Chapter 9

The Origin of Sound Patterns in Vocal Tract Constraints

JOHN J. OHALA

I. Introduction

The ultimate task of phonology is to discover the causes of the behavior of speech sounds. To do this phonologists must refer to the way speech is created and used by humans, including how it is stored in the brain, retrieved, executed, perceived, and used to facilitate social interaction among humans. The domain of phonology is therefore mind, matter, and manners. This chapter is about matter: some aerodynamic and anatomical properties of the vocal tract and how they influence the shape and patterning of speech sounds. A secondary aim of this chapter is to show not only that the study of the physical aspects of speech assists phonology but also that phonology can return the favor: A careful, perhaps inspired, analysis of sound patterns in language can help us to discover and understand some of the complexities of speech production (Ohala, 1975a, 1975b, 1978a, 1978b, 1980, 1981; Ohala & Riordan, 1979; Shattuck-Hufnagel, Chapter 6, this volume; MacKay, 1972).

Language is a very complex human activity and, as mentioned, sound patterns can be determined by psychological and social factors as well as physical factors. But such nonphysical factors tend to vary widely from one community to another or even from one individual to another. Thus, their influence on speech sound behavior should be quite different when viewed over widely divergent languages. Physics and human physiology, however, represent a universal substrate on which all speech is built. Therefore, to be sure we are dealing with sound patterns that are due primarily to these universal factors, it is necessary to look for them repeated in several unrelated languages.

In fulfilling this task I will cite what might seem like quite dissimilar pieces of data from different languages: allophonic variation, sound change, dialect variation, morphophonemic alternation (i.e., contextually determined variation in the phonetic shape of a given morpheme within a single language), and patterns in segment inventories. In fact, I believe it is safe to regard all of these as manifestations of the same phenomenon caught at different stages or viewed from slightly different angles. I assume that the allophonic variations cited arise from constraints of the vocal tract, the topic of interest. Some of these allophonic variations become sound changes. If a sound change affects words in one linguistic community but not another, dialect variation results. If the sound change affects a given morpheme in one phonetic environment but not another, then morphophonemic variation results. If one consequence of the sound change is to eliminate a segment from or introduce a segment into the language, then it would influence the language's total segment inventory.

It might be thought that if the same physical factors have been at work shaping all human speech, then all languages should be tending toward the same phonological state. It is true that the more we look at diverse languages' phonologies, the more we find very similar patterns or metapatterns. Thus, although it is surprising to learn from Ladefoged (chapter 8, this volume) that one language has some 80 click phonemes in addition to nonclick sounds, in general, none of the phonemes or features utilized in the Khoisan languages requires us to stretch the conceptual and descriptive framework laid down for other languages' sound systems. Nevertheless, languages' phonologies differ very much in details, and there is no detectable trend toward convergence. One reason for this is that there are many degrees of freedom in the design of a vocal–auditory signaling system and that several designs (i.e., phonologies) can serve the primary function of communication and still stay within the bounds set by articulatory (and auditory) constraints. Another reason for diversity in languages is that the psychological and social factors shaping speech may run counter to the influence of purely physical factors.

II. Speech Aerodynamics

A. Preliminaries

The speech production mechanism can be viewed as a device that converts muscular energy into acoustic energy. It does this by creating within the vocal tract direct-current (dc) pressure differences that, when allowed to equalize with atmospheric pressure, create turbulence in the rapidly moving air which in turn produces the alternating-current pressure variations we call sound. It is therefore useful to consider how these dc pressure changes are made.

Figure 9-1 gives a schematic representation of the vocal tract as a collection

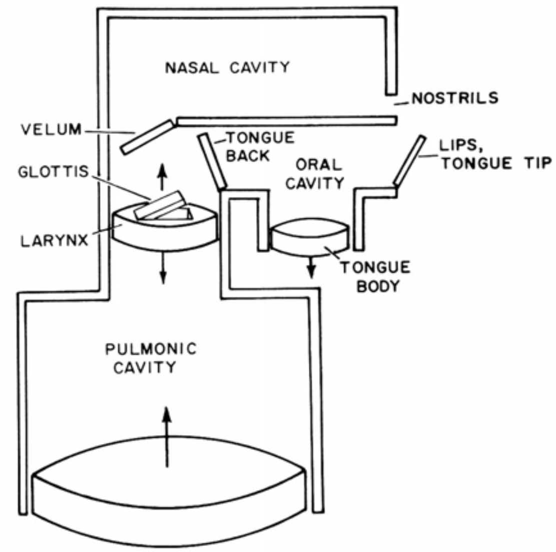

Figure 9-1. Schematic representation of the vocal tract as a device for the production of local dc pressure variations.

of pistons, valves, and piston chambers that can produce slowly varying localized pressure changes. There are three pistonlike structures in the vocal tract: the chest wall, the larynx, and the tongue. Sounds created with these three mechanisms as the initiator of the pressure change are called *pulmonic, glottalic*, and *velaric* sounds, respectively. If these pistons compress air in the chamber they are associated with, the sound is said to be *egressive*; if they rarefy the air, that is, create a negative pressure vis-à-vis atmospheric pressure, the sound is called *ingressive* (Ladefoged, 1971; Catford, 1977a).

B. Preferred Segment Types

Although it is physically possible for these three pistons to move in both directions to create both ingressive and egressive sounds, in fact, as indicated by the arrows near these structures in Figure 9-1, only four of the six possible sound types are found in human languages: pulmonic egressives, for example, [p, l, a, ʔ, s];[1] glottalic egressives, or "ejectives," for example, [p', t'];

[1]The phonetic transcription used throughout, except as noted to the contrary, is that approved by the International Phonetic Association as of 1979. Forms in square brackets [. . .] represent detailed or narrow phonetic transcriptions, those bounded by slashes / . . . / represent broad or

(continued next page)

glottalic ingressives or "implosives," such as [ɓ, ɗ, ʄ]; and velaric ingressives or "clicks," such as [ʇ, ʖ]. Pulmonic ingressive vocalization is not found except as a stylistic variant of pulmonic egressive speech, for example, Swedish [ja] (on ingressive voice) "yes" (emphatic), French [wi] (ingressive voice) "yes" (used primarily by females). Velaric egressive sounds are even rarer, being found only (as far as I know) as imitations of animal sounds or flatulence, the latter used for mockery or insults.

Why should two of the possible six sound types not be used? The lack of pulmonic ingressive sounds, if I may speculate, is probably due to the shape of the vocal cords in normal voice (modal register), which, in coronal section (see Figure 9-2), are seen to be asymmetric about the plane that is normal to the airflow and that passes through them at the point of closest approximation. The vocal cords have more bulk below this plane than they do above it. If airflow is egressive, that is, has greater sub- than supraglottal pressure, the upward movement of the vocal cords will necessarily also involve their lateral movement, thus smoothly and effectively opening the valve that vents the subglottal air. If airflow is ingressive, however, it would seem that a downward movement of the vocal cords would involve a slight bulging of the lower tissues, which would not move laterally as easily in order to release an excess of supraglottal pressure. (This argument would not apply to falsetto voice, where the vocal cords are considerably thinned and thus have a more symmetric coronal profile. Accordingly, I find that I can phonate in falsetto voice about as well ingressively as egressively.)

Of course, it is also true that some fricatives, notably sibilants such as [s, ʃ], cannot be produced as well ingressively as egressively. No doubt this is because during ingressive airflow the primary location of the noise source (the point where the air exits and expands from the narrow channel it is forced through) is on the wrong side—the inside—of the oral constriction, which, because it has very high acoustic impedance, does not permit the sound generated to radiate to the atmosphere.

Velaric egressives may not make good speech sounds, I would speculate, because the characteristics of the tongue blade as a valve permit higher negative pressures (but not positive pressures) to develop and to be released in a suitably abrupt fashion before the seal fails.

