PART III

Interactions between segments and features

Acoustic and aerodynamic factors in the interaction of features

The case of nasality and voicing*

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This paper presents an account of the physical factors responsible for cross-linguistically common patterns of co-occurrence between values of the features [voice] and [nasal]. Specifically, it offers explanations for why nasals are typically voiced and why voiced obstruents are often accompanied by nasalization, or in terms of features, why [+voice] and [+nasal] co-occur so often and in such a variety of ways. First, it addresses the *acoustic-auditory* factors responsible for glottal vibration favoring the perceptibility of nasalization. Second, it examines the *aerodynamic* factors responsible for nasality facilitating glottal vibration. In particular, it suggests that nasal leakage is a maneuver to facilitate voicing in the stop and to preserve the voicing contrast. The paper also argues that if the interaction between the two features can be explained by phonetic principles, then there is no need to encode the patterns of co-occurrence as redundancy rules or constraints in universal grammar. Furthermore, phonological representations that assign the nasal valve and the larynx to separate nodes cannot capture the interaction between nasality and voicing and the co-occurrence patterns.

1. Introduction

This paper addresses the dependency relations of features within a segment and when segments follow one another. Specifically, it focuses on the dependency between nasalization and voicing, that is, the likelihood that the two features combine into segments and that they occur in contiguous segments. We review experimental data and sound patterns illustrating the interaction of the two features and present an account of the physical factors responsible for such interaction.

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We argue that abstract feature specifications, e.g. [+nasal], [–voice], or [+cont], devoid of detailed phonetic content cannot adequately account for how features combine into segments and how they affect each other when they occur in contiguous segments, for example, in context-dependent phonological processes or sound change. In particular, we argue that restrictions on the combination of features, in particular the features [nasal] and [voice], are partly determined by phonetic factors.

Phonological approaches within generative linguistics, and Articulatory Phonology, view independent articulators, such as the oro-nasal valve, the laryngeal valve and the oral articulators as belonging to different nodes or tiers. Since velic opening and closing is generally independent of the movements of the oral articulators and the action of the vocal folds, different velum positions (open/closed) can in principle occur simultaneous to different articulatory constrictions and glottal states. All the logical possibilities of combinations of feature specifications, however, do not occur in languages, nor are all features equally likely to combine. There seem to be dependency relations between independently controlled gestures which fail to be captured by formal representations that separate features by assigning them to different nodes, as convincingly argued by Ohala (2005). Such dependency relations are partly due to physical (e.g. aerodynamic or biomechanical) interactions between articulatory gestures, or the acoustic-auditory consequences of such interactions. Prior work on phonetically-based restrictions on the combination of features includes the aerodynamic voicing constraint (Ohala 1983; Westbury & Keating 1986) that accounts for the difficulty involved in maintaining voicing during an obstruent, particularly a long or a back articulated obstruent; the dependency between voicelessness and frication, by which sonorants and high vowels become fricatives when devoiced (Ohala 1983, 1997), and the perceptual consequences on vowel height of vowel nasalization (such as those giving rise to the lowering of nasal vowels in French, e.g. *fin* [fɛ̃] "the end" vs *finir* [finiʁ] "to finish"; *brun* [brœ̃] "brown" vs *brune* [bryn] "brown-haired" (fem.); Beddor, Krakow & Goldstein 1986), amongst others.

Focusing on nasalization, Ohala & Ohala (1993) provide a thorough account of the aerodynamic and acoustic factors underlying how nasality interacts with other features, in particular manner and place features. In the following sections we will examine the phonetic basis for the interaction between nasality and voicing in the light of recent research and will argue that what happens at the glottis affects nasal coupling and perceptibility of nasalization and what happens at the velopharyngeal port influences the continuation or extinction of voicing.

The dependency between nasalization and voicing, or in terms of features, why [+nasal] and [+voice] co-occur so often and in such a variety of ways, has received considerable attention in the phonological literature. For example, dependency relations between the two features within segments, such as the tendency for nasals to be voiced, have been accounted for by 'redundancy rules' (such as 'nasals are redundantly voiced'; Jakobson, Fant & Halle 1951:43) and Optimality Theory constraints (e.g. NAS/VOI: A nasal must be voiced (Itô, Mester & Padgett 1995); Not Co-occurring (+sonorant, –voiced): Sonorants must be voiced (Stemberger & Bernhard 1999)). Similarly, the dependency relations between nasality and voicing across segments—such as post-nasal voicing and prenasalization of voiced but not voiceless obstruents—as been captured by the 'IDENTICAL CLUSTER CONSTRAINT [VOICE]: a sequence of consonants must be identical in voicing' (Pulleyblank 1997:64, 69ff) and the more specific *NC̥ constraint which disallows nasal-voiceless obstruent clusters (Pater 1999). Possibly the most extreme claim of the dependency between nasality and voicing is made by Nasukawa (2005), who within an Element Theory approach—which posits a restricted set of prime elements capturing the properties of both consonants and vowels—proposes a single nasal-voice category, {N}, which may be manifested as either nasality or voicing depending on its headship status. In a non-Element Theory analysis, the choice of the prime element {N} over 'voicing' suggests that voicing is predictable from the nasal feature specification of the segment.

The purpose of the present paper is to provide an account of the physical factors responsible for cross-linguistically common patterns of co-occurrence between nasality and voicing and to argue that if the co-occurrence between the two features arises due to the physics, physiology and perception of speech and can therefore be explained functionally, then it does not need to be explained by redundancy rules or constraints in universal grammar. In the following sections we first review the acoustic-auditory factors which underlie the increased perceptibility of nasalization with a periodic sound source and which are at the origin of nasal and nasalized sounds being largely voiced. Second, we examine the aerodynamic factors responsible for nasality favoring glottal vibration and the phonological patterns that can be derived from this principle. We propose that nasal leakage is a maneuver to facilitate voicing in the stop and, ultimately, to preserve the voicing contrast. Finally, we argue that formal phonological notations which represent the nasal valve and the larynx at different nodes fail to capture the interaction between nasality and voicing.

2. Voicing favors nasality

Acoustic-auditory reasons are at the origin of nasal and nasalized segments being predominantly voiced. It is known that the sound source (glottal pulsing or turbulence) mostly excites the cavities anterior to the constriction where the sound is generated, which contribute to resonances and antiresonances, whereas the back cavities do not contribute much acoustically[1] (Fant 1960; Stevens 1998). The different nature and location of the sound source for voiced and voiceless nasals accounts for their different acoustic result. As illustrated in Figure 1, in voiced nasals, glottal pulses excite the oral and nasal cavities, which contribute the low frequency resonances and the characteristic nasal zeros.

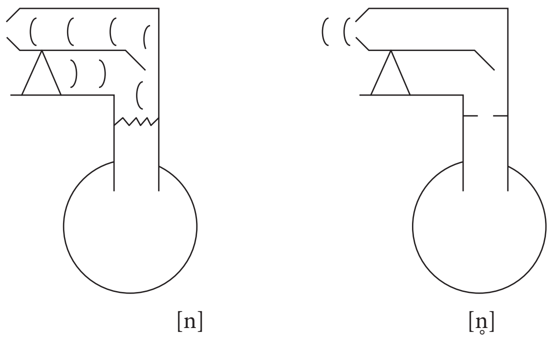

Figure 1. Schematized vocal tract configurations and resonances for voiced (left) and voiceless nasals (right)

For voiceless nasals (as for voiceless vowels) there is no glottal excitation of the oral and nasal cavities and, hence, no low frequency resonances; there is some turbulence generated at the vocal folds which is selectively amplified in the oropharyngeal and nasal cavities, but by virtue of this turbulence not having low frequency periodic components, the low frequency nasal murmur and resonances characteristic of nasals are missing. The large volume of air flowing through the open glottis during the articulation of the voiceless nasal gives rise to turbulence generated primarily at the nostrils (the point of maximum constriction) (see Figure 1, right), whatever the place of articulation of the nasal. Since the oral and nasal cavities posterior to the nostrils do not contribute resonances, the different nasals [m̥ n̥ ɲ̥ ŋ̊] do not differ much spectrally (except in the transitions in adjacent vowels), and because there is no downstream cavity to amplify the frication at the nostrils, voiceless nasals have a weak intensity (Ohala 1975; Ohala & Ohala 1993).

1. The back cavities, however, may be excited under certain circumstances. For example, in sounds involving a large glottal abduction, as in breathy voice or in voiceless fricatives, the subglottal cavity is excited and subglottal resonances interact with the supraglottal resonances and create by this interaction antiresonances which exert a detectable influence on the speech spectrum (Stevens 1998:196–8).

As a result, voiceless nasals do not have the auditory cues associated with nasal coupling and form a distinct sound from voiced nasals.

This is illustrated in Figure 2, which shows distinctive voiceless nasals, [m̥ n̥ ɲ̊ ŋ̊], and voiced nasals, [m n ɲ ŋ], in Burmese. Voiceless nasals lack the low frequency resonances characteristic of nasal coupling, and the resulting frication has a low intensity and indistinct spectral characteristics, which makes them nonoptimal sounds auditorily and thus rarely used in languages.[2] Note that the voiceless nasals in Figure 2 are, in fact, phonetic sequences of voiceless nasal + voiced nasal or voiceless nasals with a voiced offglide—e.g.[n̥n] (Dantsuji 1984; Ladefoged & Maddieson 1996:113). As noted, place distinctions in voiceless nasals are obscure, but many languages that have phonemic voiceless nasals have them at more than one place of articulation. Thus, they are frequently produced with a brief voiced portion. In this way different places of articulation can be differentiated—by both the distinctive resonances of the voiced nasal and the transitions in adjacent vowels.

