Turbulence & Phonology

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In this paper we aim to provide an account of some of the phonological patterns involving turbulent sounds, summarizing material we have published previously and results from other investigators. In addition, we explore the ways in which sounds pattern, combine, and evolve in language and how these patterns can be derived from a few physical and perceptual principles which are independent from language itself (Lindblom 1984, 1990a) and which can be empirically verified (Ohala and Jaeger 1986). This approach should be contrasted with that of mainstream phonological theory (i.e., phonological theory within generative linguistics) which primarily considers sound structure as motivated by 'formal' principles or constraints that are specific to language, rather than relevant to other physical or cognitive domains.

For this reason, the title of this paper is meant to be ambiguous. The primary sense of it refers to sound patterns in languages involving sounds with turbulence, e.g., fricatives and stops bursts, but a secondary meaning is the metaphorical turbulence in the practice of phonology over the past several decades. We'll treat the latter topic first.

1. Turbulence in Phonology

Anyone familiar with the history of phonological science in the 20th century will have to concede that there has been considerable turbulence in the theoretical domain. To be sure, there were controversies in phonology in the 19th century, too, for example, the dispute as to whether Sanskrit should be taken as the oldest ancestor of what became known as the Indo-European language family or whether an attempt should be made to reconstruct a parent language of which even Sanskrit was an off-shoot. Schleicher, the advocate of the latter view, eventually won that dispute. There were also disputes as to the causes and mechanisms of sound change; these disputes have not been satisfactorily resolved even to this day. Nevertheless, this domain of phonological science -- historical linguistics -- made steady and remarkable progress from its beginning in the18th century (e.g., ten Kate 1723, des Brosses

1765)[1]. The methodology, the "comparative method", has been refined and proven itself. Beginning around the turn of the 19th to 20th centuries, a new program developed, spurred by the writings of Kruzewski, Baudouin de Courtenay, Saussure, Sapir and others. This was to be an account of the psychological aspect of language, i.e., how individual distinctive speech sounds and their contextual variants arise and are maintained and managed in the mind of the speaker-hearer. Turbulence in linguistic theory arose when patterns arising from physical and physiological factors, that had previously been judged to be extra-linguistic, were claimed by generative grammarians in the mid-20th century to be incorporated into the posited psychological lexicon and grammar of the speaker. The dust still hasn't settled on this controversy. In form these supposed psychological representations of language and the methods used to discover them were largely identical to the descriptive entities and methods of the historical phonologist.

Against this historical background, we declare that the explanations we give below for sound patterns involving noise (turbulence) are strictly physical phonetic. In our view there is no mystery about how physical phonetic factors can become phonologized and manifested in languages' sound patterns: the variation in the speech due to these physical constraints can lead to the listener's misperception, misparsing, and misconstruing of the speaker's target pronunciation. Listener error, then, can lead to a change in the pronunciation norms just as manuscript copyists' error led to different variants of ancient texts in the time before printing (Ohala 1981b, 1989).

The ultimate purpose of the experimental approach to phonology illustrated in this paper is to demonstrate that phonological theory must be based on mechanisms and principles coming from the subsystems involved in speech production and speech perception (Ohala 1981a, 1981b, 1992).

For ease of presentation, we group the sound patterns according to aerodynamic factors (section 2), acoustic-auditory factors (section 3), and timing factors (section 4), but most of the patterns involve the interaction between a number of these factors.

2. Aerodynamic factors relevant to turbulence

2.1. Basic principles

From an aerodynamic point of view, we can think of the vocal tract as two air cavities, the lung cavity and the supraglottal cavity, ultimately connected to the atmosphere. The two cavities are connected by the glottis which allows pulmonic air to flow into the oral cavity as

[1] Not to neglect worthy precursors even before that, e.g., van Boxhorn (1647)

pulmonic forces (from muscular activity or passive recoil) compress the lungs. The supraglottal cavity is connected to the atmosphere by the mouth (and the nose) which can impede the air flowing out with changes in articulatory constriction of the lips and tongue. Thus the two main valves (along with the nasal valve) that regulate the airflow used in speech are the glottis and the oral constriction, and turbulent noise can be generated at both of these constrictions.

The generation of audible turbulence, i.e., noise, in the vocal tract is necessary for the production of fricatives, the fricative release of affricates and the burst of stops. However, audible turbulence may also be associated with the production of vowels and sonorants in certain conditions. Although there is some degree of low-level air flow turbulence even for the most open of speech sounds, i.e., something like [ɛ] (because the air flowing into the vocal tract acquires some turbulence upon passing through the vibrating vocal cords) it is only when the turbulence reaches a level to become audible that it can play some role in speech.

Turbulent airflow is determined by a multiplicity of factors, including roughness and length of the channel, shape of the orifice, and whether the air downstream of the constriction is already turbulent, but it is the *speed* of air flowing through the constriction which is the main factor. The speed of air (or 'particle velocity', *v*), in turn, depends on the volume of air flowing through the constriction (called the 'volume velocity', *U*) and on the cross-sectional area of the constriction (A), as indicated in (1). Thus the larger the volume of air per unit time and the smaller the constriction, the higher the velocity, and the more intense the frication noise.

$$v = U/A \qquad (1)$$

where *v* is the particle velocity in cm/sec; *U* is the volume velocity in cm^3/sec, *A* is the cross-dimensional area of the constriction in cm^2.

The volume of air, *U*, that will flow through a constriction depends on the size of the aperture, A, and the pressure difference across the aperture, that is, the difference between the upstream pressure and downstream pressure, $P_{upstream}$-$P_{downstream}$, as shown in (2) (Warren and DuBois 1964). In the case of an oral constriction, this will be the difference in pressure between the oral cavity and the atmosphere (P_{oral}-$P_{atmospheric}$)[2], and in the case of a glottal

[2] Although atmospheric pressure (absolute) is roughly 1033 cm H_2O at sea level, it is common to take atmospheric pressure as zero (0) and express pressure in the vocal tract as *x* cm H_2O with respect to that. Nothing is lost with such a mathematical convention.

constriction, the difference in pressure between the subglottal (or pulmonic) cavity and the oral cavity ($P_{subglottal}$-P_{oral}). The greater the difference in pressure and the larger the area of the constriction, the larger the rate of flow. The exponent, *a*, varies between .5 and 1, depending on the nature of the flow; it is 1 when the flow is smooth or laminar, and .5 when the flow is turbulent. In the conditions found in speech production, i.e., what is called 'nozzle flow', this number may vary continuously between these two extremes (Jaeger and Matthys 1970). Naturally, the direction of air flow will always be from the cavity with greater pressure to that with lesser pressure.

$$U = A\,(P_{upstream} - P_{downstream})^{a}\,c \qquad or \qquad U = A\,(\Delta P)^{a}\,c \tag{2}$$

where *P* is the pressure in cm H_2O; *c* is a constant.

As mentioned, traditionally, the critical velocity at which the change from laminar to turbulent flow occurs is determined by a number of factors, including particle velocity, the diameter and roughness of the channel the air passes through, etc. The relative contribution of these factors for certain flow conditions is quantified in the Reynolds number. When the Reynolds number exceeds a certain threshold the airflow is supposed to change from smooth or 'laminar' to turbulent. However, it is the case that in irregularly-shaped channels like the vocal tract and with airflow that usually has a turbulent entry into the vocal tract (certainly the case as the air passes several "rough" surfaces –narrow alveoli in the lungs, tracheal rings, vocal cords, ventricular folds, epiglottis, etc.), some turbulence, even audible turbulence can occur in conditions where the Reynolds number is far below the ideal threshold between laminar and turbulent flow. So it is simplest just to state the relation between air velocity and noise in a purely qualitative way: the intensity (i.e., loudness) and center frequency (i.e., pitch) of frication noise varies monotonically with the particle velocity of the air flow, as given in (3a), below (Catford 1977: ch. 3; Stevens 1971; Flanagan and Ishizaka 1976; Flanagan, Ishizaka, and Shipley 1975, 1980; Shadle 1990). A variant of this relation, stating that intensity of frication at a supraglottal constriction increases with increasing oral pressure and decreasing aperture of constriction (therefore, conflating principles 1 and 2), is given in (3b) (Stevens 1971).

$$I_{frication} \sim v \tag{3a}$$

$$I_{frication} \sim P_o^{3/2}\,A^{1/2} \tag{3b}$$

The articulatory constriction for vowels, glides and sonorants is not typically narrow enough to cause a pressure difference across the constriction (in other words, P_{oral} is not much higher than $P_{atmospheric}$), so that particle velocity, *v*, through the constriction is kept low and does not reach a level sufficient to generate audible frication (but see below for exceptions when these are voiceless). Obstruents such as fricatives, stops and affricates, on the other hand, are produced with a narrow or complete constriction which causes the P_{oral} to rise substantially over $P_{atmospheric}$; upon release the particle velocity is high and the airflow becomes more turbulent.

Additional turbulence can be also generated when an air jet that has passed through the major oral cavity constriction encounters any sharp discontinuity: either an abrupt enlargement of the channel or the opposite, i.e., an additional barrier or "baffle". The former occurs (a) when air passes through the vocal cords during voicing ("voicing" consists of periodic short-term noise bursts occurring at a rate equal to the fundamental frequency) and (b) when the air flows past the sharp-edged constriction at the teeth in a labio-dental fricative such as [f]. The latter occurs when an air jet emerging from an apical-alveolar constriction is directed at the upper and lower incisors. (It is this factor which accounts for the somewhat impoverished apical fricatives made by children who have lost their incisors as part of the change from baby teeth to permanent dentition at approximately age 6 and on.)

A final factor needs to be mentioned regarding the acoustic amplitude of the noise which the turbulence generates: other things being equal, the intensity of the noise is greater, the larger is the resonating cavity downstream of the point where the turbulence occurs. For this reason palatal and velar fricatives have more intense noise than labial and labio-dental fricatives.

2.2. Generalizations on phonetic and phonological universals deduced from aerodynamic principles

In the following sections we review a number of sound patterns, involving the emergence or extinction of turbulence, which can be deduced in part from variations in glottal flow, U_g (section 2.2.1), changes in area of oral constriction, A_o (2.2.2), and changes in oral pressure, P_o (2.2.3).

2.2.1. Variations in glottal flow

It is known that the glottis regulates the flow of air from the lungs into the oral cavity. Vibration at the vocal folds for voiced obstruents causes a diminished rate of flow through the glottis and a significantly lower oral pressure vis-à-vis voiceless obstruents which, in contrast, have a large glottal opening and continuous flow. A relatively low oral pressure is necessary to maintain a sufficient pressure differential across the glottis so that there will be continuous transglottal flow and thus voicing during the obstruent[3].

Since by principles (2) and (3), intensity of turbulence is dependent on the pressure difference across the oral constriction, a lower oral pressure for voiced obstruents will result in a lower intensity of high frequency noise during the fricative constriction or at stop release vis-à-vis voiceless obstruents. In addition, due to the reduced transglottal flow, voiced obstruents take longer to build up oral pressure behind the oral constriction, which results in a delayed onset of audible frication for fricatives (Solé 2002b) and a weaker burst for stops compared to their voiceless counterparts. Thus, the characteristic cues for obstruency – abrupt amplitude discontinuities and high intensity noise cues – are enhanced in voiceless obstruents due to the larger rate of flow through the glottis. In sum, for aerodynamic and auditory-acoustic reasons *voicelessness favors or enhances obstruency* (i.e., high intensity frication and release burst). The following phonological generalizations can be derived from this principle.

I. Voicelessness favors obstruency

A. Sonorants (glides, laterals and nasals) become fricatives when devoiced.

As stated in 2.1, the common description of the articulatory difference between an approximant and a fricative is that they have different degrees of constriction (e.g., Clark and Yallop 1990:81; Laver 1994: 134-135). A difference based on constriction degree is endorsed by the present structure of the IPA phonetic alphabet. While this is generally an adequate description, there are cases with considerable phonological interest where this is not completely true.

In general, approximants have a constriction that is large enough to allow the airstream to flow through it without causing turbulence. Nevertheless, by equation (1), $v = U/A$, they may cross the threshold into obstruents if the constriction (A) narrows further or if a higher rate of

[3] Other factors have been reported to contribute to keeping a low oral pressure for voiced obstruents, for example, an increased volume of the oral cavity (Ewan and Krones 1972; Kent and Moll, 1969; Bell-Berti 1975) and/or intentional relaxation of vocal tract muscles resulting in more passive expansion of the walls (Svirsky, Stevens, Matthies, Manzella, Perkell, and Wilhelms-Tricarico 1997).

flow (*U*) passes through the same constriction. Approximants, e.g., [ʊ j w l ɹ ɻ], and nasals, which by definition are non-obstruents, are usually voiced. When voiceless, however, without any variation in the configuration of the oral articulators, they can become fricative (and thus obstruents), e.g., [f ç ʍ ɸ ɬ r̥ s̬] and [m̥ n̥ ɲ̥ ŋ̊]. This happens simply due to the increased airflow passing through the constriction created by these consonants -- the increased airflow being caused by the greater opening (and thus lesser resistance to airflow) at the glottis (see Catford 1977:120ff.). Thus, it is the higher rate of flow through the glottis which creates the higher particle velocity of the airflow through the supraglottal constriction (velocity being directly proportional to flowrate, for a given aperture, $v = U/A$) and leads to turbulence. Hence the obstruent character of the voiceless (former) sonorants. Some phonological consequences of the frication of devoiced sonorants are the following.

