of phonemic nasal vowels: Articulatory evidence from Hindi

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There is increasing evidence that fine articulatory adjustments are made by speakers to reinforce and sometimes counteract the acoustic consequences of nasality. However, it is difficult to attribute the acoustic changes in nasal vowel spectra to either oral cavity configuration or to velopharyngeal opening (VPO). This paper takes the position that it is possible to disambiguate the effects of VPO and oropharyngeal configuration on the acoustic output of the vocal tract by studying the position and movement of the tongue and lips during the production of oral and nasal vowels. This paper uses simultaneously collected articulatory, acoustic, and nasal airflow data during the production of all oral and phonemically nasal vowels in Hindi (four speakers) to understand the consequences of the movements of oral articulators on the spectra of nasal vowels. For Hindi nasal vowels, the tongue body is generally lowered for back vowels, fronted for low vowels, and raised for front vowels (with respect to their oral congeners). These movements are generally supported by accompanying changes in the vowel spectra. In Hindi, the lowering of back nasal vowels may have originally served to enhance the acoustic salience of nasality, but has since engendered a nasal vowel chain shift. © *2012 Acoustical Society of America*. [DOI: 10.1121/1.3665998]

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I. INTRODUCTION

A. Dispersion Theory

The shape and structure of vowel inventories are typically explained with respect to three directives: (1) maximize the number of contrasts; (2) maximize the distinctiveness (acoustic contrast) between forms; and (3) minimize articulatory effort (Liljencrants and Lindblom, 1972; Lindblom, 1986; Flemming, 2004). Certain vowels are typologically uncommon or subject to merger because they do not maximize a given phonetic characteristic, e.g., rare unrounded back vowels fail to maximally lower F2. Moreover, certain pairs of vowels are unlikely to occur because they are relatively indistinct or confusible with one another. Increasing numbers of phonemic vowels in an inventory will thus tend towards the periphery of the vowel space, with this peripheralization checked by the speaker's tendency to minimize effort. According to this "Dispersion Theory" (Flemming, 2004) the balance between these tendencies becomes more tenuous as the number of contrasts increases. Phonemic nasal vowels present an interesting case, since they are almost always paired with corresponding oral vowels (Hajek, 2005). Nasalization increases the number of contrasts but the distinctiveness of these contrasts is inhibited by nasalization itself, as it is well known to alter the height relations of vowels (Sec. I B). In a crowded oral/nasal vowel space, Dispersion Theory predicts increased perceptual distinctiveness is necessary to distinguish oral/nasal vowel pairs, which may result in increased articulatory effort. In this paper, we will examine the articulation and acoustics of dispersion in the relatively crowded nasal/oral vowel space of Hindi.

B. The acoustic-articulatory mapping of nasal vowels

The coupling of the nasal and oropharyngeal tracts significantly alters the low-frequency domain of the sound spectrum (Hawkins and Stevens, 1985; Kataoka *et al.*, 2001; Pruthi *et al.*, 2007). The lowest pole associated with the nasal transfer function (the so-called 'nasal formant') perceptually merges with the lowest pole of the oro-pharyngeal transfer function (Maeda, 1993). As a result, the spectra of nasal vowels are considered less distinct than those of their oral counterparts. Nasal vowels have been judged to be more similar to each other than oral vowels (Mohr and Wang, 1968; Bond, 1975; Butcher, 1976). For oral vowel configurations yielding high F1, additional nasal coupling is known to lower the center of gravity in the F1 region ("vowel raising") while for oral vowel configurations yielding low F1, additional nasal coupling is

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known to raise the center of gravity in the F1 region ("vowel lowering").

F1 and F2 are most typically modulated independently of velopharyngeal opening (VPO). F1 frequency is determined mostly by the vertical position of the tongue in the oral cavity (Perkell and Nelson, 1985; Stevens, 1998, among others) but F1 is also well-known to interact with the listener's percept of nasality (Wright, 1975; Hawkins and Stevens, 1985; Beddor *et al.*, 1986; Wright, 1986; Krakow *et al.*, 1988; Beddor and Hawkins, 1990; Beddor, 1993).

It is less clear whether F2, most typically modulated by forward–backward movement of the tongue body (Stevens, 1998, p. 203), has a strong effect on the percept of nasality. Front (high F2) vowels are more often perceived as nasalized, though the effects are often weak or limited to only a few vowels (House and Stevens, 1956; Lintz and Sherman, 1961; Bream, 1968; Maeda, 1982, 1989). Conversely, Delvaux (2009) shows that F2 lowering may help trigger the percept of nasality in French. In oral/nasal vowel systems, it is possible that observed acoustic adjustments are intended to make vowels more distinct from one another; in only some cases can we reason these adjustments make nasal vowels 'more nasal.'

Nasal vowels typify speech production's classic 'many-to-one problem': situations where a variety of physical articulations may each result in a comparable acoustic output. For example, a lowered F1 frequency observed in [ɑ̃] (with respect to oral [ɑ]) may be due to nasal coupling, tongue raising, or both. Accurately describing the acoustic-articulatory mapping of nasal vowels is challenging because tongue position and VPO influence acoustic spectra and their perception in overlapping ways.

If the degree of VPO is known or estimated, acoustic models of nasalization (Rong and Kuehn, 2010; Pruthi *et al.*, 2007; Feng and Castelli, 1996; Maeda, 1993) may help disambiguate oral articulation and VPO. While VPO can be estimated using a variety of techniques (Baken and Orlikoff, 2000; Chap. 11), the acoustic consequences of nasalization also depend on measures of nasal tract geometry, which are even more difficult to assess (Engwall *et al.*, 2006; Dang and Honda, 1996; Pruthi *et al.*, 2007). Our approach is to measure the physical configuration of the oro-pharyngeal cavity during nasal and oral vowel congeners. In this study, we will explore the articulation of nasal vowels in Hindi, a language with a relatively high number of phonemic nasal vowels (Maddieson, 2007). With its crowded vowel space, Hindi provides an opportunity for us to study how contrastive vowel nasality is produced and maintained through articulatory adjustment.

C. Oral configuration of nasal vowels: Prior work

Zerling (1984) found evidence of consistent tongue retraction in the realization of French [ɔ̃], protrusion of the lips in [ɑ̃], and lip rounding in [ɔ̃]. Bothorel *et al.* (1986) later confirmed these labial gestures.