Many other constraints on the form of speech stem from the properties of the speech system represented in Figure 9-1. It is evident, for example, that a chamber in which an appreciable pressure change is created ($\Delta p = \pm 5$ cm

phonemic transcriptions, and the remainder, including those in italics, are purposely ambiguous as to the level of phonetic detail that they represent (in some cases they represent the standard orthographic form of the word). Forms marked with an asterisk (*) are hypothetical, and in most cases are reconstructed. The symbols (>) and (<) stand for "became" and "derived from," respectively. A tilde (~) between cited forms means "freely alternates with." Tone and stress are not marked, and vowel length is marked with a macron (¯) in the Latin examples.

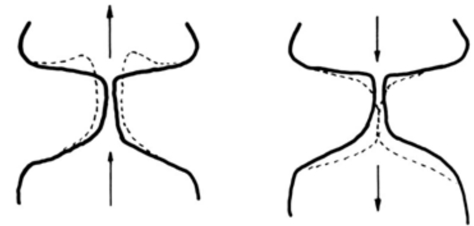

Figure 9-2. Hypothetical coronal sections of the vocal cords showing the pattern of vibratory movement during egressive voice (left) and ingressive voice (right) (arrows show direction of airflow). Solid lines show positions of vocal cords when transglottal pressure is relatively low; dotted lines represent their position as the transglottal pressure builds up to a maximum, that is, as the excess pressure is being vented. Egressive voice, but not ingressive voice, allows lateral movement of the vocal cords and thus easy venting of the excess pressure.

H_2O), and that has to be vented through one valve in order to create an audible sound, must have all other valves closed. Thus there can be no nasalized [p]. Also, there can be no glottalic sonorants, for example, ejective [m], implosive [l]. This is because any pressure change created by the larynx acting as a piston would equalize immediately by leakage across the rather large valvular openings characteristic of sonorants. For similar reasons, all oral obstruents that are released at the uvular region or farther forward (except clicks) must have the soft palate elevated (i.e., the velopharyngeal valve closed). Pharyngeal or glottal obstruents (the latter including, from a physical point of view, all vowels and voiced sonorants) would not require soft palate elevation—the open velopharyngeal valve does not connect to, and therefore does not vent air pressure in, the pharyngeal or subglottal cavities. (This assumes, of course, that these sounds are not distinctively nasal, e.g., [ĩ].) I will explore below some phonological consequences of this point.

Another sound pattern deducible in part from aerodynamic considerations is that evident in languages' segment inventories. Tables 9-1 and 9-2 give the consonant inventories of Abkhaz and Yala, respectively. On the basis of such data, Hockett (1955, pp. 104ff.) offered the generalization that the more consonants a language has, the greater is the ratio, r, of obstruents to nonobstruents. Yala has 28 consonants, of which 18 are obstruents, giving an r of 1.8. In Abkhaz, which has 58 consonants, $r = 7.3$. Salient acoustic signals are those that involve rapid spectral modulations (Stevens, 1980). Obstruents, especially those that involve a transient burst due to the rapid equalization of an appreciable difference in air pressure, create more rapid spectral changes and thus are able to carry more information and make many more distinctive sounds than can nonobstruents. This accounts for Hockett's observation.

Table 9-1. Consonant Inventory of Abkhaz

m	n													
b	d	dʷ					gʲ	g	gʷ					
p	t	tʷ					kʲ	k	kʷ					
p'	t'	tʷ'					kʲ'	k'	kʷ'	qʲ'	q'	qʷ'		
	dz	dzʷ	dʒ		dʐ									
	ts	tsʷ	tʃ		tʂ									
	ts'	tsʷ'	tʃ'		tʂ'									
v	z		ʒ		ʐ	ʐʷ								
f	s		ʃ		ɕ	ʂʷ				ʁʲ	ʁ	ʁʷ		
w			l	r	j	ɥ				χʲ	χ	χʷ	ħ	hʷ

Note. From Catford (1977b).

C. Constraints on the Voicing or Devoicing of Stops

Voicing—vibration of the vocal cords—has two physiological requirements: First, the vocal cords must be in a suitable configuration—typically, lightly adducted; and second, there must be sufficient air flowing past them. If either one or both of these conditions are missing, there will be no voicing. To the extent that both of these conditions are approached during a voiceless segment, the chance of that segment becoming voiced is greater.

There is a well-recognized difficulty in maintaining voicing during a stop (in which, by definition, all exit valves are closed) because the air flowing through the glottis accumulates in the oral cavity, causing oral pressure to approach subglottal pressure. When this happens the air flowing through the glottis gradually diminishes and voicing is extinguished.

In view of this, it is not surprising to find that of the 706 languages whose segment inventories were surveyed by Ruhlen (1975) 166 have only voiceless stops and 4 have only voiced stops (the remainder using both voiced and voiceless stops). Even if the reliability of such large-scale surveys may be questioned, the decisive "tilt" toward voicelessness in the stops could not be reversed by a few inaccuracies.

Table 9-2. Consonant Inventory of Yala (Ikom)

m		n		ɲ		ŋ		ŋ͡w
m͡b							ŋ͡mgb	
b		d		ɟ		g	g͡b	g͡w
p		t		c		k	k͡p	k͡w
f		s				x		
		s͡j						
	l		r					
				j	ɥ		w	

Note. From Armstrong (1968).

The longer the stop closure is held, the greater is the likelihood that voicing will be extinguished. Thus the tendency for long voiced stops (so-called geminates) to become voiceless is particularly strong. Phonological data from Mõré, which illustrates this, are given in Table 9-3. (See also Jaeger, 1978, for further evidence on this point.) Conversely, the shorter a stop closure is, the more likely it is to remain voiced, or if originally voiceless, to become voiced. There is, therefore, a very widespread tendency among languages to have voiced stops (or voiced obstruents in general) shorter than their voiceless counterparts (Lehiste, 1970, pp. 27ff.).

There is also extensive evidence that voicing sits more comfortably on stops, pulmonic or implosive, made at some places of articulation rather than at others (Greenberg, 1970; Gamkrelidze, 1975; Sherman, 1975). Table 9-4 provides some representative data, the stop inventories from three languages. Sherman conducted one of the most extensive surveys on this pattern; out of over 570 languages whose stop inventories were examined (these did not include implosives), he found 87 that had gaps. The distribution of these "stop gaps" are shown in Table 9-5 (some languages had more than one gap). From such data it is clear that velar stops and voicing show the greatest incompatibility, labial stops and voicing the greatest compatibility. (These data also show that voicelessness does not sit well on bilabial stops. Although to some extent this may be a reflection of the greater hardiness of [b] over [p], or that [p] has a greater tendency to become voiced and thus merge with [b], it is also likely that acoustic–auditory factors are a more important determinant of this pattern: as Stevens (1980) has pointed out, [p] has the lowest amplitude and spectrally most diffuse burst of any of the voiceless stops and is thus less salient auditorily.)

It was once thought that the relative volumes of the oral cavities of the stops [b, d, g] were responsible for this pattern of stop gaps (Greenberg, 1970; Smith, 1977). It was reasoned that the larger volume of the oral cavity for [b] would accommodate more glottal airflow before pressure built up to the point where the transglottal pressure drop fell below the level necessary to maintain voicing, and conversely, that the smaller oral volume for [g] would accommodate less air, thus causing voicing to cease relatively soon. This reasoning is technically

Table 9-3. Morphophonemic Variation in Mõre

Morphophonemic form	Phonemic form	French gloss
pabbo	> papo	*frapper*
daw-ba	> dapa	*hommes* (w < b, cf. dibla, *petit mâle*)
bad + do	> bato	*corbeilles*
lug + gu	> luku	*enclos*
boγ + γo	> boko	*trou* (γ < g)

Note. From Alexandre (1953); transcription simplified.

Table 9-4. Stop Inventories of Thai (Abramson, 1962), Kalabari (Ladefoged, 1964), and Efik (Ward, 1933) Showing Absence of Voiced Velars

Thai			Kalabari					Efik				
p	t	k	p	t		k	k͡p		t	k	k^w	k͡p
p^h	t^h	k^h	b	d	ɟ	g	g͡b	b	d			
b	d		ɓ	ɗ								

correct but the magnitude of the effect of initial oral cavity volume on the length of voicing during stops is negligibly small. Calculations suggest that if the oral volume does not change during the stop closure, voicing can be maintained for approximately 10 msec during [g] and 15 msec during [b] (Catford, 1977a, p. 74; Ohala & Riordan, 1979).

