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Vocalic context as a condition for nasal coda emergence: aerodynamic evidence

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Abstract

Nasal coda emergence (NCE) (sometimes referred to as “restoration”) is the process by which a nasal vowel develops an excrescent nasal coda which may or may not have been present in an earlier form of the spoken language. NCE is operative in the Carioca (Rio de Janeiro) dialect of Brazilian Portuguese (CBP), an Ibero-Romance language with five phonemically nasal vowels. The output of NCE (in this language) is usually a velar nasal. It has been suggested that the process may be a function of tongue position (Hajek 1991: 262). To test the null hypothesis that NCE does not correlate with vowel height or anteriority, aerodynamic (nasal and oral flow) signals were obtained from three speakers of CBP. The speakers uttered words ending in nasal vowels while wearing a circumferentially-vented pneumotach split-flow air mask. For comparative purposes, parallel data were gathered from a Hindi and a French speaker as well. The maximum nasal percentage of total flow and the maximum real nasal flow (in ml/s) were measured for each token, averaged across vowels and, in the case of CBP, across speakers. For CBP, the null hypothesis is rejected, lending support to the alternative: vowel height and anteriority indeed condition the emergence of NCE. This suggests a role for the lowered velum and/or raised tongue body in the development of coda obstruents on nasal vowels.

1 Introduction

Romance philologists note the existence of a process that reverses the diachronic deletion of nasal coda consonants through emergence (sometimes called “restoration”) of a nasal consonant after a nasal vowel (see Sampson 1999: 146, 150-151, 207, 260 for cross-linguistic examples, particularly in Galician and northern Italian). Sampson (1999: 260) remarks that the emergent coda is generally “of variable duration and degree of occlusion.” It may also have a variable place of articulation, sometimes based on the quality of the preceding vowel.

Furthermore, it has been suspected for over a century that a mysterious segment lurks at the edge of Brazilian Portuguese word-final nasal vowels (Nobiling 1903). This has provoked debate concerning the phonological status of nasal vowels in the language (Reed and Leite 1947; Morais-Barbosa 1961; Lipski 1975; Cagliari 1977; Mattoso Câmara 1977; Parkinson 1983). Nobiling (1903) was one of the first to posit an underlying nasal consonant in this position. He noted that it resembled a velar nasal consonant “without complete oral closure” (as cited in Lipski 1975: 72). The present study emphasizes the aerodynamics of nasal coda emergence (NCE) in Carioca Brazilian Portuguese (CBP) and concludes with suppositions about the articulatory conditions affecting its development. It is likely that the character of the oral occlusion in CBP is typically velar, though the issue has not been resolved, nor is it settled here (cf. Reed and Leite (1947) for a discussion of palatal and velar nasals in contrasting vocalic environments).

Hajek (1991) introduces an explanation for NCE called “nasalized glide hardening.” He notes that dorsal raising in the articulation of a nasalized glide “facilitates contact between the raised tongue body and the lowered velum, resulting in the closure of the oral cavity” (1991: 262). Thus, he proposes a correlation between tongue height and NCE. Along these lines, it is reasonable to suggest that increased posteriority of a vowel—bringing the tongue body into closer proximity with the lowering velum—may also correlate with NCE. By analyzing aerodynamic data, this study aims to determine what, if any, correlation exists between NCE and vocalic context.

NCE is an aerodynamic event characterized by the observation of a nasal stop consonant in an environment where, for present purposes, only a nasal vowel is expected. A nasal stop consonant is characterized aerodynamically by the simultaneous presence of positive nasal flow and zero oral flow. Thus, aerodynamic data is perhaps the most useful means of certifying the occurrence of NCE among individual speakers.

In the present study, the null hypothesis is as follows: Given a pre-vocalic context, for each high/low and front/back pairing of nasal vowels, NCE will not show a significant tendency to occur more frequently among tokens where the nasal vowel under investigation is higher and/or more back. Conversely, the research hypothesis states that nasal codas will indeed emerge preferentially after high and/or back vowels.

2 Method

2.1 Subjects

Five native speakers (three of Brazilian Portuguese, one of French, and one of Hindi) between the ages of 25 and 30 were paid to participate in the study. At the time of the experiment, all had lived in the United States less than five years. Of the three Brazilian speakers (one female and two males), all reported their dialect as “Carioca” (i.e., from Rio de Janeiro). The French speaker is a male from Clermont-Ferrand, in central France. However, the speaker reported that because he was raised in various locations in Northern and Central France, he does not speak with a Meridional French accent (noted, according to one anonymous reviewer, for having an excrescent velar nasal coda attached to its nasal vowels). The Hindi speaker is a male from Nagpur, in Uttar-Pradesh.

2.2 Corpus

Word-final nasal vowels in CBP (all monophthongs) were the primary focus of the study. CBP has five: /ĩ ẽ ã õ ù/. While the primary goal of the study was to assess the null hypothesis for CBP, it was determined that the reliability of the aerodynamic method could be corroborated by using data from different languages. Thus, data were also collected from Hindi and French (where NCE is not necessarily suspected). Hindi has seven nasal vowels: /ĩ ẽ ẽ ã õ ù/. French has three: /ẽ ã õ/ ([œ̃] is replaced by [ɛ̃] in many dialects, including that of the present speaker (cf. Martinet 1945; Fougerson and Smith 1999: 79)).

The speakers uttered nine words containing each phonemic nasal vowel (see Appendices 1, 2, and 3 for a complete listing). All nasal vowels occurred in word-final position. All tokens were repeated twice, uttered about ten minutes apart. Between speakers, the total number of tokens was: CBP=270; Hindi=126; and French=54.

Tokens were uttered in a carrier phrase which controlled the quality of the nasal vowel terminal transitions by adjoining them uniformly to a low back vowel. For CBP, the carrier phrase was [dʒiɣə ____ aɣərə] ‘say X again’; for French, [di ____ apʁe] ‘afterward I said X’; and for Hindi, [təb ʃəbd ____ ata hɛ] ‘The word X came [into usage] at that time.’ Speakers were asked to pronounce the sentences at a casual rate, but the nature of the experiment undeniably elicited so-called “laboratory speech.”

Because nonce words were avoided as much as practicable among the tokens, the consonant before the nasal vowel varied in place and manner of articulation. It should be noted, however, that in a cinefluorographic study of four American English vowels, variation of non-nasal consonant across place and manner of articulation produced no significant differences in velopharyngeal closure (Moll 1962:36). A more recent study (Amelot 2004) suggests that for French, velopharyngeal closure does depend on the place and manner of articulation for the preceding consonant. To control for this factor, nonsense syllables with invariant consonantal place of articulation may be preferable in future studies.

2.3 Equipment and procedures

While uttering the stimuli, speakers wore a circumferentially-vented pneumotach mask split into two chambers to separately measure oral and nasal flow (Model S/T-1, Glottal Enterprises, Inc., Syracuse, NY). The capacity and construction of the pneumotach mask has been described in detail in Rothenberg (1977). Cohn (1990) discusses the procedures for acquiring aerodynamic data with such a mask. She notes, in particular, the precautions that should be taken to ensure that the mask fits snugly against the face of the speaker. To record aerodynamic data, two flow transducers (Models PTL-1 and PTW-1, Glottal Enterprises) were inserted into the mask.

Audio was recorded simultaneously with a head-mounted microphone positioned near the mask. The quality of the audio was naturally reduced by the acoustic impedance of the plastic mask, making the resulting signal unsuitable for spectral analysis. Nonetheless, the robust acoustic distinctions (e.g., between fricatives and vowels) were easily detected in the waveform. This proved helpful later when the signals were segmented.

Aerodynamic and acoustic signals were digitized at a sampling rate of 1.375 kHz using PCQuirer (Scicon R&D, Inc., Encino, CA).