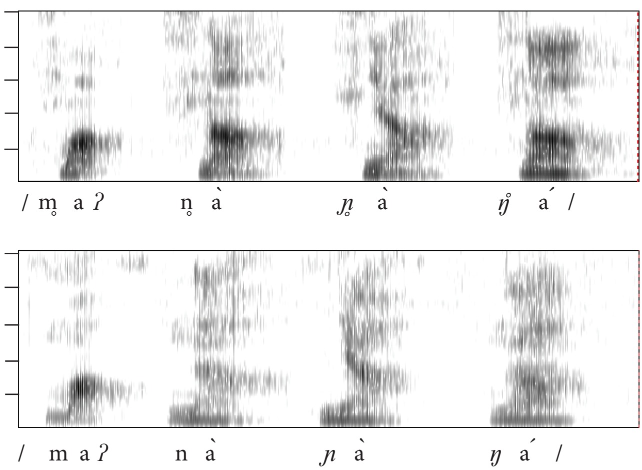

Figure 2. Spectrogram (0–5kHz) for Burmese /m̥aʔ/ "from", /n̥à/ "nose", /ɲ̊à/ "considerate", /ŋ̊á/ "borrow" (top), and /maʔ/ "lift up", /nà/ "pain", /ɲà / "right", /ŋá/ "fish" (bottom)

There is not a great deal of perceptual data on voiceless nasals, but the available data indicate that nasality and place are more difficult to detect in a voiceless than a voiced nasal/nasalized vowel. For example, Arai (2006) found that when

2. The same is true of voiceless nasal vowels (with low acoustic intensity and altered spectral properties; Blankenship 1997) which have not been reported to be contrastive in languages (Ladefoged & Maddieson 1996:315).

a higher amplitude of aspiration (hiss noise) was added to nasalized vowels, perceived vowel nasality decreased. Upon examining voiceless nasals in Burmese, Dantsuji (1986) found no significant cues for place of articulation in the voiceless portion of the nasal[3]—while the voiced murmur portion contains cues to convey place distinctions—which would suggest that place distinctions are harder to detect in a voiceless than a voiced nasal, hence the common voiced portion of phonologically voiceless nasals.

We have seen that the acoustic-auditory consequences of a lowered velum are not uniform for voiced and voiceless segments; in other words, the perceptibility of nasalization is dependent on the voicing specification of the segment. Nasalized fricatives provide another example showing that glottal vibration favors the perception of nasalization. The aerodynamic difficulty involved in concurrent nasalization and frication has been addressed in a number of studies (Ohala 1975; Ohala & Ohala 1993; Ohala, Solé & Ying 1998; Shosted 2006; Solé 2007). A lowered velum for nasality vents the air through the nasal cavity, lowers the oral pressure (P_o) and thus reduces the high rate of flow necessary to generate audible frication at the oral constriction. Nasalized fricatives, however, have been reported to occur in languages and it has been observed that *voiced* nasalized fricatives tend to retain nasalization and lose their friction. For example, voiced nasalized fricatives are phonetically nasalized frictionless continuants (e.g. Waffa /**β̃**/ [**β̞̃**], Stringer & Hotz 1973; Umbundu /ṽ/ [**ʋ̞̃**], Schadeberg 1982), and voiced fricatives tend to lose their friction due to spreading nasalization and become nasalized approximants (e.g. [v **ɣ**] ~ [**ʋ̞̃ ɰ̞̃**] in Guaraní, Gregores & Suarez 1967). In contrast, *voiceless* nasalized fricatives tend to retain frication and lose nasality (Cohn 1993; Ladefoged & Maddieson 1996:132). Thus two different processes need to be explained: loss of friction in voiced but not voiceless nasalized fricatives, and loss of nasalization in voiceless but not voiced fricatives. Aerodynamic factors may account for the former process while acoustic factors account for the latter.

Due to aerodynamic factors, for the same degree of velopharyngeal opening, frication is more severely impaired in voiced than in voiceless fricatives. This is so because voiced nasalized fricatives have two additional mechanisms, other than nasal venting, that impair strong frication (a function of air speed or particle velocity past a constriction which is dependent on oral pressure): increased glottal resistance—which results in a lower oral pressure and inhibits the air vented through the nasal passage from being resupplied from the lungs (as is the case for

3. Maddieson (1983), however, reports that spectral differences may be found during the voiceless portion, e.g. greater relative amplitude in the lower frequencies for labials than for nasals at other places of articulation.

voiceless fricatives with an open glottis)—and the need to keep oral pressure low for voicing. Thus, Ohala, Solé & Ying (1998) report that when voiced and voiceless fricatives are vented with a pseudo-velopharyngeal valve—a tube inserted at the sides of the mouth via the buccal sulcus and the gap behind the molars—simulating different degrees of nasalization, when the valve has a similar impedance to that at the oral constriction (and as a result air flows out through both the nose and the mouth) voiced fricatives become frictionless continuants[4] while voiceless fricatives retain their frication (though the intensity of friction is attenuated). In sum, the combination of high resistance at the glottis and lower oral pressure for voicing, and hence a lower rate of flow and particle velocity through the oral constriction (monotonically related to the intensity of turbulence), accounts for why voicing impairs audible frication.

Why nasality is retained in voiced as opposed to voiceless fricatives may have an acoustic explanation. For the reasons stated earlier, nasalization contributes more acoustically to voiced than to voiceless fricatives. Glottal vibration for voiced fricatives resonates in the nasal cavity—as well as in the oral cavity—thus adding perceptible acoustic properties of nasal coupling (intense low frequency murmur, spectral zeros, and increased F1 bandwidth in neighboring vowels) to the weak (or nonexistent) frication. In contrast, in voiceless fricatives the sound source is forward of the velopharyngeal opening (except for glottal and pharyngeal fricatives)[5] and the sound generated mostly excites the anterior cavity with little acoustic coupling with the posterior nasal cavity. As a consequence, nasalized voiceless fricatives with audible frication do not differ much auditorily from non-nasalized fricatives, that is, the acoustic cues for nasalization are hardly detectable (Cohn 1993; Ladefoged & Maddieson 1996). In sum, for acoustic-auditory reasons glottal vibration favors the percept of nasality. Such acoustic reasons account for a number of cross-linguistic sound patterns,[6] such as nasal consonants, nasalized

4. The aerodynamic explanation for voiced fricatives with a nasal leak becoming frictionless continuants is in line with historical data showing that voiced fricatives coarticulated with following nasals tend to weaken to approximants, taps or nasals, [zn] > [jn], [ɾn], [nn], or are lost altogether (Solé 2007).

5. Glottal and pharyngeal fricatives and stops, for which the build-up of pressure takes place further upstream than the velic valve, with the result that a lowered velum would not affect the pressure build-up, can be nasalized. Nasalized glottal fricatives, i.e. /ɦ̃/, have been widely reported in languages (Ladefoged & Maddieson 1996), and they occur phonetically in American English, e.g. *home* [ɦ̃õʊ̃m].

6. Rhinoglottophilia (Matisoff 1975:265) is a marginally related phenomenon. Matisoff noted the dependency relations between nasality and laryngeal action and coined the term 'rhinoglottophilia' to describe the behavior of vowels becoming nasalized in the context of a

sonorants and nasalized vowels being predominantly voiced, and the different result of voiced and voiceless nasalized fricatives.

3. Nasality facilitates voicing

Due to aerodynamic reasons nasality favors voicing in neighboring obstruents. It is well known that when two segments are in contact their articulations necessarily overlap. Coarticulation with neighboring segments may cause modifications of the aerodynamic conditions in the vocal tract which can, in turn, affect the acoustic and auditory result. The interaction between nasality and voicing in consecutive segments is illustrated in post-nasal voicing. When a voiceless stop is preceded by a nasal, voicing into the stop closure is prolonged, vis-à-vis postvocalic stops, by nasal leakage before full velic closure is achieved and continued velic raising even after velic closure has occurred, thus expanding the volume of the oral cavity. Nasal leakage and oral cavity expansion lower the oral pressure which accumulates in the oral cavity and thus prolong transglottal flow for voicing (Rothenberg 1968; Westbury 1983; Ohala & Ohala 1991; Bell-Berti 1993; Hayes & Stivers 2000). These factors lead to postnasal voiceless obstruents being phonetically partially voiced and with a weaker stop burst (which may in turn lead to their being reinterpreted as voiced). Such phonetic effects have phonological significance (i) in languages with a phonological post-nasal voicing rule (Japanese, Zoque, Kikuyu, and Modern Greek dialects amongst others; see Hayes & Stivers (2000) and references therein), by which voiceless obstruents become voiced after nasals, as illustrated in (1) for Japanese; (ii) in phonological alternations between voiceless stops and prenasalized voiced stops (e.g. Terena, where nasalization is affixed at the beginning of the word and spreads until an obstruent blocks it, and the obstruent becomes voiced in the process, see (2)); (iii) in progressive voicing

laryngeal consonant, such as /h/, in Austronesian languages, Indo-Aryan languages, and Thai, amongst others. Such spontaneous nasalization of vowels adjacent to segments requiring wide laryngeal abduction, such as /h/, voiceless fricatives and aspirated stops, has been accounted for by Ohala & Ohala (1993) in the following terms. The open glottis required for high airflow segments extends to the margins of adjacent vowels. The coupling of the oral and subglottal cavities during glottal abduction adds spectral effects to the vowels that resemble nasalization (i.e. the coupling of the oral and nasal cavities)—increased F1 bandwidth, decreased intensity in the higher frequencies—and may be interpreted as intended nasalization. Though this process results from misinterpretation of the acoustic effects of an added resonator (the subglottal or nasal cavity), rather than laryngeal modulation facilitating the perception of nasality as in the cases of interest, it illustrates the role of acoustic-auditory factors in phonological patterns.

assimilation in stops following nasals, see (3); and (iv) in historical sound change, for example, in the development from Classical Armenian to the Armenian language of New Julfa, exemplified in (4). Post-nasal voicing is also Reporte in infant phonological acquisition of English where the voiced realization of initial voiceless stops is always preceded by a nasal, as illustrated in (5).

