INVESTIGATING THE AERODYNAMICS OF NASALIZED FRICATIVES[*]

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ABSTRACT

Nasalized oral fricatives do not exist in phonemic opposition to oral fricatives in any language of the world. It has been claimed that nasalized fricatives cannot exist phonetically; however, numerous grammatical descriptions suggest otherwise. This claim is addressed by measuring the presence of nasal airflow during the production of various anterior fricatives in conditions of coarticulatory nasalization. If nasal exhalation is taken as the definition of nasalization, then nasalized fricatives are shown to occur in speech. The potential acoustic and perceptual consequences of nasal flow during oral fricatives are discussed.

Keywords: Nasalization, fricative, aerodynamics

1. INTRODUCTION

The incompatibility of nasalization and oral obstruency has been used to argue against the existence of nasalized fricatives [6]. Indeed, from a mechanical standpoint, nasals and oral fricatives appear to have antagonistic aerodynamic specifications, the former requiring a lowered velum (hence, low intraoral pressure) and the latter requiring high intraoral pressure (hence, a raised velum). In some cases, this has been interpreted to mean that oral fricatives cannot be nasalized[1] [8, 14, 18].

There are, however, numerous reports of nasalized post-velopharyngeal fricatives, though the segments are never claimed to be phonemic [2, 4, 12, 15]. While these reports vary considerably in their level of detail and in their methodological approach, their common claim deserves further investigation.

It has also been observed that among languages with nasal harmony, it is relatively uncommon for nasalization to 'spread' through fricatives [16]. This may be taken to suggest a phonetic constraint (either aerodynamic, acoustic, or perceptual) on the preservation of nasal flow during a fricative. However, the existence of nasal harmony systems with transparent fricatives may also be taken (from a coarticulatory standpoint, at least) as evidence supporting the claims in favor of nasalized fricatives.

Gerfen [2] and Ali et al. [1] alone have presented aerodynamic evidence of nasalized fricatives. Unfortunately, in neither case is this evidence coupled with sufficient acoustic data to indicate how nasalized fricatives differ spectrally from oral fricatives. The present study inquires whether and to what extent nasal flow may be present during the production of oral fricatives.

2. METHODS

Speakers of French, Brazilian Portuguese, and Hindi uttered nonsense VCV sequences where C included the set of voiceless post-velopharyngeal fricatives of the language. The three languages were chosen because they have phonemically nasal vowels and a variety of voiceless post-velopharyngeal fricatives. For Brazilian Portuguese, the set of nasal vowels includes [ĩ, ẽ, ã, õ, ũ]; for Hindi [ĩ, ẽ, ɛ̃, ã, ɔ̃, õ, ũ]; and for French [ɛ̃, ã, ɔ̃]. The fricatives for Brazilian Portuguese include [f, s, ʃ, x]; for Hindi and French [f, s, ʃ].

For this study, vowels were limited to a set of three, at the corners of the language's vowel space. For Brazilian Portuguese and Hindi, [ĩ, ã, ũ] were recorded; for French, [ɛ̃, ã, ɔ̃]. All of the above-mentioned fricatives were included. The VCV sequences were composed of all language-appropriate sequences of V1, fricative, and V2 in two nasal control groups. These groups consisted of different nasalization environments where either both vowels were nasal (ṼCṼ) or oral (VCV). Stimuli for each language were presented in native orthography with care taken to eliminate any orthographic ambiguities, particularly in the representation of nasal vowels (see [13] for details). The stimuli are enumerated below:

1. Hindi: 3 vowels × 3 fricatives × 3 vowels × 2 nasal control groups = 54;
2. Brazilian Portuguese: $3 \times 4 \times 3 \times 2 = 72$; and
3. French: $3 \times 3 \times 3 \times 2 = 54$

Audio, oral flow, and nasal flow were sampled simultaneously, as illustrated in Figure 1. Audio was recorded using a cardioid dynamic microphone