To calibrate, the mask was placed over a special gasket on a pneumotach calibration unit (Model MCU-4, Glottal Enterprises) and air was discharged into the mask at five rates of flow (1000, 500, 0, -500, and -1000 ml/s). The electrical responses of the transducers were related to the flow rates using least-squares linear regression and the resulting equation was used to calibrate the aerodynamic signals. Each time the mask was calibrated (before a new recording session) the electrical output showed a highly consistent degree of correlation with the known values of flow in both the oral and nasal compartments (on average, $r > 0.999$). These results suggest the proper functioning of the mask and pressure transducers.

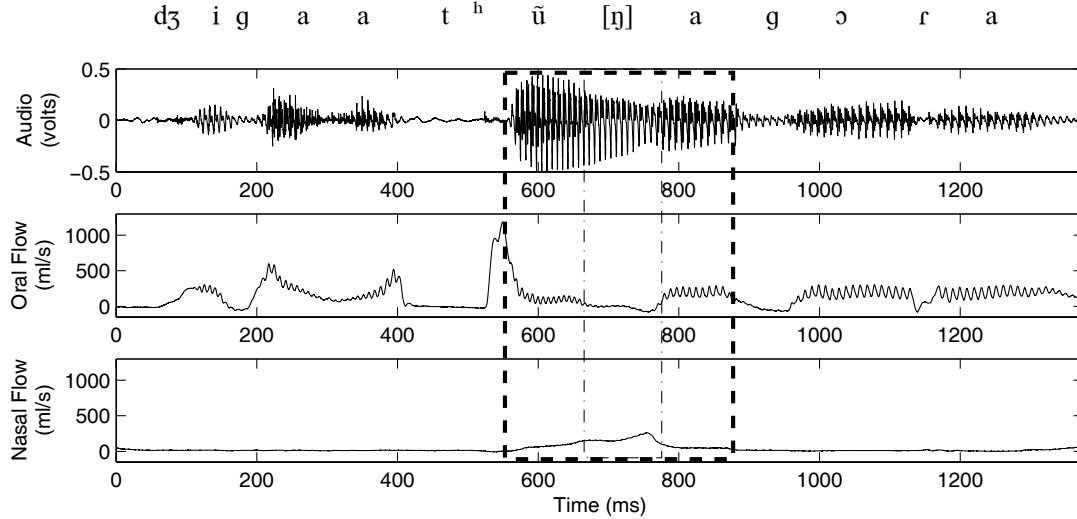


FIGURE 1. Physiological data signals (audio, oral air flow, and nasal air flow) for the CBP sentence *diga atum agora* ‘say tuna again’. Non-positive oral flow during positive nasal flow (NCE) at the end of the word *atum* /atũ/ is highlighted by a light dashed rectangle. The portion of the signal excised for analysis is highlighted by a bold dashed rectangle.

Once calibrated, the aerodynamic waveforms appeared as in Figure 1. Notice how the peak in the nasal signal is synchronous with a depression in oral flow, suggesting the proportional allocation of transglottal flow among the oral and nasal cavities. In the output signal there are also manifestations of purely oral events like aspiration in the release of the voiceless obstruent [t^h] (a sharp peak in oral flow at around 550 ms). In Figure 1, the region outlined by the light dashed rectangle is said to be characteristic of NCE. The region outlined by the dark dashed rectangle is the portion of the signal excised for further analysis.

Values of the aerodynamic signal were extracted from a window whose left endpoint corresponded to the release of the preceding consonant (e.g., [t] in /atũ/) and whose right endpoint corresponded to the onset of the following consonant (e.g., [g] in /agərə/). Thus, in Figure 1, we are interested only in the sequence /ũa/ or the region outlined by the dark dashed rectangle. Characteristics of the aerodynamic signal (e.g., the spike in oral flow corresponding to the aspiration in [t^h] and the slightly negative airflow of [g]) allowed the sequence to be isolated.

The simultaneous audio recording also aided in judging the dimensions of the extraction window. For example, aerodynamic principles suggest that nasal flow during the production of oral fricatives should be zero, or in other words, buccal obstruents require velic closure (Ohala and Ohala 1993). Thus, a period characterized by high oral flow and negligible nasal flow might well be labeled a fricative, which is especially convenient if one is already aware of a fricative in the acoustic signal. By using as landmarks surrounding segments that are independent of any emergent nasal coda consonant, the technique described here avoids the circularity of depending on increased nasal flow to locate NCE. Regardless of whether nasal flow increased dramatically, the material between the two consonants was extracted and exported into further calculations.

In the first token depicted in Figure 1, as in all others, the first vowel in the sequence is nasal and the second is oral (the second is generally nasalized, though sometimes to a lesser extent, due to some

carryover of nasal airflow). Note that there is always a word boundary between the final nasal vowel and following vowel, e.g., *atum* | *agora*. If present, NCE should materialize somewhere in this boundary, between the nasal and oral vowel. It is crucial that the presence of NCE be detected between vowels rather than between a vowel and an obstruent. An example will illustrate the problem: In a CBP phrase like *diga atum duas vezes* ‘say *tuna* two times’, oral occlusion may be trivially present at the onset of [d].

Once the aerodynamic signals were extracted from the appropriate window, the data appeared as in Figure 2.

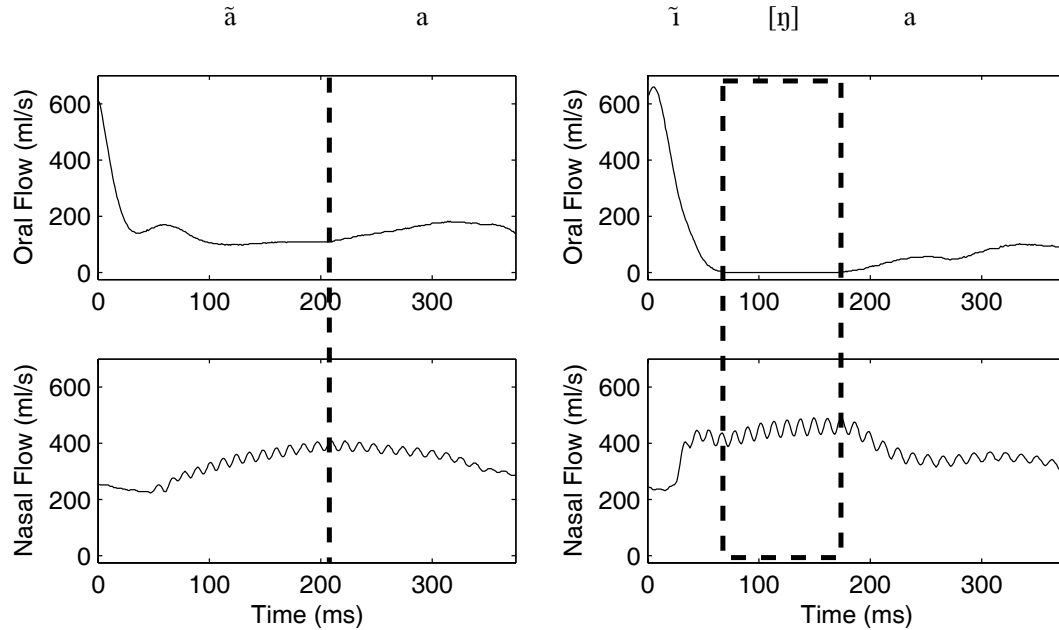


FIGURE 2. Nasal and oral airflow for vocalic sequences /ãa/ (left) and /ia/ (right) uttered by CBP Speaker 3. Sequences are excised from the phrases *diga sã agora* and *diga sim agora* (the high oral peak at the left in both tokens is the terminus of the fricative). NCE (oral flow = 0 while nasal flow > 0) occurs from about 60 to 175 ms in the right-hand token /ia/ and is marked by a dashed rectangle. A similar effect does not occur in the left-hand token /ãa/, where the boundary between vowels is marked by a dashed line.