(1) Japanese post-nasal voicing (Itô, Mester & Padgett 1995)

root	- te 'gerundive'	- ta 'past'
mi- "see"	mi+**t**e "seeing"	mi+**t**a "saw"
yom- "read"	yon+**d**e "reading"	yon+**d**a "read"

root + root	
fumu + **k**iru	fuŋ**g**iru "give up"
fumu + **h**aru (from ***p**aru)	fum**b**aru "resist"

word internally	
un**z**ari "disgusted"	*un**s**ari
tom**b**o "dragonfly"	*tom**p**o

(2) Terena alternations between voiceless stops–prenasalized voiced stops (Bendor-Samuel 1960: cited in Ohala & Ohala 1993).

piho "I went"	^{m}**b**iho "he went"
i**s**o "I hoed"	ĩ^{n}**z**o "he hoed"
owo**k**u "my house"	õw̃õ^{ŋ}**g**u "his house"

(3) Progressive voicing assimilation in nasal+stop clusters (Rohlfs 1949:88–89; Rohlfs 1970)

Southern Italian	*santo* [ˈsan**d**ə] "saint"
	pampano [ˈpam**b**anə] "hopscotch"
	bianco [ˈjɛŋ**g**ə] "white"
Gascon	[kanˈ**d**a] "to buy" from Lat. *cantare*

(4) Historical change (Vaux 1998:506)

Classical Armenian	New Julfa
ənkanel	**əng**aniel "fall"
ajn**t**eł	**əndieʁ** "there"
t͡ʃan**t͡ʃ**	**t͡ʃ**an**d͡ʒ** "fly"

(5) Child phonology (Seth between ages 1;10 and 2;2; Kager, van der Feest, Fikkert, Kerkhoff & Zamuner 2007)

[sən**d**æn] for "sun tan"
[n **d**a ˈaf] for "N turn off" (where the nasal is apparently a realization of 'want')

The interaction between nasality and voicing, however, is not restricted to postnasal voicing. More generally, there is a dependency between contiguous nasals and voiced stops. In other words, there is a bias toward nasals occurring, being preserved or emerging next to voiced but not voiceless stops; symmetrically, voiced but not voiceless stops tend to be preserved in a nasal context. The former is illustrated in the following sound patterns. Nasals occur before voiced but not before voiceless stops (nasal deletion) in the Kelantan dialect of Malay (Teoh 1988), and in a number of African languages, such as Venda, Swahili and Maore (cited in Pater 1999:319). Nasals are preserved before voiced but not before voiceless stops (denasalization), as illustrated in (6a) for Mandar, an Austronesian language spoken in parts of Indonesia. A similar process is found in American English whereby nasals are lost before tautosyllabic voiceless stops but not before voiced stops, see (6b).[7] In Hindi, nasals emerge between a nasalized vowel and a voiced but not a voiceless segment, see (7).

(6) Preservation of nasals before voiced but not voiceless stops.

a. Mandar (Mills 1975).
/maN+tunu/ ma**tt**unu "to burn"
/maN+dundu/ ma**nd**undu "to drink"

b. American English nasal loss[8] (Malécot 1960)
tent /tent/ [tʰẽ**t**] *can't* /kænt/ [kʰ**æ̃t**] *camp* /kamp/ [kʰ**æ̃p**]
tend /tend/ [tʰẽ**nd**] *canned* /kænd/ [kʰ**æ̃nd**]

(7) Nasal epenthesis, e.g. Hindi (Ohala & Ohala 1991)

Sanskrit	Old Hindi	Modern Hindi
čhandra	čhã:dra	[t͡ʃã**nd**] "moon"
danta.	dã:ta	[dã**t**] "tooth"

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7. A related case may be nasal deletion and vowel lengthening before fricatives (e.g. Proto-Greek **pans* > Ancient Gk. *pa:s*). The loss of nasals with concomitant vowel lengthening, especially before fricatives, documented in a variety of languages (see Ohala & Busà 1995), has been explained in the following terms. Due to the aerodynamic requirements for frication, nasal consonants are shorter and the preceding vowel more extensively nasalized in VNFricative than in VNStop sequences, as shown by phonetic data (e.g. Busà 2007). A shorter nasal may be more difficult to detect, resulting in nasal loss, and the reported perceptual association between vowel length and nasalization (Whalen & Beddor 1989) may explain vowel lengthening. The sound change may involve an additional perceptual component. Perceptual data shows that nasals are harder to detect before voiceless fricatives than before other consonants, most likely because these segments are produced with a large glottal opening, spreading through coarticulation to adjacent vowels, which creates acoustic effects on the vowels similar to nasalization. Such acoustic effects resembling nasalization are attributed to the large glottal abduction and thus factored out. Listeners may factor out nasals actually occurring in this context and sound change may result (Ohala & Busà 1995, Busà 2007).

8. One reviewer suggests that rather than the nasal being lost before a voiceless stop in these examples, the voiceless obstruent shortens the preceding sonorant interval such that the nasal consonant portion is truncated, while lack of shortening of that interval before voiced obstruents preserves the nasal consonant. In other words, it is not voicing *per se* that determines how much of a nasal is realized, but rather the effect of voicing on the

Examples of the latter—i.e. the preservation of voiced stops but the loss or replacement of voiceless stops in a nasal context—are presented below. In Indonesian (Halle & Clements 1983) and in OshiKwanyama (Steinbergs 1985; spoken in Angola and Namibia), root-initial voiced stops are preserved after a nasal, but voiceless stops become a homorganic nasal (nasal substitution), illustrated in (8a) for Indonesian. This process is replicated in American English in the assimilation of nasality in /nt/—but not /nd/—clusters when they occur between a stressed and an unstressed vowel, resulting in "winter" and "winner" being pronounced the same, see (8b). In German and many dialects of English, a /t/ is realized as a glottal stop or irregular glottal pulsing when followed by a nasal, as exemplified in (9), whereas /d/ is preserved in the same context. In such contexts, the voiceless stop would be nasally released and would lack the strong fricative release burst, which is a perceptual cue for voiceless stops (Ali, Daniloff & Hammarberg 1979), whereas a glottal stop (with a constriction and build-up of pressure further upstream than the velic opening) allows velic lowering while showing a discontinuity in amplitude and a release burst characteristic of a stop (Kohler 2001). Along the same lines, a tendency for /t/ to be more prone to deletion than /d/ before a nasal (e.g. *sweeten* vs *Sweden*) in American English, due to the lack of a release burst in this environment, is reported by Zue & Laferriere (1979) (see also Raymond, Dautricourt & Hume (2006) on /t, d/ deletion in spontaneous American English).

(8) Assimilation of nasality

a. Indonesian (Halle & Clements 1983)

/məN+bəli/	[mə**mb**əli] "to buy"
/məN+dapat/	[mə**nd**apat] "to get, to receive"
/məN+ganti/	[mə**ŋg**anti] "to change" BUT:
/məN+pilih/	[mə**m**ilih] "to choose, to vote"
/məN+tulis/	[mə**n**ulis] "to write"
/məN+kasih/	[məŋasih] "to give"

b. American English

*ce**nt**er* [nn] vs *se**nd**er* [nd]

*i**nt**ernational* [nn] vs *i**nd**icational* [nd]

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preceding sonorant interval's duration. There are a number of problems with this interpretation. First, empirical data show that in vowel+sonorant sequences before tautosyllabic voiceless obstruents, it is not only the sonorant that is shortened, but also the vowel and the vowel+sonorant interval (Raphael, Dorman, Freeman & Tobin 1975), which runs against the 'truncation' interpretation. Second, the effect of obstruent voicing is not the same for all vowel+sonorant sequences. In VNC sequences the nasal is commonly absent preceding a voiceless obstruent, while in VlC and VrC sequences (e.g. built-build, bird-Bert) the

(9) Glottalization (Kohler 2001)

German	*zweiten* [ˈtsvaɪ̯ʔn̩], [ˈtsvaɪ̯n̩] "second" vs *leiden* [ˈ**laɪdn̩**] "pain, to suffer"
American English	*mountain* [ˈ**mãʊ̃nʔn̩**] vs *abandon* [**ə**ˈ**bæ̃ndə̃n**]
	captain [ˈ**kʰæpʔm̩**] vs *Ogd*en [ˈ**ɑgdn̩**]

The reviewed sound patterns exhibit a bi-directional dependency between contiguous nasals and voiced stops. The dependency is bi-directional (or symmetrical) in the sense that, in some cases, the conditions for nasal preservation are created by the voicing of the stop, and in other cases, a nasal context determines the preservation or loss of the stop depending on its voicing specification. Such symmetrical relations in adjacent sounds are not common and indicate the intricate nature of the interaction.

3.1 Explanations for the sound patterns

The basis for the interaction between nasalization and voicing may be found in phonetic factors. Phonetically, voiced obstruents exhibit more nasal leakage preceding and following nasalized vowels and nasal consonants than voiceless obstruents. Cohn's (1990:108,199) nasal flow data for French and Sundanese ṼC and VNC sequences shows that nasal flow is present during most of the duration of voiced stops—the soft palate is raised just before the stop is released, to ensure that the release is oral—whereas nasal flow drops abruptly at the onset of voiceless stops. Huffman's (1990:61, 65) data shows velic leakage (i.e. nasal airflow) during the closure of voiced but not voiceless stops in CṼ and ṼC sequences in Yoruba. Ohala & Ohala's (1991) nasal pressure data for Hindi and French Ṽ#C sequences exhibits velic lowering during the oral closure of voiced stops (essentially prenasalized stops) but much shorter or non-occurring nasal leakage for voiceless stops. Basset, Amelot, Vaissière & Roubeau's (2001) nasal airflow data for French shows that voiced stops and fricatives preceding and following contrastive nasal vowels (CṼ, ṼC) showed significantly more cases of anticipatory and carryover nasalization (78% of the cases) than voiceless obstruents (34%), and a longer temporal extent of velum lowering (throughout the duration of the voiced obstruent vs half of

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sonorant is preserved. Third, Beddor (2007) notes that extensively nasalized vowels covary with short or absent nasals in VNC sequences in American English, and suggests perceptual equivalence between Ṽ and N. Taken together, these data suggest that the case of nasal loss exemplified in (6b) is not the effect of the obstruent voicing on the preceding sonorant's duration. Rather, the early onset and offset of the nasal gesture in $VNC_{voiceless}$ sequences (Beddor 2007) is probably an effect of the low tolerance of voiceless, but not voiced, stops to coarticulatory nasalization that might threaten their voiceless percept (Ohala & Ohala 1991).

the duration of the voiceless obstruent). Further evidence of voiced stops, but not voiceless stops, showing nasal leakage is reviewed in Ohala & Ohala (1991:213).

These data show that the velum may be lowered during the first part of the voiced stop but may close before the release so as to produce an oral burst, or the velum may be lowered throughout the stop, which is likely to result in a relatively weak burst.[9] As noted, voiceless stops tend to inhibit coarticulatory velic lowering during the stop constriction. Partial or incomplete velopharyngeal closure may prevent the build-up of intraoral pressure necessary for a noisy release of a stop. Such nasal leakage would have a larger perceptual effect on voiceless than on voiced stops, as high intensity noise is a perceptual cue for voiceless stops (Ali, Daniloff & Hammarberg 1979).

Ohala & Ohala (1991) provide an acoustic-auditory explanation for voiceless stops having less tolerance for nasalization than voiced stops in terms of coarticulatory nasalization undermining the stop or voiceless character (i.e. the spectral and amplitude discontinuity, and noisy release burst) of voiceless stops, while voiced stops can meet their auditory requirements with a partially lowered velum. On the basis of the lower tolerance of voiceless stops to coarticulatory nasalization, Pater (1999) analyzes some of the cases in (1)–(9) as resulting from a phonetically motivated constraint against NC̥ clusters. Thus, the *NC̥ constraint bans nasals from occurring before voiceless segments, and postnasal voicing (Examples 1–5 above), nasal deletion, denasalization (Example 6), and nasal substitution (Example 8) are ‘repairs’ to eliminate disallowed NC̥ clusters.