A.1. Laterals and /r/s

First, there are cases where a fricative and an approximant alternate and there is co-variation between frication and voicelessness, such that the fricative is voiceless and the approximant is voiced. For example, in Kwakiutl (Boas 1947) there are morphophonemic alternations between 'plain' (voiceless), 'hardened' (ejectives), and 'weakened' (voiced) obstruents and laterals. Of special interest is the fact that the lateral alternates also in manner: the plain voiceless is a fricative /ɬ/ and the weakened form is the voiced approximant /l/, as illustrated in (1). In Welsh (Ball and Williams 2000) there are morphophonemic alternants known as 'soft mutation', involving the alternation of voiced-voiceless pairs. Part of these alternations involves the alternation of voiceless and voiced laterals and trills, with the voiceless counterpart being fricative [ɬ] and [r̥] (spelled 'll' and rh', respectively) and the voiced, simple sonorants [l], [r], see example (2).

(1) Kwakiutl (transcription simplified and converted to IPA) (Boas 1947)

/t͡s'ōɬ/ 'to be black'

/t͡s'ōlato/ 'black-eared'

(2) Welsh (Ball and Williams 2000)

llyfr	[ɬ]	'book'
ei lyfr	[l]	'his book'

A.2 Glides

In Northern and Central Standard Swedish preaspiration of voiceless stops following stressed vowels has commonly been observed. However, fricativization rather than aspiration is produced between long high vowels, which are diphthongal, and the voiceless stop (Millardet 1911; Rositzke 1940; Helgason 2002: 88). No frication, however, is found for the non-high vowels, see (3). Helgasson (2002) notes another factor which may contribute to the observed friction: the tendency to produce friction noise at the end of long, close vowels, regardless of whether or not a consonant follows (e.g. *bi* [biˌj] 'honey bee'; *gud* [gʉ̟βd] 'God'). Particularly, in a sequence of a long, close vowel and a voiceless stop, the early glottal abduction for the stop (i.e., preaspiration) during the preceding high vowel will enhance the tendency for friction by increasing the velocity of air across the oral constriction. Similar patterns have been reported for the Jutland dialect of Danish by Andersen (1972).

(3) Fricated glides in Swedish (Millardet 1911; Rositzke 1940)

bit [biçt]	'a bit, a bite'
kut [kʉ̟ɸt]	'seal puppy'
BUT:	
tack [tahk:]	'thanks'
peka [pehkᵽ]	'point'

Bauer (1982) reports fricativization of syllable-initial /w/ into either a voiceless bilabial fricative [ɸ] or a voiced labio-dental fricative /v/ in Hong-Kong Cantonese. The voiceless realization —with increased flow of air through the open glottis— may well give rise to turbulence at the oral constriction, without changing the articulatory configuration. However, considering that a voiced realization may also give way to frication, in the pronunciation /v/, we cannot dismiss the possibility that a closer articulatory constriction syllable initially is responsible for the turbulence and spirantization.

Some varieties of American English retain the older pronunciation [ʍ], a labial velar fricative, in words such as *which, whether*, and *white*, rather than the voiced approximant [w]. The correspondence of the voiceless fricative and the voiced glide illustrates the covariation between voicing and frication.

A.3 Nasals

In voiced nasals, vocal fold vibration resonates in the oral and nasal cavities resulting in the low frequency resonances and zeroes characteristic of nasals. Voiceless nasals, on the other hand, have an open glottis for most of the oral closure giving rise to turbulence generated primarily at the nostrils (the point of maximum constriction) no matter what the place of articulation of the nasal. Since the turbulence generated at the nostrils is not very intense and is not amplified and shaped by a downstream cavity[4], the frication has a weak intensity and there will not be much spectral difference between [m̥ n̥ ɲ̥ ŋ̊] during the consonant constriction, though of course they can be still be differentiated by their transitions in adjacent vowels. Although Maddieson (1983), reports that spectral differences may be found during the voiceless portion, nevertheless, as noted, place distinctions in voiceless nasals are obscure. Even so, many languages with distinctive voiceless nasals usually have them at more than one place of articulation. These voiceless nasals usually have a brief voiced period in the last portion of the oral closure, thus they are phonetic sequences [n̥n], etc. In this way different places of articulation can be differentiated —both by the distinctive resonances of the voiced nasal and the transitions in adjacent vowels.

Evidence that voiceless nasals are obstruent-like, specifically, fricatives is provided by Ohala & Ohala (1993). First, distinctive voiceless nasals frequently derive from original /s/+nasal clusters. This is the case for Burmese, where present-day /n̥a/ 'nose' stems from Proto-Burmese-Loloish **sna* (Bradley 1979), and corresponds to orthographic *sna* in Tibetan. Parallel cases are found in Primitive Greek and Old Irish, where /m̥/ and /n̥/ seem to derive from Indo-European *sm,*sn. Second, children learning English sometimes produce target #*sm*- and #*sn*- as [m̥] and [n̥], e.g. [m̥æk] *smack* and [n̥id] *sneeze* (references in Ohala & Ohala 1993: 233). These cases suggest that the voiceless nasal is an adequate auditory substitute for a fricative.

B. Emergence of 'buccal' fricatives due to /h/ coarticulating with high vowels

A related phonological pattern, due to the interaction of aerodynamic and acoustic factors, is the emergence of supraglottal fricatives when /h/ is coarticulated with high vowels. For example, the glottal fricative /h/ in Japanese has distinct palatal, [ç], and labial, [ɸ], variants before high front and high back vowels, respectively, and [h] before more open vowels. This

[4] The sound source excites mostly the cavities anterior to the constriction where the sound is generated, whereas the back cavities do not contribute much acoustically (Fant 1960, Stevens 1998). Since the oral and nasal cavities posterior to the nostrils do not contribute resonances, the different nasals do not differ much acoustically.

is illustrated in (4) below. (Note that high vowels are allophonically devoiced between voiceless sounds and optionally devoiced when following a voiceless consonant or utterance-finally):

(4) *hikaku*	/hikakɯ/	[ç̥ikakɯ]	'comparison'
futa	/hɯta/	[ɸɯ̥ta]	'lid'
BUT:			
happyaku	/happjakɯ/	[hapʲ:akɯ]	'eight hundred'

In present-day English, /h/, which is the voiceless version of the following vowel or glide (Lehiste 1964, ch. 5), has the fricative allophone [ç] before /j/ and /i:/, Hugh (a name) [çju:], heal [çi:ɬ]. Similarly, in Fante /h/ is phonetically [ç] before /ɪ/ (Schahter and Fromkin 1968). The emergent fricatives in Swedish, illustrated in (3) above, are a further example[5].

In segments involving a glottal and a supraglottal constriction, and turbulent noise generated at both of these constrictions as is the case for voiceless high vowels and sonorants− acoustic factors are also relevant. In general terms, in sounds with more than one constriction, the major noise source is contributed by the constriction with a smaller cross-sectional area, other things being equal (e.g., smoothness of the channel surface, presence of an obstacle). The area of supraglottal constriction for high vowels like [i] and [u] is about 0.2 to 0.3 cm^2 (Chiba and Kajiyama 1941; Fant 1960; Baer, Gore, Gracco and Nye 1991), and hence comparable to the area of the open glottis, approximately 0.3cm^2 (Stevens 1998: 37). Thus, if the two constrictions are of about the same size ($A_o = A_g = 0.3$ cm^2) the relative noise level at each constriction is about the same. However, the transfer function of the two sources is not the same, the major noise source is contributed by the outer constriction (Stevens 1998: 442-3). This is because the cavity anterior to the outer constriction enhances the amplitude of the frequencies of the front-cavity resonance for [i] (F3 peak), and thus palatal frication dominates over glottal frication. Similarly, for [ɯ] [u] the amplitude of the labial or velar frication (F2 peak) is greater. Hence the distinct 'buccal' fricatives resulting from voiceless high vowels.

C. Stop releases engender frication on adjacent glides, high vowels and sonorants

[5] A related phenomenon is the preservation of Latin word-initial /f/ only before /w/ in Spanish (e.g., *fuente* ['fwente]< *fonte* 'fountain'). /f/ became /h/ and was later lost preceding all other vowels (e.g., *hablar* [a'β̞ laɾ] <*fabulare* 'to talk', *hierro* ['jero]< *ferru* 'iron', *hondo* ['ondo] < *fundu* 'deep') (Menéndez Pidal 1968: 122).

A stop release is in itself a brief period of turbulence noise – due to the high rate of airflow which arises from the high back pressure developed during the consonantal closure. However in some cases the turbulence noise is prolonged at the release of a stop followed by a high vowel or a glide and this leads to the emergence of a fricative (Stevens 1971, Ohala 1983b) . When a stop is followed by segments involving a high tongue position, such as high vowels and glides (and to a certain extent liquids /r, l/), the air pressure build-up behind the stop constriction is released through a narrow channel (A) which offers a high resistance to exiting air and thus increases the particle velocity and turbulence (by equation (1)). It can take a few tens of milliseconds for the P_{oral} to approach $P_{atmospheric}$ and during this time the air will be forced through the constriction at a higher rate. Hence the initial portions of the vowel or glide can be fricated. The phonologization of the stop as an affricate is due to the listener parsing the prolonged frication with the stop, not the vowel. Such emergent affricates do not develop before more open vowels with a wider constriction.

In addition, onset of vocal fold vibration after a stop is delayed in high vowels and glides vis-à-vis open vowels (Ohala 1976, 1981a, 1983b, Chang 1999), due to the slower release of the oral pressure through the narrow constriction and the longer time needed to achieve the pressure differential for voicing. This results in a longer period of turbulent flow, which contributes to the percept of frication. This is illustrated in Fig. 1 which shows that that oral pressure impulse from the stop decays more slowly for /tjɑ:/, /twɑ:/, /trɑ:/ vis-à-vis /tɑ:/ due to the exiting air encountering greater resistance. For these sequences the high velocity airflow passes through a narrow constriction, enhancing turbulence, for a relatively long time creating the percept of an affricated stop release.

INSERT FIG. 1 HERE

Although most phonological descriptions describe this process as the *stop* becoming affricated, synchronic phonetic evidence (illustrated below) suggests that it is the initial part of the close *vowel* or *glide* that becomes (devoiced and) fricated immediately after the stop release. Frication cannot be attributed merely to the narrower aperture of the close vowel or glide immediately after the stop release because (af)frication is not found in words such as *canyon, million, savior,* or *burial*, where the same glide or vowel apertures are involved but there are different preceding consonants. As there is no considerable pressure build up during the production of C1 in /nj, lj, vj, rj/ sequences, the air velocity is not high enough to cause

frication noise. Thus, it is the joint effect of a vowel or glide with a narrow aperture and the pressure build up for the stop which are responsible for the resulting frication.

Most likely, the same principles are responsible for the historical fricativization of high front vowels following sibilants in the transition from Middle Chinese to Modern Mandarin, for example, */si/→ [sz̩] 'poetry', */s̬i/→ [s̬z̩] 'lion' (Chen 1976). The high pressure build-up for the voiceless sibilant is released through the narrow constriction for the high vowel, generating frication.

The affrication of stops followed by high vowels and glides (i.e., segments impeding the free flow of air) is at the origin of a number of cross-linguistic sound patterns and present-day synchronic variation. Some of these are illustrated in (5) and (6) (see Hall and Hamann 2003 for a typological study of alveolar assibilation in 45 languages):

(5) Affrication of alveolars/dentals

Historical

a. English /tj dj/ > /t͡ʃ d͡ʒ/

/t͡ʃ/ *actual, nature, mature, picture*

/d͡ʒ/ or /dj/ *residual, soldier, remedial*

b. Latin /tj dj/ > Old Catalan /t͡s d͡ʒ/ > Mod. Catalan /s (d)ʒ/

Latin *petia* > *peça* ['pesə] 'piece'

Latin *diurnum* > *jorn* [ʒorn] ~ [d͡ʒorn] 'day'

c. Japanese /t, d/ > [t͡ɕ, d͡ʑ]/__ /i/; /t, d/ >[t͡s, d͡z]/__/u/ (=[ɯ])

/tii/ > [t͡ɕii] *chii* 'social status' /tja/ > /t͡ɕa/ [t͡ɕa] *cha* 'tea'

/di/ > [d͡ʑ] [d͡ʑiɽemma] 'dilemma'

/katu/ [kat͡sɯ̟] 'win' (pres.)

d. Ikalanga (Mathangwane 1996, cited in Ohala 1997a), stop frication before the high front vowel /i/, and distinctive aspiration before high vowels /i, u/, but not before the next lower vowels /ɪ ʊ/. The high and high-mid vowels have now merged.