During the right-hand token in Figure 2, nasal flow is positive while oral flow drops to zero, indicative of a nasal stop consonant. Strictly speaking, zero flow is not the only possibility for the oral component of a nasal consonant. Oral flow can also run negative, as it does in several of the tokens manifesting NCE effects (the nasal consonant in Figure 1 is an example). This is probably due to rarefaction of the air space anterior to the oral occlusion, perhaps most likely to occur when the surface area of the lingual seal is large. For the purposes of accurately expressing the nasal flow as a percentage of total oral flow, however, negative oral flow has been normalized to zero.

In Figure 2 (right-hand token), the duration of oral occlusion (marked by the dashed rectangle) is approximately 115 ms, beginning at 60 ms. During this time, nasal air flow is between 400 and 500 ml/s. The combination of zero oral flow and positive nasal flow defines a nasal stop consonant (Ladefoged 2001: 274). Thus, in the right-hand token of Figure 2 we observe an emergent nasal consonant during the production of a vocalic sequence.

As mentioned previously, the combination of zero oral flow and positive nasal flow is the simplest aerodynamic definition of a nasal stop consonant. This definition is crucial to the present analysis because it also serves as the functional definition of NCE in the targeted environment. During the production of a nasal vowel, if oral flow drops to zero and nasal flow remains positive, NCE is said to obtain.

We do not observe NCE in all tokens. The low vowel [ã], for example, almost never manifests the effect. In the left-hand token of Figure 2, oral flow in /ãa/ never drops to the zero level, indicative of a typical nasalized vowel with both positive nasal and oral flow.

Because each vocalic sequence varied in duration, an averaging technique was necessary to normalize the time scales. Normalizing durations allowed for comparisons across vowels and speakers. The oral and nasal signals were divided into 25 equal regions. An average value was computed for each region of the signal, so that each signal could be described by a series of 25 data points all resulting from a regional average. A similar technique was used for measuring F0 in Roengpitya (2001).

Normalized data from the 18 tokens for each vowel produced by each speaker were pooled to suggest the characteristics of a typical nasal vowel of a given quality produced by that speaker. For CBP, where the vowels of three speakers were examined, the averaged vowels of each speaker were subsequently pooled to offer an even more general idea of nasal vowel characteristics in CBP. For French and Hindi, the data from only one speaker per language were included in this study, but the same normalization techniques applied.

Figure 3 depicts the normalized segmental sequence /ĩa/ for CBP Speaker 3. The time scale in the figure has been normalized to 25 units. Only the relative timing of events within the signal can now be compared (for example, peak nasal flow occurs at unit 5, one-fifth of the way through the signal).

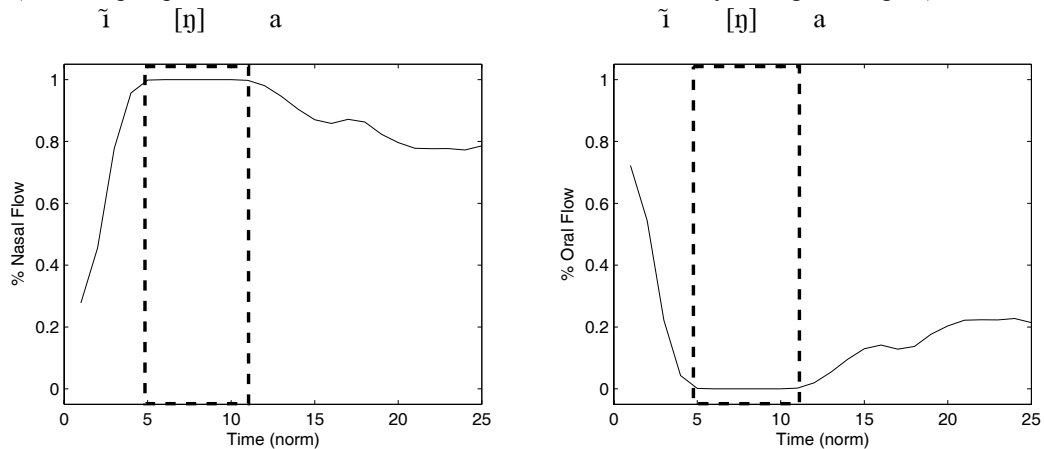


FIGURE 3. Percentage of nasal and oral flow (time-normalized) for the vocalic sequence /ĩa/, CBP Speaker 3.

Some of the features typical of the first, isolated token (Figures 2 and 3) are still evident even after the token has been averaged with 53 more (Figure 4). There is still a tendency for an increase in nasal flow and a concomitant decrease in oral flow, and the timing of these events is comparable. Complete oral occlusion (100% nasal flow or 0% oral flow) does not occur in the averaged signals unless occlusion occurred in all of the tokens. Nonetheless, in the data represented in Figure 4, NCE has obtained in enough tokens to lower the average oral flow below 20% for a significant proportion of the averaged, normalized signal. Tokens such as these are the objects that will be submitted for statistical comparison.

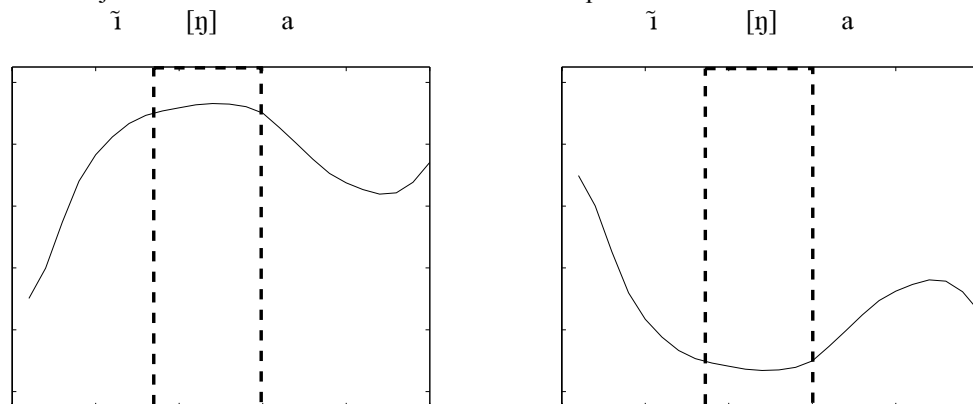


FIGURE 4. Normalized nasal and oral percentages for the vocalic sequence /ĩa/ averaged for CBP (3 speakers * 9 words * 2 repetitions = 54 tokens).

2.4 Measures

The characteristics of the extracted vocalic sequences were quantified using the variables MaxP(N) and MaxR(N). MaxP(N) is a discrete random variable having the Bernoulli distribution. It is the nasal proportion of total flow. MaxR(N), the real maximum value of nasal flow in ml/s, is a continuous random variable assumed to have the normal distribution (as will be demonstrated in §3.3.1).

2.4.1 MaxP(N)

Nasal proportion of total flow (MaxP(N)) is a simple arithmetical measure: nasal flow divided by the sum of nasal and oral flow. For a token with MaxP(N) = 1.0, a success {1} was tabulated. Where MaxP(N) < 1, a failure {0} was tabulated. Thus, MaxP(N) is a discrete random variable where $R \rightarrow \{0,1\}$, having the Bernoulli distribution with n trials, mean p, and variance p (1-p). In other words, MaxP(N) represents the frequency of NCE for any given vowel.

2.4.2 MaxR(N)

This is the real maximum value of nasal flow in ml/s. It is suggestive of maximum velic aperture during the vocalic sequence. Unlike MaxP(N), MaxR(N) is a continuous variable with an approximately normal distribution.

