Postnasal Voicing

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Abstract

Many of the world's languages display a phonetic pattern whereby obstruents appear as voiced when following a nasal consonant. This article proposes a phonetic mechanism that favors postnasal voicing. The mechanism is based on two effects, which sometimes reinforce, and sometimes contradict each another. One effect is "nasal leak," the leakage of air through a nearly closed velar port during the coarticulatory period between an oral and a nasal segment. The other is "velar pumping," which arises from the vertical motion of a closed velum.

The main purpose of the article is to test this proposal, in two ways. First, a computational simulation of vocal tract aerodynamics is used to show that, under a range of plausible assumptions, the mechanisms posited would indeed produce a substantial phonetic effect in the direction of postnasal voicing. Second, measurements were carried out of the productions of 5 native speakers of English producing stops in a controlled comparison context (postnasal / [ˈtam___ə] vs. / postoral [ˈtaɹ___pə]). The results indicate that postnasal voicing present as a quantitative effect even in a language whose phonology lacks a qualitative postnasal voicing process.

1.   Introduction

Many of the world's languages display a phonetic pattern whereby obstruents appear as voiced when following a nasal consonant (Ferguson 1975). For example, in Wembawemba (Hercus 1986), there single phonemic series of stops, which normally appears as voiceless (1)a, but is voiced postnasally (1)b:

(1)	a.	/taka/	[ˈtakʌ]	'to hit'
		/milpa/	[ˈmɪlpʌ]	'to twist'
	b.	/yantin/	[ˈyandɪn]	'me'
		/panpar/	[ˈpanbʌr]	'shovel'

The pattern is widespread; here are some languages that show postnasal voicing; we list also the pages from our source material where postnasal voicing is discussed.

(2) Arusa (Levergood 1987, 204)
Eastern Armenian (Allen 1951, 202-3)
Japanese (Ito and Mester 1986)
Modern Greek dialects (Newton 1972)
Waorani (Saint and Pike 1962, xxx)
Western Desert Language (Douglas 1958, 3)
Zoque (Wonderly 1951, xxx)

Many of the listings in were located by Locke (1983), who checked the 197 languages of the Stanford Universals Project, and found 15 with specifically post-nasal voicing. To the extent that the Stanford sample is representative, it is plausible to conclude that postnasal voicing is found in a non-negligeable fraction of the world's languages.

Postnasal voicing has been the subject of recent theoretical discussion in phonology. Ito et al. (1995) treat the process as a kind of assimilation, whereby the voicing of the nasal perseverates (spreads) to the following obstruent, despite the fact that voicing on nasals in the relevant languages is characteristically not phonologically contrastive. They propose an ingenious mechanism for permitting such assimilations while retaining underspecified phonological representations.

Pater (1995, 1996) finds fault with the Ito et al. account. He notes, among other things, that Ito et al.'s theory would predict that obstruents *preceding* nasals would be likely to be voiced as well. In fact, in the data Pater examines (as well as in the examples we have seen), this does not occur.[1] Pater suggests that the basis of postnasal voicing is likely to be phonetic, and provides some outline suggestions along these lines.

The purpose of this article is to explore the phonetics of postnasal voicing in greater detail. We discuss two possible mechanisms that, in combination, might be expected to yield the typological pattern just noted. The article has two parts. First, we will test the proposed mechanisms by means of aerodynamic modeling. Second, we attempt to establish that a phonetic tendency toward postnasal voicing is present even in a language (American English) that lack postnasal voicing in its phonology. We will suggest that together, our results support a view of phonological postnasal voicing that is tied fairly directly to its phonetic origins.

[1] Obstruents are occasionally voiced before nasals, as in xxx, but in all such examples we have seen, they are voiced before other voiced sonorants (e.g., liquids) as well. This suggests that in such cases, the casual mechanism for voicing is not closely connected to nasality. In contrast, for the post-nasal cases, there are a fair number of instances in which it is only nasal consonants that can induce voicing.

2. Review of the Mechanisms of Obstruent Voicing

The conditions under which obstruents will be voiced have been examined by Warren (1976), Ohala (19xx), Westbury (1979, 1983), Westbury and Keating (19xx), among others. According to Westbury (19xx, 1), "voicing obtains in speech when the vocal folds are properly adducted and tensed, and a sufficient transglottal airflow is present. The absence of voicing obtains, by contrast, when at least one of these conditions is not met."

In obstruents, the maintenance of transglottal airflow is in particular peril, since the exit of air from the oral chamber is partially or fully blocked. This blockage leads to a rapid buildup of supraglottal air pressure, hence to the cessation of transglottal airflow and of voicing. Voicing is prolonged if the buildup is averted or sufficiently delayed. A number of factors determine whether this will happen:

Pharyngeal Expansion. Voicing is favored if the pharynx is expanded during the course of an obstruent. This is because such expansion permits more air to pass through the glottis, so that the time during which there is sufficient pressure drop across the glottis is extended. Expansion of the pharynx can take place by appropriate movements of the tongue root, the larynx, and the pharyngeal walls (Westbury xxx).

Subglottal Pressure. Where subglottal pressure is lower, the pressure drop across the glottis is reduced, and devoicing will be favored. Typically, subglottal pressure responds to utterance position, being fairly constant utterance-medially but lower at utterance beginnings and especially endings. This gives rise to a tendency for languages to employ only voiceless obstruents in utterance-final (and to a lesser extent) utterance-initial position (Westbury and Keating 1986).

Vocal Fold Adjustments. Abduction of the vocal folds will in general lead more rapidly to a cessation of voicing. This is due in part to the lesser propensity of the vocal folds to vibrate when abducted, and in part obstruents) to the fact that abducted vocal folds will permit a faster buildup of air pressure in the oral cavity and thus block voicing sooner. It is probably for this reason that aspirated stops are typically voiceless; voiced aspirates require particular additional mechanisms (Rothenberg 1968); (Dixit 19xx UCLAWPP) to preserve voicing. Halle and Stevens (1971), based on a computational model of the vocal folds, argue that a stiffening of the vocal cords will likewise discourage voicing. [xxx read]

Place of Articulation. Places of articulation nearer the front of the mouth provide larger surfaces of soft tissue in the vocal tract walls, the yielding of which permits more air to be accommodated supralaryngeally before voicing would be suppressed. [xxx refs.]

Velum-Related Factors. There are two factors in voicing control that involve the velum and thus will play a crucial role in the discussion here.

(a) **Nasal Leak**. At the highest range of possible velum heights, the velar port is fully closed, and any linguistic sound resulting will be fully non-nasal. When the velum is sufficiently lowered, the velar port is sufficiently open so that any linguistic sound produced will be fully nasal. In addition, there are intermediate velum positions in which air "leaks" through the velar port, but there is no significant acoustic coupling between the nasal and oral cavities. A sound made with "nasal leak" will sound oral, [2] and presumably should be classified phonologically as oral. Rothenberg (1968), and, tentatively, Kent and Moll (1969) xxx have claimed that nasal leak is a mechanism used by some speakers in maintaining voicing in obstruents. Ohala (1983xxx) suggests that nasal leak may be the link whereby certain voiced stops have historically evolved into prenasalized stops or nasal + stop sequences, in which the nasality has become acoustically patent. The interaction of nasal leak with nasal coarticulation is discussed further below.

(b) **Velum Raising**. Bell-Berti (1975) and Bell-Berti and Hirose (1975) have observed an additional factor that can influence the voicing of a consonant. To understand this, one must consider an important aspect of velar anatomy, described as follows by Bell-Berti (19xx, video; italics ours): "There is a well-established relationship between the size of the open velar port and the position of the velum. In addition, though, to varying with port area, velar position also varies when the port is completely closed. These adjustments result from the anatomical relationship between the velum and the levator palatini muscle. Since the muscle's superior attachment lies well above the level at which port closure is complete, increasing contraction of this muscle continues to raise the velum even after closure has occurred." Our inspection of various cinefluorographic films kept in the UCLA Phonetics Laboratory confirms Bell-Berti's observations, at least insofar as such inspection can determine the point of velar closure (Bjørk 1961).

The movements that Bell-Berti describes are in principle capable of changing the volume of the oral cavity, increasing it as the velum rises and decreasing it as the velum falls. Since changes in oral cavity size influence voicing, this mechanism is thus a second potential link (after nasal leak) between voicing and velum movement.

A factor that increases the likelihood of velum raising influencing voicing is that obstruents typically have the highest velum positions of all segments, usually higher than oral sonorants (Bell-Berti 19xx). The reason for this pattern is not known, but the pattern is apparently robust.