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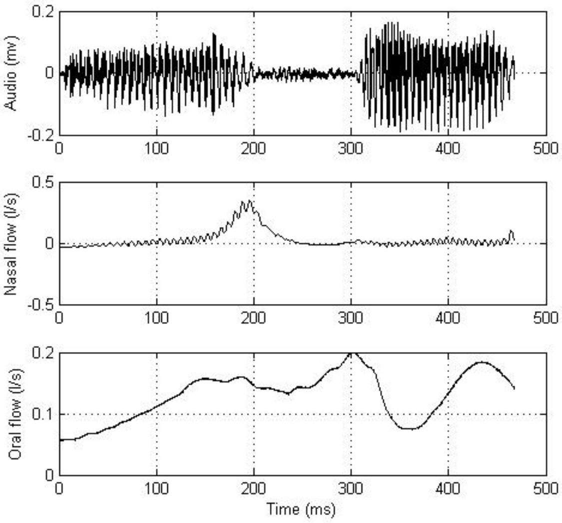
positioned approximately 5 cm from the oral mask. While the audio quality was degraded by the oral mask, the audio signal was still adequate for segmentation of the aerodynamic signals.

Figure 1: Audio, nasal, and oral flow for the sequence [ãfã] in Hindi.



An oral mask was connected to a low-frequency transducer [11]. A nasal mask intended for use in the medical treatment of respiratory problems was used to collect nasal flow. The nasal mask was connected to a wide-band transducer. The output of both transducers was low-pass filtered at 75 Hz using an analog filter. The configuration of separate oral and nasal masks eliminated the potential for leakage between chambers that may occur when using a single split-flow mask design.

One challenge in aerodynamic studies is achieving an accurate calibration of the signals. Sources of error may be the behavior of the transducers or insufficient coupling of the mask to the calibration device. Both sources of error were controlled in this study. Care was taken to ensure that the masks fit snugly against the apparatus and prevented air from escaping during calibration. Calibrations were performed before each speaker was recorded. It was hoped that repeating the calibration procedure would yield increased accuracy, e.g. in the event of performance variations in the transducers between sessions.

The relationship between the electrical responses of the transducers and the known input of the calibration unit varied across languages, speakers, and tokens. It is not entirely clear why this should be the case, but the effect is probably due to small mechanical fluctuations in the behavior of the transducers, ambient temperature changes, and/or changes in the seal between gasket and mask. To determine the reliability of each calibration and reduce the risk of calibration error, the correlation of the predicted versus actual responses was calculated. If the correlation coefficient for a session was less than 0.95, the calibration was performed again. Fortunately, this occurred on only a few occasions, so it is assumed that the calibrations for the various sessions were reliable.

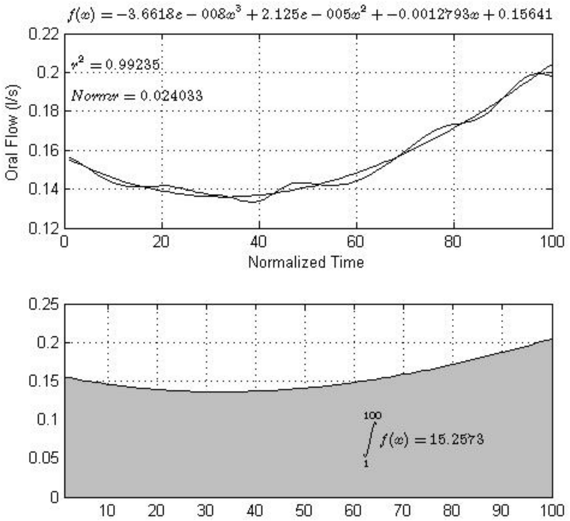
It should be noted, however, that a reliable calibration does not guarantee the accuracy of the results. Once the subject secures the mask, any slippage can reduce the accuracy of the aerodynamic recording, whether or not the transducers have been calibrated accurately. For this reason, it was necessary for the experimenter to pay attention to the seal of the mask (particularly the oral mask) around the subject's face. If the mask slipped in any observable way, the recording of the token was repeated.