3 Results

3.1 Descriptive statistics

Table 1 presents mean and standard error estimates of the Bernoulli random variable MaxP(N) for CBP, French, and Hindi nasal vowels. Note that in Table 1, any value greater than zero indicates that at least some of the tokens showed signs of NCE. Table 2 reports mean and standard error estimates of the normally-distributed random variable MaxR(N).

	CBP		French		Hindi	
	M	SE	M	SE	M	SE
ĩ	0.722	0.061	---	---	0.000	0.000
ẽ	0.037	0.026	---	---	0.000	0.000
ẽ̃	---	---	0.000	0.000	0.000	0.000
ã	0.000	0.000	0.111	0.074	0.000	0.000
õ	---	---	0.556	0.117	0.056	0.054
õ̃	0.259	0.059	---	---	0.167	0.087
ũ	0.852	0.048	---	---	0.111	0.074

TABLE 1. Mean (M) and standard error (SE) estimates of MaxP(N) for the nasal vowels of CBP, French, and Hindi. For each nasal vowel in CBP: n=54; French and Hindi: n=18.

	CBP		French		Hindi	
	M	SE	M	SE	M	SE
ĩ	364.2	126.0	---	---	307.3	89.9
ẽ	287.9	111.4	---	---	154.7	48.0
ẽ̃	---	---	303.9	59.3	120.4	32.8
ã	245.0	127.6	245.0	38.0	166.4	60.2
õ	---	---	346.1	63.8	169.1	82.6
õ̃	292.1	140.9	---	---	164.7	44.8
ũ	380.8	113.7	---	---	228.6	61.9

TABLE 2. Mean (M) and standard error (SE) estimates of MaxR(N) for the nasal vowels of CBP, French, and Hindi. Sample populations are as in Table 1. Estimates are presented graphically in Figure 5.

In CBP, NCE is observed most frequently in the high back vowel, followed by the high front vowel. NCE is more frequent in the back mid-close vowel than the front mid-close vowel. It is unobserved in the low vowel [ã]. In Hindi, we observe NCE exclusively among the back (non-low) vowels, where it is more frequent in the mid-close vowel than in the high vowel. In French, NCE occurs most frequently in [ɔ̃], the highest back vowel of the set, followed by the low vowel (for which NCE is relatively infrequent). NCE does not occur in the French front (nasal) vowel.

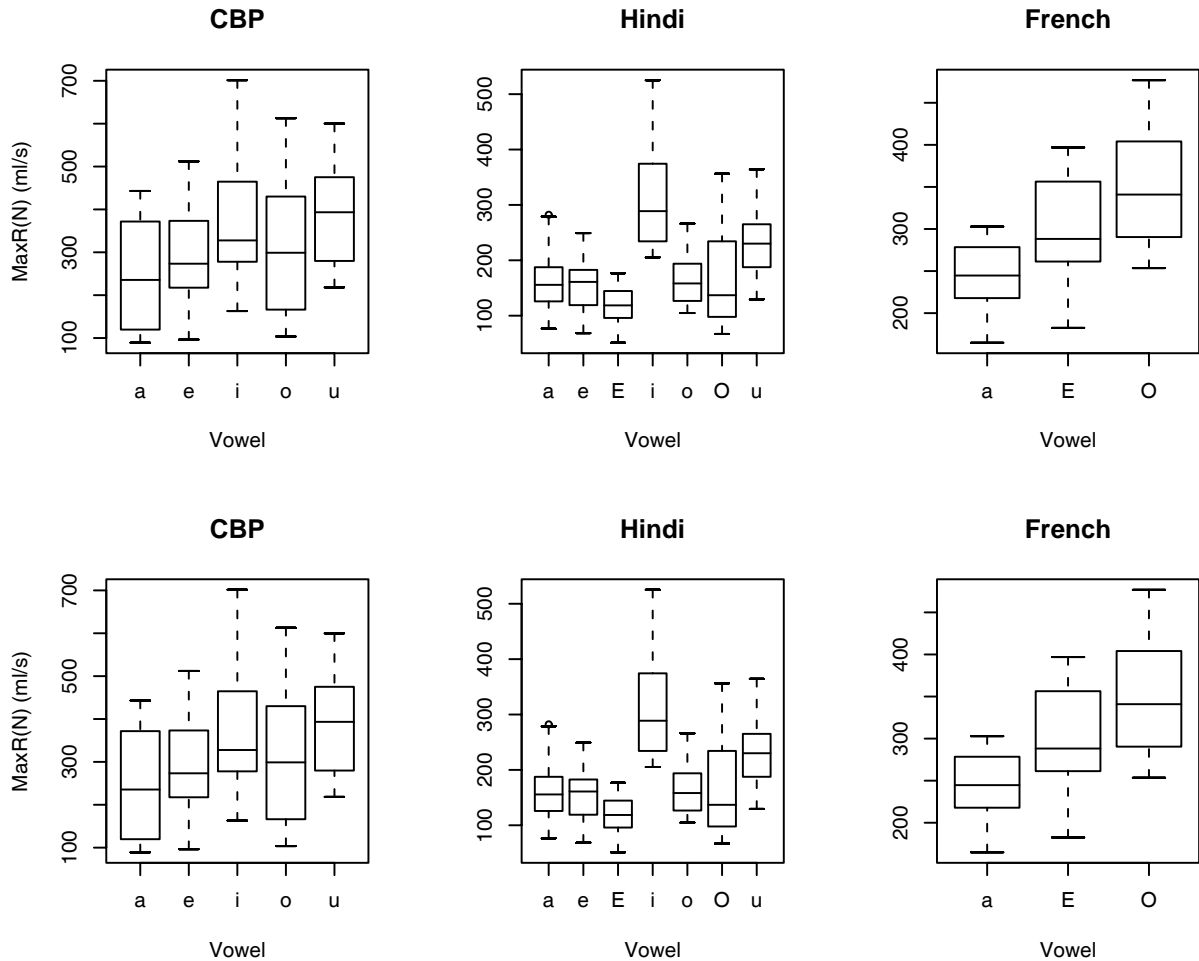


FIGURE 5. Boxplots of MaxR(N) for the nasal vowels of CBP, Hindi, and French.

MaxR(N) is suggestive of maximal velic opening during the vowel sequence. Boxplots of MaxR(N) for the vowels of each language are presented in Figure 5. MaxR(N) provides us with the actual rather than proportional amount of nasal flow. Patterns of MaxR(N) are similar to those of MaxP(N). In CBP, we observe the mirror image of the MaxP(N) results: The high back vowel has the highest level of nasal flow, followed by the high front vowel, the back mid-close vowel, the front mid-close vowel, and finally the low vowel.

In French, maximum nasal flow follows the same orderly pattern, proceeding from the mid-close back vowel to the mid-close front vowel, leaving the low vowel with the lowest value.

In Hindi, which has the highest number of nasal vowels in the study (seven), the same pattern is not maintained. The high front vowel has greater MaxR(N) than the high back vowel, contrary to the pattern we have observed so far. Higher nasal flow is not necessarily paired with greater vowel height, but back vowels generally have higher nasal flow than their front counterparts (of the same height), except for the notable case of [ũ] and [ĩ]. A further wrinkle is that the low vowel has a higher MaxR(N) than the back and

front vowels of the mid-close set. The following sections will present evidence as to whether differences between these vowels are statistically significant.

3.2 Binomial model hypothesis test (MaxP(N))

Under the assumptions of the binomial one-sample model, we can test the null hypothesis that the estimated probability of success (i.e., MaxR(N)=1.0) for a given vowel is equal to the estimated probability of success for another vowel. There are 21 pairs of vowels in Hindi, 10 in CBP, and three in French. The estimated mean difference in MaxR(N) for each vowel pair was calculated along with the estimated standard error for each difference. In Table 3, the significance for each vowel pairing is reported.

