AN EMA-AERODYNAMIC APPROACH TO THE VELIC OPENING HYPOTHESIS: EVIDENCE FROM HINDI VOWEL PAIRS

Ryan K. Shosted

University of Illinois at Urbana-Champaign, USA
rshosted@illinois.edu

ABSTRACT

Some aerodynamic approaches to the estimation of velopharyngeal opening (VPO) are confounded by oral impedance, which varies with tongue height and affects nasal flow. Here the relationship between nasal flow and tongue height is investigated using a synchronized EMA-aerodynamics system. A corpus of Hindi nasal and oral vowels is examined. Tongue height and nasal flow are weakly but positively correlated for nasal and oral vowels. This extremely weak correlation suggests a relatively large role for factors besides oral impedance, including VPO, in determining nasal flow. Furthermore, VPO seems to explain as much nasal flow variance for nasal vowels as it does for oral vowels. If VPO were differentially specified for nasal vowels of various phonological heights, the correlation of tongue height and nasal flow would be weaker for nasal versus oral vowels (i.e., VPO would account for more of the variance), an effect not observed here.

Keywords: nasal vowels, tongue height, EMA, aerodynamics, velopharyngeal opening

1. INTRODUCTION

1.1. The velic opening hypothesis

Estimation of velopharyngeal opening (VPO) between the nasal cavity and oro-pharynx has numerous phonological, phonetic, and clinical applications. One key aspect is the substantiation of the VELIC OPENING HYPOTHESIS (VOH): low vowels systematically manifest greater VPO with respect to high vowels [7]. It has been claimed that the VOH can account for patterns of nasal vowel evolution observed in Old French, Teke, and Chinese, as well as for instances of spontaneous nasalization whereby low vowels acquire phonological nasalization. A fairly large number of studies attest to the phonetic validity of the VOH, indicating that the velum is in a higher position during high vowels. Proponents of the VOH often attribute the phenomenon to the activity of the palatoglossus (PG) muscle, which can raise and/or retract the tongue body and may also lower the soft palate [9].

PG activity in Hindi vowel production has been studied extensively. [4] found low levels of PG activity among Hindi's front oral vowels, high levels for central and back oral vowels, high levels for all nasal vowels except the mid front vowels, and differing levels for long and short vowels. [5] reported relatively higher levels of PG activity in Hindi nasal versus oral vowels, except for the high back vowels (tense and lax) and the mid-open front vowel. Temporal alignment of PG activation and LVP (levator veli palatini) suppression suggests that speakers of Hindi use PG to lower the velum for front nasal vowels (but not for central and back nasal vowels). This supports [10]'s so-called 'gate-pull' model in which PG helps lower the velum for front vowels, in particular.

Counterexamples to the VOH are numerous and inter-speaker variability is high even in those studies which seem to support it [7]. For example, [1] argues that in Gujarati and Hindi, high back vowels, not low vowels, manifest the highest degree of velopharyngeal opening.

The VOH has not been tested extensively among phonemic nasal vowels. For this kind of vowel, low-level physiological effects associated with the VOH may be washed out by the phonological demands of a significantly lowered velum.

This paper presents the results of an EMA-aerodynamic study of phonemic nasal and oral vowels in Hindi. The method outlined here provides an opportunity for separating oral impedance and nasal airflow. By examining the relatively crowded vowel space of Hindi, this study will provide a higher resolution articulatory map than could be achieved using a language with fewer nasal vowels. Two questions will be explored, the first having relatively more phonological implications than the second. First, do the oral and nasal vowels of Hindi manifest different degrees of correlation between tongue height and VPO? Second, what is the phonetic relationship between nasal flow and the vertical position of the tongue? The first question contemplates whether the VOH is operative regardless of the phonological nasal/oral specification of a given vowel. The second question explores a relatively simple, aerodynamic option for estimating VPO.