3.2 Further interactions between nasalization and voicing

Ohala & Ohala’s (1991) explanation in acoustic-auditory terms (and the *NC̥ constraint) may in part account for why voiceless obstruents, in order to preserve the segment’s integrity, tend to inhibit coarticulatory nasalization more than voiced obstruents, and hence for the different fate of nasals in a voiced or a voiceless context (Examples 6, 7 above), and the loss of buccal voiceless, but not voiced, stops in a nasal context (Examples 8, 9). However, it does not account for prenasalization of voiced stops in an oral context, the emergence of non-etymological nasals adjacent to voiced but not voiceless consonants, and maintenance of the voicing contrast only in a nasal context. Indeed, languages with distinctive voiceless stops, [p t k], and prenasalized voiced stops [^{m}b, ^{n}d, ^{ŋ}g], but no simple voiced stops—such as languages in Austronesia, Papua and South America (Maddieson & Ladefoged 1993:256), for example, Waris, illustrated in (10)—suggest that such prenasalized

9. The same velopharyngeal timing patterns have been observed in contrastive prenasalized voiced stops (Henton, Ladefoged & Maddieson 1992; Ladefoged & Maddieson 1996).

stops form the voiced stop series (Maddieson 1984:67). In fact, prenasalized stops have been analysed as plain voiced stops in some varieties of Mixtec (Piggot 1992; Iverson & Salmons 1996). These languages, as well as languages with contrastive voiced and voiceless stops but with the voiced series being optionally phonetically prenasalized (e.g. Bola, exemplified in (11); Tok Pisin, Smith 2002) or being realized as nasals in certain contexts (e.g. Rotokas, Hyman, to appear) suggest that nasal leakage is utilized to facilitate voicing in the obstruent. Note that, as opposed to Examples (1) to (9), these cases neither contained a nasal etymologically nor occur in a nasal context, and the prenasalized stop, therefore, cannot simply be the result of the 'preservation' of historical traces or coarticulatory nasalization.

(10) Contrastive voiceless stops and prenasalized stops, Waris, Papua New Guinea (Brown 2001)

[**p**]	***p**anda* "pitpit type"	[^{m}**b**]	***b**anda* "snake"
	*no**p**o* "eye"		*tom**b**ol* "dry"
[**t**]	***t**ata* "meat"	[^{n}**d**]	***d**amba* "tree sp."
	*lo**t*** "banana type"		*wa**nd*** "pitpit grass"
[**k**]	***k**ao* "tree sp."	[^{ŋ}**g**]	***g**ao* "go!"
	*o**k**ala* "distant"		*en**g**ala* "hand"

(11) Optional prenasalized stops, Bola, Malayo-Polynesian (Wiebe 1997)

[**b**] ~ [^{m}**b**]	***b**ahele* "crocodile"
	***b**e**b**e* "butterfly"
[**d**] ~ [^{n}**d**]	***d**agi* "dig"
	*ma**d**e* "sit"
[**g**] ~ [^{ŋ}**g**]	***g**e* "3rd pers. Fem"
	*a**g**a* "canoe"

The suggestion that nasal leakage is used to favor voicing in the stop is consistent with the finding that in the 19 languages in the UPSID database with prenasalized segments, they are all voiced obstruents and are overwhelmingly stops (Maddieson 1984:67). Instrumental data of nasal flow during a voiced stop are provided in Figure 3 for Karitiana, a Tupi language spoken in Brazil, which lacks phonemic voiced stops but features phonetic voiced stops as allophones of nasals word-initially (Demolin 2007). Figure 3 shows that the stop is voiced throughout—though evidence of voicing during the stop is hardly observable in the audio signal, as noted in the glottal pulses in the oral pressure trace (channel 2)—and that there is nasal flow preceding the stop constriction (beginning halfway through the segment when the oral pressure starts to rise) and to a lesser degree, during the stop closure.

Prenasalization (and postnasalization) of voiced stops, but not voiceless stops, in the absence of contextual nasals ('spontaneous' nasalization) is also found in data from first and second language acquisition. Although child phonology generally shows simplification of consonant clusters, various authors report cases where English-learning infants add a nasal before voiced stops (Clark & Bowerman

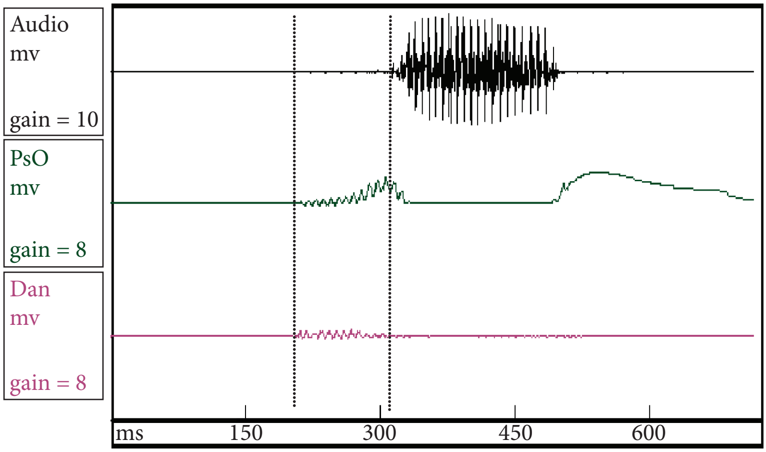

Figure 3. Audio (channel 1), oral pressure (channel 2) and nasal flow (channel 3) for the Karitiana word [ᵐbap˺]. The prenasalized voiced stop appears between vertical lines. (From Storto & Demolin in press)

1986) or after voiced stops (Labov & Labov 1978), as shown in the realizations in (12), in order to facilitiate voicing in coda stops. Insertion of epenthetic nasals before initial voiced stops has been reported for French infants (Allen 1985). Along similar lines, Kong, Beckman & Edwards (2007) attribute the early mastery of voiced stops in Greek-learning infants to prenasalization of initial voiced stops (illustrated in (12)), though in this case prenasalization is not 'spontaneous' but rather a variant pronunciation of voiced stops in Standard and dialectal Greek. Adult American English learners of Spanish (a language with a voicing contrast between prevoiced and unaspirated stops) may show prenasalization of initial voiced stops in Spanish, exemplified in (13), to ensure prevoicing during the consonant constriction. Lewis (in press) reports that speakers using this strategy showed longer prevoicing in production of Spanish /b/ and their tokens were the least likely to be misperceived as /p/ by native Spanish listeners.

Evidence of nasalization during voiced stops has been observed by a variety of investigators. For example, Pape, Mooshammer, Hoole & Fuchs (2003) report that German speakers may use prenasalization to avoid devoicing of stops. Velopharyngeal opening has been found during utterance-initial and intervocalic breathy voiced stops for Hindi and Telugu (Rothenberg 1968:7.4) and for Sindhi voiced stops (Nihalani 1975). Taken together, these data suggest that speakers make use of nasal leakage as a strategy to achieve voicing during the stop consonant.

(12) Child phonology

English [bent] for *bed* [bed], [pɪŋk] for *pig* [pɪg] (Clark & Bowerman 1986)
English [dædn] for *dad* [dæd] (Labov & Labov 1978)
Greek [ᵑgol] for [gol] "goal" (Kong, Beckman & Edwards 2007)

(13) Second language acquisition
[ˈ^{m}ba**ɲ**o] for *baño* [ˈba**ɲ**o] "bathroom" (Lewis in press)

Cases of postnasalization of stops have also been reported. For example, Jones (2001) examines the spontaneous postnasalization of voiced stops in Lancashire dialects of English, documented in Wright (1952) and Orton & Halliday (1963). Postnasalization involves the emergence of a homorganic nasal at the end of voiced stops and voiced affricates phrase-finally, as illustrated in (14), and also before phrase-final plurals (e.g., [**lɛgŋz**] for "legs"). The fact that the nasal offglide is homorganic with the stop reflects that the velum is lowered during the latter part of the stop closure, resulting in a nasal release. Jones rightly suggests that postnasalization results from a strategy to prolong voicing during the stop constriction, by venting the air through the nose, in order to maintain the voicing contrast phrase-finally.[10] That is, as the voicing contrast in stops is endangered in phrase-final position due to passive devoicing, velic lowering during the voiced stop helps to prolong voicing and preserves the voicing contrast. Thus in some Lancashire dialects voicing in final stops covaries with (and is cued by) postnasalization, possibly in addition to preceding vowel duration as in most dialects of English. Similar nasal releases to final voiced (but not voiceless) stops occur in the South American languages Kaingang and Içua Tupí (Herbert 1986:206, cited in Laver 1994:232), in Vietnamese dialects, and Senegalese Wolof (Ward 1939, cited in Jones 2001).

(14) Postnasalization of phrase-final voiced stops in Lancashire dialects of English (Jones 2001)
[ˈ**kɔːv ə ðɪ** ˈ**lɛgŋ**] *calf of thy leg*
[ˌ**uːz** ˈ**wɛdn**] *she's wed (married)*
[ˈ**spɪt ə** ˈ**gɒbm**] *spit a gob (phlegm)*
[ˈ**kabɪdʒn**] *cabbage*

It is of interest to note the different patterning of postnasalization and prenasalization in the languages reviewed. Postnasalization, [**b^{m} d^{n} g^{ŋ}**], is associated with phrase-final position, where voicing is difficult to maintain due to the increase

10. Jones notes that this interpretation does not account for voiceless affricates also being postnasalized in phrase-final position, e.g. in March [ɪˈmaː^{ɹ}tʃm]. He suggests that postnasalization in voiceless affricates may reflect an attempt to keep them distinct from heavily aspirated voiceless stops phrase-finally. Indeed, the fact that, differently from nasals following voiced stops and voiced affricates, the nasal segment following the voiceless affricate [tʃ] is not homorganic suggests that velum lowering is not present during the affricate constriction and is therefore triggered by a different mechanism.

in oral pressure during the stop closure while subglottal pressure (Ps) decreases phrase-finally (Westbury & Keating 1986; Slifka 2000). Conversely, prenasalization, [^{m}b ^{n}d ^{ŋ}g], tends to occur in word-initial and therefore utterance-initial position, where phonation is more difficult to initiate due to the lowered subglottal pressure utterance-initially and the larger pressure difference required to set the vocal folds into vibration vis-à-vis sustained voicing ($P_{subglottal}$-P_{oral} > 3–4cmH2O vs 1–2cmH2O, respectively, Baer 1975). These patterns of post- and pre-nasalization are consistent with the interpretation that nasal venting is used to facilitate the required transglottal pressure difference in order to prolong or initiate vocal fold vibration during the stop closure.