Such periods of voicing are negligible in comparison with the typical duration of voiced stops (ca. 70 msec; Lehiste, 1970, pp. 27ff.). Clearly, initial oral volume by itself cannot explain why [b] is more common than [g] (Ohala, 1975a, 1976; Javkin, 1977). Voicing can be maintained beyond the limits cited if the oral volume increases *during* the stop closure, that is, expands to accommodate the accumulating glottal airflow (Ohala, 1975a, 1976). Such oral cavity enlargement can be accomplished *passively*, that is, as a result of the natural compliance of the walls of the oral cavity; or *actively*, by lowering the larynx, the mandible, and so on (see Chao, 1936; Javkin, 1977; Catford, 1977a).

Ohala and Riordan attempted to determine how long voicing would last if only passive expansion of the vocal tract took place. They had an adult male American English speaker say $V_1C{:}V_2$ utterances where $V_1 = V_2 =$ [i, u, e, a] and C: was an abnormally prolonged voiced stop [b, d, g]. The stop could be prolonged indefinitely because the oral pressure built up during the stop was vented through a nasal catheter. At unpredictable moments, however, a solenoid-activated valve closed the catheter so that oral air pressure would rapidly rise and voicing would be extinguished. The duration of voicing beyond the moment of complete closure was measured on signals from a throat microphone and an air pressure transducer that sensed oral air pressure. The results are presented graphically in Figure 9-3. Over all conditions the median

Table 9-5. Incidence of Stop Gaps According to Place or Articulation and Voicing in 87 Languages

	Labial	Apical	Velar
Voiceless	34	0	0
Voiced	2	21	40

Note. From Sherman (1975).

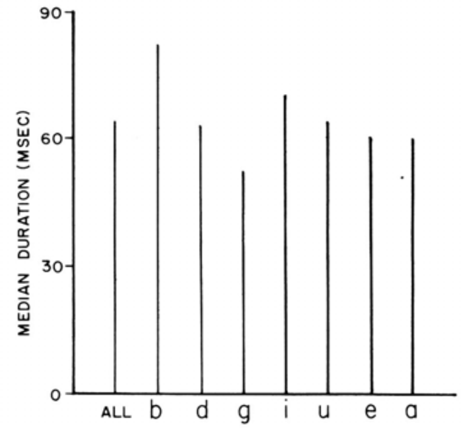

Figure 9-3. Median duration of voicing during stops when only passive expansion of the vocal tract occurs (data from Ohala & Riordan, 1979).

duration of voicing was 64 msec, but it was greatest for [b] (82 msec), least for [g] (52 msec). Moreover, with one exception, the stops coarticulated with the high vowels [i, u] permitted voicing to continue longer than those coarticulated with low vowels. The one exception was that [b] coarticulated with [a] had the longest stretch of voicing (91 msec), presumably because only this combination of consonant and vowel involved passive oral cavity expansion by the highly compliant cheeks.

These results can be accounted for by considering the net compliance of the surfaces on which oral air pressure impinges during the production of the stops. For velar stops only the pharyngeal walls and part of the soft palate can yield to the air pressure; in dentals, these surfaces plus the greater part of the tongue surface and all of the soft palate are involved; and in labials, these surfaces plus all of the tongue surface and some parts of the cheeks participate (see Houde, 1968; pp. 88–92; Rothenberg, 1968). Moreover, as Smith (1977) has indicated, the high vowels [i, u], by virtue of their greatly enlarged pharyngeal cavity, have greater oral volume (and thus greater surface area) than do the nonhigh vowels.

If active expansion were to be investigated in a similar way, presumably roughly similar patterns could be expected: Voicing could be extended several hundred milliseconds in this case, but still longer for labials than for velars, as with passive expansion. As Chao remarked:

> Between the velum and the glottis, there is not much room to do any of the tricks that can be done with the larger cavity for a **b** or a **d**.

(See also Javkin, 1977.)

In view of the preceding discussion it is interesting to note that one of the sources of voiced implosives (sounds involving active expansion of the oral cavity) may be former voiced geminates. This is the case, for example, with the implosives of Sindhi, an Indo-Aryan language; see Table 9-6.

Khubchandani (1969) reports that not all dialects of Sindhi have the same number of implosives. The pattern of gaps is entirely consistent, however, with our expectations regarding which places of articulation can most easily support voicing during stops: The B'ani dialect has the maximum number, four, / ɓ, ᶑ, ʄ, ɠ/; Maṇḍvi has two, / ɓ, ɗ/; and Vagdi has only one, / ɓ /.

A morphophonemic alternation in Nubian (Bell, 1971; Ohala & Riordan, 1979) also exemplifies two of the tendencies discussed; see Table 9-7. In Nubian the noun inflection that means "and" involves the gemination of the stem-final consonant and the addition of the sequence /—ɔn/. When a final /b/ is geminated it remains voiced; /d, ʤ, g/, however, the stops (and affricate) with farther-back points of articulation, become devoiced to /t, tʃ, k/.

Given the evidence cited here from Ohala and Riordan, we would predict that stops coarticulated with high vowels would more readily retain voicing than those coarticulated with nonhigh vowels. I have not found much support for this in the phonological literature, however. The one bit of data that may be a reflection of this effect (as well as the effect of place of articulation of the stop) is given in Table 9-8. These data show that of the original Proto-Bantu initial voiced stops (column 1), it is the */b/ which seems to preserve both voicing and stoppedness in the modern reflexes in Duala and Ngɔm (albeit as implosives), whereas */g/ loses voicing and/or stoppedness. In the case of */d/, its fate depends on the height of the following vowel: Before the high vowels /i, u/ it behaves similarly to */b/ in preserving both voicing and the stop character (the forms above the dashed line), whereas before other vowels it loses one or both of these features, as was the case with */g/ (the forms below the dashed line).

It should be mentioned at this point that, as illustrated by the Bantu data in Table 9-8, the resolution of the "conflict" between voicing and stops is not always done by devoicing the stop—it may also be accomplished by unstopping the stop, that is, changing it to a voiced fricative or, better, a voiced approximant. (The phonetic symbols [v, β, ð, γ] are often used for either fricatives or frictionless continuants.)

Table 9-6. Origin of Sindhi Implosives from Prakrit Voiced Geminate Stops

Prakrit		Sindhi	English gloss
*pabba	>	paɓuɳi	lotus plant fruit
gaddaha	>	gaɗahu	donkey
-(g)gaṁtʰi*	>	ɠaɳɗʰi	knot
bʰagga	>	bʰa:ɠu	fate

Note. From Varyani (1974).
*This "ṁ" is the conventional transliteration of the Devanagari *anusvara*, best regarded as symbolizing a nasal homorganic to the following obstruent.

Table 9-7. Morphophonemic Variation in Nubian

Noun stem	Stem + "and"	English gloss
/fab/	/fab:ɔn/	father
/sɛgɛd/	/sɛgɛt:ɔn/	scorpion
/kadʒ/	/katʃ:ɔn/	donkey
/mʊg/	/mʊk:ɔn/	dog

Note. From Bell (1971) and Ohala and Riordan (1979).

The evidence presented so far suggests that the farther forward in the vocal tract a stop is articulated, the better able it is to accommodate voicing. From my own reading of the phonological literature I think this is the dominant pattern. There are complications, however, which could override this generalization. The probability of a voiced stop remaining voiced (or a voiceless one becoming voiced) depends in a major way on the duration of the stop closure, a shorter duration allowing voicing to be maintained for all of, or a majority of, the stop duration. Stop closure duration may be affected by such factors as articulator mobility. A less massive and therefore faster articulator such as the tongue tip may be capable of making and then breaking a stop closure in a very brief interval.

In American English, for example, it is the apical stop /t/ (and not /p/ or /k/) that has become voiced in certain environments, for example [fæt] "fat" but [færɚ] "fatter." But the duration of this [ɾ] is extremely short (ca. 30–40 msec), whereas /p/ and /k/ in the same environment are usually much longer (Fox & Terbeek, 1977).