In an MRI study of Belgian French, Engwall *et al.* (2006) showed that the tongue body was retracted and raised towards the velum during nasal vowels. The authors argue that speakers may do this to shift the oral formants in such a way that they are not canceled by the nasal anti-formants, thus preserving the underlying oro-pharyngeal vowel quality despite the acoustic effects of VPO (p. 9). Conversely, Maeda (1993) claims that the retraction of [ɔ̃] observed by Zerling (1984) is intended to cancel or weaken F2 by bringing it into the vicinity of the (first) nasal anti-formant. The labialization of [ɑ̃], likewise is intended to lower F1 to bring it in line with the anti-formant.

Though English does not have phonemic nasal vowels, Arai (2004) examined mid-sagittal tongue position during English oral and contextually nasalized vowels using EMMA (electromagnetic midsagittal articulometry). He found that [ɑ̃] was produced with a lower tongue dorsum than [ɑ], which he attributed to compensation for the acoustic effects of nasalization. In an articulatory-aerodynamic study, Carignan *et al.* (2011) found that English [ĩ] was characterized by a higher tongue body than [i], which the authors also regard as a compensatory strategy.

Dixit *et al.* (1986) studied electromyographic activity in the palatoglossus (PG) muscle, which can raise and/or retract the tongue body, narrow the distance between the faucial pillars, and may also lower the soft palate (Lubker and May, 1973; Lubker, 1975). Dixit *et al.* demonstrated low levels of PG activity for Hindi's front oral vowels, but high levels for central and back oral vowels, high levels for all nasal vowels except /ẽ ɛ̃/ and differing levels for long and short vowels.

In another study of Hindi, Dixit *et al.* (1987) observed relatively higher levels of PG activity in nasal vs oral vowels, except for the pairs /u ũ/, /ʊ ʊ̃/, and /ɛ ɛ̃/. The temporal alignment of PG activation and levator veli palatini (LVP) suppression suggests that speakers of Hindi may use PG for active velar lowering in front nasal vowels (where PG activation and LVP suppression are synchronized), but not central and back nasal vowels (where PG activation precedes LVP suppression by a significant interval). The authors argue that this evidence "unambiguously supports the 'gate-pull' model of nasal sound production" for Hindi's nasal front vowels. The gate-pull model (Lubker *et al.*, 1970) suggests that, besides its uncontroversial role in positioning the tongue body, PG may also help lower the velum. Differences in PG activity for nasal and oral vowel pairs are relevant to the current study because they may also suggest both inferior/superior and anterior/posterior differences in the lingual articulation of (at least) the vowels /i ɪ e ə ɑ ɔ o/ and their nasal congeners (Dixit *et al.*, 1987).

D. Hindi vowels

Hindi has ten phonemic oral vowels /i ɪ e ɛ ə ɑ ɔ o ʊ u/ and ten phonemic nasal vowels: /ĩ ɪ̃ ẽ ɛ̃ ə̃ ɑ̃ ɔ̃ õ ʊ̃ ũ/ (Ohala, 1994, 1999; Dixit *et al.*, 1987; Sharma, 1958; Guru, 1972). The so-called "lax" vowels /ɪ ə ʊ/ of Hindi, along with their nasal congeners, are also considered short vowels in some phonological analyses; phonetically, they are indeed shorter than the other vowels (Dixit, 1963; Kelkar, 1968). The categorical perceptual distinction between oral and nasal vowels in Hindi is well-supported experimentally (Beddor and Strange, 1982; Hawkins and Stevens, 1985). Attending to a manipulated continuum between [bɑ] and [bɑ̃], Hindi speakers manifested a categorical discrimination function, while American English speakers perceived the vowel distinction continuously (Beddor and Strange, 1982). Moreover, while English speakers discriminated better between vowels at the non-nasal end of the continua for [ɑ u] (and possibly for [i]), Hindi listeners showed a decrease in sensitivity at the non-nasal end of the continua for the vowels [i u ɑ]. Both speaker groups manifested similar discrimination functions for the vowels [e] and [o], with reduced discrimination at the extremes of the nasal continuum (Hawkins and Stevens, 1985).

The acoustics of Hindi oral vowels have been documented only sparsely and there appears to be no published data on the formant frequencies of nasal vowels. Dixit (1963) reports F1 frequency data for the oral vowels which support the traditional vowel quadrilateral, with /ɛ/ and /ə/ manifesting comparable F1 values. Data for the related language Maithili, which has eight nasal vowels, suggest that the nasal vowels of that language have higher F1 values than their oral counterparts, irrespective of height (Jha, 1986). In published spectrograms of Gujarati's nasal and non-nasal vowels (Hawkins and Stevens, 1985, p. 1561), it is evident that F1 rises in nasal /ĩ ũ/ and perhaps /õ/ but falls in /ẽ/ and /ɑ̃/.

The articulation of Hindi oral and nasal vowels has been studied in some detail, with relatively greater emphasis on the oral set. Dixit and Daniloff (1991) report that x-ray microbeam data "do not support the traditional descriptions of Hindi [oral] vowels given in terms of either tongue height or vocal tract openness." For example, tongue dorsum position is higher for /e/ than /ɪ/, with minimal differences in tongue dorsum position for /ʊ/ versus /o/ and /ɑ/ versus /ʌ/ (/ə/). The jaw was lower for /ɔ/ than /ɑ/. Dixit (1985) noted differences in LVP activity for high/low and front/back vowels, suggesting differences in velopharyngeal aperture. Using static palatography, Qadri (1930) showed increased and more anterior linguopalatal contact for the vowels /e ɪ i/, progressively. For the back vowels the anterior-posterior contact patterns were similar and potentially indeterminate. Al-Bamerni (1983) found no statistically significant difference in VPO for Hindi oral vowels of differing heights (nasal vowels were not investigated). While the vocal tract geometry of Hindi nasal vowels has not been studied directly until now, velopharyngeal muscle activity in Hindi nasal vowels, which may provide some clues, has been investigated extensively by Dixit *et al.* (1986) and Dixit *et al.* (1987) (Sec. I C).