Crucially, crosslinguistic data suggests that coarticulatory (or spontaneous) velum leakage facilitates voicing in obstruents, thus helping to preserve the voicing contrast. A case of preservation of the voicing contrast exclusively in a nasal environment is found in Basaa, a Bantu language spoken in South West Cameroon. In Basaa there is a contrast between voiceless stops [p t k k^{w}], voiced stops [b d g g^{w}], and prenasalized stops [^{m}b ^{n}d ^{ŋ}g]. The contrast between voiceless and voiced stops, however, is only present after a nasal, as illustrated in (15a). That is, voiceless stops can occur in all positions, initially, medially—following oral and nasal segments—and finally, but voiced stops only occur after the nasal (nominal) prefix N-. As a result, the voicing contrast in stops is only present postnasally (Teil-Dautrey 1991). It is instructive to examine Teil-Dautrey's (1991) historical data on the origin of voiced stops. Present-day voiced stops in Basaa are reflexes of Proto-Bantu (PB) *b, *d, *g and *p *t *k in nouns with a nominal class 9/10 prefix N-. That is to say, Proto-Bantu *p *t *k were voiced and *b *d *g were preserved as voiced stops in Basaa only when they followed the nasal nominal prefix N- (but not other nasals), as exemplified in Examples 1–3 in (15b). In all other contexts, preservation of voicing in Basaa involves de-stopping or implosivization (Examples 4–8; this will be addressed further in the next section). Although morphological factors are clearly at play, the historical data illustrate that coarticulatory nasalization facilitates maintenance of voicing in following stops.

(15) Basaa, Bantu language

a. distribution of voiceless and voiced stops (Teil-Dautrey 1991)

pên "color"	*li-pém* "honor"	*m-pen* "prong of a fork"	*lép* "water"
–	–	*m-bên* "handle"	–
ter "to crush"	*li-tɔ́n* "stain"	*n-tɛ́l* "length"	–
–	–	*n-deŋg* "love"	–
kap "share"	*li-kaŋ* "science"	*ŋ-kɔl* "prisoner"	*lék* "burn"
–	–	*ŋ-gos* "parrot"	–

b. diachronic data (Teil-Dautrey 1991)

1.	PB **tope*	*n-**dɔβɔ*** 9/10	"mud"
2.	PB **diŋg*	*n-**deŋg*** 9/10	"love"
3.	PB **tete*	*n-**tɛr*** 3/4	"basket"
4.	PB **bég*	***ɓέk***	"break"
5.	PB **gubú*	***ŋ-guβí*** 9/10	"hippopotamus"
6.	PB **díg*	*lék*	"burn"
7.	PB **díŋg*	*yéŋ*	"search"
8.	PB **púd*	*pɔr* (also *pɔt*)	"speak"

(16) Majorcan Catalan, stop voicing contrast preserved postnasally (Dols & Wheeler 1995)

/b/	/p/
*do**bl*** [pl] "I double"	*aco**pl*** [pl] "I fit together"
*sem**bl*** [bl] "I think"	*um**pl*** [pl] "I fill"

Similarly, data from Majorcan Catalan suggests that a preceding nasal facilitates voicing in a following obstruent, thus preventing final obstruent devoicing. In Standard Catalan, underlying voiced stops become voiceless before a pause (Final Obstruent Devoicing, FOD). In Majorcan Catalan, however, the underlying stop voicing distinction is maintained post-nasally in word-final stop + nonsyllabic /l, r/ clusters (Dols & Wheeler 1995; Llach 1999; Recasens, Espinosa & Solanas 2004). Thus postvocalically, the voicing contrast is neutralized (/pl/ and /bl/ both have voiceless stops due to FOD, as shown in the first Example in (16)), whereas postnasally the two clusters differ in stop voicing (second Example in (16)), with the voiced stop showing more voicing during the closure, a shorter stop closure duration and a longer preceding nasal than the voiceless stop (Recasens et al. 2004; Llach 1999). Thus the presence of a nasal helps to maintain the underlying stop voicing distinction in word-final stop + liquid clusters in Majorcan.[11]

An example of spontaneous nasalization developing in order to maintain the voicing contrast in final stops was suggested by Jones (2001) for Lancashire dialects and was reviewed above (illustrated in (14)).

3.3 Nasalization as a maneuver to prolong/initiate voicing

The data in 10–14 illustrates the emergence of phonetic nasalization next to voiced but not voiceless stops. Such patterns cannot be explained in terms of the lower tolerance of voiceless stops for nasalization, postnasal voicing or a constraint

11. The voicing contrast in Majorcan stop + nonsyllabic liquid clusters is only preserved in the first and third person singular (if no final epenthetic vowel is introduced) of the present tense in the second and third conjugations.

against nasals preceding voiceless stops simply because these cases do not contain a nasal etymologically or occur in a nasal context. Similarly, the data in 15–16 illustrating the maintenance of voicing in stops, and hence of the stop voicing contrast, cannot be explained only in a nasal context by the principles above. However, these patterns may be explained in terms of nasalization facilitating voicing in adjacent stops. As noted, due to aerodynamic factors, a slightly lowered velum reduces the oral pressure and thus increases the rate of airflow through the glottis, which favors voicing.

The specific physical factors are the following. Voicing is maintained if the vocal folds have the appropriate degree of adduction and tension, and if there is sufficient airflow through the glottis (U_g) to sustain vocal fold vibration. For sufficient transglottal airflow, the pressure difference across the glottis must be about 1–2cmH2O, that is, the subglottal pressure must be at least 1–2cmH2O higher than the oral pressure (Figure 4, time 1). Since transglottal flow for voicing is pressure (*P*) dependent, as shown in equation (17) below, and a high oral and nasal resistance for obstruents increases oral pressure as air continues to flow from the lungs and accumulates in the cavity, over a few dozen milliseconds the pressure differential drops below the required threshold and transglottal flow, and voicing is extinguished (Figure 4, time 2). Note that voicing ceases due exclusively to aerodynamic factors ('passive devoicing') and not to active laryngeal adjustments. As illustrated in Figure 4 (time 2'), decreasing the nasal resistance by lowering the velum reduces oral pressure, and hence increases the rate of flow through the glottis, with the result that voicing is prolonged.

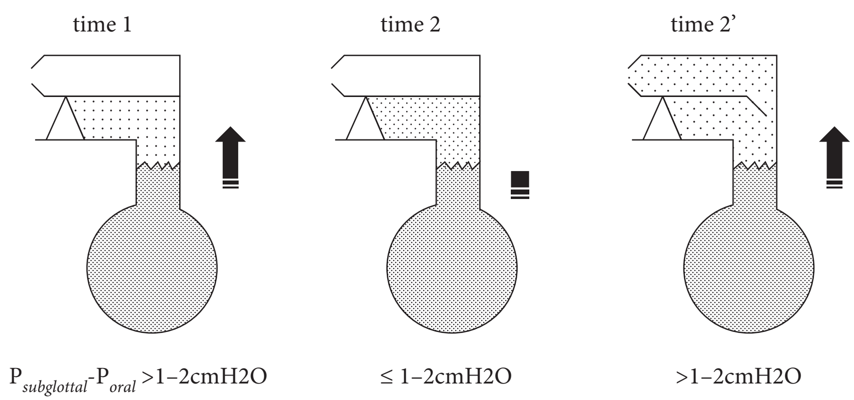

Figure 4. Diagrammatic representation of the pressure difference required for continued transglottal flow

(17) $U_g = A_g\,(P_{subglottal} - P_{oral})^a\,c$
where A_g is the glottal area; *a* varies between 0.5 and 1; *c* is a constant

Similarly, voicing initiation—which requires a larger pressure difference ($P_{subglottal}$ - P_{oral}> 3–4cmH2O; Baer 1975) than that required to sustain it, due to the need to overcome inertial effects—can be facilitated by reducing the oral pressure through the nose and maximizing transglottal flow. Nasal venting might be particularly helpful to initiate voicing phrase-initially and sustain voicing phrase-finally due to difficulty involved in achieving the pressure differential with a lower subglottal pressure in these environments (Westbury & Keating 1986; Slifka 2000).

Nasal leakage is one of a number of articulatory maneuvers, used singly or in combination, which may be used to reduce the oral pressure and thus facilitate transglottal flow for voicing. These maneuvers are directed at reducing the oral pressure by (1) diminishing the air flowing into the oral cavity (i.e. decreasing the area of glottal opening and/or increasing the adductive tension of the vocal folds); (2) releasing air from the oral cavity, by diminishing the oral resistance—i.e. allowing air to escape through the oral constriction—or diminishing the nasal resistance—i.e. nasal leakage; or (3) actively enlarging the volume of the oral cavity, by lowering the larynx, fronting the articulatory constriction, raising the velum or relaxing the walls of the supraglottal cavity (Rothenberg 1968; Bell-Berti 1993; Westbury 1983). Such active articulatory gestures aimed at prolonging or initiating voicing have been referred to as 'active voicing'.

A number of such maneuvers to sustain voicing are illustrated in the historical data for Basaa. According to Teil-Dautrey (1991), Proto-Bantu *b, *d, *g became voiceless in Basaa except when following the nasal nominal prefix N-, most likely due to coarticulatory nasalization (as argued for Examples 1–3 in (15b) above). Voicing in the stop was also preserved in the case of labial *b as an implosive [ɓ] word-initially or a fricative [β] intervocalically (Examples 4–5 in (15b)), both gestures involving maneuvers to prolong transglottal flow (larynx lowering and oral cavity expansion in the case of implosives, and reduction of the oral resistance in the case of the fricative). Similarly, voicing was preserved in the case of *d when it developed into a /l, j, r/, that is, when the oral resistance for the stop was decreased in magnitude (resulting in a lateral or glide /l, j/, Examples 6–7 in (15b)) or in time (resulting in a flapped /r/, Example 8 in 15b), thus preventing the build-up of pressure over time and favoring transglottal flow. Elsewhere Proto-Bantu voiced stops became mostly voiceless stops or were lost. These data reveal that in the development from Proto-Bantu to Basaa maintenance of vocal fold vibration in stops was linked in all cases to active gestures to lower oral pressure in order to facilitate transglottal flow for voicing. The data also illustrate that, as expected, more anterior places of articulation are more likely to preserve voicing. Similar maneuvers and phonetic results (i.e. prenasalization, fricativization, lateralization, gliding, flapping and implosivization) have been reported for a variety of languages (e.g. Rotokas, Firchow & Firchow 1969:274, cited in Hyman, to appear; Sindhi, Turner 1924; Palenquero, Piñeros 2003).

