Feature Patterns

Their Sources and Status in Grammar and Reconstruction

A thesis submitted for the degree of
Doctor of Philosophy in the University of Cambridge

by

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25 May 2012

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Abstract

This work investigates feature co-occurrence trends, with special focus on the phonology of the larynx and its interaction with supralaryngeal articulation. My examination of the phonological behavior and phonetic realization of various features, especially [voi], [spr], [cst], and [son], probes the causes behind a wide range of cross-linguistic trends in segment inventory structure, along with the representation of several sound types including breathy-voiced stops and implosives. The most general insight from the roughly eighty patterns investigated is that their specific content can be plausibly derived from non-cognitive factors. This poses a major duplication problem if the same patterns are attributed to innate cognitive stipulations.

I address this problem with a critical review of recent trends in grammar design, arguing for a theory where as much as possible grammatical structure is learned rather than innate and where as much as possible optimization occurs during acquisition rather than during mature speech. After exploring the logical relationships among several major components of existing grammar design theories, I recommend integrating generation with evaluation and configuring grammatical directions in a representational format. I also review research on the interface between linguistics and cognitive science and argue that my proposal is well suited for implementation through distributed, continuous, and highly parallel processing systems.

The main feature co-occurrence insights in the earlier chapters also facilitate a reanalysis of one of the oldest unsolved problems in historical linguistics: the evolution of the Indo-European stop series. In the process of developing a novel solution, I show how the use of features can increase the efficiency and comprehensiveness of reconstruction.

By highlighting the extent to which feature co-occurrence patterns can be derived from independently evident non-cognitive factors, this work contributes to a growing body of research focused on removing innate/learnable duplication problems. While most of the grammatical details of sound systems seem best removed from the innate endowment, I do not conclude that phonetic content and phonological cognition never interact directly. In each of the three main dimensions of this work – developing phonological profiles of specific sound types, exploring implications for grammar design, and historical problem solving – I find evidence that cognition maintains extensive awareness of the phonetic values of the variables it manipulates.

This thesis is the result of my own work, neither previously nor currently submitted in whole or part for any other qualification at any other university. It includes nothing which is the outcome of work done in collaboration except where specifically indicated in the text.

Length: 76,774 words excluding bibliography

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Abbreviations

Alb.	Albanian
Arm.	Armenian
BS	Balto-Slavic
C	Celtic
cf.	compare with
f.	and the next section
G	Greek
Gm.	Germanic
Hitt.	Hittite
IE	Indo-European
In.	Indic
Ir.	Iranian
It.	Italic
L	Latin
Myc.	Mycenaean Greek
n.	note
n.d.	no date
OT	Optimality Theory
p.	page
p.c.	personal communication
PIE	Proto-Indo-European
pp.	pages
Sk.	Sanskrit
TH	Tiberian Hebrew
Toch.	Tocharian
VOT	voice onset time
#	word boundary
$	syllable boundary
*	penalized; non-occurring; reconstructed
†	rejected (constraint)
>	becomes (in sound changes)
<	comes from (in sound changes); less than (in rankings); non-explosive (when superscripted)
→	maps to
←	maps from
↔	maps to/from (no directional restriction expressed)
~	alternates with
:	contrasts with
( )	optional elements (in a string) (other uses are defined locally in the text)

[ ]	phonetic (if enclosing segmental symbols); feature (if enclosing feature abbreviations); phonological output forms not necessarily containing only contrastive information
/ /	phonemic, contrastive
{ }	set

Acknowledgments

Navigating the interfaces between phonology and phonetics, synchrony and history, theoretical universals and the deepest, darkest details of Armenian would have been impossible without the combined guidance of experts in several disciplines. James Clackson, Bert Vaux, and my examiners Francis Nolan and Jane Stuart-Smith provided the most intense and rewarding linguistic conversations and feedback I have ever had.

Jeff Mielke generously read and discussed the sections where I quote him most. Steve Parker and two anonymous reviewers helped me transform a chapter for early publication, and Patricia Shaw offered unexpected encouragement in the process. Robert Blust, Charles Barrack, Matthew Gordon, Johanna Nichols, and Philomen Probert graciously provided feedback on other draft sections. Other linguists who answered questions or helped me access material include Luca Busetto, Marc Brunelle, François Dell, Didier Demolin, Adamantios Gafos, William Idsardi, Máté Ittzés, Gregory Iverson, Ranko Matasović, Joyce Mathangwane, Pramod Pandey, Joe Pittayaporn, Rachid Ridouane, Catherine Ringen, David Rood, Joseph Salmons, Bridget Samuels, Rebecca Scarborough, Paul Sidwell, Kenneth Stevens, Rupert Thompson, and Michael Weiss. I am grateful for all their help.

Susan Prince instigated this project as a conference paper. The excellent hosts of GLIEP I at Cambridge later edited the proceedings for the University Press. The College of the Holy and Undivided Trinity provided funding and an unparalleled living environment for the next three years. Since then I have owed particular thanks to David Rood and Lise Menn for ongoing help and inspiration, and to Norlin Library for special access to resources.

Among friends I owe Jesse Bangs for nearly two decades of brilliance and inventive insight in all things linguistic including several discussions of this project, and my brother Jason for troubleshooting and rebuilding my laptop. The David, Daniel, and Joe Rice families, Jerusha and Kenny Pretty On Top, Derek Schreinert, Susie Siders, Josiah Bigelow, Gary and Marvia Robbins, Chuck and Kay Rice, the Buford King family, Dean Ness, Phil Klotzbach, Dustin Rapp, John Young, Robert Patterson, Alex Ievins, Drew and Stacy Frazer, Brian and Heather Hanneman, Josh Dillard, Aaron and Jody Britton, Alec Battles, Cole McGinnis, and my coworkers at the Erie Rec Center enriched my life beyond the page.

My parents Brad and Jeanne Miller have proven indispensible friends and helpers. I honor my master Jesus Christ, First and Last, Breath of Life, for holding everything together and for being the most faithful.

1 Introduction

1.1 Introduction

This chapter begins with some basic terminology about features, grammar, and sound change. Summaries of later chapters follow.

The thesis of this work is that the particular properties of phonological features and their combinatorial behaviors emerge through language acquisition and sound change thanks to the way non-cognitive factors such as acoustic physics and vocal tract physiology interact with general cognitive abilities that may also be relevant to non-linguistic learning activities. Stipulating either features or their co-occurrence patterns as part of innate human linguistic knowledge is therefore redundant. Major implications for theories of grammar design and sound change are explored with attention to four topics: how features come to exist in grammars, how grammars manipulate features, how information about the features of prehistoric languages can be inferred from attested descendant languages, and how important such information is for understanding prehistoric phonologies.

1.2 Features

Phonetics is the study of sounds in general; phonology studies the way sounds are organized in particular languages. Fairly standard, traditional introductions to these respective topics include Ladefoged and Maddieson (1996) and Kenstowicz (1994). New discoveries and proposals are constantly emerging, and many of them are discussed in this work.

One of the main insights of modern phonology is that distinguishable sounds or *segments* can be analyzed into grammatically significant components called *features*. Features cross-classify segments, defining *contrasts* between different segments and defining *classes* of segments based on shared traits, such as participation in a grammatically significant sound pattern. Because features play these two roles, it is natural that many linguists have also used features to describe the differences and similarities among languages.

In order to signal differences and similarities between segments in speech, features must relate to aspects of sound that speakers can produce and listeners can hear. This makes it important to study the articulatory and acoustic correlates of features (also known as *gestures* and *cues* respectively). Yet features themselves are not simply actions of the speaker's vocal tract or aspects of the sound wave traveling through the air to the listener. In order to carry meaning, features must also exist in the minds of language users. Linguists are consequently interested in features as elements of the user's mental *representation* of speech. There is ongoing debate about how these elements are translated into articulation during speech production and back out of the acoustic signal by the auditory component during speech processing; for a recent overview see Clements and Hallé (2010).

Studying the role of features in defining phonological classes is important for understanding how speakers transform mentally stored representations of parts of words into seamless spoken utterances. For example, the most common English plural marker is realized as *s* after the segments *p t k f θ* and with a *z* sound in other environments. The productivity of this pattern has been repeatedly proven by experiments like the *wug* test, where young children shown pictures of an imaginary animal called a *wug* were consistently able to infer that the plural was pronounced *wug*[z], not **wug*[s] (Berko 1958). Rather than describing this pattern by listing all the segments separately, we can describe it more simply with the insight that the plural marker ends up being voiceless after voiceless sounds and voiced elsewhere: in other words, we can distinguish these classes of sounds with a single feature [voice]. While that change may not seem to simplify this particular example much, the power of features is more dramatically evident in some polysynthetic languages, where speakers more often find themselves forming very long words (equivalent to whole English sentences) which they may not have heard before and in which there are much more complex relationships among the sound patterns (e.g. Blackfoot, Menomini, Wichita: §5.7). Speakers also betray some of their own abstract generalizations about the sound patterns of their language in how they adapt loanwords from other languages (Pierrehumbert 2001: 138-139).

Turning to the second major function of features, we say that features are *contrastive* when a change in feature can change the meaning of a word. For example, the words *met* and *bet* can be distinguished by noting that the segment *m* has the feature [+nasal] while *b* does not. Seminal discussions of this topic include Jakobson, Fant, and Halle (1954) and Jakobson and Halle (1956). One of the related issues they address is when the distribution of one feature can be predicted from that of another. The predictable relationship can be either complementary or redundant; two examples will illustrate the difference.

In English, the segment *p* is typically followed by a puff of air at the beginning of a stressed syllable unless preceded by *s*. If we represent this puff of air with a feature – say, [+spread glottis] or [+spr] for short (§3.3.6) – then in English, we can predict that sounds like *p* are [+spr] at the beginning of a stressed syllable unless preceded by *s*. For such sounds in those environments, the plus and minus values of [±spr] are *allophonic*, meaning that they represent variant sounds found in predictable, complementary distribution. To illustrate the second type of predictable relationship between features: *b* typically has air pressure buildup in the mouth behind the closed lips, while *m* does not because the air escapes through the nose. If we were to represent lack of significant air pressure buildup with a feature – say, [+sonorant] (§3.3.8) – then we would find that in English, [+nasal] sounds are also [+sonorant], while [-sonorant] sounds are also [-nasal]. In such cases, we might say that only one of the features encodes differences in meaning, while the other is *redundant*. When a redundant feature appears to make the contrast expressed by another feature more perceptible, the redundant feature is sometimes called an *enhancement*, following Stevens and Keyser (1989, 2010).

There is ongoing debate about how to decide which member of a cooperative feature pair is the redundant one, and when to leave predictable features out of a mental representation of speech (*underspecification*). These debates relate to a broader one about how abstract features are in the minds of ordinary language users. In the examples above, we identified features directly with articulatory configurations that control airflow in particular ways (nasality, oral air pressure buildup, glottal widening). How are such details stored in the mind? When a speaker is retrieving feature representations of words from memory and beginning to manipulate them in order to plan an utterance, are the features just abstract mental elements – which only get translated into specific phonetic content later, by a subsequent and separate *module* of the speaker's grammar – or are language users ever more aware of phonetic content, and can this awareness influence other areas of linguistic knowledge during language development (including historical sound change)? In turn, the debate on feature abstractness relates directly to the question of how to compare languages: how similar must a sound in one language be to a sound in another language in order for them to be defined with the same feature? Two major discussions of these topics can be found in Chomsky and Halle (1968: 295-298) and Ladefoged (1999).

Another question closely related to the ones just mentioned is whether features are innate. A fairly small, innate set of features universally shared by healthy human beings might be quite abstract; at the other extreme, if features are not innate but *emerge* by induction as the learner analyzes patterns heard during language acquisition, then some features may be much more closely tied to phonetics, and different speakers of the same language might even induce features with different definitions (Brunelle 2010, Mielke 2008a). At several points in this work I argue for the emergent view of features, as well as a not discretely modular view of the relationship between mental feature representations and phonetic awareness. This is supported by recent work in psycholinguistics (e.g. Menn 2010, Vihman et al. 2009), research on phonetic differences among speakers of the same language (e.g. Brunelle 2005, 2010, Wayland and Jongman 2003), and other topics that will be introduced later. Only some of my arguments depend on emergent features, though, and I continue discussing alternative implications of emergent and innate approaches throughout the thesis.

1.3 Grammar and sound change

A grammar can be defined as a person's systematic knowledge needed for communicating in a language by converting mental information to physical speech and vice versa (cf. Ussishkin 2011). Sound patterns that a person must understand in order to use a language are part of the grammar. Exactly how features are used in grammar depends on one's theory of grammar design. One of the dominant early paradigms was that speakers perform a series of operations called *rules* on an input representation in a certain order, and the output is then pronounced. The rules are often stated in terms of features; a seminal example of such work is Chomsky and Halle's (1968) analysis of English. More recently, linguists have experimented with groups of *constraints* that weed out incorrect but theoretically possible output forms for a given linguistic input. Again, the constraints are often expressed using features. The best-known pioneering example of this approach is Prince and Smolensky's (1993) Optimality Theory. Recent comparisons of rule- and constraint-based approaches include Odden (2011) and Vaux and Nevins (2008).

Sound change refers to how the systematic sound patterns of a language change over time (for introductions see Bermúdez-Otero 2007 and Fox 1995). Because of this systematic aspect, models of sound change are inextricably linked to ideas about how grammars are structured and how they are learned. Based on the idea that grammars encode sound patterns through series of rules, it was popular for a time to model at least some sound changes as the reordering, addition, or deletion of rules (Picard 1994: 33-38, van der Hulst 1980). On the alternative supposition that grammars encode at least some sound patterns by ranking innate constraints, it makes sense to model at least some sound changes as changes in constraint ranking (Holt 2003, McMahon 2000) or constraint activation (Calabrese 1992, 1995).

A third approach to sound change, promoted in this work, is emergent: the detailed contents of grammars are induced afresh by each learner, and sound change occurs when learners conventionalize novel analyses of the data they observe (e.g. Blevins 2004, Ohala 1981b, 1983). Hale (2007: 33-35) compares this approach to earlier models via an analogy of grammar as a rock: sound change is not like a rock rolling down a hill, but rather like a sequence of people observing the rock left by the previous person and trying to set beside it a rock which looks more or less the same. Misperception and novel generalizations thus play a central role in why learners induce different grammatical structure from their predecessors (Blevins 2004, Mielke 2008a, Ohala 1989, Stuart-Smith 2004). Learners' understanding of their languages remains malleable into adolescence and beyond (Kerswill 1996, Sankoff and Blondeau 2007).

1.4 Chapter summaries

The larynx plays an important role in many sound patterns. Chapter 2 reviews evidence on several laryngeal gestures and cues, focusing on the roles of vocal fold abduction and tensing in voiceless unaspirated stops, strategies for sustaining voice during stop closure, and different kinds of breathy voice.

Chapter 3 uses this information to develop an emergent understanding of laryngeal features and the kinds of contrastive and redundant behaviors they show, with special attention to enhancements of voiced stops and the characteristics of stop inventories in which more than half of the contrastive series are voiced. A well-known distributional restriction on breathy-voiced stops ("Jakobson's universal") is reviewed and reinterpreted in light of a principle of feature economy interacting with enhancement. Relationships between economy, enhancement, and contrast neutralization are briefly examined. More broadly, several arguments are synthesized to support the view that features emerge through the learning process rather than being innate.

In this view, learners induce features by identifying groups of cues as patterning together in a functionally significant way for the communication of meaning. Learners often diverge in the details of which cues they identify for this purpose and which gestures they identify as appropriate for producing those bundles of cues; this results in phonetic variation among speakers of the same language. Physiology and physics create natural relationships among phonetic correlates; these relationships ("phonetic geometry") influence cross-linguistic trends in feaure-correlate mapping and limit the maximum number of features that a speaker can distribute to a given set of cues.

Chapter 4 shifts focus from features to cross-linguistic trends in the combinatorial behavior of features, arguing from over seventy examples that feature co-occurrence trends can be plausibly explained as emerging through sound change, whether features themselves are learned or innate. While respecting arguments that sound change is not goal-oriented, I argue that many conceivable patterns are rare because they are needlessly complex and that attrition of existing omissible complexity plays a role in sound change due to articulatory negligence, especially in less careful speech styles.

Chapter 5 applies the findings of chs. 3-4 to the question of how grammars are designed, arguing that features and feature co-occurrence trends, as well as evidence from psycholinguistics and language acquisition, support a theory of grammar design in which grammars differ in their contents, not just in how the contents are organized. A framework for modeling grammar design is proposed in which grammatical information about sound patterns is encoded in partial representations which are combined with lexically stored representations of idiosyncratic information about particular linguistic expressions to create a total representation of what speakers need to know in order to utter those expressions. Such a total representation or parts of it may then be remembered for various lengths of time without being reassembled every time the expression is repeated.

Chapter 6 applies the foregoing insights about laryngeal phonetics, features, feature co-occurrence trends, and grammar design to the topic of historical reconstructive methodology with a detailed case study of the laryngeal stop contrasts in Proto-Indo-European. My critique of past proposals and new possibilities illustrates the importance of reconstructing the phonological categories of prehistoric languages in accordance with natural physical relationships among phonetic correlates. These relationships constrain the ways in which successive generations reanalyze a language's sound system and thus function as guideposts for the linguist trying to retrace those analytical steps – the paths of sound change.

1.5 Feature definitions

Features mentioned repeatedly in this thesis are listed in Tables 1.1 and 1.2 with working definitions couched in terms of phonetic correlates. The features and most of the definitions reflect fairly standard views (e.g. Hall 2007). Exceptions and relevant controversies will be handled as they arise; most of those discussions are indexed in the tables.

As a final comment on terminology, features are notationally binary throughout this work rather than privative; e.g. the opposite values of [voi] are written [+voi] and [-voi] rather than [voi] and nothing. This is simply to facilitate clarity and implies nothing about the phonological activity or inactivity of features or about default vs. non-default values. Generalizations on those topics will be identified separately. For a more integrated discussion of gradient and heterogeneous diagnostics of feature activity see Mielke (forthcoming a). Most of the features discussed in much detail here have correlates that can be plausibly viewed as either present or absent, making binary feature treatment relatively straightforward. Some features have been defined with more than two values for phonetically obvious reasons, like vowel height (Clements and Hume 1995), or accused of having more than two values for abstract phonological reasons such as archiphonemic underspecification (Samuels 2009a: 81, 95-98); most of those topics are not addressed here (see Vaux 2010).

Table 1.1 Some features with working definitions

Feature	*Abbr.*	*Definition*
[consonantal]	[cons]	active supralaryngeal constriction greater than that of vowels and (usually) glides (§3.3.8)
[sonorant]	[son]	relatively low oral air pressure (″)
[continuant]	[cont]	(conventionally oral) egressive airflow (″)
[voice]	[voi]	periodic vocal fold movement producing pitch (§3.3.7)
[spread glottis]	[spr]	glottal turbulent noise (§3.3.6.4)
[constricted glottis]	[cst]	true and false vocal fold adduction and often narrowing of the laryngeal vestibule (§2.4, 2.6.2)
[nasal]	[nas]	more lowered velum and nasal resonance than in oral sounds (§2.3.1, 4.3.2.2)
[lateral]	[lat]	airflow out of the mouth over lowered tongue sides but not over the tongue center
[rhotic]	[rhot]	lingual trills, taps, or flaps; glides with similar articulatory vectors (§4.3.1.3)
[strident]	[strid]	frication with heightened turbulence (§4.3.2.3)
[labial]	[lab]	actively articulated with one or both lips
[round]	[rd]	adducting and protruding the lips (§4.3.1.2)
[coronal]	[cor]	articulated with roughly the front half of the tongue (§4.3.1.1)
[anterior]	[ant]	the further forward of two options (″)
[distributed]	[dist]	a more plane- than point-like articulation (″)
[dorsal]	[dor]	articulated with roughly the back half of the tongue

Several other proposed features have definitions that are either relatively clear from their names, or too complex or debatable to be listed here:

Table 1.2 Features and definitions (continued)

Feature	*Abbr.*	*see*
[advanced/retracted tongue root]	[ATR]	§2.4, 4.3.1.4, 4.3.3
[tense]	[tns]	§3.3.6.4
[raised/lowered larynx]	[RL/LL]	§3.3.7.3
[stiff/slack vocal folds]	[stiff]	″, §3.3.7.2
[high], [low], [back]	[hi], [lo], [bk]	§4.3.3

2 Laryngeal Phonetics

2.1 Introduction

This chapter explores the acoustic and aerodynamic effects of the interaction between laryngeal articulation and stricture (supraglottal constriction), with special focus on voiceless unaspirated stops, different kinds of breathy voice, and active voicing in stops. The findings of this chapter help illustrate how phonological categories – the grammatical sound structures of particular languages – are built within a universal, gradient space of phonetic possibilities determined by physics and physiology, such that asymmetries within the universal phonetic space extensively influence the patterning of features within the phonologies of particular languages.

2.2 The larynx

The larynx can make a variety of sounds. One way of organizing these sounds is to arrange them in a continuum of glottal width, where the overall size of the glottis (the opening in the larynx) increases in one direction and decreases in the other (see Gordon and Ladefoged 2001, Henton, Ladefoged, and Maddieson 1992, Ladefoged 2001, Ladefoged and Maddieson 1996):

widest	⟷					**narrowest**
wide-open	breathy	slack	modal	stiff	creaky	closed

Figure 2.1 Glottal width continuum.

The sources just cited refer to the wide-open and closed states at the two ends of the continuum as voiceless while the five states between them are described as having voice (defined next). This is accurate for many but not all sound types: roughly the same degree of glottal width is compatible with both voice and voicelessness depending on stricture (§2.3.2), both the slack and stiff configurations are reported in voiceless stops (§2.5.5), and the glottal width range compatible with modal voice is only accompanied by actual voice depending on aerodynamic factors (§2.6).

Modal voice, the middle state in this continuum, can be thought of in most languages as a person's normal speaking voice; studies of various languages have found voiced sounds occurring more frequently in ordinary speech than voiceless sounds do (Catford 1977: 107, Vaissière 1997: 115-116). The standard theory of voice production is called the myoelastic-aerodynamic theory of voicing and can be summarized in the following way (see Hirose 2010: 140-141, Hoole 2004, Lisker and Abramson 1964: 415-416, Shadle 2010: 56, Stuart-Smith 2004: 167). The vocal folds are first adducted into close enough proximity that pulmonic egressive air pressure builds up behind them. Air is forced to speed up as it passes between the vocal folds, due to the Venturi effect (which correlates a constriction in a passage with accelerated movement of a fluid or gas forced into the passage). At the same time, the accumulated air pressure behind the vocal folds causes them to begin separating, increasing the volume of air moving at an accelerated speed through the widening glottis. This rapid escape of air reduces air pressure between the vocal folds by the Bernoulli effect (which correlates accelerated movement with reduced pressure). When the air pressure has decreased enough, the greater air pressure around as opposed to between the vocal folds along with the natural tension of the vocal folds themselves forces them back together again. Then the cycle repeats.

This rapid, quasi-regular emission of small bursts of air from the glottis due to the opening-closing cycle of the vocal folds is heard as voice, a relatively homogeneous sound with pitch. Mechanical oscillations are also possible with other vocal tract constrictions, including trilling of the lips, tongue tip, uvula, aryepiglottic folds, and ventricular folds (also called the false vocal folds, located within the larynx slightly above the vocal folds) (Edmondson et al. 2007, Shadle 2010: 56). These oscillations are sufficiently slower than voice that they are not perceived as a single sound (Brosnahan and Malmberg 1976: 54); compare the frequency of most trills at 20-35 Hz with the frequency range for voice, from around 40 Hz for creaky voice to 1000 Hz for a soprano or child's voice (Shadle 1999: 50).

The range of glottal widths we have just seen is controlled by multiple muscles acting in concert (DiCanio 2008: 180-187, Hirose 2010: 139-140, Hunter and Titze 2007). The vocal folds are attached to a point at the front of the throat below the epiglottis; their posterior ends, toward the back of the throat, are attached to two movable cartilages called the arytenoids. The primary muscle that abducts, or widens, the glottis is the posterior cricoarytenoid (PCA), which attaches to the arytenoids and rotates them apart when it contracts. Cricothyroid (CT) contraction can also slightly increase the size of the glottal opening by elongating it (§2.3.3.2). Another set of muscles is able to adduct the vocal folds, bringing them together and narrowing the glottis. The interarytenoid (INT) draws the arytenoids together, the lateral cricoarytenoid (LCA) rotates the arytenoids to compress the vocal folds medially (cf. Gobl and Ní Chasaide 2010: 396), and the thyroarytenoid (TA) draws the arytenoids forward to compress the body of the vocal folds by shortening them. This last action by itself relaxes the covering of the vocal folds, but the cover can be separately stiffened by the vocalis (VOC) muscle, which is inside the TA and can be contracted separately. (See Berry 2001 on ways in which the body/cover two-mass model of the vocal folds appears to be a categorical simplification of a more gradient reality.) All these muscles are classified as intrinsic laryngeal muscles, meaning that they do not extend beyond the larynx. Extrinsic laryngeal muscles, which include the suprahyoid and infrahyoid, connect the larynx to other structures in the throat and play a role in raising and lowering the larynx (e.g. Harris 1981: 21-22, Ohala 1972).

Glottal widening and narrowing are opposite gestures. PCA and INT in particular are said to be reciprocally active and mutually antagonistic, meaning that their activities directly conflict; each is normally active only to the extent that the other is not (Hirose 2010: 142, Hirose and Gay 1973, Sawashima 1997: 71). This norm is not always maintained. Stuttering typically involves "simultaneous, presumably antagonistic, abductor-adductor activity" along with increased LCA activity (Freeman and Ushijima 1974: 110-111; 1975, 1976). Further, Löfqvist and Yoshioka (1979: 117, 120) found that while PCA triggered abduction during voiceless obstruent clusters as expected, the waning phase of these gestures (the phase of return to an adducted position) did not always correlate with greater INT activity, suggesting that PCA and INT activity are not always inversely correlated even in healthy speech.

Activity of other intrinsic laryngeal muscles is often lower in consonants than in vowels. In a Hindi speaker (Kagaya and Hirose 1975: 32-36), VOC began decreasing around 30-40 ms before stop closure and then increased again after stop release; the stop types ranked in ascending order of total VOC decrease were voiced unaspirated < voiced aspirated < voiceless unaspirated < voiceless aspirated. Various other studies have simply noted general VOC suppression in consonants (Hoole 2006a: 23-28, cf. Hoole and Honda 2011: 133-134). In American English speakers, Hirose (1971a: 115) found more INT activity for vowels than for voiced consonants, and VOC and LCA were active in vowels but mostly suppressed in consonants. Jaiswal (2011: 4) summarizes a lengthy array of studies that found TA and LCA activity largely suppressed for consonants but increasing in preparation for following vowels, with TA reaching higher levels more quickly after voiceless than voiced consonants. Controlling the degree of VOC and LCA suppression also appears important for realizing stop contrasts in Korean (§2.5.5.3.1).

The following sections give a more detailed look at the laryngeal articulations seen in various types of stops. For descriptions of invasive articulatory measurement techniques such as electromyography (EMG), fiberoptic laryngoscopy (fiberscopic video), and photoelectroglottography (PEG), with lists of additional experiments using these methods, see Dixit (1989), Harris (1981), Hirose (1971c), Honda (2008), Hoole (2006a), Titze (1979).

2.3 Laryngeal articulations of voiceless unaspirated stops

2.3.1 Utterance-initial prephonation

Voiceless unaspirated stops are widely treated as a default (simplest or "unmarked") stop category on the grounds that other kinds of stops are phonologically defined by additional laryngeal specifications (see Vaux and Samuels 2005, Hall 2007: 317). These additional specifications are required to produce voice throughout closure, laryngeal constriction, aspiration, and so on (§2.6, 3.2.7, 3.3.6), while voiceless unaspirated stops are regarded as "plain" in the sense that they eschew all those properties by default. This does not necessarily mean that voiceless unaspirated stops lack systematic phonetic laryngeal activity, however.

Is there a neutral or least active laryngeal state in speech? Trubetzkoy (Blevins 2004: 74) identified quiet respiration or ordinary breathing as a kind of default from which phonological complexity could be measured (cf. Hirose 1997: 128). Respiration is not properly a speech state at all, however. Chomsky and Halle (1968: 300) write:

> In most X-ray motion pictures of speech, it can readily be observed that just prior to speaking the subject positions his vocal tract in a certain characteristic manner. We shall call this configuration the "neutral position" and shall describe some of the ways in which it differs from the configuration of the vocal tract during quiet breathing. In the latter state the velum is lowered, thereby allowing air to pass through the nose; in the neutral position, on the other hand, the velum is raised...

After describing oral and pulmonic differences between this neutral position and ordinary respiration, Chomsky and Halle then focus on the larynx:

> During quiet breathing, the vocal cords must be held widely apart since practically no sound is emitted. On the other hand, there is good reason to believe that prior to speaking the subject normally narrows his glottis and positions his vocal cords so

> that in the neutral position they will vibrate... in response to the normal, unimpeded air flow.

Somewhat similarly Ladefoged and Maddieson (1996: 50) write, "The physiological position for modal voice can be regarded as one in which the arytenoid cartilages are in a neutral position for speech, neither pulled apart nor pushed together (Stevens 1988). The vocal folds would be very slightly apart, if there were no air flow."

The laryngeal configuration that Chomsky and Halle describe as the "neutral position" preparatory to speech closely resembles what a more recent stream of research has described occurring during utterance-initial voiceless unaspirated stops in various languages. In this context, this laryngeal state has been called "prephonation."

> Our observations of Thai, Cantonese, Pame, Tibetan, Yi, and Bai (cf. Edmondson et al., 2000) confirm that at stop onset, the arytenoids are adducted as for voice, but the space between the vocal folds remains parted. We propose the term 'prephonation' to refer to this state of the glottis accompanying voiceless unaspirated oral stops. Our research has also shown that this configuration precedes an initial vowel in modal voice when [the vowel is] not preceded by a glottal stop. (Esling and Harris 2004: 1, cf. Edmondson, Esling, Harris, and Wei 2004: 54)

> Laryngeal observations of the state of the glottis during the articulatory stricture phase of initial unaspirated oral stops and affricates by Harris (1999) indicate a state of the glottis... referred to as 'prephonation.' Prephonation, as distinct from other voiceless states of the glottis such as breath, is made with the arytenoid cartilages adducted as for modal voice, but with the vocal folds forming a narrowed convex-convex opening medially in the glottis during which there is presumably insufficient subglottal air pressure to initiate airflow through the partially open glottis throughout the closure phase of oral articulatory stricture. (Esling and Harris 2005: 357, cf. Esling and Harris 2003, Esling 2006: 130 with film clip 6 in the online version).

The "initial" environment in which prephonation has been observed appears to be utterance-initial. Harris (2001: 7) refers to "the isolative style data" elicited for Standard Thai. Esling and Harris (2005: 357) also report observing prephonation immediately before a modally voiced initial vowel "that is not heavily stressed and does not have a glottal stop before it" in Thai and North American English: presumably this vowel is post-pausal, since otherwise it could not be preceded by the silent laryngeal configuration which they describe as prephonation. The same configuration was fiberoptically observed by Sawashima (1970: 187) just before an utterance-initial English [ɹ]: "the arytenoids are closed, while a narrow spindle-shaped opening is seen along the membranous portion of the glottis."

2.3.2 Silent abduction after voiced segments

Voiceless unaspirated stops that are not in utterance-initial position have been observed with laryngeal configurations different from prephonation. Fiberoptic and EMG investigations of a Hindi speaker by Kagaya and Hirose (1975: 43) found that intervocalic voiceless unaspirated stops and voiced aspirated stops had an abduction gesture of roughly comparable duration, peaking at roughly comparable glottal widths. The duration of abduction in voiceless aspirated stops was typically longer, and peak glottal width was roughly twice as great. The voiceless unaspirated and voiced aspirated stops differed in the timing of their abducted phase: it mostly coincided with closure for the voiceless unaspirated stops but occurred mostly after release for the voiced aspirates, which had vocal fold vibration during closure. All the stops were measured in two environments: between vowels as the onset of a stressed syllable in a nonsense word, and as the onset of a stressed syllable at the beginning of a nonsense word immediately preceded by a vowel-final word. Abduction was found to be slightly greater for the word-initial tokens, and full adduction for modal voice was often not resumed until 20-40 ms or occasionally even longer after stop release (Kagaya and Hirose 1975: 29-31).

The measure of how long voice is delayed past consonant release is called Voice Onset Time or VOT. In Japanese, where /p/ and /t/ average around 20-30 ms VOT while

/k/ averages 40-56 ms VOT (Itoh et al. 1979: 126-127, Itoh et al. 1980, Riney et al. 2007), varying degrees of vocal fold abduction have been observed in post-vocalic utterance-medial position, with the word-initial stops tending to have higher peak glottal width (Saito 1992: 35). In American English, Sawashima (1970) laryngoscopically observed abduction during the closure of voiceless unaspirated stops, usually beginning slightly before stop closure, with vocal fold vibration ceasing at or often slightly after the moment of stop closure; the arytenoids returned to an adducted position and voicing resumed around the moment of stop release (versus considerably later, in voiceless aspirated stops). Nuancing such findings, a set of EMG, transillumination, articulography, aerodynamic, and acoustic measurements by Lisker and Baer (1984: 133-134) found PCA contraction and INT suppression in intervocalic voiceless unaspirated stop tokens in American English, but sometimes without any noticeable glottal opening.

While the data we have seen so far unfortunately do not include experimental verification of prephonated voiceless unaspirated stops occurring utterance-initially and moderately abducted ones occurring intervocalically in the same language, an aerodynamic motive has been proposed which appears to explain both types of articulation. Kagaya and Hirose (1975: 42-43) suggest that moderate abduction in voiceless unaspirated stops helps turn off the voicing of the previous sound to ensure that the stop is voiceless. Use of abduction for active devoicing was also suggested by Lindqvist (1972: 3). Without a mechanism for turning off voicing, voice would be expected to continue part-way into the closure of the stop; oral air pressure buildup would cause voicing to fail, but not immediately, and vocal fold inertia might prolong vibration somewhat. (There is debate about how quickly voicing would cease under these conditions: §2.6.) In an utterance-initial voiceless unaspirated stop, however, there is obviously no voicing to turn off. Kagaya and Hirose's explanation for moderate abduction in Hindi intervocalic voiceless unaspirated stops thus readily expands to account for why such abduction has been found absent in utterance-initial voiceless unaspirated stops in various other languages.

If this idea is correct, then abduction can serve two distinct acoustic purposes in a language with an aspiration contrast. In voiceless unaspirated stops, abduction can occur intervocalically to turn off voicing, but in that usage it has no other auditorily significant result. In voiceless aspirated stops, on the other hand, a large portion of the abducted phase is timed to occur after stop release, generating turbulent airflow heard as aspiration (§3.3.6.4). The laryngeal contour seen in Hindi voiceless unaspirated stops may thus be a product of strategies that have to do with the surrounding segments rather than being determined by the stop's own phonological specifications in isolation: first PCA activity turning off the voicing of the previous segment, then activation of the adductors at roughly the midpoint of the stop in order to reach the configuration for voicing in the following vowel.

On adduction being initiated before voicing occurs, compare Löfqvist and Yoshioka's (1979: 119) finding that adduction begins just before stop release in Swedish voiceless aspirates. They observe that "no aerodynamic factors could be responsible for the initiation of the gesture" at that point in time and refer instead to the "continuous" or "ballistic" nature of glottal widening and narrowing gestures throughout speech (pp. 105-107). Similarly Löfqvist (1980: 484) writes, "A general feature of laryngeal articulation for voiceless obstruents that emerges from all these investigations is that the vocal folds seem to be constantly moving in what can be described as a single ballistic opening and closing gesture." In light of this and our discussion so far, it may be that there is no laryngeally inactive state in speech. Instead, the laryngeal default involves arytenoid adduction, in the sense of both a starting point (if Chomsky and Halle 1968 are correct about the "neutral position") and also frequency (at least in languages where modally voiced segments are the most frequent type: §2.2). Various gestural strategies then provide options for moving away from this neutral position (cf. Steriade 1995: 152-153) and subsequently back to it, as in the abduction-adduction sequence in Hindi and English voiceless unaspirated stops. The timing of this continuous sequence of glottal width changes can be plausibly attributed to the auditory goals of controlling voice and aspiration (§3.3.6.4, 3.3.7.1).

Further evidence supports the idea that moderate abduction serves as an active strategy for producing silent closure in contrastively voiceless unaspirated stops after voiced sounds. First, the gesture is hard to explain otherwise. Oral air pressure continues to build during stop closure; if glottal width were passively determined by the stop's pressure contour, then we would expect glottal width to continue increasing until stop release, instead of peaking around the middle of the closure as in Kagaya and Hirose's (1975) data (Nolan, p.c.). On the other hand, if glottal width were controlled independently of distinctions in audible voice and aspiration, it is unclear how else the glottal width differences would be perceived and what role such an independent glottal width parameter would play in the phonological organization of languages with a contrastive voiceless unaspirated stop series. Finally, PCA activity is not the only gesture which appears to function as a strategy for turning off voicing in unaspirated stops. Other gestures are found occurring at the same time or instead, as described next.

2.3.3 Proposed roles of vocal fold tensing

2.3.3.1 Devoicing

The cricothyroid muscle (CT) has frequently been found active in voiceless stops. CT contraction lengthens the vocal folds, increasing their tension (Hirose 2010: 139). VOC and LCA activity also affect vocal fold tension, as we will see later (§2.4, 2.5.5.3.1), but here we will focus on CT.

Kagaya and Hirose (1975: 38, 43) report that unlike their study, Dixit (1975, cf. 1989) found no significant glottal opening in Hindi voiceless unaspirated stops; instead he found relatively consistent CT activity in both unaspirated and aspirated voiceless stops. This led him to conclude that CT rather than PCA activity played a key role in defining voicelessness in stops. A similar conclusion was reached by Dixit and MacNeilage (1981) and, in English and Dutch, Löfqvist et al. (1989). In Kagaya and Hirose's (1975: 34-35) Hindi speaker, however, CT activity moderately peaked at the onset of closure for the voiceless unaspirated stops, but was less active for the voiceless aspirates; it also showed considerable activity during the latter part of closure for voiced unaspirated /b/ and /$b^{ɦ}$/. Kagaya and Hirose (1975: 38) remain open to possible inter-speaker variation in the use of devoicing gestures.

Hirose (1971b: 162) found that CT activity did not correlate with the voiceless-voiced distinction in Japanese and concluded that (generally) reciprocal PCA and INT activity were probably the main gestures articulating the distinction. Jaiswal (2011: 2) found increased CT activity in voiceless consonants (including unaspirated stops) in VC transitions for only half of the eight American English subjects who participated in a study that included EMG recordings of CT and TA muscle activity, audio signals, and video nasendoscopy. For all but one subject, however, CT activity was similar or lower in CV transitions with a voiceless consonant than with a voiced one. CT activity showed no statistically significant differences correlating with aspiration.

2.3.3.2 Glottal widening and pitch raising

That correlation is precisely what Hoole (2006a: 109-115) found in a transillumination study of German speakers, however: rather than peaking around stop closure as would be expected in a devoicing strategy, the timing of CT activity was correlated with abduction, suggesting that for these speakers, CT contraction helps widen the glottis without being primarily aimed at devoicing. Hoole explains the role of CT contraction in glottal widening by noting that the glottal opening is triangular, with the base at the arytenoids: the area of the triangle can be enlarged by abducting the arytenoids, but stretching the vocal folds longitudinally increases the triangle's height and thus can also help enlarge the glottal area.

Besides assisting in devoicing and in glottal enlargement, another and more consistently reported function of CT is to serve as the primary control of pitch (see Baer et al. 1976, Gobl and Ní Chasaide 2010: 396, Hirose 2010: 147, Hoole and Honda 2011: 149). However, pitch is also affect by other mechanisms, some of which do not seem entirely subject to speaker control though they may be actively enhanced (Hoole 2006a, Hoole and Honda 2011: 136, 151). Voiceless stop contrasts correlating largely or mainly with the pitch of the following vowel occur in various languages (§2.5.4, 3.2.4, 3.3.7.3), but most of these studies rely on auditory impressions or acoustic measurements, hindering identification of the laryngeal muscles involved.

Shyrock (1995) argues from a detailed acoustic comparison of Musey (Chadic) with several other languages that the primary articulatory correlate distinguishing the two contrastive stop series in Musey may be vocal fold length as controlled by CT contraction, which would be responsible for one of the series exhibiting both higher pitch and very slightly greater VOT. The latter correlate would be due to slight enlargment of the glottis caused by CT contraction.

2.3.4 Voiceless unaspirated stops: conclusion

We have seen that various laryngeal muscles do not correlate with acoustic cues in a one-to-one fashion but rather synergize with effects on voicing, aspiration, and the pitch of the following vowel. We have also seen significant variation both across languages and among speakers of the same language in terms of what gestures they use to produce voiceless unaspirated stops. This suggests that phonological distinctions involving the laryngeal configurations of stops may be better defined in auditory rather than articulatory terms for languages with clear contrastive stop voice and aspiration (§3.3.6-

3.3.9). We turn now from voiceless unaspirated stops to examine a series of other laryngeal configurations.

2.4 Laryngeal constriction and whisper

Once the vocal folds have been adducted for modal voice, reducing the size of the glottis even further requires the activity of other muscles besides the vocal fold adductors. Some of these other muscles are located higher in the larynx and in the epiglottal area above the larynx. The boundaries between the larynx, epiglottis, and pharynx are fairly ill-defined, but we will use the term "laryngeal constriction" in reference to any muscle activities which exert a significant squeezing effect on the larynx to narrow the glottis beyond the configuration appropriate for modal voice, other things being equal.

One situation where other things are not equal is when laryngeal constriction combines with vocal fold abduction to create hoarse whisper. The existence of such an articulation shows that laryngeal constriction and vocal fold abduction are not mutually antagonistic, even though there are other sounds in which laryngeal constriction does synergize with vocal fold adduction in opposition to abduction. We will examine that synergy first, before looking at the combination of abduction with laryngeal constriction in whisper.

During full glottal closure as seen in the glottal stop and in swallowing, an EMG study of English (Freeman and Ushijima 1974) found activity of both VOC and LCA. PCA was suppressed in this environment but showed a slight burst of activity coinciding with reopening of the glottis for modal voice. Other EMG studies have also found TA activity during glottal closure, along with supraglottal laryngeal constrictions (Hirose 2010: 147). Laryngoscopic work by Esling et al. (2005: 386-387) across an unspecified variety of languages found a range of laryngeal constrictions in the production of glottal stops. The minimum observed was "slight partial adduction of the ventricular folds", but more often they also saw moderate constriction of higher muscles causing “moderate narrowing of the laryngeal vestibule”.

> The laryngeal vestibule is defined as the supraglottal cavity of the larynx that extends from the ventricle of the larynx upwards through the aditus laryngis [into the pharyngeal cavity]... it is formed anteriorly by the epiglottis, posteriorly by the apices of the arytenoid cartilages, and laterally by the aryepiglottic folds with the prominent cuneiform cartilages as hinge points. The aryepiglottic folds extend from the sides of the epiglottis to the apices of the arytenoid cartilages. A slight retraction of the tongue and epiglottis also appears to be a component of the constriction of the whole laryngeal vestibule. (Esling et al. 2005: 386-387, cf. Lindqvist 1972: 3, Moisik and Esling 2011, Moisik et al. 2011)

While laryngeal constriction and release typically work together with adductor and abductor activity during the closure and release of a glottal stop, this type of cooperation is not physiologically necessary. As already noted, glottal abduction and laryngeal constriction actually combine in the production of whisper (Hirose 2010: 146):

> In whisper, there is arytenoid separation at the vocal process with an adduction of the false vocal folds taking place with a decrease in the size of the anterior-posterior dimension of the laryngeal cavity. For this type of laryngeal adjustment, PCA continues to be active and the thyropharyngeal activation is also observed most likely for realization of supraglottal constriction... This particular gesture for whispering is considered to contribute to the prevention of the vocal fold vibration... as well as to facilitate the generation of turbulent noise in the laryngeal cavity.

This passage describes voiceless whisper. A similar articulatory configuration is possible with voicing, producing whispery voice. Whisper with both voiceless and voiced phases occurs contrastively upon release in some stops in Zhenhai Wu (Chinese: Rose 1989). Zulu depressor stops involve contraction of the laryngeal vestibule for some speakers (Traill et al. 1987: 265) and have also often been impressionistically described as triggering breathy voice on following vowels (see Chen and Downing 2011, Traill et al. 1987); whispery voice will be analyzed as a kind of breathy voice below (§2.5.2).

Whispery voiced nasals in Rwanda have been found to involve mild pharyngeal pressure increase during oral closure that takes longer to occur than in stops and suggests active reduction of the pharyngeal cavity (Demolin and Delvaux 2001: 2). Articulatory and aerodynamic data on whispery voice thus supports Hirose's (2010) definition of whisper as involving laryngeal constriction and some compression of the pharyngeal cavity, in addition to vocal fold abduction.

The boundaries are still being explored between this type of laryngeal constriction and other articulations involving the aryepiglottic folds and sometimes larynx raising or lowering, which are found in various sounds including stiff or "tense" voice, pharyngeals, and epiglottals (Bellem 2005, 2007, 2009, Edmondson 2000: 3, 2004, 2006, Edmondson and Esling 2006, Edmondson et al. 2001, 2005: 383, Esling 2002c, Esling and Harris 2004, Esling et al. 2005: 396-403, Moisik, Czaykowska-Higgins, and Esling 2011, Moisik and Esling 2011, Moisik, Esling, and Crevier-Buchman 2009, Rose 1989: 236-241, Shahin 2011). As a brief introduction, Esling (2000, 2002a,b) provides fiberoptic visuals of several of these sound types with phonetic comparison and some examples of the complex phonological interactions that can occur among them. Transitioning back in the opposite direction – decreasing articulatory constriction – we find whispery voice shading into breathy voice both acoustically and articulatorily, so they are treated together in the next section.

Two other comments on whisper are in order. The first regards a universal-feature proposal known as "Dimensional Theory," in which laryngeal features are grouped in dimensions or pairs where each pair is correlated with reciprocally antagonistic muscles and the general principle is that only one member of a given dimension can be active in a given speech sound (Avery and Idsardi 2001: 44; Ahn and Iverson 2003: 5). The mutually exclusive antagonism which this model posits between glottal spreading and laryngeal constriction appears to contradict the physiology of whisper. Second, we will see later how the range of laryngeally unconstricted glottal widths that can occur contrastively in a sound is partly dependent on stricture (§3.4). That relationship can only be identified if the reciprocal relationship between the abductor and adductor muscles is distinguished from laryngeal constriction, because segments can be laryngeally constricted regardless of their stricture. Thus, recognizing that laryngeal constriction is distinct from abductor-adductor reciprocity is important for elucidating phonological patterns.

2.5 Breathy voice

2.5.1 Introduction

"Breathy voice" is an expression used with varying degrees of precision for sounds that include both voicing and a range of other acoustic cues such as glottal turbulent noise, lowered fundamental frequency, an amplified first harmonic, and various acoustic configurations involving increased amplitude in the lower harmonics and decreased amplitude in the higher ones (spectral tilt). These cues tend to co-occur, but there is great variation of detail among languages and even individual speakers.[1]

On the articulatory side, "breathy voice" in the broadest sense may include active abduction of the vocal folds with high medial compression and perhaps some supraglottal laryngeal constriction, causing a small chink at the posterior end of the glottis while the vocal folds are fairly closely adducted along the anterior glottis. The more precise name for this configuration is "whispery voice," while "breathy voice" in a stricter sense has moderate vocal fold abduction without these other gestures, allowing the vocal folds to flap more loosely without ever fully closing. Larynx lowering and concomitant vocal fold slackening with little or no active abduction can also generate many of the cues associated with breathy voice in the broad sense, though resulting glottal turbulent noise is expected to be less salient; this third configuration is termed "slack voice."

[1] Formants are bundles of amplified harmonics, which in turn are resonant frequencies (overtones) that are multiples of the fundamental frequency of a sound. The fundamental frequency of a complex periodic wave is the frequency of the slowest wave component and is thus also the rate at which the total pattern of the wave repeats; the first harmonic is equivalent to the fundamental frequency since it is the fundamental frequency multiplied by one (Johnson 2003: 9, 138, cf. Stevens 1998, 1999).

Articulatorily, then, whispery voice shades into strict breathy voice in proportion to a decrease in active gestures that compress or constrict the larynx, while strict breathy voice shades into slack voice with a decrease in active glottal widening.

The correspondence between these articulatory strategies on one hand and the acoustic cues just mentioned on the other are very imperfectly understood, partly because most descriptions of the relevant languages are either acoustic or impressionistic auditory ones; a limited number of fiberoptic observations exist, but their significance is somewhat unclear pending direct measurements of muscle activity by methods like EMG. The complex gradient relationships among the relevant gestures and cues not only challenge linguistic description, however; they also appear to elicit diverse analyses by individual learners during acquisition, leading to extensive fine variations among speakers of individual languages, as we will see.

The next few sections compare the articulations of whispery and strict breathy voice, then summarize relevant acoustic literature on breathy voice in the broader sense. This sets the stage for the treatment of slack voice (§2.5.5).

2.5.2 Whispery and strict breathy voice: articulation

According to Gobl and Ní Chasaide (2010: 400), whispery voice involves (1) some arytenoid separation, abducting the posterior, cartilaginous part of the vocal folds, but also (2) moderate longitudinal tension and (3) moderate to high medial compression ensuring vibration of the more anterior, ligamental part of the vocal folds. Given the foregoing discussion, these three conditions presumably require PCA, TA, and LCA contraction respectively, though Gobl and Ní Chasaide's description does not mention the muscles by name:

> *Whispery voice* is characterized by low adductive tension, moderate to high medial compression, and moderate longitudinal tension. As a consequence, there is a

> triangular opening of the cartilaginous glottis, whose size varies with the degree of medial compression. In weak whisper the medial compression is moderate and the opening may include a part of the ligamental glottis as well as the cartilaginous. Whisper with increasingly higher intensity has increasingly higher medial compression and smaller glottal opening, until only the cartilaginous glottis is open. Laryngeal vibration is assumed to be confined to that portion of the ligamental glottis which is adducted, and the whispery component to the triangular opening between the arytenoids. It is very inefficient and there is a considerable degree of audible aspiration noise.

Whispery voice occurs at the release of the voiced aspirates in some Indic languages (Stuart-Smith 2004: 169). It is also reported occurring as aspiration on a voiced stop in White Hmong (Fulop and Golston 2008), but previous acoustic work found the situation somewhat complex, with closure voicing failing just before release in a way that has prompted impressionistic descriptions of a glottalized catch (Jarkey 1987: 57-60; further data in Kehrein and Golston 2004: 339). Gobl and Ní Chasaide's description of whispery voice does not suggest any supraglottal laryngeal constriction, but given its similarity to Hirose's description of voiceless whisper, it seems hard to exclude the possibility of such constriction in whispery voice as well (presumably shading into epiglottal frication as aryepigglotic valve activity increases).

In the direction of decreased constriction, Gobl and Ní Chasaide (2010: 400) describe whispery voice as shading into breathy voice the more freely the vocal folds are allowed to vibrate and the more the noise component at the posterior glottal opening is reduced. Such reduction occurs as decreased medial compression (due to LCA suppression: Hirose et al. 1972: 189) and decreased longitudinal tension allow the vocal folds to move more loosely, to the point where they no longer fully adduct even when they approach each other most closely.

The auditory similarities and gradient phonetic differences between breathy and whispery voice have received inconsistent treatment in earlier phonetics literature (see Fulop and Golston 2008: 8, Stuart-Smith 2004: 164-165). Both voice qualities have been found in different speakers' realization of the voiced aspirates in Indic language (Stuart-

Smith 2004: 169). To distinguish breathy voice in the more precise sense from the broader usage which may include whispery voice and also slack voice, we will continue referring to the more precise category as strict breathy voice.

2.5.3 Voiced aspirates

Voiced aspirate stops measured in Hindi and Maithili have shown a typical pattern involving modal voicing during the first part of stop closure, followed at some point (often quite close to the stop release) by a glottal widening phase that peaks after release before adducting back to modal voice. Investigations agreeing on this pattern include PEG work by Dixit (1989), fiberoptic and EMG work by Kagaya and Hirose (1975), and other experiments discussed in Stuart-Smith (2004: 168). Breathy voice is heard during this abduction phase. As we have seen (§2.3.2), this abduction is roughly comparable in duration and magnitude with that of voiceless unaspirated stops and roughly half that seen in voiceless aspirates, though it can range from 70 to 130 ms (Stuart-Smith 2004: 168, 174).

Vocal fold vibrations typically last throughout the closure and aspiration of voiced aspirate stops, straight into the modal portion of the following vowel (Ladefoged and Maddieson 1996: 59, Stuart-Smith 2004: 167). Abduction beginning before stop release may contribute to a decrease in voicing amplitude sometimes seen toward the end of closure in Hindi voiced aspirates as compared to the unaspirated voiced stops (e.g. Ladefoged and Maddieson 1996: 59). At least in the case of strict breathy voice, the slackness of the vocal folds due to lack of medial compression may cause them to have a higher open quotient than in modal voice even apart from active abduction (see Stuart-Smith 2004: 168). Open quotient, or the proportion of time during voing that the vocal folds are apart rather than fully adducted, also increases as air pressure builds up during stop closure (Bickley and Stevens 1986). It has been shown instrumentally that pitch lowering tends to be significantly greater with breathy-voiced than with modally voiced stops (Hombert, Ohala, and Ewen 1973: 47, Mikuteit 2009: 48-60, Kagaya and Hirose 1975: 36-37, Schiefer 1986), and both increased open quotient and larynx lowering would be natural articulatory contributors to this (see Jessen and Roux 2002: 27, Stuart-Smith 2004: 167).

The modal vowels before voiced aspirates tend to be slightly lengthened (see Keating 1984a: 293, Ladefoged and Maddieson 1996: 60). Some studies have also found the closure of voiced aspirates shorter than those of voiced unaspirated stops (Jessen 2002: 154, 175, Kagaya and Hirose 1975: 37), which in turn are often shorter than those of voiceless unaspirated stops (§2.6).

2.5.4 Breathy voice: cues

The actions of particular muscles are important for differentiating whispery voice, strict breathy voice, and slack voice. In practice, much of the evidence from relevant languages is impressionistic or acoustic, forcing us to deal with descriptions that refer to breathy voice in a broader sense which may include various degrees of whispery or slack voice.

Wayland and Jongman (2003) describe several techniques that have been developed for studying breathy-voice cues, most of which involve measuring the amplitude difference between various pairs of harmonics. Indicators reported for breathy voice in various languages include lowered fundamental frequency (F0) due to the slower vibration of the slackened vocal folds, an amplified first hamonic (H1), reduced amplitude of the first formant (F1), additive noise from increased glottal turbulence which can mask or replace the third and higher formants, and other changes in spectral tilt involving amplified lower harmonics and reduced amplitude of higher harmonics compared to the spectral slope of modal voice. Wayland and Jongman (2003: 186) note that since glottal additive noise amplifies higher frequencies while breathy spectral tilt decreases them, “the spectral balance of breathy signals is affected by two separate phenomena acting in opposite directions,” making it hard to measure breathy spectral tilt unless the periodic and noisy components are distinguished. Further, there are multiple ways to try to quantify the effect of spectral tilt distributed across multiple harmonics (Blankenship 2002, Brunelle 2005: 163-165, Gordon 2001, Jessen and Roux 2002: 7-8, Park 2002).

Lowered F1 frequency is also reported in breathy vowels in some languages, though not in others (Thurgood 2004: 280); this has been linked to larynx lowering, which lengthens the supraglottal vocal tract (Brunelle 2010: 8-10; §3.3.7.3). Wholly or partly breathy-voiced vowels may also be longer than modal vowels (Thurgood 2004: 280, Wayland and Jongman 2003: 187), possibly in some cases to compensate auditorily for their reduced amplitude or the masking effect of additive noise on upper formants (see Gordon 1998).