The experimental data on whether raising of the closed velum is actually used by speakers to maintain obstruent voicing is contradictory. Studies in which voicing in obstruents was apparently facilitated by velum raising include Perkell (1969; discussed in Bell-Berti 19xx), Bell-Berti (19xx; xx), Bell-Berti et al. (1979) and Hiroto, Hirano and Umeno (1963). However, equal or higher velum positions for voiceless obstruents have been observed by Westbury (1979, 1983) and by xxx. Our interest here, however, concerns not whether velum raising is always used as a mechanism of voicing control (it probably is not), but rather the distinct issue of whether, given velum raising, voicing will be facilitated. In the context to be considered below, velum raising may be taken as given, as it is coarticulatory in origin.

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[2] We find that we can produce a "syllabic b" ([b̩::::::]) which sounds reasonably non-nasal and can last as long as the air supply holds out. Since there is nowhere else for this much air to go, it seems clear that nasal leak must be responsible for the maintainance of voicing.

3. Velum Raising, Voicing, and Nasality

Turning to obstruents in the environment of nasal consonants, we can now attempt to predict what mutual influences might occur on the basis of the mechanisms just outlined. Bell-Berti (19xx), xxx, and other studies of velar motion have shown that there are substantial coarticulatory effects at the phonetic transition between an oral and a nasal segment. In particular: (a) the portion of the nasal which is adjacent to an oral segment will be articulated with higher-than-usual velum position; and (b) that portion of the oral segment which is adjacent to the nasal will be articulated with lower-than-usual velum position.

Under these conditions, we expect that nasals would tend to induce voicing on a neighboring obstruent. In particular, if the coarticulatory lowering of velum position during (all or part of) the obstruent is sufficient to achieve "nasal leak" (in the sense described above), then voicing for the obstruent will be facilitated.

This mechanism has been discussed by Ohala and Ohala (1991), in an account of the formation of phonetic prenasalized stops following nasalized vowels in Hindi and French. The Ohalas observe that this is only possible in voiced stops, and attribute the difference to nasal leak: "voiceless stops have less tolerance for [nasal] leakage because any nasal sound—voiced or voiceless—would undercut either their stop or their voiceless character" (p. xxx).

We asserted above that while postnasal voicing is abundantly attested, cases of (specifically) prenasal voicing apparently do not occur. This asymmetry is difficult to explain solely on the basis of velar coarticulation and nasal leak, which should in principle work in either direction. Our suggestion is that the asymmetry arises from the additional factor of (expansion/contraction) of the supralaryngeal cavity, caused by the (rise/fall) of a closed velum, discussed above. We will consider both postnasal and prenasal obstruents.

(a) **Nasal + Obstruent**. We assume that during the nasal, the velum will typically be rising, proceeding from the low position characteristic of nasals to the fully raised position that is characteristic of obstruents (Bell-Berti 1993). We assume that the obstruent begins at a point that may be perceptually defined, namely, where the velum has risen high enough to decouple the oral and nasal chambers acoustically. In our studies (described below), this point corresponds (in the case of nasal-stop sequences) to a fairly salient acoustic boundary, the loss of virtually all energy above about 500 hz. During the course of the obstruent, the rise of the velum would normally yield three significant phases, as follows:

(3) Post-Nasal Obstruents

i. Initially, the velum is only just high enough to decouple the oral and nasal chambers. Since this level is short of full velic closure, nasal leak will be present, and voicing is facilitated.

ii. The velum is high enough to cut off nasal leak. However, it continues to rise toward the high position characteristic of obstruents, so the volume of the oral cavity is expanded, and voicing is facilitated.

iii. The velum is in a fully raised position. If the stop articulation continues beyond this point, any voicing must be preserved by other mechanisms noted above in section xxx.

The upshot is that two mechanisms, namely nasal leak and velum raising, facilitate voicing in this context.

(b) **Obstruent + Nasal**. Here, the velum will fall, from the high position characteristic of an obstruent to the low nasal position. The three phases are as follows.

(4) Pre-Nasal Obstruents

i. The velum is high, and has not yet begun its descent. There will be no nasal leak to encourage voicing.

ii. The velum is high enough to block any passage of air through the nasal port. Moreover, it is descending, compressing the supralaryngeal cavity. The latter factor impedes voicing.

iii. The velum has passed the point at which nasal leak becomes possible. At this point, the factors are reversed: nasal leak should encourage voicing.

The situation here is thus more complex, with a voicing-inhibiting factor shortly followed by a voicing-enhancing factor.

What differentiates the two cases ((3) and (4)) is that in nasal + obstruent clusters, rarifaction from coarticulatory velum raising facilitates voicing; whereas in obstruent + nasal clusters, compression from coarticulatory velum lowering facilitates devoicing. However, the two cases are not mirror images: in both, nasal leak facilitates voicing. Qualitatively, then, we can see the basis of a possible explanation of postnasal voicing typology: in the postnasal environment, two factors work together to encourage voicing; in the prenasal environment, the two factors are mutually opposed; and in fully oral environment no particular factor is present to favor voicing. The mechanisms discussed here thus could in principle lead to a preference for voicing in just the postnasal position, which matches our cross-linguistic findings.

4. Modeling the Factors

The above qualitative scenario can tested by examining the behavior of an quantitative aerodynamic vocal tract model, to which suitable articulatory movement functions have been supplied. In this section, we discuss the results of such modeling.

The model we have employed is a version of the circuit-analog vocal tract model devised by Rothenberg (1968) and developed in software implementations by Müller and Brown (1980), Westbury (1983), Keating (1983, 1984), and Westbury and Keating (1986); the Westbury/Keating implementation is employed here. The model inputs the factors that determine pressures and flows through the vocal tract, and computes the time course of subglottal pressure, transglottal flow, oral pressure, and oral flow. Keating (1984) serves as a manual for the version of the program that we used; and we followed many of the default parameter values (taken from earlier literature) that it provides.

We have modeled three phonetic sequences, employing the bilabial place of articulation:

(5) a. nasal + stop: /VmPV/
b. stop + nasal: /VPmV/
c. intervocalic stop: /VPV/

In the schemata given above, /V/ stands for an indeterminate vowel. /P/ represents a bilabial stop that emerges with varying degrees of closure voicing and voice onset time, depending on the settings input to the model. Comparison of /VmPV/ with /VPV/ tests the difference between a preceding nasal vs. a preceding oral sonorant. Comparison of /VmPV/ with /VPmV/ tests the effect of ordering the nasal before or after the consonant.

4.1 Inputs

The inputs to the model were determined as follows.

Segment Durations: Stops were assumed to last for 100 ms, nasals 75 ms. The first vowel in the /VPV/ configuration was given a duration of 100 ms., long enough to stabilize its aerodynamic behavior from the initial conditions.

Subglottal Factors: We assumed that the relevant sequences were utterance-medial. Under this assumption, expiratory force could be assumed to be roughly constant over time (Westbury and Keating 1986). The default values of the program for factors governing expiratory force were adopted.

Vocal Tract Walls and Volume: Values for these factors for bilabials and for other places of articulation modeled below were taken from Keating (1984, 24-5), adopting the "default case—walls like tense cheeks" option.

Glottal Opening: We examined three possibilities: (a) An invariant average glottal opening of .022 cm; this closely adducted setting tends to favor voicing. (b) A glottal-opening contour with spreading from a .022 cm baseline to a maximum of .044 cm. The shape of this contour and its timing relative to the stop were closely similar to the pattern shown in Table BIIA(11-14) of Müller and Brown (1980). (c) A more vigorous glottal opening to .088 cm, with the same contour shape and timing as the previous case. Note that all three degrees examined fall short of glottal openings typically observed in aspirated stops, which would be in the range of .180 cm (Keating 1984, 25).

[xxx These should perhaps be given as areas: .044, .088, .176, .360 cm2)
Oral Closure: Constriction sizes for labial, alveolar, and velar closures were taken from Keating (1984, 24-25). We assumed temporal transitions for oral closure taken from Müller and Brown (1980, Fig. B1).

Nasal Leak: A critical value in modeling nasal-stop interactions is the degree of nasal flow that occurs at the stop-nasal or nasal-stop transition. Because of the "nasal leak" phenomenon reported above, this is not zero: a stop can have a certain amount of nasal flow and still sound oral. Here some varying observations on this point from the literature:

(a) According to Warren (1975), "excepting in extremely rare instances, when the [velar] opening is less than .05 cm^2 ... any nasal emission present is inaudible."

(b) Moll and Daniloff (1971) publish data from a token of English /mt/ (in "warm tanks") in which the midsaggital [xxx ask how to use this word] velar port opening appears to be about 1.4 mm at the acoustic boundary between /m/ and /t/. In light of the data in Bjørk (1961, 41) relating midsaggital opening to cross-sectional area, this would correspond to a velar port cross-section of about .08 cm^2.

(c) In studies of cleft-palate speakers, Isshiki et al. (1968) and Warren (1967), have found that the maximum that the velar port can be open while retaining naturally oral-sounding speech is about .20 cm^2.

[xxx cited in Bell-Berti 1973. Check this out.]

We adopted a value of .10 cm^2 as a default, but also examined the behavior of other values.