The fact that diminished nasal resistance is a way to moderate oral pressure and maintain vocal fold vibration has been observed by previous investigators (e.g. Rothenberg 1968; Lisker & Abramson 1971; Bell-Berti 1993) and the fact that nasal venting may be exploited in languages to facilitate voicing has been noted for some isolated patterns, such as prenasalization of voiced stops (Kaiser 1934 for Sumbanese (cited in Rothenberg 1968); Henton, Ladefoged & Maddieson 1992:71; Piñeros 2003 for Palenquero); the analysis of prenasalized stops in Mixtec as simple voiced stops (Iverson & Salmons 1996), and postnasalization of voiced stops to maintain the voicing contrast (Jones 2001). However, the overarching principle relating the seemingly disparate patterns pertaining to the preservation of voicing in stops, the emergence or preservation of nasals, prenasalization or postnasalization of stops, and the maintenance of voicing contrasts was not noted previously.

3.4 Distribution of prenasalization and aerodynamic constraints on voicing maintenance/initiation

If prenasalization was indeed an articulatory maneuver to facilitate voicing in stops, one would expect it to apply most often to stops in which voicing is more severely endangered (i.e. velars, with a smaller back cavity, smaller area of compliant tissue, and less capacity to expand actively), followed by coronals and labials, with a comparatively larger cavity, greater area of compliant tissue, and a greater capacity for active expansion (Westbury 1983; Ohala & Riordan 1979; Ohala 1983). This is precisely what the distribution of prenasalization in Japanese dialects (Yamane-Tanaka 2005) in Table 1 shows:

Table 1. Phonetic manifestations of voiced stops in Japanese dialects

Dialect group	Phonetic manifestation
A	[^{m}b ^{n}d ŋ]
B	[b ^{n}d ŋ]
C	[b d ŋ]
D	[b d g]

Of those dialects which prenasalize voiced stops intervocalically, some prenasalize the three voiced stops [b d g], others prenasalize only [d g], and still others prenasalize only [g], such that there is an implicational relationship [^{m}b] ⊃ [^{n}d] ⊃ [ŋ]. This means that the velar stop is prenasalized in virtually all Japanese dialects where this process occurs (33/34), [d] is the next most commonly prenasalized stop (15/34), and prenasalized [b] has the most restricted distribution (11/34). Interestingly, Yamane-Tanaka (2005) shows that the historical process was in fact one of loss of prenasalization, since all voiced stops were prenasalized in Old and

Early Middle Japanese. Historical records show that prenasalization in the central dialects of Japan was first lost in labials in Middle Japanese, [^{m}b] > [b], later in coronals in Modern Japanese, [^{n}d] > [d], and only recently in velars. Thus, the distribution of prenasalized stops reflects historical stages in the language. The progression in the loss of prenasalization correlates with well-known aerodynamic constraints on the maintenance of voicing related to back cavity size and compliance, and thus provides support for the hypothesis that nasal leakage is an adjustment to favor transglottal flow for voicing, utilized most often where voicing is more severely compromised.

Iverson & Salmons (1996) note a similar distribution of prenasalization in voiced stops in Mixtec dialects. As illustrated in Table 2, labials are not prenasalized in most dialects (with only optional prenasalization word-initially in Chalcatongo Mixtec), coronals always appear with prenasalization, whereas voiced velars are rare, do not occur word-initially, and are always prenasalized word-medially.

Table 2. Distribution of prenasalization in word-initial and medial position in Mixtec varieties (Iverson & Salmons 1996)

Word-initiavl	Word-medial
$^{(m)}$b	b
^{n}d	nd
–	ŋg

The pattern of prenasalization is in line with the difficulty involved in initiating and maintaining voicing (i) in velar stops vis-à-vis stops at places of articulation farther forward, and (ii) word-initially vis-à-vis intervocalically (Westbury & Keating 1986). The maintenance of voicing is easier for bilabial stops vis-à-vis stops at more posterior places of articulation. Hence active articulatory maneuvers intended to facilitate voicing—such as reducing the nasal resistance or prenasalization—are not commonly found in bilabial stops while they are found in coronal and velar stops.[12] Similarly, voicing is more difficult to initiate phrase-initially than medially, and more prenasalization is found word- and phrase-initially, at least in the bilabial series. In velar stops, voicing is only

12. In some dialects, such as Alacatlazala and Ayutla, the labial stop is realized as fricative [β], suggesting that the oral resistance is reduced in order to facilitate voicing (Iverson & Salmons 1996).

present when the aerodynamic conditions conducive to voicing are maximized: word-medially and prenasalized.

3.5 Discussion

The data reviewed suggest that Ohala & Ohala's (1991) acoustic-auditory explanation for voiceless stops being more resistant to nasalization than voiced stops (in terms of nasalization undercutting the stop or voiceless character of voiceless stops) may be complemented by aerodynamic factors. Voiced stops favor nasalization because nasal leakage in the initial portion, or during the whole closure, of the stop contributes to keeping a low oral pressure which favors transglottal flow for voicing. Thus nasal leakage (pre- or postnasalization) may be considered a way to fine-tune the conflicting requirements of low oral pressure for voicing and high oral pressure for obstruency. Indeed, nasal leakage and a lower oral pressure (which is detrimental for obstruency) can be tolerated precisely by voiced stops which do not rely as heavily on high intensity noise cues as voiceless stops do.

This interpretation suggests that nasal leakage may be an independently controlled gesture accompanying glottal adduction that is aimed at preserving vocal fold vibration. Note that Ohala & Ohala's account, on the other hand, implies that speakers actively inhibit coarticulatory velic lowering during the oral closure for voiceless, but not voiced stops, to prevent venting the oral airflow required for an intense stop burst. Thus, both explanations rely on active velopharyngeal adjustments linked to stop voicing. Phonetic data available in the literature provide support for the interpretation that the velum is actively controlled during voiced and voiceless sounds. For example, measurements of velopharyngeal closure force using a pressure sensing bulb and EMG activity (Kuehn & Moon 1998) indicate that the velum closure force tends to be greater for voiceless than for voiced consonants. Rothenberg (1968) notes that for certain voiced stops two constrictions are utilized to control the airflow—one at the glottis and the other at the velopharyngeal opening: the nasal passage is adjusted to be quite narrow in order to permit venting sufficient air to maintain vocal fold vibration.

The claim that nasal leakage may be used in some languages as an active adjustment to ensure voicing is compatible with the view of a speech regulating system in which respiratory and articulatory movements are aimed at regulating speech pressures for sound production (Warren 1986). Evidence of compensatory responses to changing aerodynamic conditions (for example, loss or addition of resistance within the vocal tract) and to structural defects (for example, velopharyngeal inadequacy) suggests that speakers attempt to maintain adequate intraoral pressures for consonant production (Kim, Zajac, Warren, Mayo & Essick

1997). Sensory information may allow adjustment of nasal resistance in response to increased oral pressure and its effect on voicing. Thus nasal leakage during the production of voiced stops may be considered an adjustment to moderate the high resistance to exiting airflow at the oral constriction, and thus keep oral pressure low for voicing.

It must be stressed that phonetic prenasalization or postnasalization of voiced stops is viewed as a maneuver to initiate or prolong voicing in the stop and is not a deliberate nasal segment. Such phonetic nasalization, however, may be reinterpreted by listeners as an intended nasal and thus get encoded in the phonology (Ohala 1983). Such perceptual reinterpretation may be assisted by the perceptual bias towards hearing nasals before voiced vis-à-vis voiceless segments found by Ohala & Busà (1995), precisely the context where nasal leakage is found. Thus, the phonological nasals we find in the patterns reviewed are most likely the result of the reinterpretation of nasal leakage to facilitate voicing.

4. Conclusions

The reviewed typological, dialectal and instrumental data indicate that the likelihood of nasalization to combine with other features, in particular voicing, depends to a large extent on physical and perceptual factors. Acoustic-auditory reasons—specifically, laryngeal vibration (but not turbulence generated downstream from the velopharyngeal opening) resonating in the nasal cavities and adding the characteristic perceptual cues to nasalization—have been shown to be at the origin of nasal segments being largely voiced. On the other hand, manipulating the nasal seal to facilitate transglottal flow and vocal fold vibration during the stop constriction accounts for prenasalization and postnasalization of stops and a variety of typological patterns relating nasalization and voicing. The analysis of nasal leakage being used in languages to facilitate and preserve voicing in stops is supported by data indicating that nasals occur predominantly more often in contexts where vocal fold vibration is more difficult to maintain/initiate, for example, in velars vis-à-vis stops at more anterior places, and in phrase-initial vis-à-vis medial position. In addition, while prenasalization is found word- and phrase-initially, postnasalization occurs phrase-finally where voicing is more difficult to sustain due to oral pressure build-up over time and decreasing subglottal pressure.

The review of the data presented here suggests that the propensity of features to combine depends on their articulatory-aerodynamic and acoustic requirements. As stated by Ohala (2005), dependency relations between features due to speech aerodynamics, acoustics or perception cannot be captured by models such as Feature Geometry. For example, the aerodynamic interaction between nasalization and voicing illustrates that what happens at the velum can influence the continuation or extinction of voicing (e.g. in postnasal voicing, preservation of voicing after a nasal) and that what happens at the glottis may be associated to velopharyngeal adjustments (e.g. prenasalization of voiced but not voiceless stops, preservation or emergence of nasals adjacent to voiced stops). Such dependency relations cannot be accounted for in a model where the nasal feature is at a different branch from the laryngeal features, with the result that neither one can specify the value of the other. Similarly, aerodynamic and acoustic factors are at the origin of nasalized voiced fricatives losing frication earlier vis-à-vis voiceless fricatives. Current phonological models, however, do not allow laryngeal features, which are at a different branch from supralaryngeal features, to dictate frication.