II. HYPOTHESES

For the purposes of our study, operationalize the drive to maximize perceptual distinctiveness (Flemming, 2004) by comparing the position of oral articulators during oral vowels with respect to their position during nasal vowels. We also compare the acoustics of these sounds. We start from the null hypothesis that oral and nasal vowels manifest the same oral articulatory positions, though their acoustics may differ (presumably as a consequence of VPO alone). If there is evidence of oral articulatory difference accompanied by an acoustic difference in the same direction, we take this as an implementation of the directive to maximize distinctiveness in oral/nasal vowel pairs. Dispersion Theory assumes that vowels under threat of losing their perceptual distinctiveness will move to maintain that distinctiveness. Additionally, at least a subset of observed articulatory differences may be regarded as enhancements of nasality in that they mimic or reinforce the acoustics of nasality. The most well-supported of these include the lowering of the tongue for non-low vowels and the raising of the tongue for low vowels. Enhancement of nasality along the F1 dimension might also include lip-rounding, which could lower F1 of low vowels (Stevens, 1998, p. 292). Though there is a small literature on the relation of F2 and nasality, we find no compelling reasons for predicting forward or backward movement of vowels as a function of nasal enhancement. Significant articulatory changes along this dimension may, however be regarded as evidence of dispersion.

III. METHODS

A. Speakers

Participants in the study were three female (S1, S2, S4) graduate students and one male (S3) graduate student from New Delhi. They are all bilingual in English and Hindi. Variation has been observed in the articulation of vowel nasalization between male and female speakers (Engwall *et al.*, 2006). Since female speakers on average have a smaller nasal cavity than males, they may be more likely to use oral articulatory strategies to enhance nasalization. With an insufficient number of male and female participants in this study (and without the aid of nasal cavity imaging), we are unable to test this hypothesis. By using a linear mixed effects model with speaker as a random variable (Sec. III G), we hope to limit the effect of this potential variation on our results but cannot rule it out entirely. While the vowels /ẽ ɛ̃/ and /õ ɔ̃/ have merged in some dialects of Hindi (Dixit *et al.*, 1987, p. 213), all four speakers in this study produced the pairs distinctly.

B. Instrumentation

Simultaneous audio, articulatory, and nasal airflow data were collected using instrumentation, as well as head-correction, normalization, and synchronization procedures described in greater detail elsewhere (Carignan *et al.*, 2011; Carignan, 2011).

The Carstens AG500 electromagnetic articulograph (EMA; Carstens Medizinelektronik, Lenglern, Germany) was used to measure articulation (Hoole and Zierdt, 2006; Hoole *et al.*, 2007; Yunusova *et al.*, 2009). Latex-covered electromagnetic sensors were dabbed with Histoacryl tissue adhesive (TissueSeal L. L. C., Ann Arbor MI) and affixed to the tongue, lips, and face of the subject. A surgical pen was used to mark the placement of the sensors before gluing them to the tongue in approximately 1.5 cm intervals, beginning 1 cm behind the tongue tip. Three tongue sensors corresponded roughly to the tongue tip (Ttip), tongue mid-point (Tmid), and tongue back (Tback). Measures of the

z-dimension (inferior-superior) displacement were used to infer the height of these three regions of the tongue. Measures of the x-dimension (posterior-anterior) displacement were used to infer the frontness of the tongue. Four sensors were fixed around the participant's mouth: one on the vermilion border of the upper lip, one on the vermilion border of the lower lip, and one at each corner of the mouth. The speaker wore a Scicon NM-2 vented nasal mask (Scicon R&D, Inc., Beverly Hills, CA; cf. Rothenberg (1977)) attached to a Biopac TSD-160 differential pressure transducer (Biopac Systems, Inc., Goleta, CA). Audio was recorded using a Countryman Isomax E6 directional microphone (Countryman Associates, Inc., Menlo Park, CA) positioned 4–5 cm from the corner of the mouth. Articulatory data were digitized at 200 Hz, acoustics at 16 kHz, and airflow at 1 kHz. All recordings took place in the Speech Dynamics Lab at the Beckman Institute on the campus of the University of Illinois. The nasal mask was tested independently for its acoustic effects on the nasal and oral vowels /a i u ã ĩ ũ/. Although the nasal mask acts as a low-pass filter for nasal vowels and seems to introduce a low-amplitude pole at around 2 kHz for the high vowels in particular, F1 and F2 are perturbed only slightly, presumably because they fall within the mask's pass-band. The mask had virtually no effect on oral vowels.

C. Materials

Test items were C_1VC_2 nonsense sequences where C_1 was balanced for place of articulation using the consonants /p t k/ and C_2 was held constant as /p/. V was balanced for quality and orality/nasality using all of Hindi's oral and nasal vowels (=20; see Sec. I D). This added up to $3 \times 20 = 60$ tokens with forms like /kĩp/, /tɑp/, and /pɔ̃p/. Items were embedded in the carrier phrase, *Rām ko shāyad___ pasand hai* 'Perhaps Ram likes ___'. Tokens were presented in three randomized blocks, with each block randomized separately for each speaker. Speakers produced 180 individual utterances, i.e., nine repetitions of each vowel.

D. Procedures

Sentences were presented to the speaker in Devanagari script (127-point Shusha True Type) using Microsoft PowerPoint software installed on a laptop computer. Each sentence appeared on a separate slide. It was established beforehand that speakers were familiar with Devanagari and could read the onscreen text without difficulty. Materials were presented in white color print on a 50% gray background to increase visibility and reduce eye strain. Nasalization was represented with a *bindu* rather than a homorganic nasal consonant, a distinction that is now considered phonetically irrelevant (Ohala, 1983). The recording took approximately 25 minutes.

E. Post-processing

Annotation of the target vowel was performed manually by the second author. The left edge of the vowel was marked at the first sign of periodicity in the waveform. The right edge of the vowel was specified as the last period whose amplitude was higher than 20% of the maximum amplitude of the vowel. This cutoff was used because of the frequent occurrence of an epiphenomenal nasal consonant between nasal vowel and oral stop. The 20% threshold was based on inspection of synchronized electropalatographic, audio, and nasal airflow signals of VN sequences collected separately by the first author for English, Spanish, and Brazilian Portuguese (Shosted, 2010). The epiphenomenal nasal consonant in Hindi, documented by Ohala (1983), was typified by a dramatic increase in nasal airflow and a reduction in acoustic amplitude. The consonant had a median duration of 107 ms and a standard deviation of 46 ms (a linear mixed effects model revealed no significant differences by vowel quality). Ohala (1983) considers the consonant a transitory phenomenon related to the mistiming of velum raising and the oral obstruent gesture. She argues that there is no distinction between ṼC and VNC in Hindi.

Sensor errors were identified by plotting the trajectories of each vowel in each onset (C_1) condition, and then manually selecting any possible outliers after visual inspection of the trajectories. The entire articulatory signal was examined in conjunction with the acoustic and aerodynamic signals to determine whether a sensor error occurred during the production of the vowel. Confirmed errors were logged and removed from the dataset prior to statistical analysis. Because EMA sensors may manifest errors independently of one another, it was only necessary to exclude tokens when the variable being measured was influenced by a particular sensor error. For example, if Tmid was judged to function properly but Ttip was not, it was necessary to exclude Ttip- but not Tmid-related measurements. The sensor error rate for Ttip was about 10%; for Tmid and Tback, 7%; for all lip sensors combined (since each was needed to calculate area), the error rate was 14%.