We must also model the time course of coarticulatory velar opening. When an obstruent abuts a nasal, this varies a great deal.

(a) In a cinefluorographic study, Bjørk(1961) found that some stops adjacent to nasals had fully closed velar ports for almost [xxx check] their entire duration. Other nasal-adjacent stops, however, never achieved

[xxx see also Dixit and McNeilage (1972), cited in Bell-Berti diss.]

full closure, and still others showed full closure during part of their duration.

(b) In Moll and Daniloff's (1971) cinefluorographic study, "velopharyngeal closure ... was always achieved at least 15 mec. before the articulatory release of a consonant preceded by nasal." Under normal closure durations, such a pattern of nasal coarticulation would leave some stops articulated with the velum slightly open for most of their durations.

(c) Westbury (1979, 1983) notes that he found virtually no nasality during stop closure for his cinefluorographic data. However, in the nasal airflow data presented in Westbury (1979), a token of the phrase "set number eleven" shows some nasal flow (roughly 50 cm^3/sec) [xxx measure this] for the entire closure of the phoneme /b/.

(d) Kent (1983) presents an extreme case: in a token of /tʌntʌntʌn.../ uttered rapidly, the velum position for /t/, measured cinefluorographically, never rose above the lowest position found for /n/ in a slow-speech version of the same utterance. To what extent the /t/'s of the fast speech utterance actually achieved an oral percept is not clear.

In light of this variation, we have assumed as a default case a degree of nasal coarticulation such that the velum is fully closed at a point exactly halfway through the stop (50 msec.), and moves so as to create intermediate degrees of opening up to a .10 cm^2 threshold at the boundary with the preceding or following nasal. We examined other nasality contours as well.

For the case of an intervocalic stop, we assumed that there is no nasal leak at all. This follows the findings of Bjørk (1961), Lubker (1973), Westbury (1979), and [xxx Arizona guys] that long sequences of phonologically oral sounds, with no nasal in the vicinity, typically have closed or virtually closed velar ports.

Compression/Rarefaction by the Closed Velum. Estimates of this effect also vary. We review some data below.

(a) Lubker and Moll (1965) measured oral and nasal flow simultaneously with cinefluorographic film recordings. Repeating an earlier observation they attribute to Young (1953), Lubker and Moll found small expiratory nasal flows "just preceding or coincidental with the initial of phonation ... This burst of nasal air flow occurs when the velopharyngeal distance is zero." Lubker and Moll suggest (p. xxx) that such bursts are due to the pumping action of a closed but rising velum, as described above. They determined the amount of air expelled by this maneuver for one token (characterized by Lubker 1968 as "typical") as 4.2 cm3. Under the assumption that this nasal flow results entirely from velum movement, we would expect that the oral cavity below the velum is expanded by a similar amount. In addition, we assume that the same gesture executed in reverse would similarly compress the oral cavity.

(b) It is possible that the amount of compression/rarifaction from a closed velum could be estimated very roughly from cineradiographic measurements as well. The portion of the velum that can move air volumes during closure is that between the (fixed) rear edge of the hard palate and the pharyngeal wall. In the measurements of Bjørk (1961), the distance between the rear edge of the hard palate and pharyngeal wall averaged 2.5 cm. for a group of 17 men and 14 women. We estimate further that the lateral dimension of the velum is about 4 cm. Finally, in the token measured by Lubker and Moll that showed a velum-propelled burst of 4.2 cm^3, the rise in velum height was approximately 0.7 cm. The rise of the velum cannot be uniform across its surface, however, since the anterior edge, attached to the hard palate, is immobile. We therefore model the space swept through by the velum as a triangular prism, of length 2.5 cm, width 4 cm, and height at rear edge 0.7 cm. The volume of such a prism is 3.5 cm^3, which agrees roughly with Lubker and Moll's estimate. The shortfall might be attributed to a greater rise within the medial surface of the velum than the triangular prism approximation would permit. Such a rise would be expected, since the attachment point of the levator veli palatini, which is the muscle responsible for velum raising, lies forward of the contact between velum and pharyngeal wall.

(c) Westbury (1979) estimates the volume of air deplaced by movement of a closed velum to be considerably lower: 1-2 cm^3. The model he assumes to measure this displacement apparently treats the velum as a piston, rising through the passage that is observed when the velum is in the lowest possible position (cross-sectional area: 2 cm^2). Under this assumption, an increase in velum height of 0.7 cm would yield a displacement of only 1.4 cm^3. This value will be modeled below as well.

It is necessary also to consider possible velar pumping effects for stops that are adjacent to non-nasal as well as nasal sonorants. This is because the velum is typically higher for obstruents than for sonorants. The size of the pumping effect is apparently smaller: the airflow measurements of Westbury (1979, xxx) on fully-oral consonant sequences showed average airflows of approximately 0.5 cm3, far less than the value measured by Lubker and Moll. We model a small effect of this sort for the /VRPV/ sequences, as well as at the release of the stop in /VmPV/ and the closure of the stop in /VPmV/.

We use the contours in Fig. xxx as defaults. They yield a total positive pumping effect of xxx cm^3 in /VmPV/, the same effect of opposite sign in /VPmV/, and a positive pumping effect of xxx cm^3 in /VRPV/. We also consider lesser values below.

Fig. xxx about here.

4.3 Outputs

The model does not actually output voicing durations, but rather the pressure difference across the glottis. Following Westbury and Keating (1986, 149) and references cited there, we assume that the vocal cords may continue vibrating as long as a pressure difference of 2 cm H_2O is maintained across them. Later, we model the lower value of 1 cm H_2O suggested by Lindqvist (1972) and [xxx].

In cases were vocal cord vibration ceases and then starts again, we assume a slight hysteresis effect, such that a pressure difference of 4 cm. H_2O is required to restart phonation. [xxx need reference here] We also consider lower values for this figure.

As rough heuristic, Keating and xxx suggest that an unaspirated stop will sound voiced if the vocal cords vibrate during at least one half of its closure. In the experiment described below (section xx), we judged that fast-speech tokens of English /mp/ produced by our consultants with this much voicing did indeed sound ambiguous between [mp] and [mb], thus supporting Keating's criterion. However, the criterion is clearly only an approximation, and perceptual judgments of voicing are likely to be influenced by other factors as well.

4.4 Results

For the values classified under "default" above, the model outputs the ranges of voicing given under (xx), which should be interpreted as follows.

(a) In many of the /Pm/ cases, the model predicts two separate voiced intervals: one following closure and one before release. This pattern is more or less what we would expect, given the scenario of (xx). Cases of this type from real speech may be seen in the French data of xxx, pp. xxxx. In the table below, the duration of the two voiced intervals is listed separately.

(b) Where a stop is voiced for its entire duration, we list the value 100 msec (the closure duration) in the first column and leave the second column blank.

(c) Voice Onset Time (VOT) is the time from stop release to the onset of voicing, as determined above. The model often predicts a short VOT even for stops that are voiced for most of their closure; this apparently results from the fairly slow stop releases assumed, in which the vocal tract still shows considerable impedance even a few milliseconds after release.

(d) To facilitate overall comparisons, we have listed the “voiceless interval” predicted for each case. This is defined as either the period between post-closure and prerelease voicing (for CN cases), or as the sum of the voiceless portion of closure and VOT.

(6) Maximum glottal opening	Consonant Cluster	Voicing following stop closure	Voicing prior to stop release	Voice onset time	Duration of voiceless interval
22 cm^2	mP	100		0	0
	RP	63	0	17	54
	Pm	32		0	57
44 cm^2	mP	60	0	16	56
	RP	34	0	18	84
	Pm	25	6	0	69
88 cm^2	mP	33	0	17	84
	RP	23	0	18	96
	Pm	19	2	0	79

xxx the above glottal opening figures are cm, not cm2]

It can be seen from (xx) that postnasal position is the most voice-inducing environment. With moderate degrees of vocal fold abduction, the model outputs what clearly would be fully voiced stops. The remaining two positions, following a nonnasal sonorant and preceding a nasal, permit considerably less closure voicing. These results suggest that within the more closed range of glottal settings, the effect of post-nasal position would would be dramatically to increase the likelihood of a stop being perceived as voiced, both relative to post-oral and pre-nasal positions. With increased glottal abduction, the effect disappears, and all three environments converge to a voiceless outcome.

The difference between the three segmental environments is most dramatic with a glottal abduction to .27 cm2 [xxx adjust to the correct units; this is really mm.]. For this degree of glottal opening, a postnasal stop remains voiceless for its entirely duration. The outputs of the model for this degree of glottal abduction are as follows:

(7) Maximum glottal opening	Consonant Cluster	Voicing following stop closure	Voicing prior to stop release	Voice onset time	Duration of voiceless interval
$27\ cm^2$	mP	100		0	0
	RP	44	0	16	72
	Pm	30	9	0	61

As noted above, the modeling just described fixes a number of variables that can have a wide range of values in real situations. To show the effects of these variables, we show the outputs of the model under different assumptions, changing one value at a time. For each chart, we repeat the voiceless interval values obtained under the default simulation.