Also, the particular trajectory the articulator makes may affect the probability of voicing being maintained during the stop closure. Velar stops in English have been shown to have a forward-moving component to them (Houde, 1968, pp.

Table 9-8. Bantu Sound Changes Showing Modification of Initial Voiced Stops as a Function of Place of Articulation of Stop and Quality of Following Vowel

Proto-Bantu		Reflex in Duala	Reflex in Ngɔm	English gloss
*-bi	>		- ɓ e	bad
*-bod	>	- ɓ ɔ-	- ɓ o	become rotten
*-dib-	>	- ɗ i	- ɓ iɗ	shut
*-dug	>	- ɗ u-	- ɗ uk-	paddle
*-dob-	>	-ɔ ɓ -	-ðɔɓ -	fish with line
*-daad-	>		-ðað-	lie down
*-godi	>	m-ɔɗ i	ŋ-kɔli	string
*-gag-	>		-kak-	go bad

Note. From Guthrie (1967–1970); transcription simplified.

93ff). (See Figure 9-4.) Such a movement constitutes a very marked form of active cavity enlargement and could more than compensate for the other factors which disfavor voicing on velars. This may, in fact, be the reason why velar stops are articulated in this way. Voiced apical stops could be voiced longer if the tongue body lowered during the stop closure. This gesture has been found in the production of /d/ in English and Japanese (Ohala & Kawasaki, 1979). This may be the reason why so many of the voiced apical implosives are retroflex (Greenberg, 1970; see also Table 9-6, where one of the Sindhi retroflex implosives comes from an earlier *dental* geminate): Retroflex stops are distinguished from nonretroflex primarily by having an enlarged oral cavity immediately behind the point of constriction—this cavity, an effective low-pass filter, is what gives retroflex sounds their characteristic "dark" auditory quality.

Some languages solve the problem of how to maintain voicing on stops by skirting the aerodynamic constraints and producing something that *sounds* like a voiced stop but that is not wholly a stop, namely, a prenasalized stop, for example, [ᵐb, ⁿd]. The air that would accumulate in the oral cavity is vented through the velic opening during the initial part of the consonant closure. Both a fully voiced stop and a prenasalized stop will create an abrupt attenuation of the speech amplitude, will have voicing throughout the closure, and will be released with a burst. It is easy to imagine that through sound change a voiced stop could be replaced by a prenasalized stop.

An otherwise puzzling aspect of the phonology of Japanese verbs may be accounted for in part by this pattern. As shown in Table 9-9, the conjunctive form of Japanese strong verbs involves replacing the last consonant in the verb stem by a geminate dental consonant whose voicing agrees with the replaced consonant (except that /r/ is replaced by /tt/). However, where a voiced

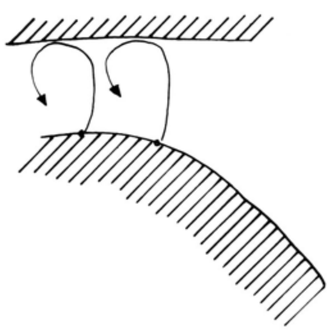

Figure 9-4. Trajectory of two points on the surface of the tongue (lower contour) during the approach to and break of contact with the palate (upper contour) in the production of the sequence [aga] (left is front, right is back) (redrawn from Houde, 1968, p. 114). The forward movement of the tongue during the closure constitutes active enlargement of the vocal tract.

Table 9-9. Morphophonemic Variation in Japanese Strong Verbs

Non-past indicative verb stem	Conjunctive		English gloss
	Standard dialect	Hachijojima dialect	
tatu	tatte		stand up
uru	utte		sell
but:			
asobu	asonde	asudde	play
jomu	jonde	jodde	read

Note. From Kawasaki (1981).

geminate consonant would be expected (and is, in fact, found in a remote conservative dialect spoken on the island Hachijojima), the standard dialect has a *nasal* + *stop* sequence. There is evidence that the NC sequence was once a prenasalized stop (Shevelov & Chew, 1971; Kawasaki, 1981). As we have seen, prenasalized stops avoid the problems associated with maintaining voicing in stops.

The stop inventory of Quileute is reported by Andrade (1933–1938) to be /b, d, p, t, k/. In addition to the lack of a /g/, the most difficult stop to voice, Andrade reports that the /d/, the second most difficult stop to voice, is phonetically [ⁿd].

D. Constraints on Voicing in Fricatives

If the problem with stops and voicing is that the accumulation of air in the oral cavity eventually quenches voicing, then this constraint should be less evident with fricatives since they have a continuous venting of oral air pressure. So much for a priori prediction, since this turns out not to be true. Table 9-10 provides tabulations of the interaction of voicing with stops (including affricates) and fricatives for the 706 languages surveyed by Ruhlen. Considering languages that utilize voicing with one of the obstruent types but not the other, the table shows that there is more than twice the probability of voicing being absent on fricatives ($p = 192/536 = .358$) as on stops ($p = 63/391 = .16$).

Two factors probably account for this pattern. First, voiced fricatives have more exacting aerodynamic requirements than do voiced stops: For the sake of continued voicing the oral pressure should be low, but for the sake of frication the oral pressure should be high, that is, the difference between oral pressure and atmospheric pressure should be high enough to cause high air velocity through the consonantal constriction. Meeting both of these requirements simultaneously may be difficult. To the extent that the segment retains voicing it may be less of a fricative, and if it is a good fricative it runs the risk of being

Table 9-10. Tallies from 706 Languages on Use of Voicing with Obstruents

No. of languages that have	No fricatives	Voiced/voiceless fricatives	Only voiceless fricatives	Only voiced fricatives	Total
Voiced/voiceless stops, affricates	15	327	192	2	536
Only voiceless stops	19	63	79	5	166
Only voiced stops	3	1	0	0	4
Total	37	391	271	7	706

Note. From data in Ruhlen (1975).

devoiced. In fact, the noise component of voiced fricatives is much less than that for voiceless fricatives (Pickett, 1980, p. 155) and on nonsibilant voiced fricatives ([β, v, ð, j, γ, ʁ]) is often so weak as to be barely detectable.

The second reason why the arguments presented above for stops do not apply to fricatives is that there is evidence that the state of the glottis may not be the same during voiced fricatives as it is during voiced stops. Hirose and Ushijima (1978) report electromyographic (EMG) data for laryngeal muscles which suggest that, at least for medial consonants, [z] has a less constricted glottis than [b, d, g]. If so, this may be necessitated by the fact that voiced fricatives, but not voiced stops, require greater glottal airflow for the sake of maintaining the trans-oral constriction pressure differential. Quantitative aerodynamic modeling of these sounds is necessary to clarify this point.

As a possible manifestation of this greater incompatibility of voicing with fricatives than stops, I have the impression, from listening to speech and examining acoustic records of speech, that in American English the "voiced" fricatives /v, z/ are more likely to be devoiced in word-final position than are the stops /b, d, g/.

E. Frication and Devoicing of Glides, Vowels

1. Mathematical Simulation of Close versus Open Vowels' Aerodynamics To illustrate some of the aerodynamic constraints that govern the phonological behavior of nonobstruents, a quantitative simulation of some of the relevant parameters was performed using a simple mathematical model of speech aerodynamics (Ohala, 1975a, 1976). Figure 9-5 shows superimposed the simulation of two V_1CV_2 utterances where C is a voiceless unaspirated stop (e.g., [p]), V_1 is an open vowel (e.g., [æ]), and V_2 is either the same open vowel (solid line) or a close vowel (e.g., [i]: broken line). The bottommost function shows the single independent parameter—area of the oral constriction—that varied between the two utterances. The top two functions, oral air pressure and

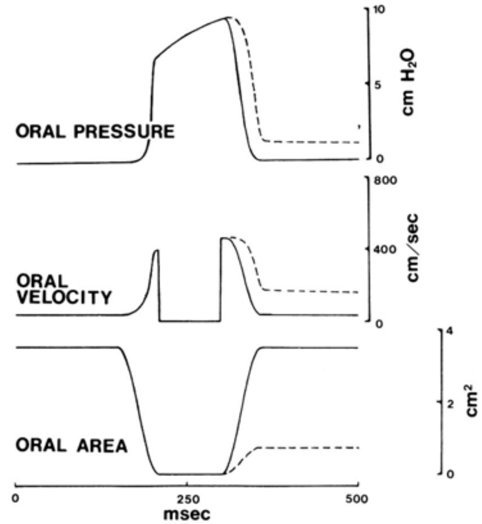

Figure 9-5. Mathematical simulation of two VCV utterances such as [æpæ] (solid line) and [æpi] (broken line). Oral area is an independent parameter, that is, input to the aerodynamic model; oral pressure and oral (particle) velocity are two dependent parameters, that is, output of the model (from Ohala, 1976).

oral (particle) velocity, are dependent parameters. There are four observations to make about the aerodynamic differences between close and open vowels. These will be taken up separately in the next four sections.