Nasal airflow was calibrated in ml/s using a vacuum pump and a custom-designed plaster mold for the nasal mask.

F. Measures

The articulatory, acoustic, and aerodynamic measures described below were all calculated using signals extracted according to the vowel boundaries described in Sec. III E.

1. Articulatory measures

As in Carignan *et al.* (2011), the time-varying position data for each lingual sensor was divided into ten contiguous frames (each one-tenth the length of the original vowel). Within each frame the average position of the sensor was calculated. Next, the value of the first frame was subtracted from all frames, so the value of the first frame for each signal was zero. This normalization procedure makes the full excursion of sensor position more comparable across tokens. The average position during the 5th normalized frame is considered the normalized temporal midpoint of the vowel. For calculation of labial aperture, a polygon was fitted to the y (sinistral–dextral) and z (inferior–superior) coordinates of the four lip sensors. The area of this polygon was calculated using MATLAB's polyarea function and subsequently used as a time-varying, holistic measure of labial aperture. Maximum and average polygon area were calculated for each vowel.

2. Acoustic measures

A Hamming transformation was applied to each vowel (Oppenheim *et al.*, 1989, pp. 447–448). Using the FFT function in MATLAB 7.9.0.529 (Frigo and Johnson, 1998) and the FREQZ function in MATLAB's Signal Processing Toolbox, 16th-order linear predictive (LP) filters were designed for oral vowels and 30th-order filters were designed for nasal vowels. Peaks in the LP filter were detected automatically in MATLAB. For oral vowels, an order of 16 was chosen to estimate approximately eight formants in the frequency range 0–8 kHz. For nasal vowels, a higher order was chosen because nasal vowels are expected to have more peaks in their spectra (especially in the low-frequency region) due to velopharyngeal coupling, asymmetrical nasal passages, and paranasal sinuses. Because linear predictive coding (LPC) is known to be precise but not robust in detecting spectral peaks, some spurious peaks/formants, usually characterized by wide bandwidth and small amplitude, could be detected. An arbitrary bandwidth threshold of 500 Hz was set to exclude such peaks.

Figures of each 1024-point FFT spectrum with an LPC overlay were generated and the vowel space for each speaker was plotted with F1 against F2–F1. Using these plots, outliers were visually identified (with reference to the median values of F1 and F2–F1) for each vowel (Gordon and Maddieson, 2004). Whenever necessary, more reasonable peaks were chosen based on the vowel's profile and their values were logged interactively in MATLAB. For nasal vowels this was particularly challenging, due to the presence of both additional formants and anti-formants in the spectra. This was handled by establishing the position of the first nasal formant ($F1_n$) through inspection of each speaker's nasal /ĩ/ tokens (where separation between F1 and F2 is greatest and the nasal formant tends to intervene). Once $F1_n$ was identified, adjacent LPC peaks were identified. Specifically, if there were two peaks below $F1_n$, these were labeled $F1_o$ (oral F1) and $F2_o$ (oral F2); if there was only one peak below $F1_n$, this was labeled $F1_o$, and the one above $F1_n$ was labeled $F2_o$; if there were no peaks below $F1_n$, the two peaks above $F1_n$ were labeled $F1_o$ and $F2_o$. Spectral measures were manually adjusted for the following numbers of tokens by speaker: (S1) 11 oral, 63 nasal (74/180: 41%); (S2) 3 oral, 62 nasal (65/180: 36%); (S3) 13 oral, 47 nasal (60/180: 33%); (S4) 2 oral, 54 nasal (56/180: 31%). As anticipated, correction of nasal tokens was necessary more often than correction of oral tokens.

Acoustic measures (F1 and F2–F1) were converted to Bark (Traunmüller, 1990) and then extrinsically normalized following Nearey (1989). For each speaker, a constant was subtracted from each value of F1 and F2–F1. This speaker-dependent constant was derived by calculating α, the mean of the logarithm of F1 (all tokens for each speaker), and β, the mean of the logarithm of F2–F1 (using the same tokens). α and β were then averaged (Harrington, 2010). These Nearey-normalized values were submitted to statistical analysis; non-normalized values (in Bark) appear in Figs. 2 and 3, 4, and 5. Finally, the length of each vowel was measured according to the annotation boundaries described in Sec. III E.

3. Aerodynamic measures

Calibrated nasal airflow was baseline-corrected for transducer drift using a MATLAB implementation of Chouhan and Mehta's algorithm (2007). The portion of the signal corresponding to the vowel was extracted according to the annotation scheme in Sec. III E. The airflow signal was then RMS-filtered using a window of 15 ms and an increment of 5 ms (Cohn, 1990, 1993). The RMS-filtered signal was normalized by averaging the values contained in five contiguous frames arrayed across its length. Using MATLAB's trapz function we performed trapezoidal numerical integration of the normalized signal (Shosted, 2009). The result was a measure of total nasal airflow volume during the vowel, normalized according to the vowel's length.

G. Statistics

Linear mixed effects models were designed with nasality as a fixed effect, speaker as a random effect, and repetition as a nested random effect (Baayen *et al.*, 2008; Pinheiro and Bates, 2000; Gueorguieva and Krystal, 2004). All calculations were performed in R 2.13 (R Development Core Team, 2011), using the NLME package for the linear mixed effects models (Pinheiro *et al.*, 2011). Dependent variables were the articulatory, acoustic, and aerodynamic measures described in Sec. III F.

IV. RESULTS

A. Articulatory results

Figure 1 shows the direction of statistically significant lingual changes resulting from the linear mixed effects model (for nasal vowels, with respect to their oral counterparts). There is a general tendency for nasal back vowels to lower and nasal front vowels to raise, with respect to their oral counterparts. Nasal vowels lower in the quadrilateral (with the exception of /ə̃/) tend to move forward, with respect to their oral counterparts.