For acoustic reasons, the nature and location of the sound source (anterior or posterior to the velopharyngeal opening) determines the acoustic coupling to the nasal cavity and the perceptibility of nasalization (in the case of voiceless vs voiced nasals and nasalized fricatives). Phonological models which represent the place of the supraglottal constriction, the nasal valve and the larynx at different nodes fail to capture the acoustic interactions between the glottal state and perceptibility of nasalization. In addition, finer quantitative detail is needed than what available phonological notations may allow us to represent. For example, in nasalized fricatives, where air flows out of the nose and the mouth, the size of the velopharyngeal opening relative to the area of the oral constriction is crucial because, due to the quantal nature of speech, small variations in the size of either opening may involve an abrupt acoustic change, such as the loss of audible frication and the percept of an approximant.

If, in effect, dependency relations between features or constraints are functional and can be explained by phonetic theory, then there is no need to encode them as constraints in universal grammar as proposed within Optimality Theory. In other words, the common patterning in languages can be accounted for by physical, physiological and auditory factors rather than by 'formal' constraints, and variation across languages would result from the way in which different languages (or dialects) deal with such physical constraints. For example, in the case of voiced stops, languages may either (i) yield to the 'aerodynamic voicing constraint' and devoice stops, or (ii) avert or resist the constraint and preserve voicing with a variety of articulatory maneuvers—such as nasal leakage, oral cavity expansion or decreasing the oral resistance—thus giving rise to the observed cross-linguistic variation. Similarly, in the case of the lower tolerance of voiceless obstruents to nasalization, some languages may yield to the effects of coarticulatory nasalization, and the characteristic burst at stop release may be weakened or absent, leading to the perceptual loss of buccal voiceless stops, other languages may inhibit nasal coarticulation and show an early raising of the velum to the occasional detriment of the nasal, thus preserving the cues for the stop, while still other languages may make the precise alignment of the oral and velopharyngeal gestures so that the nasal and the voiceless stop are preserved. These patterns will certainly be encoded in the grammars of particular languages, given that languages differ in the patterns they exhibit, most likely in the form of allowable ranges of phonetic values for the sounds and sound sequences in the language.

In sum, one should be cautious about positing formal constraints to account for the dependency relations between features—and taking these constraints as being explanatory—when phonetic factors have not been discarded. As we advance in our understanding of the physical, physiological and auditory-perceptual aspects of speech, the need for formal statements of constraints is likely to dwindle significantly.

References

Ali, Latif, Ray Daniloff & Robert Hammarberg. 1979. "Intrusive Stops in Nasal-Fricative Clusters: An aerodynamic and acoustic investigation". *Phonetica* 36:2. 85–97.

Allen, George D. 1985. "How the Young French Child Avoids the Pre-Voicing Problem for Word-Initial Voiced Stops". *Journal of Child Language* 12:1. 37–46.

Arai, Takayuki. 2006. "Cue Parsing between Nasality and Breathiness in Speech Perception". *Acoustical Science and Technology* 27:5. 298–301.

Baer, Thomas. 1975. *Investigation of Phonation Using Excised Larynxes*. Ph.D. dissertation, Massachusetts Institute of Technology, Cambridge, Mass.

Basset, Patricia, Angélique Amelot, Jacqueline Vaissière & Bernard Roubeau. 2001. "Nasal Flow in French Spontaneous Speech". *Journal of the International Phonetic Association* 31. 87–99.

Beddor, Patrice S. 2007. "Nasals and Nasalization: The relation between segmental and coarticulatory timing". *Proceedings of the XVIth International Congress of Phonetic Sciences, Saarbrücken, 6–10 August 2007,* 249–254.

Beddor, Patrice S., Rena A. Krakow & Louis M. Goldstein. (1986). "Perceptual Constraints and Phonological Change: A Study of Nasal Vowel Height". *Phonology Yearbook* 3. 197–217.

Bell-Berti, Fredericka. 1993. "Understanding Velic Motor Control: Studies of Segmental Context". *Nasals, Nasalization, and the Velum* ed. by Marie K. Huffman & Rena A. Krakow, 63–85. San Diego: Academic Press.

Bendor-Samuel, John T. 1966. "Some Prosodic Features in Terena". *In Memory of J.R. Firth* ed. by Charles E. Bazell, John C. Catford, Michael A.K. Halliday & Robert H. Robins, 30–39. London: Longmans.

Blankenship, Barbara. 1997. *The Time Course of Breathiness and Laryngealization in Vowels*. Ph.D. dissertation, University of California, Los Angeles.

Brown, Robert. 2001. "Waris (Walsa) Language". SIL. PNG Language resources. Waris Organised Phonology Data. http://www.pnglanguages.org/pacific/png/pubs/0000361/Waris.pdf

Busà, Maria Grazia. 2007. "Coarticulatory Nasalization and Phonological Developments: data from Italian and English nasal-fricative sequences". *Experimental Approaches to Phonology* ed. by Maria-Josep Solé, Patrice Speeter Beddor & Manjari Ohala, 155–174. Oxford: Oxford University Press.

Clark, Eve V. & Melissa Bowerman. 1986. "On the Acquisition of Final Voiced Stops". *The Fergusonian Impact*: *From phonology to society* ed. by Joshua A. Fishman, vol. 1, 51–68. Berlin: Mouton de Gruyter.

Cohn, Abigail C. 1990. "Phonetic and Phonological Rules of Nasalization". *UCLA Working Papers in Phonetics* 76. 1–224.

——— 1993. "The Status of Nasalized Continuants". *Nasals, Nasalization and the Velum* ed. by Marie K. Huffman & Rena A. Krakow, 329–367. San Diego: Academic Press.

Dantsuji, Masatake. 1984. "A Study on Voiceless Nasals in Burmese". *Studia Phonologica* XVIII. 1–14.

——— 1986. "Some Acoustic Observations on the Distinction of Place of Articulation for Voiceless Nasals in Burmese". *Studia Phonologica* XX. 1–11.

Demolin, Didier. 2007. "Coarticulatory Timing and Aerodynamics of Nasals and Nasalization". *Proceedings of the XVIth International Congress of Phonetic Sciences, Saarbrücken*, *6–10 August 2007,* 271–274.

Dols, Nicolau & Max W. Wheeler. 1995. "El Consonantisme Final del Mallorquí i el 'Llicenciament d'Obertures'". *Caplletra* 19. 51–64.

Fant, Gunnar. 1960. *Acoustic Theory of Speech Production*. The Hague: Mouton.

Firchow, Irwin B. & Jacqueline Firchow, J. 1969. "An Abbreviated Phoneme Inventory". *Anthropological Linguistics* 11. 271–276.

Gregores, Emma & Jorge Suarez. 1967. *A Description of Colloquial Guaraní*. The Hague: Mouton.

Halle, Morris & George N. Clements. 1983. *Problem Book in Phonology*. Cambridge: MIT Press.

Hayes, Bruce & Tanya Stivers. 2000. "Postnasal Voicing". Ms., Dept. of Linguistics, UCLA.

Herbert, Robert K. 1986. *Language Universals, Markedness Theory, and Natural Phonetic Processes*. New York: Mouton de Gruyter.

Henton, Caroline, Peter Ladefoged & Ian Maddieson. 1992. "Stops in the World's languages". *Phonetica* 49. 65–101.

Huffman, Marie K. 1990. "Implementation of Nasal: Timing and Articulatory Landmarks". *UCLA Working Papers on Phonetics* 75. 1–149.

Hyman, Larry. To appear. "Universals in Phonology". *The Linguistic Review*. http://linguistics.berkeley.edu/phonlab/annual_report/2007/Hyman_Phono_Universals_PL.pdf

Itô, Junko, Armin Mester & Jaye Padgett. 1995. "Licensing and Underspecification in Optimality Theory". *Linguistic Inquiry* 26. 571–614.

Iverson, Gregory K. & Joseph C. Salmons. 1996. "Mixtec Prenasalization as Hypervoicing". *International Journal of American Linguistics* 62:2. 165–175.

Jakobson, Roman, Gunnar Fant & Morris Halle. 1951. *Preliminaries to Speech Analysis*. Cambridge: The MIT Press.

Jones, Mark J. 2001. "The Historical Development of a Phonological Rarity: postnasalized stops in Lancashire dialects". Paper presented at the *9th Manchester Phonology Meeting*. http://kiri.ling.cam.ac.uk/mark/Jones%20Marshside%20Man%20Phon%202001.pdf

Kager, René, Suzanne van der Feest, Paula Fikkert, Annemarie Kerkhoff & Tania S. Zamuner. 2007. "Representations of [voice]: Evidence from Acquisition". *Voicing in Dutch: (De)voicing, phonetics, phonology and psycholinguistics* ed. by Jeroen van de Weijer & Erik Jan van der Torre, 41–80. Amsterdam: John Benjamins.

Kaiser, L. 1934. "Contribution to the Description of Stops in the Sumbanese Language". *Arch- Neerl. Phon.*10. 58–64.

Kim, Jong-Ryoul., David J. Zajac, Donald W. Warren, Robert Mayo & Greg K. Essick. 1997. "The Response to Sudden Change in Vocal Tract Resistance during Stop Consonant Production". *Journal of Speech, Language, and Hearing Research* 40:4. 848–857.

Kohler, Klaus. 2001. "Plosive-Related Glottalization Phenomena in Read and Spontaneous Speech. A stød in German?". *To Honour Eli Fischer-Jørgensen. Travaux du Cercle Linguistique de Copenhague*, vol. 31, ed. by Nina Grønnum & Jørgen Rischel, 174–211. Copenhagen: Reitzel.

Kong, Eunjong, Mary E. Beckman & Jan Edwards. 2007. "Fine-Grained Phonetics and Acquisition of Greek Voiced Stops". *Proceedings of the XVIth International Congress of Phonetic Sciences, Saarbrücken, 6–10 August 2007,* 865–868.

Kuehn, David. P. & Jerald B. Moon. 1998. "Velopharyngeal Closure Force and Levator Veli Palatini Activation Levels in Varying Phonetic Contexts". *Journal of Speech, Language, and Hearing Research* 41. 51–62.

Labov, William & Teresa Labov. 1978. "The Phonetics of *Cat* and *Mama*". *Language* 54: 816–852.

Ladefoged, Peter & Ian Maddieson. 1996. *The Sounds of the World's Languages*. Oxford: Blackwell.

Laver, John. 1994. *Principles of Phonetics*. Cambridge: Cambridge University Press.

Lewis, Anthony M. In press. "The Production and Perception of Initial /b, d, g/ in Spanish by Spanish-English Bilinguals". Paper presented at the *3rd Conference on Laboratory Approaches to Spanish Phonology*, University of Toronto, October 2006.