Proto Bantu */tima/ > Ik. /t͡sʰima/ 'well'

BUT PB*/tɪma/ > Ik. /tima/ 'heart'

Proto Bantu */tudi/ > Ik. /t^{h}ud͡zi/ ‘shoulder’

BUT PB */tʊndʊ/ > Ik. /tundu/ ‘basket’

Synchronic

e. English

[t^{ʃ}j] or [t͡ʃ] *Tuesday, tune, got you*

[t^{ʃ}r] *train, truck*;

[t^{s}i:] *tea*

f. Brazilian Portuguese (Albano 1999)[6]

/di/ *Gandhi* [gə̃nd͡ʒi]

/ti/ *internet* [internɛt͡ʃi]

g. Italian dialects (Tuttle 1997)

Standard Italian /tj/ *tieni* ‘hold’(imperative), Venetian [t͡ʃeŋ]

Standard Italian *alti* (plural –i) ‘tall’ (pl.), Ticino [alt͡ʃ], [ɛlt͡ʃ]

(6) Velar softening

Historical

[k] /[g] + [i ɪ e y j] > [t͡ʃ t͡s ʃ s] / [d͡ʒ d͡z ʒ z]

a. English

O.E. *ciele, cele* [k] > *chill* [t͡ʃ] (but ‘cold’ [k])

O.E. *cirice* [k] > *church* [t͡ʃ] (cf Scots ‘kirk’ [k])

Gk. *Gymnasion* [g] > *gymnasium* [d͡ʒ]

b. Italian

Lat. *cena(m)* [k] ‘dinner’ > *cena* ['t͡ʃe:na]

Lat. *regia(m)* [g] ‘palace’ > *regia* ['redd͡ʒa]

c. Tai (Li 1977: 221)

[6] Palatalization and affrication of dental stops is a geographical dialect marker in Brazilian Portuguese. Dental stops are palatalized and affricated when followed by a high vowel [i], which may be lexical or inserted after a word-final dental stop in borrowed words (as BP only allows /s, r, n, l/ syllable-finally).

Lungchow	Po-ai	
kjau	*t͡ʃau*	’head’, ‘knot of hair on top of the head'
kjaa	*t͡ʃaa*	’rice seedlings'
kjooŋ	*t͡ʃooŋ*	‘drum’

Synchronic

d. Paduan affrication (Krämer 2004)

	Standard Italian	Paduan
ghiaccio	['gʲatt͡ʃo]	['d͡ʒaso] ‘ice’
chiama	['kʲama]	['t͡ʃama] ‘he/she calls’

The ‘fronting’ of /k g/+/i j e/ sequences into alveolar or palatal affricates or fricatives has been the focus of much investigation (Grammont 1933, Bhat 1978, Guion 1998, to name a few). In contrast to articulatory accounts of the sound change, in terms of coarticulatory palatalization of the velar, Ohala (1989, 1992) provides an acoustic-auditory motivation for velar fronting. Chang, Plauché and Ohala (2001) present evidence that if the characteristic mid-frequency spectral peak of the burst in [ki] is degraded (and consequently perceptually missed), an alveolar sequence [ti] is reported by listeners, in line with confusion studies (e.g., Winitz, Scheib and Reeds 1972). Moreover, the [ki] tokens with the mid-frequency peak filtered out received better /t͡ʃ/ goodness scores than unfiltered tokens. Since variation of the acoustic cues of the stop burst influenced the direction of the consonant confusion –and paralleled the direction of the sound change– they argue that acoustic-auditory factors underlie ‘velar fronting’ (see also Ohala 1985, 1993). See Ohala (1983a, 1997c) and Plauché, Delogu & Ohala (1997) for asymmetries in the direction of confusion patterns and sound change, i.e., ki > ti but not the reverse.

A corollary to the generalization that stops tend to engender frication on adjacent glides and high vowels is *D*.

D. Voiceless stops plus high vowels, glides and sonorants tend to be affricated more often than voiced stops.

Another generalization that can be accounted by aerodynamic factors is that frication especially emerges after voiceless stops, though it may also emerge after voiced stops (Ohala 1976), as illustrated in (5) and (6) above. The higher incidence of affrication in voiceless than

voiced stops has been noted cross-linguistically (Bhat 1978 for velar stops; Hall and Hamann 2003 for dental-alveolar stops) and is illustrated in the English example (5.a) above. While historically the /tj/ sequence in *nature, actual*, and *picture* has been lexicalised as /t͡ʃ/, in comparable voiced sequences, e.g., *soldier, medial, individual*, the /dj/ > /d͡ʒ/ change has not lexicalised as often, and these words may be pronounced either [dj] or [d͡ʒ]. Similarly, in German the sequence /tj/ developed into [t͡s] whereas /dj/ did not affricate (e.g., *nation* [na't͡sjo:n] vs *indianisch* [ɪn'dja:nɪʃ] 'indian'). The effect of the voicing of the stop on 'stop assibilation' in Latin and Romance languages has been observed by a number of investigators. For example, Pope (1952: 129, 131) notes that, in Latin, [t͡sj] is attested for /tj/ in the 4th century (e.g., iusti**tia** [t͡sj] 'justice') but this process did not affect /dj/. Affrication of /dj/ is not reported till Late Latin when palatalization and affrication of both /tj/ and /dj/ are attested. Hall and Hamann (2003) on the basis of observed assibilation of /tj/ and /dj/ sequences in 45 languages posit that 'voiced stops cannot undergo assimilation unless voiceless ones do', such that there is an implication relationship /dj/ assibilation ⊃ [tj] assibilation.

The differential effect of voicing in the stop was addressed in section 2.2.1. To recall, the vibrating vocal folds for voiced stops constitute a relatively high resistance to air flowing from the lungs, and allow less air pressure to build up behind the stop constriction vis-à-vis voiceless stops, with an open glottis and a large and unimpeded flow. Consequently, there is a lower oral pressure at the release of a voiced stop, and thus less turbulence is generated (by equations 2 and 3). Empirical data corroborate that a higher amount of airflow and a longer duration of the release phase is found in /tjV/ than in /djV/ sequences (Hamann and Velkov 2005).

Since affricates frequently derive from stops with a long noisy release, a corollary to the diminished glottal flow and lesser affrication for voiced vis-à-vis stops, is the observation that voiced affricates are less frequent in languages of the world than voiceless affricates (ratio 1:3; Maddieson 1984: 38-39)

In sum, the generalization that 'stops engender frication on adjacent glides, high vowels and sonorants' is moderated by voicing effects, with 'voiceless stops tending to be affricated more often than voiced stops'.

II. Voicing impairs obstruency

For the same reasons that increased glottal flow during voiceless sounds favors supraglottal turbulence, the reduced glottal flow due to voicing, impairs the high intensity noise (and abrupt spectral discontinuities) characteristic of obstruency.

E. Voiced fricatives are hard to make; if voicing is strong, there is a tendency to de-fricate; if frication is achieved, there is a tendency to devoice.

Voiced fricatives are relatively difficult to produce due to the antagonistic aerodynamic requirements for frication at the supraglottal constriction (high oral pressure) and voicing (low oral pressure) (Note that this does not apply to the glottal fricative, [ɦ], for which both turbulence and voicing are generated at the vocal folds). Voiced fricatives require a pressure difference (ΔP) across the oral constriction sufficient to generate turbulence. This implies high oral pressure. That same high oral pressure, however, tends to impair the transglottal flow required for voicing. Thus, voiced fricatives involve very finely tuned aerodynamic conditions so that a pressure drop is maintained across both the glottal and the supraglottal constrictions[7] (Ohala, 1983b; Solé 2002b).

During the production of voiced fricatives, if voicing is present, the reduced transglottal flow tends to impair strong frication (as intensity of turbulence is proportional to rate of flow), and if strong frication is achieved, the high oral pressure will tend to impair vocal fold vibration. Thus, voiced fricatives tend to devoice or to defricate, as evidenced synchronically and diachronically in the patterns below.

E.1 Voiced fricatives are relatively rare cross-linguistically.

The difficulty to produce simultaneous voicing and frication is reflected in segment inventories. Overall, voicing contrasts in fricatives are much rarer than in plosives, and they are found only in about a third of the world's languages as compared to 60 percent for plosive voicing contrasts (some languages, however, have voiced fricatives without corresponding voiceless fricatives emerging from weakened stops or fortition of initial approximants; Maddieson 2005). Furthermore, considering languages that utilize voicing with one of the

[7] Solé (2002b) estimated the allowable range of aerodynamic variation for voiced fricatives from aerodynamic data. For one of her subjects, she estimated a subglottal pressure (Ps) of 7.6 cmH_2O during fricative production. Since transglottal flow to maintain voicing requires a pressure drop across the glottis (Ps-Po) of at least 1-2 cmH_2O (and higher values to initiate voicing, 2-3 cmH_2O), that leaves a Po of approximately 5.6 cmH_2O. Generation of turbulence for voiced fricatives ceases when the transoral pressure drops to about 3cmH_2O (Ohala, Solé and Ying, 1998; Catford, 1977:124; Stevens, 1998:480), which means that Po may vary between a rather narrow range of 5.6-3 cmH_2O in order to sustain voicing and frication.

obstruent types but not the other, the probability of vocal fold vibration being absent on fricatives is double that found for stops (Ohala 1983b: 201).

E.2. Voiced fricatives tend to defricate

For the same magnitude of the oral constriction, voiced fricatives have a lower intensity of friction than voiceless fricatives, which makes them more likely to be perceptually heard as frictionless continuants (e.g., glides, rhotics, approximants) or missed altogether. The reason is diminished airflow through the glottis for voiced vis-à-vis voiceless fricatives due to vocal fold vibration (i.e., increased glottal resistance), and the need to keep oral pressure low for voicing. In addition, voiced fricatives are known to be shorter than voiceless fricatives, thus they allow less time for air to accumulate behind the constriction and create a high pressure build-up. These mechanisms -- lowered rate and duration of transglottal flow -- are responsible for a lower oral pressure, and a lower intensity of noise vis-à-vis voiceless fricatives (by equations (2) and (3)). As a phonological consequence voiced fricatives resemble more closely the so-called "frictionless continuants" such as [j w ɹ], and, indeed, diachronically this is often their ultimate fate, as illustrated in (7a, b). Approximants or frictionless continuants are the common phonetic manifestation of /v ð/ in Danish, e.g., [maˌð] *mad*, 'food' (cf. OE *mete*, Swedish and Norwegian *mat*, Icelandic *matur*). In Spanish and Catalan, the medial voiced stops /b d g/ are 'spirantized' to [β̞ ð̞ ɣ̞][8], see (7c), these latter sounds being more adequately described as approximants rather than fricatives (Martínez Celdrán 1991, 2004; Romero 1995). In Spanish these approximants may even disappear in some cases, for example, in past participles ending in –ado, e.g., *hablado* [a'β̞lao] 'talked' (cases of 'hypercorrection', i.e., insertion of non-etymological [ð̞] in similar sequences e.g., [β̞aka'lað̞o] for *bacalao* 'cod', are common).

(7) Defrication of voiced fricatives[9]

a. Gliding and vocalization. In Middle English the voiced velar fricative allophone of /g/ (a voiced stop in OE) became /w/ or /u/ and the palatal allophone either became /j/ ~ /i/ or was lost (Mossé 1952).

[8] Spirantization of voiced stops may be a maneuver to lower oral pressure in order to facilitate voicing (Ohala 1983b)

[9] It has been reported that voiced stops may become voiced approximants without an intermediate fricative stage (see, e.g., Villafana Dalcher 2006 for Florentine Italian). In such cases defrication of voiced fricatives may not be necessarily at work.

[ɣ] > [w]	[j̯] > [j], [i]
OE *swelgan* > ME *swolwen* 'swallow'	OE *genog* > ME *inough* 'enough'
OE *boga* > ME *bow* 'bow'	OE *mægden* > ME *maiden* 'maid'
OE *sorg* > ME *sorow* 'sorrow'	OE *sægde* > ME *said*

b. S-rhotacism (Solé 1992)

Latin *cerasea* > Catalan *cirera* 'cherry'

Prelit. Catalan *Tolosanu* > Catalan *Tolrà*, *Toldrà* (placename)

English *was* - *were* (< O.E. wesan)

lost - *forlorn* (< O.E. forleosan)

Yurak *fiire* 'nest' cf. Finnish *pesä*

Yurak *kuro-* 'to cough' cf. Lappish *gossâ-*

c. Spirantization

Spanish	*sabe*	/sabe/	['saβ̞e]	'(s)he knows'
	cada	/kada/	['kað̞ə]	'each'
	pega	/pega/	['peɣ̞a]	'(s)he hits'

E.3 Voiced fricatives tend to be weakened or lost earlier than voiceless fricatives.