In addition to cross-linguistic variation in the degree of breathiness detected by these various criteria, different studies have found striking dialectal and inter-speaker variation, suggesting a range of fine articulatory adjustments. An acoustic study of Eastern Cham dialects (Austronesian: Brunelle 2009: 14) provides a dramatic example of dialect variation in the realization of the register distinction (a contrast between two sets of cues realized on vowels but conditioned by a contrast in the preceding stops; see also Brunelle 2009, Wayland and Jongman 2002: 101-105):

> [I]t seems that the initial portion of low register vowels is very breathy in Kompong Chhnang Cham, whereas their high register counterparts are modal. Both registers then seem to become modal before ending on a breathier voice quality. Most Eastern Cham speakers follow the same general trend, but the amount of overlap between their registers is much greater. Finally, Châu Đốc Cham register seems to be “ballistic”. The low register starts breathy and then become modal (or even tense), while the high register starts modal and then becomes breathy. It is difficult to isolate a clear pattern at the end of the vowel, but it suffices to say that the voice quality distinction seems lost by then. Overall, the salience of voice quality distinctions

> seems too low [in these dialects] to be used alone for contrasting registers, but it could possibly reinforce a contrast in other phonetic properties.

Chanthaburi Khmer illustrates inter-speaker variation (Wayland and Jongman 2003: 197-198). For the female speakers, the register contrast was between breathy and modal voice, while the males contrasted modal voice with a phonation (voice quality) involving steeper positive spectral tilt due largely to an enhanced second harmonic (H2). Fairly steep positive spectral tilt is associated with creaky voice and can be visualized as rotated counter-clockwise from the moderately rising tilt of modal voice, while the tilt of breathy voice can be visualized as rotated in the opposite direction; however, creaky voice also typically involves slowed vocal fold vibrations which may produce a visibly choppy effect in spectrograms (see Gordon 2001). Wayland's impression of the male Chanthaburi Khmer speakers' higher (steeper) register was not one of creaky voice, and he suggests calling it "tense" instead (cf. §2.5.6). A breathy vs. modal register contrast has similarly shifted to modal vs. steeper spectral tilt in various other languages (see Brunelle 2005: 147).

In a second variation within Chanthaburi Khmer, two of the three female speakers produced their breathy vowels with a slightly higher F0 than their modal vowels, which is unusual (Wayland and Jongman 2003: 187, 194-195). One possible articulatory cause that could be investigated is whether the type of breathy voice used by these two speakers is whispery voice with relatively high medial compression and little larynx lowering. As we already saw (§2.5.2), lower medial compression creates a longer posterior glottal opening and leaves the vocal folds free to vibrate more loosely along more of their length, which tends to slow down their vibration and thus, like larynx lowering, tends to lower pitch. We turn now to examine the interaction between larynx lowering and another type of breathy voice: slack voice.

2.5.5 Slack voice

2.5.5.1 General

Ladefoged and Maddieson (1996: 63-66) describe slack voice as having a slightly larger glottis and higher airflow than modal voice, but still considerably less than strict breathy voice. Amplified lower harmonics, decreased spectral tilt, F1 lowering, and increased VOT are reported after slack stops in Javanese, while F0 lowering and F2 differences are less consistent (Brunelle 2010: 8). Similar sounds are reported in Wu Chinese dialects (Cao and Maddieson 1992). In both languages, Ladefoged and Maddieson refer to slack voiced stops. Since the stops themselves are admittedly voiceless during closure, however, with their distinctive cues being realized on following vowels, we will call them slack stops instead, with the implication that the slack quality automatically carries over into the voice of the following vowel but without implying that voice is an active strategy specified by the stop.

Below we will examine two distributional patterns of voiceless slack stops – that is, stops with entirely or mostly voiceless closure and cues of the slack quality being heard on the following vowel. In the first pattern, the slack stops occur initially and medially, while in the second pattern they occur only initially, with voiced medial allophones that are not consistently associated with cues of slack voice on the following vowel. The languages in which we will examine these patterns are listed in Table 2.1. The possibility of voiced slack stops (stops with closure voicing that trigger the cues of slack voice on a following vowel) is considered later (§3.3.7.2).

Table 2.1 Voiceless slack stop types.

Voiceless	*Voiceless initial with voiced medial allophones*
Javanese	Korean
Xhosa, Zulu	Wu Chinese
Eastern Armenian variety	Various Armenian dialects

Besides acoustic and fiberoptic investigations of slack voice in Javanese and Wu Chinese, impressionistic descriptions of the relevant Armenian dialects repeatedly mention breathy voice, murmur, glottal noise, and the like as auditorily salient properties (§2.5.5.4). Similar impressionistic descriptions of Xhosa and Zulu have been qualified by later acoustic studies that found considerable inter-speaker variation (§2.5.5.2). Several acoustic measures of breathy voice based on harmonic amplitude do not correlate reliably with glottal turbulent noise (Wayland and Jongman 2003: 184-185), indicating the difficulty in measuring glottal turbulence, let alone inferring glottal width, from acoustic data alone. This contrasts with research on Hindi-type voiced aspirates, where glottal widening and salient turbulence are consistently reported (e.g. Ladefoged and Maddieson 1996: 57-64, Stuart-Smith 2004: 164-166).

Several writers have linked the acoustic cues of slack voice to existing hypotheses about larynx lowering and vocal fold slackening (Brunelle 2005, 2010: 10-11, Jessen and Roux 2002, Thurgood 2008: 20-21, Traill et al. 1985, Wayland and Jongman 2003). The anterior convexity of the spine seems to play an especially interesting role: as the larynx lowers, the spinal curve and the natural range of the cricoid joint cause the front part of the cricoid cartilage to slide in a downward posterior direction in advance of the thyroid cartilage above it while the back part of the cricoid rotates forward (fig. 2.2). The arytenoids are attached to the back of the cricoid cartilage, and the vocal folds stretch from these to the interior surface of the front of the thyroid cartilage. The sliding or rotation of the cricoid thus rocks the arytenoids forward, which naturally decreases the longitudinal tension of the vocal folds, causing them to vibrate more slowly and lowering the pitch (Honda 2008: 12). This presumably increases the open quotient and thus the rate of airflow. Larynx lowering presumably also increases subglottal pressure, and this along with additional vertical factors may increase open quotient as well (Brunelle 2010: 11). The consequent airflow increase then causes turbulence heard as breathiness. Increased open quotient also correlates with decreased spectral tilt, though it seems possible to mitigate this by fine muscular adjustments to vocal fold tension independent of larynx height (Wayland and Jongman 2003: 187-188). Similar adjustments (e.g. of TA or CT) could also presumably assist or hinder the effect of larynx lowering on pitch.

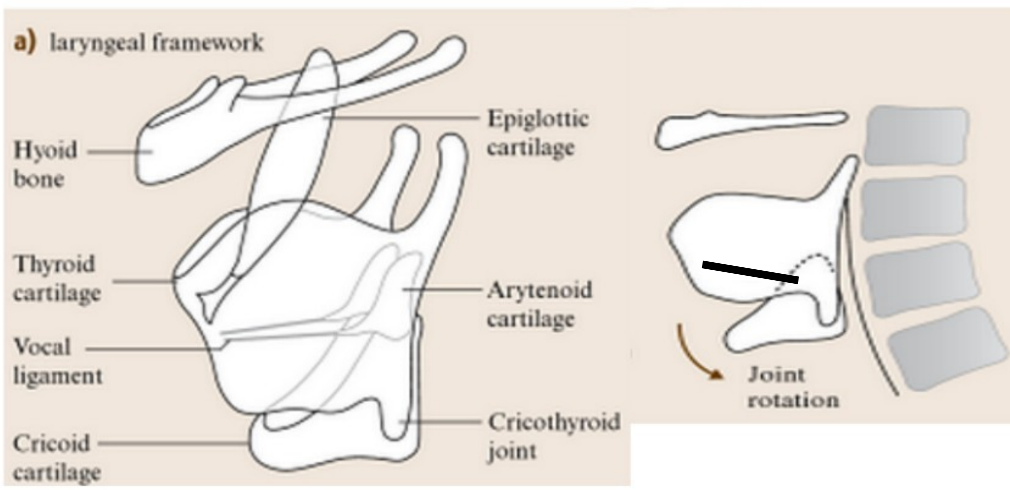


Figure 2.2. Cricoid rotation during larynx lowering shown at right. The thick, dark line inside the thyroid cartilage represents the axis of the vocal folds, which shorten as the cricoid rotates in the direction of the arrow. The vocal folds (ligaments) are depicted more clearly with the arytenoids at left. In both diagrams the anterior direction faces left. Adapted from Honda (2008: 9, 12).

This picture of slack stops again differs from that of Hindi-type voiced aspirates, where closure voicing and turbulence during the offset (the period immediately following stop release) can be explained by the sequential activity of the adductors and abductors and where the degree of larynx lowering needed to explain pitch lowering is unclear (since other factors may contribute to slower vocal fold movement and thus lower pitch:

§2.5.3). Based on such considerations, Jessen and Roux (2002: 38-43) suggest that slack stops share a different articulatory strategy from voiced aspirates like those of Hindi, with slack stops relying on larynx lowering which contributes to vocal fold slackening, while voiced aspirates rely (at least inter alia) on closure voicing with an abduction gesture peaking after stop release.

This in turn furnishes an explanation for why slack stops can have voiceless closure while the higher-airflow aspiration occurring after Hindi voiced aspirates has not been clearly documented at the release of voiceless stops (though it often occurs briefly at the tail end of voiceless aspiration as the abducted vocal folds return to the position for modal voice: Jessen and Roux 2002: 8). When abduction is phased so that it creates significant glottal turbulence after the release of a voiceless stop, the resulting aspiration is largely voiceless, presumably because voice initiation requires a narrower glottis and a higher transglottal pressure drop than voice maintenance does (see Hirose and Niimi 1991: 388, Kagaya and Hirose 1975: 39, Kingston et al. 2009: 10). Thus, a strategy relying largely on abduction to generate voiced turbulent airflow upon stop release might require voiced closure. Larynx lowering and vocal fold slackening, however, can increase offset airflow and generate some degree of turbulence without either devoicing the offset on one hand or requiring voiced closure on the other. If production strategy differences of this sort really do distinguish voiced aspirates of the Hindi type from slack stops, then that distinction might motivate different phonological feature specifications for them as well (§3.3.7.2).

2.5.5.2 Voiceless slack stops occurring initially and medially

2.5.5.2.1 Javanese

As already noted, fiberoptic and acoustic studies have found voiceless slack stops initially and postvocalically in Javanese (Austronesian), typically with slightly wider glottis, longer (though still short) VOT, and breathier spectral tilt than after the other contrastive type of stop; some speakers also have larynx lowering in the slack stops, conditioning lower F0 and F1 on the following vowel (Brunelle 2010: 8, Ladefoged and Maddieson 1996: 63-66, Thurgood 2004). The slack stops are normally voiced in postnasal position (Brunelle 2010: 1). The other contrastive stop series is referred to as tense (Brunelle 2010) or as "stiff voiced," with a smaller glottis possibly related to VOC contraction; this series too is normally voiceless during closure, and is associated with higher pitch and increased (more positive) spectral tilt on the following vowel (see Ladefoged and Maddieson 1996: 55-56, 63-64; §2.5.6).

2.5.5.2.2 Xhosa

Jessen and Roux (2002) present acoustic measurements of the depressor stops which lower the pitch of a following vowel in Xhosa (Niger-Congo: Bantu). They studied stem-initial position followed by a stressed vowel, with and without a preceding prefix, and in all cases with a vowel-final preceding word. They concluded that these stops can also be classified as slack, with zero or negligible closure voicing comparable to that of the contrastive voiceless aspirates and ejectives. The depressor stops had VOT ranging from 11-17 ms (Jessen 2002: 162) and were followed by breathy voice (measured by the difference between H1 and H2) for five out of eight speakers. For four of those five, this breathy voice was greater than that seen at the tail end of voiceless aspiration. All but one or two of the speakers also had breathy voice after the depressors comparable to that at the tail end of voiceless aspiration as measured by H1-A3 (Jessen and Roux 2002: 20-24; A3 is the most amplified harmonic in F3, the third formant). Further, besides lowering the pitch of the following vowel, the depressors lowered F1 throughout most of the following vowel for four speakers except in postnasal position, for one speaker only in postnasal position, and for one speaker only early in the vowel, with additional speaker variation in the magnitude of lowering (Jessen and Roux 2002: 18-19).

The depressors were normally voiced in postnasal position (Jessen and Roux 2002: 2), where they had "very short closure durations...usually below 30 ms", which were "not systematically longer" than the amount of closure voicing found in any of the three contrastive voiceless stop series in postvocalic position (Jessen and Roux 2002: 4, cf. Jessen 2002: 167). The slack stops of Xhosa contrast with voiceless aspirates and ejectives that often lose their ejection medially except in careful speech; there is also a voiced bilabial implosive. (On variously conditioned loss of ejection in other Nguni languages see Fallon 2002: 287-289.)

After hypothesizing that larynx lowering triggers vocal fold slackening which generates the acoustic cues found in Xhosa depressors, Jessen and Roux (2002) suggest that this larynx lowering is extensive enough to prevent voicing:

> [B]eyond a certain level of vocal fold slackening transglottal airflow becomes so high that it actually works against the maintenance of closure voicing, since it leads to a fast buildup of intraoral air pressure. If such extensive levels of vocal fold slackening are achieved by additional larynx lowering, it is expected that f_0 lowering becomes more extensive as well and achieves the status of a strong perceptual cue... It is also likely that the high levels of transglottal airflow in extensive vocal fold slackening lead to levels of breathy voice that are [more substantial].

Larynx lowering can be relatively rapid and extensive in voiced implosives, where it correlates with voicing crescendo rather than devoicing; implosives also tend to raise the pitch of the following vowel (see Demolin et al. 2002, Ladefoged and Maddieson 1996: 84-85; §2.5.5.2.3, 2.6.2). Given known laryngeal muscle functions (§2.2), these traits might be due to medial compression of the vocal folds helping limit transglottal airflow and maintain vocal fold vibration. CT contraction might also contribute to the higher pitch correlate. This raises the possibility that the Xhosa depressors are voiceless not because they have extreme larynx lowering beyond that normally found in any type of stop with closure voicing, but rather because of less medial compression and CT activity. Since LCA activity is associated with medial compression, it is worth noting that Kagaya and Hirose (1975: 34) found considerable LCA in /b/ as compared to other labial stops in Hindi, as well as moderate CT activity. If the voiceless closures of Xhosa depressor stops depend on LCA and CT suppression rather than on extreme larynx lowering, we would have no need to wonder why breathy voice is not more substantial and consistent across Xhosa speakers.

2.5.5.2.3 Zulu

Zulu is closely related to Xhosa within the Nguni group of Southern Bantu. The phonetic profile of the Zulu depressor consonants that emerges from fiberoptic and acoustic research (Chen and Downing 2011, Traill et al. 1985) is very similar to what we have already seen for Xhosa – except for the claim that "no voicing whatsoever was found during the closure" of postvocalic depressor stops (Traill et al. 1985: 266), an observation questioned below. Zulu depressors have short positive VOT (10-16 ms for labials and coronals, 20-37 ms for velars: Midtlyng 2011: 110). Breathy voice in the following vowel has been reported impressionistically in several studies but was not consistently evident in laryngographic traces (Traill et al. 1987), nor was it detected in Doke's (1926) kymographic waveforms (Jessen and Roux 2002: 6). The exception is fricatives, which Traill et al. (1987) found frequently associated with breathy voice; further, their description of the breathy-voiced depressor transcribed as /ɦ̤/ suggests whispery voice in particular ("a slight chink in the intercartilaginous glottis" which "disappears on release" pp. 267, 271). They also highlight the fact that pitch depression lowers the tone of the following vowel (high or low) quite considerably: more than the distance between non-depressed high and low tones (p. 270). Finally, the depressors are normally voiced in postnasal position (p. 266).

Traill et al.'s (1987) fiberoptic investigation found that depressor stops and fricatives had "very slightly abducted vocal folds" (p. 266), with "a spindle-shaped glottis...most frequently in the membranous [ligamental] portion of the vocal folds"; the arytenoids when visible "were almost always adducted." This spindle-shaped opening recalls the description of prephonation (§2.3.1) and suggests lack of medial compression. Additionally, depressor stops involved contraction of the laryngeal vestibule (§2.4) in two speakers. The gesture was considerably "more extreme" for one speaker than another and is analyzed as follows (p. 265):

> The observable movements involve an anterior movement of the arytenoids and the posterior movement of the tubercle of the epiglottis... Since we know that this adjustment is associated with extra-low pitch, it seems reasonable to assume that it induces an unusual degree of shortening of the vocal chords [*sic*] with a consequent lowering of their rate of vibration.

Traill et al. speculate that in subjects which did not have this gesture, CT relaxation contributed to pitch depression because larynx lowering "was not observed." It is not clear exactly how they gauged larynx lowering other than by imprecise visual observation. Presumably the extreme degree of larynx lowering that Jessen and Roux suggest was responsible for the mostly voiceless closures of Xhosa depressors would have been visually detected if it occurred in Zulu, but possibly lesser degrees would not.

Traill et al. (1987: 266, 271) assert that "no voicing whatsoever was found during the closure" of postvocalic depressor stops in their Zulu speaker; instead "voicelessness coincides with closure" as determined by oral airflow measurements synchronized with laryngographic waveforms of vocal fold pulses. In contrast, the depressor fricatives and postnasal depressor stops had clear closure voicing. Based on this difference, Traill et al. suggest that Zulu postvocalic depressor stops involve an active devoicing gesture, probably one primarily involving the vocal folds since aerodynamic data did not seem "compatible with vocal tract tensing or reduction" (p. 266; also recall the lack of visible larynx lowering mentioned above). They tentatively suggest that VOC activity is responsible for this devoicing by increasing tension in the cover of the vocal folds in spite of the body of the folds being relaxed and shortened (p. 271). More recent work has confirmed the independence of VOC and TA in controlling the cover and body of the vocal folds (§2.2). A spike in CT activity around the moment of closure might also contribute to devoicing in Zulu depressor stops, just as it appears to do in Hindi voiceless unaspirated stops (§2.3.2).

However, I observed 20-30 ms of closure voicing in depressors produced by a different Zulu speaker. The recording of this speaker is stored in the UCLA Phonetics Lab Archive (UCLA 2007a), and I analyzed it with PRAAT (Boersma and Weenink 2010). Example waveforms and spectrograms are given below (figs. 2.3-2.8). I identified the approximate duration of voicing past closure onset as the portion of the fundamental frequency which continues with noticeably decreased amplitude after other harmonics have failed. These examples of depressor prevoicing are highlighted in the waveforms.

Regarding transcription in these examples, the orthographic system follows the UCLA record, where *bh d g* are depressors, *b* is a non-depressor voiced stop, and *k* is an ejective which often becomes [g] intervocalically (cf. Fallon 2002: 239, 271, Halpert 2010). Figures 2.3 and 2.4 compare the bilabial depressor with the non-depressor *b*. The latter is phonetically transcribed in the UCLA record as an implosive. Traill et al. (1987: 245) note that this traditional classification appears incorrect in their data since this segment lowers the tone of a following vowel in all their subjects (though not nearly as much as the depressors do) and has positive pharyngeal air pressure. This contrasts with reports of progressive increase in voice amplitude and formant clarity in the Xhosa bilabial implosive, which are more consistent with the identification of that sound as an implosive (see Flemming 2004: 259, Jessen 2002: 160-161). Traill et al. conclude that the so-called bilabial implosive in Zulu is an ordinary voiced stop. In line with this, I have provisionally retranscribed the sound as [b] below because the speaker in this recording pronounced the segment without audible implosion, with relatively low pitch at the onset of the following vowel, and with amplitude comparable to that of the velar stop phonetically transcribed as [g] in the UCLA source. Otherwise, the phonetic transcriptions below essentially follow the UCLA source, which renders the depressor stops as voiced stops with a breathy umlaut. A more accurate alternative is discussed later (§2.5.6).

In all of the following samples of Zulu postvocalic depressor stops, voicing clearly leaks past stop closure for 20-30 ms, or roughly 4-5 glottal pulses. For at least this Zulu speaker, there is no clear evidence that an active devoicing gesture is necessary in the depressor stops. Instead, the slight prevoicing seen below in the postvocalic depressor stops and the full voicing that Traill et al. observed in the postnasal depressor stops and in the depressor fricatives might be due to differences in stricture rather than in laryngeal articulation. If the postnasal depressor stops are commonly as short as those in Xhosa, then they would be fully voiced simply because they are short, and if it has been argued correctly (Park 2002: 70) that voice is aerodynamically easier to maintain in fricatives than in stops, then the Zulu depressor fricatives would be fully voiced for this reason and not because of a laryngeal devoicing strategy uniquely present in postvocalic depressor stops.

Figures 2.3-2.8: Zulu depressors and fully voiced stops (adapted from UCLA 2007a).

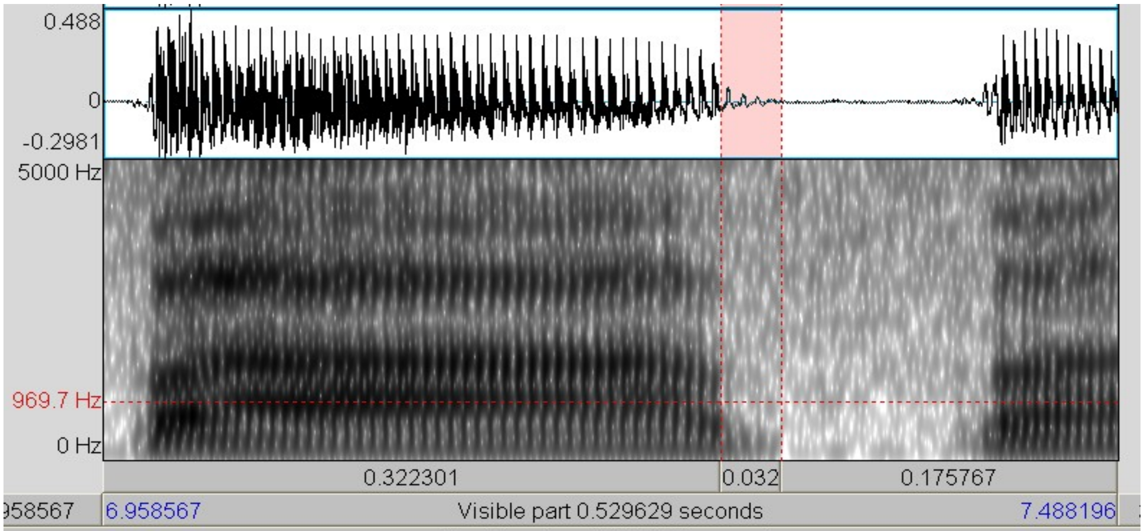


Figure 2.3. Zulu *bhabha* [b̤a̤ːb̤a̤] ‘trap’ shown with partial final vowel. Medial depressor prevoicing highlighted (32 ms).

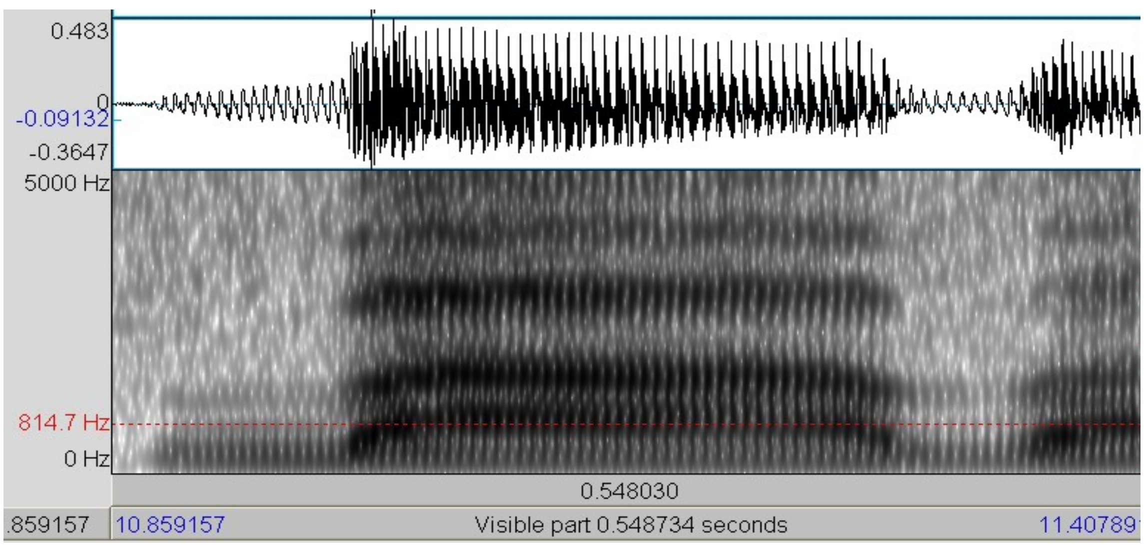


Figure 2.4. Zulu *baba* [baːba] ‘father (direct address)’ with partial final vowel; both stops have full closure voicing.

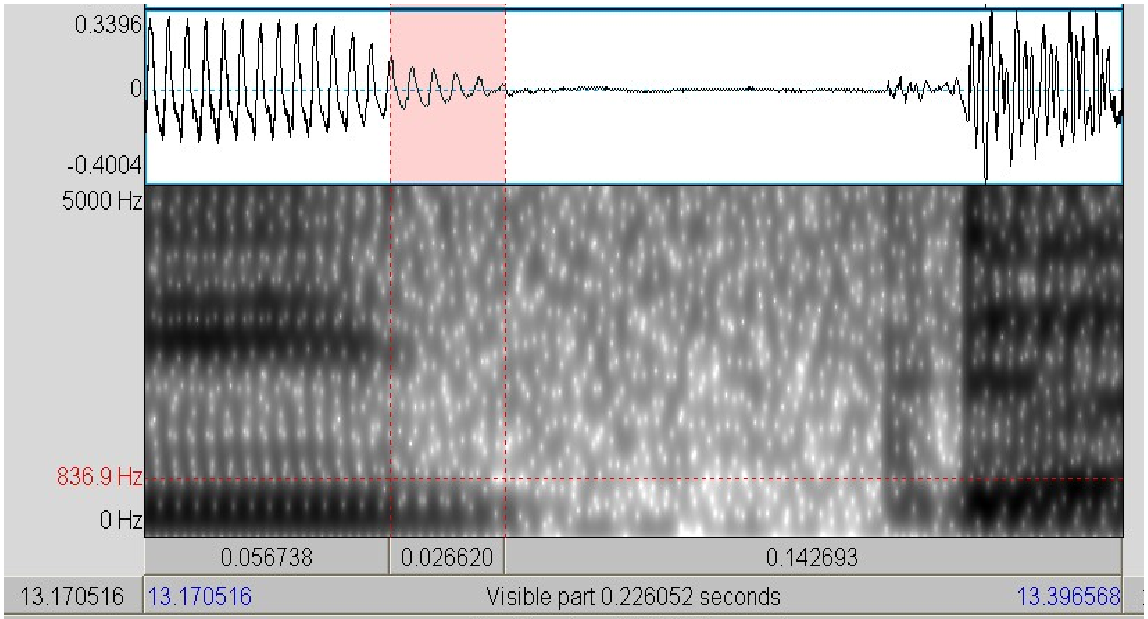


Figure 2.5. Zulu *idada* [iˈd̤a̤d̤a̤] ‘duck’. First stop with adjacent vowels shown; medial depressor prevoicing highlighted (27 ms).

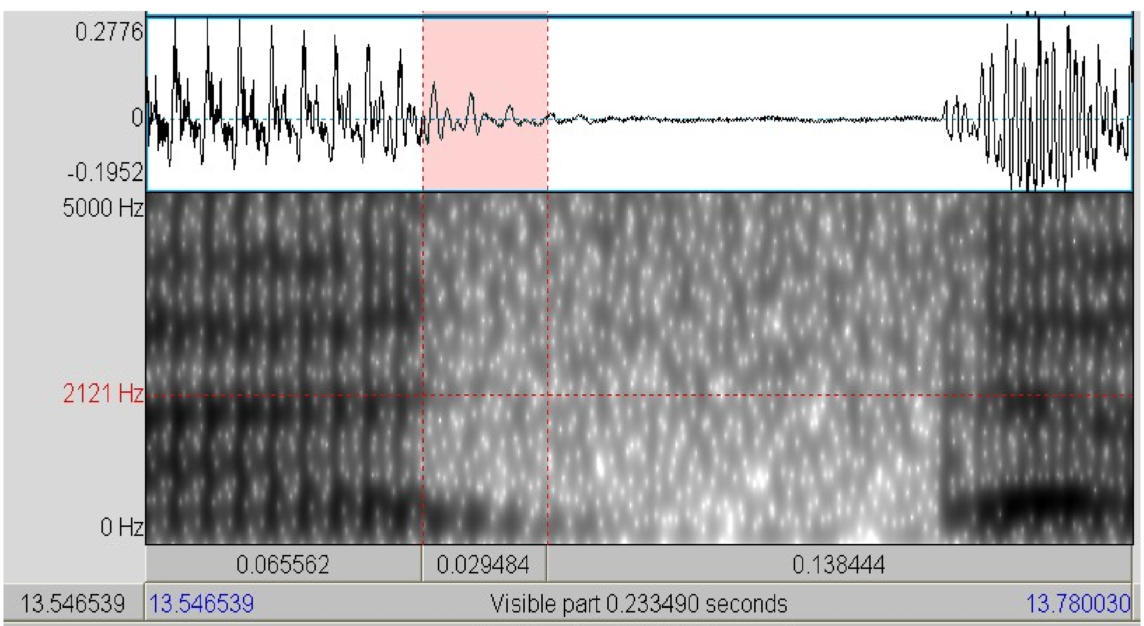


Figure 2.6. Zulu *idada* [iˈd̤a̤d̤a̤] ‘duck’. Second stop with adjacent vowels shown; medial depressor prevoicing highlighted (29 ms).

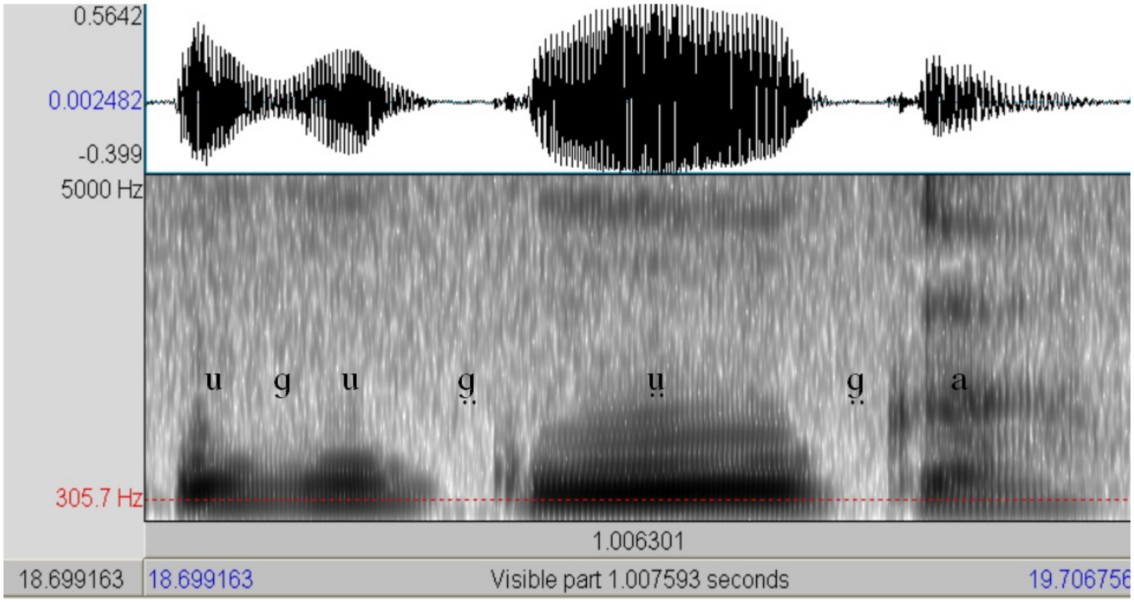


Figure 2.7. Zulu *ukuguga* [uguˈğ̤ṳğ̤a] ‘to grow old’. Only the first stop has full closure voicing. In spite of the release irregularities, the depressors were not audibly aspirated.

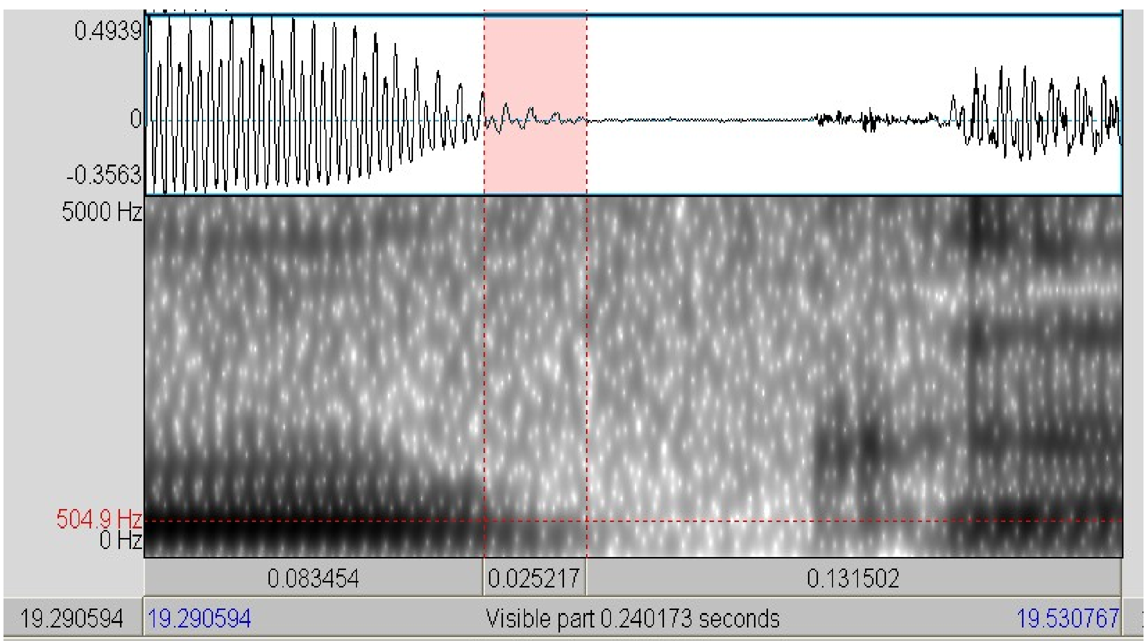


Figure 2.8. Zulu *ukuguga* [uguˈg̤ṳg̤a] ‘to grow old’ (close-up). Last stop and adjacent vowels shown; depressor prevoicing highlighted (25 ms).

Figures 2.9-2.10 Hindi intervocalic voiceless unaspirated stops (audio and transcriptions: UCLA 2007b).

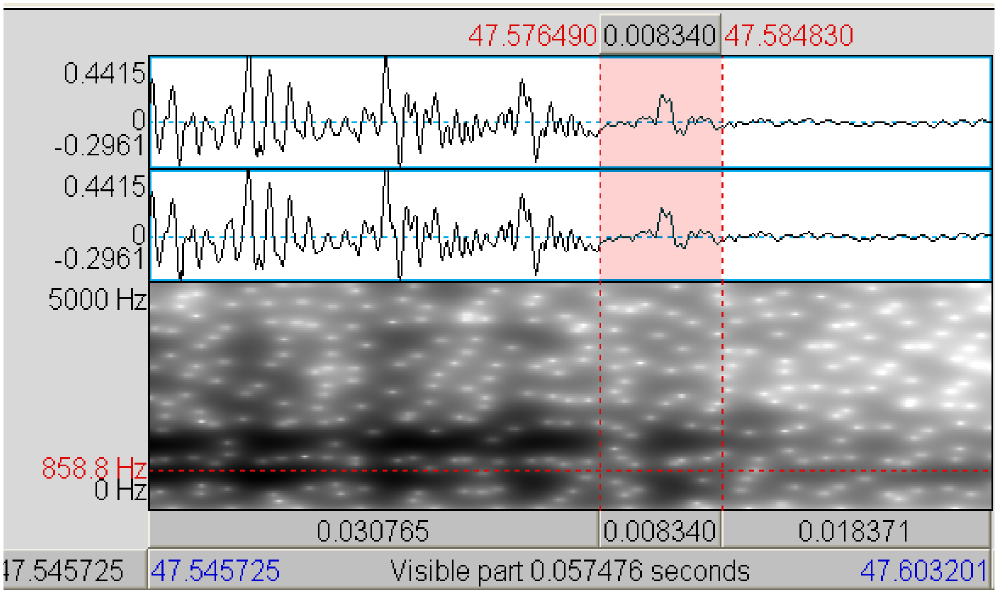


Figure 2.9. Hindi *ata* [aːta] 'he comes'. VC transition shown; stop prevoicing highlighted (8 ms).

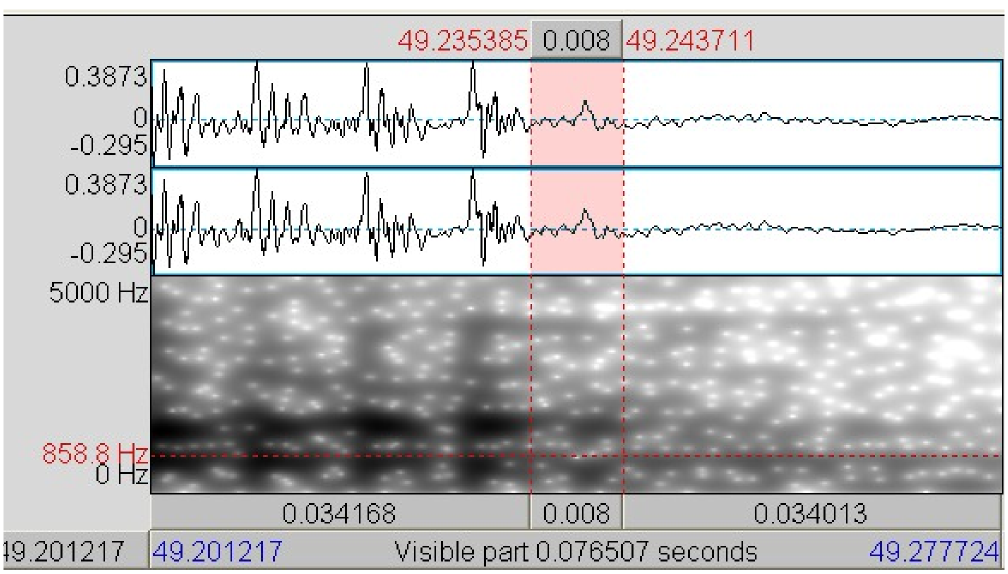


Figure 2.10. Hindi *mata* [maːta] 'mother'. VC transition shown; stop prevoicing highlighted (8 ms).

For comparison to Zulu, figures 2.9-2.10 illustrate intervocalic voiceless unaspirated stops from a Hindi speaker (UCLA 2007b, transcriptions unchanged). The waveforms and spectrograms, again made with PRAAT, show fairly abrupt cessation of voicing at the onset of stop closure, consistent with the claims of multiple researchers that active devoicing occurs in that environment in Hindi (§2.3.2, 2.3.3). Comparing this with the roughly 20-30 ms of closure voicing illustrated above in Zulu depressors and mentioned in the previous section for all three explosive stop series in Xhosa suggests that the latter two languages may not have active postvocalic stop devoicing, or at least not the same degree as Hindi. As a further comparison, since the laryngeal contrast of English stops has interesting differences from these other languages, with evidence for phonetic control of both voice and aspiration (§2.6.1, 3.3.9), it bears noting that two experiments found 20-27 ms of voicing leak on average into English postvocalic "voiceless" stops (Docherty 1992: 33-34).

2.5.5.2.4 An Eastern Armenian speech variety

Sounds described in terms reminiscent of slack stops have been observed in an Eastern Armenian speaker with influences from both the New Julfa and Erevan dialects (Allen 1950, cf. Vaux 1997, 1998b). In this speech variety, Allen (1950: 200-201) describes the relevant sounds as "generally voiceless stops, though in intervocalic position some voicing may be present in the early part of the stop". While lacking voiceless aspiration, they induce "markedly stronger breath-force and a lower pitch" on the following vowel. Kymographic tracings show decreasing amplitude throughout these vowels, unlike vowels after ejectives in the same speech variety, which had amplitude peak around the middle. The stops that trigger breathy voice normally have closure voicing in postnasal position (Allen 1950: 202). They contrast with voiceless aspirated stops and with ejectives whose glottal closure is "never very strong," "weakest at the commencement of a medial unstressed syllable," and sometimes simply inaudible (Allen 1950: 188).

2.5.5.2.5 Conclusion

The laryngeal distinctions in the stop inventories of the languages examined above are strikingly similar: in every case the stops described as slack or in similar terms contrast with a voiceless unaspirated series that has some degree of glottal narrowing ranging from vocal fold tensing to actual ejection, and in each language except Javanese there is a further contrastive voiceless aspirate series. Also in all these languages the slack or similarly described stops are normally voiced in postnasal position.

A similar type of three-series stop system also seems to occur word-initially in Wu Chinese, Korean, and Sivas Armenian. At least in Wu and Korean, allophones in some medial positions are voiced and are reported as not conditioning breathiness on the following vowel. (Information on Sivas medial stops was not available.) These languages are treated next.

2.5.5.3 Voiceless slack stops with voiced medial allophones

2.5.5.3.1 Korean

Korean has three contrastive stop series which have elicited a great deal of phonetic attention and phonological debate (e.g. H. Kim et al. 2005, M. Kim and Duanmu 2004). The three series are realized at various places of articulation by both stops and affricates; there is also a contrast between two types of *s*, which Kim et al. (2010) argue are fortis and lenis. We will continue focusing on stops.

One series is aspirated, the other two frequently described as showing a fortis/lenis or tense/lax contrast. All have voiceless closures, except for gradient voicing of the lenes between vowels that are not devoiced. This medial voicing of the lenis series is consistent within words and optional across word boundaries (Kim and Duanmu 2004: 86-88). Word-initially, the stop series are differentiated by the cues of the following vowel. The lenes condition lower pitch, often with breathy voice covering at least half the vowel (Cho, Jun, and Ladefoged 2002: 220, Garellek 2010, Kim and Duanmu 2004: 64); this breathy quality is more specifically identified as slack voice on the basis of acoustic measurements in Zhou et al. (2010). The fortes trigger cues on the following vowel that resemble those of creaky voice (Cho et al. 2002, Garellek 2010: 71). The phonatory differences conditioned by the three stop series also exhibit considerable inter-speaker variation in small details, though for most of the speakers tested by Cho et al. (2002) the lenes still sounded breathier and the fortes creaker (fig. 2.11).

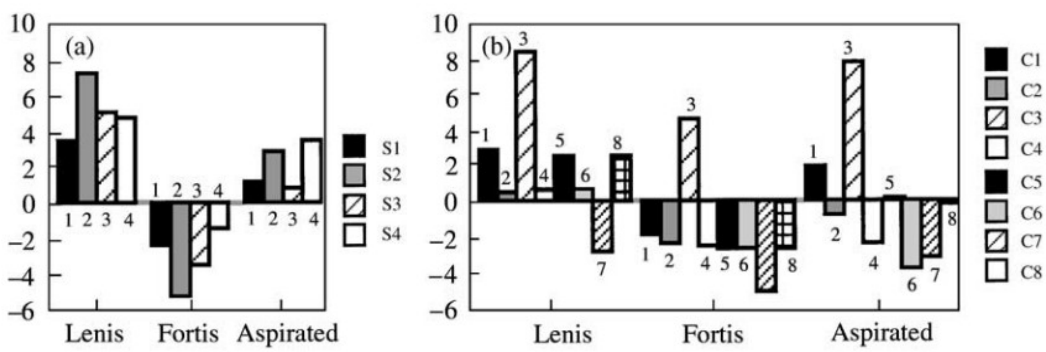


Figure 2.11. Korean inter-speaker variation in stop-conditioned vowel phonation, showing H1-H2 measured in dB for twelve speakers of (a) Seoul and (b) Cheju dialects. Reproduced from Cho et al. (2002: 208).

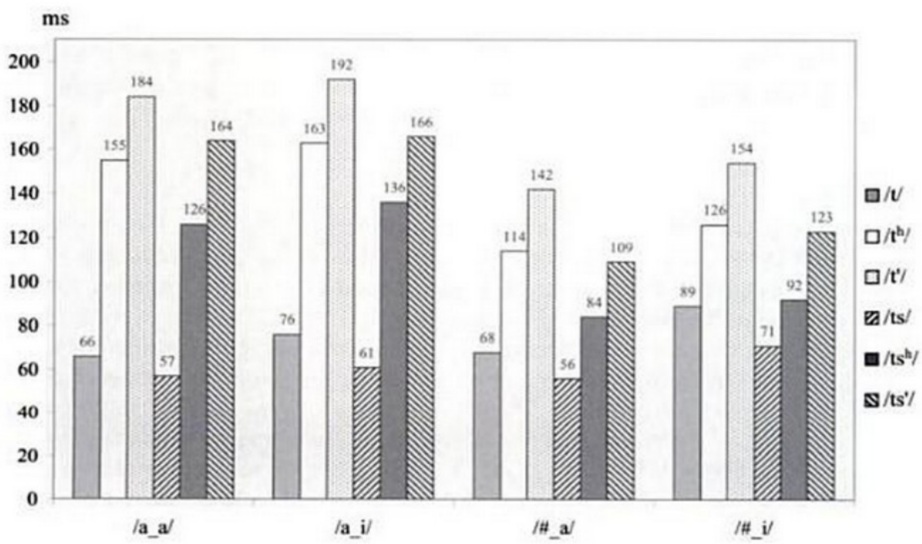
In word-initial, utterance-medial Korean stops, fiberoptic and EMG experiments by Hirose et al. (1973) found VOC activity peaking just before release in the fortes, rising to a somewhat lower peak located shortly after release in the aspirates, and rising to a still lower peak occurring after release in the lenes. LCA activity was similar to VOC. The same LCA pattern was seen in some word-medial stops, for which VOC data is not given. Later EMG work nuances the description of the VOC pattern: Hong et al.

(1991: 30) found VOC peaking sooner and higher for fortes than lenes, while in the aspirates they found later but faster activation, to a peak comparable to that of the fortes. The VOC peak occurred just before release in the aspirates and perhaps slightly later in the fortes (it's hard to tell since contours after release are not shown). Hong et al. (1991) highlight Hirose et al.'s (1973) claim that steep VOC activation is characteristic of the tense series and disagree, at least for their speaker. Roughly in reverse of the VOC pattern, Hong et al. (1991) found PCA activity highest in the aspirates, moderate in the lenes, and minimal in the fortes. PCA peak in lenis stops was about half that of aspirate stops; PCA peak in the lenis coronal affricate was closer to that of the aspirate counterpart but shorter in duration (with more of a spike shape). Also interesting is that the aspirates /k^h/ and /ts^h/ had peak PCA activity roughly 200 ms and /t^h/ roughly 100 ms before release (Hong et al. 1991: 23-27), since in Hindi voiceless aspirates peak PCA activity has been found much closer to release (Kagaya and Hirose 1975: 30-31).

Hirose et al. (1973) found CT activity roughly constant for all three stop series, suggesting that CT activity does not explain the higher pitch that tends to occur after Korean initial fortis and aspirated stops. Given the role of LCA in decreasing the glottis and the role of VOC in tensing the vocal-fold cover (§2.2), it seems appropriate to classify the Korean fortes as tense. Some feature analyses treat the aspirates as [+tense] too, however (e.g. Kim et al. 2005; cf. Kim and Duanmu 2004), so we will continue using the fortis/lenis terminology although its cross-linguistic uses are disparate and often vague (Butcher 2004, Cser 2003, Holton 2001). Incidentally, Fischer-Jørgensen and Hirose (1974b) and Hirose et al. (1973: 200) also found a trend of increased VOC and LCA activity in the articulation of the Danish prosodic phenomenon known as *stød*. The Danish *stød* has given impressions of glottalization (e.g. Kortlandt 1988b), though Fischer-Jørgensen and Hirose (1974b) found no difference in PCA and INT activity between *stød* and non-*stød* words in a speaker that they tested. Similarly, the Korean fortes have repeatedly been analyzed as [+cst] without clear articulatory support (Kim and Duanmu 2004: 81-82, Lee 2006: 4); Ladefoged and Maddieson (1996: 55-57) prefer the term “stiff voice”, described in terms similar to the “tense” register of some male Chanthaburi Khmer speakers (§2.5.4).

Lisker and Abramson (1964: 397) acoustically measured nearly zero, moderate, and high VOT in Korean fortis, lenis, and aspirated stops respectively; similar findings by Kim (1965) are discussed in Chomsky and Halle (1968: 327). Kim (2005: 289) mentions that fiberoptic and acoustic work by Kagaya (1974) found small, moderate, and large glottal width in the same series. An MRI study of coronals (Kim et al. 2005, Kim 2005: 294-295, 298) found that peak glottal width, glottal height, tongue blade height, duration of stop closure, and duration of peak glottal height increased in the order lenis, aspirated, fortis, suggesting coordinated tongue and larynx movement and simultaneous but independent control of glottal width. Kim (2005: 302) correlates glottal width with the decrease in airflow measured across the same three series respectively by Cho et al. (2002). Further, aspirates and fortes “have more extended palatal contact” than lenes (Kim 2005: 303), and this effect is noticeably greater word-medially than word-initially (Cho and Keating 2001). An electromagnetic articulography experiment (Brunner, Fuchs, and Perrier 2011, cf. Brunner 2005, Brunner et al. 2003) also found that the oral closing gesture in Korean velar stops accelerated faster in the order lenis, aspirated, fortis.

The feature analysis of the three Korean stop series is much contested (see Kim 2005, Kim et al. 2005, Kim and Duanmu 2004). Here we will only mention the proposal in several works (including Ahn and Iverson 2003, Averi and Idsardi 2001 and others mentioned in Kim and Duanmu 2004: 289) that the fortis stops are phonologically geminates. This proposal incurs a number of objections. The fortes are not significantly longer than other stops initially, and aspirates are almost as long as fortes medially (Kim 2005: 296-297). The duration ranking is fortis > aspirated > lenis, with the fortis and aspirated stops very roughly 40 ms shorter initially than intervocalically but maintaining about a 25 ms difference between each other. Since the aspirates in turn vary from about 90 (initial) to 40 (medial) ms longer than the lenes, we see that the aspirates are much closer to the fortes in duration, and that those two series differ by a more nearly constant, as well as smaller, factor than the factors that differentiate them from the lenes (fig. 2.12). Kim (2005: 298) points out that the geminate analysis of the fortes does not explain either how long the aspirates are or the fact that the fortes are still slightly longer.



Mean measurements of the closure duration of the consonants in the word-medial /a_a, a_i/ and word-initial contexts /#_a, #_i/ (based on H. Kim 2002)

Figure 2.12. Korean coronal stop closure durations (from Kim 2005: 297).

Regarding the phonetic effects of Korean stops on following vowels, Kim and Duanmu (2004: 60-64) highlight how Korean neutral-speech pitch patterns differ from the standard stop-pitch correlations of tense-high and lax-low: after word-initial aspirates and fortes there is high pitch up through the first two syllables of a word, while after word-initial lenis stops and nasals there is low pitch on the first syllable and high pitch on the second. There is considerable variation in pitch from third syllables onward, but this was not found to depend on the initial consonant. Medial consonants also do not categorically affect pitch patterns. Kim and Duanmu (2004: 64) summarize several phonetic studies on Korean with a list of correlates in fortis ("tense") vs. lenis ("lax") stops, adapted in Table 2.2.

Table 2.2. Phonetic differences between Korean initial fortis and lenis stops (adapted from Kim and Duanmu 2004: 64).

	Fortis	*Lenis*
Following pitch	higher	lower
VOT	shorter	longer
Glottal opening	narrower	wider
H1-H2	smaller	larger
Intensity	stronger	weaker
Airflow at release	lower	higher
Oral air pressure before release	lower	higher

2.5.5.3.2 Wu Chinese

A number of northern and southern Wu dialects of Chinese including the Shanghai dialect have three contrastive stop series: voiceless aspirates, voiceless unaspirated stops, and a series classified as slack by Ladefoged and Maddieson (1996: 64). According to Cao and Maddieson (1992), this third series is voiceless in prestressed and utterance-initial positions, with lowered pitch in the following vowel and breathy voice on the first part of the following vowel. For detecting breathiness, Cao and Maddieson used H2-H1 and A1-H1 (where A1 is the most amplified harmonic in the F1 region, cf. Jessen and Roux 2002). Medially before an unstressed vowel, the same phonological series is voiced during closure. Cao and Maddieson did not find significant breathiness in the vowels following these voiced allophones; they report that most other studies agree on this point, with Ren (1987) an exception. They also made aerodynamic measurements and found higher transglottal airflow in syllables with an initial slack stop than than in syllables with a non-slack voiceless unaspirated initial. From acoustic and transillumination data by Ren, they report minimal or no difference in VOT between the slack stops and the other voiceless unaspirated series, but a wider glottis just before release in the former.

Gao et al. (2011) however found peak glottal width occurring earlier in the slack stop series than in the other voiceless unaspirated series in the Shanghai Wu dialect. They also detected slack voice in onsetless and nasal-onset syllables bearing certain tones, suggesting that in the Shanghai dialect, slackness is synchronically a property associated with some tones rather than with stops alone (further on the tonal restrictions see Chen 2008). Steed (2011) argues from tone sandhi patterns that slack voice is a property of morphemes in the Qingtian Wu dialect (cf. Rose 1994 arguing for both depressor and register components in Wenzhou Wu tone representation). Steed (2011: 1895) also mentions that the non-slack unaspirated stops of Qingtian Wu often have free variation between voiced and voiceless closures, a trait he calls rare for Wu dialects and one that we will see again in Sivas Armenian (§2.5.5.4). This should not be confused with cross-dialect variation between slack and voiced stops: Cao and Maddieson (1992) cite reports that in some Wu dialects, the cognates of the slack series have full closure voicing even in prestress position.

Cao and Maddieson (1992) note that tonal distinctions are fully or nearly neutralized in unstressed vowels. Chen and Downing (2011: 260) say that tone is assigned to a “roughly...bisyllabic” domain in the Shanghai dialect as opposed to a polysyllabic domain in Zulu and Xhosa. Chen and Downing (2011) highlight the apparent complementarity in the phonetic realization of the contrast between the slack stops and the other voiceless unaspirated series: utterance-initially and in prestress position, the contrast depends on the phonation and pitch of the following vowel, while medially in unstressed syllable onsets it depends primarily on stop closure voicing. Another Chinese dialect reported with the same three types of initial stop as described for Shanghai Wu is the Lengshuijiang dialect of Hunan province (Zhang 2009).

The stop system in Wu dialects like Shanghai has several similarities with Korean (Kim and Duanmu 2004: 89): in both languages, besides a contrastive voiceless aspirate series, there is an initial contrast where fortis stops are voiceless followed by higher pitch and lenis stops are voiceless followed lower pitch and some degree of breathiness, while medially the fortes and lenes are voiceless and voiced without categorical effects on pitch. The lenes differ from the voiced series of languages like French in being initially voiceless and apparently in having more salient pitch-lowering effects. If features are innate, we must ask whether this difference is small enough for the lenis stops of Korean and Wu still to be viewed as phonologically voiced. If features are emergent, the question is moot (§3.3).

2.5.5.4 Voiceless slack stops and voiced stops in phonetic contrast

Khachaturian (1983) mentions several Eastern Armenian dialects that have voiceless stops followed by breathy voice in word-initial position with plain voiced medial allophones. Unfortunately, she does not present the inventories or much other detail.