2. Devoicing of Vowels, Glides Figure 9-5 shows that a close vowel creates an appreciable back pressure (ca. 1 cm H_2O) in comparison with open vowels. Thorsen (cited by Fischer-Jørgensen, 1963) demonstrated this empirically. Although the magnitude of the oral back pressure is not very great, it does reduce the transglottal pressure drop and could, in conjunction with other factors (see below), contribute to vowel devoicing. Greenberg (1969) and Jaeger (1978) surveyed a total of 30 languages that allophonically devoiced a subset of their total vowel inventory and found a strong tendency for high vowels to exhibit devoicing as opposed to low vowels. Table 9-11 presents a sample of the data they surveyed.

The other factors that contribute to vowel devoicing are (1) partial assimilation to adjacent voiceless segments or pause (i.e., the vocal cords become slightly abducted), (2) lowered subglottal pressure, as would be encountered on unstressed vowels and/or vowels following consonants characterized by heavy airflow (e.g., English *potato* as [pʰətʰeĭroŭ̥]), and (3) the shortness of the vowel, since the shorter it is, the more it can be influenced by the first two factors.

Table 9-11. Distribution of Voiceless and Voiced Vowels

Language	Voiceless and voiced	Voiced only
Awadhi	i, u, e	a, o
Campa	i	o, e, a
Chatino	i, u	o, e, a
Dagur	i, u, ə	o, a
Huichol	i, ɨ, e	u, a
Serbo-Croatian	i, u	e, o, a
Tadjik	i, u, a	e, o, ú
Tunica	u	i, e, ɛ, a, ɔ, o
Uzbek	i, u	e, ɔ, o, a

Note. Sample from Greenberg (1969).

3. Frication of Vowels, Glides A second point to note about the difference between close and open vowels as revealed in Figure 9-5 is that close vowels give rise to a higher velocity of the oral airflow. The greater the velocity of the airflow, the greater is the turbulence and thus the frication of the segment (Stevens, 1971). Close glides, because they often have a constriction smaller than vowels, should be particularly subject to the development of frication. Phonological data support this.

According to Millardet (1911), the long high vowels of Swedish, which are diphthongized, may end in fricated glides, these glides being voiceless before a final voiceless obstruent, otherwise voiced. No frication, however, was found for the nonhigh vowels. See Table 9-12 (where modern IPA transcription has been substituted for that used by Millardet, except for [j^], a voiced palatal fricative; these data may not be representative of Modern Swedish). Similar data have been reported for the Jutish dialect of Danish (Andersen, 1972).

A well-known variation among Spanish dialects attests the sound change [j]→[ʒ]: Andalusian [kabajo] "horse," Argentine [kabaʒo]. Similarly, Latin *iugam* and Sanskrit *yugam* "yoke" corresponds to Classical Greek *dzugon*, from which we get the stem of the English word *zygomatic*. In American English, one can find the following dialectal or even ideolectal variation among [tj—], [tʃ—], and [tʃ(ɹ)—]: [tʰjuzdi]~[tʃuzdi] "Tuesday" (Kurath & McDavid, 1961), [tʰɹʌk] ~ [tʃʰɹʌk] "truck." Benjamin Franklin's (1806) phonetic transcription of his speech reveals that he pronounced *natural* as [nætjuɹəl]; today the pronunciation is [nætʃɚəl].

4. Affrication of Stops Before High Vowels There is also a strong tendency for stops to develop an affricated release when they precede simple close vowels, since (as Figure 9-5 shows) the high velocity of the airflow created upon release of a stop lasts longer when the stop precedes a close vowel as opposed to an open vowel. Table 9-13 presents evidence of a sound change from Proto-Bantu

Table 9-12. Fricated Glides in Swedish

Swedish orthography	Phonetic	English gloss
vit	viçt	white
krig	kri:j^g	war
plog	pluβg	plow
bro	bruβ	bridge
gud	gʉβd	God
fru	frʉβ	madame
knyta	knyj^çta	to tie, knot
by	byj^	village
but:		
tack	tak:	thanks
dö	dø:	to die
tåg	to:g	train
lag	lɑ:g	team

Note. From Millardet (1911).

to Mvumbo, which is based on this tendency. (In these data, the changes in place of articulation of the initial stop, although interesting for what they reveal about acoustic–auditory constraints, are irrelevant to the point being made.) In Japanese the dental stop phonemes are realized as affricates before the high vowels /i, ɯ/ (e.g., /tɯti/ = [tsɯtʃi] "ground"). Similar patterns can be found in other languages.

5. Aspiration of Stops Figure 9-5 reveals that after the release of a stop the time required to reduce oral pressure to a given level, say 4 cm H_2O, is greater when a close vowel follows (ca. 38 msec) than an open vowel (ca. 17 msec). Insofar as voicing requires some minimum transglottal pressure drop, it follows that voice onset should be appreciably delayed when a close as opposed to an open vowel follows a stop. In other words, stops preceding close vowels should be more aspirated than those preceding nonclose vowels. Several phonetic studies show this to be the case (Ohala, 1981, and references cited there). There are many reports in the phonological literature of languages having stops with more aspiration (allophonically) before high vowels than nonhigh vowels (Cook, 1969; Vogler, 1968).

F. Nasalization Blocks Devoicing and Affrication

Earlier I mentioned that if air under pressure is to be released through one of the vocal tract's valves, then all other valves that would vent that air must be closed. If another valve is open, then a noisy audible flow of air through the intended

Table 9-13. Sound Change in Bantu Showing Development of Affricated Release to Stops at a Function of Following Vowel

Proto-Bantu		Mvumbo	English gloss
*-buma	>	bvumo	fruit
*-dib-	>	dʒiwo	shut
*-dut	>	-bvure	pull
*-tiitᴜ	>	tʃir	animal
*-tud-	>	-pfule	forge
*-gida	>	ma-tʃie	blood
*-gubᴜ	>	m-bvuu	hippopotamus
*-kiŋgo	>	tʃiuŋ	neck, nape
*-kuba	>	pfuwo	chicken
but:			
*-bod	>	-buo	become rotten
*-dɪ	>	-di	eat
*-toog	>	-tuog	boil up
*-gada	>	-kala	mat
*-konde	>	kwande	banana

Note. From Guthrie (1967–1970).

valve will be lessened or eliminated. From this we would predice that the devoicing and frication of vowels and glides discussed in the preceding section should be blocked by nasalization—the open velopharyngeal port acting to reduce the oral pressure that contributed to these effects. This prediction (which I made, by the way, before knowing whether there was phonological evidence for it) is borne out (Ohala, 1978b). In English /h/ becomes the voiceless palatal fricative [ç] before the palatal glide /j/, for example, "human" /hjumən/ is [çjũmə̃n]. But in a heavily nasalized environment the palatal frication is apparently blocked and the /h/ is manifested simply as a glottal fricative: "unhuman" is [ʌ̃nhj̃ũmən], not *[ʌnçjũmə̃n].

Similarly, in Fante (Schachter & Fromkin, 1968) the word with "underlying" form /hɪ/ "border" is realized phonetically as [çɪ] but the word /hɪ̃/ "where" is [hɪ̃], not *[çɪ̃].