Interestingly, historical data indicate that voiced fricatives tend to be weakened or lost earlier than voiceless fricatives. This is illustrated in fricative weakening[10] in Gallo-Romance. Preconsonantal /s/ was voiced before a voiced consonant, and [z] was weakened (into vowel, glide or tap) and lost as early as the 11th century, whereas voiceless [s] was pronounced well into the 13th century. Thus, for example, in Old French /s/ weakening and loss is found earlier in *blâmer* < *blasmer* < Lat. **blastemare* 'blame' and *mêler* < *mesler, medler* [ðl] < Lat. *misculare* 'meddle' than in *fête* < *feste* < Latin *festa* 'holiday' and *epuzer* < *espozer* < Latin **sponsare* (Pope 1952: 151, 449). Further, the different fate of etymological /s/ in the English words in (8) shows that [z] but not [s] had been lost at the

[10] The term fricative 'weakening' is used here to indicate attenuation of the high frequency noise which characterizes fricatives, due to gestural reduction or aerodynamic factors. Fricative loss is considered the endpoint of the weakening continuum, i.e., extreme attenuation leading to the segment becoming inaudible. In perceptual terms gradient attenuation of the friction noise may result in identification of a discrete segment (e.g., a frictionless continuant, a vowel, a tap, an assimilated segment, or /h/) or in the perceptual loss of the segment (i.e., deletion).

time of the Norman Conquest, when the words were borrowed into English (Pope 1952: 151).

(8) *[z] + voiced C*	*[s]+ voiceless C*
dine < O.Fr. disner	feast < O.Fr. feste
hideous < O.Fr. hisdos	espouse < O.Fr. spuse
male < O.Fr. masle	esquire < O. Fr. esquier

The aerodynamic and acoustic differences for voiced as opposed to voiceless obstruents have phonological significance in a number of patterns below (2.2.2.*F*; 2.2.3.*I*)

2.2.2 Changes in magnitude of the constriction.

Intensity of turbulence is dependent on the shape and area of the constriction through which the air has to pass. In this section we will review sound patterns involving the generation or impairment of turbulence due to variations in the area of constriction. Such variations in the cross-dimensional area of the constriction may result from coarticulation with adjacent sounds or position in the syllable.

F. Lingual fricatives tend to weaken when followed by consonants involving conflicting tongue configurations

Lingual fricatives exhibit highly constrained articulatory, aerodynamic and time requirements (Bladon and Nolan 1977). They require articulatory positioning to form a constriction within a certain critical range (approximately 0.1cm^2; Stevens 1998: 47) and creating sufficient pressure difference across the oral constriction to generate frication. This requires sufficient rate of flow through the glottis and sufficient time to build up oral pressure behind the oral constriction. Precisely because they are highly constrained, lingual fricatives allow less articulatory and aerodynamic variation – in magnitude and time – than other segment types[11]. Solé (2002a, b) has shown that apical trills have similar, if not more

[11] For example, because the constriction shape and area of lingual fricatives is critical, they tolerate less coarticulation with neighboring sounds (Recasens, Pallarès & Fontdevila, 1997), they are less overlapped (Byrd 1996), and they show lesser articulatory reduction in magnitude (Byrd and Tan, 1996) than other segment types (*e.g.*, stops); and because temporal factors are also critical, fricatives are less susceptible to temporal reduction vis-à-vis other segments (Klatt, 1976; Byrd and Tan 1996).

constrained positional, shape, aerodynamic and elasticity requirements, and that they do not allow much articulatory variation if trilling is to be present.

FIG. 2

When lingual fricatives are followed by apical trills, involving antagonistic conflicting positional requirements of the tongue-tip/dorsum –raised and advanced tongue dorsum and a central groove for /s z ʃ ʒ/ vs. predorsum lowering and postdorsum retraction with a lax tongue-tip touching the alveolar ridge for the trill (see Figure 2)–, anticipatory tongue gestures for the trill may perturb the critical articulatory configuration (i.e., cross-sectional area of constriction) and/or temporal requirements for the generation of turbulence, and the fricative may be weakened or lost. Palatographic and aerodynamic evidence for fricative-trill sequences suggests that early onset of movements for the trill– within 30ms from the onset of lingual movements for the fricative – perturbs the articulatory trajectory and the critical constriction area for friction. In cases of lesser overlap, motor commands for the trill may arrive after the articulator attains the cross-sectional area for frication, but within the time needed to build up sufficient pressure difference to create audible frication (approximately 50ms from onset of oral pressure rise for voiced fricatives, with increased glottal resistance, and 30ms for voiceless fricatives. In such cases turbulent noise will not be generated (Solé 2002b).

S-weakening (into a tap or assimilated to the following sound) is also common before the conflicting lingual fricative /θ/ in Spanish (for example, /sθ/ > [ɾθ], [θ:] in *ascenso* ‘promotion’*, piscina* ‘swimming-pool’, Navarro Tomás 1980:111).

Examples of fricative weakening and loss in lingual fricative-trill sequences[12] are illustrated in (9).

(9) Examples of fricative weakening in lingual fricative-trill sequences

(a) Iberian Spanish

/sr/ *dos-reales* [ˌd̪ore'ales] ‘halfpenny’ (Navarro Tomás, 1980); *Osram* ['oram]

/θr/ *voz ronca* [ˌbo'roŋka] ‘hoarse voice’, *Cruz Roja* [ˌkru'roxa] ‘Red Cross’

[12] In reverse sequences, /rs/, where the trill is in coda rather than onset position, the trill is commonly detrilled and may assimilate to the fricative, e.g., Latin *bursa, morsicare* > Catalan *bossa, mossegar* ‘bag’, ‘to bite’ (Badía 1951: 202); /rs/> [s̪] (retroflex fricative) in Scots English (Bähr, 1974: 132ff) or Standard Swedish.

BUT:

/sl/, /sb/, /sk/ *desleal* [d̪ezle'al] ‘disloyal’, *esbozar* [ezβ̪o'θaɾ] ‘to sketch’, *asco* ['asko] ‘disgust’

/θl/, /θm/, /θk/ *hazlo* ['aðlo] ‘do it’, voz melodiosa [ˌboð melo'ð̪josa] ‘pleasant voice ’, *mezcla* ['meθkla] ‘mixture’

(b) Catalan

/sr/ *les Rambles* [lə'rambləs] (Recasens 1993)

/ʃr/ *mateix rotllo* [məˌt̪e(j)'rəd̪ʎu] ‘same story’

/ʒr/ *boig rematat* [ˌbɔ(j)d̪rəmə't̪at̪] ‘real crazy’

BUT:

/sl/, /sb/, /st/ *fes-li* ['fezli] ‘do it’ (for him), *les bledes* [ləz'β̪lɛð̪əs] ‘the chard’, *costellada* [kust̪ə'ʎað̪ə] ‘barbecue’

/ʃʎ/, /ʃp/ mateix llit [məˌ t̪eʒ'ʎi t̪] ‘same bed’, *mateix poble* [məˌ t̪eʃ'pɔplə] ‘same town’

/ʒb/, /ʒp/ *boig valent* [ˌbɔdʒβ̪ə'len] ‘brave crazy man’, *boig per tu* [ˌbɔtʃpər 't̪u] ‘mad about you’

(c) Portuguese

[ʒR] [ʒr] *dos reis* [du 'Rɐjʃ], [du 'rɐjʃ] *‘of the kings’, Israel* [iRɐ'ɛɬ], [irɐ'ɛɬ]

Note that in the languages illustrated in (9) coda fricatives are voiced before a trill due to regressive voice assimilation, and thus they are more likely to be defricated (see *E.2* above). Only the single trill realization is exemplified for the Spanish and Catalan data, but a long trill [r:] or a sequence [ɻ̞r] ([ɻ̞]= fricative r) are also possible. The Portuguese data in (9c) illustrate that the uvular and apical variants of trills – the former involving the tongue dorsum –assimilate predorsal fricatives. In Italian, on the other hand, the fricative is preserved (e.g., /s # r/ *autobus rosso* [ˌaut̪obusᵊ 'rɔsɔ] ‘red bus’, *Israele* [iz^{d}ra'ɛlɛ], [iz^{d}ra'ɛlɛ]) most probably due to the widespread insertion of epenthetic sounds at consonant release which allows the sequencing (*i.e.*, lack of overlap) of the gestures for the fricative and the trill. Whereas fricative to trill assimilation is probably an articulatorily gradient process (Solé 2002b), due to varying amounts of consonant overlap, the perceptual result is mostly categorical, that is, no frication is produced and the percept is commonly that of a trill or a long trill. Indeed, this process has led to reinterpretation in some placenames in Catalan, where the fricative has

disappeared in the lexical form, *e.g.*, *Purroi* < etym. *Puigroig* /tʃ+r/ (Alcover and Moll, 1979), *Puigreig* [pu'retʃ] < [ˌpudʒ'retʃ].

Additional evidence for the claim that the competing lingual requirements for trills impact on the generation of turbulence in preceding fricatives comes from (i) the more common and historically earlier weakening of lingual fricatives before trills (and also before laterals and nasals; see section 4) vis-à-vis other voiced consonants in Romance (Pope 1952:151footnote, 449; Rohlfs 1949; Torreblanca 1976; Recasens 2002: 352, 360), and (ii) electropalatographic and acoustic evidence that lingual fricatives lose their frication and are lost more commonly before trills (and also laterals and nasals) than before voiced stops and fricatives (e.g., in Majorcan Catalan, Recasens 2006).

G. Fricativization of syllable initial glides

Whereas the emergence of frication in glides in *A.2* and *C* above was attributed to an increased rate of flow through the glottis when devoiced or when coarticulating with adjacent voiceless consonants, the frication of [j] word and syllable initially in dialects of Spanish, illustrated in (10a-c), is most likely due to a narrower oral constriction (principle 2). (Such narrowing of the constriction may give rise to an affricate [dʒ], see (10b, c)). There are two main reasons for this interpretation. One is that fortition (narrowing of a constriction) is common utterance and word-initially (Keating, Wright & Zhang 1999; Keating, Cho, Fougeron and Hsu 2003). Second, that fricativization of [j] also takes place in voiced contexts (intervocalically in Argentinian Spanish, and after a voiced consonant in Iberian Spanish, as illustrated in (10b, c)) and, therefore, cannot be attributed to increased transglottal flow. It is the case, though, that these emergent fricatives may be devoiced in Argentinian Spanish, i.e., [ʃ]. Most likely, the devoiced variant results from increased narrowing of the constriction area and passive devoicing (see Ohala's 'aerodynamic voicing constraint' 1983b). Similar cases of fortition are found during the development of the Romance and Germanic languages.

The labial velar glide [w] is also fricativized or stopped word-initially in Spanish being pronounced [ɣw], [gw] and, less commonly, [βw] (see 10d).

(10) Frication of glides ([ʝ] = voiced palatal fricative)

a. *buey* [bwej] 'ox' vs *bueyes* ['bweʝes], ['bweʒes] 'oxen'

ley [lej] 'law' vs *leyes* ['leʝes], ['leʒes] 'laws'

b. Iberian Spanish (Navarro Tomás 1980:127ff.)

yo [jo], [ʝo], [dʒo] 'I'; *yeso* ['jeso], ['ʝeso], ['dʒeso] 'chalk'

cónyuge ['koɲʝuxe], ['koɲdʒuxe]'spouse'; *subyugar* [suβʝu'ɣaɾ], [subdʒu'ɣaɾ] 'subjugate'

c. Argentinian Spanish (Colantoni 2006)

ayuda, [a'ʝuð̞a], [a'ʒuð̞a], [a'dʒuð̞a], [a'ʃuð̞a] 'help'

calle ['kaʝe], ['kaʒe], ['kadʒe], ['kaʃe] 'street'

d. Iberian Spanish (Navarro Tomás 1980:64)

huevo, ['weβo], ['ɣweβo], ['gweβo] 'egg'

huelga, ['welɣa], ['ɣwelɣa], ['gwelɣa] 'a strike'

2.2.3 Changes in oral pressure

Changes in oral pressure, such as those brought about by opening the velopharyngeal valve, will impact on the intensity of the resulting frication or stop burst. We review here a number of patterns illustrating that strong frication or a high intensity noise burst are difficult to achieve with concurrent or coarticulatory nasalization. Specifically, patterns showing that nasalization induces defricativization, and that buccal fricatives and stops do not tolerate nasalization. This leads to the generalisation that nasalization impairs obstruency.