Free variation between voiced and voiceless realization of non-slack unaspirated stops in Qingtian Wu was already mentioned (§2.5.5.3.2). The allophones with closure voicing are thus in contrast with slack stops in initial position. I refer here only to the phonetic realizations of the contrasting sounds; their supposed phonological specification is a separate topic (§3.3.7.2; for a similar situation with nasalized laterals see §4.3.3.2).

A similar contrast is reported in the Western Armenian dialect of Sivas (or Sebastian; Adjarian 1899, Busetto 2007: 57, Kortlandt 1985: 188, Scripture 1901: 369-370, Vaux 1998b: 8-9). This dialect is described as having three contrastive series of stops: voiceless aspirate, plain voiced, and a series that conditions breathy voice on the following vowel. Adjarian (1899) coordinated measurements of oral egressive airflow and voicing for all three types of stop in word-initial position, detecting vocal fold movement with a capsule externally attached to the larynx. In the plain voiced series he found voice starting 15-80 ms before stop release, while in the breathy series he found substantially higher airflow upon release and voice starting 20-30 ms after stop release, and in the voiceless aspirates VOT was roughly 10-40 ms. These figures in his discussion of the three series (pp. 125-127) reflect the tokens for which he presents data (pp. 120-123). In particular, the latter show roughly 60-80 ms of closure voicing in the plain voiced series for the stops properly speaking, with much lower or negligible closure voicing in the affricates of the same series. Substantial closure voicing variation for individual phonemes within this series is not reported.

Adjarian's description of the breathy series agrees with portrayals of so-called voiced aspirates in Armenian dialects more generally, where these sounds are sometimes called "half-voiced" (Vaux 1997, 1998b) or "voiceless breathy" (Pisowicz 1998) and described as having voiceless closure with audibly breathy offset (Khachaturian 1983, Sievers in Rousselot 1899: 132, Weitenberg 2002: 149) associated with lowered pitch (Allen 1950: 200, Khachaturian 1992: 123). Following the release of the breathy-offset stops in Sivas, Adjarian (1899: 125) says "la masse d'air employée est... considérable, ce qui me donne l'impression... d'un bruit confus dans la gorge". It is unclear whether this turbulence is a result of glottal widening, vocal fold slackening at least partly mechanically triggered by larynx lowering, or some combination (§2.5.5.1).

The Eastern Armenian dialect of Nor Bayazet also appears to have an unpredictable and thus lexically specified distinction between initial voiceless slack and plain voiced stops: in addition to inherited tokens of the former it has borrowed words with initial plain voiced stops from literary Armenian, though there do not seem to be any minimal pairs (Khachaturian 1992). To this situation one may compare an unpredictable place distinction reported as dental vs. alveolar in Mapudungun (or Mapuche, formerly known as Araucanian), a language of debated genetic affiliation spoken in Chile and Argentina: here again minimal pairs do not seem to be documented, and the contrast itself may now be moribund (Smeets 2008, cf. Chomsky and Halle 1968: 312, Salamanca and Quintrileo 2009).

2.5.6 Conclusion

Slack stops are relatively under-documented, with perhaps the most familiar examples being from Javanese and Shanghai Wu Chinese thanks to Ladefoged and Maddieson (1996). We have seen similar stops in several other languages, with a number of intriguing phonological parallels. These include a contrastive voiceless unaspirated series conditioning higher pitch and often associated with variable laryngeal constriction realized as ejective release or as creaky or stiff voice on the following vowel (cf. §2.4); there is also often a contrastive voiceless aspirate series. The slack stops have voiced allophones in postnasal position (except that in Wu and some Eastern Armenian dialects, I did not find information on postnasal realizations); the slack stops have intervocalic voiced allophones in some languages as well. Mutually unpredictable distribution of slack and ordinary voiced stops is rare but reported in Sivas and Nor Bayazet Armenian and in Qingtian Wu Chinese. Phonological implications are discussed in the next chapter.

Voiceless slack stops that condition some degree of breathiness on the following vowel, as reported in Sivas Armenian, in some Xhosa and Zulu speakers, and in Korean (§2.5.5), can be transcribed as [p̤ t̤ k̤] etc., following a suggestion for Korean by Zhou et al. (2010: 5). Here the breathy diacritic can be interpreted as indicating a laryngeal configuration which triggers higher than modal airflow on the following vowel. The virtue of this transcription as opposed to [p^{ɦ} t^{ɦ} k^{ɦ}] etc. (used for Javanese and Wu Chinese by Maddieson 1984) is that the latter can be misunderstood as indicating breathiness with even higher airflow or with a more salient concentration at the beginning of the vowel, such as is found with the aspiration of voiced aspirates. That characterization is inappropriate for slack stops (§2.5.5.1).

We now turn finally to the subject of stop closure voicing.

2.6. Articulatory strategies for maintaining closure voicing

2.6.1 General

Voicing requires not only adducted vocal folds but also a sufficiently higher air pressure below the glottis than above it in order to maintain the transglottal airflow necessary for vocal fold vibration. In stops, all other things being equal, airflow into the closed oral cavity raises air pressure there, leading to transglottal air pressure equilibrium and voicing cessation (Gordon and Applebaum 2006, Hayes 1997, Kenstowicz 1994: 36, Ohala 1989: 177, 1997, Thurgood 2008: 20). Under these conditions, voicing can fail before stop release if the stop is long enough.

Devoicing has a higher incidence and aspiration tends to be longer in stops with more posterior oral place articulations. Both trends have been attributed to the fact that oral air pressure builds up more quickly the smaller the cavity size (or more precisely, the smaller the cavity wall surface area: Keating 1984b: 30). On the correlation of place with voice see Blevins (2004: 12), Hayes (1997), Howe (2003: 73-74), Keating (1984b, 1985: 124), Maddieson (1984: 35-37), Ohala (1989: 177, 1997), Ohala and Riordan (1979); both voice and aspiration: Gordon and Applebaum (2006: 6-9), Helgason and Ringen (2008: 623-624). Helgason and Ringen note that the pressure buildup explanation does not work for the same place correlation which they observed with preaspiration in Swedish, but they suggest that articulator speed may fill this explanatory gap. The aerodynamic argument for voice failing sooner given smaller supralaryngeal cavities has also been extended to findings that females show less voicing leak from a vowel into a following stop than men do (German: Jessen and Ringen 2002: 206, Swedish: Helgason and Ringen 2008: 611; cf. Koenig and Lucero 2008: 1083). Overall, the research appears to support the idea that the duration of closure voicing in stops is limited by place-related mechanical factors. The influence of such mechanical effects is limited by active strategies that show considerable inter-speaker variation, however (Midtlyng 2011: 114-115).

Clements and Osu (2002: 305–306) describe several attested mechanisms for prolonging stop closure voicing:

> These may include increasing subglottal pressure, slackening the vocal folds, or decreasing supraglottal pressure. The latter adjustment can be achieved either by venting the airstream outward through the nasal cavity during part of the occlusion, or by expanding the oral cavity...
>
> The last of these adjustments, oral cavity expansion, is of particular interest... It can be achieved by several different but complementary maneuvers, including larynx lowering, tongue root advancement, relaxation of the soft tissues of the vocal tract walls, raising of the velum, shifting of the oral closure forward to expand cavity size longitudinally, and lowering of the jaw... Most of these mechanisms, including larynx lowering, have been observed in the production of "ordinary" voiced obstruents in better-studied languages such as English and French, often in combination.

Parker (2002: 138-139) has a similar list with further references, mentioning also the frequently shorter duration of voiced stops. Although this last trait has a clear aerodynamic function (Gordon and Applebaum 2006: 5), it has been repeatedly found in various languages that this stop durational difference also trades off with the duration of a preceding vowel in what appears to be an actively controlled fashion (Kingston et al. 2009: 9, Solé 2007; exceptional languages: Keating 1985: 120-124; interaction of duration with F0 in perceived rhythm: Cumming 2010). Wide inter-speaker variation in stop closure duration (e.g. in Kabardian: Gordon and Applebaum 2006: 5-6) also indicates active control of the duration of singleton stops. In a further correlation, Keating (1984b) found evidence that prestress position favors more stop closure voicing than other positions. She relates this to the higher subglottal air pressure associated with stress (cf. §3.3.6.2). Again, cross-linguistic variation in her results suggest some degree of active control by speakers.

It is not clear how long stop voicing can continue if supported by no other adjustments than passive vocal tract expansion in response to increasing air pressure. Ohala and Riordan (1979: 90) estimate that without such passive expansion, stop voicing would fail in 5-15 ms, but that with it, voicing lasts 50-100 ms depending on oral articulation. Clements and Osu (2002: 305) cite Westbury (1983) as estimating that stop voicing lasts 7-80 ms depending on the tension of the different tissues bounding the vocal tract. Ladefoged and Maddieson (1996: 53) consider 50 ms of voicing "consistent with models of passive cavity expansion." Traill et al. (1987: 266 citing Hutters 1985) extend the range up to 70 ms. These estimates imply that intervocalic stops can be passively voiced throughout closure if closure does not last beyond somewhere in the range of 70-100 ms. Jessen and Ringen (2002: 190) agree that intervocalic stops can be passively voiced, again citing Westbury (1983).

However, Kingston et al. (2009: 11) note that Westbury (1983) detected tongue root advancement and larynx lowering in the intervocalic voiced stops that he recorded, and that Bell-Berti and Hirose (1975) found the soft palate actively raised in post-sonorant voiced compared to voiceless stops – another cavity resizing gesture which would help prolong voicing. Active cavity expansion in voiced stops is also documented in several other studies (Koenig and Lucero 2008: 1077). Both Westbury (1983) and Bell-Berti and Hirose (1975) used English data, which is significant because the laryngeal contrast in English stops is not implemented with consistent closure voicing comparable to French or Hindi. Iverson and Salmons (2003b: 49-53) model the stops in English and most other Germanic languages as having an aspiration contrast, with stops only voicing passively to the degree that intersegmental conditions aerodynamically favor this; Jessen and Ringen (2002) apply the same analysis to German with more acoustic detail. Yet neither of these works (nor Ohala and Riordan 1979, Ladefoged and Maddieson 1996: 53, nor Traill et al. 1987: 266) mention measurement of larynx height or tongue root advancement in their estimates of passive voicing duration. Kingston et al. (2009: 9-13) conclude that systematic passive voicing throughout the closure of intervocalic stops in a language has not been confirmed, and suggest that it does not occur. Keating (1985: 124) infers from additional cross-linguistic evidence that "voiceless unaspirated stops are favored, even in intervocalic position, contrary to popular belief".

Nevertheless, Jessen (1998: 306-307) reports the intervocalic unaspirated stops of seven German speakers averaging 36-60 ms of voicing followed by 6-16 ms (13-16 ms for five speakers) between voicing failure and closure release. Some tokens have even less voicing and a longer voiceless portion, and some tokens are short (around 30 ms) and fully voiced (e.g. Jessen and Ringen 2002: 199). It is unclear why voice leak in the range of 30 ms would require active voice sustaining efforts, and the idea that it can occur passively would explain why it seems actively prevented in some languages (e.g. Hindi with its clearly contrastive phonetic voicing §2.3.4, vs. Xhosa, Zulu, and English which favor other interpretations of their laryngeal contrasts §2.5.5.2). In Jessen and Ringen's German data, the relatively short duration of voicing leak into unaspirated intervocalic stops much of the time and for several of the speakers, as well as the trend of voice failing sooner in more posterior stops (Jessen 1998: 322-324, Jessen and Ringen 2002: 205) and sooner in females (Jessen and Ringen 2002: 206), suggests that any active voicing support is very limited. The mechanical factors which plausibly contribute to such place or gender variation can clearly be overridden by speaker intention, as seen in any language where speakers show more complete or consistent closure voicing across such variables.

As mentioned by Jessen (1992: 324), Docherty (1992) concluded that his British English subjects do actively control voicing, given their lack of correlation between voice leak duration and stop place anteriority. Docherty (1992: 120-149) reports a number of other factors indicating stop voicing control in British English. Inter-speaker range in VOT differences by place was considerable, as was VOT range for both stop series; there was significant VOT overlap between the two series in some environments, including VOT overlap between homorganic members of the two series in some speakers – an ambiguity which Docherty interprets as not impeding comprehension due to top-down processing (expectations drawing on other grammatical and lexical information available from the context; cf. Menn 2010). Docherty (1992: 139) concludes that much of this inter-speaker variation is due to the varying implementation strategies of different speakers, since it is unclear how the details could be modeled as purely mechanical.

The question of how long passive voicing can extend into a stop remains unanswered. Since it is independently evident that speakers sometimes control other non-contrastive phonetic properties (e.g. control of V-C duration ratios earlier in this section, active generation of negative oral air pressure in §2.6.2, and enhancement in §3.2.4), it is not clear what relationship we should expect between the degree of control that English or German speakers exert over intervocalic stop voicing, on one hand, and the contrastive specifications of stops in these languages, on the other (§3.3.9).

2.6.2 Non-explosion

Voiced implosives have traditionally been distinguished from ordinary voiced stops with the additional characteristics of laryngeal constriction, negative oral air pressure generated by lowering the constricted larynx during closure, and ingressive airflow upon release; however, a growing body of research reveals that none of these traits is necessary for implosives (Clements and Osu 2002: 302). This challenges theories which specify implosives with [+constricted glottis] (e.g. Halle and Stevens 2002[1971]: 51) or [+lowered larynx] (Avery and Idsardi 2001: 44).

Maddieson (2003: 28) writes that implosives tend to be modally voiced rather than laryngeally constricted in Bantu languages. Ladefoged (2009[1964]: 6-7) found that the velarized bilabial implosive in three dialects of Igbo (Niger-Congo) had negative air pressure only about eight percent of the time, while three quarters of the time it had between one and three quarters of the oral air pressure found in the plain voiced explosive /b/ in similar environments. Along similar lines, Clements and Osu (2002: 316–334) found that the voiced bilabial implosive of Ikwere (Niger-Congo) is typically characterized by the absence of positive oral air pressure buildup rather than by negative oral air pressure or ingressive airflow, and that the sound relies on neither larynx lowering nor laryngeal constriction; instead, it evidently avoids pressure buildup through passive expansion of the oral cavity by incoming air as well as active lip protrusion, jaw lowering, and perhaps tongue root retraction or velarization. Clements and Osu found no evidence for velar stopping and hence did not classify this sound as labial-velar, though labial-velars can possess oral air pressure rarefaction effects like those of implosives (Greenberg 1970: 128-129).

This creates a few challenges. A terminological challenge is evident even in Ladefoged's (2009: 6-7) remarks, calling implosives ingressive but immediately adding that they are usually not ingressive in the languages that he measured because air entering the oral cavity from the lungs during stop closure tends to counteract any oral air-pressure rarefying effect from larynx lowering. This is not always the case; for example, most of the implosive tokens measured and reported in Seereer-Siin (Niger-Congo; McLaughlin 2005) have negative oral air pressure. Yet the fact still remains: for implosives, "it is often the case that the airflow through the glottis" is enough to keep oral air pressure "from becoming negative" (Ladefoged and Maddieson 1996: 82), suggesting that in some languages, including those mentioned by Ladefoged (2009) and Ikwere as measured by Clements and Osu (2002), the articulatory goal for implosives is to ensure substantially lower oral air pressure than in contrastive voiced explosive stops – not necessarily negative oral air pressure.

Clements and Osu (2002: 299) subsume both truly imploded stops and stops that simply avoid substantial positive oral air pressure buildup under the umbrella term *nonexplosive* because the two do not seem systematically distinguished in any language. I follow suit, adding a hyphen to the neologism (*non-explosive*). Clements and Osu (2002) further argue that non-explosive stops are not obstruents; one of their reasons for this claim is that like sonorants, non-explosives are typically voiced (a fact also noted by Maddieson 1984: 111-115; further on the correlates of sonorance see §3.3.8).

Since truly imploded stops and other kinds of non-explosives do not seem to contrast in any language, grouping them together seems phonologically useful. The non-contrastive category probably extends beyond non-explosion, though, including preglottalized and creaky-voiced stops regardless of their oral air pressure levels during closure. According to Clements and Osu (2002: 300, 313) and Greenberg (1970: 125), the only known contrast among all these types of stops is between a voiceless (closed-glottis) type and a voiced one; their remaining differences are notably gradient and prone to under-documentation. To the degree that the increased laryngeal constriction in creaky as opposed to modal voice temporarily decreases transglottal airflow, it would seem to be another potential strategy for prolonging closure voicing. Creaky voice and preglottalization are sometimes found co-occurring with larynx lowering and other cavity-expanding gestures in voiced stops (Ladefoged and Maddieson 1996: 55).

Non-explosion itself is not always contrastive. Nyangi (Eastern Sudanic) reportedly contrasts voiceless stops and voiced non-explosives without a separate series of voiced explosive stops (Flemming 2004: 259-260, Maddieson 1984: 113; for further examples in Chinese dialects and Bantu subgroups see Cun 2005: 1, Grégoire 2003: 353). In some languages, voiced explosive stops are reported as a narrowly conditioned allophone of voiced non-explosives whose distribution is less restricted (Greenberg 1970: 134-135). Non-explosion and explosion can even be in gradient variation with each other. Murrinh-Patha (Australia: Butcher 1992) has two contrastive stop series reported as “fortis” and “lenis”; they typically differ in voicing, but they have other differences as well:

> Visual observation of the Murrinh-Patha speaker at the time of recording confirmed that the larynx is lowered quite substantially during the *lenis*

> articulations, presumably to facilitate the prolongation of glottal pulsing into the stop closure. This is clearly the reason for the low, fluctuating, and sometimes negative intraoral pressure values recorded during these fully voiced stops (in the case of this speaker's initial *lenis* stops, more than half the tokens were fully implosive). (Butcher 1992: 288, emphasis original)

Similarly, "many languages of South America have a full set of voiceless stops (say, /p t c k/) and a contrastively defective series of voiced stops which are often imploded, namely /b d/" (Kaufman 1968: 154, listing Cayapa, Colorado, Aguaruna, Cashinahua, and Huitoto as examples). Prenasalized and preglottalized variants of a voiced stop series are also reported in Oi (Mon-Khmer: Bahnaric; Sidwell 2003).

2.7 Conclusion

This chapter highlighted multiple roles of active vocal fold abduction in voiceless unaspirated stops, whisper (with laryngeal constriction), breathy voice, and release of glottal stops, as well as multiple articulatory strategies for sustaining voicing during stop closure. Some of the latter strategies are also found in slack stops that have entirely or mostly voiceless closures. Phonological implications of the many-to-many relationship between laryngeal gestures and cues are explored in the next chapter.

3 Laryngeal Phonology

3.1 Introduction

This chapter treats several topics in laryngeal phonology, drawing on notions of economy and enhancement to model a variety of cross-linguistic trends in the laryngeal structure of stop inventories without recourse to innate feature co-occurrence stipulations (§3.2). Arguments are marshaled for the emergence of features themselves, for a range of degrees of phonetic naturalness and cross-linguistic probability in features, and for a distinction between features with articulatorily and auditorily organized implementations. Several major proposals about particular laryngeal features are assessed, and sources of feature ambivalence are discussed along with implications for innate vs. emergent feature theories (§3.3). Feature Geometry is addressed similarly, with arguments for it emerging from phonetic sources in a cross-linguistically variable way; asymmetric interactions between the larynx and stricture receive special attention here (§3.4). The overall picture suggests, finally, that enhancement and positional partial neutralization differ from the default type of feature-correlate mapping primarily in the number of phonetic correlates involved (§3.5).

3.2 Economy and enhancement

3.2.1 Introduction

A notion of phonetic economy may explain why the stops in languages without laryngeally contrastive stop series are typically voiceless unaspirated or laryngeally unspecified (§3.2.2) and why positional neutralization of all surface stops or obstruents to voice is unattested (§3.2.3). Economy is violated by phonetically unmotivated complexity but not by phonetically motivated enhancements. Such enhancement occurs when a contrast is realized in some languages with a larger bundle of naturally related phonetic correlates than is found in the realization of a similar contrast in some other languages. The relations may be articulatory, aerodynamic, or acoustic. I present the results of a large typological survey showing that in dozens of languages, enhancements of voiced stop series involve gestures that aerodynamically facilitate voicing (§3.2.4).

Several of the same gestures are found realizing contrasts responsible for preponderantly voiced stop inventories (inventories where more than half the contrastive stop series are voiced). This type of inventory is interesting since voice is generally considered "marked" in stops (§2.3, 2.6); preponderantly voiced stop inventories have even been considered impossible, a claim that has impacted the discussion of how to reconstruct the stop system of Proto-Indo-European (see Stewart 1973: 141, 1993: 4). Also noteworthy is the lack of evidence for aspiration as a contrastive property responsible for preponderantly voiced stop inventories. The diachronic development of both contrastive and non-contrastive breathy offsets on voiced stops appears attested and phonetically explicable, but tends not to develop a clear aspiration-like quality (high airflow localized at the start of the vowel) without closure devoicing (§3.2.5).

This suggests an insight into a famous statement by Roman Jakobson about the restricted distribution of voiced aspirates. The fact that aspiration has no apparent phonetic basis as an enhancement on voiced stops and the fact that aspiration seems unattested as the factor responsible for preponderantly voiced stop inventories may share a common explanation in economy (§3.2.6). The same concept of economy in conjunction with the understanding of voice-supporting strategies in stops also plausibly explains the lack of evidence for diachronic voicing processes specifically targeting ejectives except as a result of oral air pressure decrease triggered at an intermediary preglottalized stage (§3.2.7).

3.2.2 Languages with a single stop series

Maddieson (1984: 27) observes that in all of the languages he surveyed with only a single phonological stop series, the series is voiceless – with a doubtful possible exception from Australia where the series was reported as voiced. Ladefoged and Maddieson (1996: 53) "suspect, however, that... in... most of the Australian languages, the [single series of] stops may be produced with no actual [glottal] opening required, with vibration ceasing due to lack of efforts to sustain it." In other words the stops retain more or less the same adducted-arytenoid position seen in neighboring vowels and in prephonation (§2.3.1), with closure voicing occurring passively during the early part of post-vocalic stops or throughout the stop if it is short enough, as might occur in postnasal position (§2.5.5.2.2). Alternatively, in inter-voiced position, such stops might involve moderate voice-sustaining strategies like cavity-resizing gestures (§2.6) as a way of simplifying the acoustic score by generalizing voice throughout the segment sequence rather than allowing it to fail partway through the stop and then resume again for the following sonorant.

These possibilities seem reflected in Clements' (2005b: 19-20) more detailed discussion of the matter. Noting four languages, "all spoken in Australia, in which *all* obstruents are classified as voiced" in the expanded UCLA Phonological Segment Inventory Database (UPSID), he found a different story upon closer examination of individual grammars:

> For example, in Mbabaram, according to a more recent description, "the allophony is as follows: (i) stops are normally voiceless in initial position, in final position, and in medial position after *y*; (ii) they are voiced after a nasal; (iii) they alternate between voiced and voiceless in medial position between vowels, or after l, r, or ɽ" (Dixon 1991: 355).

Similarly Clements found that in Dyirbal, voicing was more common between vowels, while voiced and voiceless stop allophones were free variants word-initially. In Yidiny, stops were mostly voiced but sometimes partly devoiced word-initially, which would be consistent with a higher incidence of pressure-reducing gestures. Clements continues:

> Generalizing over Australian languages, Yallop observes: "The plosives of aboriginal languages may be pronounced sometimes as voiced sounds (*b*, *d*, etc.) and sometimes as voiceless sounds (*p*, *t*, etc.) – but the voiced and voiceless counterparts are either freely interchangeable or in complementary distribution" (Yallop 1982, 56)...

The absence or rarity of languages where the stop inventory is limited to a single series systematically realized with voice throughout most or all of stop closure is paralleled by the absence or rarity of languages where the stop inventory is limited to a single series systematically realized with any laryngeal configuration other than unaspirated with fully or mostly voiceless closure. One possible explanation for this pattern is that other laryngeal configurations require more activity in terms of glottal widening, ejection, or voice-sustaining strategies. This perspective is reflected in the common phonological analysis of voiceless unaspirated stops as default or "unmarked" in various senses (§2.3.1; Haspelmath 2002, 2006, 2008a, Steriade 1995: 152-153 for critical reviews and discussions of the concept of markedness).

3.2.3 Neutralization

The previous section suggested that stops in inter-voiced position might be targeted by moderate voice-sustaining strategies such as cavity-resizing gestures as a way to simplify the acoustic score by generalizing throughout stop closure the voicing that would otherwise passively leak into only part of the closure. Intriguingly, languages that neutralize all stop series to full closure voicing in any position other than inter-voiced seem rare or non-existent. In each case that I have seen, neutralization does not affect all surface stops in the language; there are always at least some segments that surface as voiceless stops in the neutralization environment. Since this topic relates closely to some important recent debates, brief elaboration is in order.

Blevins (2006b) argues that in a number of languages, one or more series of obstruents voice in syllable- or word-final position. Kiparsky (2006) rejects all her examples. A review of the evidence suggests that some stop series may indeed voice in final position in some of the languages, though the details also seem open to alternative interpretations; either way, however, we still find contrastive voiceless stops occurring in syllable- and word-final positions.

Lezgian (Nakh-Dagestanian: Yu 2004) has an alternation between plain voiceless and voiced stops where the voiceless alternant occurs in onsets and the voiced one in codas at the end of a large set of monosyllabic stems (these codas are word-final unless followed by suffixes or by the second element of a compound). The alternating stops contrast with non-alternating voiced stops, voiceless aspirates, and ejectives, all of which are found in both onsets and codas including monosyllabic word-final position. The question is how to represent the alternating pair phonologically. If the onset alternant is taken as basic (as in Blevins 2006b: 150-152 and Yu 2004), then Lezgian has a pattern in which otherwise plain voiceless stops are voiced in codas.

Kiparsky (2006) instead takes the coda allophone as basic and underlyingly geminate, treating the alternation as a case of onset devoicing and degemination. Yet while the coda alternant does appear to be the historically more conservative one, it is not clear whether Lezgian learners would consider it either underlying or geminate. As seen in Yu (2004), its closure duration is about a quarter longer than the duration of its voiceless intervocalic onset alternant, about a third longer than onset non-alternating voiced stops, and about a fifth longer than coda non-alternating voiced stops. Would these length differences provide a sufficient basis for treating the coda alternant as geminate while treating all the other sounds just mentioned as singletons? Kiparsky notes that onset devoicing occurs in other languages but does not provide examples where voiced or any other kind of geminate stops surface only when not followed by a vowel. In fact, Yu's (2004) historical analysis is that the coda alternants were singletons and that they geminated in onsets (which for independent reasons were generally pretonic), subsequently devoicing and then degeminating in Lezgian.

The closure and voicing duration differences between alternating and non-alternating coda voiced stops – 25 and 34 ms average in the tokens measured – shows that they do not completely neutralize (Yu 2004: 81-83; see §3.5). If Lezgian does not involve categorical neutralization of alternating and non-alternating coda voiced stops, then it is not a counter-example to Kiparsky's claim that such neutralizations are non-existent. It would still involve final voicing of an underlyingly voiceless or laryngeally unspecified stop series if the onset alternants are taken as basic, but again it is unclear which alternant learners select as basic. Yu (2004: 76-78, 87-88) notes that Lezgian has additional lexically restricted alternations between prevocalic ejectives and word-final voiced stops or aspirates. In at least the former case, the prevocalic ejective alternant can be derived by assimilation with an underlying root-initial ejective, leaving the word-final voiced alternant as basic. The word-final voiced alternants of prevocalic ejectives are virtually identical in closure and voicing duration to those of prevocalic plain voiceless stops (the final alternants of the prevocalic ejectives average 7 ms longer in closure duration and 10 ms shorter in voicing duration than those of the plain voiceless stops in the tokens measured; Yu 2004: 81). At the same time, the restriction of both voicing alternations (with plain voiceless and ejective onsets) to particular sets of monosyllables within Yu's data could mean that neither alternation is synchronically productive; monosyllables with non-alternating voiced stop codas include both obvious loans and less easily explained forms, and Yu does not discuss other factors which might indicate which patterns are currently productive (see Yu 2004: 89-92). This seems to leave open the possibility that the putative phonological neutralization to voice in Lezgian codas is neither productive, nor a neutralization, nor a process with a voiced outcome.

In another controversial case, Somali (East Cushitic), we find two contrastive stop series, one aspirated and the other unaspirated. Unaspirated stops at the bilabial, coronal, and velar places of articulation are medially voiced between voiced segments; except for the lone (coronal) implosive, they are also spirantized between vowels unless the second vowel is a phonetic schwa offglide as described further below (Edmondson, Esling, and Harris 2004, cf. Gabbard 2010: 20-22). Word-initially, unaspirated stops other than the glottal and epiglottal-uvular are described by Edmondson, Esling, and Harris (2004) as partly voiced, with at least the bilabial being entirely voiceless in the speech of one informant. Gabbard (2010) shows 86-115 ms of voicing for the bilabial, coronal non-implosive, and velar unaspirated stops in apparently utterance-initial position (i.e. preceded by a flatline waveform), so perhaps the degree of word-initial voicing varies considerably by speaker.

Gabbard (2010: 7, 10) generalizes that non-uvular voiceless stops are aspirated, but without providing any evidence or argumentation for voice in coda stops. Edmondson, Esling, and Harris (2004: 2-5) go into more detail. At the end of a word (perhaps when not followed by a vowel-initial word, though this is not stated), unaspirated stops other than the glottal stop are followed by a schwa offglide "in careful, overly correct speech", with non-uvular ones being voiced. In the same environment in "conversational style", stops apart from the implosive are voiceless glottalized; the examples are all unaspirated, and it is stated that aspirated stops are not found in codas. Coda unaspirated stops as the first member of a word-medial geminate are also identified as voiceless glottalized. This last point disagrees with Gabbard (2010: 14, 28-29), who transcribes orthographic voiced geminates phonetically as voiced singleton stops, but he provides no experimental evidence on either closure duration or uniformity of closure voicing.

On the whole, regardless of how the laryngeal contrast in Somali stops is phonologically specified, it appears that only unaspirated stops occur in codas, that they are voiceless glottalized in ordinary speech, and that in especially careful speech, some underlyingly final stops are voiced with a schwa offglide. The fact that underlyingly final epiglottal-uvular stops are followed by this schwa without being voiced makes it harder to argue that the schwa is merely a result of sustaining underlying voice through stop release. Conceivably, the schwa is an artefact of stop release itself in careful speech, and the more anterior stops have become voiced before it as a result of being phonetically intervocalic and prone to greater degrees of voice leak from a preceding vowel (on the aerodynamic correlation of voice with anteriority see §2.6.1). This would entail that spirantization is more restricted than voicing since it would apply only between underlying vowels. We will not pursue the problem further here.

In addition to the descriptions of final voicing above, we also find reports in Howe (2000: 139) of stop voicing in various pre-voiced positions:

> [L]anguages in which obstruents are systematically voiced before tautosyllabic sonorants [include] Mohawk (Iroquoian), in which all and only prevocalic stops are voiced... (e.g. Halle and Clements 1983:59, 121-3). Other examples include Tsimshianic Nisga'a (Tarpent 1987) and Smałgyax (Dunn 1995). As Dunn (1995:I:5) describes: "The letters b, d, dz, g, and g generally occur between vowels and before vowels... The letters k, k, p, and t generally occur at the end of words and in clusters." Yet another example is Amele (spoken in Papua New Guinea) which Roberts (1987) describes as having only voiced stops prevocalically.

However, none of these cases of voicing seem to involve all surface stops that occur in the relevant pre-voiced environments in these languages. Mohawk has initial and medial pre-sonorant voiceless aspirate stops that are phonologically analyzed as clusters (see Beatty 1974: 16-18, Bonvillain 1978: 38, 1985, Dinneen 1990: 72-82, Hall 2010: 7, Hopkins 1987: 453; on the apparently universal lack of contrast between monosegmental voiceless aspirates /T^h/ and tautosyllabic underlying-cluster voiceless aspirates /Th/ see Kehrein 2002, Kehrein and Golston 2004). Among the Tsimshianic languages, Nisgha

(Nisga'a) maintains ejectives before vowels (Brown 2008: 5, 105, 175). Smalgyax also maintains ejectives before vowels, and its pre-vocalic voicing of non-ejective stops is defined as having exceptions, such as *kyooxk* 'grass', *puksk* 'to spit, spitoon', *taaɢan* 'planking for a boat', *taalsgmts'ooxs* 'stocking' (see Dunn 1995: 4). In the related Gitksan, a rule voicing stops before voiced segments is reported by Hoard (1978) according to Kirchner (1998: 184) and Rigsby and Ingram (1990), but the latter found from careful examination of their fieldwork audio recordings that the rule did not affect ejectives and that Gitksan also has intervocalic phonetic voiceless aspirates from underlying clusters. Brown (2008: 80, 109-114) confirms this impressionistically. Finally, while Roberts transcribes most Amele prevocalic stops as voiced, /t/ and /d/ are listed and exemplified as separate phonemes including between vowels (Roberts 1987, cf. 1991: 128, 144; 2001: 206). More precise phonetic data on some of these languages would be helpful.

If word-initial voicing and word-final voicing of all obstruents or stops in a language are non-existent or even just rare patterns, there would seem to be something disfavored about them. Some languages are reported with general neutralization of coda or word-final stops to other laryngeal configurations besides voiceless unaspirated, but in these cases the neutralization outcomes are still voiceless (aspirated or laryngeally constricted: Iverson and Salmons 2011, Vaux and Samuels 2005). The active laryngeal gestures involved in these outcomes could conceivably be devoicing strategies motivated either by regressive assimilation to the silent respiration following an utterance-final stop, in the case of neutralization to aspiration (see Iverson and Salmons 2011 §2.3), or as part of an anticipatory generalization throughout closure of the voicing failure which naturally occurs in final stops that are unexploded or otherwise long enough to achieve transglottal pressure equilibrium. (See Kingston et al. 2009: 6 on the possible use of coda stop glottalization to turn off voicing; cf. §2.3.3.1.) While such speculations may be permanently inconclusive, they identify plausible environmental triggers for these attested laryngeal neutralizations. Such triggers do not seem available to motivate full neutralization of all stops to voice in any position other than inter-voiced. Additionally, such triggers do not seem available to motivate the diachronic development of single-series stop systems predominantly realized with any laryngeal configuration other than voiceless unaspirated (§3.2.2). One conceivable exception to both these generalizations is acoustically motivated voice assimilation, where stops would neutralize to active closure voice in order to become acoustically more similar to adjacent passively voiced sonorants. If this development were phonetically natural, we would expect to see it relatively often producing word-initial or final neutralizations to voice in some languages and all-voiced stop systems in others. As reviewed above, though, those patterns seem very rare or non-existent.

These observations raise the possibility that the same factor opposes both the neutralization of all stops to voice outside of the inter-voiced environment and the development of single-series stop inventories predominantly realized with any laryngeal configuration other than voiceless unaspirated. One candidate for this factor is a principle of economy such as that formulated by Clements (2005b: 1, cf. 2009): languages avoid distinguishing segments with unmotivated accumulations of multiple features at the phonological level. Since we are not presently concerned with the division of labor between phonology and phonetics, we will provisionally extend this principle to the phonetic level. The concept of *unmotivated* combinations at the phonetic level naturally refers to combinations of gestures and cues which have no natural relationships in physics or physiology. The impact of such connections on the way phonological contrasts are realized is discussed in the next section under the aegis of another concept to which any successful definition of economy must be sensitive: enhancement. (For further investigation of how principles of economy may formally impact phonological representations see Weijer and Hinskens 2004.)

3.2.4 Enhancement

3.2.4.1 Voiceless aspiration

A contrast between generally voiceless aspirated and generally voiced stops, once thought non-existent, is in fact well-attested in Swedish and has been analyzed with the notions of enhancement and dispersion (Helgason and Ringen 2008: 624): that is, instead of differentiating the two series with a single feature such as voice or aspiration, such a system uses both strategies simultaneously. They enhance each other, making the two series perceptually more distinct or dispersed from one another (see Clements 2005b, 2009, Flemming 2003: 14-15, 2004, Keyser and Stevens 1994, Stevens and Keyser 1989, 2010, Vaux and Samuels 2005: 410-13, Weijer 2004. Blevins 2004: 10-11 discusses early dispersion proposals by Trubetzkoy and notes that the topic “can be viewed in either synchronic or diachronic terms”.)

Enhancement for perceptual dispersion is widely considered plausible but also clearly needs to be constrained. For example, dispersive enhancement on its own would be satisfied by inventories in which place and laryngeal features enhanced one another – such as a language where only labials were aspirated and only velars were prenasalized – but this would clash with the principle of economy introduced above, and in fact we do not find such inventories (see Clements 2009, Maddieson 1984, Mielke 2008a, Ruhlen 1975). Stevens and Keyser (2010) discuss cases of enhancement where the enhancing element increases a phonetic property which would already be present in the sound without the enhancement, but the examples are not much concerned with laryngeal distinctions in stops. Below, we will investigate to what degree a similar rationale succeeds in explaining attested laryngeal enhancements in stops.

Before we proceed with this task it is worth noting that perceptual clarity is not the only motive which has been suggested for enhancement. Another is variation in strictness of timing. Vaux and Samuels (2005) suggest on the basis of a wide variety of evidence that non-contrastively aspirated voiceless stops are articulatorily and perceptually easier to handle than unaspirated voiceless stops in at least one respect: they require less exact control over the relative timing of stop release and vocal fold adduction (or in Vaux and Samuels' terms, voice onset. Initiation of adduction reverses a previous abduction gesture and can determine VOT.) The idea is that salient aspiration is easily perceived anywhere after a few centiseconds of voice onset delay, so preventing this percept requires deliberately maintaining a VOT below that boundary. This resembles the idea of a phonetic anchor discussed by Midtlyng (2011): in languages with contrastive stop series characterized by high, minimal, and negative VOT, the middle of these three series may exhibit less VOT variation than the others and act as a sort of perceptual benchmark from which the other two series phonetically diverge.

However, Kong et al. (2011) argue that the minimal VOT of Korean fortis stops makes them auditorily simpler because they involve fewer cues (closure rather than closure plus aspiration), and that this is why most Korean children learn to produce the fortes earlier than the aspirates (with high VOT) and lenes (with medium VOT plus pitch depression; §2.5.5.3.1). Also, Löfqvist (1980: 487) reviews a study finding that while adult American English speakers had a larger VOT range for initial aspirated than unaspirated stops, two-year olds had the reverse, again suggesting that the wide range of VOT values available to voiceless aspirated stops is not necessarily auditorily helpful during acquisition even if it does imply an opportunity for less strict articulatory timing. Kingston et al. (2009: 34-38) provide further arguments that a voice contrast is not necessarily harder to aquire or maintain than an aspiration one. Possibly neither contrast is inherently more favored than the other; at any rate, they can certainly synergize, as in Swedish.

3.2.4.2 Laryngeal tension

Additional laryngeal enhancements include the variable use of vocal fold stiffening and/or laryngeal constriction in an unaspirated voiceless stop series contrasting with a series characterized by vocal fold slackening (§2.5.6). In these systems there is no voiceless unaspirated stop series that is consistently neither slack nor laryngeally constricted. Historically, such patterns could conceivably have developed from an earlier voiceless : voiced contrast via an intermediate stage where gestures regulating the aerodynamics of voice by manipulating laryngeal height and vocal fold tension (§2.6) with effects on pitch (§3.3.7.2) were reinforced by more substantial vocal fold tensing in the voiceless series and/or slackening in the voiced series. Tensing of the voiceless series was then open to reinforcement from additional laryngeal constriction mechanisms, which often synergize (§2.4), while the voiced series could have been further slackened by loss of medial compression which eventually resulted in devoicing in most positions (§2.5.5). Such natural phonetic development of pitch and voice quality distinctions with loss of closure voicing is reconstructed in some Mon-Khmer languages, where the first register has cues suggestive of creaky voice and/or the second register associates with slack voice (e.g. Brunelle 2005: 145-166, Wayland and Jongman 2003; further works on register cited in §2.5.4, 3.2.6.1). This suggests that the historical development of ejection in the non-slack unaspirated series in Xhosa (see Doke 1954, Hyman 2003) and Eastern Armenian (see Pisowicz 1976, Tragut 2009: 17-18) may not have been simply the addition of a random cue to the series to distinguish it from the slack stops, but in fact the gradual increase of phonetic elements already present.

3.2.4.3 Non-explosion and prenasalization

A range of enhancements is also reported with voiced stops, including non-explosion and prenasalization (Table 3.1). Notably, the gestures responsible for these non-contrastive properties also occur in smaller degrees in plain voiced stops as articulatory strategies for sustaining voicing (§2.6); thus again the enhancements do not seem to be random additional cues for perceptual dispersion, but involve strategies already natural to the maintenance of voicing. Further, the more pronounced velic lowering and cavity resizing responsible for audible prenasalization and implosion not only sustain voicing but tend to amplify it, arguably increasing its perceptual salience (Flemming 2004: 258-261).

Table 3.1. Stop inventories with enhanced voice series.

Type	Examples
/T ^{N}D/	San Colorado Mixtec (Flemming 2004: 259-260), Apinaye, Kewa, Luvale, Paez, Wantoat, Washkuk (Maddieson 1984), Lusi, Umbundu, Ura (Mielke 2007a) (total 10)
/T $D^{<}$/	Maasai, Nyangi (Maddieson 1984; differently on Maasai see Mielke 2007a); other unspecified Bantu languages and Chinese dialects (§2.6.2)
/T T^{h} ^{N}D/	Hakka, Nambakaengo (Maddieson 1984), Pileni (Mielke 2007a). Sedang (Maddieson 1984) adds a creaky-voiced stop series
/T T^{h} $D^{<}$/	Eastern Cham (Brunelle 2005: 55), Sgaw Karen, Swahili (Maddieson 1984; differently on Swahili see Mielke 2007a)

Here and in Table 3.2, the inventory types are defined using capital coronal symbols as cover symbols for all places of articulation. The cover symbol for voiced non-explosives $D^{<}$ includes stop series reported as implosive, preglottalized, and creaky, because these articulations do not appear to contrast in any language and the distinctions between them are subject to extreme under-documentation (§2.6.2). It should be assumed that the primary sources are impressionistic auditory fieldwork unless otherwise stated.

To sum up, we have seen several cases where enhancement can be plausibly explained as a perceptually motivated increase or facilitation of articulatory or aerodynamic properties already present in the stop, rather than merely increasing the perceptual difference between two categories of sounds by adding properties that are phonetically unrelated to the properties those sounds already have. This fits well within Stevens and Keyser's (1989, 2010) view of enhancement.

3.2.5 Preponderantly voiced stop inventories

Where a language has a greater number of contrastive stop series with closure voicing than without closure voicing, the contrasts among series with closure voicing often involve the same gestures that we have already seen used non-contrastively as voiced stop enhancements. Several dozen examples are listed in Table 3.2.

Table 3.2. Preponderantly voiced stop inventories.

Type	Examples
/T D $D^{<}$/	Angas, Dan, Doayo, Hamer, Ik, Kadugli, Katcha, Kpelle, Logbara, Margi, Mursi, Tama, Tarok (Maddieson 1984), Bari, Degema, Dhaasanac, Egene, Epie, Gwari, Lorma, Muktile, Mumuye, Mupun, Pero, Pulaar, So, Tirmaga, Zina Kotoko (Mielke 2007a), Mbatto (Stewart 1989, 1993) (total 29)
/T D ^{N}D/	Siriono (Maddieson 1984), Abun, Chomo, Chori, Dholuo, Gade, Kinyamwezi, Korowai, Kutep, Mende, Tiv, Yukuben (Mielke 2007a); also Acenhnese (cf. Durie 1994) except that the third series is treated as /N^{D}/ by Ladefoged and Maddieson (1994: 104-106, cf. Botma 2004: 204) (total 11 or 12)
/T ^{N}D $D^{<}$/	Fyem (Mielke 2007a), Lawa, Stieng (Huffman 1976: 579) (prenasalization occurs on only half the second series in Fyem and is optional in Stieng)
/T D ^{N}D $D^{<}$/	Gbeya, Ngizim, Sara, Yulu (Maddieson 1984), Bata, Fulfulde (a Mali dialect), Giziga, Hurza, Lele, Mada, Mofu, Moloko, Muyang, Noon, Rao, Sango, Tangale, Zulgo (Mielke 2007a) (total 18)
/T $T^{<}$ D ^{N}D $D^{<}$/	Ngiti (Mielke 2007a)
/T T’ D ^{N}D $D^{<}$/	Dahalo (Mielke 2007a)

3.2.6 Why voiced aspirates are different

3.2.6.1 General

While cavity resizing and velic lowering can sustain stop voicing, serve non-contrastively as enhancements, and serve contrastively to create preponderantly voiced stop inventories, I have not found aspiration in any of these functions. It is worth considering whether this could be explained by the principle of economy explored above: avoidance of the accumulation of phonetically unrelated material within a phonemic category.

The change of voiced non-explosive to voiced explosive stops and the development of breathy voice after voiced stops are both sound changes that have been reconstructed in a fair number of languages, so one might expect that the occurrence of both these changes could produce contrastively breathy voiced stops in a language without voiceless aspirates. But the rise of salient breathy voice after voiced stops is typically reported with concomitant closure devoicing, as in sundry Mon-Khmer languages (Brunelle 2005: 146-147, Diffloth 1982, Ferlus 1992, 1983, 1979, 1977, Gregerson 1976: 335, Headley 1998, Huffman 1976, Pinnow 1979: 123, Sidwell 2005: 197, 2006, Theraphan 1990, cf. Thurgood 2008: 20-21. Most of these sources rely on auditory impressions, but e.g. Brunelle, Gregerson, and Theraphan include acoustic data.) Gregerson (1976: 341-342) cautions that breathy voice as well as pitch and vowel quality differences often reconstructed as having developed in tandem with devoicing of original plain voiced stops may have been present in Proto-Mon-Khmer itself, which is conventionally reconstructed with the stop system */T D $D^{<}$/ (cf. Sidwell 2005: 197, 2006).

Only one language has come to my attention where contrastive breathy voice reportedly developed on stops without concomitant devoicing. Cao Bang (Tai; Pittayaporn 2007: 110-111) is thought to have undergone */b d ɓ ɗ/ > /b̤ d̤ b d/. In this case *Tr > T^h is also posited, however, changing the putative Proto-Tai stop system */T D $D^{<}$/ to /T T^h D D̤/ and suggesting (Weiss 2009) that the development of a contrastive voiceless aspirate series may have facilitated the development of the breathy voiced series contrasting with the plain voiced series (cf. Kiparsky 2005a on “priming” effects).

3.2.6.2 Jakobson’s universal and Proto-Indo-European

The limited distribution of voiced aspirates has sparked considerable interest for a long time, since the “standard” reconstruction of the longest and most extensively studied prehistoric language, Proto-Indo-European, posits a stop system /T D $D^{ɦ}$/ which has no attested parallels (ch. 6). This problem was famously highlighted by "[a]rguably the most influential voice in the history of phonological feature theory" (Morén 2007: 10), Roman Jakobson:

> To my knowledge, no language adds to the pair */t/* – */d/* a voiced aspirate */d^h/* without having its voiceless counterpart */t^h/*, while */t/*, */d/*, and */t^h/* frequently occur without the comparatively rare */d^h/*, and such a stratification is easily explainable (cf. Jakobson-Halle [1956: 43f.]); therefore theories operating with the three phonemes */t/* – */d/* – */d^h/* in Proto-Indo-European must reconsider the question of their phonemic essence. (Jakobson 1962[1958]: 528)

Jakobson's generalization about voiced aspirates has been called "Jakobson's universal" (Fallon 2002: 12-13) and has considerable support: clear examples of voiced aspirates – with consistent closure voicing and breathy aspiration involving substantially higher airflow than modal voice – do tend to come from stop systems containing at least four series of the form /T D T^h $D^{ɦ}$/. The majority of these hail from the Indian subcontinent, though a few other Asian and African examples are reported (Clements 2003: 209-211) including some Igbo dialects (Niger-Congo: Ladefoged and Maddieson 1996: 60, Maddieson 1984: 292). Similar also is /T D T^h $T^{ɦ}$/ ascribed to Ikalanga (Niger-Congo: Bantu; Mathangwane 1999) and the system reported in Cao Bang (§3.2.6.1).

Alleged counter-examples to Jakobson's universal include Madurese and Kelabit, two Austronesian languages reported with /T D D^h/ stop systems. Closer examination of the aspirates in these languages reveals quite different phonetic profiles from the Hindi-type voiced aspirates (cf. Stuart-Smith 2004: 18), though the phonological picture is more challenging as we will see shortly (§3.2.6.3f).

Limited as our typological knowledge is, numerous linguists have argued that there is still benefit in investigating possible theoretical principles which would motivate the absence of certain logically conceivable segment inventory types in the data we do have (see Croft 1993, Garrett 1991: 795-96, Kortlandt 1993, Matthews 1982). We will now consider two explanations that have been proposed for the apparent restricted distribution of Hindi-type voiced aspirates.

Jakobson and Halle's (1956: 43) explanation relies on two ideas: (1) in obstruents the primary sound source is oral, while voice is only a secondary sound source, therefore not "optimal", and (2) consonants and vowels are under a universal pressure toward acoustic dispersion: consonants are acoustically "primarily characterized by reduction of energy" in contrast to vowels, so voiced aspirates are not "optimal" since they have unnecessary acoustic energy. What it means to call voice a secondary sound source and how this status is meant to oppose the non-contrastive occurrence of voice in obstruents is not clear to me; neither is the basis for the acoustic-intensity dispersion claim. Various works have claimed that languages often do increase the perceptibility of some contrasts through dispersion of acoustic cues (§3.2.4), though the generality and force of such trends seem limited (Hale, Kissock, and Reiss 2006). Ladefoged (2006) and Kirchner (1998) are examples of works recognizing a role of articulatory effort reduction among (at least diachronic) influences on phonology. But the plausibility of such arguments depends heavily on the details of particular cases, and the wider scope of such ideas in shaping phonologies as a whole is still unclear. For example, Jun (2004) persuasively argues that the relative infrequency of heterorganic nasal-stop clusters relates to their being harder to perceive, not more complex to produce, and Henke et al. (in press) argue that Modern Greek favors fricative-stop realizations of obstruent clusters because these are easier to perceive, even though this does result in more complexity of manner of articulation than fricative-fricative or stop-stop clusters. Further examples are treated in ch. 4, along with the question of whether and in what sense sound changes can optimize phonologies.

Another explanation offered for the apparent restriction that Jakobson identified on voiced aspirates has to do with *economy*, as summarized by Salmons (1993: 12, cf. Barrack 2003a: 3-4):

> Martinet (1955:114-115, see now Martinet 1991 as well) makes a claim similar to Jakobson's somewhat earlier, namely that "a series of the type bh, dh, gh only appears to be attested in languages in which there also exist a series of voiceless aspirates, ph, th, kh." He finds this easily explicable in terms of economy. That is, a voiced aspirate series would be doubly marked – by voice and aspiration – within a three-series system.

Clements (2003: 309-311) also uses economy to explain his research finding voiced aspirates only in languages with both voiceless aspirates and voiced unaspirated stops. More general discussions adopting a favorable view of feature economy include Clements (2003, 2009), Ladefoged (1999: 587), and older works noted in Helgason and Ringen (2008: 624). In the previous sections we have seen evidence that economy is sensitive to enhancement, however, and the examples of enhancement that we reviewed involved the exploitation of phonetic material already present in the target sounds rather than the accumulation of phonetically unrelated properties. Defining feature economy as the avoidance of that type of accumulation apparently provides a more specific explanation for Jakobson's universal than acoustic dispersion, acoustic "optimality" of sound sources, or economy *tout court*. This explanation also covers more ground by simultaneously explaining the more general rarity or absence of aspiration functioning as an enhancement of voiced stops or as the crucial contrast responsible for preponderantly voiced stop inventories (§3.2.6.1).

Such typological generalizations need not be exceptionless to retain value within frameworks like Evolutionary Phonology (Blevins 2004) and Emergent Feature Theory (Mielke 2008a). Approaches of that sort tend to generate more detailed proposals about trends in language change and acquisition than about the set of possible languages. A basic insight is that inventories which sound changes are unlikely to produce should be rare, though they may occur (cf. Morén 2007: 21). The advantage of this perspective is that it seeks explanations for trends without insisting on unprovable all-or-nothing predictions about what is possible (which Maddieson 2007: 104 considers a permanently invalid exercise anyway). It is along such lines that Weiss (2009) examines the evolution of voiced aspirates, highlighting *inter alia* two Austronesian languages that have attracted attention as possible counter-examples to Jakobson's universal. These are considered next.

3.2.6.3 Madurese

The Madurese stop series transcribed as voiced aspirates *bh dh gh* etc. contrasts with voiceless unaspirated and voiced unaspirated stop series (Barrack 2003, Hock 1991: 625-26, Woodhouse 1995), but the limited experimental evidence available on this language only gives evidence for a voiceless realization of the aspirate series (Cohn and Lockwood 1994, Cohn and Ham 1998). Both the aspirates and the plain voiced stops lower F1 and F0 in a following vowel (Cohn and Lockwood 1994: 79, 86), traits normally associated with voiced obstruents (see Blust 2004: 133, Mielke 2008a: 94-95, Vaux 1998b). Cohn and Lockwood found F0 lower by an average of 60 Hz for the female speaker and 20 Hz for the male speaker at voice onset after aspirated than unaspirated voiceless stops. For comparison, in a male Hindi speaker (Kagaya and Hirose 1975: 37) and in female Taiwanese speakers (Lai et al. 2009), F0 respectively averaged 10 Hz and 3 Hz higher at voice onset after aspirated than unaspirated voiceless stops, while studies of Thai (Perkins 2011: 2, 22-23, cf. Downing and Gick 2001: 74) have found F0 higher after aspirated than unaspirated voiceless stops in some speakers, with the reverse in other speakers and no significant effect in still other speakers. While pitch lowering and tongue raising could reflect a voiced historical origin of the Madurese aspirates, their observed voiceless closure and the conflicting cross-linguistic results on the pitch perturbation effects of aspirated vs. unaspirated voiceless stops weigh against analyzing them as synchronically voiced. No particular confidence can be placed in the use of voiced symbols in the standard orthography or in an ambiguous phonetic description of the aspirates as "soft" in a grammar from over a century ago (Kiliaan 1911 in Barrack 2003). On the basis of the pitch effect, Trigo (1991: 129) alludes to the Madurese aspirates as similar to the Javanese slack-voiced stops, citing Kenneth Stevens, but the latter (p.c.) is decidedly agnostic on the laryngeal phonetics of the series.

On historical and comparative evidence, a voiced predecessor for the Madurese aspirate series is inferred by Stevens (1966), who considers the possibility that the Madurese aspirates and voiced stops split from a single parent voiced series with the conditioning environments being subsequently effaced by dialect admixture. There seem to be several typological parallels for the elements of this scenario. A complex array of historical factors has created a remarkably large number of doublets within Austronesian as a whole (Blust 2011). As for the diachronic addition of laryngeal contrasts to a stop inventory, Hajek (2010) finds aspiration developing by a combination of borrowing and lexically-diffusing innovations (often in initial voiceless stops with a liquid coming soon after) in several languages of the Malay peninsula that have had contact with Thai, which has phonemic aspirates. Hajek and Bowden (2002) describe how the Austronesian language Waimoa has developed contrastive voiceless aspirates, along with contrastive ejectives (currently known in only one other member of the family, Yapese). Other languages which appear to have enlarged their phoneme inventory by innovating most or all of their aspirated phonemes include Kusunda (Nepali isolate: Watters 2006) and Limbu (Sino-Tibetan: Mielke 2007a).

Alternatively, Nothofer (1975) derives the Madurese voiced stops from earlier glides and the aspirates from earlier voiced stops. Regardless of whether this or Blust's hypothesis is more accurate, positive evidence seems lacking for a stage at which the Madurese stop system possessed both a plain voiced series and a contrastive aspirate series with systematic voice during either closure or offset. By the time Madurese gained a contrast between aspirates and plain voiced stops, the aspirates may well have been completely voiceless. Arguments that voiceless stops which trigger pitch lowering on a following vowel are synchronically phonologically voiced in some abstract sense will be treated below (§3.3.7.2).