Beasely and Pike (1957) report that in Jivaro voiceless vowels appear in word-final position when unstressed but voiceless nasal vowels were not found to occur.

In Yuchi, according to Wagner (1933–1938), voiceless spirants appear predictably between all vowels and following lingual stops but not if the vowel is nasalized.

In Chinese, dialectal data reveal the existence of a sound change by which the palatal vowel /i/ develops into some kind of voiced apical fricative, for example, */siəp/, /siəj/, and so on → */si/ → [sz]. However, if the original syllable ended in a nasal and the vowel became nasalized, the frication of the vowel does not occur: */siən/ ↛ [sẓ] (unless, of course, the nasalized vowel first became denasalized; Steve Baron, personal communication).

G. Stop Epenthesis

The valves we have been discussing—the lips, tongue, and glottis—do not open and close instantaneously; they take an appreciable amount of time to switch from one state to another. This is because (1) they have some inertia, (2) some muscular slack needs to be taken up before the articulators can move, and (3) the neuromuscular control system may have some limited temporal resolution. Assimilation is probably the neuromuscular control system's way of compensating for these constraints. Occasionally assimilation of one valvular state to another has rather dramatic effects on the shape of words. The production of a sequence of nasal consonant followed immediately by an oral segment having an articulation different from the nasal may result in partial denasalization of the nasal due to anticipatory assimilation of the velic closure required by the oral segment. A segment may be "oral" because it is required for aerodynamic reasons (e.g., [s, θ, k]), or for acoustic-auditory reasons, that is, nasalization would distort the acoustic characteristics of the sound (e.g., any distinctively oral sonorant or in some cases any segment, distinctively oral or not, that has a low first formant—the formant that would be most distorted by nasalization, such as [l, w, i, u]; Ohala, 1975b). Thus in English, one finds so-called intrusive or epenthetic stops in words such as those in Table 9-14. Similar data exist for other languages; see Table 9-15.

Although it is more common to find anticipatory assimilation (Javkin, 1979), perseveratory assimilation may occur, and this accounts for the variants /kr̩ʂɳa/ ~ /kr̩ʂʈɳa/ "Krishna" in the Indo-Aryan languages (Varma, 1961, p. 123).

Much the same phenomenon underlies a phonological process misnamed "nasal strengthening." Table 9-16, columns 1 and 2, provides representative data from Kongo (Bentley, 1887). A common analysis of this alternation is that the nasal prefix "strengthens" the stem-initial consonant by increasing its degree of obstruency. This, however, is not the correct analysis (as was explicitly pointed out by Jacottet, 1927, in his analysis of this phenomenon in Sesuto). As the fourth column in Table 9-16 shows (from Guthrie, 1967–1970), these words originally started out with obstruents, which have been retained following the nasal but which have undergone sound changes turning them into nonobstruents in word-initial position. We may imagine that whatever forces acted on these initial stops to change them in this way did so in both environments. However, a preceding nasal consonant, as we saw above, will have the effect of carving out a stop from the nasal preceding the oral segment. In this way the stop will be preserved when there is a preceding nasal. "Nasal preservation" may be a better name for this process. The phonological literature

Table 9-14. Epenthetic Stops in English

Orthographic representation	Phonetic	Source
warmth	[wɔɻmpθ]	< warm + [θ]
something	[sʌmpθɪŋ]	< some + thing
Thompson	[tʰɑmpsən]	< Thom + son
glimpse	[glɪmps]	< gleam + s
teamster	[tʰimpstɚ]	< team + ster
youngster	[jʌŋkstɚ]	< young + ster
length	[lɛŋkθ]	< long + [θ]

contains abundant examples of this process. For example, in most dialects of Spanish an original set of medial and final voiced stops have become cognate voiced spirants except after nasals. See Table 9-17. This, of course, is precisely the same phenomenon exemplified diachronically in Kongo (Table 9-16). Similar patterns may be found in Gadsup (Frantz & Frantz, 1966) and Camsa (Howard, 1967).

In Latin the reflex of original Indo-European *gʷ and *ghʷ is usually /w/ (or written v). However, the stop element is most often preserved after a nasal; see Table 9-18.

H. Nasal Prosody

The incompatibility between obstruents and velic opening has consequences for the phonology of languages like Sundanese (Robins, 1957) and Trique (Hollenbach, 1977), which have a remarkable type of perseveratory nasalization. In general, these "nasal prosodies" work as follows: After a nasal segment all following segments are nasalized, with nasalization spreading all the way to the end of the word unless blocked by an oral obstruent. See Table 9-19, which gives data from Sundanese. As would be predicted, the glottal obstruents [h,ʔ] do not block spreading nasalization, since in their case the air under pressure could not be vented by the velic valve. Schourup (1973) has documented several cases of this sort.

Tereno, one of the Arawakan languages of South America, also has perseveratory spreading of nasalization as part of the first-person inflection (where the nasalization is started at the beginning of the word). In this case voiceless stops block spreading nasalization but become prenasalized voiced stops in the process. Again, nonobstruent consonants and [ʔ] do not block nasalization but, contrary to our expectations, [h] does, and in the process becomes [ⁿz]. See Table 9-20. We could dismiss this exception as just a language-specific peculiarity but there is no need to: There is comparative evidence (Bendor-Samuel, 1966; Noble, 1965, pp. 49–50) that at least some of Tereno's [h]'s derive from earlier dental obstruents (e.g., Tereno /ɨhɨ/, Piapoco /izipi/, Ipeca

Table 9-15. Examples of Assimilatory Denasalization of Nasal Consonants.

Language	Source	Example	English gloss
Spanish	Spaulding (1965)	vendre (<Latin *ven(i)re*)	sell
		temblar (<Latin *trem(u)lar*)	tremble
		Alhambra (<Arabic *al hamra*)	the red (house)
Ulu Muar Malay	Hendon (1966)	ban ~banᵈʊ	doorsill
Korean	Chen and Clumeck (1975)	mul ~ mᵇul	water
Telefol	Healey (1964)	/su:m/ = [su:ᵇm]	banana
Parintintin	Pease and Betts (1971)	/õmoapɨ/ = [õᵐboapɨ]	he cooks
		/ɲãnu/ = [ɲãⁿdu]	spider
Tenango Otomi	Blight and Pike (1976)	/mohi/ = [mᵇohi]	plate
		/nĩne/ = [nĩnᵈe]	your mouth

Table 9-16. So-Called Nasal Strengthening in Kongo

Verb stem	Gerund	English gloss		Proto-Bantu	English gloss
mona	mbona	a sight	<	*-bon-	see
vunda	mpunda	a resting	<?	*-puum-	breathe, rest
landa	ndanda	a following	<	*-dand-	follow

Note. From Bentley (1887) and Guthrie (1967–1970).

/itsipi/, Rio Icanna Baniva /itipi/ "tail"). Rather than being an exception to the phonetically based principles of which sounds should and should not block spreading nasalization, it is very probably a regular example of another phonetically based process: nasal preservation. (See also Court, 1970, who cites cases in Indonesian languages where spreading nasalization does *not* pass through nasals *m*, *n*, etc.—a surprising pattern on the surface but not when it is made clear that these nasals derived from earlier *mb*, *nd* and that the spreading nasalization is a historical relic.)

III. Conclusion

Liljencrants and Lindblom (1972) have challenged those who ask, "Why do speech and language have the form and behavior that they do?" to attempt to derive the answers deductively by considering the real-world constraints—physical, physiological, psychological, and social—within which language is used. This chapter is offered as a modest addition to the growing number of contributions, including those of Lindblom and his colleagues, that have taken up this challenge. I have attempted to show how certain cross-language regularities in the behavior of speech sounds stem from universal physical phonetic properties of the speech mechanism, in particular its aerodynamic properties.

Such work should be viewed as but one aspect of a much larger effort recently undertaken in biology and related disciplines to explain the behavior, especially the social behavior, of animals and man by reference to the ecological situation in which the species exist (Maynard Smith, 1974; Wilson, 1975; Krebs & Davies, 1978; Morton, 1975). Within phonology, as in biology, prior qualitative work has shown us the great promise of this approach (Passy, 1890; Martinet, 1955). Nevertheless, if we can learn anything from the recent work in biology, the real breakthroughs will come only when we can employ reliable, formal, but empirically motivated, quantitative models of the complex "ecological" forces that shape speech and language.