III. Nasalization and obstruency do not mix.

Obstruents are characterized by high intensity frication and/or a noisy release burst. Since intense turbulence is pressure dependent (by equation (3b)), obstruents require a high build-up of air pressure behind the constriction in order to create audible turbulence when the pressure is released. If the obstruent constriction is downstream of the velopharyngeal port (i.e., 'buccal', labial to uvular), a tightly sealed velum is necessary to build up oral pressure. A lowered velum for nasality would vent the airflow through the nasal cavity, thus reducing or eliminating the required pressure difference across the oral constriction for intense turbulence. As a consequence, an open velopharyngeal port for nasality impairs high amplitude turbulence in buccal obstruents. In the case of glottal and pharyngeal fricatives and stops, for which the build up of pressure takes place further upstream than the velic

valve, a lowered velum would not affect the pressure build up, and thus they can be nasalized (Ohala 1975, Ohala and Ohala 1993). Nasalized glottal fricatives, /h̃/, have been widely reported in languages (Ladefoged & Maddieson 1996: 131-134), and they occur phonetically in American English, e.g. *home* [hõʊ̃m]. Thus the requirement of a raised velum, and consequently the incompatibility of nasalization and obstruency, applies exclusively to obstruents articulated in front of the point of velic opening (buccal obstruents).

The antagonistic requirements of nasalization and obstruency, in addition to being predictable from aerodynamic and acoustic-auditory principles, have been demonstrated empirically. First, studies where oral pressure during the production of speech sounds was varied with a pseudo-velopharyngeal valve (a tube inserted at the side of the mouth via the buccal sulcus), simulating different degrees of nasalization (Ohala, Solé and Ying 1998), show that in producing a fricative there can be some opening of the velic valve, but the resistance at the velum has to be high relative to the resistance in the oral constriction so that the air will mostly escape through the aperture with lower resistance and create friction at the consonantal constriction. If resistance at the velopharyngeal port is lower than that at the oral constriction the air will escape through the nose (*i.e.*, the fricative will be nasalized), but supraglottal frication will be impaired. Ohala et al (1998) argue that velic openings which do not impair the build up of pressure for audible turbulence would be insufficient to create the percept of nasalization in the consonant or even adjacent vowels. Shosted (2006) obtained similar results with a mechanical model of the vocal tract with which he generated fricatives with different degrees of velopharyngeal opening.

Second, studies on velopharyngeal impairment (e.g., as presented in clinical cases of cleft palate) suggest that a velic opening of less than 10mm^2 during the production of oral stops exhibits normal aerodynamic values and can be tolerated without any perception of nasality, but velic openings of 10-20 mm^2 show diminished pressure and airflow values and the perception of inadequate nasal resonance (Warren, Dalston and Mayo 1993)[13]. Third, studies on coarticulatory nasalization in obstruents (e.g., Rothenberg 1968, Cohn 1990, Ohala and Ohala 1991; Basset, Amelot, Vaissière and Roubeau 2001) show that (mostly voiced) obstruents exhibit coarticulatory velic leakage preceding and following nasal vowels and nasal consonants, but that the velum may close before the release, allowing pressure to build up behind the constriction so as to produce frication or an oral burst, or that the velum may be slightly lowered throughout the obstruent, resulting in a relatively weak frication or burst.

[13] This contrasts with the requirements for nasal consonants which require a velic opening greater than 20mm^2 and typically between 50 and 100mm^2.

The evidence presented so far suggests that obstruency and nasality do not mix. To the extent that an obstruent is a good obstruent perceptually (i.e., with intense frication or noisy release burst), it cannot be a good nasal (i.e., with perceptible nasal coupling); to the extent that it is perceptibly nasalized, it does not have the high amplitude noise cues for obstruency.

We review the phonological consequences of nasalization on fricatives and stops separately. We will address fricatives and nasalization first.

H. The rarity of nasal buccal fricatives.

Languages of the world have nasal stops, nasal taps, nasal approximants, nasal glides and nasal vowels but no nasal fricatives. Segments reported as nasalized fricatives are more adequately described as (i) frictionless continuants or approximants, due to the lack of high frequency aperiodic noise (*e.g.*, in Umbundu, Schadeberg 1982; Coatzospan Mixtec, Gerfen 1996; and Waffa, Stringer and Hotz 1973) or (ii) as sequences of nasal and fricative segments, i.e., prenasalized fricatives (in Bantu languages, Kwa languages, and Igbo; Welmers 1973: 70-73) (Ohala 1983b, Ohala and Ohala 1993, Ohala et al. 1998). As shown above, if turbulence is created further upstream the point of velic opening – as in glottal and pharyngeal fricatives– velic lowering is of no consequence to the pressure build up, and the fricative can be simultaneously nasalized (see Ladefoged and Maddieson 1996:131-134 for examples).

I. Nasalization is associated with defricativization. The effect of voicing.

Nasalized fricatives, though rare, have been reported to occur in languages and it has been observed that they tend to be defricated if voiced –evidencing the difficulty to produce simultaneous frication and nasalization with reduced transglottal flow for voicing– and to lose their nasality if voiceless. For example, *voiced* nasalized fricatives are phonetically nasalized frictionless continuants (e.g., Waffa /β̃/ [β̞̃], Stringer and Hotz 1973; Umbundu /ṽ/ [ṽ̞], Schadeberg 1982), and voiced fricatives tend to lose their friction due to spreading nasalization and become nasalized approximants (e.g. [v ɣ] ~ [ṽ̞ ɯ̞̃] in Guaraní, Gregores and Suarez 1967). In contrast, nasalized *voiceless* fricatives retain frication but do not differ much auditorily from non-nasalized fricatives, that is, the acoustic cues for nasalization are hardly detectable (Ohala 1975, Cohn 1993, Ladefoged and Maddieson 1996: 132).

The loss of friction in voiced but not voiceless nasalized fricatives follows from the aerodynamic factors reviewed. 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, impairing strong frication: (i) increased glottal resistance –which results in a lower oral pressure and inhibits the air vented through the nasal passage to be resupplied from the lungs (as it is the case for voiceless fricatives with an open glottis)– and (ii) the need to keep oral pressure low for voicing[14]. The differential effect of voicing in nasalized fricatives further illustrates the tendency for voicing to disfavor frication (section 2.2.1*E*). Other sound patterns illustrating the principle that nasalization induces defricativization are given in *J* and *K* below.

J. Failure of frication to emerge in a nasal context

Ohala (1983b:205-7) and Ohala and Ohala (1993: 228) provide the following examples of frication failing to emerge in a nasal context.

1. In the development from Middle Chinese to Mandarin, high vowels become fricatives when preceded by a sibilant fricative (e.g., */ʂi/→ [ʂʐ̩] 'lion'), as stated in section 2.2.1*C* above. However, vowel assibilation fails to occur when the vowel is followed by a nasal consonant and is, consequently, nasalized. For example, */ʂiəm/→ [ʂən] 'forest' but not *[sʐ̩n] (Chen 1976).

2. In English, /h/ has the allophone [ç] before /j/, as in *huge* [çju:d͡ʒ], as noted in section 2.2.1*B* above, but frication at the supraglottal constriction is not present if there is coarticulatory nasalization, e.g., *inhuman* [ɪ̃n'h̃j̃ũm̃ən], not *[ɪ̃n'ç̃j̃ũm̃ən].

3. In Yuchi, voiceless fricatives appear predictably between all vowels and following lingual stops, but fail to occur if the vowel is nasalized (Wagner 1934).

K. Fricatives are weakened or lost more often when followed by nasal than by non- nasal segments

[14] Thus, Ohala, Solé and 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 is flowing out both through the nose and the mouth) voiced fricatives become frictionless continuants while voiceless fricatives retain their frication (though the intensity of friction is attenuated).

Coarticulation – the overlap of the articulatory configurations of contiguous segments – is well known and arises because it takes some minimum time to move articulators from one position to another. The antagonistic requirements of turbulence generation (a tightly closed velum to allow turbulent airflow in the oral tract) and nasal coupling (a lowered velum) in contiguous fricatives and nasals severely constrain the timing of velic movements if both segments are to be preserved. The relative phasing of velic and oral gestures in fricative + nasal (N or $\tilde{V}$) sequences have resulted in several sound changes, including (i) fricative weakening and loss, (ii) stop epenthesis, and (iii) vowel epenthesis (the latter two outcomes will be dealt with in section 4). Of interest here is fricative weakening or loss when followed by a nasal segment. Aerodynamic and acoustic data for fricative-nasal sequences shows that there might be anticipatory velopharyngeal opening for nasality during the acoustic duration of the fricative. Such nasal leakage diminishes the oral pressure build-up behind the fricative constriction, and attenuates the amplitude of frication, which may lead to fricative weakening or loss (Solé 2007a).

Although fricative weakening may also occur before non-nasals (e.g., Latin *misculare* ‘ to mix’ > O.Fr. *mesler* > *mêler;* Germanic **bruzdon* ‘to embroider’> Old Occitan *broidar* (where the ‘i’ is the result of the weakening process); Latin *festa* > French *fête* ‘holiday’) a number of scholars have noted that this process is favored by a following voiced consonant and, in particular, by a following [n], [m], [r] or [l] (Pope 1952: 151footnote, 449, Rohlfs 1949, Torreblanca 1976, Recasens 2002: 352, 360). Whereas /s/ weakening before [r] may be attributed to antagonistic positional requirements of the tongue-tip and blade (see section 2.2.2.*F*), the weakening of fricatives before nasals (and laterals) may result from anticipatory velum (or tongue sides) lowering, thus affecting the aerodynamic requirements for the generation of turbulence.

Examples of fricative weakening due to coarticulatory nasalization resulting in vocalization or gliding (see 11a), rhotacism (exemplified in 11b), nasal assimilation (illustrated in 11c), and elision (see 11d) are found in historical sound change, morphophonological alternations and dialectal-stylistic variation.

(11) Examples of prenasal fricative weakening and loss

a. [ɣn] > [jn], [wn] Latin *agnu* ‘lamb’, *ligna* ‘line’ > S. Italian dialects ['ajənə], ['lɛwna] (cited in Recasens 2002).

b. [zn], [zm] > [ɾn], [ɾm] Latin **dis(ju)nare* ‘to eat breakfast’ > Old Occitan *dirnar/disnar* (cf. Cat. *dinar*) (Grandgent 1905: 53).

S. Spanish *mismo* ['miɾmo] 'same' (Recasens 2002).

c. [zn̩] > [nn̩], [jn] *isn't* [ɪnn̩t], *ain't* [eɪnt]*; doesn't* [dʌnn̩t]; *wasn't* [wɒnn̩t] (Gimson 1962).

BUT: *is there?* ['ɪzðər], *is she?* ['ɪʒʃi], *does he?* ['dʌzi]

d. [sm] [sn] > [m], [n] IE **gras-men* > Latin *grāmen* 'fodder', English *grama, gramineous*;

BUT: IE *gras-ter > Greek *gāster* 'stomach', English *gastric, epigastrium* (Watkins 1985).

IE **dhus-no* >Welsh *dwn* 'dull, brown colour', OE *dun(n)* 'dark brown';

BUT: IE **dhus-ko*>Latin *fuscus*, OE *dox,* English *dusk* (Watkins, 1985).

L. Lower transitional frequency of fricatives followed by nasals

Fricatives combine less frequently with following nasals than with non-nasals. Solé (2007b) found a lower lexical frequency of word medial fricative + N sequences than of comparable fricative + C sequences in English, German and Dutch (the languages available in the CELEX database). Similarly, Rossato (2004) reports a bias against fricative + nasal sequences in a cross-linguistic count in 14 languages. Thus the transitional probabilities in the sequencing of sounds reflects the constraint against fricatives followed by nasal segments that endanger their high airflow requirements.

In sum, the data in *H* to *L* show that fricatives tend to lose their frication more often and earlier when they are nasalized, when they occur before a nasal vis-à-vis an oral sound, and that they combine less frequently with following nasals than with non-nasals, illustrating the generalisation that nasalization bleeds obstruency or, put another way, that fricatives do not tolerate nasalization.

M. In languages with nasal harmony, obstruents, including fricatives, block spreading nasalization

The incompatibility between obstruents and velic opening is evident in languages with nasal harmony. In such languages a nasal segment precipitates the spreading of nasalization to all following segments unless blocked by an oral obstruent. However, only buccal obstruents (labial to uvular), requiring a sealed velum, block spreading nasalization. The glottal obstruents [h ʔ], which do not require a raised velum since in their case frication is

generated further upstream of the velic valve, do not block nasalization. This is captured by Schourup's (1973) scale of permeability of segment types to nasalization (which ranks laryngeal obstruents low in the scale, next to vowels), but not by other hierarchies (e.g., Walker 1998). Schourup (1973), Ohala (1983b), and Ohala and Ohala (1993) have pointed to a number of languages showing this patterning. The case of Sundanese, illustrated in (12a), shows that nasalization, following a nasal consonant, spreads until blocked by a sonorant consonant or a buccal obstruent such as [k] or [s]; however, it passes through the glottal obstruents [h ʔ]. Another example comes from Capanahua (a Panoan language of South America), where the leftward spreading nasal harmony from nasal consonants is blocked by buccal obstruents – such as [p], [b] or [s] – and /r/, but not by glottal stops, see (12b).