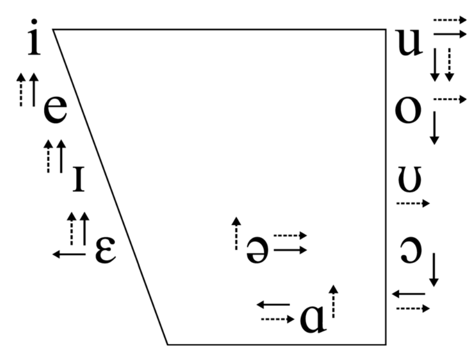

FIG. 1. Arrows indicate direction of articulatory and acoustic shifts in the production of nasal vowels with respect to their oral counterparts using a traditional vowel quadrilateral for Hindi, cf. Ohala (1999). Articulatory shifts are represented by solid arrows; acoustic shifts by dashed arrows. For example, tongue position for /ĩ/ is more elevated with respect to /ɪ/ while /õ/ is more depressed with respect to /o/. Acoustically, nasal /ĩ/ is higher (has a lower F1) than its oral counterpart while /õ/ is more back (has a lower F2).

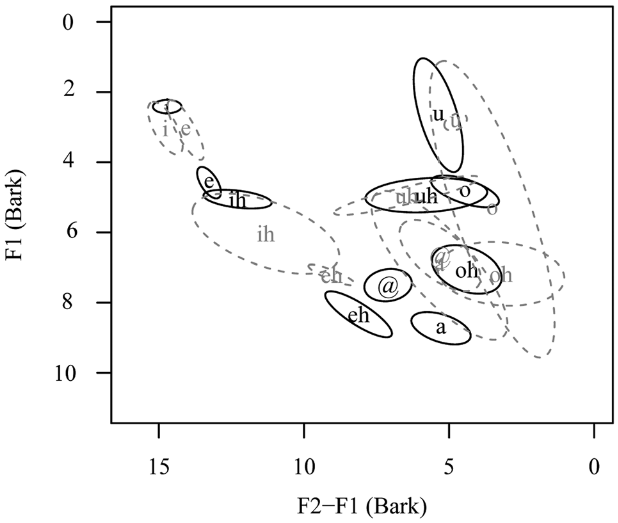

FIG. 2. Vowel space of S1. Ellipses represent 90% confidence intervals for up to nine repetitions of each vowel. Nasal vowels are plotted in gray/dashed, oral vowels are in black/solid. ih = [ɪ]; uh = [ʊ]; @ = [ə]; eh = [ɛ]; oh = [ɔ]; a = [ɑ].

1. Lingual position

Table I and Table II show results of the linear mixed effects model in the *z*-dimension (inferior–superior) and *x*-dimension (anterior–posterior) dimensions, respectively. Measures correspond to the normalized position of the Ttip, Tmid, and Tback sensors at the normalized temporal midpoint of the vowel (Sec. III F 1). Model results are given along with means and standard deviations for nasal and oral vowels. Larger values in the *x*-dimension (Table II) represent more anterior tongue positions while larger values in the *z*-dimension (Table I) represent more elevated tongue positions. The nasal vowels /ẽ ĩ ɛ̃/ are articulated with a higher tongue position than their oral counterparts. The nasal vowels /õ ũ ɔ̃/ are articulated with a lower tongue position (Table I). The nasal vowels /ɛ̃ ɑ̃ ɔ̃/ are articulated with a more anterior tongue position and the vowels /ə̃/ and /ũ/ are

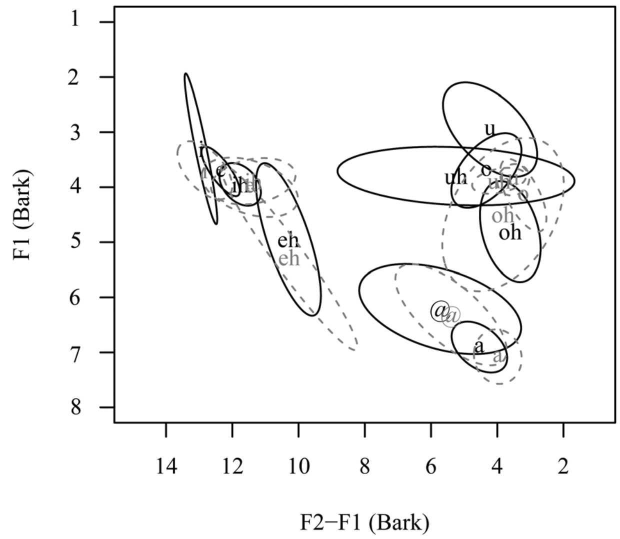

FIG. 4. Vowel space of S3 with conventions as in Fig. 2.

articulated with a more posterior tongue position (Table II). Only the nasal vowels /ĩ/ and /ʊ̃/ show no lingual articulatory divergence from their oral counterparts.

2. Labial aperture

No statistically significant effects for labial aperture were found, which leads us to conclude that labial aperture plays no role in distinguishing the oral-nasal vowel pairs in Hindi or that our measures were unable to capture such an effect.

B. Acoustic results

The acoustic vowel spaces (oral and nasal) of the four speakers are plotted in Figs. 2, 3, 4, and 5. These plots contain ellipses representing 90% confidence intervals around the vowels, plotted in Bark-transformed F1 and F2–F1 (Sec. III F 2). Nasal vowels are plotted in gray/dashed and oral vowels are plotted in black/solid ellipses. Each ellipse is based on up to nine utterances of the same vowel (Sec. III C).

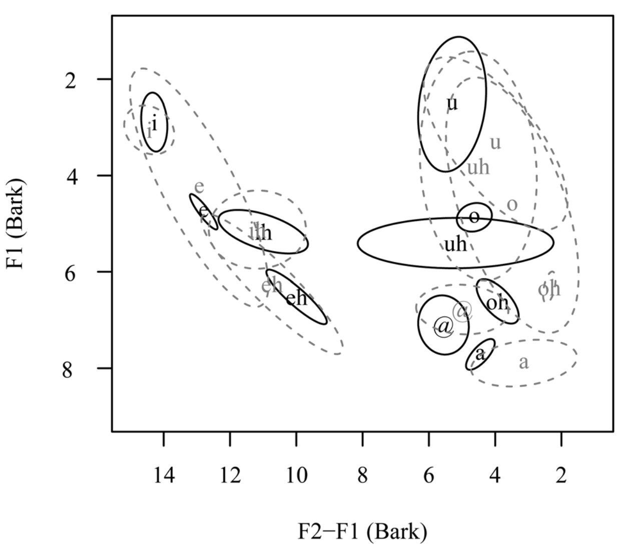

FIG. 3. Vowel space of S2 with conventions as in Fig. 2.