(a) Point of articulation: with the defaults set in the manner that yielded the outputs of (xx), but with oral volumes and wall compliances set to the values for alveolars and velars from Keating (1984, xx), we obtain:

(8) Alveolars:

Maximum glottal opening	Consonant Cluster	Voicing following stop closure	Voicing prior to stop release	Voice onset time	Duration of voiceless interval	Duration of voiceless interval
$22\ cm^2$	nT	100		0	0	0
	RT	54	0	17	63	54
	Tn	28	11	0	61	57
$44\ cm^2$	nT	53	0	16	63	56
	RT	31	0	18	87	84
	Tn	23	6	0	71	69
$88\ cm^2$	nT	31	0	17	86	84
	RT	21	0	17	96	96
	Tn	17	3	0	80	79

(8)	Maximum glottal opening	Consonant Cluster	Voicing following stop closure	Voicing prior to stop release	Voice onset time	Duration of voice-less interval	Comparison with defaults
	Alveolars	:					
.	22 cm2	nT	100		0	0	0
		RT	54	0	17	63	54
		Tn	28	11	0	61	57
.	44 cm2	nT	53	0	16	63	56

		RT	31	0	18	87	84
		Tn	23	6	0	71	69
.	88 cm2	nT	31	0	17	86	84
		RT	21	0	17	96	96
		Tn	17	3	0	80	79

(9)Velars:

.	22 cm2	ŋK	100		0	0	0
		RK	48	0	18	70	54
		Kŋ	25	8	0	67	57
.	44 cm2	ŋK	45	0	17	72	56
		RK	28	0	18	90	84
		Kŋ	21	5	0	74	69
.	88 cm2	ŋK	27	0	18	91	84
		RK	19	0	18	99	96
		Kŋ	16	2	0	82	79

In these simulations, for the .22 cm2 value of glottal abduction, the postnasal stops remain fully voiced, while the other stops receive less voicing, as would be expected at these places of articulation; thus the postnasal effect is slightly greater. As before, the postnasal effect is gradually cancelled with greater glottal abduction.

(b) Nasal port size at stop-nasal boundary: instead of .10 cm2, we employ .04 cm2, interpolating appropriately scaled values across the duration of the nasal:

(9)	Maximum glottal opening	Consonant Cluster	Voicing following stop closure	Voicing prior to stop release	Voice onset time	Duration of voiceless interval	Comparison with defaults
.	22 cm2	mP	100		0	0	0
		RP	63	0	17	54	54
		Pm	32	0	8	76	57
.	44 cm2	mP	42	0	17	75	56
		RP	34	0	18	84	84
		Pm	25	0	8	83	69
.	88 cm2	mP	25	0	17	92	84
		RP	22	0	18	95	96
		Pm	19	0	9	90	79

For the .22 cm2 abduction value, the prenasal case receives the least voicing, since it has less nasal leak to aid in retention of voicing, but retains the handicap of velar compression. As before, the effects cancel out with increasing glottal abduction.

For the high value of .20 cm2, we obtain:

(10)	Maximum glottal opening	Consonant Cluster	Voicing following stop closure	Voicing prior to stop release	Voice onset time	Duration of voiceless interval	Comparison with defaults
.	22 cm2	mP	100		0	0	0
		RP	63	0	17	54	54
		Pm	32	27	0	41	57
.	44 cm2	mP	74	0	16	42	56
		RP	34	0	18	84	84
		Pm	25	20	0	55	69
.	88 cm2	mP	43	0	17	74	84
		RP	23	0	18	95	96
		Pm	19	12	0	69	79

This alternation usually results in a slight increase in voicing for /mP/ and /Pm/, as one would expect; however, the overall pattern remains the same.

(b) Time course of nasal opening: velar port is open for 25% of the stop, rather than for 50%:

(11)	Maximum glottal opening	Consonant Cluster	Voicing following stop closure	Voicing prior to stop release	Voice onset time	Duration of voiceless interval	Comparison with defaults
.	22 cm2	mP	100		14	14	0
		RP	63	0	17	54	54
		Pm	45	1	0	54	57
.	44 cm2	mP	59	0	18	59	56
		RP	34	0	18	84	84
		Pm	33	1	0	66	69
.	88 cm2	mP	33	0	18	85	84
		RP	23	0	18	95	96
		Pm	23	0	0	77	79

This slightly reduces the postnasal voicing affect, since a voiceless interval is added after the stop closure. (Such an interval arises because during the period after stop release, the lips are still sufficiently adducted to permit a slight increase in supraglottal pressure.)

Velar port is open for 75% of the stop, rather than for 50%:

(12)	Maximum glottal opening	Consonant Cluster	Voicing following stop closure	Voicing prior to stop release	Voice onset time	Duration of voiceless interval	Comparison with defaults
	.22 cm2	mP	100		0	0	0
		RP	63	0	17	54	54
		Pm	33	25	0	42	57
	.44 cm2	mP	82	0	16	34	56
		RP	34	0	18	84	84
		Pm	25	11	0	64	69
	.88 cm2	mP	42	0	17	75	84
		RP	23	0	18	95	96
		Pm	19	4	0	77	79

Velum is closed only just before stop release (NC) or just after stop closure (CN):

(13)	Maximum glottal opening	Consonant Cluster	Voicing following stop closure	Voicing prior to stop release	Voice onset time	Duration of voiceless interval		Comparison with defaults	
	.22 cm2	mP	100		0	0		0	0
		RP	63	0	1	7	5	4	54
		Pm	49	33		0	1	8	57
	.44 cm2	mP	91	0	1	5	2	4	56
		RP	34	0	1	8	8	4	84
		Pm	27	16		0	5	7	69
	.88 cm2	mP	46	0	1	7	7	1	84
		RP	23	0	1	8	9	5	96
		Pm	20	6		0	7	4	79

Both changes slightly diminish the postnasal voicing effect for the .22 cm2 degree of adduction, but slightly increase it for the .44 degree.

(c) Compression/rarefaction effect of velum height shift. If this factor is halved in all contexts where it is present, we obtain:

(14)	Maximum glottal opening	Consonant Cluster	Voicing following stop closure	Voicing prior to stop release	Voice onset time	Duration of voiceless interval	Comparison with defaults
	.22 cm2	mP	100		0	0	0
		RP	59	0	17	58	54
		Pm	39	13	0	48	57
	.44 cm2	mP	50	0	17	67	56
		RP	32	0	17	85	84
		Pm	27	6	0	67	69
	.88 cm2	mP	32	0	17	85	84
		RP	21	0	18	96	96
		Pm	20	2	0	78	79

Halving it again from the above values, we obtain:

(15)	Maximum glottal opening	Consonant Cluster	Voicing following stop closure	Voicing prior to stop release	Voice onset time	Duration of voiceless interval	Comparison with defaults
	.22 cm2	mP	96		1	18	0
		RP	57	0	16	59	54
		Pm	45	15	0	40	57

.44 cm2	mP	48	0	17	69	56
	RP	32	0	17	85	84
	Pm	29	6	0	65	69
.88 cm2	mP	32	0	17	85	84
	RP	21	0	17	96	96
	Pm	20	2	0	78	79

If we eliminate the effect of velum pumping entirely, we obtain:

(16)

Maximum glottal opening	Consonant Cluster	Voicing following stop closure	Voicing prior to stop release	Voice onset time	Duration of voiceless interval	Comparison with defaults
.22 cm2	mP	84		1	30	0
	RP	55	0	16	61	54
	Pm	55	17	0	28	57
.44 cm2	mP	46	0	17	71	56
	RP	31	0	17	86	84
	Pm	31	7	0	62	69
.88 cm2	mP	32	0	17	85	84
	RP	20	0	17	97	96
	Pm	20	2	0	78	79

It can be seen that for all three alternatives, the stops that are adjacent to nasal retain a voicing advantage, because of nasal leak. However, with lessened velar pumping, the difference between prenasal and postnasal position gradually disappears.

(d): No hysteresis effect for voicing; assume that voicing can begin with 2 cm H20 transglottal pressure drop:

(17)

Maximum glottal opening	Consonant Cluster	Voicing following stop closure	Voicing prior to stop release	Voice onset time	Duration of voiceless interval	Comparison with defaults
.22 cm2	mP	100		0	0	0
	RP	63	0	11	48	54
	Pm	32	20	0	48	57
.44 cm2	mP	60	0	10	50	56
	RP	34	0	12	78	84
	Pm	25	15	0	60	69
.88 cm2	mP	33	0	11	78	84
	RP	23	0	12	89	96
	Pm	19	9	0	72	79

Under this hypothesis, the effects of postnasal position is slightly reduced.

(e) Low pressure drop (1 cm H2O) needed to sustain voicing; 2 cm H2O to start it.