Acknowledgments. This work was supported in part by the National Science Foundation and by the Committee on Research of the University of California

at Berkeley. I am also grateful to my friends and colleagues for help and advice, especially Mariscela Amador, Jeri Jaeger, Carol Justus, Haruko Kawasaki, Björn Lindblom, Yakov Malkiel, Manjari Ohala, Steve Pearson, and Carol Riordan. I assume responsibility for the accuracy of the data and for the ideas presented here.

Table 9-17. Preservation of Voiced Stops After Nasals in Spanish

Phonemic	Phonetic	English gloss		Phonemic	Phonetic	English gloss
/sobɾa/	[soβɾa]	surplus	*but:*	/sombɾa/	[sombɾa]	shadow
/rodaɾ/	[roðar]	tọ roll	*but:*	/rondaɾ/	[rondaɾ]	to go around
/mago/	[maɣo]	magician	*but:*	/mango/	[maŋgo]	handle

Table 9-18. Preservation of Stop Element of Indo-European *g(h)^{w} Following a Nasal Consonant in Latin

Proto-Indo-European		Latin	English gloss
*g^{w}iōu-		vivus	living
*terg^{w}-		torvus	wild
*weg^{w}-		ūvidus	moist
but:			
*dn̥gh^{w}ā		lingua	tongue
*eng^{w}-		inguen	abdomen
*ong^{w}-		unguō	to anoint
cf. also:			
*sneigh^{w}-		nivis	snow (noun, genitive)
	But:	ninguit	snows (verb with nasal infix)

Note. From Pokorny, (1959) and Poultney (1963).

Table 9-19. Perseveratory Assimilation of Nasalization in Sundanese

Example	English gloss
[ɲãĩãn]	to wet
[bɤŋ̃hãr]	to be rich
[ɲãh̃õkɤn]	to inform
[mĩˀãsih]	to love

Note. From Robins (1957).

Table 9-20. Perseveratory Spreading of Nasalization in Tereno

Third person (no nasalization)	English gloss	First person (spreading nasalization)	English gloss
[piho]	he went	[^{m}biho]	I went
[ahjaˀaʃo]	he desires	[ã^{n}ʒaˀaʃo]	I desire
[iso]	he hoed	[ĩ^{n}zo]	I hoed
[owoku]	his house	[õw̃õ^{ŋ}gu]	my house
[ajo]	his brother	[ãj̃õ]	my brother
[emoˀu]	his word	[ẽmõˀũ]	my word
[iha]	his name	[ĩ^{n}za]	my name

Note. Data from Bendor-Samuel (1960, 1966).

References

Abramson, A. S. The vowels and tones of Standard Thai: Acoustical measurements and experiments. *International Journal of American Linguistics*, 1962, Publication *No. 20.*

Alexandre, R. P. *La langue möré.* Dakar: Mémoires de l'Institut français d'Afrique noire, 1953, *No. 34.*

Andersen, H. Diphthongization. *Language*, 1972, *48*, 11–50.

Andrade, M. J. Quileute. In F. Boas (Ed.), *Handbook of American Indian languages* (Part 3). New York: Columbia University Press, 1933–1938, pp. 154–292.

Armstrong, R. G. Yala (Ikom), a terraced-level language with three tones. *Journal of West African Languages*, 1968, *5*, 49–58.

Beasley, D., & Pike, K. Notes on Huambisa phonemics. *Lingua Posnaniensis*, 1957, *6*, 1–8.

Bell, H. The phonology of Nobiin Nubian. *African Language Review*, 1971, *9*, 115–159.

Bendor-Samuel, J. T. Some problems of segmentation in the phonological analysis of Tereno. *Word*, 1960, *16*, 348–355.

Bendor-Samuel, J. T. Some prosodic features in Terena. In C. E. Bazell, J. C. Catford, M. A. K. Halliday, & R. H. Robins (Eds.), *In memory of J. R. Firth.* London: Longmans, 1966, pp. 30–39.

Bentley, W. H. *Dictionary and grammar of the Kongo language.* London: Trübner & Co., 1887.

Blight, R. C., & Pike, E. V. The phonology of Tenango Otomi. *International Journal of American Linguistics*, 1976, *42*, 51–57.

Catford, J. C. *Fundamental problems in phonetics.* Bloomington: Indiana University Press, 1977. (a)

Catford, J. C. Mountain of tongues: The languages of the Caucasus. *Annual Review of Anthropology*, 1977, *6*, 283–314. (b)

Chao, Y. R. Types of plosives in Chinese. *Proceedings of the 2nd International Congress of Phonetic Sciences.* Cambridge: Cambridge University Press, 1936, pp. 106–110.

Chen, M., & Clumeck, H. Denasalization in Korean: A search for universals. In C. A. Ferguson, L. M. Hyman, & J. J. Ohala (Eds.), *Nasálfest: Papers from a symposium on nasals and nasalization.* Stanford: Language Universals Project, 1975, pp. 125–131.

Cook, T. L. *The pronunciation of Efik for speakers of English.* Bloomington: African Studies Program and Intensive Language Training Center, Indiana University, 1969.

Court, C. Nasal harmony and Indonesian sound laws. In S. A. Wurm & D. C. Laycock (Eds.) *Pacific linguistic studies in honour of Arthur Capell.* Canberra: Australian National University, 1970. pp. 203–217.

Fischer-Jørgensen, E. Beobachtungen über den Zusammenhang zwischen Stimmhaftigkeit und intraoralem Luftdruck. *Zeitschrift für Phonetik, Sprachwissenschaft und Kommunikationsforschung*, 1963, *16*, 19–36.

Fox, R. A., & Terbeek, D. Dental flaps, vowel duration and rule ordering in American English. *Journal of Phonetics*, 1977, *5*, 27–34.

Franklin, B. A scheme for a new alphabet and reformed mode of spelling. In *The complete works of Dr. Benjamin Franklin* (Vol. 2). London, 1806, pp. 357–366.

Frantz, C. I., & Frantz, M. E. Gadsup phoneme and toneme units. *Linguistic Circle of Canberra Publications* (Series A), 1966, *7*, 1–11.

Gamkrelidze, T. V. On the correlation of stops and fricatives in a phonological system. *Lingua*, 1975, *35*, 231–261.

Greenberg, J. H. Some methods of dynamic comparison in linguistics. In J. Puhvel (Ed.), *Substance and structure of language.* Los Angeles: Center for Research in Languages and Linguistics, 1969, pp. 147–204.

Greenberg, J. H. Some generalizations concerning glottalic consonants, especially implosives. *International Journal of American Linguistics,* 1970, *36*, 123–145.

Guthrie, M. *Comparative Bantu* (4 vols.). Farnborough: Gregg, 1967–1970.

Healey, A. Telefol phonology. *Linguistic Circle of Canberra Publications* (Series B), 1964, Monograph No. 3

Hendon, R. S. The phonology and morphology of Ulu Muar Malay. *Yale University Publications in Anthropology*, 1966, *No. 70.*

Hirose, H., & Ushijima, T. Laryngeal control for voicing distinction in Japanese consonant production. *Phonetica*, 1978, *35*, 1–10.

Hockett, C. F. A manual of phonology. *International Journal of American Linguistics*, 1955, *Memoir 11.*

Hollenbach, B. E. Phonetic vs. phonemic correspondence in two Trique dialects. In W. R. Merrifield (Ed.), *Studies in Otomanguean phonology*. Arlington: Summer Institute of Linguistics, 1977, pp. 21–33.

Houde, R. A. *A study of tongue body motion during selected speech sounds.* Speech Communication Research Laboratory (Santa Barbara), 1968, Monograph *No. 2.*

Howard, L. Camsa phonology. In V. Waterhouse (Ed.), *Phonemic systems of Colombian languages.* Norman, Okla.: Summer Institute of Linguistics, 1967, pp. 73–87.