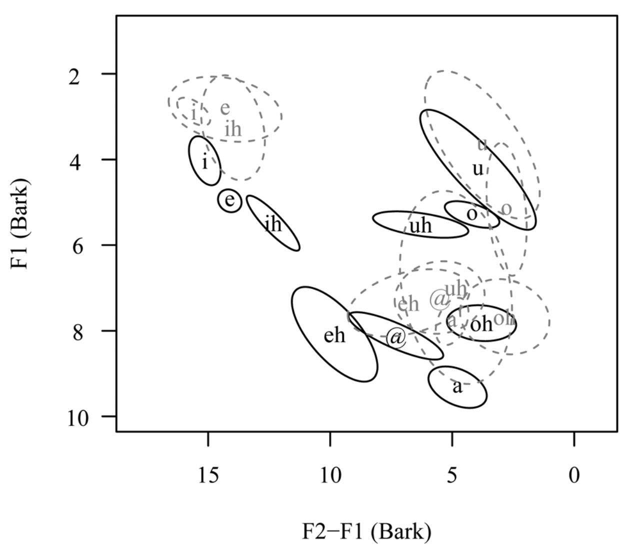

FIG. 5. Vowel space of S4 with conventions as in Fig. 2.

TABLE I. Inferior–superior dimension results for significant sensors. Nasal and oral mean position estimates are given, with standard deviations in parentheses, organized by vowel.

Vowel	Sensor	Model result	Nasal (mm)	Oral (mm)
ɪ	Tback	$F(1,54) = 4.4$, $p = 0.0407$: N>O	– 1.17 (0.46)	– 1.66 (0.43)
e	Tmid	$F(1,53) = 6.89$, $p = 0.0113$: N>O	– 0.49 (0.41)	– 0.96 (0.38)
e	Tback	$F(1,53) = 12.53$, $p = 0.0008$: N>O	– 0.47 (0.37)	– 1.18 (0.33)
ɛ	Tmid	$F(1,50) = 7.7$, $p = 0.0077$: N>O	– 3.83 (0.48)	– 4.89 (0.42)
ɔ	Tback	$F(1,50) = 4.99$, $p = 0.0301$: N < O	– 4.6 (0.47)	– 3.88 (0.35)
o	Tback	$F(1,50) = 8.11$, $p = 0.0064$: N < O	– 3.12 (0.5)	– 1.99 (0.44)
u	Tback	$F(1,52) = 5.57$, $p = 0.022$: N < O	– 1.4 (0.53)	– 0.77 (0.49)

Our data confirm that the (oral) vowels /ɪ/ and /ʊ/ have F1 values comparable to or greater than those of /e/ and /o/, respectively. This corroborates the articulatory differences observed by Dixit and Daniloff (1991) in an x-ray microbeam study. We note a high degree of F1-variation among some of the nasal vowels. While it is possible that this is an artifact of the protocol described in Sec. III F 2, the variation seems consistent with the auditory quality of these vowels, e.g., low-F1 variants of /õ/ (S1) sound relatively like [ũ] and the high-F1 variants for the same speaker sound relatively like [ɔ̃]. Perceptual tests on these or similar materials are recommended for future study.

Table III and Table IV present significant results of linear mixed effects models for F1 and F2–F1, respectively. These are summarized graphically in Fig. 1 (with dashed arrows).

F1 is lower for /ẽ ɪ̃ ɛ̃/ than it is for the oral counterparts of these vowels. /ẽ ɪ̃ ɛ̃/ are also articulated with higher tongue positions than /e ɪ ɛ/ (Sec. IV A). While F1 is also lower for /ə̃ ɑ̃/ with respect to /ə ɑ/, the tongue is not significantly higher during the nasal vowels.

The distance between F2 and F1 is smaller for the non-front nasal vowels /ə̃ ɑ̃ ɔ̃ õ ʊ ũ/ than it is for their oral congeners. /ə̃ ũ/ are characterized by a more retracted lingual articulation with respect to their oral counterparts, while /ɑ̃ ɔ̃/ manifest a more anterior tongue position.

C. Aerodynamic results

Aerodynamic results confirm that nasal vowels manifest more nasal flow than the oral vowels of Hindi. Unsurprisingly, integrated nasal flow (Sec. III F 3) was associated with nasality: (S1) [$F(1,58) = 102.01$, $p < 0.0001$]; (S2) [$F(1,58) = 63.03$, $p < 0.0001$]; (S3) [$F(1,58) = 49.85$, $p < 0.0001$]; (S4) [$F(1,58) = 133.54$, $p < 0.0001$].

Citing Lubker and Moll (1965), Al-Bamerni (1983), and Rochet and Rochet (1991), Hajek (1997, p. 129) argues that generally "nasal airflow results indicate that high back vowels are most nasalized." As Hajek points out, this is because oral impedance (maximized for high back vowels) shunts more airflow through the nasal cavity. In our measures, the high back vowels have the greatest degree of nasal airflow. We are, however, hesitant to draw direct conclusions between nasal flow and the acoustics or perception of nasalization, since it is the degree of nasal-oral coupling that is ultimately responsible for spectral modifications, not the amount of airflow through the nose. The main drawback of using nasal airflow as a proxy for VPO is that subglottal pressure and oral resistance both have direct, independent impacts on nasal airflow, so the relationship between VPO and nasal flow is not monotonic.[1]

V. DISCUSSION

A. Comparison of articulatory and acoustic results

By studying the position and movement of the tongue and lips during oral and nasal vowels, we are able to separate the effects of VPO and oral configuration on the acoustic output of the vocal tract. Accordingly, we can predict four types of oral/nasal vowel pairs in which the nasal vowel manifests: (Type-I) No acoustic or oral articulatory difference (with respect to the oral vowel); (Type-II) Oral articulatory difference with no acoustic difference; (Type-III) Acoustic difference with no articulatory difference; and (Type-IV) Both articulatory and acoustic differences.[2]

For vowel pairs that fall in Type-I, VPO may be insufficient to lead to a change in F1 or F2. With regard to height, these vowel pairs include /ĩ ʊ̃/ and their oral counterparts. With regard to frontness/backness, the pairs include /ĩ ɪ̃ ẽ/ and their oral counterparts. With the exception of /ĩ i/, all

TABLE II. Anterior–posterior dimension results for significant sensors. Nasal and oral mean position estimates are given, with standard deviations in parentheses, organized by vowel.