(18)	Maximum glottal opening	Consonant Cluster	Voicing following stop closure	Voicing prior to stop release	Voice onset time	Duration of voiceless interval	Comparison with defaults
.	22 cm2	mP	100		0	0	0
		RP	83	0	11	28	54
		Pm	39	20	0	41	57
.	44 cm2	mP	91	0	10	19	56
		RP	44	0	12	68	84
		Pm	30	15	0	55	69
.	88 cm2	mP	41	0	11	70	84
		RP	29	0	12	83	96
		Pm	23	9	0	68	79

Here, the difference between postnasal and post-oral position is small for the .22 cm2 glottal abduction. Oddly, in this condition, it is the .44 cm2 condition in which the postnasal voicing effect is the greatest.

To summarize: there appears to be a range of conditions, falling well short of universal coverage, but nevertheless fairly broad, under which a stop will emerge with consderably greater closure voicing in postnasal position than in postoral or prenasal position.

4.5 Interpretation

Since the original goal of our model is to explain why postnasal (but not prenasal, or postliquid) voicing is phonologically so common, it is worth comparing our results with other cases of phonetic explanation.

First, the effect of postnasal position, in most of our simulations, is larger than the effect of having a relatively fronter place of articulation. Consider the values output by the model for the default inputs and .22 cm2 glottal opening at bilabial, alveolar, and velar places of articulation. We list below only the “duration of voiceless interval” statistic.

(19)	Bilabial	Alveolar	Velar
mP,nT,ŋK	0	0	0
RP,RT,RK	54	63	70
Pm,Tn,Kŋ	57	61	67

[compare postnasal k, postliquid k, and postliquid p]. [xxx these are similar to the differences found with the same model by Keating 1983 WP] The effect of consonant place on voicing has long been adduced as a case of phonetic effects in phonology: a fair number of languages lack /p/ or lack /g/ (Sherman 1975, Ohala 1983, Maddieson 1984). The consensus view on this difference is that it is due to to the relative difficulty of preserving voicelessness in the presence of a large surface of yielding vocal tract walls, or analogously of preserving voicing with a small such surface. Given that the place of articulation effect has phonological consequences in a number of languages, we would plausibly expect that the larger post-nasal voicing effect would also have phonological consequences, perhaps even more dramatic. Our preliminary impression is that postnasal voicing may indeed be more widespread phonological phenomenon than voicing asymmetries in stop inventories.

We can also compare the effects of oral cavity expansion from velum raising (4.2 cc's, in Lubker and Moll's measurement) with other ways in which the oral cavity can be expanded. Westbury's (1979, 1983) study indicated that advancement of the tongue root can expand the oral cavity by about

[xxx you need to read the rest of Westbury]

10xxx, a comparable value. This connection is phonologically evident in Madurese, where there are tight connections between obstruent voicing and the advanced/retracted tongue root opposition of the vowel harmony system (xxx).

[xxx Larynx height? work of Poser?]

Our conclusion is that if our estimates of the magnitude of the mechanisms we have examined are correct, there is good reason to think that they could easily be relevant to phonological patterning.

Finally, we wish

[xx need discussion of variation, and what the model can be expected to predict]

5. Post-Nasal Voicing As A Phonetic Rule

An implication of a phonetic account of postnasal voicing is that NC̥ sequences should demand special treatment in any language in which they occur. Under a phonetic account, there are two principal things that a language can do with NC̥ sequences. First, it could simply abandon the attempt to produce them; this is what happens in the languages noted in (xx), which are described as having a phonological rule of postnasal voicing. (The same thing would be found in languages where postnasal voicing embodies an entirely static phonotactic pattern.) Second, a language could make special phonetic accommodations in order to maintain voicelessness—at least to some degree—in postnasal obstruents.

In this respect, a phonetic account of postnasal voicing differs from traditional phonological analyses (e.g., that of Ito et al. (1995), in which the presence of postnasal voicing reflects some particular rule or constraint of a language's phonological system. In the view advanced here, the postnasal voicing "problem" is one faced by every language with NC̥ sequences, and the option of eliminating the voicing distinction in postnasal obstruents is only one of the many ways of dealing with the problem.

This point is made from a phonological point of view by Pater (in press), who argues that what most generally characterizes the phonological typology is not post-nasal voicing per se, but rather the avoidance of voiceless obstruents in post-nasal position. Pater shows that this disfavored configuration is eliminated phonologically in a variety of ways: deleting the voiceless obstruent; deleting the nasal or assimilating it to the voiceless obstruent; xxx etc.

What remains to support this universalist view is to consider languages in which essentially no overt "phonology" at all (of the kind traditionally conducted with ear, pencil, and paper) centers around NC̥ clusters. Such languages also face the articulatory problem of NC̥, and if our view is correct, they should take steps to accomodate it. Such steps would be phonetic, not phonological, since the basic contrast of voiced vs. voiceless consonants after nasals in these languages is preserved.

To this end, we have examined data from one such language, American English, to test what, if any, is the English "response" to the NC̥ problem.

6. NC̥ Clusters in English

The majority of English dialects have no phonological patterning driven by the NC̥ syndrome,[3] and the five consultants whose speech is described below maintain a clearly audible contrast of voiced and voiceless stops in the / N ___ V environment. Our experiment focused on the phonetic treatment of such clusters in their speech.

[3] Bailey (19xx) notes that certain [xxx which] dialects have undergone a sound change voicing stops after nasals when both surrounding vowels are atonic [xxx check]. Postnasal devoicing also appears to occur in the speech of some individuals from the New York City area, as noted by Malécot (1960). Three of our speakers (CF, RW, and TS xxx check others) show a minor phonological alternation in the numeral suffix -ty: sixty [ˈsɪks+ti] vs. seventy [ˈsɛvən+di] and ninety [ˈnaɪn+di] (but, oddly, twenty [ˈtwɛnti, ˈtwɛ̃ɾi]). We are unaware of any other postnasal voicing alternations in our consultants' speech.

6.1 Design

Our experiment was an acoustic study of the pronunciation by five native speakers of three pseudo-words, one including a NC̥ sequence; the others acting as controls. The following are the independent variables in the experiment.

(a) **Consonant Clusters**. The pseudo-words of English that were used were /ˈtɑmpə/, /ˈtɑɹpə/, and /ˈtɑmbə/. They were presented to our speakers in orthographic form, as *tompa*, *tarpa*, and *tomba*, and will be referred to as such here. Some subjects initially pronounced *tompa* and *tomba* as [ˈtompə] and [ˈtombə]; these subjects were corrected by asking them to interpret the words as ordinary English rather than as foreignisms.

The distinction between *tompa* and *tarpa* enables us to assess the effects of a preceding nasal on the obstruent /p/. The distinction between *tompa* and *tomba* enables us to assess the difference between voiceless /p/ and voiced /b/ in the same environment. We chose pseudo-words with a stressed-stressless syllable pattern to avoid the strong aspiration that accompanies voiceless stops in English in pretonic contexts.

Ideally, a sequence such as /ˈtɑpmə/ should have been examined as well. However, since syllable-final voiceless stops in English are very often glottalized (even when no nasal follows), it was felt that such a sequence would not usefully illuminate the supraglottal mechanisms of voicing control.[4]

(b) **Speakers**. Five native speakers of English, all young adults, read a script containing multiple repetitions of each word. Of the speakers, three were female (TS, CF, CS) and two male (RW, HC). All were graduate or undergraduate students in linguistics at UCLA, and volunteered to participate. We selected linguistics students in hopes that they would feel more comfortable speaking in a recording booth and would provide more natural speech. None of the speakers, however, was aware of the purpose of the experiment.

(c) **Prosodic Context**. To obtain what we hoped would be a collection of tokens diverse in speaking rate and stress level, we trained the speakers (using other example words) to recite the sample words in a rhythmic frame, which was depicted orthographically as *tarpa* ... *tarpa* ... *tarpa*, *tarpa*, *tarpa*. Generally, of the five repetitions (referred to in order with the letters A-E), A, B and E tended to be pronounced with greater stress and duration; whereas C and especially D tended to be given more rapid, less distinct pronunciations. These were only tendencies, however. Statistical analysis of the effect of prosodic context is given below.

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[4] Westbury's (1979, 1983) cinefluorographic study showed a token of /pm/ in which the velum was fully lowered during the /p/;. Westbury suggests here that voicelessness in /p/ was due entirely to the glottal adduction gesture; the fully open velum made no difference to its acoustic realization. Such tokens might be rendered as [ˀmm] in a narrow transcription.

The script which we asked our consultants to read consisted of thirty sequences of five repetitions like the one just noted, arranged in pseudo-random order. In the analysis, we excluded the first and last rhythmic sequence for each of the three pseudo-words. Thus each consultant produced eight rhythmic sequences for each pseudo-word. In summary, for every combination in (xx), our data include eight repetitions.