Jacottet, E. *A grammar of the Sesuto language.* [*Bantu studies*, Vol. 3, Special Number.] Johannesburg: University of Witwatersrand Press, 1927.

Jaeger, J. J. Speech aerodynamics and phonological universals. *Proceedings of the Annual Meeting of the Berkeley Linguistics Society*, 1978, *4*, 311–329.

Javkin, H. Towards a phonetic explanation for universal preferences in implosives and ejectives. *Proceedings of the Annual Meeting of the Berkeley Linguistics Society*, 1977, *3*, 559–565.

Javkin, H. R. Phonetic universals and phonological change. *Report of the Phonology Laboratory (Berkeley)*, 1979, *No. 4*.
Kawasaki, H. *Voicing in Japanese*. Unpublished manuscript, University of California at Berkeley, 1981.
Khubchandani, L. M. Sindhi. *Current trends in linguistics*, 1969, 5, 201–234.
Krebs, J. R., & Davies, N. B. (Eds.). *Behavioural ecology: An evolutionary approach*. Oxford: Blackwell, 1978.
Kurath, H., & McDavid, R. I. *The pronunciation of English in the Atlantic States*. Ann Arbor: University of Michigan Press, 1961.
Ladefoged, P. *A phonetic study of West African languages*. Cambridge: Cambridge University Press, 1964.
Ladefoged, P. *Preliminaries to linguistic phonetics*. Chicago: Chicago University Press, 1971.
Ladefoged, P. Chapter 8, this volume.
Lehiste, I. *Suprasegmentals*. Cambridge, Mass.: MIT Press, 1970.
Liljencrants, J., & Lindblom, B. Numerical simulation of vowel quality systems: The role of perceptual contrast. *Language*, 1972, *48*, 839–862.
MacKay, D. G. The structure of words and syllables: Evidence from errors in speech. *Cognitive Psychology*, 1972, *3*, 210–227.
Martinet, A. *Économie des changements phonétiques*. Berne: Francke, 1955.
Maynard Smith, J. *Models in ecology*. New York and London: Cambridge University Press, 1974.
Millardet, G. Insertions de consonnes en suédois moderne. *Revue de Phonétique*, 1911, *1*, 309–346.
Morton, E. S. Ecological sources of selection on avian sounds. *American Naturalist*, 1975, *108*, 17–34.
Noble, G. K. Proto-Arawakan and its descendants. *International Journal of American Linguistics*, 1965, Publication No. 38.
Ohala, J. J. A mathematical model of speech aerodynamics. In G. Fant (Ed.), *Speech communication* (Vol. 2: *Speech production and synthesis by rule*). Stockholm: Almqvist & Wiksell, 1975, pp. 65–72. (a)
Ohala, J. J. Phonetic explanations for nasal sound patterns. In C. A. Ferguson, L. M. Hyman, & J. J. Ohala (Eds.), *Nasàlfest: Papers from a symposium on nasals and nasalization*. Stanford: Language Universals Project, 1975, pp. 289–316. (b)
Ohala, J. J. A model of speech aerodynamics. *Report of the Phonology Laboratory (Berkeley)*, 1976, *1*, 93–107.
Ohala, J. J. The production of tone. In V. A. Fromkin (Ed.), *Tone: A linguistic survey*. New York: Academic Press, 1978, pp. 5–39. (a)
Ohala, J. J. Phonological notations as models. In W. U. Dressler & W. Meid (Eds.), *Proceedings of the 12th International Congress of Linguists*. Innsbruck: Innsbrucker Beiträge zur Sprachwissenschaft, 1978, pp. 811–816. (b)
Ohala, J. J. The application of phonological universals in speech pathology. In N. J. Lass (Ed.), *Speech and language: Advances in basic research and practice* (Vol. 3). New York: Academic Press, 1980, pp. 75–97.
Ohala, J. J. Articulatory constraints on the cognitive representation of speech. In T. Myers, J. Laver, & J. Anderson (Eds.), *The cognitive representation of speech*. Amsterdam: North-Holland, 1981, pp. 111–122.

Ohala, J. J., & Kawasaki, H. *The articulation of [i]'s*. Paper presented at the 98th meeting of the Acoustical Society of America, Salt Lake City, November 1979.
Ohala, J. J., & Riordan, C. J. Passive vocal tract enlargement during voiced stops. In J. J. Wolf & D. H. Klatt (Eds.), *Speech communication papers*. New York: Acoustical Society of America, 1979, pp. 89–92.
Passy, P. *Étude sur les changements phonétiques*. Paris: Librairie Firmin-Didot, 1890.
Pease, H., & Betts, L. Parintintin phonology. In D. Bendor-Samuel (Ed.), *Tupi studies I*. Norman, Okla.: Summer Institute of Linguistics, 1971, pp. 1–14.
Pickett, J. M. *The sounds of speech communication*. Baltimore: University Park Press, 1980.
Pokorny, J. *Indogermanisches etymologisches Wörterbuch*. Berne: Francke, 1959.
Poultney, J. W. Evidence for Indo-European alternation of initial /g^w/ and /w/. *Language*. 1963, *39*, 398–408.
Purnell, H. C., Jr. *Phonology of a Yao dialect spoken in the province of Chiengrai, Thailand*. Hartford Studies in Linguistics, 1965, *No. 15*.
Robbins, F. E. Quiotepec Chinantec syllable patterning. *International Journal of American Linguistics*, 1961, *27*, 237–250.
Robins, R. H. Vowel nasality in Sundanese. In *Studies in Linguistic Analysis*. Oxford: Blackwell's, 1957, pp. 87–103.
Rothenberg, M. *The breath-stream dynamics of simple-released-plosive production. Bibliotheca Phonetica*, 1968, *No. 6*.
Ruhlen, M. *A guide to the languages of the world*. Stanford, 1975.
Schachter, P., & Fromkin, V. A phonology of Akan: Akuapem, Asante, and Fante. UCLA Working Papers in Phonetics, 1968, *No. 9*.
Schourup, L. C. A cross-language study of vowel nasalization. *Ohio State University Working Papers in Linguistics*, 1973, *15*, 190–221.
Shattuck-Hufnagel, S., Chapter 6, this volume.
Sherman, D. Stop and fricative systems: A discussion of paradigmatic gaps and the question of language sampling. *Stanford Working Papers in Language Universals*, 1975, *17*, 1–31.
Shevelov, G. Y., & Chew, J. J., Jr. Open syllable languages and their evolution: Common Slavic and Japanese. In G. Y. Shevelov, *Teasers and appeasers. Essays and studies on themes of Slavic philology*. München: Wilhelm Fink Verlag, 1971, pp. 15–34.
Smith, B. L. *Effects of vocalic context, place of articulation and speaker's sex on "voiced" stop consonant production*. Paper presented at West Coast Phonetics Symposium, March 1977, Santa Barbara, California.
Spaulding, R. K. *How Spanish grew*. Berkeley: University of California Press, 1965.
Stevens, K. N. Airflow and turbulence noise for fricative and stop consonants: Static considerations. *Journal of the Acoustical Society of America*, 1971, *50*, 1180–1192.
Stevens, K. N. Discussion during symposium on phonetic universals in phonological systems and their explanation. *Proceedings of the 9th International Congress of Phonetic Sciences*, 1980, *3*, 185ff.
Varma, S. *Critical studies in the phonetic observations of Indian grammarians*. Delhi: Munshi Ram Manoharlal, 1961.
Varyani, P. L. Sources of implosives in Sindhi. *Indian Linguistics*, 1974, *35*, 51–54.

Vogler, P. Esquisse d'une phonologie du baoulé. *Annales de l'université d'abidjan* (Series H): Linguistique, 1968,*1*, 60–65.
Wagner, G. Yuchi. In F. Boas (Ed.), *Handbook of American Indian languages* (Part 3). New York: Columbia University Press, 1933–1938, pp. 300–384.
Ward, I. C. *The phonetic and tonal structure of Efik*. Cambridge, Mass.: Heffer, 1933.
Wilson, E. O. *Sociobiology: The new synthesis*. Cambridge, Mass.: Belknap Press, 1975.