Aerodynamic signals were segmented with reference to the synchronous acoustic signal: The beginning and ending of aperiodicity in the waveform were taken to be the boundaries of the fricative.

The airflow traces for each fricative were excised according to these established boundaries. The fricative was then automatically segmented into 100 equally-spaced intervals and an average value was computed for each interval. A third-degree polynomial was calculated to fit each time-normalized aerodynamic signal in a least-squares sense, using Matlab 7.0.4. Cubic polynomials were selected because their characteristic shape models the oral flow pattern for fricatives which tend to consist, maximally, of a peak, a valley, and a peak. Similarly, for nasal flow (in the ṼCṼ context) there will be a peak, a valley and a peak, where the peaks correspond to the nasal vowels and the valley corresponds to the fricative. The top frame of Figure 2 illustrates oral flow during the fricative in the sequence [ɑ̃fɑ̃] (Hindi). A cubic polynomial has been fitted to the aerodynamic data. The four coefficients of the equation are given at the top of the figure.

The correlation coefficient of the normalized signal data and the cubic polynomial were computed. In addition, a norm of residuals was calculated for the cubic polynomial fit to each normalized signal. Tokens in which either the oral or nasal polynomial fit had a norm of residuals greater than three standard deviations from the mean or a correlation coefficient greater than three standard deviations below the mean were excluded from further statistical analysis. Such tokens were considered outliers. For such tokens, it was judged that a cubic polynomial could not reasonably approximate the normalized airflow

Figure 2: Top frame: Oral flow during the fricative in [ãfã] (Hindi) and a third-degree polynomial fitted to the oral flow. Bottom frame: The shaded portion represents the numerical integral of the flow $\int_1^{100} f(x) = 15.2573$.



geometry of the fricative.

Using Matlab 7.0.4, the polynomial coefficients for each aerodynamic signal were passed to anonymous functions. These functions were then fed into a numerical integration algorithm that tries to approximate the integral of a function from a to b (the start- and end-points determined by acoustic segmentation) to within an error of 1×10^{-6} using recursive adaptive Simpson quadrature [5]. Integrals were approximated for integrands corresponding to both the oral and nasal flow signals of each token. The resulting values, approximations of the areas beneath the curves of the normalized airflow signals, were taken to be holistic estimates of nasal flow and oral flow during the production of each fricative token. This is illustrated in Figure 2.

In addition, maximum values (in l/s) were tabulated for the oral and nasal signals. The measure of flow at the temporal center of the aerodynamic signal was also tabulated.

3. RESULTS

Data from one speaker from each language have been used for the aerodynamic analysis. The population of nasal and oral fricatives was slightly reduced when correlation coefficients and norms of residuals for the polynomials showed them to be poor fits to the time-normalized data. Approximately 5% of the tokens were discarded for these reasons. The numbers of fricatives analyzed aerodynamically are presented in Table 1.

Table 1: Raw numbers of fricatives analyzed aerodynamically. Nasal tokens appear on the left, oral tokens on the right

Lng	s	ʃ	f	x
Hindi	18, 18	18, 16	18, 18	0, 0
BP	15, 18	18, 18	18, 17	18, 18
French	18, 18	17, 18	18, 16	0, 0
Totals	51, 54	53, 52	54, 51	18, 18

Mean values of aerodynamic measures for the various fricatives are presented in Table 2.[2] ‘Max’ refers to the maximum flow recorded during the fricative and ‘TC’ refers to the flow value at the temporal center of the fricative (in liters/second). ‘Int’ refers to the numeric integral of flow calculated throughout the duration of the fricative.

Table 2: Mean values for aerodynamic measures. Values for nasal context appear at the left of the comma, oral context right. Max and TC measures are in liters/second.