	CBP		French		Hindi	
	M	SE	M	SE	M	SE
ĩ	0.722 ^u	0.061	---	---	0.000 ^{Oou}	0.000
ẽ	0.037 ^a	0.026	---	---	0.000 ^{Oo}	0.000
ẽ̃	---	---	0.000 ^a	0.000	0.000 ^o	0.000
ã	0.000 ^e	0.000	0.111 ^E	0.074	0.000 ^o	0.000
õ	---	---	0.556	0.117	0.056 ^{icou}	0.054
õ̃	0.259	0.059	---	---	0.167 ^{ieEaOu}	0.087
ũ	0.852 ⁱ	0.048	---	---	0.111 ^{iOo}	0.074

TABLE 3. Means (M), standard error (SE) estimates, and significance results of binomial one-sample hypothesis test for MaxP(N). Means (M) with superscript vowel(s) *do not* differ significantly ($p > 0.05$) from the mean(s) of the superscript vowel(s) (in the same language). For example, CBP [ĩ] does not differ significantly from CBP [ũ], but it is significantly different ($p < 0.05$) from CBP’s three other vowels, viz., [ẽ ã õ]. Hindi [õ̃] does not differ significantly from any other Hindi vowel so they are all superscripted next to the mean for Hindi [õ̃]. In the superscripts, capital letters are used to represent the mid-open vowels [ẽ̃] and [õ̃]. In short, if superscripts occur, the superscripted vowels are statistically indistinguishable ($p > 0.05$) from the base vowel.

In CBP, MaxP(N) differences are significant for all vowel pairs, with two notable exceptions: The difference between the high back vowel and the high front vowel are not significant, nor are the differences between the front mid-close and low vowels. Thus, the null hypothesis (that NCE occurs as frequently in high vowels as in low vowels and as frequently in front vowels as in back vowels) is rejected for CBP. In other words, there is some validity to the claim that NCE occurs more frequently among vowels that are higher and more back.

In French, there are only three differences under analysis. As in CBP, there is no significant difference in MaxP(N) between the low vowel and [ẽ̃], the lowest front vowel of the set. However, there are significant differences between the back and front mid-close vowels and the high back vowel and the low vowel. The null hypothesis is also rejected for French, but with reservation due to the low frequency of NCE among any of the French vowels (as seen in Table 1 (§3.1), the maximum frequency is only 55.6% for [õ̃]).

The MaxP(N) data for Hindi are problematic because NCE does not occur in any of the tokens for four of the seven vowels (three front vowels plus the low vowel). Thus, there is no sense in which these four vowels are or are not significantly different from one another. Recall from Table 1 (§3.1) that MaxP(N) of Hindi [õ̃] was anomalous: NCE occurred more frequently in this vowel than in the high back vowel. The binomial model hypothesis test indicates, however, that the two vowels are statistically indistinguishable in terms of MaxP(N). In other words, NCE probably occurs as frequently in [ũ] as in [õ̃]. In fact, the null hypothesis is supported for all of the back vowels, where the various MaxP(N) values may as well be equal. NCE occurs more frequently in the high back vowel than in the low vowel as well as the mid-close and mid-open front vowels. However, the only significant results for Hindi emerge in vowel-pairings where MaxP(N) for one of the vowels is zero. In light of these mixed results, the null hypothesis is accepted for MaxP(N) in Hindi.

3.3 Logistic regression model (MaxP(N))

The MaxP(N) data were included in a logistic regression model. Binary logistic regression is used when the dependent variable (in this case, MaxP(N)) is a discrete variable that can take on one of two possible values: either NCE does occur {1} or does not occur {0} for any given token. According to Gahl and Garnsey (2004: 760), “A logistic regression analysis is a statistical model that relates one or more predictor variables to a categorical dependent variable... In a model with multiple predictor variables, a predictor variable is said to have a significant effect when its inclusion in the model yields a significantly better account of the variation in the dependent variable.” Following Gahl and Garnsey (2004: 760-762), the odds ratio (OR) associated with each predictor variable is presented. This denotes the change in the odds of a vowel experiencing NCE for a one-unit increase in the predictor variable (i.e., a change from one vowel to another).

A few examples using data from Table 1 (§3.1) will serve to clarify how to interpret the results of logistic regression. In CBP, the odds of a success (the appearance of NCE) in the vowel [ĩ] are 0.722/(1-0.722) or nearly 3 to 1. By contrast, for CBP [ẽ] the odds of success are much lower: 0.037/(1-0.037) or 0.038 to 1. This means the odds of failure (the non-appearance of NCE) in CBP [ẽ] are actually quite large, roughly 26 to 1. The odds ratio (OR) is simply the odds of success for one group divided by the odds of success for another. So when we compare BP [ĩ] and [ẽ] we determine their OR to be (0.722/(1-0.722))/(0.037/(1-0.037)) = 67.6. Thus, NCE is about 68 times as likely to occur in BP [ĩ] than it is in BP [ẽ]. The OR’s for all the vowel pairings in all three languages are reported in Tables 4 and 5.

Hindi								Carioca Brazilian Portuguese (CBP)							
	ĩ	ẽ	ẽ	ã	õ	õ	ũ		ĩ	ẽ	ẽ	ã	õ	õ	ũ
ĩ		/	/	/	0.0	0.0	0.0	ĩ		68	---	∞	---	7.4	0.5
ẽ			/	/	0.0	0.0	0.0	ẽ			---	∞	---	0.1	0.0
ẽ				/	0.0	0.0	0.0	ẽ				---	---	---	---
ã					0.0	0.0	0.0	ã					---	0.0	0.0
õ						0.3	0.5	õ						---	---
õ							1.6	õ							0.1
ũ								ũ							

TABLE 4. Odds ratios of success (MaxP(N)=1) in the vowels of Hindi and CBP. Recall that a number divided by zero is infinite ‘∞’, as in the case of the BP vowel pair [ĩ] and [ã]; zero divided by a number is zero, as in the Hindi pair [ĩ] and [õ]; and zero divided by zero is not a number ‘/’, as in the case of the Hindi pair [ĩ] and [ẽ]. ‘---’ indicates vowel pairings that do not occur in a given language.

French							
	ĩ	ẽ	ẽ	ã	õ	õ	ũ
ĩ		---	---	---	---	---	---
ẽ			---	---	---	---	---
ẽ				0.0	0.0	---	---
ã					0.1	---	---

ĩ						---	---
õ							---
ũ							

TABLE 5. Odds ratios of success (MaxP(N)=1) in the vowels of French. Conventions are as in Table 4.

A number of outcomes should be discussed to clarify the presentation of the odds data and to justify a crucial step in the logistic regression analysis later on. As Table 4 indicates, the odds of increasing NCE by switching vowel (the odds ratio) are zero for many vowel pairs. In each case where OR = 0, one of the vowels in the pair never experiences NCE (i.e., zero divided by a number is zero). In cases where the odds are “infinite,” it just so happens that zero is in the denominator and an actual number is in the numerator (a number divided by zero is an infinite expression). The infinite OR’s and zero OR’s are interchangeable since the decision as to which value to place in the numerator was arbitrary. Finally, in some cases, we have a zero in both the numerator and denominator, meaning that the result is undefined. For present purposes, there is no need to differentiate these three kinds of OR’s. However, it is important to understand the effect that their presence has on the logistic regression analysis.

One of the assumptions of logistic regression is the exclusion of all irrelevant variables. When the model includes irrelevant variables with no predictive power, it is possible that the variance they share with predictive, relevant variables may be wrongly attributed to the irrelevant ones. Hence, the greater the correlation of the irrelevant variable(s) with other independents, the greater will be the standard errors of the regression coefficients for these independents (Hosmer and Lemeshow 1989). Hence, vowels with an average MaxP(N) of zero will be excluded because they are considered to be of no predictive value and therefore irrelevant to the analysis.