Vowel	Sensor	Model result	Nasal (mm)	Oral (mm)
ɛ	Tmid	$F(1,52) = 11.88$, $p = 0.0011$: N>O	– 2.77 (0.52)	– 3.69 (0.49)
ɛ	Tback	$F(1,52) = 11.60$, $p = 0.0013$: N>O	– 2.29 (0.68)	– 3.46 (0.64)
ə	Tback	$F(1,55) = 8.01$, $p = 0.0065$: N < O	– 3.21 (0.33)	– 2.34 (0.24)
ɑ	Tmid	$F(1,52) = 5.47$, $p = 0.0232$: N>O	– 2.87 (0.48)	– 3.78 (0.39)
ɔ	Ttip	$F(1,52) = 8.16$, $p = 0.0061$: N>O	– 1.12 (1.19)	– 2.88 (1.09)
u	Tback	$F(1,52) = 4.82$, $p = 0.0326$: N < O	– 3.43 (0.84)	– 2.73 (0.82)

TABLE III. Significant F1 results. Nasal and oral means are given (in Nearey-normalized Bark) with standard deviations in parentheses, organized by vowel.

Vowel	Model result	Nasal (norm)	Oral (norm)
ɪ	$F(1,57) = 6.52$, $p = 0.0134$: N < O	− 0.27 (0.08)	− 0.17 (0.07)
e	$F(1,57) = 39.29$, $p < 0.0001$: N < O	− 0.5 (0.07)	− 0.24 (0.06)
ɛ	$F(1,57) = 6.30$, $p = 0.0149$: N < O	0.08 (0.07)	0.14 (0.07)
ə	$F(1,57) = 24.61$, $p < 0.0001$: N < O	0.18 (0.02)	0.23 (0.02)
ɑ	$F(1,57) = 19.57$, $p < 0.0001$: N < O	0.27 (0.03)	0.36 (0.02)
u	$F(1,56) = 6.64$, $p = 0.0126$: N>O	− 0.52 (0.1)	− 0.64 (0.09)

oral and nasal vowel pairs of Hindi are internally differentiated in terms of their oral articulation and/or their position in the traditional (acoustic) vowel space. This suggests the phonemic distinction between /ĩ/ and /i/ relies on acoustic cues other than F1 or F2 and on articulatory characteristics other than lip rounding or lingual position. Acoustically, this pair may be best differentiated by formant bandwidth and/or the position of the nasal formant.

For Type-II vowels, the acoustic effects of VPO may mask the potential acoustic effects of an oral articulatory difference. For Type-II vowels in particular, it is difficult to discern what the motivation for an oral articulatory difference may be, since this is not evident in the resulting acoustic signal. With respect to height, Type-II vowel pairs include /ɔ̃ õ/ and their oral counterparts. With respect to frontness/backness, the only Type-II vowel pair consists of /ɛ̃/ and its oral counterpart. For the vowels undifferentiated by F1 (/õ ɔ̃/), both have lower tongue positions than their oral congeners.

For Type-III vowels, acoustic differences may be most directly related to the effects of VPO. We acknowledge that this amounts to an *argumentum ad ignorantiam*, since observed acoustic differences may in fact be related to an unmeasured oral articulator (e.g., pharyngeal cavity size) or to some aspect of lingual or labial articulation not contemplated here. With that caveat in mind, however, the acoustics of nasal vowels we have grouped in Type-III are still the most likely to be affected by VPO alone. With regard to height, these vowel pairs include /ə̃ ɑ̃/ and their oral congeners. We find these vowels to have a lower F1 than their oral counterparts, though there is no discernible articulatory difference within each pair of oral and nasal vowels. With regard to frontness/backness, Type-III vowel pairs include /õ ʊ̃/ and their oral counterparts. /õ ʊ̃/ are acoustically more back than their oral congeners. If VPO is purely responsible for these observations, we might hypothesize that in Hindi, increased VPO centralizes nasal vowels in terms of height and peripheralizes them in terms of frontness/backness. However, a more reasonable explanation for the decrease in F2–F1 may be the constriction in the velar region associated with the lowering of the soft palate, which would depress F2.[3] This effect is associated with the non-front nasal vowels, all of which have a lower F2 than their oral congeners.

For vowels that fall in Type-IV, the observed oral articulatory and acoustic changes may be correlated (e.g., tongue raising and F1-lowering; Type-IVa) or uncorrelated (e.g., tongue raising and F1-raising; Type-IVb). Interpreting cause and effect for Type-IV vowels is complicated. In the case of Type-IVa vowels, articulatory gestures may have the same acoustic consequence as VPO, thus enhancing nasalization. At the same time, the articulatory gesture in Type-IVa vowels may simply be strong enough to yield the observed (and predicted) acoustic consequence. The nasal vowel /ũ/ manifests a higher F1 than its oral counterpart, along with a lower tongue position. To the extent that F1-raising is associated with nasality (except in the case of heavily nasalized low vowels) (Fujimura and Lindqvist, 1971; Diehl *et al.*, 1990), the lowered tongue position of /ũ/ may serve to enhance nasality for this vowel. In this sense, the oral articulatory gesture may be said to ‘follow’ the acoustics of nasalization. On the other hand, /ĩ ẽ ɛ̃/ manifest lower F1 and higher tongue position, suggesting that both their acoustics and oral articulation run counter to predictions for (non-low) nasal vowels.

With respect to height, no Type-IVb vowel pairs are observed in our Hindi data, i.e., there are no nasal vowels where the direction of F1-change and tongue position counter each other. With respect to frontness/backness, the picture is more complex. While the Type-IVa vowels /ə̃ ũ/ are acoustically more posterior than their oral counterparts and also manifest tongue retraction, the Type-IVb vowels /ɑ̃ ɔ̃/ are acoustically more posterior but more anterior in articulatory terms. The dynamics behind Type-IVb vowels are difficult to explain, particularly because the effects of VPO on frontness/backness remain controversial. Further investigation of these vowels, considering pharyngeal and nasal cavity volume, direct measures of VPO, and the position of the soft palate with relation to the tongue dorsum, may help explain these contradictory results.

TABLE IV. Significant F2−F1 results. Nasal and oral means are given (in Nearey-normalized Bark) with standard deviations in parentheses, organized by vowel.