1.2. Estimating VPO

VPO estimation remains a significant technical challenge. The acoustic consequences of nasality can be modeled with precision when the sizes of the relevant cavities are stipulated [13]. However, the measurement of nasality in real speech, when a variety of dimensions are unknown, can be vexing. By coupling the nasal tract to the oro-pharyngeal tract, the low-frequency domain (F1 region) of the sound spectrum is significantly altered. Because of the many-to-one mapping between articulation and acoustics, it is difficult to separate tongue height from VPO in explaining observed F1 differences for oral/nasal vowel pairs. Even when VPO is estimated or even directly measured, nasal tract geometry plays a significant role in determining the effect of VPO on the sound spectrum. A further complication is that phonologically ‘oral’ sounds can manifest low levels of physiological VPO [15].

Numerous technologies have been applied to the problem in order to supplement the fundamentally ambiguous oral-nasal sound pressure signal. These include ultrasound, photodetection, electromagnetic articulography (EMA), magnetic resonance imaging (MRI), endoscopy, air flow, air pressure, and strain gauge transduction [2]. Because the velopharynx is relatively inaccessible and sensitive to invasive procedures, it is likely that novel combinations of these technologies will best improve our understanding of the articulatory and acoustic consequences of VPO.

Unless it is feasible to also measure nasal and intra-oral pressure (i.e., the hydrokinetic method) [16], it has been argued that the measurement of nasal airflow cannot guarantee an accurate assessment of VPO [2]. This is primarily due to the fact that, as the tongue rises in the oral cavity, oral impedance will increase and more airflow will naturally be shunted through the nasal cavity. This means that even if VPO is held constant, high vowels will manifest greater nasal airflow than low vowels. (It should be noted that nasal airflow itself may not have phonological consequences, since the acoustics of nasalization are determined by the degree of velopharyngeal coupling). In the present study, the gravity of this technical problem will be evaluated by directly measuring the position of the tongue while simultaneously measuring nasal flow.

1.3. Hindi

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 / [12]. The three so-called ‘lax’ oral vowels, along with their nasal congeners, are phonologically and phonetically short.

There appears to be no published data on the formant frequencies of Hindi nasal vowels [14]. In the related language Maithili (with eight nasal vowels), nasal vowels consistently have higher F1 values than their oral counterparts. Some evidence suggests this may be true in Gujarati, as well.

Regarding Hindi oral vowels, [6] reports that the tongue dorsum is higher for /e/ than /ɪ/ and the jaw is lower for /ɔ/ than /ɑ/. Also with respect to the oral vowels of Hindi, [3] noted differences in LVP activity for high/low and front/back pairs, suggesting differences in velopharyngeal aperture. [1], however, found no statistically significant difference in VPO for Hindi oral vowels based on height (nasal vowels were not investigated).

Finally, [14] report that the front nasal vowels of Hindi are articulated with a somewhat higher tongue position than their oral counterparts and the back nasal vowels are articulated with a somewhat lower tongue position, again with respect to their oral congeners. Because these discrepancies contravene phonological expectations, in the analysis that follows, vertical tongue position will be correlated with nasal flow for oral and nasal vowels regardless of phonological vowel height.

2. METHODS

2.1. Speakers

Participants in the study were three female (S1, S2, S4) and one male (S3) graduate student from New Delhi. They are all bilingual in English and Hindi. All distinguished oral/nasal /e ɛ/ and /o ɔ/ [5].

2.2. Instrumentation

The Carstens AG500 EMA system records 3D sensor position data at a sampling rate of 200 Hz [8]. Twelve sensors (including references) were affixed to flesh points on the tongue and face using a tissue adhesive. Sensors were affixed to the speaker's tongue at approximately 1.5-cm intervals, beginning 1 cm behind the tongue tip. These three sensors were used for measuring the respective positions of the 'tongue tip', 'tongue midpoint', and 'tongue back'. (These quasi-anatomical terms should be treated with caution since, in practice, the first sensor is not placed on the tongue tip and the third sensor is placed as far back on the tongue as the speaker can tolerate, about 4 cm behind the tongue tip). Measures of the z-dimension (vertical) displacement were used to infer the height of these three portions of the tongue. The AG500 sensors were calibrated before the recording; head-movement correction, using Carstens software, was performed afterward. Only the position of the 'tongue back' sensor will be referred to in this paper.