Lng	Nas Int	Nas Max	Nas TC
Hindi	13.10, 0.00	0.23, -0.10	0.06, 0.013
BP	2.8, 0.83	0.14, 0.10	0.03, 0.00
French	19.32, 56.46	0.40, 0.75	0.14, 0.55
	Ora Int	Ora Max	Ora TC
Hindi	22.61, 51.20	0.26, 0.80	0.08, 0.44
BP	5.36, 10.67	0.02, 0.21	0.07, 0.10
French	19.32, 56.46	0.40, 0.75	0.14, 0.55

Tables 3 and 4 report the F-statistics and p-values resulting from a one-way ANOVA with the various aerodynamic measures as dependent variables and nasal context as independent variable. Results are given for each language individually and for all languages collectively.

Table 3: ANOVA results for nasal aerodynamic measures by nasal context ($p < 0.05$ = ‘*’; $p < 0.01$ = ‘**’; $p < 0.001$ = ‘***’).

Lng	Nas Int	Nas Max	Nas TC
All	132.4809***	8.2307***	0.56675
Hindi	119.05***	13.96***	0.52
BP	32.00***	0.10	0.25
French	46.04***	6.16*	0.00

The integral of nasal flow proved significant ($p < 0.001$) in nasal and oral contexts for each language, as reported in Table 3. Boxplots of these results for each individual language appear in Figure 3.

Maximum nasal flow significantly differentiates fricatives in nasal and oral contexts for Hindi and marginally for French. The effect does not achieve significance for Brazilian Portuguese (see Table 3). Figure 4 shows the relationship between the distributions of nasal flow maxima in both contexts, for

Table 4: ANOVA results for oral aerodynamic measures by nasal context ($p < 0.05$ = '*'; $p < 0.01$ = '**'; $p < 0.001$ = '***').

Lng	Ora Int	Ora Max	Ora TC
Hindi	23.99***	27.43***	21.04***
BP	40.62***	2.41	0.58
French	198.75***	6.73*	83.56***

each language.

The measure of nasal flow at the temporal center of the token is not a significant predictor of environment for any language. A boxplot showing the results for each language is given in Figure 5.

As shown in Table 2, integrated oral flow is consistently greater for fricatives in oral contexts than nasal contexts in each language. This effect achieves significance ($p < 0.001$) for all languages individually as demonstrated in Table 4. Figure 6 illustrates the distributions of this variable in the oral and nasal context for each language.

In some cases, oral flow maxima are higher for oral fricatives, vis-à-vis fricatives in nasal contexts (see Table 2). Table 4 indicates that this effect is statistically significant for Hindi and marginally so for French. The effect does not achieve significance for Brazilian Portuguese. The distributions for oral flow maxima in the two contexts for each language are given in Figure 7. Raw oral flow taken at the temporal midpoint of the fricative differs significantly for all languages except Brazilian Portuguese. The oral flow at this moment is typically greater for oral fricatives than it is for fricatives in nasalized contexts (see Figure 8).

Figure 3: Boxplot of integrated nasal flow produced during fricatives in nasal and oral contexts.

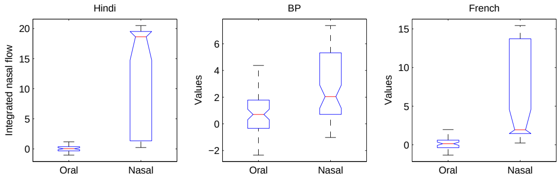


Figure 4: Boxplot of nasal flow maxima (l/s) produced during fricatives in nasal and oral contexts.

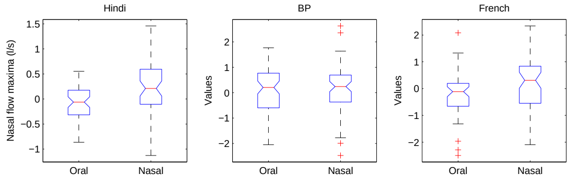


Figure 5: Boxplot of nasal flow (l/s) at temporal center of fricative produced in nasal and oral contexts.