(12) Nasal harmony

a. Sundanese (Robins 1957)

ɲãh̃õkɤn 'to inform'	kumãh̃ã 'how?'
mĩʔ̃ãsih 'to love'	bɤŋh̃ãr 'to be rich'
ŋãtur 'to arrange'	ɲãĩãn 'to wet'

b. Capanhua (Loos 1969).

t͡ʃipõ̃nki 'downriver'	t͡ʃĩʔ̃ĩn 'by fire'
bãw̃ĩn 'cafish'	wɯɾãnjasãʔ̃nwɯ 'push it sometime'

N. Consonants relying on high intensity noise cues, such as voiceless stops, do not tolerate nasalization.

When stops occur in a nasal context, partial or incomplete velopharyngeal closure during the stop constriction may vent the pressure necessary for a strong fricative release burst. 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). In line with this, it has been noted that phonetically voiceless stops tend to inhibit coarticulatory nasalization, that is, they show a shorter temporal extent of velum lowering preceding and following nasalized vowels and nasal consonants vis-à-vis voiced stops (Rothenberg 1968:7.4; Cohn 1990: 108; Ohala and Ohala 1991; Basset et al. 2001). Ohala and Ohala (1991) provide an acoustic-auditory explanation for voiceless stops having less tolerance for nasalization than voiced stops in terms of nasal leakage undermining the stop or voiceless

character (i.e., the spectral and amplitude discontinuity, and noisy release burst) of voiceless but not voiced stops. Such phonetic motivation is the basis for Pater's (1999) *NC̥ constraint.

The lower tolerance of voiceless stops to coarticulatory nasalization is evident in sound patterns showing (i) that if the nasal is preserved, the voiceless (buccal) obstruent is impaired (see (13)), and (ii) that if the obstruent is preserved, the nasal tends to be lost (see 14)).

(13) Nasals impair voiceless obstruents

a. Loss of voiceless but not voiced stops in a nasal context, e.g., Indonesian (Halle and 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/	[mə**ŋ**asih] 'to give'

b. Assimilation of nasality in /nt/ [nn] –but not /nd/– clusters in American English, resulting 'winter' and 'winner' being pronounced the same, e.g..

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

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

c. Glottalization of voiceless stops. 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 below, whereas /d/ is preserved in the same context[15]. 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. 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).

German (Kohler 2001)

zwei**t**en [ˈt͡sva̰ɪ**ʔ**n̩], [ˈt͡sva̰ɪn̩] 'second' *vs* lei**d**en [ˈlaɪ**d**n̩] 'pain, to suffer'

[15] Kohler (2001) reports that in a nasal environment (i.e., preceded and followed by nasals), voiced as well as voiceless stops may be nasalized and glottalised in German (e.g., Stun**d**en [ˈʃtʊn**n̰**n] 'hours', könn**t**en [ˈkœn**n̰**n] 'could'), with a higher occurrence of stop nasalization in voiced than in voiceless stops both in read (53,4% vs 24,5%) and spontaneous speech (80,8 vs 64,9%).

American English

Clinton [ˈklo̞ ĩn**ʔ**n̩] *vs* Brandon [ˈbræ̃n**d**ə̃n]

cap**t**ain [ˈkʰæp**ʔ**m̩] *vs* Ogden [ˈɑg**d**n̩]

Along the same lines, a tendency for /t/ to be more likely to be deleted 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 and Laferriere (1979).

d. Postnasal voicing [16]

Phonological evidence of the tendency of voiceless stops to become voiced after a nasal is provided by languages with a post-nasal voicing rule, as illustrated in (d.1) for Japanese; 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 (d.2)); progressive voicing assimilation in stops following nasals, see (d.3); and historical sound change, for example, in the development from Classical Armenian to the Armenian language New Julfa, exemplified in (d.4).

Examples of post-nasal voicing

d.1. Japanese (Itô, Mester and 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'

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

piho 'I went' ^{m}**b**iho 'he went'

[16] Post-nasal voicing is an aerodynamically and perceptually-based process by which voiceless stops become voiced after nasals. 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 and Ohala 1991; Bell-Berti 1993; Hayes and Stivers 2000). These factors lead to postnasal voiceless obstruents being phonetically partially voiced and with a weaker stop burst, which leads to being reinterpreted as voiced.

i**s**o ‘I hoed’ i$^{\mathbf{n}}$**z**o ‘he hoed’

owo**k**u ‘my house’ õw̃õ$^{\mathbf{ŋ}}$**g**u ‘his house’

d.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

d.4. Historical change (Vaux 1998: 506)

Classical Armenian	*New Julfa*	
ən**k**anel	ən**g**aniel	‘fall’
ajn**t**eɬ	ən**d**ieʁ	‘there’
t͡ʃan**t͡ʃ**	t͡ʃan**d͡ʒ**	‘fly’

Whereas the examples above illustrate that voiceless buccal obstruents do not tolerate nasalization, and that they tend to be lost, replaced or changed in a nasal environment, the examples in (14) illustrate that voiceless obstruents may preserve their spectral integrity (i.e., a strong release burst) by inhibiting coarticulatory nasalization, and thus for the different fate of nasals in a voiced or a voiceless context.

(14) Nasals do not emerge or are lost next to voiceless but not voiced obstruents

a. Nasals occur before voiced but not before voiceless obstruents in the Kenlantan dialect of Malay (Teoh 1988), and in a number of African languages, such as Venda, Swahili and Maore (cited in Pater 1999: 319).

b. Nasals are deleted before voiceless but not voiced stops, e.g., in Mandar (Mills 1975).

/maN+tunu/ ma**tt**unu ‘to burn’

/maN+dundu/ ma**nd**undu ‘to drink’

A similar process is found in American English whereby nasals are lost before tautosyllabic voiceless stops but not before voiced stops.

American English nasal loss (Malécot 1960)

/tent/ [t^{h}ẽ**t**] /kænt/ [k^{h}æ̃**t**] /kamp/ [k^{h}æ̃p]

BUT:

/tend/ [t^{h}ẽ**nd**] ~ [t^{h}ẽ**n]**

c. In Hindi, nasals emerge between a nasalized vowel and a voiced but not a voiceless stop.

Hindi (Ohala and Ohala 1991)

Sanskrit	*Old Hindi*	*Modern Hindi*
čhandra	čhã:dra	[t͡ʃã**nd**] 'moon'
danta	dã:ta	[dã**t**] 'tooth'

3. Acoustic-auditory factors.

3.1. Basic acoustics of fricative production

Flowing air can have one of two states: laminar or turbulent. Turbulence will occur even in a smooth bore conduit if the air flows at a particular critical speed or even at lower speeds if it encounters anything which induces eddies in the flow, e.g., a barrier, rough surfaces, or another air jet– in short any substantial resistance to smooth flow. Turbulence will also be created when airflow expands suddenly on exiting a narrow constriction – as is the case of fricatives. If the motion of air is sufficiently turbulent i.e., intense, an audible sound is generated. This, essentially, is how stop bursts and fricative noises are produced and can be exploited to create different speech sounds. Fricative noise can be combined with periodic sound as in voiced fricatives but in this case the noise is pulsed at the same rate as that of the vocal cords (with each glottal pulse a puff of air is released and it is this higher-than-normal airflow which creates a momentary peak in the noise generated).

The intensity and thus audibility of the turbulent noise is determined by the degree of turbulence which in turn is determined by the velocity and random motion of the air stream and by the resonance cavities excited by the turbulent noise. In most cases of stops and fricatives, it is primarily the *downstream* cavities, if any, which have resonances that can affect the turbulent noise. An exception to this occurs in the case of non-speech whistling where the turbulence occurs at the pursed lips but it is the upstream cavities which resonate; thus different whistled frequencies are controlled by modifying the shape of the upstream, i.e., the buccal, cavity. The case of whistling is special also because there is a coupling

between the resonator and the source, i.e., the resonator dictates, as it were, the frequencies dominant in the source[17].

Given that turbulence noise is predominantly high frequency, higher output intensity usually results when the downstream cavity has high resonant frequencies and, therefore, amplifies the noise in the high-frequency range. This is the case with the anterior sibilant fricatives, such as [s] and [ʃ], with a relatively short downstream cavity, since, other things being equal, the resonant frequencies of a tube are inversely proportional to its length. Thus, apical to palatal articulations have resonances ideally matched to the inherent high frequencies of fricative sources; fricative articulations made further back in the vocal tract, e.g., velars, uvulars, etc. do not and this no doubt contributes to their relative infrequency vis-à-vis more forward fricatives. The above generalization included the qualifier "other things being equal"; among the 'other things' that may not be equal is an additional constriction or narrowing in the downstream cavity, e.g., added lip constriction tends to lower resonant frequencies.

3.2. Generalizations on phonetic and phonological universals derived from acoustic-auditory principles

The following cases illustrate the role of acoustic-auditory factors in phonological patterns.

O. The effect of intensity

Voiceless stops

Among the voiceless pulmonic stops, the labial /p/ has the weakest release burst (and spectrally most diffuse) due to lack of a downstream resonator, and is thus less auditorily salient. /p/ is missing in many languages' sound inventories even though these languages may have pairs of voiced and voiceless stops at other places of articulation, e.g., Arabic and other Afro-Asian languages (Sherman 1975; Maddieson 1984: 35). /p/ can also be unstable, often changing to a voiceless fricative such as [ɸ]. In Japanese, for example, /p/ has a highly asymmetrical distribution. Unlike stops at other places of articulation, a voiceless bilabial stop is limited to loanwords (/pan/ 'bread'), onomatopoeic words (/pa͡tʃiŋko/ 'pin ball

[17] This is not usually the case. In normal voiced speech the impedance of the sound source, i.e., the vibrating vocal cords, is so much greater than the impedance (inertia) of the resonances of the vocal tract that there is a negligible amount of coupling between the source and the tract.

game'), medial geminates (/tepːanˌ/ 'iron plate'). Morphophonemic alternations reveal that there was an original /p/: reduplicated forms such as /hitobito/ 'people' (< /hito/ (now [çito] 'man, person'). The word-initial */p/ changed to /h/ (philological evidence reveals this to have the following path: /p/ > /ɸ/ > /h/) whereas the intervocalic /p/ changed to its voiced counterpart /b/ (as happens in general with voiceless obstruents that end up in such an environment due to morphemic concatenation, e.g., /tokidoki/ 'sometimes' < /toki/ 'time, hour').

Voiceless fricatives

Similarly, among voiceless fricatives, the bilabial [ɸ] and labial-dental [f] are less frequent in languages of the world in comparison to the more common and louder sibilants [s] and [ʃ] (Maddieson 1984: 45). Sibilants are known to have high intensity partly because they have some downstream resonating cavity in the space between the point of constriction and the teeth and because the air jet passing through the apical-palatal groove also strikes the incisors which produces added turbulence (known as 'obstacle turbulence').

Voiced fricatives

The aerodynamic factors responsible for a reduced intensity and lesser perceptibility of frication in voiced vis-à-vis voiceless fricatives, and the phonological consequences, were addressed in 2.2.1*E* above.

Non-pulmonic obstruents

But the physical intensity cannot be the only factor determining the frequency of occurrence of obstruents in languages' segment inventories. If it were then more languages would have ejectives (glottalic egressives) or clicks (velaric ingressives) than is the case. Since the magnitude of the pressure differential between the oral cavity and the atmosphere is what determines the intensity of the turbulence, these segment types, clicks in particular, would have wider incidence. Here the concept of *Maximum Utilization of Available Features* (MUAF; Ohala 1979) comes into play. The MUAF principle posits that sound systems are not only shaped by perceptual-motor factors, such as maximization of perceptual dispersion and perceptual contrast (Lindblom 1986, 1990b) or quantal effects (Stevens 1972, 1989), which would predict the use of multiple contrastive features. Instead, systems tend to limit their use of phonetic features, such that a given feature tends to combine systematically with the existing features in the system, thus maximizing the use of the available features. New

segments can arise via sound change as modifications of existing segments. For example, ejectives and glottalized sops may arise from sequences of pulmonic stop + glottal stop (see Ohala 1995). But this point needs further research.

Nevertheless, though non-pulmonic obstruents are less frequent than pulmonic, within the ejective stops, labial ejectives have a lesser incidence that non-labial ejectives, paralleling the distribution in voiceless pulmonic stops (Greenberg 1970: 127, Maddieson 1984: 103).