After excluding the irrelevant vowels, the data were fitted to a generalized linear model. Coefficients were assigned to the vowels included in the model for each language. The models for each language accurately capture the trends in the data, as demonstrated in Table 6. The output of the regression model is presented in the following table with the mean estimators from Table 1 (§3.1) in parentheses:

	CBP		French		Hindi	
	LR	M	LR	M	LR	M
ĩ	0.722	(0.722)	---	---	x	(0.000)
ẽ	0.037	(0.037)	---	---	x	(0.000)
ẽ	---	---	x	(0.000)	x	(0.000)
ã	x	(0.000)	0.111	(0.111)	x	(0.000)
ĩ	---	---	0.556	(0.556)	0.056	(0.056)
õ	0.264	(0.259)	---	---	0.167	(0.167)
ũ	0.868	(0.852)	---	---	0.111	(0.111)

TABLE 6. Output of the logistic regression (LR) analysis with the original mean (M) estimators of MaxP(N) in parentheses. The differences between LR and M are quite small—notable only for CBP [ĩ] and [ũ]. ‘x’ denotes vowels excluded from the logistic regression analysis.

In logistic regression, we can interpret p-values to mean the likelihood that the value of a coefficient may as well be zero, i.e., that it is useless in predicting the value of the dependent variable (here, the occurrence of NCE or MaxP(N)). Thus, we might say that the lower the p-value (and the higher the OR), the better the vowel performs as a predictor of NCE. Moreover, to the extent that vowels are good predictors of NCE, the null hypothesis is invalidated.

Vowel quality was indeed a significant predictor in the CBP logistic regression model. For the vowel [ĩ] (OR = 67.60, p < 0.001); [ẽ] (OR = 0.04, p < 0.001); [ĩ] (OR = 9.33, p < 0.001); and [ũ] (OR = 33.80, p < 0.001). The same can be said for French, where for [ã] (OR = 0.13, p < 0.01) and [ĩ] (OR = 1.76, p <

0.01). As might be expected from the results of the binomial hypothesis test (§3.2), vowel quality performs a weaker role in predicting NCE in Hindi. Even when irrelevant vowels are excluded from the Hindi logistic regression model, the results for [ɔ̃] (OR = 0.29, p = 0.31) and [ũ] (OR = 0.625 p = 0.631) support the null hypothesis. Both vowels are insignificant predictors of NCE. The low vowel [ã], however, performs marginally better as a predictor of NCE (OR = 0.20, p = 0.01).

3.3 ANOVA (MaxR(N))

3.3.1 Normality

We first test for the normality of the distribution of MaxR(N) to justify the use of ANOVA. Table 7 lists the correlation values (r) between expected and observed quantile plots for MaxR(N).

	CBP	French	Hindi
ĩ	0.967	---	0.955
ẽ	0.984	---	0.990
ẽ̃	---	0.984	{0.303}
ã	0.923	0.983	0.965
õ̃	---	0.981	{-0.185}
õ	0.958	---	0.967
ũ	0.967	---	0.980

TABLE 7. Correlation values (r) between expected and observed quantile plots for MaxR(N) for the nasal vowels of CBP, French, and Hindi. Unacceptably low values are in curly brackets.

The generally high correlation values in Table 7 suggest that MaxR(N) is indeed normally distributed for most of the vowels, with the exception of the Hindi mid-open vowels. We will accordingly regard the outcome of ANOVA for Hindi, and for these vowels in particular, with some skepticism.

3.3.2. ANOVA results

Three one-way ANOVAs (one for each language) were performed with the category Vowel as independent variable and MaxR(N) as dependent variable. The results for CBP were F(4,263) = 11.12; for Hindi F(6,119) = 17.34; and for French F(2,51) = 15.45. In all three cases, p < 0.001.

Thus, ANOVA suggests a high degree of statistical significance for MaxR(N) differences between nasal vowels in all three languages. The Tukey-HSD test revealed which pair-wise differences among MaxR(N) means were significant, as reported in Table 8.

	CBP		French		Hindi	
	M	SE	M	SE	M	SE
ĩ	364.2 ^u	126.0	---	---	307.3	89.9
ẽ	287.9 ^{ao}	111.4	---	---	154.7 ^{EaOo}	48.0
ẽ̃	---	---	303.9 ^O	59.3	120.4 ^{eaOo}	32.8
ã	245.0 ^{eo}	127.6	245.0	38.0	166.4 ^{eEOou}	60.2
õ̃	---	---	346.1 ^E	63.8	169.1 ^{eEaou}	82.6
õ	292.1 ^{ea}	140.9	---	---	164.7 ^{eEaO}	44.8
ũ	380.8 ⁱ	113.7	---	---	228.6 ^{aO}	61.9

TABLE 8. Means (M), standard error (SE) estimates and Tukey HSD results. Means with superscript vowel(s) *do not* differ significantly from the mean(s) of the superscript vowel(s) (in the same language) according to Tukey HSD (p>0.05). For example, CBP [ĩ] does not differ significantly from CBP [ũ] but it is significantly different (p<0.05) from CBP [ẽ ã õ̃]. Hindi [ã] does not differ significantly from the Hindi vowels [ẽ ẽ̃ õ̃ õ̃̃], so they are all superscripted next to the mean for Hindi [ã]. Because Hindi [ã] is significantly different from Hindi [ĩ], the high front vowel is not superscripted. In the superscripts, capital letters are used to represent the mid-open vowels [ẽ̃] and [õ̃]. In short, if superscripts occur, the superscripted vowels are statistically indistinguishable (p>0.05) from the base vowel.

In CBP, mean differences in MaxR(N) between the back vowels and the low vowel are all significant. Differences between the high front vowel and the mid-close front vowel are also significant. Differences between front and back vowels of the same height, however, are not significant. In CBP, therefore, the null hypothesis is rejected for vowels of differing heights but accepted for vowels of differing anteriority. For the same reasons, the same conclusion is reached for French.

In Hindi, differences in mean MaxR(N) achieve significance for only some of the front/back pairs and only some of the high/low pairs. Significant differences in Hindi, furthermore, include only those pairs where the high vowel is a member. This means that the observed difference in MaxR(N) where [ũ] < [i] (Table 2, §3.1) is in fact significant. The Hindi high vowel data accordingly suggest that nasal flow may be greater during front vowels than back vowels. The fact that this pattern is not supported at any other vowel height, however, makes it appear less reliable than the consistent patterns that emerged in CBP and French. Based on these mixed results, it is impossible to conclusively reject the null hypothesis for Hindi. Accordingly, NCE may be considered inoperative in the language.

3.3.3 ANOVA of individual CBP speakers (MaxR(N))

Because data from the three CBP speakers were pooled in the earlier analysis, an investigation into a possible speaker effect was warranted. Accordingly, three one-way ANOVAs (one for each CBP speaker) were performed. Results indicate that vowel was a significant ($p < 0.001$) factor in determining MaxR(N) for all three speakers: for CBP1 $F(4,85) = 31.17$; for CBP2 $F(4,85) = 9.09$; for CBP3 $F(4,85) = 15.82$. Thus, we can discount the possibility of a strong speaker effect on the CBP data. The boxplots of MaxR(N) for the three CBP speakers are presented in Figure 6.