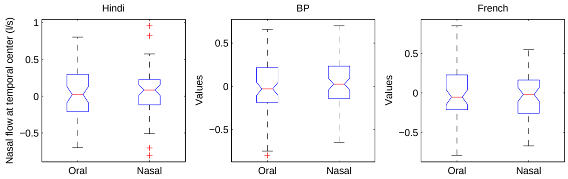


Figure 6: Boxplot of integrated oral flow produced during fricatives in nasal and oral contexts.

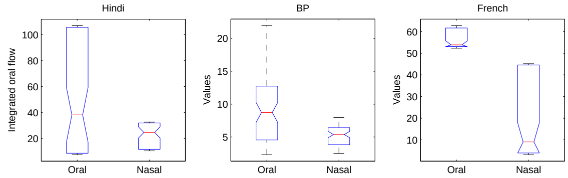


Figure 7: Boxplot of oral flow maxima produced during fricatives in nasal and oral contexts.

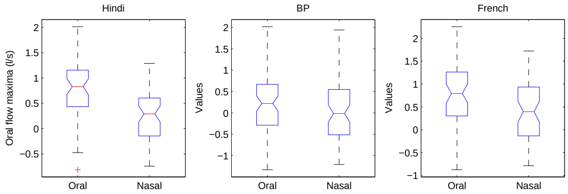
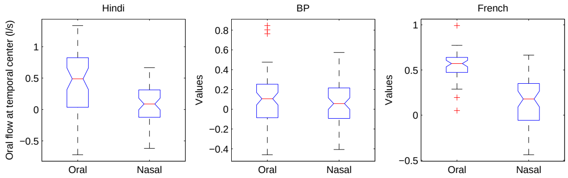


Figure 8: Boxplot of oral flow at temporal center of fricative produced during fricatives in nasal and oral contexts.



4. DISCUSSION

Fricatives differ from each other with respect to integrated nasal flow when they occur in nasal and oral contexts. They generally differ significantly with regard to maximum nasal flow. Flow at the temporal center is not significantly different between nasal and oral contexts, suggesting that nasal flow is greater at the edges of the fricative and that nasal flow approaches levels found in an oral context by the middle of fricative articulation. This pattern can be explained by the gradual closure of the velopharyngeal port. Presumably, maximum closure is reached after the initial stages of fricative production, as has been suggested by Ali et al. [1].

Moreover, oral flow tends to be greater in fricatives produced under the oral condition, suggesting that oral flow is depleted during the production of nasalized fricatives.

These results demonstrate that nasalized fricatives are phonetic possibilities in natural speech. Indeed, we can surmise that one possible source of nasalization in fricatives is their proximity to nasal segments.

This result does not, however, constitute a counterclaim to the basic aerodynamic laws that govern the movement of air in the vocal tract—for that matter, neither do reports of phonetically nasalized fricatives in various languages [2, 4, 12, 15].

Nasalization is a gradient phenomenon, dependent (strictly in aerodynamic terms) on the size of the velopharyngeal aperture and the amount of transglottal flow. If the port to the nasal cavity opens up to even a small degree, fundamental principles of aerodynamics dictate that a physically detectable amount of air will pass through the nose. However, it is still not clear how much air must pass through the nose in order to produce an acoustic contrast between oral and nasalized fricatives. Assuming a constant rate of transglottal flow, if any air is shunted from the oral cavity, then the acoustic characteristics of any oral sound, including a fricative, will be altered.

It is not enough to posit a ban on the production of nasalized fricatives based on aerodynamic principles alone. As this study demonstrates, it is indeed possible for air to pass through the nose *and* mouth while a speaker is uttering a phonemically oral fricative. If nasalization and frication can indeed coexist, why might a speaker bother to raise the soft palate during the production of an oral fricative? Is it necessary to do so? The answer to this question no longer pertains to aerodynamics alone, but involves the acoustics and perceptibility of the sound produced. In acoustic and perceptual terms, are fricatives altered by nasal escape?