P. When generating noise, labiovelars behave as labials

The labiovelars [w], [ʍ], [k͡p] [g͡b] and [ŋ͡m] are doubly-articulated consonants with two simultaneous primary constrictions, labial and velar. In spite of their two constrictions, in certain cases these sounds pattern as labial, and in other cases as velar (Ohala & Lorentz 1977; Ohala 2005). Of interest here is that when generating noise (frication or stop bursts) labiovelars tend to behave as labials[18]. For example, in Sentani (Cowan 1965) /h/ is realized as [s] after certain sounds (the vowel /i/, nasals and glides); however, after the labiovelar glide /w/ it is optionally realized as labial [f] or [s], e.g., *kɛwfike* or *kɛwsik*e, but not * *kɛwhike* 'he threw away' (aorist). In Tenango Otomi the /h/ before /w/ is realized as the voiceless labial fricative [ɸ] (Blight and Pike 1976). The labiovelar glide in the borrowed French word *lieutenant* is pronounced as a labial fricative in British English, [lefˈtenənt]. Similar evidence is found in a wide the variety of languages (see Ohala and Lorentz 1977: 587 for a list of languages and sources). In addition, auditory impressions of the perceptual dominance of the frication produced at the labial constriction over that produced at the velar constriction are reported by Pike (1943:132) and Heffner (1964:160) among others.

The reason why in a fricativized labiovelar, with turbulent airflow produced at each of the two strictures, the noise generated at the labial constriction dominates is provided by acoustic factors. It is known that the intensity of a sound is a function of its inherent intensity and its transfer function, that is, the way the resonating cavities the sound passes through modify the intensity at various frequencies. Since turbulent noise is inherently high-frequency, the noise at the velar constriction would be attenuated by the low-pass filtering effect of the downstream resonator (Fant 1960; Stevens 1971; Stevens 1998), whereas the labial noise source would not have such attenuation.

[18] In the case of doubly articulated labiovelar stops, [k͡p] [g͡b], the auditory impression from the release is that of a labial, rather than a velar. This seems to be due to the timing of the two closures. The dorsal closure leads the labial closure, which is released at a later stage. Hence the acoustic similarity of the [k͡p] release to the [p] release (Ladefoged and Maddieson 1996: 336-339).

4. Timing of the articulators

Stops emerging in the transition between nasals or laterals and adjacent consonants have been extensively studied (see references in Ohala 1995). Ohala (1983b, 1997b) proposed a unified account of emergent stops in terms of variation in interarticulatory timing, specifically, when the articulatory configurations for adjacent segments overlap, they may result in transitional stops.

IV. At the junction of nasal and laterals, stops emerge.

The vocal tract has two major exit valves for the pulmonic airflow, the oral and the nasal passage. For a nasal consonant, the oral passage (controlled by the tongue or lips) is closed and the nasal passage (controlled by the velum) is open; for an oral consonant it is the reverse. Stops, by definition, have all exit valves closed. Laterals and apical fricatives may also be considered as having two independent exit valves: the tongue sides and the apex, see Fig. 3, bottom. For a lateral, the lateral valve (controlled by one or both sides of the tongue) is open and the apical valve is closed. For the central fricatives like [θ s ʃ] (and to some extent for trills) it is the reverse, the tongue sides are raised and help to channel the air through the midline opening. As shown in the figure, sequences such as [mt] and [ls] require a simultaneous and opposite change of state of the two exit valves (cf. Fig. 3a and 3c). If, in the transition between these segments, both exit valves are closed (Fig. 3b), then air flowing from the lungs accumulates in the oral cavity, oral pressure rises, and when the oral constriction is released it causes a burst and an obstruent is created. The place of articulation of the epenthetic –or better, the 'emergent'[19]– stop, i.e., its release, will be at the valve which is the first to open. In NC clusters, any epenthetic stop will be homorganic with the nasal since the oral constriction for the nasal is released first. In /ls/ and /lr/ clusters, the first valve to be released after the transitional stop is that of the second member of the cluster and the emergent stop will be homorganic with C2. (It may be difficult to evaluate this latter claim since the [l], the first member of the cluster, is necessarily homorganic or near-homorganic to the second member).

[19] Although the term 'epenthetic' is more common to describe stops such as the [p] in "warm[p]th", the term 'emergent' is preferred: 'epenthetic', by its etymology implies that the stop was simply "inserted", i.e., it came out of nowhere, whereas the term 'emergent' correctly implies that the stop emerged from pre-existing pre-cursors, e.g., a temporal overlap of the pre-existing closures at the velum and in the oral cavity.

FIG. 3

Q. 1. Emergent stops in nasal clusters

As shown in Fig. 3b (top), such transitional stops involve denasalization of the latter portion of the nasal due to anticipatory velic closure when the oral constriction for the nasal has not yet been released. Such early velic closure may be required for (i) aerodynamic reasons or for (ii) acoustic-auditory reasons. (i) If an obstruent like [θ s ʃ], a heterorganic stop or a trill follows, the velopharyngeal valve must be closed in order to build up pressure behind the oral constriction and generate continuous noise in the case of fricatives, transient noise in the case of stops, or to set the tongue tip into vibration for trills. An early velic raising (and anticipatory glottal abduction) during the oral constriction for the nasal, will ensure sufficient time and rate of flow to create a pressure differential across the oral constriction for turbulence or tongue-tip vibration (Ali et al. 1979). Indeed the requirement of a closed velum will only apply to 'buccal' obstruents, as explained in section 2.2.3.III, and hence these are the only segments that will trigger emergent stops. Examples of epenthetic stops emerging in nasal-obstruent and nasal-trill sequences (or nasal-rhotic; see below for other variants of rhotics) are given in (15). (ii) A segment may require a closed velopharyngeal valve due to acoustic-auditory factors since nasal coupling would distort the acoustic characteristics of the sound. This is the case for any distinctively oral segment, including oral (*vs* nasal) vowels, and any segment, distinctively oral or not, that has a low first formant – such as [l, w, i, u], since this formant would be most distorted by nasal coupling, the effect of which is seen primarily in the low frequencies (Fant 1973; Fujimura and Lindqvist 1971; Bell-Berti 1993), accordingly it is vowels and sonorants with a low F1 which tend to trigger an early velic raising and emergent stops (Ohala 1975). Taps may have the same acoustic motivations as [l] for remaining oral if they are to maintain contrast with [n] (for nasalized laterals alternating with nasals, see Cohn 1993 and Ohala 1975; examples of nasalized taps alternating with nasals are the sound change /n/ > /ɾ̃/ in Middle Indo-Aryan (Skt. *manah* > dial. MIAr. *mano* [maɾ̃o] (Hock, 1986: 82), and /n/ > /ɾ/ in Rumanian, presumably through [ɾ̃] (Rosetti, 1978; Sampson, 1999)). Examples of segments like taps, [l], high vowels, and distinctive oral vowels promoting emergent stops in adjacent nasals are given in (15.3) and (16).

(15) 1. Nasal-fricative sequences

a. English *Hampstead, Hampshire* < Old English *hām + stede, sc̄īr*

b. English *once, sense, prince* [n^{t}s]

Banff [m^{p}f], *warmth* [m^{p}θ]

strength, *length* [ŋ^{k}θ]

c. Eastern Catalan *anxova* [əɲ'ʃɔβə] ~ [əɲ'$\widehat{\text{tʃ}}$ɔβə] 'anchovy'

menjar [məɲ'ʒa] ~ [məɲ'$\widehat{\text{dʒ}}$a] 'to eat'

d. Central Italian *penso* ['pɛn$\widehat{\text{ts}}$o] 'I think' (Busà 2007)

e. Dutch *langs* [laŋs] ~ [laŋks] 'along' (Warner and Weber 2001)

2. Heterorganic Nasal+ stop sequences

a. *empty* < Old English *ǣmtiġ; peremptory* < Middle French *peremtoir; Hampton* < O.E. *Hamtun.*

b. English *dreamt* [dremt] ~ [drempt]

c. Dutch *hangt* [haŋt] ~ [haŋkt] 'hangs' (Warner and Weber 2001)

d. Catalan *comte* ['komtə]~ ['komptə] 'count'

e. Latin *prom-p-tus* < past participle of *promere; exem-p-tus* < *eximo* 'take away' (Meillet and Vendryes 1924:82)

3. Nasal-rhotic sequences

a. Spanish *vendrá* < Latin *ven(i)re* 'he will come'

Alhambra < Arabic *al hamra* 'the red'

b. Catalan *cogombre* < Latin *cucumere* 'cucumber'

cendra <Latin *cinere* 'ash'

c.French *chambre* < Latin *cam(e)ra* 'chamber'

gendre < Latin *genere* 'gender'

d. Cl. Greek *andros* < *an(e)ros* 'man'

e. English *thunder* < O.E. *þunor*

slumber < cf. Middle English *slumeren*, O.E. *sluma*

f. Pali (Oberlies 2001)

amba < *ambra* < Sanskrit **āmra*

tamba < *tamb(r)a* < Sanskrit **tāmra*

g. Swedish dialects (Ivars 1996; cited in Engstrand, Björsten, Bruce and Eriksson 1998)

Pernå /semberi/ for Standard Swedish /semre/ ‘worse’

(16) 1. Nasal-lateral sequences

a. Swedish dialects (Ivars 1996; cited in Engstrand et al 1998)

Lappfjärd /sa:mblast/ for Standard Swedish /samlades/ ‘gathered’

b. English (Mossé 1952) *spindle* < O.E. *spinel*

bramble < O.E. *brēmel*

humble < O.Fr. *humble* < Latin *hum(i)lis*

c. Spanish *temblar* < Latin *trem(u)lus* ‘to shiver’

d. Catalan *semblar ,* French *sembler* < Latin *sim(u)lare* ‘to seem, appear’

e. Latin (Millet and Vendryes 1924:83ff)

templum	<**tem-lo*	‘a section’
exemplum	<**ex-em-lo*	‘a sample’

2. Nasal-high vowel or nasal-oral vowel sequences (see Ohala 1983b for citations to the source data)

a. Ulu Muar Malay	ban ~ ban^{d}ʊ	‘doorsill’
b. Korean	mul ~ m^{b}ul	‘water’
BUT:		
	mal	‘language’
c. Telefol	/su:m/ [su:^{b}m]	‘banana’
d. Tenango Otomi	/mohi/ [m^{b}ohi]	‘plate’
	/nĩne/ [nĩn^{d}e]	‘your mouth’
e. Parintintin	/õmoapɨ/ [õ^{m}boapɨ]	‘he cooks’
	/ɲãnu/ [ɲã^{n}du]	‘spider’

In the case of reverse sequences, specifically fricative-nasal sequences, variations in the relative timing of velic opening for the nasal results in several outcomes historically, including (i) fricative weakening and loss (that we suggest, results from anticipatory velic opening as reviewed in section 2.2.3.*K*), or (ii) preservation of the fricative but the

emergence of an epenthetic stop or an epenthetic vowel. A stop emerges due to a delayed velic opening, i.e., a prolonged velic occlusion of the fricative during the oral constriction for the nasal (e.g., Middle English *listen* < O.E. *hlysnan*; Sanskrit *kr̥̊sṇā* > *Krishna* ~ *Krish**t**na, grīṣma-* ~ *grīṣ**p**ma-* 'heat'; Ohala 1997b). Similarly, the insertion of an epenthetic schwa in /sm̰/ >[sᵊm̰] and /sn̰/ > [sᵊn̰] sequences in Montana Salish (Ladefoged and Maddieson, 1996:109-110) reflects a delayed velic lowering and oral closure for the nasal relative to the end of the fricative. In both cases, the delayed opening of the velic valve preserves frication. Parallel patterns in the timing of the velum and the oral articulators in fricative-nasal sequences are found phonetically (Solé 2007a).

Q.2 Emergent stops in lateral clusters

Emergent stops also occur in the transition between laterals and apical fricatives. As mentioned, laterals and fricatives have opposite requirements for the lateral and apical valves (Fig. 3 bottom). The relative phasing of the exit valves (closure of the lateral valve and release of the central valve) for these segments may result in a transitional state where both valves are closed, oral pressure builds up and a stop burst is produced. Stops emerging from laterals require that the fricative is homorganic or nearly so, that is, that the two sounds in sequences share the same exit valves. Emerging stops in homorganic lateral-fricative clusters are common synchronically and diachronically, as exemplified in (17.1).

Emergent stops from reverse lingual fricative-lateral sequences, resulting in a laterally-released stop, have been attested in a variety of languages (see Ohala 1997b, 2005 and references therein) and are illustrated in (17.2).