3.2.6.4 Kelabit and Lun Dayeh

In the Bario dialect of Kelabit and the closely related Long Semado dialect of Lun Dayeh, we find voiceless unaspirated stops and voiced unaspirated stops contrasting with "voiced aspirates" phonetically realized as [DT^h], where the aspiration is "apparently" weak or absent for "many" speakers at least in Bario (Blust 2006: 316, cf. 313). These sounds resemble clusters or geminates in their relatively long duration and in their restriction to intervocalic position in both dialects. Their partial devoicing and aspiration can be plausibly explained as having developed from oral air pressure buildup in earlier voiced geminates, a reconstruction strongly supported by comparative evidence (Blust 2006). Historically the aspirates derive from voiced geminates that developed in turn from earlier clusters in CVC reduplications and from single stops following initial stressed schwa. The "schwa is retained in most dialects of Lun Dayeh and Kelabit, but initial schwa from any source has been lost in other North Sarawak languages," where the reflexes of the voiced geminates thus occur both initially and medially and include voiced implosives, voiceless fricatives, and both voiced and voiceless stops (Blust 2010: 50). Exceptionally, Long Lellang Kelabit has aspirate reflexes of the geminates, optionally drops initial schwa before the aspirates (e.g. /(ə)bhar/ 'loincloth', /(ə)dhəh/ 'one'), and has lost earlier initial schwa everywhere else (Blust p.c.).

It is unclear whether the Kelabit aspirates should be treated as occupying one or two phonological timing slots. Blust (2006: 313-318) presents several arguments for a singleton analysis: (1) all other surface clusters result from schwa syncopation across a prefix-stem boundary, (2) phonetic aspiration does not otherwise occur in the language, nor does [ʃ], which often occurred in the release of the alveolar aspirate for some of his speakers, (3) high vowels lower before non-glottal codas but do not lower before aspirates, (4) the aspirates alternate under affixation with plain voiced stops, and (5) the cognates in various other Kelabit and Lun Dayeh dialects are single stops or fricatives.

Individually, these arguments seem inconclusive. The first two explain some phonotactic behaviors at the expense of others: why are the aspirates phonetically fairly long, why are they banned from initial position in most Kelabit and Lun Dayeh dialects, and why in Long Lellang Kelabit does initial schwa delete optionally before the aspirates when it has fully deleted before other consonants? Against the duration objection, Blust (2006: 317) suggests that voiced aspirates may tend to be relatively long anyway because of their articulatory complexity and sequential nature (mostly voiced closure followed by glottal widening timed to occur mostly after release). In fact various studies have found the closure of voiced aspirates shorter than that of other stop series (§2.5.3). On the other hand, singleton consonants can vary dramatically in length (§2.5.5.3.1, 4.4.2). Impressionistic estimates of phonetic length may not be a clear criterion for deciding how many timing slots the Kelabit aspirates occupy. The other, phonotactic factors just mentioned remain in conflict, some seeming to indicate one timing slot and others two.

Blust's third argument seems ambivalent: if glottal consonants are separate segments, why not the voiced components of the aspirates? Neither induce high vowel lowering. As for his fourth and fifth arguments, alternation predicts nothing about how many timing slots an alternant may fill, and different dialects/languages have different grammars. Blust integrates these last two arguments by asking why the synchronic Bario pattern has a voiced alternant of the aspirate while some of the cognates from other dialects are voiceless, but this question remains regardless of whether the aspirates are analyzed as singletons or not. Chance probably plays a major role in language evolution (e.g. McMahon 2000), but there is no reason to think that language learners are constrained or normally even able to consider linguistic prehistory or cross-dialect commonalities when inducing the grammar of a particular language.

Blust (2006: 327) observes that "the alternation of plain voiced stops and voiced aspirates in Kelabit appears under exactly the conditions that produce allophonic gemination in many other languages: if a preceding schwa is unstressed, the following consonant is not geminated, but if it is stressed, gemination of the following consonant is automatic (Blust 1995).” This process geminates consonants following stressed schwa (which survives medially) in Kelabit, with the notable exception of plain voiced stops, which instead turn to aspirates in dialects like Bario (Blust 2006: 316-317, 324). If the aspirates are phonologically geminates, then the exception is removed. This is certainly not decisive, of course.

In fact none of the considerations so far seem decisive either way. A network of historical changes has created a synchronic asymmetry in Kelabit which may admit no tidy analysis, as is true of various patterns in other languages (§3.3.1). Unless it can be shown that users of a language are innately hardwired to assign all sound sequences in the language unambiguously to a particular number of segment timing slots, it may be more plausible to describe the Kelabit aspirates as sounds having some properties of singletons and some properties of geminates. Alternatively, one may simply conclude that the aspirates are singletons; a number of other contour segment types (§3.3.6.3) are commonly treated as singletons in the absence of evidence to the contrary.

Elsewhere in Austronesian, the cognates of the Kelabit aspirates have the form /DT/ in Ida’an Begak (Blust 2010: 56-57, 99-101, Goudeswaard 2005: 4), where loss of initial schwa has even brought these sounds into initial position, along with true voiced geminates (Blust 2006: 318). Voiceless aspirates developed from geminates and certain clusters in Southern Subanen (Lobel and Hall 2010), and voiceless aspirates arose from /DT/ clusters in Maranao, where they trigger “tensing and raising” of following vowels as in Madurese (though unlike in Madurese, the contrastive voiced stops only optionally have this effect; Lobel 2010).

For earlier literature on the Kelabit aspirates see Blust (1969: 90, 1973, 2002), Hayward (1989: 46), and Stuart-Smith (2004: 18). Similar aspirates are described as word-initial clusters in Zhu|’hõasi (Khoisan) along with prevoiced ejectives (see

Ladefoged and Maddieson 1996: 63, 80, Henton, Ladefoged and Maddieson 1992: 87, and for some similar sounds in Zambian Tonga, Hayward and Lindsey 1988).

3.2.6.5 Conclusion

Jakobson's universal remains unrefuted insofar as it concerns Hindi-type voiced aspirates rather than aspirates that are systematically voiceless for all or part of their duration. A tendency for languages to avoid the accumulation of phonetically unrelated material within a phonemic category – i.e. a principle of economy sensitive to phonetic enhancement – seems to furnish plausible motive for Jakobson's universal, the lack of evidence that aspiration ever serves as the contrast responsible for preponderantly voiced stop inventories, and the lack of evidence for Hindi-type voiced aspirates occurring as an enhanced voice series (without contrastive unaspirated voiced stops).

The pitch-lowering effect of the Madurese voiceless aspirates and the phonetics and peculiar phonotactics of the Kelabit and Lun Dayeh half-voiced aspirates remove them from being counter-examples to any of these generalizations unless we formulate the generalizations in more abstract phonological terms (e.g. applying to [+spr, +voi] sounds) and argue convincingly that these Austronesian aspirate types belong in the same phonological category. I am unaware of arguments to that effect (see §3.3.6f).

Further support for motivating Jakobson's universal from the interaction of economy with enhancement comes from evidence that aspirates can be non-contrastively voiced at the same places of articulation which favor non-contrastive voicing in unaspirated stops. Didayi Gta (Austro-Asiatic: Munda; Pandey in press) reportedly has /b^{ɦ} ɖ^{ɦ}/ without */p^{h} ʈ^{h}/; filling out the unaspirated stop set /p b t d ʈ ɖ k g/, the only voiceless aspirates are marginally phonemic /t^{h} k^{h}/. The occurrence of /b^{ɦ} ɖ^{ɦ}/ without */p^{h} ʈ^{h}/ may be compared with the fact that a fair number of languages have /b/ without

/p/ (Maddieson 1984) and /ɖ/ without /ʈ/ (Tryon 1994). The pattern of /b/ without /p/ has been attributed to the larger oral cavity of bilabial stops facilitating voicing (see Maddieson 1984, Mołczanow 2007: 61-62, and §2.6.1). The pattern of /ɖ/ without /ʈ/ may be compared with reports that voiced coronal implosives, which are very often retroflex even if other coronals in a language are not (Greenberg 1970: 129), are also the most common selection other than /ɓ/ in inventories possessing only one non-explosive (Greenberg 1970: 126-128, cf. Maddieson 1984: 112; further on the example of Somali: Edmondson, Esling, and Harris 2004: 5). Similarly, in phoneme inventories with only one voiced stop (not described as any kind of non-explosive), the most commonly reported place of articulation is bilabial, followed by coronal (Maddieson 1984: 35). Aerodynamic arguments relating place of articulation with favorability to voicing in unaspirated stops seem applicable to the voiced aspirates of Didayi Gta as well, though analyses of highly gapped inventories are tentative since such inventories exhibit wide variation (cf. Salmons 1993: 68).

The next section explores the interaction of economy with enhancement in another area: the conditions under which ejectives undergo diachronic voicing.

3.2.7 Diachronic ejective voicing

Extensive diachronic connections and some synchronic variation have been reported between ejectives and voiced non-explosives (Bomhard 1981: 374-375, Carlson and Esling 2003: 188, Fallon 2002: 258-264, Schrock 2011: 20-21), but evidence for a direct, unconditional sound change from ejectives to voiced explosive stops is strikingly difficult to find. Miller (2007) surveys evidence on this question from a variety of sources, concluding that all the candidate instances are either unsuitably synchronically conditioned, reconstructed with non-explosive intermediaries, or (in a few cases) produced by historical sound changes where it is unclear whether non-explosive intermediaries were involved or not. For example, there has been widespread ejective voicing in the evolution of Chechen and Ingush (Northeast Caucasian) and there is widespread synchronic variation of ejectives with voiced stops in Slave (Athapaskan), but in both languages the voicing is limited to an environmentally conditioned process of lenition that embraces additional series. Fallon (2002: 275-77) also reports "quasi-voiced" ejectives or ejective-like sounds in Kabardian and Munda, but Kabardian involves explicit reports of larynx lowering and slight implosion, while Munda is explicitly neutral to both larynx height and voicing. Thus none of the data presents a clear case of a direct, unconditional sound change from ejectives to voiced explosives.

A possible explanation is that relaxation of laryngeal constriction throughout stop closure is normally insufficient by itself to induce voicing throughout closure, because that typically requires additional, active strategies (cf. §2.6). Notably, the other type of closed-glottis stop besides ejective – voiceless implosive – is repeatedly described as having glottal closure released shortly before the release of oral closure, with the intervening period voiced (see Demolin 1995, Demolin and Vuillermet 2006, McLaughlin 2005, Ladefoged and Maddieson 1996: 87-89). This would fit with the negative or at least very low oral pressure typical of non-explosives, which is naturally maintained during glottal closure if the larynx does not rise significantly as it does in many ejectives (Fallon 2002). The majority of preglottalized stops are also reported as voiced (e.g. Maddieson 1984), which is compatible with the role of glottal closure in staving off oral air pressure buildup as already suggested – not to mention the pervasive documentary ambiguity between preglottalized stops and non-explosives already (§2.6.2).

Thus if an ejective series does not involve larynx raising or undergoes a sound change removing larynx raising, and if the same series also undergoes a sound change that causes glottal closure to be released sooner, then voicing seems likely to result through the rest of oral closure – to the degree that the period of glottal closure staves off oral air pressure buildup. This is tantamount to saying that laryngeally constricted stops are prone to become voiced stops to the degree that they reduce oral air pressure buildup, which we have already seen proposed as the defining strategy of non-explosives. Put another way: when the period of glottal closure shortens or disappears in ejectives through sound change, the resulting sounds apparently do not develop voice as a phonetic enhancement unless this is economical – favored by aerodynamic conditions already present. (On articulatory mistiming as a source of sound change see Stuart-Smith 2004: 170; on vertical larynx movement variation observed in ejectives and resulting variation in pitch and phonation see Fallon 2002, Kingston 2005: 152.)

3.3 Features

3.3.1 Introduction

This section investigates the motives for phonetically natural and unnatural features (§3.3.2), the topic of how features and feature-correlate maps may be acquired (§3.3.3), and universal constraints on feature-correlate mapping (§3.3.4). Several major proposals about specific features are critiqued with a focus on the representation of aspiration (§3.3.6) and voice (§3.3.7). I conclude in favor of auditorily organized feature definitions for voice and aspiration, while noting that laryngeal correlates can also be organized in other ways which do not clearly align with either of these categories. Finally, I summarize evidence for several cases of feature ambivalence and their basis in phonetic singularities (§3.3.8, 3.3.9). The case for feature emergence develops and strengthens in each of these sections.

3.3.2 Phonetically natural and unnatural features

In a late and unfinished manuscript, Ladefoged (2006: 20-28) distinguishes two basic types of features, corresponding to two extremes in a continuum of possible phonological classes identified by Mielke (2008a). The first type of feature is phonetically natural, and may be most simply defined with either articulatory or auditory correlates depending on the case. Auditory correlates are particularly useful for sounds which can be produced in several different ways but which count as realizations of the same phoneme in a language, as for example English /r/ (Ladefoged 2006: 28), which has great articulatory variation among different speakers although it can be produced relatively consistently by individual speakers (see Mohanan et al. 2009: 6). The second basic type of feature is phonetically unnatural (Ladefoged 2006: 22):

> There are other examples of patterns arising from historical processes that were, when they occurred, due to articulatory or auditory aspects of the sounds in question, but which now cannot be explained in terms of how they are currently heard or produced. These patterns have to be described in terms of *ad hoc* features that have neither an auditory/acoustic nor a physiological basis. ... It should be noted that any non-physical arbitrary feature that simply groups segments as a result of diverse historical events in a particular language or group of languages is not part of a universal phonetic feature set.

Ladefoged (2006: 27) continues: “In considering phonological universals we can use only phonological features that reflect an articulatory or auditory property of some kind”. In other words, sound-system universals can involve features to the degree that the features are phonetically natural, but not all features are phonetically natural. In agreement with this insight, many other works (e.g. Albright and Hayes 2006: 14, Bach and Harms 1972, Blevins 2008, Buckley 2000, Hale 2007, Hale and Reiss 2000a, Hayes et al. 2008, Mielke 2008a, and Vaux 2008) document how historical extensions of phonological patterns beyond their original phonetic motivations create phonetically unnatural phonological classes. These works argue persuasively against indiscriminately incorporating phonetic factors directly into cognitive grammatical representations.

The existence of phonetically unnatural features makes it extremely probable that the grammars of individual languages differ in their feature inventories. This ties in closely to another topic that has long challenged feature-based cross-linguistic comparison, again summarized by Ladefoged (2006: 30-31):

> There are problems in the notion that each feature should be definable in terms of a specified property... Across languages there are often situations that are partially the same, and we would miss a significant generalization if we did not group them together. For example, there are similarities in the processes referred to as vowel harmony in African languages and register distinction in Mon Khmer languages... These distinctions often involve several articulatory parameters that are related to one another, such as tongue-root movements, tongue height variations, vertical larynx movements, and changes in laryngeal tension (and hence in phonation type). But these factors are not all describable in terms of a single feature. We undoubtedly need some way of expressing these similarities.

One solution is to view phonological features as language-specific regions in the inventory of possible gestures and cues. These regions would be defined by each learner during the process of grammar construction guided by learner analysis of ambient language data. Individual learners might induct slightly different mappings of features to phonetic correlates, causing systematic phonetic variation among speakers of the same language. We have already seen several examples of this (§2.5.5). Brunelle (2010: 20-21) considers what inter-speaker variation implies for the representation of the two contrastive stop series of Javanese in particular:

> [U]nless we rigidly adhere to universalist assumptions, there is no reason to believe that all learners develop an identical phonological representation for the register contrast. As long as all speakers 1) have cognitive categories that correspond to the high register (tense stops) and the low register (lax stops); and 2) acoustically produce the contrast in a way that is similar to the way that the rest of their speech

> community (or of one well-established dialectal or social subgroup) produces it, the way in which the contrast is represented in individual grammars and articulated by different speakers can vary widely. Therefore, instead of proposing that the Javanese stop contrast is captured by a single articulatory feature, it seems more economical to propose that speakers have a contrast between two relatively abstract categories... and that they learn the phonetic properties that are associated to them through exposure and through trial and error.

Other recent phonetic, phonological, and psycholinguistic research marshals additional support for this framework. These works include Mielke (2008a) on the emergence of features, Samuels (2009a) on the emergence of feature geometry, Menn (2010) and Sosa and Bybee (2009) on the potential for general powers of human observation, analysis, and memory to handle the acquisition of phonology, and Archangeli (2011) and Mohanan et al. (2009) on what phonological computation might look like without an innate universal battery of constraints. The trend of minimizing the amount of innate structure posited is not limited to phonology, but owes some of its impetus to Chomsky's similar minimalist exhortations framed primarily in the context of syntax over the last several years (Samuels 2009a: 1-3). These broader themes of grammar design are pursued further in ch. 5; here we will continue focusing on the implications of emergent theory for features in particular.

Innate feature theories, according to Mielke (2008a), posit a finite, universal, cognitively innate set of features linked to phonetic correlates; the learner uses these features to construct representations of phonological classes and rules/constraints. Innate hierarchical organization of features is a popular development of innate feature theory since Clements (1985) and aims to group features with mutually dependent behaviors under shared nodes. Of course, the richness of the innate phonological endowment increases further and astronomically with Optimality Theory (Prince and Smolensky 1993) discarding rules for a universal constraint set, if the set is understood to be innate and fully present in all languages. While Optimality Theory remains officially agnostic on this point, it is difficult to motivate a learned universal constraint set (§5.5, 5.7).

In contrast, Emergent Feature Theory proposes that as definers of segment classes and as objects manipulated by phonological processes, features are abstract in the sense that they are not *necessarily* closely related to phonetic content (Mielke 2008: 9, 98-99). This matches Ladefoged's (2006) argument that both phonetically natural and unnatural, language-specific features exist. Further, since learners in the emergent framework are under no pressure to specify phonologically active classes using features drawn from an innate universal set, they are also under no pressure to create complex feature specifications for classes by combining features; instead, they may just as well assign one feature to each class unless there is positive, language-specific phonological evidence to the contrary (Mielke 2008a: 99). A possible case of the latter sort has to do with the independence of voice and aspiration in some Indic languages (§3.3.4).

One noteworthy way that phonetically unnatural features may develop is through sound change by generalization. While some sound changes result from across-the-board phonetic processes, others involve shifts in the boundaries of already existing phonological classes based on speaker generalizations that evidently involved cognitive evaluation of similarities in the phonetic content of sounds (Blevins 2004: 32-34). Mielke (2008: 85-95) discusses several phonological patterns that seem to have developed in this way. In each case, it appears that a phonetically natural phonological rule became unnatural when one of the segment classes involved in the pattern was expanded to include new sounds that shared with the members of the original class some phonetic trait which was not crucial to the original rule. Further illustration appears in an ongoing New Zealand English vowel merger (Warren, Hay, and Thomas, forthcoming; Warren and Hay, forthcoming; Hay, Warren, and Drager 2006) where increasingly younger speakers clearly tend to merge more than older speakers but retain considerable ability to distinguish non-merged tokens. This merger too seems to have begun in a narrow, phonetically natural environment and then analogically spread to broader, phonetically less natural environments. The speaker generalizations that seem necessary for such sound changes to occur involve categorical judgments about the phonetic traits of sounds.

3.3.3 Feature acquisition

Hale, Kissock, and Reiss (2006) distinguish three strictly separate modules in the human faculty that makes use of linguistic sound systems: a phonological computer which manipulates features, a perceptual transducer which translates acoustic input into features for the computer, and an articulatory transducer which translates features from the computer into a gestural score for the production system. These modules are unable to see each other's activities, and the transducers have very restricted learning ability. Features and their mapping through the transducers to percepts and gestures are presumed to be innate because features, acoustic signals, and gestures are such different entities. Hale and Reiss (2000b: 9-11) point out the difference between mental 3D comprehension and 2D images on a piece of paper which do not even need fully connected lines, and similarly the difference between the potentially equivalent complexity in mental plans for pushing a feather and pushing a bar of gold, on one hand, and the disparate effort required in actually pushing the two objects, on the other. When cognitive representations, physical stimuli, and physical production are so different, how could categorical mappings between them ever be learned?

Decades of psycholinguistic debate show that this question is far from merely rhetorical, however (Menn 2010: 93):

> There has been intense controversy for many years between those who think that much knowledge of possible linguistic patterns is built into human minds genetically, so that what children need to do is figure out which of those patterns are used in the language around them, and those who think that what is built into our minds is not knowledge of language, but an extraordinary ability to respond to and extract the patterns that are present in the thousands of examples that we hear, examples of greetings and commands, questions and relative clauses, casual speech and prayers.

One of the strongest arguments for the existence of this generic learning ability is when the general structural character of a familiar type of knowledge that many scientists had argued must be innate is unexpectedly replicated in a new context and in a new body of knowledge. Sign languages have garnered increasing attention for this very reason. Sign languages develop as a solution to the needs of particular minority populations and communicative contexts, so it is less plausible to treat the features of sign languages as universally innate to humanity. It would also be much more costly to do so, because the feature inventories and feature geometries of sign languages tend to be considerably larger than those of spoken languages – and as with speech, the feature geometries of sign languages reveal asymmetries that match human anatomy, increasing the redundancy of stipulating the same patterns in the innate cognitive endowment (Mielke 2008a: 15-19, Morén 2007: 19, 41, Samuels in press). Far more probably, "whatever the mechanism is that allows humans to learn emergent sign language features and combinations should also be available for use in learning emergent spoken language features and combinations" (Morén 2007: 41).

Other activities besides speech exhibit the same traits: functionally driven patterns emerge as general cognitive powers of categorical perception are applied to new types of data and new relationships are identified between causes and effects. Illiterate and improvisatory musicians learn to recognize and play notes, intervals, melodies, chords, and progressions that vary significantly among cultures – presumably without innately mapped connections between the specific patterns involved in the auditory, cognitive, and motor domains. Video games are mastered through learning to map hand movements to intricate audiovisual stimuli in order to get particular results within a framework that is often radically removed from any real-world context; here too there is no reason to presume a detailed innate endowment of gaming knowledge. In all these activities, various conceivable combinations of stimuli or gestures are avoided for transparently functional reasons (some chords are impossible to play, some color combinations are hard to read on-screen, etc.).

The complexity of learning to identify segments, assign phonetic cues to them, and remember the various bundles in which these cues typically associate does not seem fundamentally different from the complexity of these other situations. Not surprisingly, humans and other creatures are born with highly sensitive powers of general acoustic categorical perception enabling them to differentiate and remember sounds that they have never made and may never be able to make; for instance, chinchillas and quail can distinguish laryngeal, place, and manner distinctions of human phonology which they will never be able to produce (Blevins 2004: 54-55, cf. Samuels in press). As in the other activities mentioned above, learning also has a filtering aspect: over time the practitioner develops expectations of what is significant and pays less attention to what is not (see Menn 2010: 91, 187-190, 350-51). The linguistic tuning of this general ability to ignore some perceived differences in favor of others occupies much of "early phonological learning" (Blevins 2004: 55). Mielke (2008a: 43-44) discusses experiments showing that many of the phonetic differences which people learn to tune out during speech processing can still be perceived by the same people when they are not in speech-processing mode.

The most parsimonious explanation for how people learn these different kinds of knowledge (speech, sign language, music...) and for the functionally motivated patterns in the structure of these bodies of knowledge seems to depend on the connection between practice and categorical perception (cf. Morén 2007: 57-61). People and animals have an extensive ability to discover correlations between different domains by repeatedly applying very general analytical powers to available inputs, including passively received stimuli and the stimuli of their own actions. All that categorical perception requires is enough range in the data for dissimilar tokens to be isolated and contrasted (see further Bybee 2010). In the case of linguistic sounds, acoustics and articulatory physiology furnish natural quantal boundaries (Stevens and Keyser 1989, 2010; see e.g. the discussion of palatals in §4.3.1.1).

A further problem with innate feature theories is that the bulk of the complexity which must be attributed to the phonetic transducers is not static but stochastic and highly variable (Pierrehumbert 2001: 143). Learned knowledge is naturally variable if it is learned under relevantly varying conditions, but capturing such variation with a hardwired knowledge apparatus requires additional stipulations which to my knowledge have not yet been clearly formulated even hypothetically.

One last argument against Hale, Kissock, and Reiss's (2006) transducer model comes from research on the capacity of auditory systems to extract spatial/gestural information from auditory or visual input. Iskarous (2010) discusses recent strides in this area particularly regarding extraction of articulatory area functions for vowels from the acoustic signal, and Vaux (2009: 77) synthesizes much previous research on Motor Theory – in general, in connection with language, and particularly regarding mirror neurons, "which are activated by both execution and observation of manual and oral actions of both first and third person agents". To sum up, several streams of recent research seem to support the claim that instead of approaching language acquisition with a highly detailed innate knowledge of phonology, learners instead rely on "an extraordinary ability to respond to and extract the patterns that are present in the thousands of examples" that they encounter (Menn 2010: 93).

3.3.4 Universal constraints on feature-correlate mapping

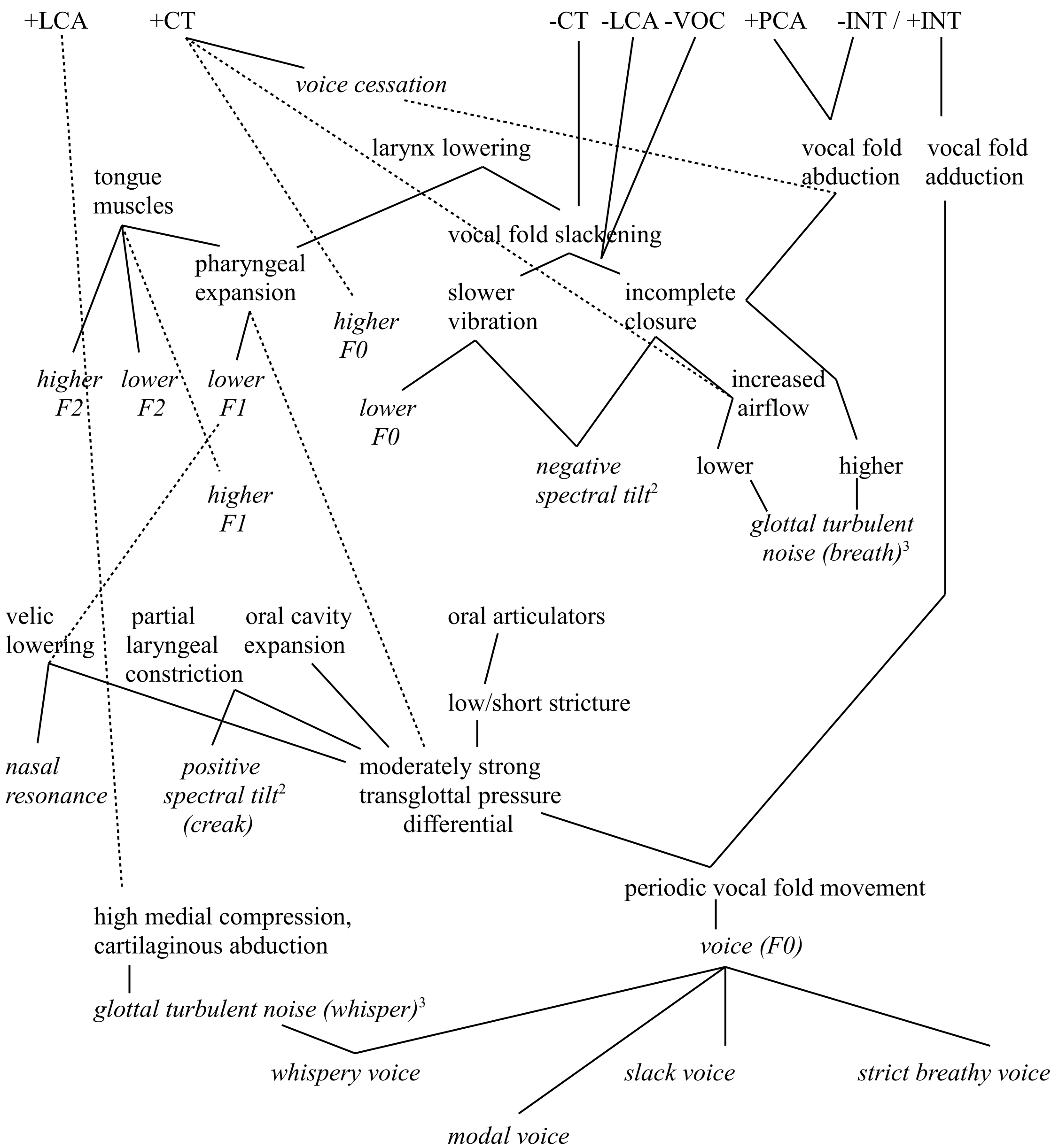
If phonological features are language-specific regions mapped by learners in the universal space of possible gestures and cues, then the study of phonetically natural features must investigate the way that the inherent structure of that landscape can influence the way learners subdivide it. For example, the release noise of an ejective and the formant structure of a low front vowel are acoustically and articulatorily dissimilar enough that they are unlikely to be identified with a common natural phonetic feature, but the gradient phonetic relationships between whispery, strict breathy, and slack voice do invite natural phonetic association. Such considerations form a basis for exploring *phonetic geometry*. To place this idea in context, let us first review the concept of Feature Geometry.

Feature Geometry (e.g. Clements 1985, Clements and Hume 1995, Halle 1995, Halle, Vaux, and Wolfe 2000) manages to capture some cross-linguistic patterns in the phonological behavior of features by positing a universal tree structure – so that place assimilation, for example, can be formulated with a Place node dominating place features instead of requiring a simple listing of place features. In this way Feature Geometry improves on a theory which offers no formal explanation as to why some groups of features occur more often in phonological patterns than others do, just as features themselves improve upon theories which offer no formal explanation as to why some groups of segments occur more often in phonological patterns than others do. Conventional models of Feature Geometry are not without their difficulties, though. The extent to which their structure mirrors the structure of the human vocal tract raises a serious duplication concern if Feature Geometry is innate (Samuels 2009a: 54-56). Yet if Feature Geometry is not innate, then it can only claim universality if we enrich its formal structure far beyond what conventional "tree" diagrams can capture (§3.4) and simultaneously acknowledge that the grammars of individual languages only make use of parts of this structure. In response to such concerns, an alternative approach allows features to be grouped into larger categories (equivalent to various nodes in Feature Geometry) during the learning process in a phonetically motivated but language-specific fashion (Blaho 2008, Reiss 2003).

The rest of this section explores the implications of this move by illustrating how the structure of the speech apparatus constrains the possible and likely groupings of gestures and cues and how these constraints in turn affect both the number of features which can be mapped into a given phonetic space and the relative positions within that space which those features may occupy.

Several phonetic correlates are shown with some of their natural physiological, aerodynamic, and acoustic relationships in figure 3.1. Cues are italicized while non-acoustic traits are not. Association lines (some of which are dashed to increase readability) connect phonetic elements in various relationships which either must or can occur, depending on the interaction of other associated factors. For example, the aerodynamic trait of a moderately strong transglottal pressure differential (sufficient for the voicing cue) is linked to several possible articulatory strategies, at least some of which must be present for the aerodynamic configuration to occur. When multiple factors must co-occur to entail a given effect, their association lines touch at that correlate; otherwise, converging association lines are generally separated by visible space, as is the case with the gestures associated to the transglottal pressure differential. It should be kept in mind that the dependents of vocal fold slackening (§2.5.5) have particularly complex relationships, so the associations shown in that area are especially incomplete. I have also omitted distinctions and relationships among the muscles that manipulate the tongue (see Baer, Alfonso, and Honda 1988, Honda 1996, 2008: 16, 20, Trigo 1991: 115) and the muscles responsible for pharyngeal and epilaryngeal contractions (§2.4). Certain other finer interactions among phonetic elements are also not identified in figure 3.1. Increased airflow and resultant glottal turbulent noise are differentiated into lower and higher degrees, but otherwise quantity distinctions are generally omitted.

Figure 3.1. Phonetic geometry (partial).

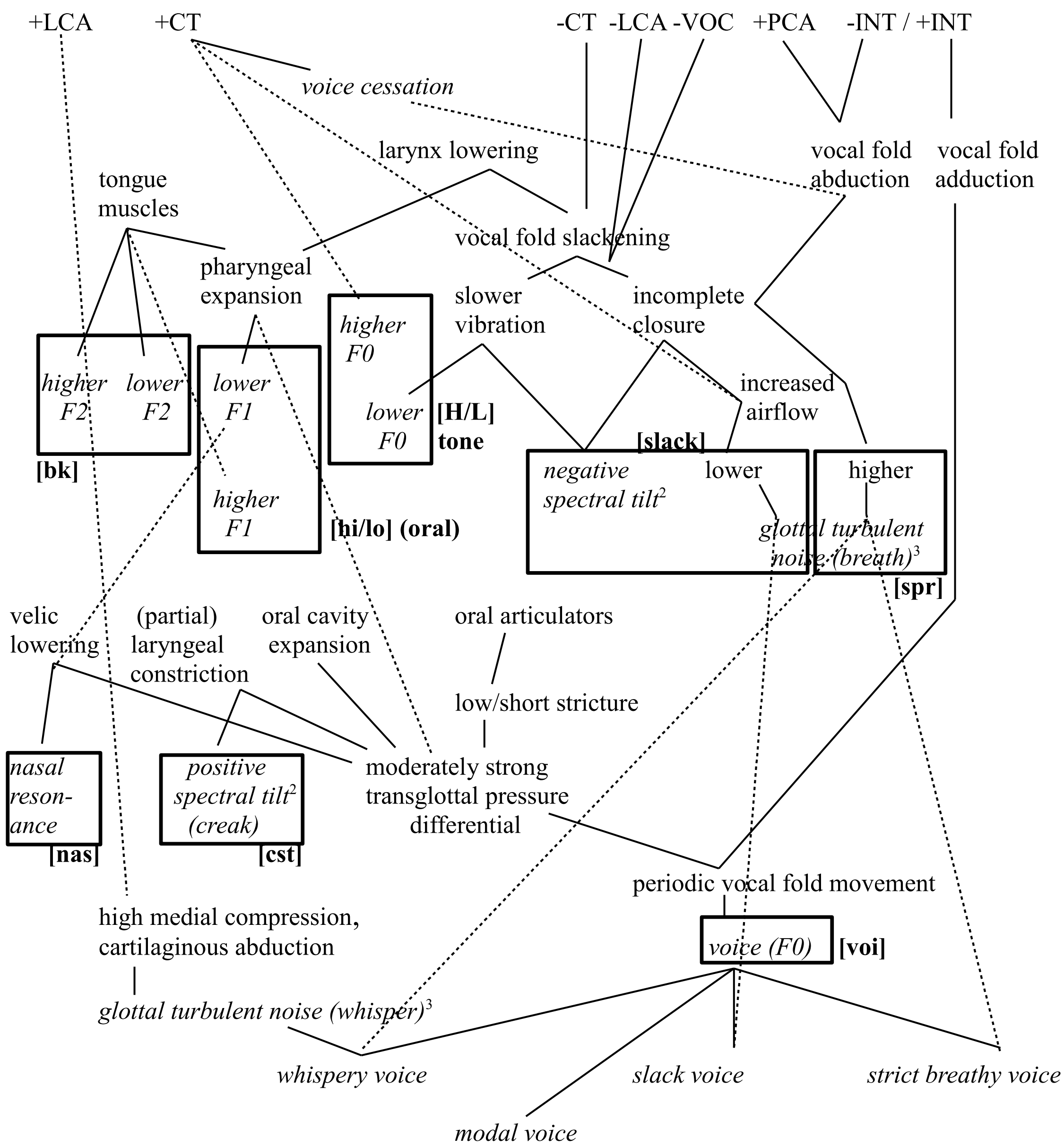


[2] Here, positive (negative) spectral tilt = higher (lower) ratio of upper to lower harmonics than that found in modal voice. Spectral tilt is generally only seen in voiced contexts.
[3] Not during stop closure.

The same phonetic information is reproduced in figure 3.2 and overlaid with an estimate of the maximum number of features among which these correlates could be distributed simultaneously. The estimate was made by first identifying the relatively auditorily distinct cues (excluding gradient differences such as between voiceless breath and hoarse whisper) and assigning them to feature categories as shown by the boxes. For convenience these categories are labeled with fairly conventional feature names (see e.g. Hall 2007, Halle, Vaux, and Wolfe 2000) except for [slack]. The choice not to represent slackening with the feature [voice] here is motivated by the following facts. Phonetically slack and voiced stops are systematically distinguished at the phonetic level in languages like Korean and Wu Chinese, and they are allophones assigned to different contrastive series in Qingtian Wu Chinese and Sivas Armenian (§2.5.5.4). Subsuming slack stops under a broad, low-frequency definition of voice also runs into additional problems (§3.3.7.2). Formally, the ideas of the feature category and the feature name [slack] have already been considered favorably by Chen and Downing (2011).

Second, it was observed that the non-modal types of voice at the bottom of the figure are phonologically composite and do not merit unique features in languages with phonological patterns that clearly differentiate voice from aspiration or glottal constriction. In Sanskrit, for example, the deaspiration but not devoicing of stops in reduplicants and word-finally suggests that voiceless and voiced aspirates are here losing a shared aspiration specification while remaining differentiated by voicing (see Janda and Joseph 1989: 248, Joseph and Janda 1988: 31). Supporting this, deaspirated voiced aspirates are indistinguishable from underlying unaspirated voiced stops (Selkirk 2004[1992]: 317). The related Indic language Marathi also has a word-final deaspiration process that targets both voiced and voiceless aspirates and produces stops that appear indistinguishable from other unaspirated voiced and voiceless stops (Selkirk 2004: 316, noting that the reports are impressionistic fieldwork). Such evidence matches the analysis

Figure 3.2. Suggested maximum number of features (bold) that can be simultaneously assigned in the phonetic space shown, with some exclusions at bottom (see discussion). Boxes show feature-cue assignment.



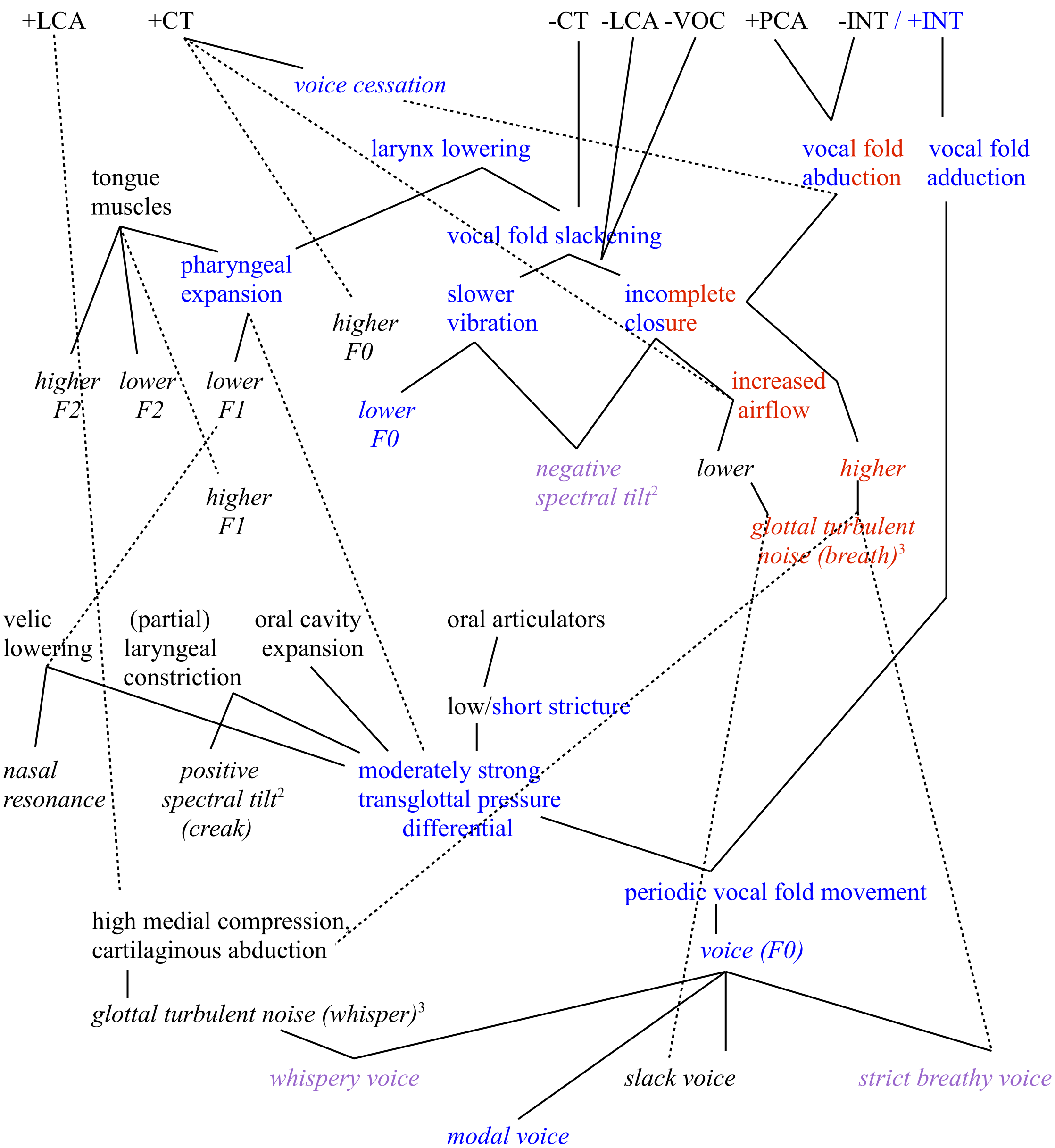
of various ancient Indian phonetic treatises, e.g. "*sōṣmōṣmaṇām ghōṣiṇām śvāsanādau*" '[the specification] of aspirates (*sōṣman*) and fricatives (*ūṣman*) that are distinctively voiced (*ghōṣin*) is breath (*śvāsa*) and voice (*nāda*)' (see Busetto 2003: 203, 213-214 citing *Ṛk-Prātiśākhya* 13.4-6).

In languages without such phonological evidence, the various non-modal types of voicing could in principle be specified by single features on a language-particular basis. It is moot to ask whether such features are phonetically more natural than composite feature specifications of non-modal phonations, though. That question boils down to whether the phonetic complexity of non-modal phonations should be treated as a natural unit or not, and there is no meaningful answer to the question without universal criteria. Therefore, in an emergent feature framework, there may be no clear basis for positing single phonetically natural features for the non-modal types of voicing. In an alternative framework with universal features, phonological evidence from languages like Sanskrit and Marathi might (if sufficiently widespread) support a universal composite representation of breathy voice. Such representations have been fairly popular in works focused on phonological features ([+spr] is combined with a specification for voice in Hall 2007, Halle and Stevens 2002[1971], Kehrein 2002, Kehrein and Golston 2004, and Vaux 1998a,b; Busetto 2003 discusses comparable analyses in the ancient Indian phonetics literature).

Since the cues in figure 3.2 (other than dependents of *voice*) are assigned to features, additional features cannot be simultaneously assigned to the non-acoustic phonetic correlates in the figure because such features would lack cues to make them recoverable in speech. Thus, in an emergent feature framework, the maximum number of phonetically natural features that can be simultaneously assigned to a set of correlates is limited by anatomy.

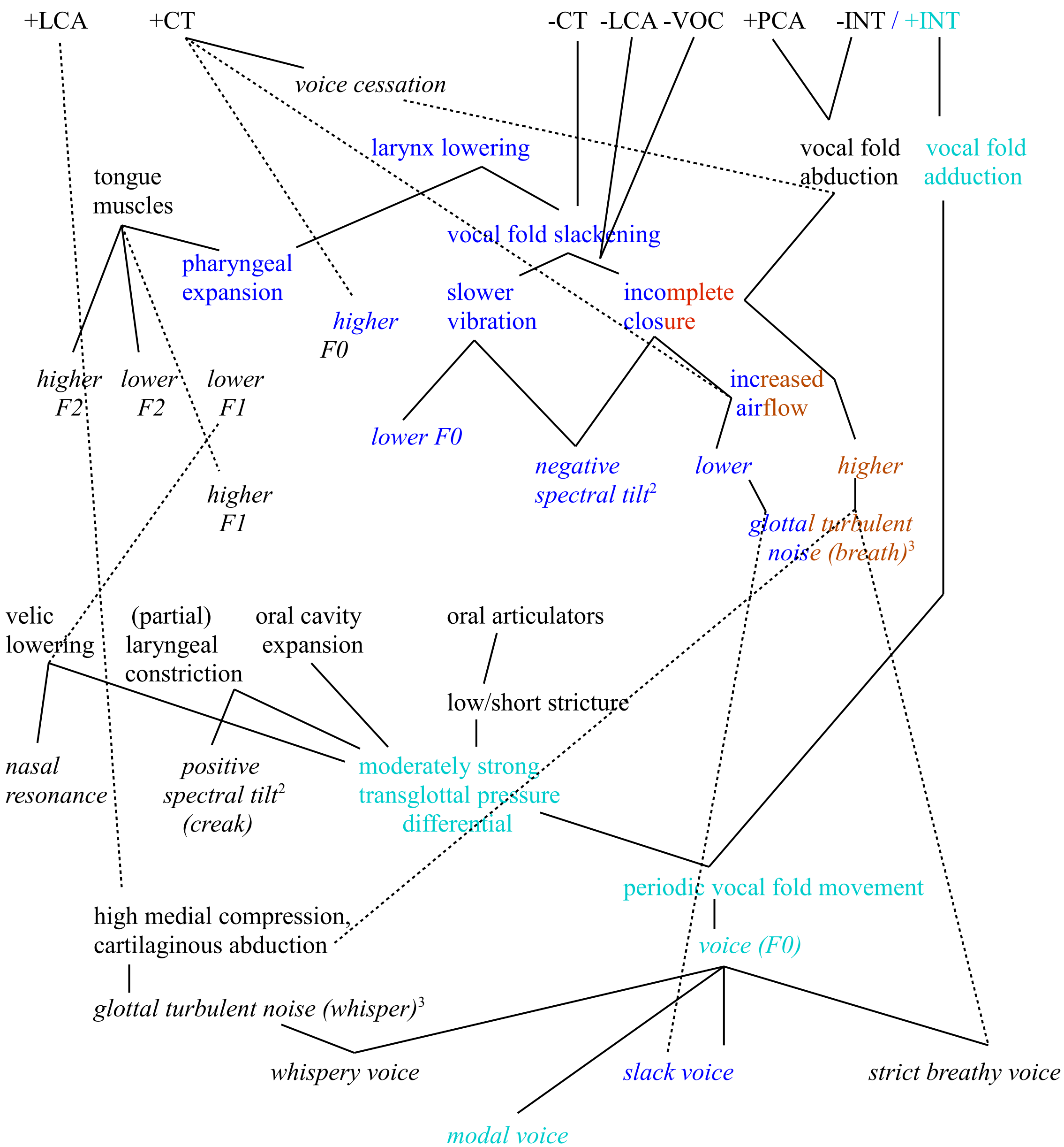
Figures 3.3 and 3.4 show possible assignments of some correlates to some features, coded by color. In figure 3.4 it should be noted that the correlation between

Figure 3.3. Association of some correlates to laryngeal features in Hindi stops.



Key: [±voi] blue, [+spr] red, [+voi, +spr] purple. Colors have not been exhaustively assigned; see discussion.

Figure 3.4. Example of phonetic correlate assignment to [slack], [spr], and [voi].



Key: [+spr] red, [+slack] dark blue, [+voi] light blue. Colors have not been exhaustively assigned; see discussion.

vocal fold slackening and low tone causes an overlap with tonology if a tonal system is present. Hence the restriction of slack stops to lower-toned syllables in some languages (Wu Chinese), though in others (Xhosa) slackening lowers both high and low tones below their normal range (§2.5.5). Two other comments on this figure are in order. First, slack voice is not highlighted as a correlate of [slack] here because slack voice might be better treated as an overlap of [slack] with phonetic voicing, at least in languages where slack stops are voiceless (on the question of voiced slack stops, see §3.3.7.2). Slack voice occurs automatically in vowels that follow voiceless slack stops because some distinctly [slack] cues are impossible during stops. This may be simply an acoustic fact that motivates particular gesture timings but does not itself have to be phonologically represented in temporal terms or with reference to [voice] (see further discussion of timing issues in §3.3.6.3). Second, slight amounts of glottal turbulent noise are associated with slack sounds in Korean, Wu Chinese, and for some speakers, Xhosa. A portion of the glottal noise correlate is colored dark blue in the figure to show this. This cue has been fiberoptically correlated with moderate PCA activity in Korean (§2.5.5.3.1).

Stops with substantial amounts of closure voicing occur alongside or even in contrast with slack stops in some languages (§2.5.5.4). In these situations, the voice correlate (colored light blue in fig. 3.4) can be implemented through various means except the combination and degree of larynx lowering and intrinsic laryngeal muscle suppression associated with the realization of [slack] in stops (dark blue, upper part of figure). The possible means include non-explosion (Xhosa) and ordinary modal voicing (Zulu, implying some combination of factors such as less larynx lowering and more medial compression than in the depressors) (§2.5.5.2).

3.3.5 Modeling phonetic variation

The requirement that features must be perceptible entails that the number of features which can co-exist in the phonetic space is considerably smaller than the number of phonetic correlates in the same space, as exemplified in figure 3.2. At the same time, there are different ways to subdivide a given range of correlates under a given number of features; for instance, a correlate bundle may be organized around particular cues or around an articulatory strategy that produces a wider range of cues in different contexts, respectively yielding an auditorily or articulatorily organized feature (§3.3.1). These considerations establish both restrictions and a range of possible variations in feature-correlate mapping which help fulfill Roman Jakobson's call for a limited "universal set of distinctive features tied to phonetics but flexible enough to allow for empirically demonstrated cross-linguistic variation" (Morén 2007: 10). In attaining this result we have not found it necessary to attribute detailed stipulations about features to the human cognitive endowment.

That fact in turn facilitates the explanation of sound changes in which particular cues are phonologically reanalyzed and assigned to different features (see Blevins 2004: 32-39). The challenge here for innate feature theory is that once the supposedly innate associations between features and their phonetic correlates can vary as required by the intermediate stages in these sound changes, there is no principled way to determine how much variation is allowed or why. If the potential variation range is gradient and not limited in a principled way by the innate feature machinery itself, then there is little meaning left in the notion of innate features and we are left locating the universal restrictions within phonetic geometry instead, as here.

A similar observation as this one about sound change can also be made about synchronic inter-speaker variation, of which we have already seen several examples. In an emergent framework, this variation is explained as a natural result of the same learning process that is responsible for the acquisition of features. Different learners achieve different results in their task of identifying and imitating the cue patterns of other speakers. The many-to-many relationship between gestures and cues opens up space for different learners to discover slightly different articulatory strategies for producing similar sounds, with some of these strategies further resulting in different acoustic side effects. In an innate-feature framework, however, inter-speaker phonetic variation occurs in spite of innate feature-correlate mappings and must be interpreted as evidence of what they do not cover. This means admitting that learners have considerable ability to analyze the acoustic signal and induce phonetic categories which show sometimes dramatic variations among speakers, but the ability to map these phonetic categories to phonological categories still supposedly requires an innate transducer. It is not clear how to justify that division of labor.

These considerations provide a coherent framework for evaluating several proposed definitions of the features responsible for two of the most important laryngeal distinctions – aspiration and voice – as well as related proposals about slack stops and larynx lowering.

3.3.6 Representing aspiration

3.3.6.1 [spread glottis]

The feature label [spread glottis] proposed by Halle and Stevens (1971) has been fairly popular in the phonological feature literature (e.g. Clements 1985, Clements and Hume 1995, Hall 2007, Halle 1995, Halle, Vaux, and Wolfe 2000, Iverson and Salmons 1995, 2011, Kenstowicz 1994, Vaux and Samuels 2005; Ridouane, Clements, and Khatiwada forthcoming, with further works listed p. 262). However, a simple articulatory correlation of the feature with glottal spreading has proven inadequate given the comparable degree and duration of vocal fold abduction found in voiceless unaspirated and voiced aspirated stops in Hindi (§2.3.2), the slight active abduction observed in the release of glottal stops (§2.4), and silent high abduction in geminates (Ridouane et al. forthcoming, cf. Ladefoged and Maddieson 1996: 70-72, Ridouane 2003). Abduction gestures may also span voiceless clusters in complex ways, creating atypical glottal width contours for some individual segments which nevertheless remain voiceless due to their intersegmental context (Ridouane 2008: 344, Yoshioka, Löfqvist, and Hirose 1979, 1980). This increases the appeal of non-articulatory explanations for vocal fold abduction patterns in stops.

3.3.6.2 [heightened subglottal pressure]

Opting for an aerodynamic focus, Chomsky and Halle (1968) claim that [heightened subglottal pressure] is a necessary condition for aspiration. This view gained little popularity (see Helgason and Ringen 2008: 608) and has since been rejected on phonetic grounds (Jessen 1998: 134-135, cf. Ladefoged 1967: 1-49, Ladefoged and Loeb 2009). One of the objections is that subglottal pressure (Ps) drops during stop aspiration and in intervocalic [ɦ] (Demolin 2007: 77-78, Ohala and Ohala 1972, cf. Ladefoged 1967: 43). More generally, pulmonic control of Ps does not appear sensitive to individual segments (Ohala 1990a: 42). Aerodynamic and acoustic experiments by Demolin (2007: 89) and Ohala (1990a) showed positively correlated Ps and intensity contours spanning multiple segments and even phrases (cf. Baer et al. 1976: 176). This is not surprising since acoustic intensity is a measure of loudness, which ranges widely across utterances depending on speaker judgments about ambient noise levels as well as emotion and focus (cf. Demolin 2007: 79). Loudness is also a common correlate of stress (Gordon and Applebaum 2010: 35), which has proven to be the environment where aspiration is strongest in some languages (Swedish: Jessen 2002: 175; American English: Hirose and Gay 1972: 147, Sawashima 1997: 71). However, stress associates with a subset of the syllables in a word, not (like aspiration) directly with segments. Ladefoged (1967) and Ladefoged and Loeb (2009) conclude from aerodynamic, acoustic, and EMG measurements that stress correlates positively with increased Ps caused by activity of respiratory muscles including the intercostals, but that segmental Ps variations are determined as a rule by glottal and supraglottal articulations rather than actively controlled by the respiratory muscles. Demolin (2007: 90) and Honda (2008: 9) arrived at the same general conclusion, notwithstanding some possible exceptions (Demolin 2007: 78, 89-90). On the evidence, heightened subglottal pressure is not a necessary or even a usual correlate of aspiration (Stuart-Smith 2005: 173-174).

3.3.6.3 VOT and timing in phonological representations

Chomsky and Halle (1968: 327) are themselves unenthusiastic about another approach to laryngeal features, one relying on VOT (Lisker and Abramson 1964, 1971, Kagaya and Hirose 1975: 43). Most phonologists have followed suit in the sense that phonological specifications of subsegmental timing information are generally avoided (see the string of works cited at the beginning of §3.3.6.1) with a few particular exceptions. We will touch on these before considering problems with VOT based representations of laryngeal distinctions.

Tonology is probably the clearest case where multiple, mutually incompatible features can associate with a single segment in a temporal sequence that needs to be phonologically specified. This is a consequence of a larger generalization: tonal specifications associate with segments in many-to-many fashion that can generate contour tones on single segments as well as level tones spanning multiple segments. Leben (2011) reviews how this fact motivated the development of autosegmental phonology, where properties not typically restricted to individual segments (and thus sometimes called "suprasegmental") were assigned their own representational tiers separate from the segment tier and capable of being associated with it in language-specific ways.

There has been major debate about whether affricates and prenasalized stops should be represented with conjunctions of both values of the features [cont] and [nas] and whether the values' temporal sequence needs to be included in the phonological representation (e.g. Clements and Hume 1995: 254-256). With affricates this seems largely not the case (Hall 2007: 331, Kehrein 2002) though there may be some exceptions (Rood 1975). The representation of prenasalized stops is less clear for other reasons (Beddor and Onsuwan 2003, Herbert 1986, cf. Bradshaw 1978, Cohn and Riehl n.d., Feinstein 1979, Hayward and Muljono 1991, Reid 2000).