(20) **Word** (*tarpa, tompa, tomba*)
Speaker (TS, CF, CS, RW, HC)
Prosodic Position (A ... B ... C D E)

The recording was made in a soundproof booth in the UCLA Phonetics Laboaratory. For all subjects except TS, we used a xxx microphone to control the distance from the speaker's mouth to the microphone. TS was recorded with a table microphone.

6.2 Measurements

Using the Kay Elemetrics CSL speech analysis system, we measured the following intervals of time (where applicable) for each token.

(a) **Nasal Murmur Duration** (*tomba*, *tomba*). The transition between vowel and nasal consonant was generally easily visible on the wide-band spectrogram display. For several speakers, this transition was also visible as a sharp dip in the amplitude of the speech waveform.

The transition point between the nasal and the following stop was considered to occur at the point where no further energy was visible above 500 hz. Repeated checking of this criterion by listening to brief portions of the signal suggested that it is fairly reliable, though not perfectly so. In cases of doubt, we retained this criterion, in the interest of excluding subjective judgments from the measurements.

(b) **Duration of Stop Voicing**. By this is meant the voicing that occurred at the beginning of virtually all the stop tokens, and for most, ceased at some point during the stop. The endpoint of this interval was taken to be the division between a weak periodic signal and complete silence on the waveform. The starting point was the end of nasality for the *tompa* and *tomba* tokens. For the *tarpa* tokens, the onset of stop closure was plainly visible on the broadband spectrogram.

(c) **Duration of Voiceless Closure**. This was considered to last from the end of the voiced portion of the stop to the moment of stop release, which was consistently detectible as a burst spike on the waveform.

(d) **Voice Onset Time**. This was xxx

We also measured two amplitudes (xxx learn how to say this)

(e) **Peak Amplitude of Nasal Murmur**. This was measured off the amplitude display provided in the CSL system.

(f) **Peak Amplitude of Stressed Vowel**; that is, the stressed vowel which immediately preceded the relevant stop or cluster. This was done as a means of controlling for token-to-token variation in loudness. In the analysis, this value was subtracted from the value found for the nasal.

6.3 Statistical Analysis

We carried out analyses of variance for all measured variables, using as independent variables Speaker, Word, and Prosodic Position. In addition, we also analysed the following computed variables:

(a) **Fraction of Voiced Closure**. This represents

$$\frac{\text{(duration of voiced stop closure)}}{\text{(duration of voiced stop closure + duration of voiceless stop closure)}}$$

(b) **Total Stop Closure**, the sum of voiced and voiceless closure.

(c) **Total Closure**, the sum of nasal closure plus voiced and voiceless stopclosure. This is different from Total Stop Closure only in the case of *tompa* and *tomba*.

(d) **Nasal Fraction of Total Closure**; that is, the duration of the nasal (where applicable) divided by total closure duration.

Statistical analysis was carried out both for the data as a whole and for each speaker separately.

6.4 Results

6.4.1 Controls

We begin with some observations about the general patterns seen in our data.

In general, speakers TS and CF spoke more slowly than the other speakers. Their average durations (all tokens) for total bilabial closure (/mp/, /mb/, /p/) were 100 and 97 msec., versus 84, 86, and 83 msec. for MD, HC, and RW, respectively. This may be related to the way in which we collected our data: seeking a variety of speaking rates, we encouraged CF, HC, and RW (but not TS and CF) to speak rapidly and casually.

The speakers did not greatly speed up or slow down during their recitations, which lasted about three minutes. This was shown by the shallow slopes of regression lines plotting Total Closure against the order of the read script.

The prosodic frame in which the tokens were uttered ("A ... B ... C D E") had the effects on the measured durations that might be expected: the C and D tokens, which were non-final in their group, usually had the shortest durations. The average durations of bilabial closure for all consultants for prosodic positions A-E were as shown below:

(9) Speaker	A	B	C	D	E	Pairs distinct at .01 significance level (Fisher's PLSD)
TS	107	106	91	93	105	C vs. {ABE}; D vs. {ABE}
CF	97	102	88	95	105	C vs. {BE}; D vs. E
HC	86	92	89	77	88	D vs. {BC}
MD	84	85	80	84	89	none
RW	87	88	71	68	100	C vs. {ABE}; D vs. {ABE}
Ave.	92	95	84	83	97	

6.4.2 Amount of Closure Voicing

The crucial comparison here is *tarpa* vs. *tompa*. Both have phonemic /p/, but in *tompa* the /p/ follows a nasal, whereas in *tarpa* it follows a non-nasal sonorant consonant.

The data are given in scattergrams below. These show the duration of voiced closure (on the vertical axis: "BDur") vs. the duration of voiceless closure (on the horizontal axis: "PDur"). Small squares indicate tokens of *tarpa*, while small circles indicate tokens of *tompa*.

Fig. xxx about here

It can be seen that the clouds of symbols are mostly distinct, with substantially larger durations for voiced closure in the *tompa* tokens, and substantially larger durations for voiceless closure in the *tarpa* tokens. In general, in the postnasal environment of *tompa*, our speakers produced more voicing during /p/.

The analyses of variance supported this contention. We give these below for each speaker separately, testing for the following dependent variables: duration of voiced closure (during the stop only), duration of voiceless closure, and the percentage of closure duration that was voiced. The speakers are listed in order of their average speaking rate, as determined above.

[xxx maybe redo this with less round-off?]

Table 1: ANOVA; Degree of Voicing During /p/

	Voiced Closure:				Voiceleless Closure:				% Voiced:			
	Mean	σ	F-value	P-value	Mean	σ	F	P	Mean	σ	F	P
TS:												
tompa	17	5	82.5	<.0001	64	13	139.7	<.0001	21.5	7.2	112.0	<.0001
tarpa	8	5			86	9			8.6	4.7		
CF:												

tompa	18	4	51.5	<.0001	59	11	186.3	<.0001	23.2	5.3	126.5	<.0001
tarpa	10	6			94	14			9.8	5.9		
HC:												
tompa	30	11	105.6	<.0001	41	13	89.4	<.0001	42.91	3.3	136.1	<.0001
tarpa	10	6			62	10			13.8	9.1		
MD:												
tompa	21	7	5.6	.0201	34	12	216.9	<.0001	38.81	3.2	80.3	<.0001
tarpa	17	6			66	12			21.1	7.2		
RW:												
tompa	24	12	15.4	.0002	33	16	37.0	<.0001	42.51	8.4	25.8	<.0001
tarpa	15	8			56	19			23.31	4.7		

Our results are in rough agreement with those of Kent and Moll (1969), who measured the "voice breaks" of intervocalic, pre-nasal, and postnasal voiceless stops. For all speakers and places of articulation, these averaged 168 msec for intervocalic stops, 156 for prenasal stops, and 134 for postnasal stops, thus showing a strong effect of postnasal position and only a weak one (which was not consistent across place of articulation) for prenasal position.

The ANOVA found effects of prosodic context only in some of the speakers. Significant differences in percentage of voiced closure between prosodic contexts (by Fisher's PLSD test) were found for the following speakers and contexts:

(10)	A	B	C	D	E	
TS:	25.1	22.5	25.5	19.8	14.8	A vs. E; p = .0024 B vs. E; p = .0197 C vs. E; p = .0018
CF:	22.7	19.3	28.2	23.9	21.8	C vs. A; p = .0254 C vs. B; p = .0005 C vs. E; p = .0097
HC:	45.6	43.1	38.0	51.9	36.0	D vs. C; p = .0348 D vs. E; p = .0168
MD:	29.4	31.1	45.7	52.7	35.3	C vs. A; p = .0026 D vs. A; p < .0001 C vs. B; p = .0062 D vs. B; p = .0001 C vs. E; p = .0452 D vs. E; p = .0014

[xxx by the Westbury/Keating criterion, many of Harold and Minna's D tokens should actually sound voiced. Listen to these.]

RW: 38.4 42.0 45.6 48.7 38.6 (no significant differences)

There are two patterns seen here. TS voiced less in the final token of the string; and CF, HC, and MD voiced more in one or both of the more rapidly uttered medial positions.

This variation by prosodic context is largely specific to the post-nasal environment. For *tarpa*, there was only one data set that showed any significant pairwise differences, namely the E tokens for speaker TS (E vs. A: p = .0256; E vs. C: p = .0167). The pairwise differences that involved greater voicing in the prosodically weaker positions (C and D) for speakers CF, HC, and MD did not reach statistical significance in the *tarpa* tokens.

Summing up, our data show a substantial effect of postnasal voicing, which for some speakers becomes greater in weaker prosodic contexts.

6.4.3 Duration of Nasality and Stop Closure

Earlier research (e.g. Malécot 1960, xxx) has consistently found that in English nasal + voiced stop clusters, the nasal tends to be long and the stop short; whereas in nasal + voiceless stop clusters, the nasal tends to be short and stop long. Maddieson and Ladefoged (1991) have also demonstrated this pattern for analogous sequences in Sukuma.