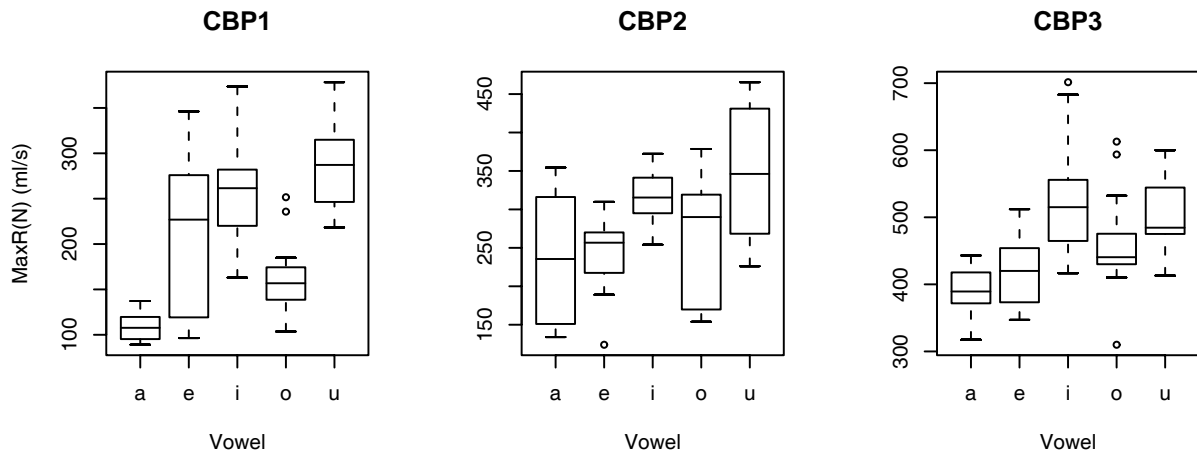


Figure 6. Boxplots of MaxR(N) for three speakers of CBP.

4 Discussion and conclusion

It is evident from the results of the binomial model hypothesis test (§3.2) and the logistic regression analysis (§3.3) that NCE follows the pattern suggested by Hajek (1991). Tongue height, and to a lesser extent anteriority, indeed influence the development of nasal codas on nasal vowels. Furthermore, when a language has higher incidence of NCE (as in French and CBP, vis-à-vis Hindi) it seems that observations of the pattern have a more solid statistical basis. That Hindi does not follow the pattern as closely seems less troublesome because NCE is relatively infrequent in this language (indeed, it occurs in only three of the seven vowels and in these three it occurs in less than 20% of the tokens). In a language like CBP, however, where the emergent nasal consonant has been observed elsewhere (e.g., Nobile 1903) and occurs frequently among the tokens in this study, the statistical evidence is strongly against the null hypothesis for all vowels.

Results of the ANOVA are more weakly opposed to the null hypothesis. However, the measure used in the ANOVA (MaxR(N)) is perhaps not as directly related to NCE as MaxP(N). Recall that MaxR(N) is a continuous variable, a measure of peak nasal flow presumed to tell us something indirectly about velic aperture. MaxP(N), on the other hand, is a Bernoulli random variable (essentially a frequency measure)

indicating how often complete oral occlusion occurs during any given nasal vowel. If the velopharyngeal port were open wider during high vowels than low vowels or back vowels than front vowels (=higher MaxR(N)), we might speculate that the lowering velum is responsible for the occlusion that typifies NCE. While this may be true, present evidence cannot make the case for a so-called “velic” occlusion. An ultrasound study may be the best way to confirm which articulator is responsible: the falling velum or the rising tongue body.

More conclusive maximum real nasal flow evidence would be helpful in supporting the correlation between NCE and tongue position, but it is not strictly necessary for doing so. Perhaps nasal flow increases during the production of some vowels because of a certain property of transglottal flow or a particular configuration of constrictions in the vocal tract. (Beside the fact that each nasal vowel occurred in stressed position, this factor was not controlled in any systematic way).

The present study reveals that in CBP, nasal consonants emerge preferentially after word-final nasal vowels where the tongue dorsum is high; similar tendencies are reported for French, and to a lesser extent, for Hindi. Intuitively, one can reason that during the production of high nasal vowels (especially back vowels) there is very little space between the tongue dorsum and the lowered velum (resulting from a relaxed levator veli palatini). There is more space between the articulators during the production of a lower nasal vowel. Thus, the epiphenomenal closure characteristic of NCE is most likely to occur in the former case, a fact that is clearly borne out by the aerodynamic data.

This is not, however, an unproblematic finding. A number of studies (Brücke 1856; Czermak 1869; Nusbaum et al. 1935; Moll and Shriner 1967; Moll 1962; Lubker 1968; Fritzell 1969; Bell-Berti et al. 1979; Henderson 1984) indicate that the velopharyngeal isthmus is in fact narrower for high vowels than for low vowels, probably due to activity of the palatoglossus (a muscle arising in the palatine aponeurosis and extending down, forward, and into the sides of the tongue dorsum) during low vowels. The present findings suggest that nasal codas emerge among high vowels, in the very situation where the aforementioned studies (Brücke 1856, etc.) anticipate the velum to be in higher position.

However, substantial cross-linguistic and inter-speaker variation suggests that velic opening does not always correlate with vowel height in the manner predicted by Brücke (1856) and his successors. Hajek (1997) contends that there are enough counterexamples to the correlation to justify excluding it from a class of nasalization universals. In a nasographic study, Clumeck (1976) investigated nasal coarticulation before a nasal consonant in six languages (American English, French, Amoy Chinese, Brazilian Portuguese, Swedish and Hindi). He found that only five speakers out of thirteen showed statistically significant differences between low and high vowels with regard to amount of velic opening. Even fewer speakers showed the predicted differences between high and mid and mid and low vowels.

In another nasographic study, Al-Bamerni (1983) found a statistically significant difference in velic opening between high and low vowels on the one hand, and low and mid vowels on the other, in five of seven languages (English, French, Kurdish, Arabic, and Norwegian). In two of these cases (French and English), there was no statistically significant difference between mid and high vowel velic opening, with high inter-speaker variation. In Gujarati and Hindi, differences in vowel height had no statistically significant effect on velic opening. For these languages, the highest levels of velopharyngeal opening occurred in mid and high back vowels.

Still other studies indicate that greater velic opening is not restricted to oral low vowels but may extend to high vowels, as reported in Ontario French and English (Bream 1968), in North African French (Condax et al. 1976), and variably (2 out of 10 speakers) in American English (Moll 1962). Furthermore, according to Hajek (1997: 127): “The extreme sporadicity of spontaneous nasalization of oral vowels in the world’s languages suggests that low levels of velic opening, particularly in low vowels, are not perceived or are easily factored out by listeners.” Finally, Hajek and Maeda (2000) are unable to confirm, upon careful review of philological and perceptual evidence, that low vowels are more susceptible to the development of distinctive nasalization than are high vowels.

One explanation of these conflicting findings is that the movement of the velum is not obligatorily conditioned by the contraction of the palatoglossus and that this interaction is somehow optional. During the articulation of retracted vowels, the tug of the palatoglossus on the velum may be controlled or offset for some languages or some speakers. An electromyographic study (Dixit et al. 1987) suggests another option: that the palatoglossus may draw the soft palate downward during the production of high vowels, potentially yielding an epiphenomenal velar closure.

It is worth considering which muscular control options might be exercised during high/back nasal vowels in CBP, where nasal codas tend to emerge. The absence of NCE among low vowels indicates that the active palatoglossus link between low vowels and a low velum is more optional than it is sometimes regarded. On the other hand, the presence of NCE among high/back vowels suggests that the findings of Dixit et al. (1987) may have wider applicability than previously imagined. In CBP, it seems that the commonly exercised option of palatoglossus activity during low vowels is not exercised, while the less commonly exercised option of palatoglossus activity during high vowels is.

If we take the traditional view of a positive correlation between velic height and vowel height, we must conclude that the velum is not the principal articulator in NCE. During high nasal vowels in CBP, for instance, the tongue dorsum must be moving beyond its normal maximum vertical trajectory to come into epiphenomenal contact with the lowered but stationary velum. We assume the velum is stationary because the positive correlation studies suggest that the palatoglossus muscle does not exert a downward vector on the velum during a high vowel.