In a much more unusual proposal, Steriade (1993, 1994) argued for phonological specification of laryngeal timing information in stops, based on gestural sequences in Huautla Mazatec that are far more complex than any we have considered so far in relation to the laryngeal distinctions in stops. Golston and Kehrein (1998) highlight concerns with her analysis, discuss Pike and Pike's (1947) original proposal that the sequences are multi-segmental, and suggest a simpler analysis in which some of the laryngeal distinctions are associated with nuclei rather than onsets (cf. Kehrein 2002: 128-130). Here it suffices to note that this particular debate has attracted attention precisely because it is unusual. In a sense it is an exception supporting the more general fact that the encoding of laryngeal timing information in contrastive phonological representations has not found widespread favor with phonologists.

VOT-based representations of laryngeal contrast raise several questions. Voiced aspirates, for instance, have modal voicing both during stop closure before the aspiration and in the vowel after it (Dixit 1979: 429-430, Stuart-Smith 2004: 163-164). In defending VOT-based models, Lisker and Abramson (1971: 142, cf. 1964: 418-419) simply note that voiced aspirates have non-modal phonation and that the phonological unity of their aspiration with that of voiceless aspirates is not self-evident. This view is also reflected in Ladefoged's feature proposals, which do not relate voiceless aspiration to voiced aspiration (see Ladefoged 1999; Schiefer 2004[1992]: 297 on Ladefoged 1971; Dixit 1979: 431 on Ladefoged 1973). However, phonological data does support the unity of both aspiration and voice in some Indic languages (§3.3.4).

VOT models of aspiration also have trouble with (post-)aspirated stops word-finally and preconsonantally (Bhatia 1974; further examples of word-final post-aspirated stops: Iverson and Salmons 2011, Vaux and Samuels 2005; aspirates before consonants including stops: Laver 1994: 239-240; both: Kehrein and Golston 2004: 335, 340, 348). Finally, Ridouane et al. (forthcoming 271-275) emphasize how timing-based definitions of aspiration cannot pin down a particular timing: vocal fold abduction overshooting release does not work in devoiced sonorants or fricatives, which in some languages pattern phonologically with aspirate stops (Vaux 1998a), nor in fricative-stop onset clusters, which can have a single abduction gesture whether the stop is aspirated or not. (For further discussion of "unwarranted phonologization of VOT" see Vaux and Samuels 2005: 406, also Halle 1973: 928, Löfqvist 1995: 105-106.)

Timing is still clearly important in the implementation of laryngeal distinctions; for instance, Kagaya and Hirose (1975: 43) emphasize that the glottal width difference in their voiceless unaspirated and voiced aspirated stops is one of timing rather than degree. Ridouane et al. (forthcoming 279) note that this creates a quandary for features defined primarily in terms of articulatory correlates, while an auditory definition of the feature responsible for aspiration easily motivates the necessary timing constraints without requiring temporal elements in phonological representations: "Timing relations follow from the requirement that the acoustic goal associated with the feature be manifested in the signal." The relevant cue will require a particular articulatory sequence in time, but those articulatory details are not necessary to the acoustic definition of the cue itself.

3.3.6.4 Auditory definitions: intensity, duration, and turbulent noise

Acoustic correlates are prioritized in the feature definitions of Jakobson, Fant, and Halle (1954: 11-13; cf. Jakobson and Halle 1956: 33-34). They identify aspiration as a phonetic correlate of their [tense] feature, which is not properly a laryngeal feature but rather correlates with duration and intensity and is measured over release noise in stops (pp. 36-39). Segmental intensity differences are notoriously variable and gradient (Parker 2002, 2008), and this use of [tense] is mainly rejected in later phonological feature literature (including the works cited at the start of §3.3.6.1). Jessen (1998: 254-268, 2001) argues for a revival of the feature. While acknowledging various serious representational issues that remain unresolved, such as the lack of a formal laryngeal category subsuming both aspiration and voice, he emphasizes the phonetic transparency of his proposal – which is in fact fairly abstract, taking some of the phonetic correlates of the abstract [voice] proposed by Kingston and Diehl (§3.3.7.2) and making them simultaneously dependent on [tense] too, as “substitute correlates” that may occur instead of the latter’s primary correlate of aspiration. Aspiration itself does not require articulatory tensing (cf. strict breathy voice: §2.5.3), nor are acoustic duration and intensity the only appealing bases for auditory definitions of the feature responsible for aspiration.

Both voiced and voiceless aspirates have glottal turbulent noise lasting from a stop edge into the adjacent vowel. Stuart-Smith (2004: 164-166) notes proposals by Davis (1994) and Dixit (1982, 1987) that aspiration should be defined in terms of this period of turbulent noise. Ridouane et al. (forthcoming 277) similarly identify “aspiration noise, i.e. aperiodic energy in the second and higher formants” as a necessary component of the definition of [+spread glottis]. The acoustic definition can be further refined; for instance, aspiration noise has high bandwidth or energy dispersal rather than concentrating amplitude at narrower frequencies as stridents do, and the extent to which it obscures vowel formants varies (see Harrington 2010a,b, Stevens 1998, 1999).

Since voiceless fricatives tend to have moderate to high vocal fold abduction, they tend to have glottal turbulent noise as well (see Jaiswal 2011: 4-5, Rice 1994: 134-135, Ridouane et al. forthcoming 5, Vaux 1998a, with further glottal width data in Saito 1992: 35, Sawashima 1997: 71). The same type of noise may also occur to some degree in voiced fricatives, but the turbulent noise of oral frication (Stevens 1998, 1999) makes detecting the presence of glottal noise difficult in fricatives generally (see Stuart-Smith 2004: 206, Vaux 1998a: 509). Phonological classes defined by aspiration but not including the class of voiceless fricatives would thus need to correlate explicitly with glottal turbulent noise *not* masked by another turbulent sound source. On the other hand, phonological classes including both voiceless fricatives and aspirated stops would be specified as [+spr] (or the equivalent), which in these cases would have to correlate with both turbulent noise and vocal fold abduction (cf. Ridouane et al. forthcoming) because the masking effect of oral frication on glottal turbulent noise in voiceless fricatives entails that there is no single acoustic noise pattern shared by voiceless (but not voiced) fricatives and prevocalic stop aspiration.

The existence in several languages of phonological classes including voiceless fricatives and aspirated stops has prompted the proposal that voiceless fricatives tend to receive the specification [+spr] at some level of grammar even in languages without clear phonological evidence for this (Clements 1985: 248, Jessen 1998: 186, 254, Rice 1988, 1994, Vaux 1998a, and others cited in Kingston et al. 2009: 32, Ridouane et al. forthcoming 263). The same idea has been extended to voiceless sonorants (Lombardi 1994: 151 in Clements 2003: 294, Vaux 1998a). In an emergent framework, though, phonological feature specifications have no reason to be induced in a given language without phonological evidence (Mielke 2008a: 99).

3.3.6.5 Broader issues

A final and fairly obvious fact to recognize in defining the phonetic correlates of the feature responsible for aspiration contrasts is the gradience of the correlates themselves. In Navajo, for instance, /k/ has a VOT of over 40 ms, /k^h/ over 150 ms; in Hindi, French, and Thai, by contrast, voiceless unaspirated stop VOT is around 20 ms or less (Ladefoged 2001: 127-131; for further cross-linguistic VOT comparisons see Lisker and Abramson 1964). If the feature responsible for aspiration contrasts is correlated with glottal turbulent noise, the correlation cannot be simply with presence vs. absence of this cue but rather with higher vs. lesser degrees. Degree here is measured relatively easily in terms of duration, though this does not exclude the possibility that listeners also attend to other cues like acoustic intensity. At least some studies have correlated greater peak glottal width with stops that are perceived as more strongly or heavily aspirated (Hong, Kim, and Niimi 2002, cf. Fischer-Jørgensen and Hirose 1974: 250); greater abduction entails higher transglottal airflow, which could in principle generate higher-intensity turbulent noise within a certain range of conditions. Vaux and Samuels (2005: 401) discuss research arguing that intensity of aspiration is perceptually even more important than duration for some speakers.

The concerns addressed in this section bear on broader questions about the relationship between articulatory and acoustic components in feature definitions. In a basic sense, all features have both articulatory and acoustic definitions because they must be both produced and heard (Ladefoged 2006: 22, Mohanan et al. 2009: 4, Robbins 1977: 60). Presumably most languages can be understood without the listener actually seeing the speaker's face and throat, and in this sense acoustic input is sufficient for the hearer (though users also learn to infer speech information from watching a speaker whether or not the speaker is audible, cf. Keating 2012, Scarborough et al. 2009). At the same time, since mature speakers have passed the babbling stage (§5.2.1), they normally do not need to *test* their productions on their own auditory systems through online repetition in ordinary speech. In this sense, articulatory input is commonly sufficient for mature production, though the speaker's production-perception feedback loop plays an important role in learning, in production monitoring (Wedel 2011, cf. Dorman, Freeman, and Borden 1976), and evidently in sound change as speaker expectations shift during adolescence and even adulthood (Kerswill 1996, Sankoff and Blondeau 2007). Thus, articulatory and acoustic information are not corequisites for feature recovery; articulatory information is generally sufficient for feature production, and acoustic information is generally sufficient for feature reception. Of course, having learned the equation for producing a set of cues, speakers may under-articulate orally, laryngeally, or pulmonically, which can lead to production tokens that are imperceptible. Oral under-articulation has been analyzed as a major source of lenition patterns (Kirchner 1998). One dramatic case that seems to involve pulmonic under-articulation happens with utterance-final vowels in Blackfoot (Algonquian) and Oneida (Iroquoian), which are normally acoustically imperceptible although still orally articulated (Gick et al. 2012).

Glottal turbulent noise presumably has acoustic qualities that tend to distinguish it from other kinds of aperiodic noise, so that listeners who have learned to produce it can also infer the involvement of the glottal sound source when they hear it. Consequently, the presence of that sound source and the presence of the acoustic cue are not necessarily corequisites for language users to identify the presence of the feature [+spread] (see Ridouane et al. forthcoming 261, 277-278). Instead, the question of whether the definition of this or any other feature is primarily articulatory or auditory depends on how the feature's correlates are organized. As Ladefoged (2006: 30) alludes, thanks to the "complex, many-to-many relationship" of gestures and cues, some features may marshal a range of articulations to generate more or less the same bundle of cues under different conditions, while other features may prioritize relatively simple gestural attributes that produce a wider range of acoustic effects under different conditions. The former sort of feature is clearly auditorily motivated, the latter articulatorily motivated. A third possibility is for some features to have simpler, more one-to-one mappings between gesture and cue bundles; in those cases it is moot to ask whether the feature is more articulatory or more auditory.

3.3.6.6 Conclusion

Our review of aspiration indicates that an auditory redefinition of the feature responsible for it has several advantages. The primary correlate which determines the organization of the other correlates that map to this feature appears to be glottal turbulent noise, though phonological classes including voiceless fricatives and aspirated stops but excluding voiced fricatives seem to rely on a more complex definition such as turbulent noise *and* vocal fold abduction, due to oral frication masking any acoustically distinct glottal turbulent noise pattern.

In languages where the definition of this feature is organized on a primarily auditory basis, the feature may need a new name. I leave this to future debate. For ease of reading here, I retain [spread], abbreviated as [spr] following Hall (2007).

3.3.7 Representing voice

3.3.7.1 Articulatory or acoustic [voice]

Chomsky and Halle (1968: 326-329) focus on the articulation of sounds commonly classified as voiced and identify this especially with two features: non-tensed supraglottal musculature and adducted vocal folds, the latter correlating with [+voice] while actual vocal fold vibration is treated as merely a consequence of the proper articulatory and aerodynamic conditions. However, subsequent work (Ladefoged and Maddieson 1996, Clements and Osu 2002) has identified a greater range of articulatory factors that combine in various ways to make voicing possible. The requirements differ depending on stricture (cf. §3.4).

Jakobson, Fant, and Halle (1954: 18, 26) and Ladefoged (1999: 611) emphasize the auditory correlates of [voice]. The primary cue of [voice] in this view is periodic fundamental frequency within the range perceived as pitch, manifested as the voicing bar at the bottom of spectrograms. The vocal folds are the only speech sound source which produce such a sound, since other periodic sound sources in the vocal tract oscillate at much lower frequencies (trilling: Stevens 1999, Shadle 2010). Ladefoged (1999: 611, 2006) concludes that the definition of [voice] is auditorily organized. In other words, audible periodic vocal fold movement is the correlate which motivates the various articulatory and aerodynamic correlates often associated with phonological [voice]; their normal function is to sustain audible voicing (§2.6).

Some of those correlates also naturally associate with other cues (cf. Clements and Hallé 2010: 4), such as audible duration differences in the ratio of consonant closure to a preceding vowel, which can compensate for loss of audible periodic vocal fold movement under special circumstances like whispered speech. (I appreciate Bert Vaux bringing this to my attention; see also the discussion of context-sensitive cue availability in §3.5.) It should be noted that if features emerge on a language-specific basis, then this auditorily organized view of [voice] would only be expected to hold for languages where the majority of sounds specified for that feature do involve audible periodic vocal fold movement which cannot be attributed merely to voicing leak from adjacent sonorants (cf. §2.5.5.2.3, 3.2.2). The organization of correlates expressing a laryngeal contrast in other languages may be quite different (§3.3.9).

3.3.7.2 Abstract low-frequency [voice]; slack and stiff stops

Another proposal, developed in Kingston and Diehl (1994, 1995), Jessen and Roux (2002), and Kingston et al. (2009) among others, defines [voice] as a relatively abstract feature associated with low frequency but not necessarily with closure voicing. The low-frequency cues include F0 lowering on the following vowel. Kingston et al.

(2009) claim that this relationship is actively controlled by speakers who deliberately co-vary different cues because they integrate perceptually. However, Hoole and Honda (2011) critique this claim in detail using EMG and other laboratory evidence. They conclude that the origin of consonant pitch-perturbation effects is indeed mechanical, though it can be actively enhanced in language communities that come to view the pattern as phonologically significant. If Hoole and Honda's account does more justice to laryngeal physiology than Kingston and Diehl's, this does not rule out perceptual integration of similar cues in an emergent-feature account, but in that framework there is no particular reason to call any abstract emergent feature [voice] rather than something else unless phonetic voicing happens to be a salient cue of the feature.

An advantage of not equating [voice] with low-frequency cues is that the phonetic and phonological behavior of slack stops and slack voice is different from voice per se: not only can slack stops have voiceless closure and not only can they apparently occur in unpredictable distribution relative to plain voiced stops (§2.5.5.4), but it appears that entities other than stops can be slack. There are sonorant depressors in the Nguni languages (Jessen and Roux 2002, Traill et al. 1987), nasal onsets trigger the same effects on following vowels as slack stops do in Korean (Kim and Duanmu 2004: 62), and syllables with some sonorant onsets or with no underlying onset consonant can contrastively bear the same cues as syllables with slack stop onsets in some dialects of Chinese (§2.5.5.3.2), prompting analyses that attribute the correlates of slackness to syllables or morphemes rather than to segments (see Chen 2008, Ga et al. 2011, Steed 2011). Notice that in these non-segmental Chinese analyses, slackness associates with only a subset of the tone inventory, but slackness still cannot be identified with a particular tone.

All of this suggests a phonetically natural feature defined by correlates similar to those found with various strategies for sustaining voice in obstruents, except that phonetic voicing itself is not consistently included and obstruence is not necessarily involved. While the goal of [voice] would be audible voicing, the goal of this distinct feature would be vocal fold slackening, typically with effects on both pitch and phonation (§2.5.5). One reasonable name for this sort of feature would be [slack], distinct from both [voice] and tone features. (Further problems with trying to conflate these three categories under the same feature representation scheme will be discussed shortly.)

Whether any segment can then be specified as both [+slack] and [+voice] depends on additional factors. In the case of slack sonorants, the answer depends on whether sonorant voicing is ever phonologically specified (cf. §3.3.7.4). In the case of stops, impressionistic descriptions in some languages of phonetically voiced stops consistently triggering audible breathiness and salient pitch lowering on the following vowel might conceivably be identified as cases of voiced slack stops (e.g. Brao: Mon-Khmer; Huffman 1976: 579), but this could be hard to motivate phonologically in the absence of contrast between voiced slack stops and voiced but not slack stops.

One kind of voiceless counterpart to slack stops typically raises pitch and increases spectral tilt, giving impressions of creaky or similar voice qualities; this stop type has been described contrasting with slack stops in Javanese and Korean, and conditioning a register that contrasts with a modally voiced register in Chanthaburi Khmer, among other languages (§2.5.4-2.5.6). One possible name for this sort of feature, again distinct from [voice] and tone features, would be [stiff]. The next section ends with a glance at [slack] and [stiff] as compared to two other proposed feature terms, [lowered larynx] and [raised larynx]. First, though, we will examine a model which puts the terms [stiff] and [slack] to a different, much broader use.

3.3.7.3 [stiff], [slack], and larynx height

In an earlier proposal about laryngeal features, Halle and Stevens (2002[1971]) *replaced* [±voice] with different combinations of [±stiff vocal folds] and [±slack vocal folds]. This move quickly sparked empirical objections (see Keating 1988: 17-22) and never gained much popularity (Kenstowicz 1994: 39), but it has still played an important role in several works on laryngeal features (e.g. Ahn and Iverson 2003, Avery and Idsardi 2001, Iverson and Ahn 2007, Iverson and Salmons 2003a,b, Vaux 1998a,b).

In this model, the stop types /T T' T^h/ are [+stiff], which correlates with CT and to some extent thyroarytenoid (TA) activity (Halle and Stevens 2002: 46). However, we have seen that CT activity does not correlate with voiceless stop articulations in some Hindi, Japanese, and American English speakers (§2.3.3), and a study of Korean found CT activity roughly comparable in all three stop series including the slack (lenis) stops (§2.5.5.3.1). Hirose and Gay (1972: 162) concluded that "there is no EMG evidence, in the form of increased CT, VOC or LCA activity, to support the concept of [+stiff] vocal cords" as being a consistent component "for the production of voiceless obstruents" in the languages they reviewed (Hombert et al. 1973: 43 note further studies to the same effect). In addition to positing these apparently inaccurate phonetic details, Halle and Stevens' model also ignores the role of vocal fold spreading in voiceless unaspirated stops (Keating 1988: 18-19).

Similarly, though the model assigns [+slack] to voiced stops (Halle and Stevens 2002: 51, Halle 2009: 71-72), we have seen that contrastive slack stops are typically voiceless in the environments where they can be phonetically distinguished from voiced stops (§2.5.5.1). The model represents Korean voiceless lenis stops as [+spread, -stiff, -slack] (Halle and Stevens 2002: 51), but the phonetic evidence indicates that they are better classified as slack stops; however, [-spread, -stiff, +slack] is already Halle and Stevens' representation of ordinary voiced stops, and [+spread, -stiff, +slack] is their representation of Hindi-type voiced aspirates. The Korean lenes thus pose a problem for the model's claim to provide distinct and phonetically accurate representations for all three types of sounds. On top of these issues, Kingston has observed (Vaux, p.c.) that replacing [+voice] with other features as in the Halle-Stevens model formally ignores the purpose of articulatory strategies that facilitate voice in obstruents.

Even the model's aptitude for representing the consonant-tone interactions that inspired it is questionable. Not only voiced but also phonetically voiceless consonants function as tone depressors in some Bantu languages and Wu Chinese dialects (Jessen and Roux 2002, Schachter 1976; Chen and Downing 2011). The pitch lowering is dramatic in Zulu and interacts with tonology in Wu, while phonetic stop voicing in both languages does not have these effects. Voiceless aspirates also lower the pitch of following vowels in Madurese (§3.2.6.3). These effects cannot be represented as spreading [+slack] from the consonant to the vowel unless modally voiced obstruent stops, voiceless slack stops, and Madurese voiceless aspirates are all [+slack] and not [+stiff], but the feature [+spread] is incapable of distinguishing all these sounds from one another and from the Hindi-type voiced aspirates. Another, more general problem is that Halle and Stevens' model predicts similar pitch effects of consonants on both preceding and following vowels, in spite of a striking lack of evidence in the case of preceding vowels (Hombert et al. 1972: 42, Ohala 1973: 7).

Besides these phonetic challenges, the model faces multiple phonological ones. It represents both phonation and tone with the same features, but these parameters are fairly independent in some languages (DiCanio 2008: 177, Keating 1988: 21, Yip 2002: 57-59). While some tone-phonation combinations seem auditorily more difficult to distinguish than others, a number of languages resolve this problem by lengthening non-modally phonated vowels (Blankenship 2002, Gordon 1998) or by realizing contrastive tone and contrastive non-modal phonation on different portions of a vowel (Silverman 1997: 236). It is unclear how the full range of phonation-tone combinations would be represented in the Halle-Stevens model. The model also handles no more than three level tones, though systems with four or five are attested (DiCanio 2008: 177, Fromkin 1972: 51, Yip 2002: 57-59), and it treats mid tone as formally unmarked, though mid tone has a more restricted distribution than low tone in some languages (Fromkin 1972: 56-50). The representation of voicelessness and high tone with [+stiff] and of voice and low tone with [+slack] also makes it impossible to describe intervocalic consonant voicing as a simple assimilatory phenomenon while adjacent vowel tones vary; vowel devoicing between voiceless unaspirated consonants cannot be represented as assimilatory either (Fromkin 1972: 51).

Finally, ejectives and voiceless implosives lack distinct representations in the Halle-Stevens model, unlike a number of other stop types not known to contrast in any language. After reviewing Ladefoged's (1973) criticisms of this inconsistency, Iverson (1983: 333) suggests a "strictly non-contrastive vertical laryngeal movement feature" which could be applied to this problem. The feature [lowered larynx] ([LL]) has also been posited as a non-contrastive specification of Madurese voiced and aspirated stops (Cohn 1993a, Trigo 1991) and as a specification differentiating first and second register stops in Eastern Cham (Brunelle 2005: 248). Larynx lowering can create cues distinct from vocal fold slackening in the case of true implosives, where sufficiently rapid and substantial larynx lowering can generate a distinctive crescendo during closure as well as an audibly ingressive release (§2.5.5.2.3, 2.6.2); in such cases, [LL] seems a phonetically reasonable way to distinguish voiceless implosives from voiceless ejectives. As an articulatory feature, [LL] also seems a plausible way of associating several of the cues of larynx lowering which co-occur in a number of register languages, as proposed by Brunelle (2005: 211-212, 236; §2.5.4), though some of these cues also result from tongue-root advancement (see Lindau 1979, and Tiede 1993 using MRI data). Other problems noted above with the Halle-Stevens model remain, however.

To conclude our discussion of Halle and Stevens (2002), while they may be right that voiceless and voiced stops tend to condition higher and lower pitch respectively on following vowels for mechanical reasons (Hoole and Honda 2011, cf. Halle 2009: 72), incorporating this fact into phonological specification by representing binary voice and pitch distinctions with the same pair of features creates a number of phonetic and phonological difficulties. An auditory feature [voice] is transparently phonetically motivated and does not face these problems, and in an emergent framework, it naturally correlates with various articulatory strategies that help sustain voicing, among their other effects (fig. 3.1). However, the [LL] feature to which Iverson (1983) alludes may be preferable over [voice] for expressing some register distinctions. In this role, [LL] might also be descriptively more accurate than [slack] in languages where the lower register has pitch or vowel quality cues but does not associate with slack (weakly breathy) voice quality (on this variable see Svantesson and House 2006, Wayland and Jongman 2003). Comparing the appropriateness of [LL] and [slack] for representing the lower register, and similarly of [raised larynx] ([RL]; Trigo 1991, cf. Moisik and Esling 2011, Moisik, Czaykowska-Higgins, and Esling 2011) and [stiff] for representing the higher register, requires a more complete phonetic and phonological picture than space has allowed us to develop here.

3.3.7.4 Split treatments: Sonorant/Laryngeal Voice and underspecification

Another important proposal about laryngeal features handles reported cases of voiced obstruents patterning with sonorants by replacing [voice] with two Feature Geometry nodes: Laryngeal Voice (LV), found only in obstruents, and Sonorant Voice (SV), found in all sonorants and itself replacing the feature [son] (Rice 1993, 2005, Rice and Avery 1991). Besides questions about how this model handles voiceless sonorants and lateral obstruents (Yip 2011), there are more general concerns that we will consider here.

The Sonorant Voice model has two major effects. First, it enables phonological classes containing sonorants and voiced phonetic obstruents to be defined as SV by stipulating that the voiced obstruents are phonologically sonorant, or in the new terminology, SV, even though they surface as obstruents. Second, in languages where the voice of sonorants is phonologically active, the relevant rules are supposed to be formulated with SV, which is present in all sonorants by definition. At the same time, in languages where the voice of sonorants is not phonologically active while the voice of obstruents is, the relevant rules are formulated with LV instead.

The first achievement appears unnecessary. It seems needless to replace [son] with SV and then use SV to capture classes including sonorants and voiced obstruents, because these classes can be captured simply with [+voi], while classes containing only voiced obstruents can be distinguished as [+voi, -son]. The second major provision of the SV proposal, a simple representational distinction between cases where phonologically active voice involves the voice of sonorants and cases where it does not, offers a solution to a problem which is arguably better solved in a different way. We will review the original problem, then compare solutions.

In a combination of autosegmental tiers with underspecification (see Goldsmith and Noske 2005: 9-10, Steriade 1995: 465-466), the spread of voice from one obstruent to another had been modeled as an operation extending the association of [+voi] from one [-son] segment to the next. When the process operated across intervening sonorants without affecting or being affected by them, the question was how to capture the fact that their voice values were invisible or “transparent” to the process. Given the fact that sonorants are predictably voiced in many languages and that lexicons are more efficiently modeled if predictable information is omitted in them and filled in later by the grammar, it seemed a simple step to delay filling in sonorant voice until after obstruent voice assimilation, thus explaining why sonorant voice was invisible to such assimilation. In addition, if [-voi] was underspecified in voiceless obstruents on the grounds that it too is predictable given the [+voi] specification of voiced obstruents, then assimilation of voiceless to voiced obstruents would be a feature-filling operation as well. This approach ran into complications, however, in languages where sonorant voicing is phonologically active under conditions sensitive to lexical information, as in heteromorphemic postnasal stop voicing in Puyo-Pongo Quechua (Botma 2011 §2.2, Rice 1993) and in Japanese, where postnasal stop voicing in Yamato-stratum words feeds Rendaku, an obstruent voice dissimilation process in morphosyntactically conditioned types of compounds (Rice 2005). Such lexical and morphosyntactic information was supposed to have been lost by the level of grammar at which predictable features would be filled in, for a variety of reasons that collectively played a major role in the paradigm of Lexical Phonology which was highly influential at the time (see Goldsmith and Noske 2006: 7-9, Kaisse and McMahon 2011).

Each of the key components of this approach to modeling phonologically inactive sonorant voice has subsequently been called into question. The psycholinguistic appropriateness of modeling segmental phonology with autosegmental tiers is debatable (Ussishkin 2011), and the properties of the relationship between autosegmentalism and underspecification theories remain unclear (Goldsmith and Noske 2006: 13). Steriade (1995) raised challenging questions about using underspecification to model transparency with tiers, and eventually the idea that predictable features are inactive (and hence underspecifiable) until late in the phonology was found plagued with significant problems (Samuels 2009a: 77-98). Even the general architecture of Lexical Phonology has proven at best a description of trends with exceptions (Kaisse and McMahon 2011).

Given formal problems with how tiers handle spreading, Samuels (2009a: 132-146) recommends replacing the Spread operation with a Copy operation. A similar approach has already proven fruitful in modeling long-distance consonant assimilations (Rose and Walker 2004). For example, obstruent voicing can be modeled as a process that searches for the nearest [-son] segment and copies [+voi] to that target. This leaves [voi] intact as a feature shared at some level by both sonorants and obstruents, facilitating the representation of processes where voice is phonologically active between sonorants and obstruents. Models which split the representation of voice into different features or nodes lack this advantage (Itô, Mester, and Padgett 1995: 577).

The recognition of flawed uses of underspecification is the more welcome because they have led to questionable increases in explanatory apparatus more times than just with the SV proposal. In at least one case where a predictable feature seems phonologically active, the paradox that it could not be unspecified at the same time was initially resolved not by creating new features but by invoking neutralization. The supposedly inactive feature [-voi] was left unspecified, and its apparent activity (spread) was reanalyzed as deletion of [+voi] from the target. The deletion then needed to be motivated on independent grounds. This led to the privative claim (Lombardi 1991) that phonological [-voi] does not exist and that apparent assimilation of one obstruent to the voicelessness of another is always an unrelated positionally triggered loss of laryngeal specifications. Among various problems with this claim (see Kim 2002, Steriade 1995) was the discovery of languages having voicelessness assimilation without positional devoicing. Wetzels and Mascaró (2001) highlighted Ya:thê: for this purpose, but San'ani Arabic (Watson 2002: 250-251) serves as well. Effectively to neutralize this discovery, another feature was then brought into play (Iverson and Salmons 2003a): [-voi] would be replaced in any given analysis by zero or [stiff] depending on whether non-specification or specification was preferable. Thus both [+voi] and [-voi] have been subjected to splitting, with the result being the pair SV/LV in one case and zero/[stiff] in the other.

Given innate universal features, allowing voiced obstruents to be specified with LV or SV (or allowing voiceless obstruents to be specified with [stiff] or zero) based simply on which is more convenient for labeling phonological classes and formulating rules or constraints is arguably too arbitrary if features have universal phonetic correlates – and not arbitrary enough if they do not. Given emergent features, phonological classes containing voiced sonorants and voiced obstruents may be defined with single features in particular languages, but there is no reason to label the voiced obstruents with "sonorant voice" because this is phonetically inaccurate.

3.3.7.5 Conclusion

Given the multiplicity and complexity of strategies for initiating and sustaining voice, it is not surprising to find such a diverse range of proposals replacing a simple voice distinction with articulatory or more abstract models of laryngeal features that jointly handle both voice and other phonologically important categories. The various shortcomings of the proposals we examined are resolved, however, with an auditorily organized definition of [voice] as a phonetically natural feature that leaves room for other ways of organizing correlates into more or less similar features within the universal phonetic geometry (§3.3.4). One of these alternative feature trends can be referred to as the [slack] type (§3.3.7.2). The next section presents a broader look at how singularities within the universal phonetic space can pose challenges for attempts at universal definitions of phonetically natural features.

3.3.8 Feature ambivalence and sonorance

Surveys of the 6000+ phonological classes compiled in P-base (Mielke 2007a) reveal that nasals and laterals phonologically pattern sometimes with continuants and sometimes with non-continuants, even in the same language (Mielke 2008a: 56-77, Samuels 2009a: 51), and similarly that glottal continuants pattern sometimes with sonorants and sometimes with obstruents (Miller in press, Parker 2011 §4, Ratelle 2009). Mielke (2008a) uses the term *feature ambivalence* for this type of situation: thus it appears that nasals and laterals are cross-linguistically ambivalent toward the feature [cont] and glottals toward [son]. Glides could also be considered ambivalent toward [cons] since they pattern sometimes with consonants, sometimes with vowels, in ways that are not explicable by syllable structure alone and that require a variety of underlying representations (see Hayes 1989: 300, Levi 2011, Nevins and Chitoran 2008, Nevins and Vaux 2007, Padgett 2008, Svantesson et al. 2005).

Each of these situations can be plausibly explained phonetically. Nasals are orally stopped but still have unimpeded egressive airflow through the nose, while laterals similarly are oral-centrally stopped but still have lateral egress; thus both sound types have continuous airflow along some parameters but not others, raising questions about how to define the feature [cont] and whether to split it into multiple features that are superfluous for most other segments (Mielke 2008a: 74-77). Similarly, glides have less constriction than most consonantal segments but often have slightly more constriction and lower acoustic intensity than the most similar vowels, causing debate about the definition of [cons] and whether to split it into two features [cons] and [vocalic] to distinguish finer degrees of stricture (see Levi 2011, Nevins and Chitoran 2008, Padgett 2008, Parker 2002). Again, this distinction is superfluous for other segments.[4]

The [son] ambivalence of glottal continuants has plausible phonetic causes as well. Glottal continuants typically have higher oropharyngeal air pressure (e.g. Parker 2002) and weaker formants (Clements 2006a: 3) than modally voiced vowels with identical oral articulations; yet this is due to the turbulence caused by vocal fold spreading, and no supraglottal constriction need be present (see Ladefoged and Maddieson 1996: 325-326, McCarthy 1994: 193). Partly due to this fact, glottal continuants can show considerably less formant damping than stops and fricatives (see Clements 2006a: 3, Clements and Osu 2002). In explosive stops and fricatives with salient frication, there is a more consistent association between airflow obstruction, increased oral air pressure, and formant damping (including reduced amplitude or even complete failure of voice), while in most other sounds there is a complementary association between freer airflow, lower oral air pressure, and clearer formant activity. The most commonly proposed phonetic correlates of [son] are drawn from this set of

[4] This particular use of [vocalic] should not be confused with other, earlier proposals that used the same feature name, such as Chomsky and Halle (1968: 303-303) and Jakobson, Fant, and Halle (1952: 18-20). Neither of those earlier uses has found much subsequent favor, as can be seen from the major sources on feature theory cited at the beginning of §3.3.6.1, but the reasons are beyond our scope here.

properties (see Parker 2002: 48, 135, Clements and Osu 2002), but glottal continuants diverge from most other sound types in behaving like sonorants with respect to only some of these properties and like obstruents with respect to others.

Non-explosives behave inconsistently with respect to the same correlates, but in roughly the opposite way that glottal continuants do, by having reduced oral air pressure on one hand with complete oral airflow stoppage and little or no formant activity on the other. Given these properties of non-explosives and glottals, Clements and Osu (2002) propose splitting [son] into two features, [son] correlating with acoustic properties and [obstruent] correlating with oral air pressure buildup. Again, this distinction is superfluous for most other sounds, which is one reason why obstruence and sonorance are generally considered antonyms (e.g. Kenstowicz 1994).

Having the concept of feature ambivalence in mind is helpful in considering a few broader issues related to sonorance. In a framework with a closed, universal feature set, the main advantage of correlating sonorance with oral air pressure that does not rise much above ambient air pressure (cf. Parker 2002: 135-145) is that this readily captures the sonorant-like behaviors of both canonical sonorants and ambivalent categories including glottal continuants and non-explosives (see Botma 2011, Clements and Osu 2002, Miller in press), while obstruent-like behaviors shown by the same ambivalent sound types can be attributed respectively to glottal widening and stophood. Glottal widening and stophood both attenuate the sound signal as compared to modal voice with an unobstructed supraglottal tract, thus arguably reducing sonority (Miller in press) and making a sound more likely to pattern with obstruents regardless of its categorical [son] value. This frees [son] to be defined in terms of correlates which other well-motivated features do not cover, like relative oral air pressure, which we already infer is actively controlled by speakers (§2.6). The feature [son] can then perform phonological work which other well-motivated features cannot do as easily. For example, nasal harmony systems are known where sonorants and non-explosives are targeted by nasalization spread while other stops are not (see Botma 2011, Clements and Osu 2002); this could be attributed to the targets sharing lower oral air pressure, which associates naturally with nasality since nasal egressive airflow is unobstructed. In this approach, non-explosives would be sonorant stops, higher in sonority than other stops due to their sonorance but lower in sonority than other sonorants due to their stophood.

Ladefoged (1999: 615) argues that if the definition of [son] is separated from the cues of voicing and periodic formant activity, then the tendency of sonorants to be voiced implies that speakers identify the phonetic combination [+son, +voi] as a "salient psychological percept... a rather far-fetched notion for which there is no evidence". Defining sonorance in relation to voice seems to be the most popular alternative to aerodynamic definitions (see Botma 2011 §2.2, 4, Parker 2002: 48, 135). Some problems with geometric redefinitions of voice and sonorance were discussed above (§3.3.7.4); here let us reconsider Ladefoged's argument for a feature [son] defined by acoustic correlates that include voice. Ladefoged argues that without audible voicing playing a key role in motivating the organization of the phonetic correlates of [son], the definition of the feature becomes psychologically implausible. However, just as correlates can be combined on an auditory basis under a common feature (§3.3.1), there seems no reason to exclude the possibility of auditorily motivated combinations of *features* (as well as feature combinations phonetically motivated in other ways: ch. 4). The example here would be defining [son] aerodynamically and explaining its relationship with [voice] as motivated by more or less the same auditory strategy that Ladefoged wanted to attribute to the feature [son] itself. Both ideas are coherent, but the aerodynamic definition of [son] results in less overlap with the definition of [voice] than does Ladefoged's auditory correlation of [son] with periodic formant activity. As a further note on psycholinguistic realism, the potential for psychological categories with multi-modal sources is also well-established both in general (§5.6.3) and for phonological categories in particular: Botma (2011 §5) discusses an experiment that found English stops likelier to be heard as aspirated when synchronized with a puff of air on the listener's hand, "suggesting that information from the auditory and the tactile domain may combine to form a salient psychological percept."

This argument for an aerodynamic definition of [son] depends, though, on a more general principle of prioritizing the parsimonious distribution of correlates among as few features as possible. This makes sense in an innate-feature perspective, but in an emergent framework it is unmotivated because there is no minimal universal feature set, only correlates which can be mapped to abstract features on a language-particular basis. In that perspective, attention turns instead to the maximum number of features possible within a given phonetic space and to natural phonetic relationships among the correlates (§3.3.4), including cases of feature ambivalence.

The emergent analysis seems supported by the fact that all the cases of feature ambivalence which we have just examined are plausibly motivated by *phonetic singularities*: regions within phonetic space where one finds divergence of properties that otherwise tend to correlate. Phonetically motivated feature ambivalence reinforces a challenge that innate feature theories already face for a variety of other reasons (cf. Mielke 2008a: 15-28, 56-77, 98, 117): how to avoid both redundant and incomplete coverage of the facts. In an innate feature theory, cases of feature ambivalence entail either features parametrization (e.g. defining nasals as continuant on a language- or pattern-specific basis) or the expansion of the set of well-motivated features with additional features that are superfluous for the vast majority of sound types (e.g. defining laterals as [laterally continuant] but not [centrally continuant]). Neither option is convincing. Why should innate features fail to retain both universal correlates and a decent functional load in specifying contrasts, and why should they consistently fail precisely where phonetic singularities are involved? This amounts to saying that innate features not only largely reflect the phonetic apparatus, which has already raised redundancy concerns (e.g. Samuels 2009a: 55-56), but more specifically that well-motivated innate features with universal correlates just happen to copy the most easily generalizable aspects of the production apparatus while failing to cover the rest. In lieu of such incomplete yet redundant coverage, it is attractive to investigate how both phonetically simple and less straightforward patterns might be acquired by the same general mechanisms. Mielke (2008a) undertakes this at length.

Below (§3.4) we consider another pattern which is similar to feature ambivalence in depending on phonetic singularities, but which involves three phonetically natural factors instead of two (like nasality and continuance). These three factors are voice, the feature responsible for aspiration, and stricture. The asymmetry in their interaction has especially interesting implications for the discreteness of features and the adequacy of conventional Feature Geometry models.

3.3.9 Laryngeal ambivalence in Germanic

The identity of the laryngeal contrast in English and German stops has been much debated. One series is consistently voiceless but has variable aspiration largely correlated with stress; the other is generally unaspirated but varies in voicing depending largely on the sonorance of adjacent sounds. Iverson and Salmons (1995, 2003b) represent the contrast with [spr], treating the variable voicing of the second series as passive; Kingston et al. (2009) argue for [voi], partly because of evidence that the second series is actively voiced word-medially between vowels in English (§2.6.1). The [voi] model must specify information about aspiration phonetically, and the [spr] model must specify information about voicing phonetically. These phonetic directions must differ from those in, say, Swedish, where one series is consistently voiceless aspirated and the other is consistently voiced in the majority of environments for the majority of speakers tested by Helgason and Ringen (2008).

If features emerge, the laryngeal contrast in English or German stops could theoretically involve a somewhat abstract phonological feature mapping to language- and even environment-specific bundles of phonetic correlates. Though we would expect the contents of these bundles to be diachronically related, it might not be the case that all the correlates associated in any environment with a given series center around a single correlate that synchronically motivates the others in a phonetically transparent way. For example, some degree of intervocalic stop voicing (devoicing) in voiceless (voiced) stops, or of aspiration (deaspiration) in unaspirated (aspirated) stops, could arise historically for phonetic reasons unrelated to lexical contrast. Several possible sources of change in voicing and aspiration have already been discussed (active and passive voicing strategies §2.6.1, presonorant voicing §3.2.3, unconditional devoicing §3.2.6, degree of aspiration correlating with stress §3.3.6.2, aspiration arising from imprecise articulator coordination §3.2.4). Subsequently, a learner might perceive and intentionally imitate or even enhance such phonetic patterns, again regardless of whether he or she perceives them as lexically contrastive or as making some other correlate more perceptually salient.

Such a process could result in a certain degree of complexity (cf. Docherty 1992: 128-129) in which it would be hard to determine whether a laryngeal contrast was organized primarily around a glottal width difference (e.g. Jessen and Ringen 2002: 192), a difference in oral air pressure during closure (cf. Butcher 2004), presence vs. absence of aspiration noise (with resistance to closure voicing switching in as a secondary correlate in post-stress intervocalic stops, for instance), or susceptibility to audible periodic vocal fold movement. In this last scenario, the key fact would be that the unaspirated series associates with greater amounts of voicing – not only through greater susceptibility to closure voicing, but also through the lengthening of preceding voiced vowels and through shorter VOT for following vowels.

Conceivably, speakers of a language might perceive a contrast as a combination of such scenarios. Individuals might also differ in their mental characterization of a contrast, thanks to different perceptions of its phonetic implementation which in turn correlate with inter-speaker phonetic variation (cf. Brunelle 2010: 20-21). Valuing descriptive rigor and insight will certainly entail identifying natural relationships among the phonetic correlates of a feature in order to detect the degree to which the feature's correlate bundle is synchronically organized in natural phonetic terms (§3.3).

3.4. Beyond Feature Geometry trees: larynx-stricture interactions

Stops are the most common segments to contrast in voice or aspiration (Kehrein 2002, cf. Maddieson 1984, Mielke 2007a). Contrastive voice is rarer in fricatives than in stops but still relatively common (Maddieson 1984: 28, 53). Distinctive aspiration occurs even more rarely in voiceless fricatives, while fricatives associated with breathy voice seem exceptionally rare (Jacques 2010, Kehrein 2002, Ladefoged and Maddieson 1996: 178). The role of abduction in fricative contrasts is not limited to control of (post-)aspiration, however. Some languages have two contrasting fricative series distinguished by duration, degree of airflow, and susceptibility to voicing; the latter two properties suggest a difference in glottal width involving control of abduction, though it does not necessarily audibly overshoot stop edge to produce aspiration (Welsh: Kibre 1997: 17, Ball and Müller 1992: 82-85; Dutch: van Rooy and Wissing 2001: 302, 311, 328). As for sonorants, they are voiced by default and appear to contrast only in presence or absence of vocal fold abduction; in other words, contrast among [n̥ n̥^{h} n̤ n̤^{ɦ}] is not reported (Kehrein 2002).

To analyze the possible role of perception in motivating some of these patterns, let us temporarily limit the term *aspiration* to a substantial period of glottal turbulent noise (§3.3.6.4) between the release of a supraglottal constriction (stricture) and the onset of modal voicing in a following sonorant. Let us also define *aspirate types* as types of aspirated sounds distinguished by stricture, and *salience* as perceptual salience. As we have just seen, the number of languages in which a given aspirate type occurs apparently decreases in tandem with stricture, suggesting that stricture degree is important to the viability of aspiration as a contrastive cue (cf. Kehrein 2002: 117). The relative rarity of contrastively aspirated fricatives, and the predominance of sibilants among them, has also been related to salience (Jacques 2011: 1519). A review of the acoustic evidence and typological data suggests the following generalization: aspiration is more salient the more it differs acoustically from the immediately preceding stricture, and this measure of salience correlates broadly with both the number of languages in which a given aspirate type occurs and the number of segments that belong to each aspirate type in individual languages.

Thus, the most salient aspirate type is an aspirated stop, where the relatively quiet stop closure has high perceptual contrast with the turbulent glottal noise of the aspiration. Aspirated stops are also the aspirate type found in the most languages, and if a language has one aspirated stop it usually has several (Maddieson 1984, Mielke 2007a).

The next most salient aspirate type is an aspirated sibilant fricative, where the relatively high-amplitude high frequency of the oral constriction has moderate perceptual contrast with the lower-amplitude and wider-bandwidth (more distributed) frequency of the aspiration. Aspirated sibilant fricatives are contrastive in several languages (Jacques 2011, Kehrein 2002: 81, Kehrein and Golston 2004: 332, Ladefoged and Maddieson 1996: 179) and in complementary distribution with unaspirated allophones in Halh Mongolian (Svantesson et al. 2005). In most of these cases there are also fricatives at other places of articulation, which are not reported as aspirated in the sources just listed. Palatal, alveo-palatal, velar, and labiodental aspirated fricatives are reported but markedly less often than aspirated sibilants, perhaps because they involve less strident noise (Jacques 2011: 1519-1520, who proposes the implicational hierarchy s^{h} > ɕ^{h} ʃ^{h} ʂ^{h} > ç^{h} x^{h} ɬ^{h} ɬ^{jh}).

The remaining aspirate types seem to have low salience because both the constriction period and the aspiration are characterized by fairly low-amplitude, high-bandwidth aperiodic noise. For example, [θ^{h} n̥^{h} l̥^{h} r̥^{h}] and [θ n̥ l̥ r̥] respectively sound very similar. I am aware of no languages in which these pairs of sounds contrast. As already mentioned, Kehrein (2002) finds no contrast between voiceless and breathy sonorants either. Botma (2011) observes that voiceless nasals tend to occur in languages with contrastive stop aspiration, supporting the suggestion already made by various other writers (see Kehrein 2002, Lombardi 1991, Vaux 1998a) that the voicelessness of sonorants and the aspiration of stops have the same feature specification. The auditory redefinition of [spr] as glottal turbulent noise would serve this purpose.

These patterns create an important phonological assymetry: as one moves from stops through strident to non-strident fricatives to sonorants, the phonetic space that languages are found using to implement independent [voi] and [spr] features goes from being clear and abundantly attested to being vanishingly small. Stricture thus apparently correlates with the number of viable laryngeal configurations and contrasts involving voice, abduction, and timing, creating a set of interesting asymmetries in the possible phonological interactions of laryngeal features. Feature Geometry was designed to represent universals in phonological feature behavior (e.g. Clements 1985, 2009), but it does not seem possible to capture the patterns that we have just examined using the standard tree structure of Feature Geometry. It is not clear what alternative representational structures would be more successful.

Ohala (2005: 8-9) has similarly argued that the natural relationships among phonetic correlates which recur cross-linguistically in phonological patterns are too complex to be captured by tree structures with strict dominance (where each element is immediately dependent on only one node) and that the solution is to model the phonetic naturalness of phonological patterns through sound change rather than in the formal representations of grammar. This point has been taken up by the emergent (Mielke 2008a), evolutionary (Blevins 2004), and minimalist streams of phonological research (Blaho 2008, Hale and Reiss 2000a,b, Morén 2007, Samuels 2009a), which continue to develop with considerable overlap (Archangeli 2011, Mohanan et al. 2009). Some of the implications are explored further in the next two chapters.

Before we conclude this chapter, one further insight about features can be gleaned from the arguments for emergence that we have developed so far. We have just seen how it becomes harder to tease correlates apart into two separate features [spr] and [voice] as stricture decreases, and in the previous section we saw how some correlates tend to pattern together except for particular types of sounds defined by singularities in the universal phonetic space. These patterns exemplify variation in the number of correlates available and in how freely they are available for phonological distinctions. As shown next, two opposite extremities in this range of variation appear to be occupied by a pair of phenomena that we touched on earlier in the chapter: enhancement and (some kinds of) positional neutralization.

3.5 Comparison of enhancement with partial positional neutralization

Phonetic correlates that are naturally related in terms of physiology or physics often combine in bundles for the realization of language-specific phonological categories (for example, Lisker 1986 identifies sixteen distinct phonetic properties that vary according to the stop "voicing" contrast in English). In the emergent framework promoted in this chapter, these language-specific phonological categories are features which may be more or less phonetically natural depending on how naturally related their phonetic correlates are. This has implications for our understanding of enhancement and partial positional neutralization.

In this framework, enhancement is readily viewed as the grouping of a larger bundle of *correlates* under a particular feature than is found under features with similar correlates in various other languages. For example, the laryngeal stop distinction in Swedish correlates with both aspiration and voice, while in various other languages it relies on one or the other (§3.2.4). This contrasts with a view of enhancement as the addition of redundant *features* to phonological specifications. For example, the tendency of voiceless fricatives to involve some vocal fold abduction has been related to a hypothetical default specification of voiceless fricatives with the feature [+spr] at some level of phonological representation distinct from mere phonetic implementation, with this default then being deactivated in languages with contrastively aspirated fricatives (Avery and Idsardi 2001: 48, Vaux 1998a: 509). For a somewhat similar treatment of different stages in the evolution of Southeast Asian register contrasts see Brunelle (2005: 268-272). In the emergent framework, this accumulation of features is needlessly complex except in particular languages where additional phonological evidence motivates multi-feature specifications of the enhanced categories. In all other cases, enhancement is more simply modeled as the association of a larger number of correlates with a feature in one language than with similar features in other languages.

At the other extreme of variation in feature-correlate mapping, partial positional neutralization can be viewed as a reduction of the number of correlates associated with a feature in a particular environment. This is precisely how Yu (2011) analyzes partial positional neutralization, contrasting it with previous works that treat the same phenomenon as a product of orthographic interference, phonetic analogy, or turbid representations. Yu relates much of this previous work to a more modular view of the phonetics-phonology interface, where the subtle cues which betray contrast in partially neutralized surface forms have no presence in the phonological representation. The phonological representation thus categorically neutralizes the segments in question, and the subtle evidence of contrast in the phonetic forms must be treated as the reappearance of a distinction that had been either erased or somehow hidden by the phonology. Yu reviews studies concluding that orthographic interference cannot explain all reported cases of partial neutralization, and he argues that experiments which found speakers much more consistent in producing than in perceiving partially neutralized distinctions can be explained without invoking categorical neutralization at the phonological level (cf.

Ernestus 2011 §2.5-2.6). Explanation of partial neutralization by phonetic analogy obviously complicates the architecture of the grammar by reintroducing previously effaced distinctions, and turbidity vastly enriches phonological representations to distinguish elements which end up being pronounced from elements which are only "projected" (structurally present but abstract). Yu's model of partial neutralization appears simpler and more natural: speakers simply map some features to smaller sets of correlates in some word positions than in others.

Yu refers to this conception of partial positional neutralization as "covert contrast," but in the emergent framework pursued here it is worth considering whether and in what sense users *hide* the contrast at any level of representation or implementation. Conceivably, a partially neutralized contrast has a higher profile in the speaker's memory as tied to production than in the auditory processing system, due to the lower perceptibility of the contrast in the neutralization position; recall the systematic production of reportedly inaudible contrasts in utterance-final position in Blackfoot and Oneida (§3.3.6.5). Independent evidence for some divergence in speakers' knowledge of production and perception has already been found in the different influences which these two kinds of knowledge exert on loanword adaptation (see Kang 2011 §3, Martin and Peperkamp 2011, Ussishkin 2011 §2.3) and in studies finding poorer auditory awareness of allophonic than contrastive distinctions, even when the allophonic distinctions are clearly systematically controlled in production (Martin and Peperkamp 2011 §2.1).

3.6 Conclusion

This chapter has argued for a principle of feature economy that biases language users against inducing grammars with unnecessarily large combinations of phonetically *unrelated* correlates in the realization of phonological specifications. The force of economy is seen in how often the laryngeal properties of stops in languages that lack laryngeal contrasts in stops are either conditioned by adjacent sounds or reduced to a uniform minimum (voiceless unaspirated). Similar effects are seen when all stop or obstruent series undergo positional laryngeal neutralization. When only a subset of the stop or obstruent inventory neutralizes, though, the neutralized outcome has a wider range of possible realizations, just as a stop series has a wider range of possible laryngeal specifications when they express laryngeal contrasts.

Phonetically *related* correlates commonly combine in bundles for the realization of language-specific phonological categories (features). In the emergent view explored here, enhancement is the grouping of a larger bundle of correlates under a particular feature than is found under a feature with similar correlates in various other languages, while partial positional neutralization is the reduction of the number of correlates associated with a feature in a particular environment. This perspective contrasts with previous analyses where enhancement is the addition of redundant features to phonological specifications and where partial neutralization is considered a symptom of orthographic interference, phonetic analogy, or turbidity invoked to allow complete neutralization of the contrast at some level of phonological representation. These previous analyses accommodate a more strictly modular view of grammar in which the phonetics and phonology components cannot "see" inside one another, while the emergent analysis presented here seems to align with abundant and increasing evidence that human cognition is much less strict than previously supposed in separating different kinds of knowledge either within memory or during processing (§5.6.3).

This chapter also noted that correlates which play an enhancing role in voiced stops in some languages frequently occur contrastively in preponderantly voiced stop inventories in other languages, while aspiration, which appears to have no natural enhancing role in voiced stops, does not seem to occur as the contrastive factor responsible for any preponderantly voiced stop inventory either. This is plausibly explained as another effect of feature economy, allowing "Jakobson's universal" to be modeled coherently within an emergent feature framework. Alleged counter-examples to Jakobson's universal were reanalyzed.

A couple of other phenomena deriving from the natural relationships among phonetic correlates were discussed in this chapter. Several cases of feature ambivalence were attributed to phonetic singularities. We also reviewed evidence against Feature Geometry being innate and against strict domination in Feature-Geometry hierarchical structure. Non-cognitive motives for cross-linguistic feature co-occurrence trends are explored further in ch. 4, with the argument that innate cognitive stipulations about such patterns are redundant.

Finally, the middle of the chapter reviewed several major proposals about the representation of aspiration and voice. Since laryngeal muscles generally are not in a one-to-one relationship with auditorily distinguishable types of stops, and since the timing of laryngeal articulations required for various types of consonants is more complex than a single VOT parameter can capture, auditorily organized definitions seem appropriate for both aspiration and voice – at least in languages where the dominant allophones of those categories are respectively realized with glottal turbulent noise and phonetic voicing. In Emergent Feature Theory, though, there are no grounds for forcing a particular feature label like [voice] onto other ways of associating phonetic correlates with phonological categories (such as slack stops) merely because the categories are somewhat similar to prototypical voice. Instead, phonological features are language-specific categories induced by learners in ways influenced by the physics of speech; features can be compared on the basis of similarity in their phonetic correlates and distributional properties, and feature types vary widely in both frequency and phonetic naturalness. The implications are developed in ch. 5 with acquisition-related arguments that grammars differ in their contents rather than simply in how the contents are organized.

4 Feature Co-Occurrence Trends

4.1. Introduction

This chapter analyzes over seventy feature co-occurrence trends and concludes that they can be reduced, with some clarification in feature definitions, to around a dozen positive conditionals whose content can be plausibly derived from an even smaller number of non-cognitive factors. This finding for segmental feature patterns is mirrored in other domains of phonology by discoveries supporting the phonetically motivated emergence of sonority (see Henke et al. in press, Miller in press) and of syllable constituent weight (Browman and Goldstein 1988, Goldstein 2009, Goldstein et al. 2007, 2008, Shaw et al. 2009 on the different timing patterns of complex onsets vs. codas; cf. Goedemans 1998, Topintzi 2006a,b).

4.2. Feature co-occurrence trends

The most comprehensive list of cross-linguistic feature co-occurrence trends that I have found is that of Calabrese (1992, cf. 2005). Calabrese formalizes these patterns as hierarchically organized negative inventory constraints, evidently innate in the initial knowledge state rather than language-particular, and variously deactivated in individual languages to capture phonological patterns.