Vowel	Model result	Nasal (norm)	Oral (norm)
ə	$F(1,57) = 32.20$, $p < 0.0001$: N < O	− 0.05 (0.04)	0.13 (0.03)
ɑ	$F(1,57) = 10.07$, $p = 0.0024$: N < O	− 0.28 (0.07)	− 0.17 (0.07)
ɔ	$F(1,56) = 27.73$, $p < 0.0001$: N < O	− 0.67 (0.08)	− 0.38 (0.07)
o	$F(1,57) = 66.13$, $p < 0.0001$: N < O	− 0.64 (0.06)	− 0.32 (0.06)
ʊ	$F(1,57) = 7.68$, $p = 0.0075$: N < O	− 0.28 (0.06)	− 0.15 (0.05)
u	$F(1,56) = 10.13$, $p = 0.0024$: N < O	− 0.37 (0.08)	− 0.21 (0.07)

B. Oral configuration, nasality, and motor equivalence

Hughes and Abbs (1976, p. 199) defined *motor equivalence* as “the capacity of a motor system to achieve the same end-product with considerable variation in the individual components that contribute to that output.” The notion of motor equivalence seems well-suited to explaining the relationship of oral articulation and the production of nasality. Motor equivalence in speech production has been tested in numerous studies that typically debilitate one speech articulator in order to better understand the compensatory strategies that may manifest in another (Perkell *et al.*, 1993; de Jong, 1997; Guenther *et al.*, 1999, among others). Such an experimental paradigm has been indirectly applied to nasalization, by artificially venting back pressure during the production of consonants (Solé, 2002). The paradigm has not been used to discover whether a perturbation in VPO might affect tongue or lip position, though such experiments are conceivable.

Unlike traditional motor equivalence studies, the present study does not involve the perturbation of an articulator. Instead, we present evidence from unperturbed speech showing, in some cases, a lingual gesture that can be interpreted as an enhancement of VPO, at least in terms of VPO's effect on F1. The findings of Arai (2004) suggest that in a language without contrastive vowel nasality, phonetic vowel nasalization (before a nasal consonant) may trigger a compensatory lingual gesture (at least for the low vowel /ɑ/). Carignan *et al.* (2011) found a similar effect for the high front vowel /i/. Engwall *et al.* (2006) and Maeda (1993) argue that in French, a language with phonemic nasal vowels, oral configuration may be adjusted to enhance the effects of VPO. Our findings suggest that this is also true of Hindi. Future work with more speakers of the language may uncover evidence of other articulatory enhancements in addition to those we report here.

The vowel space of Hindi is crowded by any metric. It may be reasonable to suggest that enhancement of acoustic nasality is useful for maintaining contrast, but it also begs the question of why the back vowels, not the front vowels, are most consistently enhanced (in this case, lowered).[4] By manifesting an elevated tongue position, the non-low front nasal vowels seem to undergo an articulatory shift that may counteract an acoustic effect associated with nasalization, i.e., F1-raising (Fujimura and Lindqvist, 1971). While we are not prepared to settle this question at present, we hypothesize that lowering back vowels may be a more salient enhancement of nasality than comparable lowering of front vowels. If such a change is taking place in Hindi, then it would explain the structural pressure exerted on the low vowels (excluding /ə̃/) which move forward, and the front vowels, which move upward, perhaps as a result. This is suggestive of a classic, clockwise chain shift, explained further in Sec. V C.

C. Nasal vowel chain shift

The differences in lingual position of the Hindi nasal vowels relative to their oral congeners may be modeled structurally by a chain shift (Hock, 1991; Labov, 1994). A chain shift is a development in which one change in a phonological system brings about other changes as a result, causing a restructuring of the system, in part or in whole.

The dynamic vowel space illustrated in Fig. 1 suggests the existence of a clockwise chain shift in the Hindi nasal vowel system compared to the oral vowel system. We have shown that several of the acoustic changes are supported (and perhaps driven) by convergent articulatory changes. Specifically, the back nasal vowels are lowered, the low vowels are fronted, and the front vowels are raised. The existence of a similar clockwise chain shift has been posited for the nasal vowel system of Quebecois French, where /õ/ lowers, /ã/ raises and moves forward, and /ɛ̃/ moves forward (Dumas, 1984; Walker, 1984). The articulatory nature of this shift has recently been confirmed using EMA (Carignan, 2011). Conversely, it has been found that there is a counter-clockwise chain shift in the nasal vowel system of Northern Metropolitan French with respect to the oral vowel system (Maddieson, 1984; Fónagy, 1989; Malderez, 1991; Hansen, 2001). The case of Quebecois French presents a strong parallel to the case of Hindi. We anticipate that Hindi /ĩ/ may be produced with a more retracted tongue position as the effects of the sound change progress, though we note that this vowel is currently one of the most stable in the vowel system, in terms of both its acoustics and articulation.

VI. CONCLUSIONS

Understanding the oro-pharyngeal configuration of nasal vowels requires articulatory evidence. This is because the acoustic effects of nasality obscure the acoustic-articulatory mapping well known in the study of oral vowels and consonants. This study has presented considerable evidence that oral articulatory adjustment plays a role in nasal vowel production in Hindi, as predicted by Maeda (1993) and confirmed (for French) by Engwall *et al.* (2006).

Dispersion Theory (Flemming, 2004) contends that if the number of distinctive contrasts in a phonological system increases, speakers will strive to increase the perceptual distinctiveness between those contrasts. While Dispersion Theory predicts only that vowels will move so as to maximize distinctiveness, the present study shows that the motion of vowels in Hindi is largely anisotropic, i.e., directionally dependent. Speakers tend to lower the lingual articulation of back nasal vowels while raising the lingual articulation of front nasal vowels. While lowering non-low back nasal vowels arguably enhances one acoustic property of nasalization (increasing the center of gravity in the F1 region), raising the front non-low nasal vowels arguably counteracts the same property of nasalization (Arai, 2004; Carignan *et al.*, 2011). Since we cannot attribute the upward movement of non-low nasal vowels to the enhancement of nasality *per se*, we can only reason that this shift is intended to maintain the contrastiveness of oral-nasal vowel pairs through an oral articulatory shift.

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[1]While Warren *et al.* (1993, p. 133) note that "[the perception of] hypernasality increases as amount of nasal emission of air increases," this view is not universally accepted; see, for example, Chen (1995).

[2]By 'acoustic differences' we refer exclusively to changes in measured (oral) F1 and F2. An anonymous reviewer has suggested that calculating the center of gravity of the first nasal formant ($F1_n$) and the first oral formant ($F1_o$) would be more relevant to the study of vowel height, at least in perceptual terms. However, because in this paper we compare the oral articulation of nasal vowels to their acoustic signature, it seems most appropriate to measure the poles of the oral transfer function, as we have done.

[3]We thank Véronique Delvaux for this suggestion.

[4]An anonymous reviewer points out that from an impedance perspective, raising the tongue could also enhance nasality by shunting more air through the nasal cavity. This is an alternative explanation for the raising of front nasal vowels with respect to their oral counterparts.

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