One answer to this question may lie in the speech of individuals with velopharyngeal dysfunction, who regularly produce oral fricatives with a partially open velopharyngeal port. It has been shown that in the speech of such individuals [s̃] is spectrally similar to a velar or pharyngeal fricative [17]. The authors concluded that low frequency excitation of F2 in the /s/ of cleft palate speakers was generally comparable to low frequency excitation in Arabic /ħ/. The spectral changes observed by Weinberg and Horii may be attributed to the presence of nasalization. A comprehensive analysis of the production and perception of cleft palate fricatives is needed.

Shosted presents results suggesting relationships between high frequency energy loss, increased spectral peak bandwidth, and nasalization [13]. However, results of this study are mixed and only partially overcome a fundamental methodological challenge: When audio and airflow are sampled simultaneously using a traditional mask design, the acoustics of the signal are degraded thereby. Even if the mask were replaced with a relatively unobstructive instruments such as a hot-wire anemometer, another challenge remains: Nasal flow is only an indirect indication of velopharyngeal aperture; hence, using flow we still cannot correlate aperture with spectral changes in nasalized fricatives. To do this, the velopharyngeal port must be opened by measureable degrees using some external instrumentality. The construction of a model vocal tract enabled the author to regulate velopharyngeal opening in precisely this manner, but with sacrifices to the organic, flexible nature of the vocal tract itself. More elaborate physical models are evidently necessary to produce more naturalistic fricatives.

Perhaps the most illuminating way forward will include ultrasound imaging of the soft palate coupled with high-quality acoustic records. This will allow us to draw strong correlations between perturbations in fricative acoustics and velopharyngeal aperture in natural speech (with minimal discomfort to research participants). So far, the acoustic correlates of nasalization in fricatives are only suggestive. Once these relationships have been confirmed, however, the perceptual salience of the acoustic perturbations can be measured. Then it will be possible to consider why nasalized fricatives, which are clearly phonetic possibilities, are not phonologized in the languages of the world.

There are several cases in which aerodynamic confounds (like nasalization and frication) are known to have linguistic consequences. For example, voicing and frication seem to be at odds. It is well known that voiced fricatives are typified by weaker noise than their voiceless counterparts. This is presumably due to the reduction in airflow caused by the rapid opening and closing of the glottis during voicing [7]. The accompanying reduction in frication leads to a network of diachronic and synchronic relationships between voiced fricatives and voiced approximants in languages like Spanish. Phonotactic restrictions on glottal aperture are also attested, e.g. in languages affected by Grassmann's Law [3, 10]. The debilitating effects of voicelessness (increased transglottal flow) on apical trills have been investigated [14]. In addition, aerodynamics have been cited as a basis of segmental fortition and lenition in a variety of Romance languages [9].

Similarly, the linguistic consequences of coarticulatory nasalization of fricatives may prove an interesting field of inquiry, where aerodynamic constraints (along with their acoustic and perceptual outcomes) meet diachronic and synchronic phonology. One potentially fruitful area of investigation may include those 'nasal harmony' languages like Gokana and Guaraní in which nasalization 'spreads through' voiceless fricatives [16]. The aeroacoustics and perception of such fricatives may help us understand the extent to which a variety of fricatives (e.g. peaked- and flat-spectrum) can support nasalization while remaining perceptually contrastive.

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[1] Nasalized fricatives such as [h̃ ɦ̃ ħ̃ ʕ̃], i.e. those with a primary constriction located 'upstream' of the velopharynx, cannot be ruled out on aerodynamic grounds.

[2] Negative values are likely the result of measurement error, either due to the calibration or the actual performance of the transducers. Generally speaking, they may be equated with zero nasal flow. If the flow is truly negative, the only possible physiological explanation is that the air mass of the nasal cavity is somehow rarefied, perhaps due to the action of the soft palate. It is not clear what may motivate such nasal flow. Since the effect is not particularly robust, it will not be investigated further at this time. As far as the present study is concerned, it is enough to note a statistically significant relative difference between the aerodynamic measures under categorically variable conditions.