The constraints are of two kinds: prohibitions, stating feature combinations that never occur, and marking constraints which ban cross-linguistically avoided feature combinations and which are deactivated in languages that use those combinations. Each constraint bans a pair of features, optionally in combination with further features which are represented as a periphery using rule environment notation. Prohibitions are asterisked, while in the marking constraints, the first feature in the pair is understood as implying avoidance of the second, which is underlined. Thus prohibitions have the form *[A, B] (/ [_, C, D, etc.]) and marking statements have the form [A, B] (/_, C, D, etc.]).

The purpose of the constraint hierarchy is that cross-linguistically more freely distributed sounds are mentioned by fewer constraints, while cross-linguistically less freely distributed sounds are mentioned by more constraints including constraints that tend to be dependent on other constraints. Dominant constraints cannot deactivate without the deactivation of their dependents, so inventories can only contain the more marked sounds banned in the dependent constraints by also permitting the less marked sounds banned in the dominant constraints. Stops are treated as the unmarked obstruents, obstruents the unmarked consonants, nasals the unmarked sonorants; hence stops are undominated, while nasals dominate liquids.

Calabrese's (1992) seventy-odd inventory constraints are shown in Table 4. Dependency is shown by indenting the dependent constraint under the dominant constraint. Where a constraint immediately depends on more than one other constraint, the indentation system shows the nearer dominant constraint if it is adjacent on the page while the remaining dominant constraints are linked to the dependent with association lines. I have saved space by collapsing Calabrese's environmental notation, turning e.g. [A, B] (/ [_, C, D...]) into [A, C, D,... B], and by specifying rhotics as [+rhot] rather than [+son, +cons, -nas] (which in Calabrese's hierarchy is read as non-lateral by default because laterals are more marked than rhotics). Constraints that I suggest should be retired are marked †. Possible additional constraints are shown in parentheses. Arguments follow in §4.3.

A striking aspect of the overall system is the large amount of content overlap. Most of the first three columns are distinguished only by [-cont], [+cont], and [+son/ +nas], for example, while for the most part each of the first several rows is distinguished only by one of Lab, Dor, [ant], [dist], [voi], [+cst], [+spr], [strid], and [+lat]. (Calabrese treats the place categories Lab etc. as Feature Geometry nodes rather than as features; cf. Halle, Vaux, and Wolfe 2000.)

Table 4. Constraint set adapted from Calabrese (1992).

Stops	*Fricatives*	*Sonorants*	*Rhotics*
	[-son, <u>+cont</u>]	[+cons, <u>+son</u>]	[+son, +cons, <u>-nas</u>]
[-cont, <u>Lab</u>]	[+cont, <u>Lab</u>]	[+nas, <u>Lab</u>]	*[+rhot, Lab]
[-cont, <u>+rd</u>]			[+rhot, <u>Gut</u>]
[-cont, <u>Dor</u>]	[+cont, <u>Dor</u>]	[+nas, <u>Dor</u>]	*[+rhot, Dor]
[-cont, <u>-ant</u>]	[+cont, <u>-ant</u>]	[+nas, <u>-ant</u>]	[+rhot, <u>-ant</u>]
[-cont, <u>+dist</u>]	[+cont, -<u>dist</u>]	[+nas, <u>+dist</u>]	[-ant, +rhot, <u>-dist</u>]
[-cont, <u>+voi</u>]	[+cont, <u>+voi</u>]	[+son, <u>-voi</u>]	([-son,+cont, <u>+rhot</u>])
[-cont, <u>+cst</u>]	[+cont, <u>+cst</u>]	[+son, <u>+cst</u>]	
[+voi, -cont, <u>+cst</u>]	[+voi, +cont, <u>+cst</u>]		*<u>Laterals</u>*
[-cont, <u>+spr</u>]	[+cont, <u>+spr</u>]	[+son, <u>+spr</u>]	[+son, <u>+lat</u>]
[+voi, -cont, <u>+spr</u>]	[+voi, +cont, <u>+spr</u>]		*[+lat, Lab]
*[-cont, +strid]†	[+cont, <u>-strid</u>]	*[+son, +strid]	[+lat, <u>Dor</u>]
[-ant, -cont, <u>-dist</u>]	[+voi, +cont, <u>-strid</u>]		[+lat, <u>-ant</u>]
*[-cont, +lat]	[+cont, -son, <u>+lat</u>]	*[+lat, +nas]	[-ant, +lat, <u>-dist</u>]
*[-cont, +RTR]	[+cont, <u>+RTR</u>]†	*[+nas, Gut]	*[+lat, Gut]
[Dor, -cont, <u>-ATR</u>]	[Dor, +cont, <u>-ATR</u>]	[+nas, <u>+cont</u>]	
	(*[-son, +cont, +nas])		([-son, +cont, <u>+lat</u>])

<u>Opposites</u>		*<u>Vowels</u>*	
*[-cons, -son]†	*[+hi, +lo]	[+lo, -cons, <u>-bk</u>]	[+lo, -cons, <u>+ATR</u>]
*[-cons, -cont]†	*[+spr, +cst]†	[+lo, -cons, <u>+rd</u>]	[-hi, -cons, <u>+ATR</u>]
*[-cons, +suction]†		[-lo, -cons, <u>-hi</u>]	[+hi, -cons, <u>-ATR</u>]
		[-cons, <u>+nas</u>]	[+bk, -lo, -cons, <u>-rd</u>]
			[-bk, -lo, -cons, <u>+rd</u>]

The complexity of the constraint set reduces further on closer inspection. Some constraints, like the prohibitions *[+spr, +cst] and *[+hi, +lo], trivially follow from definitions of those features as incompatible opposites – though we have seen both physiological and phonological evidence that in fact this is probably not the case with [+spr] and [+cst] (§2.4). In connection with incompatible opposites it bears noting that a number of other gesture combinations have been identified as possible but phonetically antagonistic – that is, relying on components that clash or are in tension with one another. These combinations include voice and supraglottal stop closure (§2.6), nasal egress and oral frication (Gerfen 2001), high vowels and tongue root retraction in vowel harmony in African languages (Downing 2009a,b), and high vowels and pharyngealization in emphasis harmony in Arabic (Thompson 2006). I find none of these antagonistic combinations reported as occurring systematically at the phonetic level except in phonological contrast with less antagonistic configurations containing each of the antagonistic gestures apart from the other.

Most of the remaining constraints in Table 4 can be attributed to a fairly small set of phonetic explanations. I sketch these next, then defend the methodology and explore the results further in §4.4.

4.3. Explanations

4.3.1 Place

By far the most common type of place distinction in stops is a three-way distinction between labial, coronal, and velar (Maddieson 1984: 31-32). In addition to any articulatory motives, this pattern seems to have a plausible acoustic motive in the way it disperses the patterns of formant perturbations that stop releases at different places of articulation cause on following vowels (Morén 2007: 46-58, Schwartz et al. 2012; further on acoustic cues of stop place see Delattre, Liberman, and Cooper 1955, Harrington 2010a, 2010b: 171-219, Lindblom and Sussman 2012, McLeod et al. 2001, Sussman and Shore 1996). In this section we examine more detailed asymmetric trends in place of articulation.

4.3.1.1 Coronals

The role of Lab and Dor in Calabrese's marking statements is almost purely to formalize Cor as the unmarked place without ever mentioning it. The arguments that have been advanced for a special status of all or some coronals in various aspects of phonology are many and varied, but the notion that the various special behaviors of coronals were generally a result of coronals having a simpler cognitive representation (e.g. Paradis and Prunet 1991) has lost some popularity. Peculiar behaviors of coronals have more recently been derived from non-cognitive factors like articulation, acoustics, and frequency (see Frisch 1997: 167-168, Gafos 1996: 3-10, 131-174, Jun 2004, Walker, Byrd, and Mpiranya 2009), and arguments have accumulated that several phenomena are inconsistent with across-the-board claims of coronal "unmarkedness" (e.g. Clements 2009: 60 citing Yoneyama, Beckman, and Edwards 2003 on dorsals being more frequent and acquired earlier than coronals in Japanese; also Howe 2004, Hume 2003, Hume and Tserdanelis 2002, Rice 2009).

This has gone hand in hand with a general shift away from Sagey's (1986) call for behavioral asymmetries in sounds to be formalized through a universal markedness hierarchy where increased markedness correlates with increased representational complexity (Mielke 2008a: 24; more generally Haspelmath 2006, 2008a). Consequently, the two-term non-liquid constraints containing Lab or Dor in Table 4 do not seem to be an illuminating way of formally acknowledging the diverse factors for unique behaviors of coronals.

As for the sub-classification of coronals, Calabrese's [dist] constraints indicate that stops and nasals generally prefer to be apical while posterior coronal liquids prefer to be laminal, but variation in the tongue shape of coronals across languages and across speakers of the same language turns out to be considerable and under-documented (see Dart 1991, Gafos 1996: 132, Ladefoged 2005: 6). This is not surprising given that the front end of the tongue is flexible and curved, inherently presenting a fluid set of multiple surfaces, and is also a uniquely agile articulator, moving quickly with minimal displacement of the formants of neighboring sounds and capable of producing similar acoustic effects from articulatory shapes that differ considerably in the exact details (see Gafos 1996: 9-10, 132-171, Steriade 1995: 145-147). While Ladefoged (2005) and Gafos (1996) conclude that traditional generalizations about the laminality of different types of coronals in various languages are fairly simplistic and misleading, Gafos makes considerable progress in relating phonological behaviors of coronal fricatives to articulatory details. On the whole, the evidence weighs against phonetically arbitrary features being needed to capture cross-linguistic phonological trends distinguishing different types of coronals. If we were to project from the incomplete state of current research, the prediction would be that whatever coronal-dependent features end up being validated will be phonetically natural. It seems too early to discuss [dist] feature trends any further here.

The notion that coronals tend to be anterior (encoded within Calabrese's markedness hierarchy by [-cont, <u>-ant</u>], [+cont, <u>-ant</u>], [+nas, -<u>ant</u>], [+rhot, <u>-ant</u>], [+lat, <u>-ant</u>]) can be attributed partly to an artifact of analysis, partly to quantal factors, and partly to a hypothesis developed shortly below (§4.3.1.4), that omissible gestures increasing the complexity of a sound are omitted in many languages and rarely exclusively relied on in any language. The artifact of analysis is that the relative backness of coronals is often not specifically documented unless it is contrastive, leading to an impression that coronals not contrasting for [ant] are [+ant] rather than [-ant]. This impression might actually not be phonetically demonstrable in some languages. If no language has only retroflex coronals, however, this may indicate that the default position of the tongue tip is relatively anterior and that curling it back to produce posterior apicals and retroflexes takes more effort. Finally, the fact that most languages avoid non-contrastive, unconditional realization of their consonantal coronals as palatals (which are [-ant, +dist]) may be related to the relative indistinctness of that place of articulation (see Stevens and Keyser 1989: 98): the lips and front and back of the tongue are distinct enough to suggest that the boundaries between them are effectively quantal, but palatals do not enjoy such a boundary with either more anterior coronals or dorsals and their acoustics are accordingly less easily distinguishable than those of anterior coronals and other places are from each other. The impression that coronals tend to be anterior may thus derive from a combination of different factors.

4.3.1.2 Rounding

Rounding correlates with lip protrusion, whereas [p b] etc. show lip compression (see Ladefoged 1999: 594-595). Labial stops obviously need to press the lips together, while in low vowels for example it is relatively difficult to round and protrude the lips because they are already spread to accommodate the fact that the mouth is more open in low vowels than in any other segment. The constraints [-cont, ±rd] and [+lo, -cons, ±rd] can thus be derived from articulatory facts. The widespread correlation of backness with rounding among vowels expressed in the last two constraints in Table 4 has been explained acoustically (see Maddieson 2008a) as a way of reinforcing lower formants.

4.3.1.3 Liquids and nasals

Notwithstanding the articulatory complexity of laterals and rhotics (Ladefoged and Maddieson 1996), their highly limited place distribution has a clear articulatory basis. Laterals must be lingual (coronal or dorsal) because laterals are defined by air escaping over the sides of the tongue. Most sounds classified as rhotic are taps, flaps, or trills, which require rapid movement that may be easier with the coronal than with the labial and uvular articulators and that appears to be impossible with the velar and pharyngeal articulators. (On labial taps and flaps see Olson and Hajek 2001, 2003; on labial trills, Ladefoged and Maddieson 1996.) The remaining sounds which have been classified as rhotics are glides with articulatory place trajectories and formants similar to those of the rhotics already mentioned. These glides are typically apical, retroflex, or bunched coronal, or uvular (e.g. [ʁ̞] in German: Kohler 1999). The corresponding syllabic sounds are not widely used as vowels in the world's languages, while the syllabic equivalents of glides that have not been analyzed as rhotic ([j w β̞ ɥ ɰ]) are more often used as vowels ([i u ʉ y ɯ]). Thus a combination of factors may explain the constrained place distribution of laterals and rhotics. The relative rarity of non-coronal laterals may also relate to the greater agility of the coronal articulator already noted, though I do not recall if I have seen this connection explicitly made in the literature.

The only nasals judged articulatorily impossible by the International Phonetic Association (1999) are those produced behind the velum and the attached uvula, because air cannot be cut off in this region and still flow through the nasal passage. I assume Calabrese's prohibition *[Gut, +nas] reflects this, but I am not sure whether it includes uvular nasals. Uvulars are discussed in the next section.

4.3.1.4 Uvulars, laryngeals, and clicks

Uvular articulation (which I presume is referred to in [Dor, -cont, -ATR], [Dor, +cont, -ATR]) involves movement of the back of the tongue not only up but backward toward the uvula, which differs from the targets of more anterior places of articulation in being neither firm (like the teeth and palate) nor subject to well-controlled movements itself (like the lips, which in bilabials are both articulators and articulatory targets for one another). This complexity and instability, especially as compared to velars, may contribute to the relative rarity of uvulars and to the fact that their presence usually implies the presence of velars too (though there are exceptions: Maddieson 2008c).

The prohibition *[-cont, +RTR]) presumably bans stops with the tongue root as the primary articulator. In light of Esling et al. (2005), this appears to be correct, but it also appears that pharyngeals in general have aryepiglottic constriction rather than tongue root retraction as their primary articulator. If no obstruents are primarily articulated with tongue root retraction, then the constraint [+cont, <u>+RTR</u>] (which refers to fricatives in Calabrese's hierarchy) should be a prohibition too. The best feature representation of pharyngeals will not concern us here, but from recent literature on laryngeals (§2.4) it appears that stops primarily articulated with a strong constriction in the upper larynx, including the aryepiglottic folds, play the phonological role of pharyngeal stops and are not only relatively rare but articulatorily quite complex. Pharyngeal continuants also appear relatively difficult to produce, since their considerable tendency to perturb surrounding formants indicates that it is not easy to navigate abruptly to and from a pharyngeal articulation (unlike with coronal liquids, §4.3.1.3).

Another instance where phonological rarity may be connected with the greater effort or complexity in implementation is the case of clicks, which require two place gestures (one velar, one ante-velar) coordinated to produce suction. (They do not require a separate suction feature; see Howe 2003. Here I refer only to clicks that are phonological, i.e. contrastive and lexically represented; phonetic clicks and other non-pulmonic consonants including clicks are also attested non-systematically in various languages as epiphenomenal realizations of other segments or segment sequences: see Ohala 1995, Simpson 2010.)

While our understanding of the correlation between effort/complexity and frequency is not advanced enough to permit many predictions, it is clear that languages do adhere to some limits of this sort; otherwise nothing would prevent the sound changes which produce less common and more difficult or complex sounds from leading to more languages with such sounds, or to languages where such sounds occurred much more often.

Perhaps a key factor is the independence of the gestures involved. All languages (see Ladefoged and Maddieson 1996, Maddieson 1984) employ place, the simple distinction between a closed and open oral passage (stops vs. vowels), modal voice as an aerodynamic default in vowels, and voicelessness as an aerodynamic default in at least some of the stops. Place is related to stricture, stricture to aerodynamics, and aerodynamics to voice. Without these elements there would not be enough segments to create a lexicon (cf. Clements 2009: 35). Laryngeal constriction and double place on the other hand are complex and not indispensible for a reasonably sized lexicon. It makes sense for independently activated, logically omissible activities to have lower cross-linguistic frequency. This in turn recommends that we consider the extent to which cross-linguistically avoided phonological configurations can plausibly, if still only hypothetically, be connected to the theme of omissible complexity or difficulty. We will consider the theoretical implications of this in greater depth shortly (§4.4) after surveying the remaining feature co-occurrence constraints mentioned above.

4.3.2 The larynx and aerodynamics

4.3.2.1 General

The constraints [+son, <u>-voi</u>], [-cont, <u>+voi</u>], and [+cont, <u>+voi</u>] in Calabrese's hierarchy express the well-established generalization that voice is default in sonorants but antagonistic in obstruent stops and fricatives. The aerodynamic basis for this is one of the most well established phonetic explanations in phonology (§2.6).

There are several cross-linguistically important relationships among [voi], [son], [spr], [cst], and [cont] which Calabrese's hierarchy does not capture but which were explored in chs. 2 and 3, including the absence of a [spr] contrast in voiceless sonorants and the reason for default voice in non-explosives. Generalizations that were made earlier (§2.6, 3.4) about how ranges in possible laryngeal feature contrast are controlled by co-occurring supralaryngeal features are difficult even to represent with an abstract feature tree but easily explained from phonetic facts.

What the two-term constraints in Table 4 involving [+spr] and [+cst] express is that these gestures are contrastive on orally placed segments in only a minority of languages. This fact about frequency may be related to the fact that contrasts in vocal fold abduction and laryngeal constriction require greater effort to produce and process, because there are more configurations to keep track of. Laryngeal constriction is also a logically omissible way to increase articulatory complexity, as noted above. Whether aspirated stops are a more complex articulation than unaspirated stops or the reverse is difficult to determine (§3.2.4)

4.3.2.2 Nasals and liquids

The active lowering of the velum necessary for categorically nasal sounds appears to be another instance of omissible effort. While the default position of the velum is arguably somewhat lower than a fully raised position, producing moderately nasal sounds (Francis Nolan p.c.), it must often be lowered even further to produce distinctively nasal sounds, suggesting that distinctively nasal sounds are not an articulatory default but typically require active velic lowering. Similarly, raising the tongue center but keeping the tongue sides low creates a more complex tongue configuration than keeping the sides and center relatively uniform. Such observations may relate to why not all languages have lateral or nasal sounds (Maddieson 1984: 61, 74) and why nasal vowels imply both oral vowels and at least phonetically nasal consonants. (Usually nasal vowels imply phonologically nasal consonants too, but in some languages nasality is contrastive only on vowels and predictable on consonants: Clements and Osu 2003.) The rarity of nasalized fricatives has been persuasively related to the aerodynamic difficulty of maintaining enough oral airflow for frication while also having nasal airflow (see Shosted, Ohala, and Sprouse 2005, Gerfen 2001). Finally, a dispreference for mixed egress paths plus the other complexities already mentioned may relate to why phonemic nasal-laterals are avoided; it is also possible that "the presence of antiresonances from *two* 'sidebranch' resonators, the nasal cavity and the short cavity behind the lateral's coronal closure... would result in an ambiguous percept" (Nolan p.c.). These patterns are expressed in Calabrese's constraint hierarchy with [+son, +lat], [-cons, +nas], [+nas, +cont], and *[+lat, +nas], as well as the implied constraint [+cons, +nas] which he formulates as [+cons, +son] because nasals are the unmarked sonorants in his hierarchy.

The prohibition on nasalized laterals cannot extend to surface distinctions, however. In Sanskrit (Renou 1961) a word-final nasal becomes a nasalized /l/ through sandhi when the following word begins with /l/, and in Catalan (Bonet and Mascaró 1997: 124), "in loans or acronyms, like *Chandler*, *Bentley*, or *INLE* (Instituto Nacional del Libro Español), the nasal becomes a (nasalized) lateral: [tʃal̃l̃ər], [bɛl̃l̃i], [il̃l̃e]." Since the same sources present each language as allowing surface [nn] and [ll], the geminate laterals with nasalization appear to be perceptually distinct even though nasalized laterals are not phonemic.

That rhotics are absent in some languages (the import of [+son, +cons, -nas] within Calabrese's hierarchy) can be attributed to factors as various as the articulation of rhotics. The iterative articulation of trills is uniquely complex. The distribution of taps and flaps is often uniquely restricted: they are favored in environments where the tongue is already moving from one position to another, which may relate to why a number of languages exclude them from word-initial position (see Ladefoged and Maddieson 1996: 216-17). However, the claim that rhotics are unmarked with respect to laterals (the import of [+son, +cons, -nas] dominating [+son, +lat] in Calabrese's hierarchy) does not seem justified; rhotics and laterals each occur in about 80% of the 548 languages and 627 language varieties in Mielke (2007a).

4.3.2.3 Fricatives

The intermediate stricture and turbulent pressure of fricatives seem to require more effort and precision than either stops or vowels do, and this conceivably relates to the fact that while all languages have stops and vowels, fricatives are absent from nearly ten percent of the languages in the UPSID database (see Maddieson 2008b). The constraint corresponding to these observations in Calabrese's hierarchy is [-son, +cont].

Phonetically, stridence is an acoustically noisy property available only to fricative sounds (see Ladefoged and Maddieson 1996, Maddieson 1984: 51-58). This is reflected in Calabrese's constraints *[-cont, +strid] and *[+son, +strid]. The acoustic salience and hence perceptual clarity of strident fricatives may relate to the fact that non-strident fricatives imply at least one strident fricative in most languages (see Maddieson 1984, 2008b); this is reflected in Calabrese's hierarchy as [+cont, -strid]. Whether stridence is phonologically associated only with fricatives is another question (see §3.3.6.3 on the representation of affricates).

The generalization that strident fricatives may be all voiceless but are never all voiced ([+voi, +cont, -strid] dominated by [+cont, (-son,) +voi] in Calabrese's hierarchy) appears correct. It does not extend to non-strident fricatives. Three Australian languages are reported as having only one fricative each, where the fricative is voiced non-strident (Maddieson 2008b). Some languages have multiple non-strident voiced fricatives without corresponding voiceless ones and without having strident voiced fricative phonemes at all (e.g. Spanish: Martínez-Celdrán 2008; Central Buang and Western Fijian: Tryon 1994). Unlike strident sibilant voiced fricatives, other voiced fricatives frequently have glide variants or are not clearly distinguished from phonetic glides in the literature (Cser

2003: 122). Since stridence is heightened acoustically salient turbulence (Stevens and Keyser 1989), audibly strident voiced fricatives presumably require a stronger airstream and greater oral air pressure than other voiced fricatives. This requirement must be met at the same time that voicing is sustained. The unique aerodynamic needs of strident and especially sibilant voiced fricatives may relate to why they have a more restricted distribution than other voiced fricatives, and why they are not reported with glide variants as often as other voiced fricatives are.

One phenomenon that does not appear explicitly in Calabrese's hierarchy is that of fricatives with a nasal, lateral, or rhotic component. True nasalized fricatives occur phonetically, but both language data and aerodynamic reasoning make it highly doubtful that they occur contrastively (§4.3.2.2). Lateral and rhotic fricatives occur fairly infrequently and involve fairly complex articulations (Ladefoged and Maddieson 1996). In coronal trills, for example, maintaining high enough stricture to impede airflow and create frication impressionistically seems prone to hinder the vibrating motion of the trill itself, the same way that dribbling a basketball is harder the closer you keep it to the ground. Manipulating one or both sides of the tongue to achieve frication while the tongue center maintains stop contact may be only slightly easier. The rarity of lateral and rhotic fricatives may thus relate to the theme of omissible complexity and effort.

Phonological constraints reflecting these facts have been added to Table 4 in parentheses: *[-son, +cont, +nas], [-son, +cont, +lat], and [-son, +cont, +rhot]. The last of these might be better framed as a prohibition if rhotic fricatives are never contrastive, but I have not ascertained this.

4.3.3 Vowels

Among Calabrese's vowel constraints, we have already discussed *[+hi, +lo], [+lo, -cons, +rd], [-cons, +nas], [+bk, -lo, -cons, -rd], and [-bk, -lo, -cons, +rd]. The remainder have plausible phonetic explanations. Low vowels have less physical room for front/back distinctions because both the tongue and the jaw move down and back when opening to the low position; hence a phonological contrast in [bk] is rare with low vowels. Calabrese's [+lo, -cons, -bk] predicts that low vowels behave phonologically as back vowels, but Mielke (2008a: 156) found that the phonological patterning of low vowels with back vs. front vowels is fairly balanced.

The idea that non-high vowels tend to be [-ATR] while high vowels tend to be [+ATR] (i.e. [+lo, -cons, +ATR], [-hi, -cons, +ATR], [+hi, -cons, -ATR]) might be explained by a preference for the tongue root and the tongue body to move together: moving the tongue body up may be easier if the tongue root advances somewhat, and having the tongue body in a lower position may be easier if the tongue root does not advance as much.

The constraint [-lo, -cons, -hi] expresses the trend for mid vowels to imply high and low vowels but not vice versa, which seems to be partly an analytical artifact (vowels cannot phonologically occupy a middle level in a vowel system unless there are both higher and lower vowels) and partly the result of dispersive tendencies (Flemming 2003). The latter, however, are not well enough understood for us to predict the degree of vowel distribution in acoustic space given only the height and backness relations of the vowels to one another (Hale, Kissock, and Reiss 2006).

Finally, Calabrese's prohibitions *[-cons, -son] and *[-cons, -cont] are trivially true or false depending on feature definitions: true if [-cons] is correlated to a lack of impedance or pressure incompatible with [-son] or [-cont], and false otherwise (cf. §3.3.8).

4.3.4 Interim reduction

Some of the constraints in Table 4 proved empirically unsatisfactory. Some, such as *[+hi, +lo], proved redundant given their feature definitions. A principle that omissible actions are not defaults can account for all constraints treating [+F] as marked where [+F] correlates with an omissible gesture. Nearly twenty constraints in Table 4 can be set aside for reasons such as these.

The remaining more than fifty negative constraints reduce to roughly a dozen conditional statements as exemplified in (1), where → marks a one-directional implication and ↔ marks a bidirectional implication. Notably, the feature [son] is key to eight of the twelve statements in (1), and both [son] and [cons] are key to six. This is not surprising if [son] is defined in terms of pressure, because pressure implies some kind of control on airflow and the controls in this case are provided by other feature specifications, primarily involving stricture.

While the contents of Table 4 thus reduce to a dramatically smaller set of conditionals in (1), the minimum number of non-cognitive explanations sufficient to cover these patterns in light of the foregoing discussion seems even lower. Around half a dozen non-cognitive motivating factors are shown in (2) and keyed to (1) with superscript letters. This is not to say that only these factors are involved, but merely that the valid and non-trivial information content of Table 4 seems plausibly derivable from these factors. The ramifications of this claim are discussed next.

(1) Conditional restatement of feature co-occurrence trends

[+cons] → [-rd],[a] {Cor (weak) [b] → [+ant] [a]}[5]

[αson] ↔ [αvoi] [c]

[αson] ↔ [αcont] [c]

[-son] → [+cons] [c]

[+strid] ↔ [+cont, -son, +cons] [d]

[+nas] ↔ [+son,[d] +cons [e]]

[+nas] → [-cont] [e]

[+lat] → Cor,[b] [+son],[f] [+cons],[d] [-nas] [e]

[+rhot] → [+cont],[d] [+son] [f]

Dor, [-son] → [+ATR] [a]

[+lo, -cons] → [-ATR, -rd] [a]

[αbk] ↔ [αrd] / [-lo, -cons] [g]

(2) Possible motives

[a] easier articulation, given the antecedent

[b] functional arguments for coronal uniqueness, such as articulatory ease and minimization of formant perturbation

[c] aerodynamic dispersion (least vs. most obstruction/pressure) minimizing intermediate configurations with their more complex articulations

[d] comprehensive feature definition

[e] favoring of oral and central egress and avoidance of egress path splitting

[f] [αson] ↔ [αcont] (itself possibly motivated by *c*)

[g] mutually reinforcing percepts

[5] Read, “Consonantal segments tend to be non-round (possibly due to motive *a*), they weakly tend to be coronal (possibly due to *b*), and if they are coronal they tend to be anterior (possibly due to *a*).”

4.4. Implications

4.4.1 Introduction

The previous section has repeatedly invoked articulatory or perceptual difficulty and complexity in offering explanations for why some sound patterns are rare or non-existent. The role of effort in phonetically based explanations in phonology is controversial. Here I hope to clarify some of the controversies.

First, effort-related explanations do not necessarily imply that phonology is biased to make languages become globally easier to speak over time. Understanding why requires us to distinguish sound changes from the static aspects of the speech production and processing systems which often influence them (§4.4.2). Second, it has been claimed that a counter-intuitive hypothetical bias favoring complexity or difficulty explains just as much data, with just as much validity, as a more intuitively plausible bias favoring ease or simplicity; the two biases are consequently supposed to cancel one another out, leaving effort-related explanations essentially useless in phonology. I argue that a wider perspective refutes this claim (§4.4.3). Implications for grammar design are treated in the next chapter.

4.4.2 Why sound change is not teleological

Ohala (1993: 262-264) and Blevins (2004: 71-78, 205, 278-280) argue that sound change is not driven by speaker goals such as making a language easier to speak or hear. It does not follow that unintentional effort reduction plays no role in sound change, however. The following analogy from Mielke (2008a: 82-83) provides a good starting point for establishing the sense in which sound changes often involve effort reduction without the nature of sound change itself being driven by a goal of making languages easier to speak.

> Due to the layout of the *qwerty* keyboard, some typographical errors are more likely than others... Acknowledging the role of the layout of the keyboard (or vocal tract) in what types of deviations from a target are most likely does not amount to saying that the result of these errors is more natural or optimal than the intended target...
>
> Although it is hard to predict when a typing error will be committed, considering the layout of the keyboard and the content of the spell checker makes it possible to predict which deviations from the target are likely to occur, and which of those are likely to persist. Taking into account the reality in which typing (or language use) occurs does not require any sense of optimization...

In the keyboard analogy, certain combinations or sequences of keystrokes involve more difficult or complex finger movements than others, such that failure to strike some key is likelier in these cases than in many others. An example is failure to capitalize, or continuing to capitalize one or two letters longer than intended. These reductions or mistimings are not evidence that the activity of typing has a natural goal of striking fewer keys or of capitalizing more letters in general. However, these kinds of mistakes do reflect the fact that people are likelier to fail to perform all parts of a task or to perform the parts at the right times when the task is more complex, difficult, or fast-paced. This last consideration is why more typing mistakes are made at higher speeds.

In the phonetic realm, similar considerations apply to articulatory reduction and mistiming. Some sounds or sound sequences are more complex or difficult to produce than others, and thus likelier to be performed incompletely or with gestural mistiming. Reduction and mistiming are also likelier in faster or less careful speech styles. Another indicator of the relationship between difficulty and speed is that correctly and completely produced sounds may simply have longer average production times when they are relatively articulatorily complex. Take for example the following situation in Nootka dialects of Nuuchahnulth (Wakashan: Carlson and Esling 2003: 189):

> The simple glottal stop of /wiːʔuː/ 'nephew'... lasts about 100 ms, while the glottalized resonant series in Nootka, consisting of /ˀm, ˀn, ˀj, ˀw/, has an articulatory structure consisting of simple glottal stop plus the resonant, lasting nearly 200 ms. Pharyngeals, such as the /ʕ/ in /ʕiħuː/ 'to cry after', require 250 to 300 ms to complete all of the articulatory maneuvers associated with the segment including preparatory constriction, radical occlusion and gliding into a subsequent segment.

Without such connections between articulatory complexity and speech rate, there would be no reason for errors like gesture reduction to be more common in faster styles of speech. A similar but perhaps more obvious connection holds between speech accuracy and attention. Thus, casual speech is often characterized by both higher speed and less complete or accurately timed articulatory performance.

One type of gestural mistiming is coarticulation, which can lead to assimilations (Blevins 2004: 144). Assimilations can simplify an articulatory sequence. Gestural reduction also has a simplifying effect by omitting all or part of a gesture. Both coarticulation and gestural reduction can thus reduce the effort required to articulate a sequence of sounds. Since coarticulation and gestural reduction are common articulatory sources of sound change (Blevins 2004: 142, 291-192), their effects can accumulate over time. However, sound systems are complex enough that simplifying the production of a word in one respect often makes it more complex in another (cf. Clements 2009: 34). The frequency of simplifying sound changes does not entail a global drive for languages to become easier to speak over time.

Crucially, a bias for languages to avoid certain kinds of effort or complexity – as well as absolute bounds which no languages are found to transgress – stem in large part from static properties of the speech production and processing systems. These properties are not diachronic anymore than the properties of the keyboard we considered earlier. The structure of the keyboard is not an aspect or goal of typographical error, and the definition of what is simple or easy to produce or perceive depends on properties of the speech system which are not aspects or goals of language change. Instead, these static and universal properties explain why some sound changes are more common than others, and also why sound changes never seem to produce certain outcomes, even cumulatively where every step in the chain is attested and unproblematic (§3.3.3, 3.2.6.1). As Kiparsky (2004, 2006) emphasizes, it is not clear how this latter fact would be handled by a theory which derives the explanation of sound patterns primarily from sound change.

4.4.3 Why phonology is not dysfunctional

Another important factor to consider in defining the role of effort in shaping sound patterns is the multiplicity of dimensions in which effort can be measured, as noted by Hale and Reiss (2000a,b). For example, neutralization can simplify articulation but increase input-output mismatch and ambiguity, forcing hearers to increase their reliance on context to determine underlying forms and meaning. This is a case where articulatory simplification arguably decreases perceptual ease. Loss of articulatory gestures can also induce greater articulatory complexity, as when vowel syncope creates consonant clusters. On the other hand, maintenance of existing contrasts can be attributed to a drive for communicative clarity and ease of processing, even though more contrasts mean more articulatory complexity (cf. Clements 2009). All of these situations can co-exist in a language, leading to phonological intricacies where complexity appears to increase in some ways while decreasing in others.

The frequency of situations in which effort or complexity increases in some ways while decreasing in others at first glance appears equally compatible with three different hypotheses: that languages favor upper bounds on effort and complexity, that they favor lower bounds, or neither. Hale and Reiss (2000a,b) label the first two hypotheses functional and dysfunctional and contrast them using the following examples: while the functional explanation would claim that a drive for articulatory ease merged contrast and led to increased perceptual difficulty in one case while a drive for perceptual ease preserved contrast in spite of consequent articulatory complexity in another case, the dysfunctional explanation of the same data would claim exactly the opposite – that a drive for perceptual difficulty (OBFUSCATE) was what led to the merger of contrast in the first place while a drive for articulatory difficulty (NO PAIN, NO GAIN) motivated preservation of contrast in the second case. Hale and Reiss (2000a,b) conclude that because some data sets are locally consistent with both kinds of explanation, neither kind should be used. This seems questionable for the following reason.

Human behavior in general shows much more sensitivity to upper than lower bounds on effort. Humans value devices that decrease cost and increase profit. Profit is whatever is desired; cost is what must be exchanged for it. The mere increase of articulatory and perceptual energy expenditure has no discernible profit, so we must presume its status is cost. The phrase NO PAIN, NO GAIN itself means that cost must be exchanged for profit, not that cost is profit. For example, it is reasonable to believe that water seeks the lowest available space in response to gravity, because that is where water is generally found and there is a wealth of other evidence for gravity regardless of how imperfect our understanding of it may be. The existence of sand bars in rivers is not evidence that water instead seeks to stay out of the sea. Similarly, it is reasonable to believe that the goal of speech is to communicate, because communication generally occurs when people speak, speech is intentional, and there is a wealth of evidence that humans and other creatures intentionally communicate in other ways. The existence of phonological complexity is not evidence that people speak with the intention of creating complicated sound patterns instead.

The dysfunctional approach to phonological explanation is thus invalidated by a lack of evidence for any profit motive, which means that it is not available to neutralize the value of the opposite approach – correlating the absence or rarity of certain sound patterns with the relatively high though still physically feasible effort and complexity they would involve. A model that acknowledges this correlation is more informative than a model that ignores it by formulating the universal restrictions as innate cognitive stipulations. And while the measurement of these properties is itself complex, as in several of the allegedly effort-increasing examples from Blevins above, the overall picture – including the principles of cost and profit, dozens of feature co-occurrence trends (§4.3), and sound changes involving coarticulation and reduction (§4.4.2) – indicates that languages extensively avoid sound patterns which are relatively difficult to produce or process, while *there is no persuasive evidence that languages avoid anything because it is simply too easy* or that they ignore effort or complexity altogether.

As noted earlier, the number of interacting properties in any given sound pattern makes effort and complexity hard enough to measure that they have very limited predictive or quantifiable value as explanatory principles. My purpose in arguing that they still play a substantial role in the shape of sound systems is not to promote a more predictive formal model of sound patterns, but simply to highlight the tremendous extent to which sound patterns can be plausibly derived from properties of the speech production apparatus. Once an extensive set of such derivations is granted – regardless of all the details in each particular case – it becomes massively redundant to derive many of the same patterns from innate cognitive stipulations.

This insight readily finds a place in theories that deny effort reduction or simplification a major role in sound change, because there are plenty of other phonetic forces to discuss as sources of many sound patterns, especially when viewed as products of sound change. The reason I have emphasized considerations of effort and complexity in this chapter is that they appear to play an extensive role in the synchronic feature co-occurrence trends examined in §4.3.

4.5. Conclusion

The wide extent to which feature co-occurrence trends can be motivated by phonetic factors without recourse to detailed innate cognitive stipulations supports the general claim of emergent and evolutionary approaches to the design of the phonological component of the grammar and its relationship to sound change. In this perspective, the structure of the phonetic apparatus manifests itself as a causal factor in grammar design when it overrides faithful inheritance during acquisition (just as the structure of the keyboard only manifests itself when a typing mistake is made). The override is a historical event reflecting structural aspects of the phonetic apparatus and resulting in a change of grammar without those aspects themselves being components of the grammar – just as typographical errors change a text and reflect structural aspects of the keyboard and of the human hand without those aspects themselves being part of the text.

The phonetic forces that shape the linguistic evolution of sound systems can involve considerations of effort and complexity without becoming teleological or arbitrary, but the least redundant grammar design theory generally seems to exclude such phonetic forces from playing a direct role in the grammar: instead, it is their products – sound patterns instantiated in word forms – that are extracted into the grammar during acquisition. This claim is developed further in the next chapter, where I argue that innate content-specific constraints unnecessarily duplicate learnable input-output mappings, that profuse generation unnecessarily duplicates typological exercises which do not belong in grammars, and that online serial execution of rules sometimes unnecessarily duplicates steps in acquisition.

5 Grammar

5.1 Introduction

The last two chapters have argued that the details of crosslinguistically common features and feature co-occurrence patterns emerge on a language-specific basis from non-cognitive, phonetic factors that operate through sound change. This conflicts with the influential framework of Optimality Theory, which posits that grammars systematically differ only in the ranking of universal constraints. This chapter briefly reassesses some of OT's goals and components and compares them with alternative approaches to grammar design.

5.2 Grammar

5.2.1 Definition

I will use the term *grammar* for the knowledge system required for mentally processing auditory input and mentally planning speech production in a given language, where the purpose of the production function is to encode meaning in sound for a listener and the purpose of the processing function is to decode meaning from sound produced by another speaker (cf. Ussishkin 2011). This code involves a mostly arbitrary mapping between sound and meaning, where sounds and meanings each have a systematic organization that allows an infinite number of possible constructions from a finite, known set of elements (see Chandler 2011, Martinet 1949, 1957, 1983, Menn 2010: 101-127, 185-199). For obvious reasons, what speakers know about their language has primarily been explored by analyzing what they say, though brain imaging technologies now also allow us limited observations of how the brain reacts during listening (Menn 2010: 196-197, 213, 390, Singer 2009, Woods et al. 2011).

In light of the errors and other idiosyncracies of individual speakers, as well as the fact that speakers never make all the statements which their language properly allows them to make or understand, it is not surprising that the distinction between knowledge and actions has played a major role in linguists' efforts to define the object of their study. Saussure explored the distinction in terms of *langue* versus *parole* (Saussure 1989[1916], W. Gordon 2004), while Chomsky has written of *competence* versus *performance* (Chomsky 1965: 3, cf. Aaronson and Rieber 1975, Morén 2007: 4). Both pairs of terms have been used in widely and somewhat counter-productively divergent ways (see G. Miller 1975, Trabant 2005). In particular, Chomsky emphasized the study of linguistic competence through intuitions about what speakers know rather than experiments measuring what they do, with a focus on finding the most restrictive model for defining the competence of a non-existent ideal speaker rather than emphasizing what actual speakers reveal that they have in common (Grace 1989, G. Miller 1975).

In this chapter we will be concerned with parsimonious modeling of what speakers systematically do – most often and in common – in order to use particular languages. This includes both actual speech and the psychological behaviors involved in producing and processing it. Not all of a person's subconscious brain activity in association with a language is necessarily part of its grammar, because cognition is multimodal, readily storing and activating large quantities of highly diverse mental associations (§5.6.3). The definition of grammar used here accounts for this by equating grammar with the competence needed for a particular kind of performance: using a language, not merely playing with it or knowing things about it. To clarify this, we now look briefly at a couple of activities – early childhood babbling and lexical innovation, especially loanword adaptation – that have sometimes been treated as windows into grammatical knowledge. I argue that these activities can change grammars but that grammars do not execute them; therefore, there is no reason to think that the patterns in these activities are codified within grammars.

5.2.2 Development

Early childhood babbling (de Boysson-Bardies and Vihman 1991, Hayes 2004, Menn 2004, Samuels in press) has been treated as evidence for highly detailed, innate, universal components of grammar (McCarthy 2002: 208-213) because it reveals cross-linguistic trends that cannot be attributed to ambient adult languages – not simply because the babbler has not yet learned the ambient languages, but more importantly because the babble trends can violate them. Such trends do not have to be derived from innate structures in cognitive competence, however. Instead, the cognitive side of babble patterns can be viewed as simply the child's analytic generalizations about the production system he is exploring. Sounds and sound patterns favored by articulatory physiology and acoustic physics as simpler or easier to produce or perceive than others can naturally become more frequent in the course of generic, undirected babbling as the child exercises his or her production system, and it is readily conceivable for some of these patterns to become habits. In other words, innovative babble patterns can be responses to pressure from the production system in its early, more exploratory stages. As children master new articulations, their production-driven patterns will change and the constraints will change. Likewise, as a child becomes more skilled at imitating ambient adult speech, production patterns that violated the grammar of the ambient language will recede. At the same time, it has also been found that production practice begins influencing perception from an early age (DePaolis et al. 2011, Vihman et al. 2006, Vihman and Keren-Portnoy in press), notwithstanding the fact that perception develops much more rapidly than production ability (Blevins 2004: 219-236, Hayes 2004: 191-192, Menn 2010, Mohanan et al. 2009: 4).

In terms of Mielke's keyboard analogy (§4.4.2), erroneous patterns during early acquisition (of language or typing skills) that do not reflect the "correct" pattern (ambient adult speech or a text to be typed) simply reveal information about the structure of the production apparatus (the vocal tract or the keyboard). It is redundant to derive the patterns of the mistakes from innate content-specific constraints (such as innate phonological constraints motivating obstruent devoicing, or innate typological constraints motivating outputs like *teh* for *the*, *from* for *form*, and so on). While much remains to be done in early-acquisition research, at this juncture there seems no mandate to derive content-specific patterns in early babbling from a universal, innate set of content-specific constraints; much recent experimentation points rather toward emergence (e.g. Menn and Vihman in press, Velleman and Vihman 2006, Vihman et al. 2006: 364, Vihman et al. 2009).

If babble patterns can diverge from the grammar of the target language under the influence of the production apparatus, there is no reason to rule out similar influence in cases of borrowing or lexical innovation that reveal phonologically innovative patterns. In both cases, the speaker is exploring sound combinations that are not already conventionalized in the target language, and in the context of this creative freedom it is unsurprising if factors other than the grammar of the target language exert some influence. These could include performance-related factors including those earlier suggested as shaping common cross-linguistic feature co-occurrence trends (ch. 4). Another factor even more clearly in evidence though is the simple recognition of the difference between what is already true of the target language and what is not. Insights of this sort are not necessarily part of the grammar, if a grammar is a system for processing and producing grammatical utterances in a given language, because these processing and production activities do not themselves require the speaker to activate much knowledge about what the language is not.

For example, there is no evidence for [q] being present anywhere in English grammar for most speakers of English, but rather than viewing this fact as a component of the English grammars of these speakers, we might want to consider it simply a generalization about what their English is *not*.[6] Such generalizations are relevant in language contact situations, when English speakers have to decide how to borrow words containing [q] in the source language. But when the words are naturalized with [q]-less forms in English, then constraints mentioning [q] are no more necessary for the perception and production of grammatical English utterances than they were before. Underlying and surface forms in the source language do not automatically equate to anything in the grammar of the target language (see Nevins 2008b, Nevins and Braun 2008). This holds true regardless of whether we attribute the avoidance of [q] in English borrowing to the fact that English already lacks [q] before borrowing, or whether we attribute it to phonetic rationales for the relative cross-linguistic rarity of uvulars. Both kinds of factors could even be involved simultaneously.

These considerations are similar to the rationale for distinguishing between synchronic grammar and diachronic trends: phonetic reasoning might explain the relative rarity of sound changes producing uvulars, and the uvular-free evolution of English might be taken as an example of this – yet none of these considerations properly belong in the formulation of synchronic English grammar, because they are unnecessary for modeling the processing and production of grammatical English utterances.

Loans and neologisms are often adapted to the native patterns of the borrowing language, and this can provide evidence for the phonology of the latter (Pierrehumbert 2001: 139). However, when borrowing and lexical innovation do result in innovative phonological patterns, they can be seen as *changing* the grammar of a language. The new grammar abides by the same definition as the old: it is the knowledge system for using the target language (cf. Nevins and Vaux 2008: 37). This is reason to keep the study of borrowing, lexical innovation, and babbling distinct from the concept of grammar. Further on the various influences that shape loanword phonology, see Haspelmath (2008b), Kang (2011), Martin and Peperkamp (2011), and Ushiskin (2011).

[6] [q] does occur as an allophone of /k/ for some speakers of Multicultural London English (Nolan p.c.).

5.3 Optimality Theory and its classic schema

OT was introduced by Prince and Smolensky (2002[1993]) and elaborated in Kager (1999), McCarthy (2008a, 2002), and Smolensky et al. (2006) among others. As summarized by Smolensky et al. (2006:1: 495-502, 523-525), OT *defines* the set of possible languages as the permutation of the ranking of a universal set of constraints. These constraints do not restrict inputs; rather, the ranked constraints of a given language map any linguistically possible input to the most grammatically correct output, by either recommending or penalizing specified output properties per se (markedness constraints) or identifying respects in which outputs should match inputs (faithfulness constraints). OT also provides ways to *visualize* this system which may be psycholinguistically inaccurate with respect to some details in the interest of making others more comprehensible. After summarizing the simplified schema that has received the most attention in the works just cited, we will consider how more detailed or psycholinguistically realistic models of OT grammar acquisition and computation depart from it.

In this classic schema, the execution of the production function of the grammar has three main phases. First an underlying form is fed into a generative component (*Gen*) which emits every linguistically possible output in total disregard for language-particular criteria of grammaticality (freedom of analysis). Then these output candidates are fed into an evaluative component (*Eval*) which contains a ranked set of violable constraints. Each candidate is evaluated against each constraint, and constraint violations are recorded. Finally, the candidate with the lowest violation score is selected as the actual output (winner) while the other candidates (losers) are discarded. The principle that candidates are scored independently of one another against a single constraint ranking is called parallelism: the candidates can be evaluated simultaneously (in parallel), and the constraints bear simultaneously on each candidate. Evaluation only occurs after blind, profuse generation.

Leading OT computational work on acquisition (Alderete et al. 2005, Albright and Hayes 2011: 7, Hayes 2004: 194, Merchant and Tesar 2005, Tesar 2007a, 2009, Tesar and Prince 2003, Tesar et al. 2003) and mature production (Karttunen 2006, Riggle 2004) emphasizes the need for narrowing down the set of structures that are evaluated. This includes the set of underlying forms that are attributed to the lexicon in the course of the learning process and the set of output candidates evaluated during production. Such "smart" models (Kager 1999: 26) explicitly restrict generation based on prior evaluation. Logically, the smartest conceivable mature grammar would normally generate only winning outputs.

This makes it especially important to understand that the proliferation of losers in the OT schema is not actually a property that OT attributes to real grammars. The schema is only an approximate way of thinking about what happens when a given input form triggers nerve activity in the brain. Activation triggered by the input must spread among the relevant neural networks and stabilize in whatever form best collectively satisfies the preferences (weights) of the nerve connections. According to Smolensky et al (2006:1:40), grammar constraints are physically expressed as distributed patterns of these weights. The constraints, or weight patterns, evaluate the nerve activity triggered by the input and direct this activity until it settles into the correct output form. The activation patterns prior to that optimal equilibrium do not systematically encode any grammatical information: they do not realize features, morphemes, or words. Thus the correct output form is normally the only form that the grammar actually produces; the losing output candidate forms evaluated in the OT schema are figments of illustration.

> A connectionist network computes an optimal representation by navigating through a space of subsymbolic representations [neural patterns] to ultimately construct the activation pattern that realizes an optimal symbolic structure [output form]. In no sense do such algorithms "generate alternative structures, evaluate them, and pick the best." In general, the only symbolic structure ever realized by such an algorithm

> is the optimal one; at prior stages of computation, the algorithm constructs activation patterns that have no symbolic interpretation. (Smolensky et al. 2006:1:525)

If the losers never actually exist, they cannot actually be evaluated in parallel. It follows that where parallelism is allegedly crucial for the satisfactory analysis of some phonological patterns, the arguments at most validate only the simultaneous presence of certain kinds of structure in grammatical directions, not a need for simultaneous evaluation of multiple output candidate forms. This conclusion appears true in the cases I have investigated (§5.4). However, if proliferation of losing output candidates is unnecessary, then the large number of constraints which might be required to filter out the profusion of losers is also unnecessary. As a result, not only does a universal constraint set not need to be innate, but it does not need to be present in individual grammars at all. This motivates an approach to grammar design and acquisition in which the details of grammatical directions are efficiently extracted from observed surface forms during acquisition and are subsequently used for the efficient construction of surface forms during speech production (§5.5).

5.4 Necessary parallelism?

5.4.1 Imdlawn Tashlhiyt Berber

Core OT texts use several languages to illustrate their claim that strict parallelism is sometimes necessary. Prince and Smolensky (2002: 22) begin with syllabification in Imdlawn Tashlhiyt Berber (ITB) (Berber: Afroasiatic). They describe the mainstream pre-OT approach to this problem as:

> one in which the structure is built (more-or-less) bottomup, step-by-single-step, with each step falling under the constraints appropriate to it. Taking this seriously... this would mean... that you first locate the nuclei – the heads of syllables; then project

> higher order structure that includes the onsets; then project the structure that includes postnuclear consonantism. In ITB, however, as in many other languages, the availability of nuclei depends on the choice of onsets: an early step in the derivational constructive procedure, working on a low level in the structural hierarchy, depends on later steps that deal with the higher levels. Indeed, the higher level constraint is very much the more forceful...
>
> In the theory advocated here... we expect exactly this kind of interaction. The whole output is open to inspection; how we choose to inspect it, or how we are forced by UG to inspect it, is not determined by the course that would be taken in bottom-up construction. The potential force of a constraint is not indexed to the level of structure that it pertains to, and under certain circumstances (UG permitting or demanding), constraint domination will be invoked to give higher-level constraints absolute priority over those relevant to the design of lower structural levels.

In fact, ITB does not call for such unrestrained interaction potential between different structural domains, but only for a "constructional algorithm" (ibid.) with a few slightly complex steps. As is generally true, the process can be modeled with a preference for each step to be as simple as possible, which may increase the number of steps, or with a preference for as few steps as possible, which will mean some steps involve more forces acting simultaneously. But either way, no step can be modeled in simpler terms than the data will allow. Pre-OT derivational phonology allowed a given rule to execute as complex an operation as necessary, and even in gradualist post-OT theories requiring "one" change at a time, the definition of "one" is determined by what the data allows (e.g. McCarthy 2010a).

Perhaps some parts of the construction process are necessarily more complex in ITB than in some other languages. ITB onsets and nuclei, for example, may need to be identified simultaneously, perhaps as a rising span of a certain size in a form's sonority curve (the graph one would make by plotting each segment's value in the sonority hierarchy: see Miller in press, Samuels 2009a: 119-121). This would indeed entail multiple forces working together, namely sonority and span size (limited by avoidance of complex margins). But it does not follow that the desired structure cannot be built according to a theoretically satisfying plan. Even the fact that simultaneous onset-plus-nucleus assignment requires scanning multiple segments at once during syllabification is not a problem; scanning multiple segments to fulfill a requirement is sometimes necessary during evaluation in OT as well.

The real item of interest in the ITB case may be that earlier proponents of the more-and-simpler steps approach to output construction had become used to building only one syllabic constituent per step, while specific properties of ITB may make this inelegant. But again this does not require abandoning directed construction for blind, profuse generation followed by evaluation of entire output candidate structures. That kind of parallelism does not essentially improve the analysis of ITB.[7]

5.4.2 Tongan

The next language Prince and Smolensky (2002) employ is Tongan, where they affirm that "it is important to have the entire structural analysis present at the time of evaluation" (p. 31). Their data can be summarized as follows: where stress falls on the first of two identical vocalic morae, the output joins these morae in one long vowel, while where stress falls on the second of two such morae, the output maps each mora to a separate short vowel with hiatus between: *húu* [huː] vs. *huúfi* [hu.ˈu.fi]. The pattern can be analyzed in terms of three requirements: that the last (bimoraic) foot be right-aligned with the word edge, that foot boundaries not fall within syllables, and (least forceful of all) that identical consecutive vocalic morae not be separately syllabified.

[7]The syllable theory that Prince and Smolensky (2002) develop largely from ITB data also formally predicts a significantly greater permutational array of viable grammars than is empirically justified, and arranges them according to principles that do not appear to be operative, such as sets of grammars whose classes of segments banned from syllable margins are defined as increasingly large chunks of the sonority hierarchy starting from the top end. See Pater (2008: 15) on subsequent rejection of margin constraints, and Dell and Elmedlaoui (2002) for a better presentation of the ITB data.

Prince and Smolensky discuss “the view that structures are literally *built by re-write rules* in a strictly bottom-up fashion, constructing layer upon layer” (p. 30) and reject an analysis of this sort which generates intermediate forms such as [hu.u], concluding that while such a “bottom-up” approach would work if “the package of constraints relevant to syllable structure completely and universally dominates the constraint-package pertaining to foot structure” (p. 31), it does not work in Tongan. Yet all this only suggests that a perspicuous constructional algorithm for Tongan cannot assign stress after building all syllable structure. This may be interesting as a refutation of certain pre-OT assumptions about the order in which prosodic constituents must be constructed, but it does not show that the Tongan structures must be generated without access to any set of directions or requirements and then evaluated entire. One possibility is to assign morae first, then stress, then syllable boundaries. Having mora specification precede other syllabic structure is not a new idea (e.g. Hayes 1989: 260). Another possibility is that at least some moraic and syllable structure can be induced simultaneously from intersegmental gesture timing information (§4.1).

5.3.3 Lardil

According to Prince and Smolensky (2002: 137), Lardil has a pattern where “the crux of the matter is that the grammar must determine which *total* analysis is wellformed – a task impeded by the use of serial algorithms to build structure step-by-step.” Basically, a /CVC/ input is deemed too short, so it is augmented. If the second input C can be a coda, then augmentation makes it a coda by adding -CV; otherwise, augmentation adds only -V. Augmentation is thus looking not merely at syllabified forms, but (according to Prince and Smolensky) at the effect its own application will have on syllabification, maximizing stem right-alignment with a syllable boundary.