To measure nasal flow, participants wore a vented Scicon NM-2 nasal mask. A tube connected the open outlet of the nasal mask with a Biopac TSD160 pressure transducer. The signal was digitized at 1 kHz and later resampled at 200 Hz. EMA and aerodynamic data were synchronized using a signal generated by the AG500 and recorded simultaneously with the nasal signal.

2.3. Materials

Test items were phonotactically licit 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). This added up to 3×20=60 tokens with forms like /kũp/ and /põp/. 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.

2.4. Annotation

Annotation of the target vowel was performed manually. 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 20% the maximum amplitude of the vowel. All vertical position and nasal flow samples corresponding to this interval were subjected to post-processing.

2.5. Data post-processing

Sensor errors were identified with reference to RMS signals recorded by the AG500 for each EMA sensor. Position values with high RMS manifest as discontinuities in the position signals; they generally fall outside the anatomical range of movement for a given articulator/sensor. Position values with RMS ≥ 50 were discarded. For each vowel, the median absolute deviation of vertical position was calculated. For each vowel, vertical positions greater or less than the median ± one median absolute deviation were considered outliers and removed. Nasal and oral vowels were treated separately with regard to this procedure.

3. RESULTS

3.1. Correlation: tongue height and nasal flow

Spearman's rank correlation (ρ), i.e. the coefficient of determination for non-normally distributed variables, was calculated to test the association between tongue height and nasal flow for both nasal and oral vowels, by speaker. On average, ρ was extremely low for both oral and nasal vowels. This suggests that tongue height can account for only a small fraction (at most 3.6%, for S3's nasal vowels) of the observed variation in nasal flow.

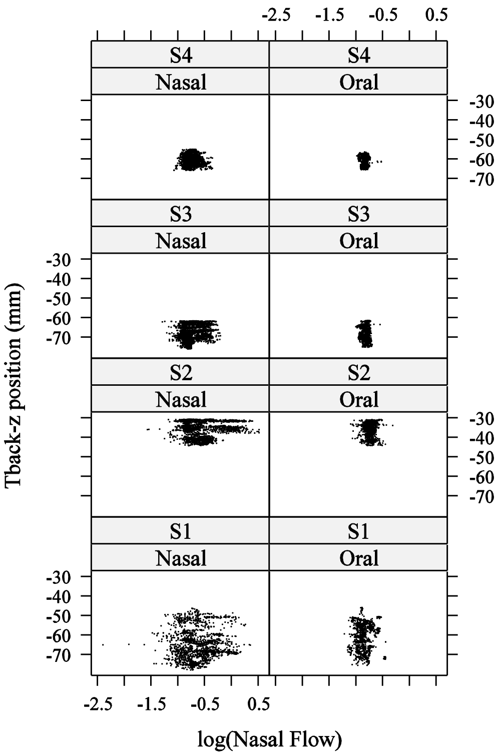
Table 1 suggests that for oral vowels, over 99% of the variance in nasal flow must be accounted for by factors other than tongue height; for nasal vowels, this figure is slightly lower. The correlation between nasal flow and tongue position does not appear weaker for nasal vowels, even though the velum is already lowered. The association between tongue height and nasal flow, small as it is, seems relatively stable across nasal/oral vowel types.

Table 1: Coefficient of determination (ρ) for the relation between tongue height and nasal flow for nasal and oral vowels, by speaker. The probability that ρ is not exactly zero (p) is given with asterisks (***, p<0.001; **, p<0.01;*, p<0.05).

Speaker	Oral (ρ)	Nasal (ρ)
S1	0.006**	0.002
S2	0.001	0.003*
S3	0.005**	0.036***
S4	0	0.006***
Mean (SD)	0.003 (0.003)	0.012 (0.016)

To illustrate these findings, tongue height and nasal flow are plotted against one another in Figure 1. Nasal flow values have been log-transformed.

Figure 1: Height of the tongue back sensor plotted against normalized nasal flow for oral and nasal vowels (S1–S4).