It is possible, however, that the positive correlation between velic height and vowel height applies only to languages without phonemically nasal vowels. A majority of studies on the topic indeed focus exclusively on languages with oral vowels only. As noted previously, Al-Bamerni (1983) argues that in Gujarati and Hindi—languages with oral/nasal vowel contrasts—high back vowels have the highest degree of velopharyngeal opening, quite the opposite of the general prediction. In the present study, this result is not corroborated for measures of maximum real nasal flow in Hindi, but it is corroborated for these measures in CBP and French.

Whether or not it is anticipated from our present understanding of velopharyngeal musculature and kinematics, NCE is clearly a function of vowel height and anteriority in CBP. Certainly, aerodynamic evidence alone cannot explain the ontology of the phenomenon. In fact, it is reasonable to suggest that NCE may be perceived before it is implemented to its fullest physiological extent (i.e., complete oral closure). As the constriction diameter narrows to zero, the resonant frequency of the oral cavity decreases monotonically. Since humans cannot distinguish frequencies below a certain threshold (around 35 Hz (Ladefoged 1996: 116)), it is reasonable to suggest that there is a constriction of some estimable size through which air may flow but which fails to generate an audible oral resonant frequency.

Using the Helmholtz Resonator as a model of the vocal tract, we can calculate resonant frequency as a function of the diameter of a narrow constriction linking two tubes. Here, the volume of the tube behind the constriction acts as an acoustic compliance and that of the narrow constriction acts as an acoustic mass (Stevens 1998: 142). Using the equation

$$f_1 = \frac{c}{2\pi} \sqrt{\frac{A_2}{A_1 \ell_1 \ell_2}}$$

where the cross-sectional area and length of the back tube are A_1 and ℓ_1 and those of the narrow constriction are A_2 and ℓ_2 , we derive the natural resonant frequency. Thus, a constriction of diameter 0.05 cm at the velar place of articulation (10-12 cm from the glottis) produces a barely audible frequency of approximately 35 Hz. A velar constriction of 0.1 cm would produce a frequency of roughly 70 Hz. Though these constrictions are quite small, air passing through them can still be detected by an airflow device, though probably not by the human ear. If this is true, then full closure is not necessary to produce an auditory percept of NCE.

However, it is still speculative whether the auditory percept of a nasal consonant in French and CBP actually aids in the recognition of nasal vowels and thereby contributes to nasal coda emergence. Speakers of French and CBP would most likely deny the presence of oral occlusion at the terminus of their nasal vowels. However, there is some evidence that speakers of Brazilian Portuguese, at least, consider nasal vowels to be bi-phonemic (vowel + nasal consonant) (Lipski 1975). If it could be shown conclusively (through perceptual experiments) that NCE helps CBP or French speakers to identify nasal vowels, then this could justify an auditory explanation for the spread of the phenomenon.

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Appendix 1. Portuguese stimuli

Stimulus	Gloss
cupim	termite
estopim	fuse
anequim	fleece
aipim	sp. of cassava
capim	sp. of grass
arlequim	clown
alfaquim	Atlantic Moonfish (<i>Selene setapinnis</i>)
botequim	café
manequim	mannequin
sem	without
aquém	on this side
harém	harem
quem	who
tem	have.3sg.present
alguém	someone
Belém	(toponym)
além	over there
desdém	disdain
tupã	god (lit. 'thunder' in Tupi)
cabatã	sp. of wasp
titã	titan
cristã	Christian (fem)
octã	repeating every eight days
concidadã	citizen (fem)
bretã	British (fem)
charlatã	charlatan
Satã	Satan
batom	lipstick
com	with
tom	tone
pompom	fastener
destom	disharmony
semitom	semitone
chitom	quiet! (interjection)
entretom	hue
marrom	brown
atum	tuna
vacum	vacuum
betum	tobacco
fortum	a bad smell
mutum	any of several sp. of birds from the family Cracidae
baticum	sound of clapping, pounding, etc.
gatum	related to cats
quantum	quantum
algum	some

Appendix 2. French stimuli

Stimulus	Gloss
lin	flax
épicurien	epicurean
Limousin	(toponym)
main	hand
boursin	type of cheese
masculin	masculine
féminin	feminine
nain	dwarf
venin	venom
votant	voter
rebutant	disagreeable
naturellement	naturally
révoltant	revolting
momentanément	momentarily
intermittent	intermittent
calmant	calming
tempérament	temperament
vraiment	truly
liseron	bindweed
limon	lemon
menton	chin
maçon	mason
canon	gun
Manon	(personal name)
canton	district
saumon	salmon
mousqueton	carbine

Appendix 3. Hindi stimuli

Stimulus	Gloss	IPA
नहीं	no	nəhī
कहीं	somewhere	kəhī
चीं चीं	chatter	tʃi tʃi
दीं	give.fem.plural.past	di
वहीं	right there	vəhī
गातीं	nonce	ɡaʈi
थीं	particle.fem.past	tʰi
यहीं	right here	jəhī
गापीं	nonce	ɡaʈi
औरतें	women	ɔrət̪ē
सिगरेटें	cigarettes	sɪɡareʈē
सड़कें	streets	səʈəkē
चोटें	injuries	tʃoʈē
चीज़ें	things	tʃizē
दोस्तें	friends.feminine	doʃt̪ē
बातें	facts	baʈē
किताबें	books	kɪʈabē
रातें	nights	raʈē
मैं	me	mē
हैं	be.1/2/3pl.present	hē
गाथें	nonce	ɡaʈʰē
गातें	nonce	ɡaʈē
गापें	nonce	ɡaʈē
गासैं	nonce	ɡasē
गाकैं	nonce	ɡakē
गाटैं	nonce	ɡaʈē
गाखैं	nonce	ɡakʰē
साड़ियाँ	saris	saʈijā
खिड़कियाँ	windows	kʰɪʈkijā
गाताँ	nonce	ɡaʈā
सब्जियाँ	vegetables	səbzijā
यहाँ	here	yəhā
गापाँ	nonce	ɡapā
छुट्टियाँ	vacations	tʃʰuʈt̪ijā
वहाँ	there	vəhā
गाकाँ	nonce	ɡakā
भौं	eyebrow	bʰi
पौधौं	sapling	poʈʰi
गाथौं	nonce	ɡaʈʰi
गातौं	nonce	ɡaʈi
गापाँ	nonce	ɡapō
गासाँ	nonce	ɡasō
गाकाँ	nonce	ɡakō
गाटाँ	nonce	ɡaʈō
गाखाँ	nonce	ɡakʰō

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औरतों	women.oblique	ɔrəʈõ
कीमतों	prices.oblique	kiməʈõ
पलंगों	beds.oblique	pələŋgõ
दीवारों	walls.oblique	ɖivarõ
किताबों	books.oblique	kiʈabõ
पहाड़ों	mountains.oblique	pəhaʈõ
शहरों	cities.oblique	ʃəhəʈõ
फलों	fruits.oblique	p ^h əlõ
लोगों	people.oblique	logõ
पढ़ूँ	study.1sg.subjunctive	pəʈ ^h ũ
करूँ	do.1sg.subjunctive	kəʈũ
पहुँचूँ	arrive.1sg.subjunctive	pəhũtʃũ
पूछूँ	ask.1sg.subjunctive	puʈʃũ
पकड़ूँ	grab.1sg.subjunctive	pəkəʈũ
तैँ	swim.1sg.subjunctive	ʈerũ
ख़रीदूँ	buy.1sg.subjunctive	k ^h əʈidũ
नाचूँ	dance.1sg.subjunctive	naʈʃũ
चढ़ूँ	climb.1sg.subjunctive	tʃəʈ ^h ũ