The pattern also shows up clearly in our data. Below we give a scattergram plotting the durations of the nasal (“MDur”) against the duration of the stop closure for speaker MD.

Fig. xxx about here

It can be seen that the data for *tompa* (triangles) and *tomba* (circles) largely divide into two distinct areas. MD, who spoke fairly rapidly in the recording; had a relatively poor separation of the two sets; for TS and CF, who spoke more slowly, the separation of the two areas is complete.

The ANOVA testing shows the same point; our findings are summarized in Table 2.

Table 2: ANOVA; Nasal and Stop Durations

	Duration of Nasal:				**Duration of Stop:**			
	Mean	σ	F	P	Mean	σ	F	P
TS: *tomba*	74	9	730.6	<.0001	23	11	989.7	<.0001
tompa	28	9			81	11		
CF: *tomba*	58	6	355.9	<.0001	26	9	615.2	<.0001
tompa	26	9			77	12		
HC: *tomba*	50	14	69.7	<.0001	23	11	989.7	<.0001
tompa	27	13			81	11		

MD: *tomba*	66	13	110.9	<.0001	13	8	450.4	<.0001
tompa	36	15			55	13		
RW: *tomba*	62	17	57.0	<.0001	22	16	135.6	<.0001
tompa	37	15			57	18		

Nasal Duration/Total Duration x 100

	Mean	σ	F	P
TS:				
tomba	76.8	10.3	1000.0	<.0001
tompa	25.8	8.0		
CF:				
tomba	69.4	8.4	702.1	<.0001
tompa	25.5	7.4		
HC:				
tomba	56.5	13.2	130.2	<.0001
tompa	26.9	11.0		
MD:				
tomba	83.9	10.0	350.7	<.0001
tompa	38.8	14.9		
RW:				
tomba	74.4	19.5	94.9	<.0001
tompa	39.3	15.2		

There were isolated effects of prosodic position; but none of these were in any way consistent across subjects.

6.4.4 VOT

The voice onset times were all fairly low, since the post-tonic location in which our consonant clusters occurred is not a position in which English voiceless stops are strongly aspirated. For all speakers, voice onset time was greater in *tompa* than in *tarpa*. For the two male speakers RW and HC, this effect did not reach statistical significance, whereas for the three female speakers it was strongly significant.

Table 3: ANOVA; Voice Onset Time

	Mean	σ	F	P		Mean	σ	F	P
TS:					MD:				
tompa	14	3	19.6	<.0001	*tompa*	15	8	35.9	<.0001
tarpa	11	4			*tarpa*	24	7		
CF:					RW:				
tompa	27	11	16.0	.0002	*tompa*	26	11	1.0	(.3247)
tarpa	20	5			*tarpa*	24	12		
HC:									

tompa	19	10	1.2	(.2781)
tarpa	17	7		

6.4.5 Summary of Timing Data

The measurements of timing are summarized in Fig. xx, which gives for each speaker and word type the division of the total intervocalic interval into nasal closure (where applicable), voiced stop closure, voiceless stop closure, and VOT. Fig. xx gives the breakdown of these averages by prosodic context.

Fig. xxx about here

Fig. xxx about here

6.4.6 Nasal Amplitude

We assessed nasal amplitudes in two ways: as raw values, and with the maximum amplitude of the preceding vowel subtracted out, as a control for the overall degree of speaking effort for a given token. For the three female speakers, *tompa* had significantly lower nasal amplitude than *tomba*, by both measures. Of the two male speakers, HC showed no significant difference, and RW showed a difference in the opposite direction that fell short of significance. The data are given in Table 4 below.

Table 4: ANOVA; Nasal Amplitude

	Raw Nasal Amplitude				Nasal Amplitude - Vowel Amplitude			
	Mean	σ	F	P	Mean	σ	F	P
TS:								
tomba	74.5	2.2	21.3	<.0001	-2.0	1.4	8.931	.0039
tompa	73.2	2.5			-2.9	1.5		
CF:								
tomba	63.7	2.2	81.9	<.0001	-10.9	1.3	52.5	<.0001
tompa	61.9	2.2			-12.9	1.4		
HC:								
tomba	63.1	1.4	.01	(.9104)	-3.4	2.1	.430 (	.5140)
tompa	63.1	1.7			-3.0	2.7		
MD:								
tomba	63.2	1.2	49.8	<.0001	-2.7	1.2 3	9.7 <	.0001
tompa	61.2	1.5			-4.4	1.7		
RW:								
tomba	66.8	2.8	.0004	(.9479)	-3.5	2.4	2.423 (	.1241)

tompa	66.9	2.8	-2.7	2.1

6.5 Discussion

Several of our experimental results may plausibly be interpreted in light of the general view taken here that there is a phonetic tendency toward post-nasal voicing.

First, the tendency itself is not entirely suppressed, even in English, where voicing is contrastive in postnasal position. There is significantly more closure voicing in the *tompa* tokens than for the *tarpa* tokens, for all speakers. Further, there is slight evidence that the tendency toward postnasal voicing is greater in rapid, less fully articulated speech: three of the five speakers showed a significantly greater tendency toward postnasal voicing in one or both of the prosodically weaker positions C and D. This tendency was toward postnasal voicing per se, and not voicing in general, since the same effect was not observed in the *tarpa* tokens.

Beyond this, two other patterns present in the data can be seen as involving strategies, some general and others speaker-specific, for maintaining a phonological distinction of voicing despite a phonetic tendency that would neutralize it.

(a) **Nasal and Stop Closure Durations**. We suggest that the durations of nasality and stop closure are appropriately arranged to encourage voicing in /mb/ and voicelessness in /mp/. To see this, we must examine a general factor that appears to affect duration in our data.

Consider the overall closure durations of all of our tokens, that is, the durations corresponding to /p/ in *tarpa*, to /mp/ in *tompa*, and to /mb/ in *tomba*. Browman and Goldstein (1986) has suggested that English nasal+stop clusters in the prosodic context we have considered (/ ‘V ___ Vû) are essentially prenasalized stops, having little more duration than a singleton stop in the same environment. Our acoustic data are quite compatible with this view. For the three word types we collected, the total labial closure, averaged across all tokens, was 85 msec. for *tarpa*, 87 msec. for *tomba*, and 99 msec. for *tompa*.

What is of interest here is how the total duration of labial closure is divided between a nasal and a following stop. A finding above which is statistically very strong (and shown in earlier work as well) is that in /mp/, the nasal is short and the stop long, whereas in /mb/ the nasal is long and the stop short. As the literature on voicing indicates, this durational pattern would tend to favor voicelessness in /mp/, since there is more time for supraglottal pressure build-up to halt translaryngeal flow. Shortness of the stop would likewise would favor voicing in /mb/.

The greater length of the stop in *tompa* relative to *tomba* may plausibly be regarded as an important factor in maintaining the percept of voicelessness in this segment. Consider that, according to Westbury and Keating (19xx), if a stop is voiced more than about 50% through its closure, then it is likely to be perceived as voiced.[5] Imagine a (counterfactual) scenario in which the duration of /mp/ clusters is awarded not preferentially to the stop, but rather is shared equally between the two segments. Under this scenario, and adopting Westbury and Keating's assumption concerning vowel perception, we calculate that a substantial number of *tompa* tokens in our experiment would have been perceived as [ˈtɑmbə], not as [ˈtɑmpə]. For each speaker, the fractions are: TS, 2/40 tokens; CF, 2/40; HC 27/40; MD 14/40; RW 21/40 tokens.

While the clusters /rp/, /mp/, and /mb/ had roughly similar overall closure durations, noted above, it is noteworthy that the longest of the three is /mp/. The 99 msec. average closure duration for /mp/ is significantly greater than the 87 msec. closure duration for /mb/ ($p < .0001$ by Fisher's PLSD test). This difference as well would tend to encourage voicelessness in /mp/ relative to /mb/.

We add that the duration of the nasal portion of closure in /mp/ and /mb/ may in and of itself serve as a perceptual cue for voicing in this context, as was demonstrated, for example, by the tape-splicing experiments of Malécot (1960). Given that durational differences serve to maintain the primary cue of stop voicing, it is plausible that the durational differences themselves could serve as an additional cue.

[xxx Various people have other explanations. See Fujimura in the syllables volume, who also cites a paper by Zue and Laferriere]

(b) **Voice Onset Time**. For the three female subjects, the /mp/ clusters showed a significantly greater voice onset time than the /rp/ clusters that served as a control. We conjecture that this represents a speaker-specific strategy for maintaining voicelessness in the /p/ of *tompa*. In particular, even where supralaryngeal conditions are favorable to the maintainance of voicing (as we believe they are in the postnasal environment), it is possible to discourage voicing by means of vocal cord abduction; we suggest that the three female speakers did just this. Since all else being equal, a greater abduction will require more time to complete, we obtain small differences of voice onset time between *tompa* and *tarpa*.