Lisker, Leigh & Arthur S. Abramson. 1971. "Distinctive Features and Laryngeal Control". *Language* 47. 767–785.

Llach, Silvia. 1999. "La Neutralització de la Sonoritat en els Grups Consonàntics Finals de les Formes Verbals sense Terminació en Mallorquí". *Proceedings of the 1st Congress of Experimental Phonetics, Tarragona*, 241–248. Barcelona: Universitat de Barcelona.

Maddieson, Ian. 1983. "The Analysis of Complex Phonetic Elements in Bura and the Syllable". *Studies in African Linguistics* 14. 285–310.

——— 1984. *Patterns of Sounds*. Cambridge: Cambridge University Press.

Maddieson, Ian & Peter Ladefoged. 1993. "Phonetics of Partially Nasal Consonants". *Nasals, Nasalization, and the Velum* ed. by Maria K. Huffman & Rena A. Krakow, 251–301. San Diego: Academic Press.

Malécot, André. 1960. "Vowel Nasality as a Distinctive Feature in American English". *Language* 36. 222–229.

Matisoff, James A. 1975. "Rhinoglottophilia: the mysterious connection between nasality and glottality". *Nasálfest: Papers from a Symposium on Nasals and Nasalization* ed. by Charles A. Ferguson, Larry M. Hyman & John J. Ohala, 265–287. Stanford: Language Universals Project.

Mills, Roger F. 1975. *Proto South Sulawesi and Proto Austronesian Phonology*. Ph.D. dissertation, University of Michigan.

Nasukawa, Kuniya. 2005. *A Unified Approach to Nasality and Voicing*. Berlin: Mouton de Gruyter.

Nihalani, Paroo. 1975. "Velopharyngeal Opening in the Formation of Voiced Vtops in Sindhi". *Phonetica* 32. 89–102.

Ohala, John J. 1975. "Phonetic Explanations for Nasal Sound Patterns". *Nasálfest: Papers from a Symposium on Nasals and Nasalization* ed. by Charles A. Ferguson, Larry M. Hyman & John J. Ohala, 289–316. Stanford: Language Universals Project.

——— 1983. "The Origin of Sound Patterns in Vocal Tract Constraints". *The Production of Speech* ed. by Peter MacNeilage, 189–216. New York: Springer Verlag.

——— 1997. "Aerodynamics of Phonology". *Proceedings of the 4th Seoul International Conference on Linguistics* [SICOL], 92–97.

——— 2005. "Phonetic Explanations for Sound Patterns. Implications for grammars of competence". *A Figure of Speech. A Festschrift for John Laver* ed. by William J. Hardcastle & Janet M. Beck, 23–38. London: Erlbaum.

Ohala, John J. & Maria Grazia Busà. 1995. "Nasal Loss before Voiceless Fricatives: a perceptually-based sound change". *Rivista di Linguistica* 7:1. 125–144.

Ohala, John J. & Manjari Ohala. 1993. "The Phonetics of Nasal Phonology: Theorems and data". *Nasals, Nasalization and the Velum* ed. by Marie K. Huffman & Rena A. Krakow, 225–249. San Diego, Calif.: Academic Press.

Ohala, John & Carol Riordan. 1979. "Passive Vocal Tract Enlargement during Voiced Stops". *Speech communication papers* ed. by Jared J. Wolf & Dennis H. Klatt, 89–92. New York: Acoustical Society of America.

Ohala, John J., Maria-Josep Solé & Goangshiuan Ying. 1998. "The Controversy of Nasalized Fricatives". *Proceedings of the16th International Congress on Acoustics (ICA/ASA), Seattle, Washington,* 2921–2922.

Ohala, Manjari & John J. Ohala. 1991. "Nasal Epenthesis in Hindi". *Phonetica* 48. 207–220.

Orton, Harold & Wilfrid J. Halliday, eds. 1963. *Survey of English Dialects. Volume I. The Six Northern Counties and the Isle of Man*. Leeds: E.J. Arnold.

Pape, Daniel, Christine Mooshammer, Phil Hoole & Susanne Fuchs. 2003. "Devoicing of Word-Initial Stops: A consequence of the following vowel?" *Proceedings of the 6th International Seminar on Speech Production*, *Manly, Sydney, Australia,* 207–212.

Pater, Joe. 1999. "Austronesian Nasal Substitution and other NC Effects". *The Prosody-Morphology Interface* ed. by René Kager, Harry van der Hulst & Wim Zonneveld, 310–343. Cambridge: Cambridge University Press.

Piggot, Glenn. 1992. "Variability in Feature Dependency". *Natural Language and Linguistic Theory* 10. 33–77.

Piñeros, Carlos-E. 2003. "Accounting for the Instability of Palenquero Voiced Stops". *Lingua* 113:12. 1185–1222.

Pulleyblank, Douglas. 1997. "Optimality Theory and Features". *Optimality Theory* ed. by Diana Archangeli & D. Terence Langendoen, 59–101. Malden: Blackwell.

Raphael, Lawrence J., Michael F. Dorman, Frances Freeman & Charles Tobin. 1975. "Vowel and Nasal Duration as Cues to Voicing in Word-Final Stop Consonants: Spectrographic and Perceptual Studies". *Journal of Speech and Hearing Research* 18. 389–400.

Raymond, William D., Robin Dautricourt & Elizabeth Hume. 2006. "Word-Internal /t, d/ Deletion in Spontaneous Speech. Modeling the effects of extralinguistic, lexical, and phonological factors". *Language Variation and Change* 18. 55–97.

Recasens, Daniel, Aina Espinosa & Antoni Solanas. 2004. "Underlying Voicing in Majorcan Catalan Word-Final Stop-Liquid Clusters". *Phonetica* 61. 95–118.

Rohlfs, Gerhard. 1949. *Historische Grammatik der Italianischen Sprache und ihrer Mundarten.* Vol. 1. Bern: A. Francke AG. Verlag.

Rohlfs, Gerhard. 1970. *Les gascons. Études de Philologie Pyrénéenne.* Tübingen: Max Niemeyer Verlag.

Rothenberg, Martin. 1968. The Breath-Stream Dynamics of Simple-Released-Plosive Production. Basel: Karger.

Schadeberg, Thilo C. 1982. "Nasalization in Umbundu". *Journal of African Languages and Linguistics* 4. 109–132.

Shosted, Ryan. 2006. *The Aeroacoustics of Nasalized Fricatives.* Ph.D. dissertation, University of California, Berkeley.

Slifka, Janet. 2000. *Respiratory Constraints on Speech Production at Prosodic Boundaries*. Ph.D. dissertation, Massachusetts Institute of Technology, Cambridge, Mass.

Smith, Geoff P. 2002. *Growing up with Tok Pisin: Contact, creolization and change in Papua New Guinea's national language.* London: Battlebridge Publications.

Solé, Maria-Josep. 2007. "The Stability of Phonological Features within and across Segments. The effect of nasalization on frication". *Segmental and Prosodic Issues in Romance Phonology* ed. by Pilar Prieto, Joan Mascaró & Maria-Josep Solé, 41–65. Amsterdam: John Benjamins.

Steinbergs, Aleksandra. 1985. "The Role of MSC's in OshiKwanyama Loan Phonology". *Studies in African Linguistics* 16:1. 89–101.

Stemberger, Joseph P. & Barbara H. Bernhardt. 1999. "The Emergence of Faithfulness". *The Emergence of Language* ed. by Brian MacWhinney, 417–446. Mahwah, NJ: LEA.

Stevens, Kenneth N. 1998. *Acoustic Phonetics.* Cambridge, Mass.: The MIT Press.

Storto, Luciana & Didier Demolin. Submitted. "Control and Timing of Articulatory Gestures in pre- and post-Oralized Nasals in Karitiana". *Phonetica*.

Stringer, Mary & Joyce Hotz. 1973. "Waffa Phonemes". *The Language of the Eastern Family of the East New Guinea Highland Stock* ed. by Howard McKaughan, 523–529. Seattle: University of Washington Press.

Teil-Dautrey, Gisèle. 1991. *Evolution Phonétique d'une Langue Bantoue du Nord-Oues: Le Basaa*. Ph.D. dissertation, Universite Lumière-Lyon II.

Teoh, Boon Seong. 1988. *Aspects of Malay Phonology Revisited. A non-linear approach*. Ph.D. dissertation, University of Illinois at Urbana-Champaign.

Turner, Ralph L. 1924. "The Sindhi Recursives or Voiced Stops Preceded by Glottal Closure." *Bulletin of the School of Oriental Studies,* vol. 3.2: 301–315.

Vaux, Bert. 1998. *The phonology of Armenian*. Oxford: Clarendon Press.

Ward, Ida C. 1939. "A Short Phonetic Study of Wolof (Jolof) as Spoken in the Gambia and in Senegal". *Africa* 12. 320–334.

Warren, Donald W. 1986. "Compensatory Speech Behaviors in Individuals with Cleft Palate: A regulation/control phenomenon?". *Cleft Palate Journal* 23:4. 251–260.

Whalen, Dough H & Patrice S. Beddor. 1989. "Connections between Nasality and Vowel Duration and Height: Elucidation of the Eastern Algonquian Intrusive Nasal". *Language* 65: 457–486.

Westbury, John R. 1983. "Enlargement of the Supraglottal Cavity and its Relation to Stop Consonant Voicing". *Journal of the Acoustical Society of America* 73. 1322–1336.

Westbury, John R. & Patricia A. Keating. 1986. "On the Naturalness of Stop Consonant Voicing". *Journal of Linguistics* 22. 145–166.

Wiebe, Brent. 1997. "Bola (Bola-Bakovi) Language". SIL. PNG Language resources. Bola Organised Phonology Data. http://www.pnglanguages.org/pacific/png/pubs/0000069/Bola.pdf

Wright, Peter. 1952. "Parasitic Syllabic Nasals at Marshside, Lancashire". *Leeds Studies in English* 7–8. 92–96.

Yamane-Tanaka, Noriko. 2005. "The Implicational Distribution of Prenasalized Stops in Japanese". *Voicing in Japanese* ed. by Jeroen van de Weijer, Kensuke Nanjo & Tetsuo Nishihara, 123–156. New York: de Gruyter.

Zue, Victor W. & Martha Laferriere. 1979. "Acoustic Study of Internal /t, d/ in American English". *Journal of the Acoustical Society of America* 66. 1039–1050.