While the set of situations where this alignment fails to occur (see Prince and Smolensky 2002: 109, 113 n. 59) suggests a possible alternative, simpler motive for the pattern – maximization of stop onsets – Prince and Smolensky's analysis itself can be reformulated in constructional terms. Abstracting with those writers away from a complication involving the tapped /r/,[8] we can simply say that if the stem-final C is a licit sonorant coda, then the augment is CV with C a regressively homorganic stop, and that the augment is V otherwise (i.e. when the stem-final C is a stop, and maybe when it is *y* or *w*, though examples are not given). Just inspecting this statement in light of the Lardil inventory reveals that the process favors stem/syllable right-alignment when licit codas are involved, and also that it avoids geminates and favors stop onsets.

Exactly how to formalize the process description, including the choice of which possible underlying forces to foreground as positive motivations for the process, is a separate issue. The point here is simply that a theoretically reasonable set of directions can be found for constructing the Lardil pattern without blind and profuse generation of losing output candidate forms.

Imdlawn Tashlhiyt Berber, Tongan, Lardil, and the handful of other prosodic problems that Prince and Smolensky (2002: 31-32) pass over very briefly in a single paragraph may indeed show that previous serial derivational theories drew the lines in the wrong places between different constructional steps, and Prince and Smolensky undertake a worthy task in critiquing this state of affairs. But proof that directed construction should be abandoned is lacking. The basic principle of a constructional approach is that in any given process, the input should supply enough information for the directions to work with. In the cases Prince and Smolensky develop, this information is indeed present in the specification of the string of input segments and their relevant features (in some cases perhaps including intersegmental timing information). Given this information, language-specific sets of directions can successfully guide the identification

[8]Their suggestion that some of the details they choose not to treat "may be relevant to a later level of phonology than we discuss" (p. 108) is curious for an approach that emphasizes direct mapping from input to output without internal hidden layers, as McMahon (2000: 25) notes.

or construction of everything else – relative sonority, moraicity, stress, syllable boundaries and foot structure – *for* generation rather than *after* it.

5.4.4 Southern Paiute, Yidiɲ, and Axininca Campa

McCarthy (2002: 138-91) mentions a few other cases, but as far as I can tell, they fare the same as the previous ones. Southern Paiute has a reduplication process which according to McCarthy's data can be directed by the constructional algorithm, "Prefix a copy of root-initial Stop – Vowel – Nasal to roots beginning with that string; and let the reduplicant segment with the Nasal specification receive a place feature from the following root-initial stop. Otherwise, prefix CV." This reflects the fact that reduplicants have codas where this creates the one type of cluster which is licit in Southern Paiute, homorganic nasal plus stop, but not otherwise. The relationship between static phonotactic constraints and a constructional algorithm is an important issue, but here our only concern is with McCarthy's claim that the Southern Paiute pattern presents an ordering paradox for rule-based approaches and needs to be treated with a model that involves the generation of multiple incorrect candidates evaluated in parallel with the right one. This claim seems incorrect in light of the constructional algorithm just described.

Another case is Yidiɲ, which in light of McCarthy's data can be governed by the algorithm, "Dissect a word into two-syllable feet starting from the left edge. Next, if any foot has a long vowel in the second syllable, make all feet in that word iambic; otherwise, make all feet in a word trochaic." Or in McCarthy's own terms, "If an even-numbered syllable contains a long vowel... then that syllable and all other even-numbered syllables are stressed. Otherwise, odd-numbered syllables are stressed" (2002: 150). Again, McCarthy claims that this pattern merits an OT treatment, with generation of multiple incorrect candidates evaluated in parallel with the right one, but it is not apparent why. It is coherent and feasible first to define syllables, then assign feet, then scan for underlying length – which secures all the structure mentioned in the *if* clauses in McCarthy's generalization about the pattern – and finally to assign stress based on length in relation to feet, which secures the structure mentioned in his *then* clauses.

Axininca Campa (McCarthy and Prince 1993, cf. Prince and Smolensky 2002: 19) has a reduplication requirement that the base fill the bimoraic minimum length requirement for the prosodic word; bases which do not do this are augmented with (C)V as necessary. The base is copied in the reduplicant, along with this (C)V augment. McCarthy and Prince (1993: 79, cf. 88-89) claim an ordering paradox for serial constructive approaches, reasoning that the triggering environment for augmentation includes the reduplicant, which must therefore predate augmentation, but the reduplicant copies the base including the augment, so the augment must predate reduplication. What triggers augmentation is not necessarily the presence of the reduplicant, however, but can instead be simply the presence of the reduplication morpheme (see Samuels 2009a: 182). The appropriate constructive algorithm will direct that if the reduplication morpheme is present, then the base should be checked for bimoraicity; if the base is too small, it should be augmented to the bimoraic length. The reduplicant is then built (or phonologically realized) by copying the whole base, augment included. Whether or not this algorithm is more elegant than what traditional generative rule-writers would have devised for Axininca Campa is irrelevant for our purposes; what matters is that it is a successful constructional algorithm.

McCarthy and Prince (1998: 119) review some of the above examples as well as a few others, remarking, "Crucial evidence distinguishing serialist from parallelist conceptions is not easy to come by; it is therefore of great interest that reduplication phonology interactions supply a rich body of evidence in favor of parallelism." In surveying their analyses of these cases, however, I reach essentially the same conclusion as in the discussion above. The reduplicative processes have somewhat complex constructional algorithms which, when triggered by the presence of the at least partially specified base concatenated with the appropriate reduplicative morpheme, call for copying of the base in the reduplicant *plus* certain additional developments which could be realized with either more serially ordered rules or rules with more complex directions. While some early rule-based theories may not have explicitly accounted for such situations, the notion that constructional algorithms cannot handle these patterns in a clear, efficient, and restrictive fashion seems mistaken.

5.4.5 Southeastern Tepehuan

Finally, Southeastern Tepehuan (Kager 1999: 177-188) syncopates the vowel in even-numbered syllables that are open, a process that could be attributed to the syncopated vowels being unstressed while the remaining vowels have secondary stress – apart from the main-stress vowel, of course. Main stress falls on the first syllable if the second underlying syllable is light, otherwise on the second syllable; from an output perspective, this means main stress falls on the second mora after syncope.

Kager objects to the idea of attributing syncope to stress patterns by asserting that there is no phonetic evidence for secondary stress, and offers instead a proposal that consonant-faithfulness constraints crucially conflict with prosodic constraints prescribing that every word has only one foot (sc. only one, primary, stress, and no evidence for secondary stress) and that as few syllables as possible should be footless. Hence, syllables are minimized by deleting vowels, but because deleting all unstressed vowels would result in unacceptable consonant clusters, consonant-faithfulness constraints effect the preservation of roughly every other vowel to prevent this. This interaction between segmental and prosodic constraints is portrayed by Kager as thoroughly intersecting multiple levels of structure and providing strong support for the classic OT analysis where (to repeat Prince and Smolensky 2002: 22) “the entire structure” is “present at the time of evaluation”.

But as McCarthy (2008b) points out, the proposed forces motivating this kind of pattern are equally well satisfied by entirely different choices of vowel deletion, so what dictates which vowels are deleted? I assume one must add some stipulation. In a constructional approach, this could be a requirement that after the stressed syllable, odd-numbered vowels are favored for syncope while even-numbered ones are favored for preservation (to ensure, for example, that /tɨɨtɨroviɲ/ yields [tɨ́ɨtropiɲ] and not *[tɨ́ɨtɨrpiɲ], a candidate Kager does not consider). Without connection to a cross-linguistic principle of alternating secondary stress, such a stipulation does not seem particularly explanatory. It is also serial since it refers to stress, which is not underlying (see McCarthy 2007: 66).

The requirement could be rewritten without reference to stress, but the result would be even more ad hoc. In OT, markedness constraints cannot refer to the input, and since stress is not underlying in Southeastern Tepehuan, faithfulness constraints cannot refer to stress. So we would have to choose among faithfulness constraints recommending the preservation of certain vowels, and markedness constraints recommending medial two-consonant clusters after certain vowels. Neither solution bears much resemblance to Kager's intentions, and neither seems very explanatory. It is also somewhat difficult to define "certain vowels". A faithfulness-dominant solution could recommend a faithful first-syllable vowel, faithful second-syllable vowel if the second syllable is underlyingly heavy and the first syllable is underlyingly short, and faithful even-numbered vowels thereafter (along with a markedness constraint forbidding consonant clusters above a certain size, apparently two). A markedness solution recommending as many as possible medial two-consonant clusters starting from the left edge of the word (without consonant epenthesis, [cons] changes, or input-output linearity violations) would work with words where the underlying second syllable had a short vowel, but not with words where that vowel was long – and markedness constraints cannot refer to underlying structure.

Southeastern Tepehuan syncope may indeed be "deeply *parallel*" (Kager 1999: 179) in a number of senses, but it is not parallel in the sense that evaluation must work with profusely generated complete output candidates, with no reference to the input other than to check faithfulness. A constructional approach actually seems not only viable but superior. As a parting note on this language, Kager's claim that there is no evidence for secondary stress may be circular. Suppose that the underlying vowels synchronically selected for syncope originally received the weakest degree of stress (i.e. none) and that all other vowels (at least medially) had secondary stress: syncope would then remove the bulk of the evidence for the difference between unstressed and secondarily stressed vowels, and the originally secondary stress level would easily be reanalyzed as a new unstressed level.

5.4.6 Review

The examples in all the languages we have reviewed involve the interaction between different domains of structure (syllables, morae, stress, epenthetic augments) not present in the input. Prosody is the realm *par excellence* where multiple domains interact, and it is no accident that OT's main claims to improved analysis of particular data mostly involve prosodic problems, while the best-known phenomena that seem to require serial derivation involve non-surface-true generalizations about interactions *within* the same domain, typically segmental phonology (cf. McMahon 2003, 2000: 24). However, even the multi-domain problems can be solved constructionally and do not require a blind, profuse Gen discrete from Eval.

Parallelism in a broader sense – the consideration of multiple factors or options before reaching a decision – remains an attractive concept, correlated with the notion of avoiding the inelegant breakdown of process descriptions into any unnecessary ordered steps. But of course that notion predates OT. While the imposition of extrinsic ordering on all generative events, even those that do not require it, is a hallmark of both *SPE*-style generative phonology (see McCarthy 2007) and gradualist post-OT theories (e.g.

McCarthy 2007, 2009b, 2010a), at least in the former tradition there was considerable freedom to replace certain groups of ordered rules with single, more complex rules that could look for multiple properties at once and react accordingly. The Elsewhere Condition is an example of such a rule structure (see McCarthy 2002: 139, 149).

5.5 The architecture of phonology

5.5.1 Grammars differ in content, not just its permutation

The question – How much grammar can be learned rather than innate? – is championed among others by Chomsky under the rubric of minimalism (Samuels 2009a: 1-3). Much minimalist work has been done in syntax, but interest in the same question has been gaining ground in phonology (Becker and Potts 2011 §5). We saw this in the last two chapters in discussions of several recent works on the emergence of phonological features and feature co-occurrence patterns from non-cognitive factors. Several arguments were reviewed (especially in §3.3.3) for the learnability of features and, by extension, feature co-occurrence patterns. We now pursue formal implications of these ideas for grammar design theory. Except as noted, the discussion will remain neutral on whether features are learned or innate, focusing instead on how feature co-occurrence patterns could be learned in a language-specific fashion as the building blocks of phonologies.

It would be superfluous for learners to acquire grammatical directions that have no effect or activity in their language, so the most natural expectation is that grammars differ in their contents, not just in how the contents are organized (Hale and Reiss 2000a: 164). The details of cross-linguistic patterns that emerge during early childhood babbling which are not part of the ambient adult language, or in loanword adaptation without having been previously present in the borrowing language, can be attributed to phonetic factors without being treated as structures that all learners encode into their grammars (cf.

§5.2.2). Thus, while OT is agnostic about whether its universal constraint set is learned as "a consequence of universal functional pressures like the architecture of the human vocal tract and perceptual system, or the task demands of communication" rather than being genetic (Smolensky et al. 2006:1:42-43), the vastly more parsimonious hypothesis is that these functional pressures only create grammatical structure on a language-specific basis – when a learner adopts a particular pattern not present in the observed usage of mature speakers, or when borrowers adopt a particular pattern not previously present in the borrowing language. In other words, cross-linguistic trends in babbling and loanword adaptation are evidence of linguistic knowledge which is only incorporated into actual grammars to the extent that it changes them. It is redundant to load grammars with a universal constraint set either innate or derived from these forces, because such a resource is unnecessary for either speaking or understanding any language. Additional arguments against the idea that the same constraint set is present in every language are presented by Ellison (2000).

The notion that grammars can differ in content, not just ranking, actually accords well with the claim of Smolensky et al. (2006:1:40) that grammatical constraints are part of the abstract (symbolic) information level, implemented at the neural level in a distributed fashion. Given that Smolensky et al. (2006) envision both grammatical forms and grammatical constraints as distributed information patterns within neural networks, given that grammatical forms are clearly learned, and given that neural connection weights can also be learned (ibid. 1:8), a reasonable hypothesis is that content-specific grammatical constraints are learned too, rather than genetically hardwired into the nervous system – and that they are incorporated into the grammar as needed, not in superfluous profusion.

5.5.2 Users optimize grammars, not just words (and not typologies)

Riggle (2004) discusses a grammar implementation model which during the learning phase establishes possible input-output paths, gives each segment of each path a constraint-violation score, and then identifies the optimal path so that subsequent mature grammar execution can simply follow that. The goal is to dispense with a certain amount of "online" optimization: once certain successful generalizations have been found, they do not need to be rediscovered during every applicable speech act. In this respect, Riggle's model aims at being smart (§5.3). It is also admittedly highly simplified since it is restricted to building outputs one segment at a time from left to right. Of interest though is that parts of Riggle's model aim at restricting online generation and optimization by having the learner lock in successful generative sub-paths and not have to recreate them for every applicable speech act.

> Finally, with the entire grammar represented as a single preoptimiz*ed* evaluation function it is possible to detect and generalize recurring patterns across the optimization of various input strings and thereby construct... a transducer that directly generates optimal output forms from underlying forms. In effect, this move obviates the need for word-by-word optimization since all of the optimization is done in the process of the creation of the transducer... to create a machine that generates all and only the optimal candidates... Specifically, I'll present here an algorithm for constructing transducers that map input forms directly to the output forms that would be selected as optimal under a given ranking of a set of constraints. With such transducers it will be possible to generate optimal output forms without the need to do optimization on each input/output pair. By encoding optimal parses directly into a finite state transducer it will thus be possible to circumvent the need for on-line optimization. (Riggle 2004: 16, 20, 43, 138-39; emphasis added)

In the final pages, Riggle addresses the danger that obviating optimization during grammar execution might be viewed as anti-OT:

> Another aspect of the model developed here that should receive further scrutiny is the representation of OT grammars... as transducers. There is some tension between ranked sets of universal constraints on one hand and finite state machines on the other. The former is far more elegant in terms of describing the range of possible languages and the relatedness of languages to one another while the latter is far more transparent in terms of describing the input/output mapping defined by a particular grammar. One might ask if one of these representations of phonological grammars was more "right" or more illuminating than the other.
>
> Considering my algorithm for turning ranked sets of constraints into finite state transducers that map inputs directly to optimal outputs, it might seem as if I've taken the OT out of Optimality Theory. That is, one might think that the low-level description of the computation of optimality is somehow closer to the "true" phonology and should therefore obviate the need for constraints and rankings. Such a conclusion would be mistaken, first and foremost, because ranked constraints provide elegant descriptions of the relations that are defined by phonological grammars and of the relationships among various grammars (languages), while the algorithms that I present here represent merely one method for computing these relations. (2004: 173-74)

Distinct topics seem conflated here, amounting to a covert switch of subject from the nature of grammars to ways of comparing grammars. If a grammar is the cognitive system speakers use for recognizing and producing speech in a particular language, why would any grammar need to be "elegant in terms of describing the range of possible languages and the relatedness of languages to one another", let alone sacrificing clarity in the description of that particular language for the sake of these cross-linguistic revelations? We are given no reason to suppose that foregrounding cross-linguistic insights is a task of individual grammars. Granting that "ranked constraints provide elegant descriptions... of the relationships among various grammars," such descriptions cannot be equated *with* grammars, and no argument is given for requiring them to be components *of* a particular grammar.

Another claim in the quotation is that "ranked constraints provide elegant descriptions of the relations that are defined by phonological grammars". This claim, assuming it is distinct from the one just analyzed about relationships among grammars, must refer to relations within an individual grammar. If so, it seems to conflate the difference between actual relations and possible ones and to make essentially the same mistake as the first claim. The actual relations that a grammar has to capture to get from inputs to outputs – which are the only relations we can prove that it does capture – are precisely the relations that Riggle's algorithms attempt to isolate by reducing online optimization "to create a machine that generates all and only the optimal candidates" (2004: 43). What other relations exist within a grammar, except for latent possible rearrangements that are entirely counterfactual? It is not a grammar's job to indicate what other grammars of the same language would have looked like, or what grammars of other languages do look like.

Riggle's comments emphasize that reducing online optimization as an activity of grammars is not necessarily better than keeping it, but the justifications given for the latter seem to switch topic from grammar to cross-linguistic typology. What if one's focus stays fixed on what grammars are – or better yet, what if one focuses on the larger picture of not only what grammars do, but also how they are acquired? The issue of locking in successfully learned patterns is then seen as a simple one of retention. In what sense is it optimal to learn the same item over again every time the item is needed? In most other contexts, successfully learning something normally implies retaining it for a significant time so that it does not have to be relearned every time it is needed. If this notion is carried over into grammar design, the optimal grammar is one where as much optimization as possible has already been carried out by the time the speaker reaches maturity.

A theory which incorporates this concern into its core will plainly differ from one which treats the search for smart grammars as a merely implementational issue of no interest for defining the essence of the theory. Reinventing the wheel is either a theoretically fundamental part of every act of driving, or it is not. But the two models of what travel entails are radically different. Formalisms which facilitate permutational typological exercises are interesting, but there is no reason to consider such activities part of the grammars of individual languages.

5.5.3 Grammars don't handle the rich base

The preceding arguments that the detailed contents of grammars are efficiently learned and that grammars consequently differ in content, not just ranking, clash with a core OT doctrine: Richness of the Base (RotB). According to this hypothesis, grammars are so designed that if all linguistically possible inputs (sequences of all possible feature combinations, Smolensky 1996: 4-5) were fed through a grammar, each input would map to a grammatical output for that particular grammar (Tesar and Smolensky 2000: 75, cf. McCarthy 2008a, Kager 1999). Smolensky et al. (2006:2:233) present the argument for RotB this way (emphasis original):

> OT is a highly output-oriented grammatical theory. The strongest hypothesis is that *all* systematic, language-particular patterns are the result of output constraints – that there is no other locus from which such patterns can derive. In particular, the *input* is not such a locus. Thus, for example, the fact that English words never begin with the velar nasal *ŋ* cannot derive from a restriction on the English lexicon barring *ŋ*-initial morphemes. Rather, it must be the case that the English grammar *forces* all its outputs to obey the prohibition on initial *ŋ*. This requirement amounts to a counterfactual: *even if there were* an *ŋ*-initial lexical entry in English, providing an *ŋ*-initial *input*, the corresponding *output* of the English grammar would *not* be *ŋ*-initial. Thus, the absence of *ŋ*-initial words in English must be explained within OT by a grammar – a ranking of constraints – with the property that *no matter what the input*, the *output* of the grammar will not be *ŋ*-initial.

The fact that language learners are most commonly exposed to correct outputs and not to incorrect outputs which are clearly identifiable as incorrect makes it inherently difficult for learners to construct grammars capable of identifying all possible losing output candidates in conformity with the Richness of the Base requirement, a problem which continues to challenge both the mechanics and the psycholinguistic realism of OT learning theories in spite of attempts to resolve the difficulty by biasing learning algorithms *against* simple (faithful) input-output mappings (see Albright and Hayes 2011: 7-8). That bias becomes even more problematic given various studies showing that learners initially tend to prefer faithful mappings and that they learn morphophonological alternants later *even* when the marked alternants reflect phonetically well-grounded constraints (see Albright and Hayes 2011: 13).

The quotation above confirms that requiring grammars to handle the Rich Base of all cross-linguistically possible inputs is a consequence of the premise that grammars differ only in constraint ranking plus the premise that only output properties can be simply recommended or penalized (markedness constraints: §5.3). I have already argued against the first premise (§5.5.1). The next section develops an argument against the second premise, leading ultimately to the conclusion that individual languages do not handle the Rich Base (§5.7).

5.6 Generalized partial representations

5.6.1 Introduction

The idea that content-specific grammatical directions (such as rules or constraints) can be learned by generalizing about recurring content patterns in observed data has been explored by Albright and Hayes (2006: 4-5), with a somewhat similar line of research in Boersma and Pater (2007). Albright and Hayes develop a procedure for deriving rules from paradigm forms. The forms are organized and subjected to iterative comparison in a way “that lines up the segments that are *most similar* to each other”; material shared by multiple forms “is collapsed using the feature system”, while material that does not match across multiple forms “is designated as optional” and represented minimally. The point of interest is that the eventual rule contains feature specifications and segment sequencing information that have been taken directly from encountered words by generalization. Whether the generalization mechanism is formulated to produce rules or constraints, the key point is that it operates largely by finding and extracting elements common to the representations of multiple words that are observed to participate in the same phonological process.

I propose modeling most grammatical directions not as a special type of operation or object (rules or constraints) distinct from the phonological representations of words, but rather as generalized partial representations extracted from patterns observed in surface forms during acquisition. In speech production, grammatical representations are combined with idiosyncratic information about a particular string of morphemes (word parts stored in an abstract underlying form in the speaker's mental lexicon) to create a more complex representation of the desired word. This complex representation contains both the underlying forms of the input morphemes and the grammatical information which other theories encode in phonological rules or constraints. After constructing this representation, the speaker applies general principles to read from it the correct phonological output – the set of categorical specifications to be implemented as gradient real-time gestures in the actual utterance of the word.

By default, lexical inputs to the phonology activate the representations of relevant grammatical patterns on the basis of content match – either identity between two elements or, possibly, a category-to-instance relation between them identified during acquisition on the basis of shared phonetic content (issues with formalizing such information and how it would relate to underspecification are broached in §5.6.3). Restricted sets of lexical items that exceptionally do not activate grammatical patterns on the basis of content match would be inhibited with respect to those patterns. Grammatical patterns can also activate or inhibit one another, but because grammatical patterns form a closed set, these interactions can be modeled as part of the grammar rather than automatically triggered by content relations. Several possible types of activating and inhibitory relationships between representations are illustrated below.

Once a lexical input and all relevant grammatical representations are in conjunction, reading the output from this total phonological representation involves evaluating all the information within each timing slot and must include a protocol for adjudicating content conflicts. Such conflicts arise when some combination of the lexical input and the grammatical patterns within the total representation make clashing recommendations about a particular kind of element (e.g. about the value of a feature) in a given timing slot. While rule-based theories resolve this sort of clash largely through rule ordering and OT handles it through constraint ranking, the representational approach to grammar suggested here uses static licensing relationships. A single grammatical representation (definition of a grammatical pattern) will typically consist of two domains of phonological elements, both sensitive to intersegmental timing information. One domain licenses the other; from the viewpoint of speech production we can call them parent and daughter. Daughters consist of information not already available in underlying forms (the equivalent of information encoded in markedness constraints in OT and generated by rules in rule-based theories). Outputs are normally read by combining the lexical input with the daughters; when a daughter element clashes in a given timing slot with a lexical input element or with an element of another grammatical representation, the winning element is the one activated through the highest number of licensing associations, counted both directly and transitively. The daughters of licensing associations that are specially marked as inhibitory are excluded from this calculation, along with any material that cannot be activated without being licensed by them.

These ideas have important antecedents. The concept of licensing figures in Itô, Mester, and Padgett (1995) and Steriade (1995), but the details are generally very different; in particular, grammatical patterns do not license each other. Psychological node theories (e.g. MacKay 1987) and connectionist network theories (Garson 2010) also employ licensing relationships of sorts, as connections between nodes or nerves, with thresholds for activation across those connections. Some of these concepts will be discussed below as they relate to the way the present model would be neurally implemented.

The following sections apply this model to several well-known types of pattern interaction. Conventional terms for these patterns are incorporated into the discussion. These terms tend to imply ordered processes, but it should be kept in mind that the pattern representations being proposed here are not ordered processes.

5.6.2 Illustrations: epenthesis and spirantization

To begin, suppose a language learner progresses to the point of sorting out stems from certain suffixes on the basis of their combinatorial behaviors. The suffixes begin with vowels, and the stems end in two-consonant clusters. The learner notices that when the same stems occur with no visible suffix, *ε* normally intervenes between the two consonants. This is a generalization about parts of the representations of multiple words and suffixes. The learner extracts this insight from the relevant observed forms and stores it as a generalized partial representation defining this pattern. Specifically, the generalization is that the presence of *ε* between two consonants at the end of a word and the absence of *ε* elsewhere is systematic (grammatical) while the identities of the two consonants are unpredictable but consistent properties of particular morphemes which must be stored in those morphemes' lexical entries. The presence of two consonants without an intervening unpredictable vowel at the end of a word licenses an intervening *ε*, as schematized in (3). Association lines connect parent (licensing) to daughter (licensed) elements.

(3) Generalized partial representation of *ɛ*-epenthesis

Parent elements　C　C　#

Daughter　ɛ

Tiberian Hebrew (Semitic) has a productive pattern of this form, illustrated in (4) with an example from Green (2004: 43). For more data see Bruening (2000), Coetzee (1999), Green (2004), and Idsardi (1997a,b, 1998, 2000). I will abstract away from a few more narrowly conditioned cases where the epenthetic vowel is other than *ɛ*; for details, see Coetzee (1999).[9]

(4) Epenthesis in TH /qodʃ/ → [qoðɛʃ] 'sacredness'

Input　/q　o　d　ʃ /　#

Grammar　C　C　#

ɛ

(Output =　[q　o　ð　ɛ　ʃ])

The unsuffixed input /qodʃ/ has a word-final consonant cluster (*dʃ #*) which matches the parent material in (3) (CC#) as shown by the vertical association lines. This match activates the grammatical representation of epenthesis. From the conjunction of the input with this relevant grammatical pattern, the phonological output is read as the totality of active material, which here includes everything since no element is inhibited. The output

[9] A very few nouns, a number of jussive/imperfective verb forms, and verbs with a 3sg fem. *-t* do not epenthesize. Here I follow what seems to be the more widely accepted analysis that this non-epenthesis is exceptional. Green (2004, cf. Bruening 2000) alternatively treats it as the default and requires all epenthesizing forms to be lexically marked as trochaic, which introduces a new (metrical) category of lexical diacritic. Under that analysis, the rest of my discussion of Tiberian Hebrew would simply require the additional metrical diacritic in the UR of epenthesizing forms. This would not affect my arguments below.

is shown at the bottom of (4) in parentheses to emphasize that it is already contained within the conjunction of the input with the grammar. The output actually licensed by (4) is an incorrect *[qodɛʃ] rather than [qoðɛʃ] because we have not yet accounted for the continuance of the second consonant.

The latter property is due to how epenthesis interacts with another Tiberian Hebrew grammatical pattern wherein non-emphatic postvocalic singleton obstruents are spirants (see Rendsburg 1997: 74-75, as well as the sources on epenthesis above). The phonetic nature of the excluded emphatic consonants is uncertain, but the most common suggestions are glottalization as in Ethiopic Semitic and dorsopharyngealization as in Arabic (Thelwall and Sa'adeddin 1999, Rendsburg 1975: 73-76). The exclusion of emphatics from this pattern must be specified in the grammar; we will use [-RTR] provisionally here (see Idsardi 1998: 50). The fact that vowels are predictably continuant is represented here as V([+cont]) (§5.6.3).

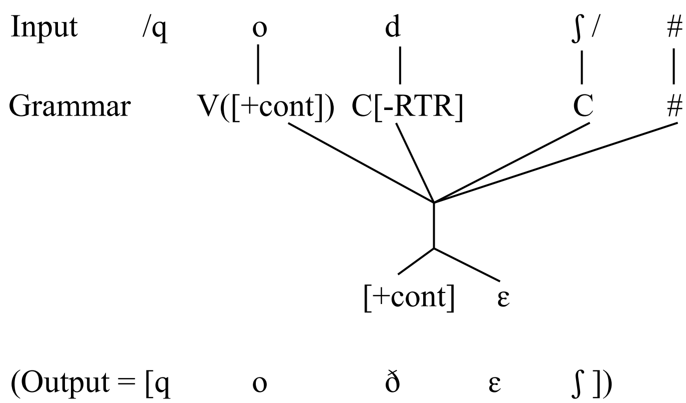
(5) TH postvocalic spirantization

Parent elements	V([+cont])	C[-RTR]
Daughter		[+cont]

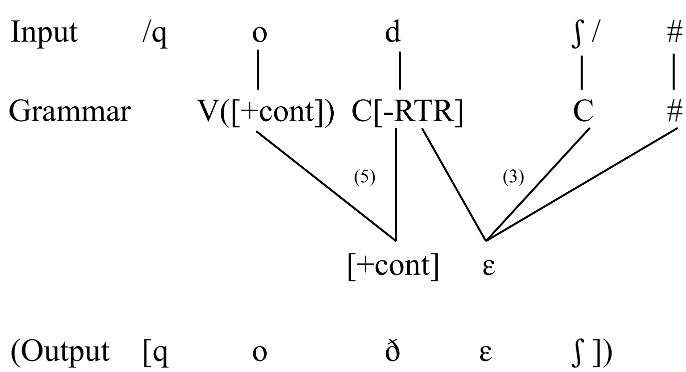
When the learner has noticed that a more narrowly conditioned grammatical pattern can be captured by combining the representations of independently motivated and less narrowly conditioned grammatical patterns (cf. Kiparsky 1982: 233-234, Vaux 2008: 9), nothing prevents the learner from establishing this connection in the grammar. Thus in /qodʃ/ → [qoðɛʃ], instead of positing the parochial grammatical direction represented in (6), the learner may combine the independently needed representations of epenthesis (3) and spirantization (5) as shown in (7).

(6-7) Representations of TH epenthesis and postvocalic spirantization in /qodʃ/ → [qoðɛʃ] 'holiness'

(6) Parochial



(7) Generalized



The parochial grammatical direction in (6) and the generalized grammar in (7) differ purely in their internal associations. In (6) there is no analysis, simply a stipulation that the string V([+cont]) – C[-RTR] – C # (using dashes to separate timing slots) licenses [+cont] in the third timing slot in the string and an epenthetic *ɛ* inserted after this slot. In contrast, the same information is analyzed in (7) as a conjunction of the representations of (3) epenthesis and (5) spirantization, shown by labeling the appropriate association-line clusters as [(3)] and [(5)].

5.6.3 Underspecification and multi-modal cognition

Having the lexical input /qodʃ/ activate the epenthesis and spirantization patterns as shown above requires a type of knowledge that we have not yet discussed: the user must be able to identify consonants and vowels.

Brain imaging studies indicate that the vowel-consonant distinction is psychologically significant in auditory processing and speech planning (Singer 2009, Woods et al. 2011), and the distinction is phonetically evident in broad activity patterns of several laryngeal muscles (§2.2, second to last paragraph). It is also phonologically evident in patterns like epenthesis, which seems to have a higher-than-chance frequency of inserting consonants between vowels or vice versa. Consonant or vowel epenthesis often relates to existing syllable structure (Samuels 2009a: 122) or to the perceptibility of segments already present; e.g. some consonants lose their most salient cues unless a vowel follows (Henke et al. in press, Wright 2004).[10] Thus the consonant-vowel distinction seems psycholinguistically real, phonologically active in a wide array of languages, and phonetically natural. Yet how is knowledge about this distinction configured in relation to lexical underlying forms? Is every consonant token somehow

[10] This summary of the natural phonetic motives for consonant and vowel epenthesis is supported by the fact that its explanatory coverage seems to have principled boundaries: common types of epenthesis not covered by this explanation appear plausibly derivable instead from natural phonetic variations in how intersegmental transitions are coordinated or perceived. These variations include failure to synchronize wholly or partly independent gestures (Ohala 2005: 10-11), decelerated transition between a stop and a more open segment (see Chomsky and Halle 1968: 319) or vice versa (Green 1997: 56), and historical development of stop release noise (Hyman 2003: 19-24) and concomitant higher-pressure airflow (Ohala 1983: 204-205) into a fricative in the constricted environment of a following high vowel (cf. Hall and Hamann 2003).

marked as such in the lexicon, or are lexical consonant tokens unspecified for the property of being a consonant, with this information being supplied by the grammar?

Notice how this question is about a different kind of structure from (3). There and in all the other representations of grammatical patterns explored below, the parents and daughters are strings distributed across multiple segmental timing slots, and everything in the parent string must be present in order to license the daughter string. The question of how users know that /d/ is a consonant, however, is a question about a list and does not involve multiple timing slots: there is simply a set of elements, every one of which counts as a consonant in and of itself. The question we just asked about this set is, in effect, whether the members are individually identified as consonants in the lexicon, or whether instead the list is stored in the grammar with its members as the parent material and its name ("consonant") as the daughter – so that a consonant in a lexical input is only formally recognized as a consonant when it has activated the grammatical list for the consonant category.

Either option is feasible. The second one conserves memory by preventing the lexicon from duplicating in multiple places a piece of information (which segments are consonants) that can easily be stored in one place. However, the brain does not seem to value that kind of conservation as much as we might expect. Instead of storing different pieces of information in separate places, the brain has an incredible propensity for translating them into different activation patterns distributed across many nerves and regulated by learned weights on the nerve connections (§5.3). Instead of vetting incoming stimuli and refusing to save information deemed already presented in memory, the brain stores information about repeated or similar experiences in a fashion that allows the mental representation of tokens to influence more general ideas and expectations about types (a focus of exemplar theories: Dogil forthcoming, Pierrehumbert 2001, Walsh et al. forthcoming). Tokens of vastly different categories also readily activate one another.

> Each memory is not a completely separate item, like a photograph in a drawer or a file in your computer would be... [P]eople do better on an exam when they are tested in the same room that they had lessons in than they do when they are given the same exam in a different room, so they must have learned information about the room along with the lessons... Clearly, our brains are not particularly selective. All the things that are going on at a given instant are linked together (and as we get older, we seem to hold onto more and more of this incidental information...)
>
> When two sets of stimuli occur together many times... the connections among them get strengthened... Knowing about the larger structures of the brain, including the language sensitive areas, is critical for understanding the effects of brain damage, but we have to work at the level of the neurons to understand how we learn and process language... Organizing [linguistic] processes into levels and sublevels does not mean that each level is isolated from the others [discretely modular and serially active]... the assembly line metaphor is not a good approximation to what goes on in the brain. (Menn 2010: 81-84, 95, 110; cf. 61, 113-115, 162, 258, 331, 390)

These insights are based on a vast body of experimental findings, some of which involve speech errors. For instance, word blends and substitutions have shown that phonological content can prime lexical retrieval:

> D. G. MacKay (1973b) found that words involved in blends were phonologically as well as semantically similar with greater than chance probability, and Dell (1980) showed that phonological and semantic similarity independently and reliably influence these errors. Dell (1980) also reported a parallel phenomenon for word substitutions... These findings indicate that lower level processes (the phonological representation) can influence higher level processes (the selection and misselection of which word gets produced), and such phenomena are problematic for theories postulating separate perception and production components, with strictly topdown processes for production... (MacKay 1987: 34)

Syllable frequency also influences phonetics, even though this contradicts a strictly modular view of phonology as a computer that manipulates morphosyntactic input specified with only lexical phonological information and that emits outputs for phonetic implementation without these different domains being able to influence one another (see Pierrehumbert 2001: 137-138, Walsh et al. forthcoming, 13; cf. Bybee 2002:

59-60, Sosa and Bybee 2009: 483 on phonetic sound changes sensitive to word frequency).

All this raises questions about the appropriateness of models that emphasize underpecification as key to understanding grammatical processes. Storing predictable phonological specifications in a separate place from lexical information and laying great importance on when that information enters into the phonological construction of word forms are ideas that strongly evoke the limited power of the computers which we are currently able to build; these ideas relate much less clearly to the highly distributed nature and liberality of association and activation which characterize the brain. This is certainly not to say that there are no characteristic orders in which different grammatical aspects of an utterance are constructed (semantic, syntactic, morphological, etc.), but it does impel us to scrutinize the phonological evidence for underspecification carefully.

In Steriade's (1995) broad review of rule-based underspecification theories, the cases where predictable information allegedly needs to be specified after the application of some rules center around the problem of modeling phonological processes as the local manipulation of association lines between autosegmental tiers without letting the association lines of elements that participate in those processes cross over the association lines of non-participants. Delaying specification of some non-participating elements until after a process is one solution to the problem. We have already noted independent arguments against this use of underspecification, though (§3.3.8). The only other arguments I have encountered for not specifying predictable material until after a certain stage of derivation have to do with lexical economy, and we have just seen that the psycholinguistic realism of such reasoning is doubtful.

Consequently, I adopt the working hypothesis that if we refrain from investigating when (or at what points in the associations among neural activity patterns) different parts of the grammar access intrasegmentally predictable information, the essential structure of grammatical patterns and their interrelationships can still be analyzed insightfully. This chapter accordingly remains agnostic about whether languages underspecify any phonological category simply because it is predictable (see Samuels 2009a: 77-98, also Goldsmith and Noske 2005, Mohanan 1991, Odden 1992, Steriade 1995, Vaux 2010).

Theories of underspecification do impact another important topic: theories of phonological operations. For example, post-vocalic spirantization can be represented in process-oriented formats as continuance assimilation from vowels to stops, unless [+cont] is deliberately excluded from the vowel specification on the grounds that continuance is predictable in vowels (so Idsardi 1998). If any instance of contextually predictable information is phonologically unspecified, then phonetically natural phonological processes dependent on that information cannot be represented in a phonetically natural way unless their application is deferred until after the unspecified material has been filled in. In personal communication, Idsardi suggested that the specifiability of contextually predictable information relates inversely to how cross-linguistically common its predictability is, so that vowels can never be specified as [+cont] because by definition they are always continuant in every language. However, information about cross-linguistic feature co-occurrence trends is normally not available to learners constructing grammars as posited by Emergent Feature Theory. This leaves learners with two ways to handle at least some phonological patterns that depend on predictable information: induce contextually predictable feature specifications based on patterns that can be deduced from the final phonological shapes of words, or construct phonetically unnatural phonological representations of the same patterns in order to have them apply to underspecified forms.

Both options are indicated noncommittally in the representation of postvocalic spirantization above (5): the first element in the parent string is spelled V([+cont]), indicating a specification of the vowel category which may or may not include [+cont]. If [+cont] is included, then the phonological representation contains contextually predictable information but also reveals a phonetically natural analysis of postvocalic spirantization as the result of an assimilation operation between adjacent segments. If [+cont] is not included, then the representation is more economical but also more arbitrary; the daughter element seems to be inserted *ex nihilo*. In that case one might ask why vowels license [+cont] on a following stop rather than licensing, say, simultaneous palatalization and rounding. However, in an emergent framework, the answer to this question is provided by the theories of sound change and acquisition, not by the theory of representations of phonological patterns, so the phonetic unnaturalness of representations involving formal *ex nihilo* insertion is not a reason to reject such representations.

In other words, it is already clear from a variety of other cases that phonetically unnatural grammatical patterns occur in languages thanks to sound changes cumulatively obscuring their predecessors' conditions (§3.3.1), so grammars have to be capable of representing phonetically unnatural phonological patterns. This suggests that phonetically unnatural representations could be constructed for some phonetically natural patterns that depend on predictable information, if learners prefer not to specify such predictable information in phonological representations. If so, there would be no clear objection to a theory of phonological representations in which general postvocalic stop spirantization and labio-palatalization were represented with the same structure; the fact that the former occurs while the latter seems unattested would be explained by the nature of acquisition and sound change, not by the nature of phonological representations. Regardless of how hard it may be to learn unnatural patterns, the formal properties of mental representations of learned information are not necessarily *responsible* for whether the information is hard to learn, any more than for whether the information has cross-linguistically common or rare properties (see Hale, Kissock, and Reiss 2006).

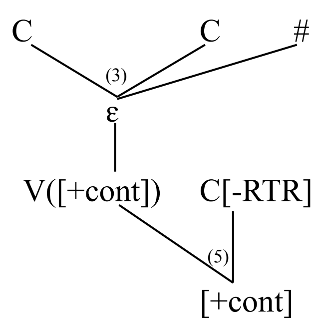
In summary, the arguments we have seen for features needing to be specified after a certain point in phonological derivation relied on a psycholinguistically unconvincing way of modeling transparency in autosegmentalism, and the argument that a feature needs to be specified before a certain point in phonological derivation in order to avoid a phonetically unnatural representation involving *ex nihilo* feature insertion depends on asking the theory of representations to handle what may actually be the responsibility of acquisition and sound change, at least in an emergent framework. In the absence of convincing evidence that predictable phonological information is not available throughout the construction of phonological representations, we will adopt the working hypothesis that it may or may not be, and that further knowledge of the matter is unnecessary for insightful analysis of the essential structure of phonological patterns.

5.6.4 Feeding

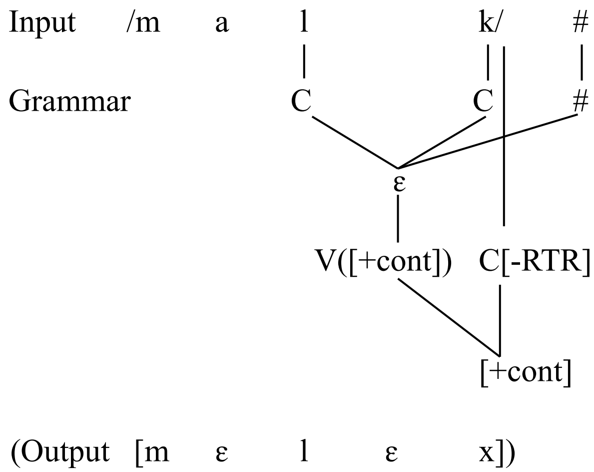
A pattern which activates another is traditionally said to feed it. Feeding and three other kinds of relationships discussed below (counterfeeding, bleeding, and counterbleeding) are traditionally captured in serial rule-based approaches by different rule orders (Mascaró 2011). There appears no satisfactory way to capture counterfeeding and counterbleeding in OT without resorting to serial derivation (McCarthy 2007).

Epenthesis feeds spirantization in Tiberian Hebrew (see the sources under (3)). This combination of (3) and (5) is represented in (8) with an example in (9).

(8) TH epenthesis feeding spirantization

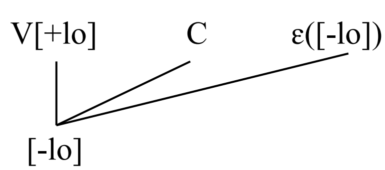


(9) TH epenthesis feeding spirantization in /malk/ → [mɛlɛx] ‘king’

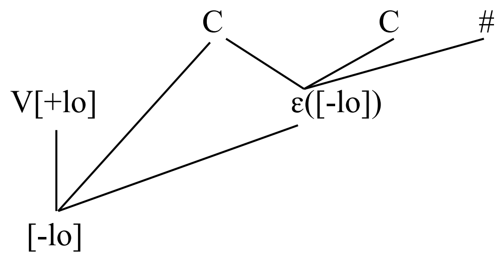


Something missing in (9) is a representation of the insight that the words which have *a* before a stem-final consonant cluster generally change it to *ɛ* in unsuffixed forms containing epenthetic *ɛ* (see e.g. Coetzee 1999, Green 2004). This pattern is shown in (10), aligned with epenthesis which activates it in (11), and exemplified with /malk/ in (12). (The notation V[+lo] for a low vowel may be taken as informal; regarding the vowel category and the notation *ɛ*([-lo]) for the predictable fact that *ɛ* is not low, see §5.6.3.)

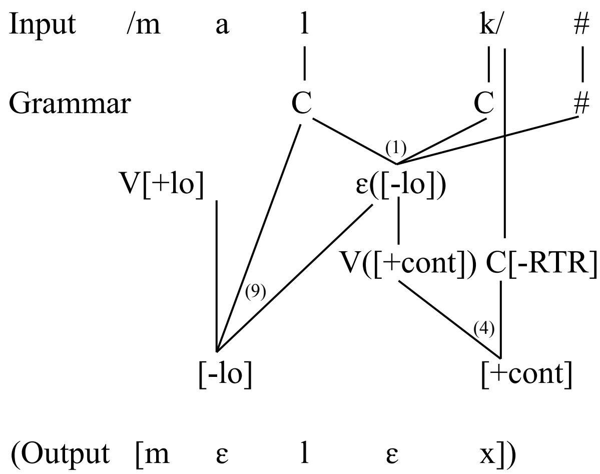
(10) TH *a* assimilating to *ɛ*



(11) TH epenthesis feeding *a*-assimilation



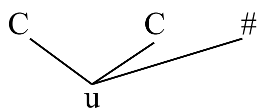
(12) TH epenthesis feeding *a*-assimilation and spirantization in
/malk/ → [mɛlɛx] 'king'



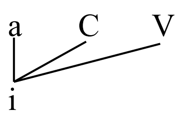
5.6.5 Counterfeeding

When pattern *x* logically could feed pattern *y* but does not, it is conventional to say that *x* counterfeeds *y*. The following counterfeeding example is taken from a dialect of Bedouin Arabic dialect where in traditional terms there are two productive processes: a process "raising short /a/ to a high vowel in a nonfinal open syllable" and "a process of epenthesis that breaks up final consonant clusters" (McCarthy 2007: 10, 26; 34). The epenthetic vowel is represented here only as it appears in this word; since its quality is not relevant to the analysis, we abstract away from any other complications in epenthetic vowel quality in this dialect. Epenthesis is shown in (13), *a*-raising in (14), their interaction in (15), and a word exemplifying the interaction in (16).

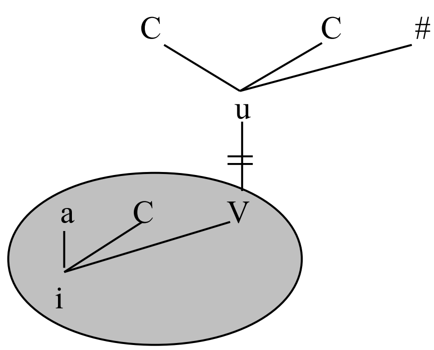
(13) Epenthesis in a Bedouin Arabic dialect



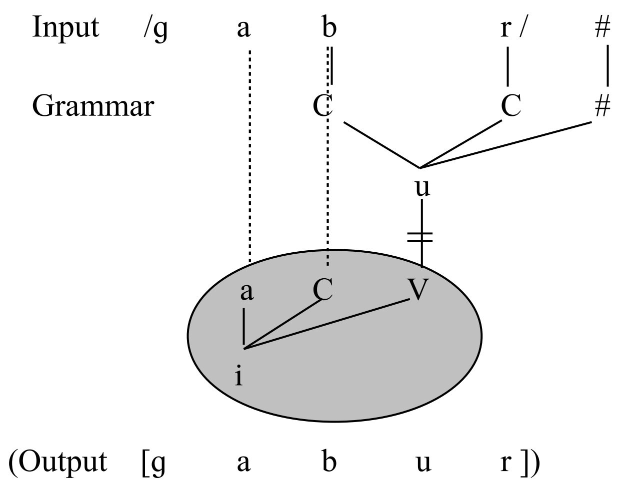
(14) *a*-raising in a Bedouin Arabic dialect



(15) Epenthesis counterfeeding vowel raising in a Bedouin Arabic dialect



(16) Bedouin Arabic counterfeeding in /gabr/ → [gabur]



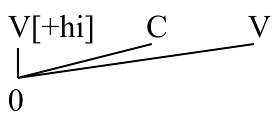
Since no plausible cross-linguistic synchronic principle has been found for predicting when a process that can feed another will do so and when it will not, stipulation is required. This is achieved by extrinsic rule ordering in traditional generative phonology (in this case, *a*-raising before epenthesis). No satisfactory way has been found to express counterfeeding in the classic parallel mode of OT (McCarthy 2007, esp. 34-35 on the failure of Local Constraint Conjunction).

The representational alternative I suggest here is an inhibitory connection between one pattern (epenthesis) and the other (*a*-raising): activation of the former licenses suppression of the latter. The inhibition is indicated by placing a double bar through the association line that joins the two patterns where they match and by greying out the suppressed pattern. As a result of this active suppression, matches between the input and the inhibited pattern are no longer strong enough to activate the latter; this is shown by dotting the appropriate association lines.

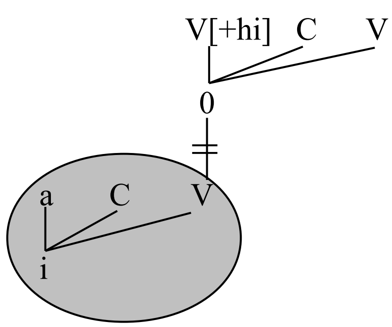
5.6.6 Bleeding and counterbleeding

Bedouin Arabic also provides the example /ʃarib-at/ → [ʃarbat]. This is described as showing a process “deleting short high vowels in nonfinal open syllables” (McCarthy 2007: 10) along with the process of raising that we saw in (14). The deletion pattern is shown in (17) and its interaction with *a*-raising is shown in (18), with a word illustration in (19).

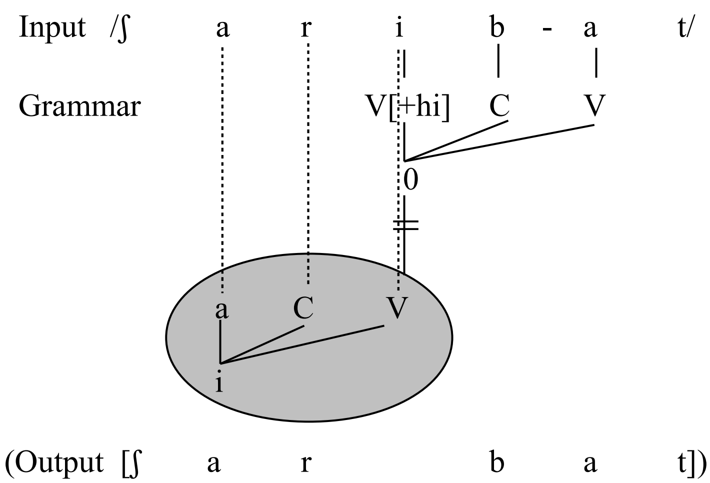
(17) Short high vowel deletion in a Bedouin Arabic dialect



(18) Vowel deletion bleeding *a*-raising in a Bedouin Arabic dialect



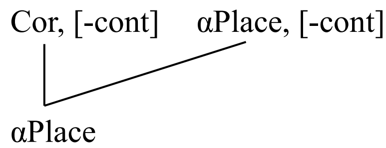
(19) Bedouin Arabic bleeding in /ʃarib-at/ → [ʃarbat]



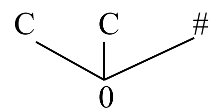
The inhibitory association is constructed in the timing slot where the inhibiting pattern has a daughter incompatible with a parent element in the inhibited pattern. Otherwise, the lack of content match between these two elements would leave them unassociated and both patterns would be activated by their content matches with the lexical input.

In that type of situation, where pattern *x* could naturally bleed *y* but does not, the conventional expression is that *x* counterbleeds *y*. Counterbleeding is a type of non-interaction between patterns. An example of counterbleeding occurs in Catalan, where coda cluster simplification counterbleeds (fails to bleed) regressive place assimilation. The two patterns are shown in (20-21), with a word illustrating their interaction in (22) (data from McCarthy 2007: 40-41). Only coronals undergo the place assimilation, and only non-coronals trigger it (Steriade 1995: 126, de Lacy 2002).

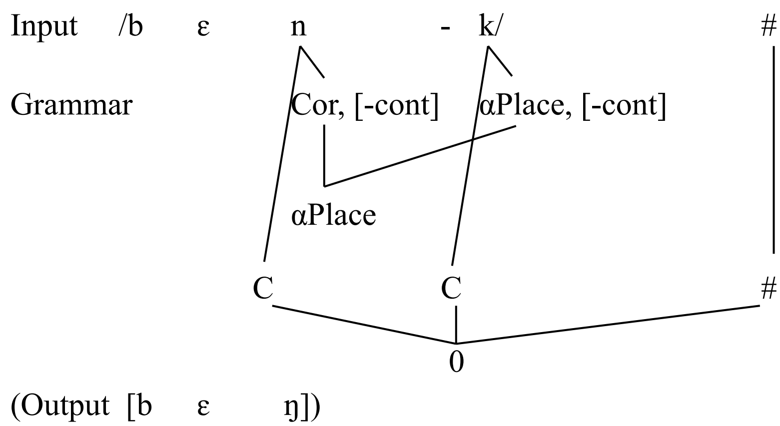
(20) Catalan regressive place assimilation



(21) Catalan coda cluster simplification



(22) Regressive place assimilation counterbleeds coda cluster simplification in Catalan /bɛn-k/ → [bɛŋ]



If (21) bled (20), the output would be [bɛn].

Since no plausible cross-linguistic synchronic principle has been identified for predicting when a pattern which could bleed another will do so and when it will counterbleed instead, stipulation is required; extrinsic rule ordering is used in rule-based phonology, but no satisfactory way has been found to model counterbleeding with parallelism in OT (McCarthy 2007: 33-34, 47-51, highlighting the failure of his earlier Sympathy Theory and various other patches proposed for OT in this area).

There has been considerable debate over which of the two, bleeding or counterbleeding, should be treated as a default with respect to the other (see McCarthy 2007, Kiparsky 1982: 72-74). In the present model, counterbleeding is formally simpler because there is no inhibitory association, but this does not necessarily mean that either pattern is formalized as being more natural than the other.

5.6.7 Do something only/except when...

The grammatical representations discussed above have a binary basic structural division between licensing material and licensed material. However, the representational format explored here easily allows for non-binary grammatical representations that straightforwardly account for additional phenomena. These phenomena include patterns described under the headings "do something only when..." and "do something except when..." in Baković (forthcoming), to which the reader is referred for examples.

In the present framework, do-something-only-when interactions can involve a grammatical representation which is unitary, containing no internal associations. It may even be a single feature. It achieves grammatical status by serving as a parent element crucial to the activation of multiple other grammatical representations. Do-something-except-when triggering can involve a grammatical representation which is unitary in the same sense, achieves grammatical status by being a daughter to multiple other grammatical representations, and suppresses them along with itself as soon as it is activated. Conflicting activation patterns and self-inhibition after activation are staple concepts in neurology (e.g. Lieberstein 1971, Smith and Jahr 2002, Yu and Choe 2006) and have also been explored in psychological node theories (see MacKay 1987: 34, 141-164).

In one famous do-something-except-when example, three-consonant clusters are avoided in Yawelmani Yokuts surface forms even though various rule interactions would otherwise produce them (Baković forthcoming 13, Kisseberth 1970). Other rules thus apply except when they would generate CCC. In the present model, any time a lexical input plus relevant grammatical patterns jointly license a CCC string in Yawelmani Yokuts, that string would activate an inhibitor which would suppress the string itself and its grammatical parents. The CCC inhibitory structure here is equivalent to a constraint *CCC, but its impact on output construction differs from both the classic OT schema (where there is no guided output construction: §5.3) and frameworks involving constraints that trigger rules which repair the outputs of previous rules (e.g. Calabrese 2005). Here, the CCC inhibitor does not trigger repair of any output form, because the output form is only read once the grammatical representations relevant to the input have reached their proper activity levels in conjunction with one another.

Another possible kind of do-something-except-when relationship is seen in Duke of York gambits. For example (McCarthy 2007: 23), Nuuchahnulth *a*) unrounds word-final uvular stops but *b*) rounds uvulars after round vowels. When a round vowel is followed by a word-final uvular stop, the latter is unrounded in the output, showing in OT terms that the constraints effecting (*a*) outrank those effecting (*b*), and in ordered-rule terms that (*a*) follows and undoes (*b*). The present model would have two grammatical representations in which *a*) a word-final uvular stop licenses [-rd] and *b*) a uvular stop after a round vowel licenses [+rd]. An input with a word-final sequence of round vowel plus uvular stop could be treated as activating both representations on the basis of content match, with (*a*) stipulated as inhibiting (*b*) to resolve the clash between them.