The use of vocal cord abduction to inhibit voicing in NC̥ clusters is attested also phonologically, as Pater (in press) has shown. In particular, in many Bantu languages, voiceless stops have historically become aspirated in the post-nasal environment. The following data (Thomas Hinnebusch, p.c.) from Pokomo show how this pattern sometimes creates phonological alternations:

(11) a. yu-kuni 'Noun class 11 pref.-piece of firewood'
n-khuni 'Noun class 10 pref.-firewood'

[5] We judge, subjectively, that this criterion is valid for our data; the tokens of tompa produced by our speakers in which closure voicing lasts for more than 50% of closure sound ambiguous to us (between [ˈtɑmpə] and [ˈtɑmbə]) when heard in isolation.

b. yu-caya ‘Noun class 11 prefix-jaw’
n-chaya 10 ‘jaws’ (UP)

ki-konde/vi- 7/8 ‘garden’ n-khonde 9/10 ‘garden’ (Upper Pok.)
yu-pfepfe 11 lightening flash m-phepfe 10 lightening flashes (LP)

Maddieson and Ladefoged (1993) likewise note that when prenasalized stops are voiceless (i.e., the exceptional case) they are frequently aspirated, or even have a voiceless nasal portion.

(c) **Nasal Amplitude**. [xxx this is a mess: do regressions on nasal duration vs. nasal amplitude.]

7. Conclusion

In this article we have discussed a possible phonetic mechanism, namely a combination of nasal leak and compression/rarifaction [xxx spelling?] by the velum, for the widespread pattern of voicing in obstruents adjacent to nasals. The compression/rarifaction mechanism crucially explains the prevalence of obstruent voicing only in postnasal position, not prenasal. We have attempted to establish the plausibility of these mechanism through vocal tract modeling.

Should further research support the validity of these mechanisms (or show the validity of alternatives), then it becomes a factor relevant to phonology that the tendency toward postnasal voicing is present in all languages that have NC̥ clusters; all languages must “deal with it”, either phonologically by abandoning the attempt to produce NC̥ clusters, or phonetically by establishing an outcome that preserves the contrast in spite of the pressure to obliterate it. We have tested this prediction against English data, and it appears to be confirmed: in our data, English both shows a certain degree of postnasal voicing, and also shows two phenomena: durational adjustment, and aspiration, that appear to be directed toward maintaining the /mp/-/mb/ distinction.

This result, should it be general, would count in our opinion as a strike against phonological theories of postnasal voicing that conceive of the phenomenon in terms of relatively arbitrary, language-specific constraints. Rather, we suggest that languages with post-nasal voicing should be treated as representing only one possible response (namely, the abandonment of a contrast) to a conundrum faced by all languages that have NC̥ clusters.

References

Bailey (19xx)

Bell-Berti, Fredericka (1975) “Control of phrayngeal cavity size for English voiced and voiceless stops,” JASA 57, 456-461.

Bell-Berti, Fredericka (1993) “Understanding Velic Motor Control: Studies of Segmental Context,” in Marie K. Huffman and Rena Krakow, eds. *Nasals, Nasalization, and the Velum*, Academic Press, San Diego, pp. 63-85.

Bell-Berti, Fredericka, Rena A. Krakow, Dorothy Ross and Satoshi Horiguchi (1993) “The rise and fall of the soft palate: The Velotrace”, videotape, Acoustical Society of America.

Bell-Berti et al. (1979)

Bell-Berti, Fredericka and Hajime Hirose (1975) “Palatal activity in voicing distinctions: a simultaneous fiberoptic and electromyographic study,” Journal of Phonetics 3, 69-74.

Bell-Berti, Fredericka, Rena A. Krakow, Dorthy Ross and Satoshi Horiguchi (1993) “The rise and fall of the soft palate: The Velotrace”, videotape, Acoustical Society of America.

Browman and Goldstein (1986)

Bjørk, Lars (1961) *Velopharyngeal Function in Connected Speech*, Acta Radiologica, Supplementum 202.

Dixit (UCLAWPP)

Dixit and McNeilage (1972), cited in Bell-Berti diss.

Ferguson, Charles (1975) “Universal Tendencies and ‘Normal’ Nasality,” in Charles A. Ferguson, Larry Hyman, and John J. Ohala, eds. Nas lfest: Papers from a Symposium on Nasals and Nasalization, Language Universals Project, Dept. of Linguistics, Stanford University, pp. 175-96.

Halle and Stevens (971)1

Hercus, Luise (1986) Victorian Languages: A Late Survey, Pacific Linguistics, Series B, No. 77, ANU Canberra.

Hiroto, Ikuichiro, Minoru Hirano, and Masayoshi Umeno (1963) “A Cineradiographic study on the Movement of the Soft Palate During Phonation of Speech Sounds,” Studia Phonologica 3, 35-46.

Ito, Junko and Armin Mester (1986) “The Phonology of Voicing in Japanese: Theoretical Consequences for Morphological Accessibility,” Linguistic Inquiry 17, 49-73.

[xxx Arizona guys] t Keating 1983 Keating (1984)

Kent (1983)

Kent, R. D. and K. L. Moll (1969) “Vocal Tract Characteristics of the Stop Consonants,” *Journal of the Acoustical Society of America* 46, 1549-1555.

K□nzel (1979) [xxx cited in Westbury 1983: higher in voiceless

Locke, John (1983) *Phonological Acquisition and Change*, Academic Press, New York.

Lubker et al (1970) cited in Westbury 1983, higher in voiceless

Lubker, James F. and Kenneth L. Moll (1965) “Simultaneous oral-nasal air flow measurements and cinefluorographic observations during speech production,” Cleft Palate Journal 2, 257-272.

Lubker 1968

Lubker, James (1973) “Transglottal airflow during stop consonant production,” Journal of the Acoustical Society of America 53, 212-215.

Maddieson 1984

Maddieson and Ladefoged (1991)

Maddieson and Ladefoged (1993)

Malécot, André, (1960) Vowel nasality as a distinctive feature in English. Language 36: 222-229.

Moll (1962) [xxx cited westbury 1983: velum higher in voiceless]

Moll, Kenneth L. and Raymond G. Daniloff (1971) “Investigation of the Timing of Velar Movements During Speech,” Journal of the Acoustical Society of America 50, 678-684.

Muller, Eric M. and W. S. Brown (1980) “Variations in the supraglottal air pressure waveform and their interpretation,” in N. Lass, ed., Speech and Language: Advances in Basic Research and Practice, Academic Press, On The Road, pp. 317-389.

Newton, Brian (1972) The Generative Interpretation of Dialect: A Study of Modern Greek Phonology, Cambridge University Press, Cambridge.

Ohala, John J. (1975) (1976) [xxx self-citations, 1983]

Ohala, John J. (1975) “Phonetic explanations for nasal sound patterns,” in Charles A. Ferguson, Larry M. Hyman, and John J. Ohala, eds., *Nasálfest: Papers from a Symposium on Nasals and Nasalization*, Dept. of Linguistics, Stanford University, Stanford, CA.

Ohala, John J. (1983) “The Origin of Sound Patterns in Vocal Tract Constraints,” in Peter F. MacNeilage, ed., *The Production of Speech*, Springer-Verlag, New York, pp. 189-216.

Ohala and Ohala (1991)

Ohala, John J. and Manjari Ohala. (1993). “The phonetics of nasal phonology: theorems and data.” In Huffman, Marie K. ed. Krakow, Rena A. ed. *Nasals, Nasalization, and the Velum*. San Diego: Academic Press.

Pater, Joe. (forthcoming) “Austronesian nasal substitution and other NC effects.” to appear in René Kager, Harry van der Hulst, and Wim Zonneveld (eds.), *Proceedings of the Workshop on Prosodic Morphology*.

Perkell, Joseph (1969)

Rothenberg, Martin (1968) *The Breath-Stream Dynamics of Simple-Released-Plosive Production*, S. Karger, Basel.

Saint and Pike (1962)

Sherman [xxx voicing asymmetries guy cited by Ohala] Sherman 1975, (same?

Ushijima and Sawashima (1972) [xxx cited westbury 1983: velum higher in voiceless]

Warren (1975)

Warren, Donald W. (1976) “Aerodynamics of Speech Production,” in Norman J. Lass, ed., Contemporary Issues in Experimental Phonetics, xxx, pp. 105-137.

Westbury, John (1979) Aspects of the Temporal Control of Voicing in Consonant Clusters in English, Texas Linguistic Forum 14. Department of Linguistics, University of Texas, Austin.

Westbury, John (1983) “Enlargement of the supraglottal cavity and its relation to stop consonant voicing,” Journal of the Acoustical Society of America 73 (4), 1322-1336.

Westbury, John and Patricia Keating. (1986). “On the naturalness of stop consonant voicing.” *Journal of Linguistics* 22: 145-166.

Young (1953) cited in Lubker and Moll (1965)