(17) 1. Lateral-fricative sequences

a. English *false* [fɒɬˢs] *else* [ɛɬˢs] *pulse* [pʰʌɬˢs] *Elsie* ['eɬˢsi]

b. Eastern Catalan *àlgebra* ['aɬʒəβɾə] ~ ['aɬd͡ʒəβɾə] 'algebra'

àlgid ['aɬʒit] ~ ['aɬd͡ʒit] 'culminating' (adj.)

c. Kwakiutl (Boas 1947)

k!wēɬt͡soᵋ < k!wēɬ - soᵋ 'to be feasted'

lɛgwi´ɬt͡sa gōkᵘ < lɛgwi´ɬ - sa gōkᵘ 'the fire of the house'

maᵉɬt͡sɛ´m < maᵉɬ - sɛ´m 'two round ones'

2. Fricative-lateral sequences

a. English *hustle* < Dutch *husseln, hutselen*

wrestle < O.E. **wræstlian*, Cf. N.Fris. *wrassele*

b. Greek (Wetzels 1985)

hestlos < *heslos*

c. Italian *schiavo*[20], French *esclave*, Spanish *esclavo* 'slave' < **stlavo* < Late Latin *slavo* < Old Slavonic *sloveninu* 'a Slav'

(18). Lateral-rhotic sequences

a. Middle English *alderbest* 'best of the all' < OE *ealra* 'of all those'

b. Spanish *saldrá* < Latin *sal(i)re+ha* 'he'll leave'

medrar < *meldrar* < *melrar* < Latin *meliorare* 'to prosper, to succeed'

c. Catalan *doldre* (dial. *mole*) < Latin *dolere* 'to hurt'

moldre (dial. *molre*), French *moudre* (O.F. *moldre*) < Latin *molere* 'to grind'

d. Swedish dialects (Ivars 1996; cited in Engstrand et al 1998)

Lappfjärd (west Findland) /ldr/ ~ Standard Swedish /lr/

(19). Fricative-rhotic sequences

a. Spanish *sidra,* French *cidre* < **sizra* < Latin *sic(e)ra* 'cider'

b. French (Millardet 1910:88; Wetzels 1985)

être 'to be' < Old French *estre* < Latin *essere*

ancêtre 'ancestor'< O.Fr. *ancestre* < Latin *antecessor*

c. Italian *Israele* [iz^{d}ra'ɛlɛ], [iz^{d}ɾa'ɛlɛ]

In the case of /lr/>/ldr/, illustrated in (18), the emergent stop may also be attributed to variability in the phasing of the lateral and central valves, as not only the trill but also the tap and fricative varieties of the rhotic require elevated tongue sides and an open central valve. The case of /sr/>/str/, exemplified in (19) cannot be explained in the same terms as both segments have a central release. However, both the tap and the trill involve an initial momentary central closure (of 25-30ms, Lindau 1985) which, on release, creates abrupt amplitude changes and may convey enough auditory cues for a stop (this is especially the case for trills, the first closure period of which involves a longer duration and a higher pressure build up than subsequent contacts in order to set the tongue tip into vibration, Solé

[20] The origin of the Italian greeting *ciao*, i.e., a much abbreviated form of the old formula meaning "your servant".

2002a). See Ohala (1995, 1997b, 2005) for the emergence of non-pulmonic stops and other epenthetic sounds.

The cases presented so far illustrate that variations in interarticulatory timing (i.e., denasalization and delateralization, principally), and associated aerodynamic and acoustic effects, account for the emergence of transient stop bursts which may be reinterpreted by the listeners as intended stops. In fact, failure to distinguish whether the stop was intended or not is probably at the origin of (i) the loss of an etymological /t/ in fricative-/t/-nasal and fricative-/t/-lateral sequences, e.g., *soften* (but *softer*)*, christen* (but *Christianity*), *hasten; castle* (but -*chester*)*, thistle, wrestle*, and (ii) the emergence of a non-etymological /t/ in *listen* and *hustle* in English. Warner and Weber (2001) provide perceptual data supporting the proposed articulatory and perceptual account; they found that listeners perceive stops the speaker did not intend, mostly in environments where the articulatory explanation predicts epenthetic stops to occur. As detailed above, such epenthetic stops originate in variations in the timing of pre-existing articulatory events and have been reported phonetically in a variety of languages (e.g., Recasens & Pallarès 2001; Solé 2007a). However, language-specific timing habits may avoid the transitional overlap of articulatory closures leading to emergent stops, thus epenthetic stops are not found phonetically in South African English (Fourakis & Port 1986) .

5. Conclusions

We have reviewed a number of sound patterns where audible turbulence in the form of frication or a brief stop burst appears where it had not been present before, or fails to appear in contexts where it is expected to occur. We have argued that turbulence may *arise* from variations in the aerodynamic conditions due to interaction of articulatory gestures (i) within a segment (e.g., devoiced approximants becoming fricatives), or (ii) coarticulation with adjacent segments (e.g., glides or close vowels becoming fricativized following stops). Turbulence may also arise from changes in interarticulatory timing across segments (e.g., transitional epenthetic stops) and perception of turbulence may be boosted due to auditory-acoustic factors (e.g., in anterior vs back fricatives; in onset vs coda position; or the emergence of buccal frication).

Audible turbulence for fricatives or stops may also be *diminished* and go undetected. This may be due to failure to create a pressure differential across the point of constriction sufficient to generate audible turbulence owing to (i) gestural interaction (e.g., an open velum or vocal fold vibration, as in voiced nasalized fricatives or stops in a nasal context), (ii)

coarticulation with conflicting consecutive segments (e.g., lingual fricatives and trills), or (iii) prosodic conditions (e.g., syllable-final or utterance-final position). Turbulence may also be perceptually missed because of strictly auditory-acoustic factors, such as the lack of a downstream resonator to amplify the weak intensity noise created at the constriction (e.g., in labial stops or fricatives without a downstream cavity), or the attenuation of friction noise produced at the velum (in labiovelar segments) due to the expansion of high velocity air at the outermost constriction.

The phonological patterns reviewed above illustrate that if sound patterns in language are to be explained, it is necessary to refer to details about the physical phonetic content of speech production and perception and, where relevant and where possible, factors that are not exclusively limited to the domain of speech. The alternative is mere stipulation: e.g., "obstruents tend to be voiceless" –even if re-coded using shorthand notations like [+ obstruent]→[-voice] or [0 voice] →[-voice] / [__] [+obstruent]. In addition, the patterns reviewed illustrate the dependency between frication and voicelessness, between defrication and nasality, between the constriction location of the obstruent (buccal or non-bucal) and nasality, etc. due to aerodynamic, acoustic-auditory factors or the timing of articulatory events. As argued by Ohala (2005), dependency relations between features due to speech aerodynamics, acoustics or perception cannot be adequately captured by models such as Feature Geometry or Optimality Theory. For example, the aerodynamic interaction between voicelessness and frication demonstrates that what happens at the glottis can influence the generation of turbulence at the oral constriction. Such dependency relations cannot be accounted for in a model where the laryngeal feature is at a different branch from the supralaryngeal features and, therefore, cannot specify supralaryngeal frication.

Finally, we would like to emphasize that what we have attempted to do here is part of a long tradition of noting common cross-language sound patterns –often referred to as "phonological universals"– and seeking explanations for them in the physical, physiological, acoustic, and perceptual domains (e.g., Bindseil 1838, Key 1852, Rosapelly 1876, Passy, 1890, Rousselot 1891, Grandgent 1896, Phelps 1937, Greenberg 1970, to mention just a few). As stated at the start of this paper, we do not claim and do not believe that these patterns are psychological or innate nor did these predecessors. Common cross-language sound patterns arise from the universality of physical phonetic constraints. Many phonologists currently are also making interesting generalizations on common cross-language sound patterns but they claim that these arise from constraints that are part of the mental grammar or of the innate human language faculty. How can it be that the generalizations they note are of the same type as those made more than a century ago but are

attributed to completely different causes? There is, of course, a crucial difference: today these generalizations are expressed in highly formal terms and are embedded in ambitious theories about universal grammar. We will not attempt to resolve this apparent incongruity but let us make the following offer: to anyone who thinks they can discover the psychological or genetic underpinnings of speech just by noticing sound patterns in languages and then formalizing them, please contact us for information on how, for a suitable fee, you can obtain the philosopher's stone (that can turn base metals into gold), the location of the fountain of youth (to give eternal life), where to find unicorns, mermaids, leprechauns, and the tooth fairy.

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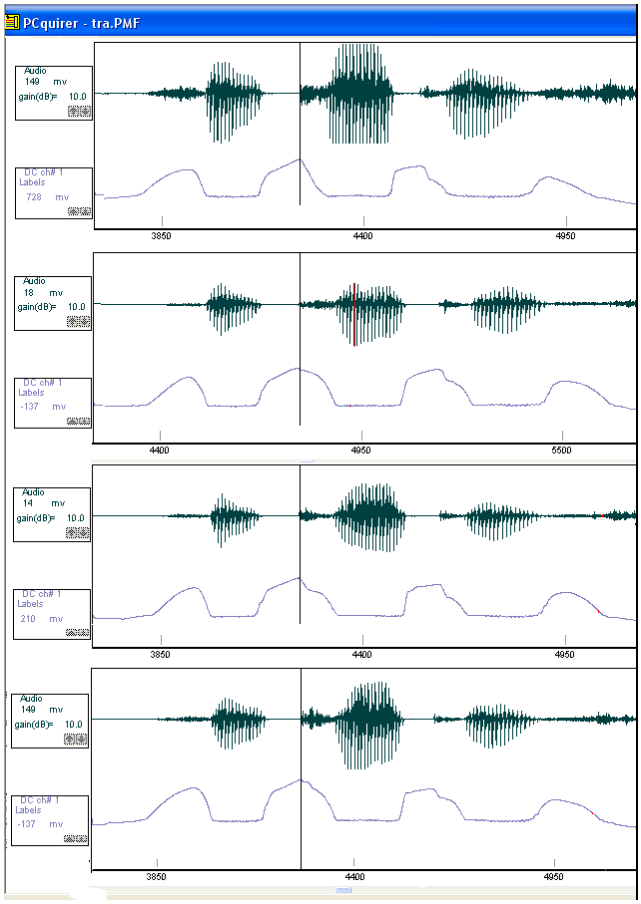

Figure 1. Audio and oral pressure for aspirated /tɑː/, /tjɑː/, /twɑː/, /trɑː/ in the carrier sentence 'Say__twice'. The vertical line is placed at the [t] release. (See text).

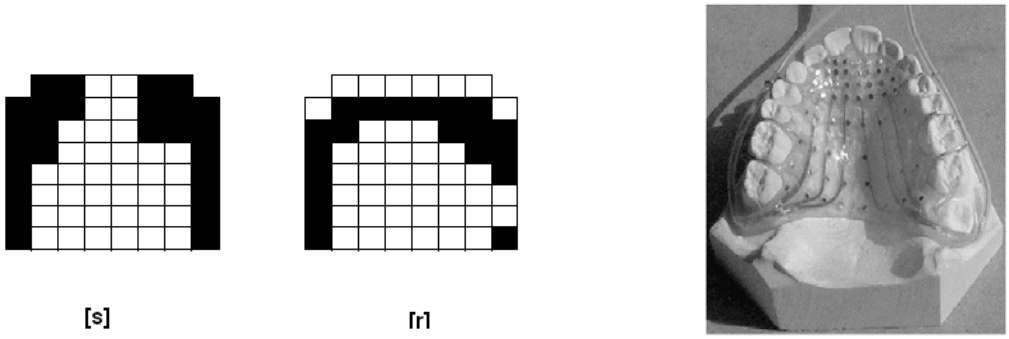

Figure 2. Left. EPG linguopalatal contact configurations for /s/ and /r/ between low vowels. Right. Artificial palate with the electrodes. Note that in the artificial palate the distance between the electrodes in the first four rows is much smaller than in the back rows. This difference in scale is not preserved in the grid on the left.

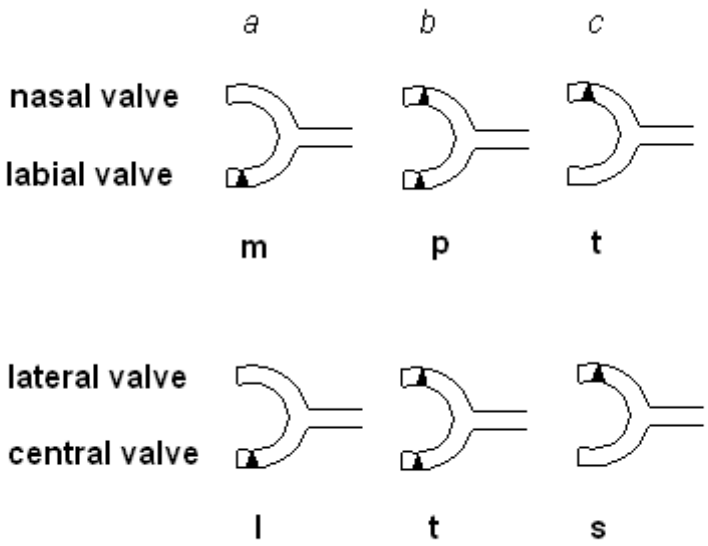

Figure 3. Schematic representation of the vocal tract with independent airways. Top: valvular configuration for a labial nasal (a), for a heterorganic oral obstruent (c), and for the emergent stop, with both airways closed (b). Bottom: valvular configuration for a lateral (a), for a central fricative (c), and for the transitional stop (c).