4. DISCUSSION AND CONCLUSION

Greater acoustic impedance in the oral cavity should shunt more air through the nasal cavity, given VPO. Some degree of VPO is expected even in oral consonants [15]. Therefore, weakly positive correlations between tongue height and nasal flow among oral vowels are not surprising. It is remarkable, however, that vertical tongue position measured at a point approximately 4 cm behind the tongue tip does not account for nasal flow more strongly. This lends some (indirect) support to the VOH. The present study concludes in favor of a relatively large role for factors other than oral impedance (including VPO) in determining the magnitude of nasal flow (both for oral and nasal vowels). As has often been argued, VPO probably varies with tongue height, though the directionality and magnitude of this relationship could not be investigated directly in this study.

Given greater VPO during nasal vowels, tongue height should be associated with nasal flow rather weakly, at least with respect to oral vowels. However, tongue height and nasal flow are correlated at approximately the same (weak) level for both oral and nasal vowels. Assuming that the unaccounted nasal flow variance in the present models can be explained only by VPO (a strong assumption), this suggests that a correlation between tongue height and VPO may be systematic for both oral and nasal vowels.

This study has demonstrated the utility of gathering tongue position and aerodynamic data in approaching the VOH and has shown that tongue height alone cannot account for observations in nasal flow. Because of the low correlations between flow and tongue position, direct imaging of the velopharyngeal port is recommended.

5. REFERENCES

[1] Al-Bamerni, A. 1983. *Oral, Velic, and Laryngeal Coarticulation across Languages*. Ph.D. dissertation, Oxford University.

[2] Baken, R.J., Orlikoff, R.F. 2000. *Clinical Measurement of Speech and Voice* (2nd ed.). San Diego, CA: Singular.

[3] Dixit, R.P. 1985. An EMG study of levator palatini during vowel production. *JASA* 77, S99-S100.

[4] Dixit, R.P., Bell-Berti, F., Harris, K.S. 1986. Palatoglossus activity during oral/nasal vowels of Hindi. *JASA* 79, S37.

[5] Dixit, R.P., Bell-Berti, F., Harris, K.S. 1987. Palatoglossus activity during nasal/nonnasal vowels of Hindi. *Phonetica* 44, 210-226.

[6] Dixit, R.P., Daniloff, R.G. 1991. An X-ray microbeam study of Hindi vowel articulations. *JASA* 89, 1871.

[7] Hajek, J. 1997. *Universals of Sound Change in Nasalization.* Oxford: Blackwell.

[8] Hoole, P., Zierdt, A. 2006. Five-dimensional articulography. *Stem-, Spraak- en TaalPath* 14 (Supplement), 57.

[9] Lubker, J. 1975. Normal velopharyngeal function in speech. *Clin. Plas. Surg* 2, 249-259.

[10] Lubker, J., Fritzell, B., Lindquist, J. 1970. Velopharyngeal function: An electromyographic study. *Quart. Prog. Stat. Rep*, Sp. Trans. Lab., KTH 11, 9-20.

[11] Ohala, M. 1983. *Aspects of Hindi Phonology*. Delhi: Motilal Banarsidass.

[12] Ohala, M. 1994. Hindi. *J. Int. Phon. Assoc.* 24, 35-38.

[13] Pruthi, T., Epsy-Wilson, C.Y., Story, B.H. 2007. Simulation and analysis of nasalized vowels based on magnetic resonance imaging data. *JASA* 121, 3858-3873.

[14] Shosted, R., Carignan, C., Rong, P. Submitted. *Managing the Distinctiveness of Phonemic Nasal Vowels: Articulatory Evidence from Hindi.*

[15] Warren, D.W., Dalston, R.M., Mayo, R. 1993. Hypernasality in the presence of 'adequate' velopharyngeal closure. *Cleft Pal.-Craniofac. J.* 30, 150-154.

[16] Warren, D.W., Dubois, A.B. 1964. A pressure-flow technique for measuring velopharyngeal orifice area during continuous speech. *Cleft Pal. J.* 1, 52-71.