When there is no independent need for the unitary elements that condition some do-something-only/except-when relationships, those elements can in principle be duplicated in each of the other grammatical representations that they help license or inhibit. In rule-based terms, this is equivalent to incorporating the avoidance of CCC into each of the rules that would otherwise produce CCC. This entails some redundancy and loss of insight (Baković forthcoming 13-15). Such redundancy does not impair the grammar's practical ability to handle the data, however. In contrast, McCarthy (2007) argues that OT's practical ability to handle counterfeeding and counterbleeding with universal constraints is seriously impaired. This bears on the central concern of Baković (forthcoming). Baković identifies do-*x*-only/except-when-*y* patterns as opaque when surface conditions are not enough to predict the occurrence of *x*, and he emphasizes that the failure of rule mechanisms to capture these patterns complements the shortcomings of OT in handling other opaque patterns like counterfeeding and counterbleeding. Thus neither rules nor OT offers an ideal treatment of all of these phenomena. The difference in practical capacity that we have just noted between how rules handle do-something-only/except-when patterns and how OT handles counterfeeding and counterbleeding suggests that the balance in this case weighs in favor of rules, however, particularly since the way information is stored and organized in human memory does seem to exhibit considerable redundancy (§5.6.3). At the same time, the representational approach to grammatical directions presented here appears to avoid the shortcomings we have just seen with rules and constraints alike. It does involve sequences of activation flow and suppression throughout networks that realize grammatical patterns, but it is already known that such activities are neurally common.

5.6.8 Summary

Encoding grammatical patterns as representations that contain and share licensing relationships enables transparent yet not intrinsically serial analyses of what have traditionally been viewed as major kinds of process interaction, including opaque interactions. The computational efficiency of this model for both acquisition and mature execution is considerable. Compared with the classic OT schema, this model reduces the output candidate search space to a grand minimum. Additionally, if grammatical directions are learned, then the model renders superfluous the presence in individual grammars of most of the constraints that OT assigns through its universal constraint pool; instead, the information equivalent of crucially related subsets of OT constraints is learned in a vastly more compressed form via the extraction of partial representations from observed words.

This embodies the emergent (Mielke 2008), evolutionary (Blevins 2004), and substance-free (Hale and Reiss 2000a,b, Hale 2007) understanding of the relationship between innate cognitive ability, the learning process, and cross-linguistic trends in detailed phonological patterns. What the present model makes especially explicit is that observed word forms mediate between the phonological contents of synchronic grammar, on one hand, and phonetic and other non-cognitive forces that shape sound patterns diachronically, on the other. This mediating role of word forms is highlighted through the idea that a grammar's phonological feature information inheres in representations extracted from observed words rather than being located in constraints that are innate or learned through babbling.

Conceivably, some conjunctions of grammatical patterns (e.g. in 12 above) and even frequently recurring elements of the output in such complex representations are remembered by language users rather than discovered afresh for each use – just as most people remember the lower values in the multiplication table rather than recomputing them every time they are needed. This possibility about grammars is transparently captured in the present model by letting complex structures like the grammatical material in (12) (i.e. 12 minus the input and output rows) remain stable in a user's memory. With serial rules or the classic OT schema, in contrast, it seems less obvious how frequently accessed patterns in the grammatical machinery could be stored as "prefabricated" elements in memory so that they would not need to be recompiled at every use. This observation seems theoretically interesting because it identifies a category of operations in both rule-based theories and the classic OT schema which appear to be unnecessary for modeling or computing grammars. While it is common for information to be equally configurable in either declarative or serial-operational terms (see Garson 2010), the transformational equivalence of those two styles of format does not make them equally transparent in representing actual grammars with psychological realism. This section has presented a fresh search for such representations.

5.7 Output-drivenness

Languages use a wide range of possible input-output mappings. There are languages with underlying distinctions absolutely neutralized in all positions on the surface; for example, Blackfoot, Wichita, and Uyghur both have two underlyingly distinct segments that neutralize to surface *i* (Frantz 1991, Rood 1975, Comrie 1997), Menomini similarly has two underlyingly distinct kinds of *n* (Bever 1961: 33-34, 75-80), and Yucatec Maya has two underlyingly distinct kinds of *h* (Orie and Bricker 2000). There are languages with surface distinctions that reflect no underlying distinction, as is abundantly illustrated by extensive, systematic, and categorical consonant allophonies in the Numic branch of Uto-Aztecan (Charney 1993, Elzinga 2000, Sapir 1992[1930]). And of course in all languages there are faithfully surfacing underlying distinctions.

One way to capture these different kinds of input-output mapping is with grammatical directions that directly define the *maps*, which necessarily means including reference to both inputs and outputs. In OT, however, the only constraints that directly describe maps are faithfulness constraints which spell out non-occurrences of input-output mismatch. In other words, instead of treating it as the default for things to remain as they are, OT makes this type of case the only context in which constraints can refer directly to maps. All other OT constraints directly refer only to outputs, a much celebrated property that has been termed *output-orientedness* (Tesar 2008, Smolensky et al. 2006:2:233, cf. Prince and Smolensky 2002: 1).

As a result, OT must capture some types of mapping circuitously and even then problems remain. For example, the case of underlying distinctions absolutely neutralized at the surface could be partly described in OT by distinguishing faithful from unfaithful surface phones, though the choice of which was which might be arbitrary. However, forcing Wichita *t* to surface as [ts] before only one of the two kinds of *i* (Rood 1975) would require inter alia a markedness constraint banning output [ti] only when the *i* was the right sort. There are no properties which distinguish these two kinds of *i* at the surface level, but OT's output-orientedness by definition requires markedness constraints to refer only to outputs.

In contrast to OT, the representational model presented in this chapter defines grammatical directions *as* map components. In this model, restricting evaluation to output forms makes no sense. Evaluation (identification of the correct phonological output) is performed on total maps. Total maps are composed of grammatical representations associated with a lexical underlying form, and the output is identified as a portion of the total map's content. This captures a more efficient and intuitive picture of outputs than is possible under the requirement that content-specific constraints apply solely to output forms. That requirement forces grammars to use larger constraint sets so that they can handle inputs they never actually receive by assigning those inputs to outputs via mappings that are otherwise unnecessary, in order to handle violations of a set of generalizations that we cannot show are ever actually violated in the language (cf. §5.5.3). Mohanan et al. (2009: 8) have already argued that such a restriction may be inappropriate in an emergent framework. This chapter's constructive, representational approach renders the restriction pointless.

In place of grammars that are output-oriented in the sense of describing input-output mismatches only in terms of output forms, the present model accesses a different concept for which I will appropriate the term *output-drivenness*. This term has been used in various ways before. Some writers seem to use it synonymously with OT output-orientedness (Liu 2009, Hyman 2006: 4, Blevins and Garrett 2004: 120, Vaux 2001). Tesar (2008) redefines it as a logically possible formal property of grammars whereby no possible input maps to a grammatical output unless all possible inputs that are more similar to that output map to it also. Output-drivenness by this definition clearly relates to RotB, since both deal with mapping all possible inputs to grammatical outputs.

This chapter presents a view of grammar that can be described as output-driven in a very different sense: the derivation of grammar from observed outputs during acquisition is maximized to reduce innate/learnable duplication problems. In this framework, the analysis of actual outputs during acquisition controls the creation of more grammatical structure than in grammars with innate content-specific constraints. Output-driven grammars by this definition contain only the information that they need to operate and that learners can reasonably be expected to learn, rather than all the information that a typologist would want in order to elegantly describe grammars as permutations of each other. Grammars of this sort are optimized during acquisition.

As described at the outset (§1.3), this emergent view of phonology entails certain ideas about sound change too: a large percentage of sound changes are predicted to occur during acquisition as people construct grammars that differ slightly from the grammars of an older age group. These differences are more substantive than just the reranking of universal constraints, and because they occur during the process of creating grammatical directions more or less from scratch (without knowing anything about the grammars inside the older age group's heads), there is no reason to model the differences as the addition, deletion, or reordering of rules in grammars initially matching those of the older age group. These claims inform the methodology for reconstructing parts of the sound systems of prehistoric languages by retracing the sound changes that have affected daughter languages. In order to compare the daughter languages and make insightful guesses about past commonalities from which they diverged, it proves important to understand natural phonetic variation in sounds and different ways of mapping phonological categories (features) onto bundles of phonetic correlates (cf. §3.3.4). This is illustrated in the next chapter.

6 Reconstruction

6.1. Introduction

Chapters 2 and 3 developed a perspective on the laryngeal phonology of stops, and chapters 4 and 5 developed insights on the emergence of feature patterns within phonology in general. This chapter applies those findings to one of the most notorious unsolved problems in historical linguistics: the laryngeal contrasts of the Proto-Indo-European (PIE) stops, and the status of an apparent gap in one series where a labial is expected.

The comparative evidence for the PIE stop series is presented first, followed by a novel reconstruction and a brief summary of why this reconstructed system is synchronically realistic (§6.2). The evolution of this reconstructed system into the daughter languages is then systematically traced in both phonological and phonetic terms, with typological parallels and again with reference to the theoretical principles developed in previous chapters (§6.3). The proposal is contrasted with previous solutions to the same problems; shortcomings are identified in these but found absent in the new proposal (§6.4). A similar routine is performed on the problem of the apparent labial gap, with a critical typology of possible reconstructions (§6.5.1), a new recommendation, and a detailed diachronic elaboration of the consequences in the daughter branches (§6.5.2). A separate controversy about the number of PIE stop series is reviewed (§6.6). Finally, the results are summed up in the context of an evaluation of the historical-comparative method and the role of subsegmental information in reconstruction (§6.7).

Etymological research on Proto-Indo-European is more extensive than for any other proto language in the world. I propose no new etymologies here but focus only on the phonological analysis of the system which has already been reconstructed on the bases of hundreds of cognate sets. For this reason and also for reasons of space, I avoid discussing individual word forms and focus on *segments* instead. Extensive lists of cognates and discussions of the reconstructions of particular words will be found in the numerous works cited from the Indo-Europeanist literature.

6.2. The Proto-Indo-European stop system

6.2.1 Comparative evidence

The simplest reading of the comparative evidence is that PIE had three series of stops, one of them voiceless unaspirated and the other two voiced. This reflects the majority of the daughter languages. The “standard” or mainstream traditional reconstruction of PIE assumes this shape and differentiates the voiced series with aspiration, following the Indic reflexes. (Standard grammatical sources include Clackson 2007, Fortson 2004, Meier-Brügger 2003, Mayrhofer 1986, Sihler 1995. The best lexical resource is Rix et al. 2001.)

The comparative evidence is given in Table 6.1 in a simplified form highlighting the main reflexes for each of the three series according to standard sources like those just listed, except for Italic where the analysis of the second series follows Stuart-Smith (2004).

Table 6.1. Comparative evidence for the PIE stops.

	In.	G	It.	Gm.	Arm.	C	BS	Hitt.1,2	Alb.	Ir.	Toch.
I.	T	T	T	Θ	T^h	T	T	T^h, T	T	T	T
II.	$D^ɦ$	T^h	Θ/Đ	D/Đ	$D^{ʔɦ}$	D	D	T, D	D	D	T
III.	D	D	D	T	T	D	D	T, D	D	D	T

A fourth series T^h is found in Indic, but cognates elsewhere generally have the same reflexes as the first series, so Indic T^h is generally not traced back to a separate phonemic PIE series (see the above sources, Barrack 2002: 78, Lehmann 1996: 57, Salmons 1993: 8, and §6.6). The interpretation of Hittite is uncertain (see Melchert 1994); two possibilities are given here separated by commas. Series II is aspirated in numerous Armenian dialects, but it is unclear whether the series was associated with breathy voice in their common source (Garrett 1991: 798-99, Pisowicz 1976).

The standard reconstruction of the three series as T $\text{D}^{\text{ɦ}}$ D (also written T D^{h} D) creates an inventory with no attested parallel, notwithstanding various counter-claims (see §3.2.6.3f) which have sometimes been counter-balanced in their turn by inaccurate criticisms.[11] On the assumption that PIE was a natural human language, any systemic properties of PIE for which we find no attested parallels deserve closer study. Are they simply empirical rarities, or do broad theoretical considerations oppose them and suggest that the standard reconstruction is incorrect?

I argue that the latter is true and propose a revised reconstruction, taking into account the Indo-European comparative evidence, global typological evidence, and a coherent feature theory of the sounds involved. This reconstruction is presented in (23). After defining the synchronic phonology of this system and motivating it from the findings in previous chapters, I analyze how it evolved in the daughter languages (§6.3), showing that the paths of sound change have good typological parallels. (The nature and importance of this kind of diachronic typology has already been described and modeled by Hayward 1989, Job 1989, 1995, Ohala 1993, and Stuart-Smith 2004, among others; cf. Ohala 1990b: 268.) I then compare my proposal with previous reconstructions (§6.4).

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[11] E.g. D seems absent in inflectional and derivational morphemes, while $\text{D}^{\text{ɦ}}$ is not, and this has been treated as a markedness problem (see Clackson 2007: 46, Hopper 1973: 141, 155, 157). But the premise that languages have a strong tendency to select affix segments based on a markedness hierarchy is not corroborated by the evidence. Bybee (2005) concluded from her typological study of verbal affixes in twenty-three “maximally unrelated” languages that while languages obey some obvious exclusions, such as one against using only phonetically complex consonants (like coarticulated or non-pulmonic ones), there is otherwise only a weak, fractional trend toward patterned exclusions, and that these are due to a variety of reasons including phonetic reduction (which privileges the non-complex) and the reuse of old affix material.

For readability, asterisks are generally omitted from hypothetical forms; attested forms are labeled as such or with the appropriate language name.

6.2.2 A new proposal

I propose that the PIE stop series were voiceless unaspirated, voiced unaspirated explosive, and voiced non-explosive (§2.6.2). This inventory type is cross-linguistically well-attested (§3.2.5).

(23) The PIE stop series

I.	/T/	[T]
II.	/D/	[D]
III.	/D$^<$/	[D$^<$]

The suggestion to redefine the second and third series as unaspirated voiced explosive and voiced implosive or non-explosive was made by Haider (1985) and developed by Weiss (2009) and Kümmel (2010); all three restrict this redefinition to Pre-PIE, leaving the standard PIE model essentially intact with whatever problems it already had. Miller (2006) suggested attributing /T D D$^<$/ to PIE itself. Miller (2008) and in more detail Kümmel (2010) highlight the dearth of traditional PIE ND clusters as typologically supporting a reconstruction of traditional D as implosive or non-explosive D$^<$.

6.2.3 Place of articulation issues

In addition to positing the contrasts in (23), I follow the standard reconstruction in positing that the PIE stops contrasted for place of articulation, including labial, coronal, velar, and labiovelar – with one probable exception. In the third series, the expected labiovelar non-explosive was probably not realized as such because that seems to be an unattested type of sound (see Ladefoged and Maddieson 1996, Maddieson 1984). Labial-velar stops such as [g͡b] and [g͡bʷ] with oral rarefaction effects like those of non-explosives are attested, however (Greenberg 1970, though contrastive non-explosion is also reported in voiced labial-velar stops: Salffner 2004: 101). Extensive diachronic interplay has been observed among labial-velars, bilabial non-explosives, and labiovelars (Cahill 2006, Williamson 2004, Grégoire 2003, Ikekeonwu 1999, Lewis 1997, Ladefoged and Maddieson 1996, Demolin 1995, Ohala and Lorentz 1977, Rountree 1972, Greenberg 1970). The attested sound typologically most comparable to a hypothetical /ɠʷ/ thus appears to be [g͡bʷ] or [g͡b]. Labial-velar stops are attested in contrast with labiovelar stops, languages with /g͡b/ but no /k͡p/ are more common than the reverse type, and languages with /g͡b/ but no /k͡p/ tend to have fewer gaps elsewhere in the system than languages of the reverse type (Cahill 2008). All of these facts harmonize well with a PIE containing a voiced labial-velar stop but no voiceless one. Instead of a voiced labiovelar non-explosive in the third series, therefore, I posit a voiced labial-velar.

Having surveyed the synchronic character and typological viability of the non-explosive reconstruction in (23), we now turn to the diachronic implications. In the next section, I show that the non-explosive reconstruction fares well in this regard.

6.3. Diachronic outcomes

Although systematically non-explosive or sonorant reflexes of the third series do not surface in any of the traditional twelve branches, this can be seen as a historical accident. The boxes in Table 6.2 with the commentary underneath show that the three stop series evolved according to three separate trends. Each of the twelve branches follows one of these basic trends.

Table 6.2. Diachronic trends.

PIE	Ind	G	It	Gm	Arm	C	BS	Alb	Ir[12]
I. T	T	T	T	Θ	T^{h}	T	T	T	T
II. D	D^{ɦ}	T^{h}	Θ/Đ	D/Đ	D^{ʔɦ}	D	D	D	D
III. D$^{<}$	D	D	D	T	T	D	D	D	D

(*a*) Series III became explosive like II, while II acquired a turbulent noise correlate (§3.3.6.6) and, in Greek, devoiced. Devoicing and aspiration of a phonologically plain voiced stop series while a voiceless unaspirated series remains unchanged is also reconstructed in Western Kammu (Mon-Khmer; Svantesson and House 2006: 310), Lawa Umpai (Mon-Khmer; Sidwell 2006: 39) and Madurese (§3.2.6.3); further parallels to the total devoicing of the aspirates in Greek are found in Armenian dialects (Pisowicz 1976) and Indic languages (Stuart-Smith 2004). The shift of non-explosives to explosives is well-attested (Greenberg 1970).

(*b*) Given voice as a default implied by non-explosion in series III (§2.6.2, 4.3.2), the loss of voice there could be taken as a default effect attendant on loss of non-explosion, or it could have postdated this. In series II, voice is not a default implied by any other property, and it survives. Series I undergoes glottal widening, manifested as aspiration in Armenian and ultimately with frication in Germanic (cf. the discussion of vocal fold abduction in voiceless fricatives, §3.3.6.4).

By treating aspiration as original to the dominant phone of series I in PIE, Gamkrelidze and Ivanov (1995) remove the main Indo-European examples of general aspiration of a voiceless series, but Khasi (Mon-Khmer) provides a non-Indo-European parallel (see Sidwell 2006: 36, cf. 2005: 197). For parallels to the loss of non-explosion in series III see (*a*); for parallels to the obstruent devoicing in series II see Khmer and

[12]Hittite interpretations 1 and 2 fall in groups *b* and *c* respectively. Tocharian is omitted because it merges all three series to voiceless obstruents, except for a zero reflex of the series III coronal (Clackson 2007).

Khmu Yuan (Mon-Khmer: Ferlus 1992, Sidwell 2006: 39), Scottish Gaelic (Green 1997: 44, Gillies 1993: 148; contrast Modern Irish: Green 1997: 41-43), Welsh (Ball and Müller 1992), and Alsatian German (Keller 1961: 121).

(*c*) This group shows loss of non-explosion in III and merger of III with II. For loss of non-explosion see (*a*).

Looking at the evolution of the stop system as a whole, we see an earlier conclusion (§3.2.6.5) borne out in the fact that aspiration and voice did not both stabilize on II except in Proto-Indo-Iranian, which developed contrastive T^h in addition to T and D. This T^h is preserved most straightforwardly in Sanskrit. Its development there may have been contingent on several other factors working together as follows.

Several PIE stems are traditionally reconstructed with clusters of a voiceless stop followed by $*h_2$, a consonant of unknown realization conventionally called a laryngeal (see the standard sources in §6.2.1; further discussions and sources are found in Reynolds et al. 2000 and Winter 1965). Sooner or later the cluster came to be realized as a voiceless aspirate series [T^h], at least in Indo-Iranian. In other branches of Indo-European, the reflex of PIE /Th_2/ is generally the same as that of PIE /T/, with original /h_2/ vanishing in this environment as in nearly all others. The development of voiceless aspirates from /Th_2/ in Indo-Iranian may be compared to the development of phonetic voiceless aspirates from /Th/ clusters in Mon and Khmer, though the latter aspirates may remain synchronically bisegmental since processes such as infixation regularly break up the clusters in morphophonemic alternations (see Ferlus 1992: 82, 1983: 77-78).

It may be significant that the inherited stock of T^h cases in Indo-Iranian are mostly coronals, since the greater quickness of the coronal articulator (Fourakis, Botinis, and Niryanakis 2002, Frisch 1997: 167-68, Gafos 1996: 3-10, 131-74) might make monosegmentalization of /Th/ easier at that place. Further, since PIE h_2 conditioned adjacent non-high vowels to *a* and is in fact the only known systematic environment in which PIE *a* occurred, accounting for the vast majority of reconstructions with that vowel, the laryngeal in the /Th_2a/ sequences had relatively low functional load to begin with. Conceivably this made it somehow easier to lose (cf. Bermúdez-Otero 2007: 512). The single branch in which this aspiration was clearly not lost, Indo-Iranian, is also the single branch in which the non-high vowels merged and the functional load of the distinction between *a* and *e*, *o* was lost – creating a unique opportunity for the functional load of the reflex of PIE h_2 to increase naturally and to stabilize with the realization of voiceless aspiration. This in turn helped license the unique rise of a voiced aspirate series with robust breathy offset and closure voicing. The interplay of these contrastive relationships is probably not entirely accidental.

6.4. Comparison with other reconstructions

6.4.1 Other kinds of voiced stops

The non-explosive reconstruction in (23) proves superior to several models that redefine the second series in other ways. While space prevents me from considering all possibilities in detail, I have tried to incorporate all the interesting ones through judicious discussion of typologically attested phonological categories and phonetic patterns.

Voiced glottalized explosive stops are probably the most similar alternative to non-explosives; indeed they are poorly distinguished in the literature from non-explosives and do not appear to contrast with them (§2.6.2). Since non-explosives do not require glottalization, however, there seems no point in reconstructing it for PIE. The objection of Barrack (2002: 91) and Gamkrelidze (1989: 99), that a bilabial "gap" becomes even less tolerable if the bilabial is non-explosive, is treated in §6.5.

Prenasalized stops, a logical possibility casually noted by Gregory Iverson (p.c.) as a conceivable value for one of the PIE voiced stop series, would have to occur in various clusters, given what we know about PIE phonotactics. Yet some of these clusters seem typologically bizarre, such as [{r, l, z}^{n}D]. In the languages with CNC sequences described by Herbert (1986: 183-184), he finds phonological evidence that the nasal is syllabic, and he concludes that prenasalized consonants tend to occur in languages that avoid syllable codas (p. 186). Syllabic nasals are already reconstructed for PIE, but with developments unrelated to the stop series (see the standard sources in §6.2.1). I conclude that prenasalized stops are no better an interpretation of the third PIE stop series than voiced glottalized stops.

Finally, reconstructing PIE series II and III as prevoiced aspirated and plain voiced explosive, with the aspirates being like those of Kelabit and Lun Dayeh (§3.2.6.4), would leave unexplained the much wider distribution of PIE series II, particularly in post-consonantal position; it is also unclear how such a reconstruction would handle the rarity of series III in postnasal position (Kümmel 2010) and the problem of the bilabial gap (§6.5).

6.4.2 Ejectives

Ejective models have probably been the most popular approach to revising PIE in the last several decades, under the heading of Glottalic Theory (Gamkrelidze and Ivanov 1995, Vennemann 1989, Kortlandt 1978, Hopper 1977a, 1973, cf. Fallon 2002). But ejective models require most of the daughter branches to undergo a subsequent T' > D sound change that clashes with what trends we can see in the typological evidence and with the most plausible reading of phonological universals underlying them – unless one posits a non-explosive intermediary ($\mathrm{T' > D^{<} > D}$), in which case there seems little reason to have the ejective stage at all. (On the typological evidence see Barrack 2004, 2003a,b, 2002, Job 1995, 1989, and for evidence from alleged loan etyma, Vennemann 2006; on relevant phonological theory see §3.2.7.) Barrack (2002: 91) and Gamkrelidze (1989: 99) object that a reconstruction back to $D^<$ runs afoul of a bilabial problem often referred to as the "*b* gap". As we will see shortly (§6.5.1.2), there is a solution to this problem that does require the non-explosives to have developed after the breakup of PIE, and hence demands a different realization such as ejectives in PIE itself; this solution is not the only possible one, however, and it is relatively implausible in that it requires every daughter branch to have innovated [ɓ] after the breakup.

There is also a subtler problem with ejective models. Given the restricted distribution of aspiration (§3.2.6), the stop inventory /T T' D/ is phonologically well-formed, but /T T' $D^ɦ$/ with the third series phonologically specified for both voice and aspiration is ill-formed. At the same time, any three-series PIE stop inventory with the first series specified as aspirated (/T^h/) creates a diachronic typological problem since it would force unconditional phonological deaspiration of [T^h] throughout most branches of the family – a situation without adequate parallel as far as I am aware. The nearest possible parallel that has been brought to my attention, Austrian German (Anna-Maria Adaktylos p.c.), is too dissimilar in both the number of series involved and their phonetic realizations (see Moosmüller and Ringen 2004). The dearth of evidence for general deaspiration without merger of laryngeal distinctions has influenced arguments about the reconstruction of the Proto-Tai stop system as well (see Pittayaporn 2009: 88). Thus, ejective models run into trouble if either of the non-ejective series is phonologically specified for aspiration.

Yet it appears that they run into another problem if aspiration is not specified. Within an ejective approach to PIE it seems that CVC roots have phonological agreement in voice but not in laryngeal constriction or aspiration (Gamkrelidze and Ivanov 1995: 29, cf. D. G. Miller 1977a). However, Hanson (2001) generalizes from typological evidence that such root voicing agreement implies similar agreement in another laryngeal feature, such as constriction or aspiration. Since neither of these features is available because they are not specified in a well-formed ejective model of PIE, root voice agreement is not expected there either. (For an alternative treatment of the relevant root patterns that does not rely on a radical redefinition of the second series, see Iverson and Salmons 1992.)

6.4.3 Fricatives

Prokosch (1939) suggested reconstructing series II as fricatives, but the suggestion works about equally well with either II or III. Reconstructing voiceless fricatives would require a typologically unsupported general voicing of that series in most of the daughter branches, but voiced fricatives would escape that problem. A voiced fricative series II would have to despirantize directly to voiced aspirates in Indic and perhaps phonetically in Armenian, a change for which I have no typological parallels, though it does not seem phonetically implausible (see Stuart-Smith 2004: 206, Vaux 1998a: 509). Otherwise, the only diachronically questionable aspect of reconstructing either II or III as voiced fricatives is the general despirantization that would be required in all the daughter branches.

I do not have parallels for such a change in the normal evolution of any language, only examples restricted in various ways – mostly to allophones at some place of articulation, to borrowing, and to child speech. Modern Hebrew has despirantized earlier [θ ð ɣ] allophones of [t d g] (Idsardi 1997a). Comanche (Numic: Uto-Aztecan) has reportedly despirantized earlier [ð ɣ z] allophones back to their dominant allophones [t k ts] (McLaughlin 2000, Charney 1993). We do find a despirantization of phonemic dental fricatives in German (*du*, *der*, *dorf* cf. Eng. *thou*, *the*, *thorpe*), but conceivably this relates to dental fricatives being relatively rare cross-linguistically. Second-language varieties of English are well known for realizing /θ ð/ as [t⁽ʰ⁾ d]. Second languages and borrowing patterns present examples of despirantization at additional places of articulation, including postvelar (Gaelic [lɔχ] 'loch', German [bɑχ] 'Bach' yielding American English [lɑk], [bɑk]) and even labiodental (e.g. an Indian reporting Marathi as his first language and speaking English sub-fluently mentioned India's [pʰeməs pʰilm stɑɹz] 'famous film stars', personal experience; cf. Iverson and Salmons 2008: 10, 13). For despirantizations in child speech see Vaux and Miller (2011). While better examples would be nice, the notion of general despirantization does not seem theoretically problematic.

As far as PIE itself is concerned, a reconstruction with T D Đ assigned in some order to the three PIE series leads to sound changes for which I lack clear typological parallels, though the changes themselves are not necessarily phonetically unreasonable.

6.4.4 Conclusion

The survey in the previous section indicates that the most coherent and typologically well supported reconstruction of the three PIE series may be the /T D D$^{<}$/ reconstruction as shown in (23). This reconstruction not only departs less from the comparative evidence than most of the alternatives, but it also has an attractive instability in the inherently temporary nature of non-explosion and other strategies for staving off oral air pressure buildup (§2.6) which may relate to why non-explosives have been estimated to occur systematically in only ten percent of the world's languages (Maddieson 1984). The non-explosive reconstruction also has more specific advantages which we will see in dealing with the next problem.

6.5. The labial "gap"

6.5.1 Critical typology of reconstructions

There is little or no comparative evidence for a bilabial in the third series (Clackson 2007, Fortson 2004, Meier-Brügger 2003, Sihler 1995, Mayrhofer 1986, in spite of Szemerényi 1996: 145, 1985: 11-12, Djahukian 1990: 5-7, Wescott 1988, Johansson 1900: 390, and Havers 1946: 96-7 and Meid 1989 in Salmons 1993). If the third series is voiced, this is typologically surprising given the other attributes of the stop system, such as its lack of gaps (which enervates comparisons with highly gapped languages, e.g. Woodhouse 1995: 180, 1993: 3; cf. Iverson and Salmons 1996, Mac and Longacre 1960: 27, Longacre 1957. Gaps have proven typologically relevant to stop voicing patterns elsewhere; Cahill 2008.) There are several possible responses to the problem posed by this apparent dearth of the PIE series III bilabial, a problem we will loosely call the "*b* gap" for convenience. Below I have tried to schematize the possible solutions exhaustively.

6.5.1.1 PIE had a /$D^{(<)}$/ series with the bilabial unusually rare or absent

The first possibility is that PIE series III was an unaspirated voiced stop series and the bilabial member of the series was rare or non-existent even though this is typologically unusual. This solution is naturally unpopular because historical linguists prefer reconstructions with broad structural traits that resemble those found in attested languages. Additionally, it is unclear what would motivate the development of this reconstructed system from a less unusual earlier system. That motivated sound changes can produce structurally atypical traits which later disappear is well known,[13] but in this case no plausibly motivated sound change is identifiable.

The only attested case I have found where the bilabial member of a phonologically voiced stop series may have undergone an unconditioned sound change

[13]Compare the rise and subsequent disappearance in English and Welsh of non-back rounded vowels (which are cross-linguistically even rarer than back unrounded vowels: Maddieson 2008a), or the weakening of final *-m* producing paradigms with zero accusative singular morphology but non-zero nominative singular morphology in Old Icelandic and Old French, a cross-linguistic anomaly subsequently disappearing from both languages (see Dixon 1994). I admit these are not particularly good examples: the first is not rare enough to be exceptional, and the other is not phonological.

not shared by the rest of the series is when the series is [ɓ d g...] (Greenberg 1970). But assigning this value to pre-PIE series III, with [ɓ] then becoming zero or merging with some other segment in PIE itself while the other stops remain voiced, raises the question of what value to assign to series I and II without causing typological problems (§6.2-6.4).

Another logical possibility is having a pre-PIE voiced stop series III with the bilabial later undergoing unconditional articulatory undershoot, or lenition, to a fricative or glide which then by a plausible separate sound change disappears or merges with another segment in PIE. The nearest example of such a labial-only lenition that I have found, in Nkore-Kiga (Gurevich 2004: 177-78, Poletto 1998, Kirchner 1998: 108, 123, Muzale 1998, Taylor 1985), appears in spite of somewhat heterogeneous documentation to be a post- or inter-vocalic lenition which targets just the bilabial member of the voiced stop series (*$b > \beta$) thanks to the fact that its historical effects on the coronal (*$d > r$) are masked by numerous loans with unlenited *d*. The lenition environment still seems conditioned, though. Broad studies of lenition or articulatory undershoot (Gurevich 2004, Kirchner 1998) do reveal that multiple previously proposed universal place constraints are invalidated by the diverse empirical data, but these studies also suggest that lenition tends to target either the environment of adjacency to sounds with lower stricture, or particular sounds that are cross-linguistically less widely distributed, like voiced velar obstruents. This weakens the case that voiced bilabial stops would lenite unconditionally while their counterparts at other places of articulation did not.

6.5.1.2 PIE had a bilabial gap, but it was natural

The next possibility is that PIE series III had some realization in which a bilabial gap would not be unusual. To avoid creating unusual gaps in the daughter languages (§6.5.1.1), this unobjectionable gap in PIE must have been filled in each of the branches before or while the rest of series III was changing. However, the possible original realizations for III in this scenario run into various wider problems that were mostly identified in §6.4. Ejectives, for example, would mean a well-attested [p’] gap (Maddieson 1984) but would also entail either an unattested direct T’ > D sound change or voicing through an intermediate non-explosive stage; in the latter case, [ɓ] must have been innovated in each of the branches before the rest of the series had finished becoming non-explosive, to prevent an unusual gap from recurring in each branch. Similarly, reconstructing series III as voiceless aspirates with a [p^h] gap would force several daughter branches to undergo unconditional T^h > D, which is typologically and phonologically dubious since it would involve unconditional deaspiration (§6.4.2) with a simultaneous and questionable addition of voice. As far as I know, a solely bilabial gap in a large system of stops which otherwise has few or no gaps is not attested when the gap is a voiced non-explosive, creaky-voiced, or voiced preglottalized stop. There do not seem to be any other, better possibilities.

6.5.1.3 Traditional PIE /b/ merged with some other segment(s) before PIE

Another conceivable option is that PIE had no bilabial gap. The semblance of one is due to a subsequent merger of the series III bilabial with another segment, which occurred separately in the daughter branches. This opens up multiple options. One is that different mergers occurred in different branches and the cognate sets illustrating this divergence have not been recognized because the historical evidence was not examined well enough. This suggestion is not convincing until someone produces new and satisfying cognate sets. The remaining options involve the same merger occurring in each of the branches.

Merger with /w/ has been proposed (see Sihler 1995), but in its simplest form this would require the branches to undergo unconditional articulatory undershoot in only the series III bilabial. Such lenition seems unattested as we have already seen (§6.5.1.1). A revised version of this merger could have an originally non-explosive third series lose non-explosion except for the bilabial (an attested pattern §6.5.1.1), followed by secondary changes introducing contrastive [b]; the lone bilabial non-explosive would then constitute its own series and presumably be free to become a glide without incurring the "labial-only lenition" objection, followed by merger with /w/. This same mechanism would work with merger to /m/ (an option noted by Mayrhofer 1986: 100). Both /ɓ/ > /w/ and /ɓ/ > /m/ are attested (Pittayaporn 2007: 106-107, Haider 1985: 11, Haudricourt 1975, Greenberg 1970: 137), although in several of these languages, one finds implosives at other places of articulation becoming resonants as well, and in none of the languages have I found it stated that this type of change affected the bilabial implosive only. Another possible merger outcome is the series III labiovelar or labial-velar, but while diachronic interplay among [ɓ, $\widehat{\text{gb}}$, $\widehat{\text{gb}}^{w}$, g^{w}] is attested (§6.2), I do not have a parallel for this particular directionality. All of these scenarios require the same merger to occur in each of the daughter branches, however, which seems relatively unlikely.

Merger of the series III bilabial (traditional /b/) with the series II bilabial (traditional /$b^{ɦ}$/) is another story. Barrack (2004) suggests that such a merger might have occurred in Pre-PIE and points out that it would have contributed to the high frequency of traditional PIE /$b^{ɦ}$/. Locating the merger in Pre-PIE, however, would have caused the problematic gap in PIE itself that we are interested in avoiding. Let us therefore examine what the merger might have looked like if it had played out *after* the breakup of PIE.

6.5.2 Merger of traditional PIE /b/ with /b^{ɦ}/ after PIE

6.5.2.1 Introduction

This section develops a model of the evolution of PIE in which traditional PIE /b/ and /b^{ɦ}/ merge in all of the daughter branches. In seven of the branches, this merger is already posited in the traditional reconstruction as part of a more general merger between series II and III. These branches therefore require no special arrangements. They will be referred to as “the simpler cases” and discussed fairly briefly below. In the five remaining branches, however, series II and III did not merge. The hypothesis that /b/ merged with /b^{ɦ}/ in these branches therefore entails more complex explanations, which will be presented in detail for each branch.

A key trait of the following proposal is that nearly all the forces motivating the merger in each of the daughter branches are already posited as being at work in the stop systems of those branches given the model of PIE in (23). The remaining sound changes that are additionally required for this merger hypothesis are fairly well supported both empirically and in terms of phonetic plausibility.

The only element not already entailed by the non-explosive model which this following proposal posits as recurring in more than one daughter branch (specifically five) is so phonetically natural that it may be likelier to occur than not. This is an element of timing and has the following basis. Higher pressure is correlated with the posterior end of the place spectrum, where the oral cavity is smallest and air pressure builds up fastest. One well attested correlate of this fact is that aspiration tends to be stronger in more posteriorly placed stops (Billerey-Mosier 2003: 6, Kobayashi 1999: 2, Gordon and Applebaum 2006: 163-64). Another is the already mentioned fact that voiced series are attested with unevenly distributed oral air pressure, such that the most anterior member, the bilabial, is non-explosive while the other members are explosive. From such facts I draw the simple inference that pressure-increasing sound changes, including loss of non-explosion and development of aspiration, may first become noticeable at the posterior end of a series and then spread forward. I will refer to the effect of this phenomenon on bilabials as “labial delay”.

I now present the hypothetical individual branch developments, supported typologically and with phonetic arguments. For data on the branches, see the standard sources in §6.2.

6.5.2.2 The simpler cases

A general merger between series II and III has already long been reconstructed in seven branches of the Indo-European family: Baltic, Slavic, Albanian, Iranian, Hittite, Tocharian, and Celtic. (Separate complications affect the series III labiovelar in Celtic and some cases of the series III coronal in Tocharian, but the details are irrelevant here.) The general merger in each of these branches has traditionally been reconstructed as PIE /$D^{ɦ}$/, /D/ merging to /D/. Under the non-explosive hypothesis, we have instead PIE /D/, /$D^{<}$/ merging to /D/. The typological support for the changes involved was given earlier (§6.3).

6.5.2.3 Armenian and Germanic

In Armenian, series I and III increased in pressure, with I aspirating and III then losing non-explosion and devoicing. The bilabial member of III experienced labial delay, only becoming explosive later. It then merged with the most similar other segment, the bilabial of series II which at this stage was phonologically either voiced or slack (cf.

§6.2). If the members of series III became explosive and voiceless simultaneously, then no more need be said, but I do not have a typological parallel for such a development. Alternatively, they lost non-explosion before voicing, but in this process they did not become confused with series II because the latter had become slack by then.

The Germanic situation is similar to the Armenian one, but series I eventually spirantized. There is debate over the contexts in which II may also have spirantized before the breakup of Proto-Germanic. No evidence for breathy offsets is reconstructed for II based on the Germanic daughter languages, but the following analysis does reconstruct this trait in order to handle a special circumstance.

In certain loanwords, stops that were arguably voiced in the source languages (Vennemann 2006) ended up as voiceless unaspirated in Germanic, including some labial examples. The main point of interest is the origin of Gmc /p/. None of the examples are securely traced back to PIE – if they were, there would be less of a PIE "*b* gap" problem. Hence it is commonly suggested that Gmc /p/ derives from borrowings, possibly supplemented by certain other innovative processes within Germanic which we cannot identify. The question is then how these borrowings fit into the evolution of the Germanic stop system from the model of PIE presented in (23). A solution is given in successive diachronic stages presented from left to right in (24). An asterisk marks the suggested earliest form of the innovated segment that became Proto-Germanic /p/. Here and in the discussion of the other branches later, parentheses have their standard value of rendering what they enclose optional or uncertain; in (24) for example they place the voicing of various segments in question, to be discussed further below. Finally, lowercase Roman numerals in this and subsequent tables and discussion refer to diachronic stages, while the uppercase Roman numerals continue to distinguish the contrastive stop series.

(24) Evolution of the Pre-Germanic stop system

<table>
<tr><td></td><td>PIE</td><td>(i)</td><td>(ii)</td><td>(iii)</td><td>(iv)</td></tr>
<tr><td>I</td><td>T</td><td colspan="4">T^h</td></tr>
<tr><td>II</td><td>D</td><td colspan="3">T̤</td><td rowspan="2">D/T̤</td></tr>
<tr><td></td><td colspan="3">ɓ[14]</td><td>b</td></tr>
<tr><td rowspan="4">III</td><td colspan="2"></td><td>(b̥)*</td><td colspan="2">p</td></tr>
<tr><td colspan="2">ɗ</td><td>(d̥)</td><td colspan="2">t</td></tr>
<tr><td colspan="2">ɠ</td><td>(g̊)</td><td colspan="2">k</td></tr>
<tr><td colspan="2">g͡b(w)</td><td>(g̊)w</td><td colspan="2">k^w</td></tr>
</table>

At the first stage of development (i), series I was phonetically aspirated and II had become slack (on the notation, see §2.5.6). These changes made it possible for the non-bilabial members of III to lose non-explosion without merging with any of the other series, yielding stage (ii). The parenthesized voiceless diacritic indicates that III may have devoiced in certain contexts but the details are not reconstructed.

It is at stage (ii) that the loanwords in question were borrowed. Plain voiced stops in the source forms were considered phonetically most similar to series III, so they were borrowed into that series, devoicing in whatever contexts that series was voiceless. Plain voiced bilabials in the source forms were adapted with the non-place characteristics of the non-bilabial members of the series – that is, explosive and perhaps devoiced under some conditions. This type of bilabial is marked with an asterisk in (24). The inherited series III bilabial, which was uniquely still non-explosive, now contrasted with an explosive plain voiced bilabial and was thus reanalyzed as occupying its own series.

[14] Originally part of series III; becomes a separate series at stage (ii).

After this, series III completely devoiced while the bilabial non-explosive became explosive, producing stage (iii). Alternatively, the bilabial non-explosive merged with series II more quickly. At any rate it had undergone this merger by stage (iv), which approximately corresponds to Proto-Germanic. By this time, series I may also have spirantized. There are two possibilities for how series II evolved to reach this stage. One is that the series lost breathy offset, voicing intervocalically like the allophones of slack stops in some languages (§2.5.5.3) and voicing at least partially in word-initial presonorant position, a pattern that again has typological parallels (3.2.3). This option essentially results in the conventionally reconstructed Proto-Germanic system. As an alternative, II may have remained slack from stage (i) all the way through Proto-Germanic itself. The other sound changes mentioned in these scenarios, including labial delay, deaspiration, devoicing, loss of non-explosion, and spirantization were discussed earlier (§6.3, 6.5.2.1).

At stage (ii), just after the borrowings that we have discussed had taken place, the Pre-Germanic stop system would have been as follows:

(25) Pre-Germanic stop system at stage (ii)

I	p^h	t^h	k^h	k^{wh}
II	p̈	t̤	k̤	k̤^{w}
III	(b̥)	(d̥)	(ğ̊)	(ğ̊)
IV	ɓ			

If the third series in this inventory was underlyingly voiceless /T/ and just phonetically voiced in some environments (such as postnasal), then the system is like that of Xhosa (§2.5.5.2.2). On the other hand, if the third series had a stronger tendency to show variable amounts of closure voicing in general, then the first three series might form a system like Sivas Armenian or Qingtian Wu (§2.5.5.4). Either way, this analysis of the evolution of the Germanic stop system has typological parallels at each of its stages, including the key stage when the borrowings that helped create eventual Proto-Germanic /p/ occurred.

6.5.2.4 Italic

In Italic, series II spirantized and initially devoiced, while the non-bilabial members of III became explosive. Secondary innovations then introduced contrastive tokens of [b] (seen mostly in the various [b] lexemes without regular PIE etyma), isolating the non-explosive structurally into a series of its own. Subsequently, the non-explosive underwent articulatory undershoot, ending up with the stricture of a bilabial fricative [β]. A similar but more drastic change in a bilabial non-explosive's stricture, resulting in a glide, has been reported elsewhere (Greenberg 1970), and glide/fricative variation is well attested for bilabials (e.g. Iverson and Salmons 1996, Maddieson 1984) and at other places (Cser 2003: 122, Howe 2003: 163, Martínez-Celdrán 2008, Vaux and Miller 2011). The Italic reflex never decreased stricture to the point of being a glide, however; instead, it merged with the by now identical reflex of series II, stabilizing as a fricative and devoicing initially.

This brings us to an early stage of Italic contrasting voiceless stops, voiced stops, and fricatives that are voiceless initially and voiced in inter-voiced environments, reflecting the revised understanding of Italic developed by Stuart-Smith (2004). This is represented in stage (iii) in (26) below. A general stopping of medial voiced fricatives and the reduction of the voiceless non-sibilant fricatives to /f h/ bring us to the Latin system, at stage (iv). As in (24), the innovative /b/ at stage (ii) is asterisked.

(26) Evolution of the PIE stop system in Italic

<table>
<tr><td></td><td>PIE</td><td>(i)</td><td>(ii)</td><td>(iii)</td><td>(iv)</td></tr>
<tr><td>I</td><td colspan="5">T</td></tr>
<tr><td>II</td><td>D</td><td colspan="3">Θ-, -Đ-</td><td>f-, h-, -D-</td></tr>
<tr><td rowspan="5">III</td><td colspan="2">ɓ</td><td>(β̞)</td><td>ɸ-, -β-</td><td>f-, -b-</td></tr>
<tr><td colspan="2"></td><td colspan="3">b*</td></tr>
<tr><td colspan="2">ɗ</td><td colspan="3">d</td></tr>
<tr><td colspan="2">ɠ</td><td colspan="3">g</td></tr>
<tr><td colspan="2">g͡b$^{(w)}$</td><td colspan="3">g^{w}, w</td></tr>
</table>

It should be observed that apart from articulatory undershoot of the lone non-explosive, everything in this hypothesis is already posited in the non-explosive model (§6.3).

6.5.2.5 Indic

Unlike Latin and Greek (below), Indic eschewed devoicing in series II thanks to having previously phonemicized a separate series of voiceless aspirates. With these in place, II developed a voiced realization with breathy offset, while III lost non-explosion. For the aerodynamic reasons already discussed, however (§6.5.2.1), the series II bilabial had weaker breathiness than the other members of that series, as it still does in Hindi (Kobayashi 1999: 2). This made it more easily confusable with the bilabial of series III, and the two segments merged. The outcome of the merger was unique, however. Due to the robust stabilization in Indic of the Grassmann's Law pattern dictating that a stop be unaspirated when the next stop in the word was an aspirate (see standard sources in

§6.2.1), I posit that the merged bilabial was analyzed as /b/ when the next stop in the word was an aspirate and as /$b^{ɦ}$/ otherwise. Subsequently, /$b^{ɦ}$/ may have developed a more saliently aspirated realization, and it is clear that a limited number of other /b/ tokens were innovated, partly through loanwords.

This analysis not only exploits the Grassmann pattern so characteristic of Old Indic, it also reflects the attested lexical distribution and frequency of /b/ and /$b^{ɦ}$/ in Sanskrit (see Whitney 1896 §50). While one could expect /b/ to be more common than /$b^{ɦ}$/ in any given language on the assumption that /b/ has a simpler specification and that it occurs in more languages than /$b^{ɦ}$/, this expectation is decisively disappointed by Sanskrit, where /b/ is in the minority and my impression of the lexicon (e.g. Benfey 1866) is that most tokens of /b/ with Indo-European etymologies are in the Grassmann environment (i.e. with an aspirate following). The expectation would also be theoretically unfounded. The number of languages in which a sound occurs and its textual or lexical frequency within a particular language do not necessarily correlate (Croft 1993), and cases of two similar phones neutralizing to the phonetically more complex one "appear to be quite common" according to Hale (2007: 161-162), who discusses /ē ō/, /ei ou/ neutralizing to [eɪ oʊ] and initial /r/, /wr/ neutralizing to [w͡ɹ] in the history of English.

6.5.2.6 Greek

In Greek, series II became slack, subsequently aspirating and devoicing, while III became explosive. Due to labial delay, the series II bilabial lagged behind the rest of the series in these changes. This effectively left a /p^h/ gap, which is well attested (e.g. Maddieson 1984). Labial delay may also have kept the series III bilabial non-explosive at this stage. The labial-velar retained the tendency for oral rarefaction induced by its double place articulation (§6.2), since this was independent of the non-explosion strategy being lost in the rest of the series. This yielded stage (i) in (27) below.

(27) Evolution of the Greek stops[15]

<table>
<tr><td></td><td>PIE</td><td>(i)</td><td>(ii)</td><td>(iii)</td><td>(iv)</td></tr>
<tr><td rowspan="2">I</td><td colspan="5">p t k</td></tr>
<tr><td colspan="4">k^w</td><td>p, t</td></tr>
<tr><td rowspan="4">II</td><td colspan="4">b</td><td>p^h</td></tr>
<tr><td>d</td><td colspan="4">t^h</td></tr>
<tr><td>g</td><td colspan="4">k^h</td></tr>
<tr><td>g^w</td><td colspan="3">k^{wh}</td><td>p^h, t^h</td></tr>
<tr><td rowspan="4">III</td><td colspan="2">ɓ</td><td colspan="2">b</td><td>p^h</td></tr>
<tr><td>ɗ</td><td>d</td><td colspan="3"></td></tr>
<tr><td>ʛ</td><td>g</td><td colspan="3"></td></tr>
<tr><td colspan="3">g͡b$^{(w)}$</td><td>/ɓ/ [g͡b]</td><td>b, d</td></tr>
</table>

The lone non-explosive /ɓ/ then lost non-explosion and merged with /b/, yielding stage (ii). This phoneme subsequently became slack on its way to devoicing and aspiration in stage (iv), since it was still a target of the the trend that had already produced those changes in the rest of original series II.

One of the environments where this trend was likely to reach /b/ soonest was before /u/, and this may have already occurred at stage (ii). The high stricture of /u/ would narrow the air passage and naturally increase air pressure slightly (cf. aspiration before the highest vowels in Bantu: Hyman 2003, Mathangwane 1999). The complexity of transitioning from the lip compression of the stop to the protruded lip rounding of the

[15] This abstracts away from certain other developments, including palatalizations induced by PIE *y* and the merger of labiovelars with velars next to **ŭ* or **w* fairly early in Greek.

vowel would additionally support an extra narrow labial aperture until the transition to a protruded articulation was completed, further facilitating pressure increase. This plus any inherited breathiness would naturally favor aspiration and attendant devoicing in this environment, more than perhaps any other. It is possible that some or all of these factors caused a phonetic difference between /b/ in this environment and in other environments, which could have contributed to the Mycenaean Greek Linear B syllabary (Thompson 2010) adopting an optional sign for the bilabial aspirate before *u* while aspirates did not have distinct signs in any other circumstances.

While the Mycenaean syllabary did distinguish the voiced coronal stop from the voiceless unaspirated and aspirated coronal stops, it did not otherwise distinguish voicing, so it leaves us in the dark concerning the laryngeal features of the bilabial series. Mycenaean may correspond to stage (ii), but the data is equally consistent with alternative interpretations including even the inherited series II and III bilabials remaining distinct in Mycenaean. Mycenaean preserved a distinct place value for the labiovelars and may have developed the series III labial-velar to [g^w], the value traditionally assumed.

In the other dialects, the velar component of the labial-velar was phonologically reanalyzed as simply a device for avoiding oral air pressure buildup. Hence the labial-velar adopted the phonological status of /ɓ/. This development appears to be typologically supported by the extensive diachronic interplay between labial-velar stops and bilabial non-explosives mentioned earlier (§6.2); as just one example, a single Igbo phoneme is realized as [g͡b] in some dialects, [ɓ] in others (Ikekeonwu 1999: 109). While the non-Mycenaean dialects may have reanalyzed the labial-velar simultaneously with the other developments that produced stage (ii), the result is presented as stage (iii) for clarity. The remaining developments concern non-Mycenaean dialects only.

The new /ɓ/ [g͡b] subsequently shifted its realization in most environments to [ɓ] and then [b] (both attested changes, cf. Greenberg 1970: 136-37). At the same time or slightly earlier, /b/ devoiced and aspirated, finishing the process that had already encompassed the rest of series II and filling the labial gap in the aspirate series. This brings us to stage (iv). One complication is that before *ḗ* in some dialects, /ɓ/ [g͡b] shifted to /d/ instead. The other labiovelars developed similarly: $k^w > t$ / _{*ḗ*, *ī́*}, else > *p*; $k^{wh} > t^h$ / _*ḗ*, else > p^h, though Allen (1957a) notes that the evidence regarding the aspirate before *ī́* is tenuous. Allen (1957a) proposes that [ʷ] > [ᶣ] / _*ḗ*, triggering palatalization of the preceding stop, followed by loss of the labial component and simplification of the remainder to a plain coronal. Within the present model, I suggest that analogy with the voiceless labiovelars induced the voiced labial-velar to palatalize similarly to them; that is, given the rise of a palatal gesture coarticulated with the voiceless labiovelars, one developed in the voiced labial-velar as well, regardless of the fact that the labial gesture in the former was rounded and vocalic while in the latter it was compressed and stopped. On possible reasons for the inconsistent role of *ī́* in triggering palatalization, see Allen (1957a).

6.5.2.7 Conclusion

The proposal that the original voiced bilabial stops merged catches a free ride on wider mergers in seven of the daughter branches and hinges on the independently supported phenomenon of labial delay in the remaining five. In Italic, the merger additionally involves a stricture reduction that is already reconstructed for series II; in Indic, Grassmann's Law was involved, and in non-Mycenaean Greek, the loss of the labiovelars. Thus the proposed solution to the "*b* gap" problem is almost entirely driven by mechanisms already needed to derive the daughter languages from the non-explosive model of PIE, while all of the alternative solutions considered in §6.5.1 either proved considerably less parsimonious or were problematic in other ways. This adds to the other, broader advantages of the non-explosive reconstruction identified in §6.4.

6.6. Alleged voiceless aspirate etyma

Earlier (§6.2)**,** I asserted that contrastive PIE voiceless aspirates are not justified by the comparative evidence. Against this claim, Elbourne (2000, 1998) lists twenty-five annotated etymologies. Other scholars have generally not embraced his argument, though it has been cursorily alluded to as a possible solution to the standard three-series reconstruction (e.g. Stuart-Smith 2004: 5). Here I briefly summarize Elbourne's etyma, citing them only according to his numbering (some are further discussed in de Decker 2010). I conclude that even if the majority of his list were accepted apart from the question of aspiration, they still present no convincing case for PIE /T^h/.

Roots where voiceless aspiration is solely evidenced in Sanskrit and *a priori* might thus be a Sanskrit innovation (nos. 7, 8, 13, 14, 18) make up a fifth of the list. There is no reason to suppose that innovated aspiration cannot spread fairly irregularly by lexical diffusion; other languages which appear to have innovated most or all of their aspirate phonemes include Limbu (Sino-Tibetan: Mielke 2007a) and Kusunda (Nepali isolate: Watters 2006).

Roots where *s*- precedes the stop make up another third of the list (nos. 3, 5, 11, 12, 22-25). A PIE in which T^h is disproportionately attested with a preceding *s* would be an odd one; by their very frequency in the list (which increases percentage-wise if one ends up suspending any of Elbourne's other etymologies), the *s*-cases weigh against reconstructing a distributionally normal, fully phonemic T^h series in PIE.

One root (1 'mussel') has only Sanskrit and Greek cognates. One root (2 'laugh') favors an onomatopoeic interpretation. Three roots (nos. 19, 21, 23) have independent evidence for "laryngeals" in the right position to trigger aspiration (see the discussion of Indo-Iranian in §6.3). Some of the remaining seven roots are clearly ambiguous for reasons that space prevents me from giving here; laryngeals could be involved with members of this set too.

6.7. Conclusion

The giant of early historical linguistics, Ferdinand de Saussure, is famous for the dictum: “dans la langue il n’y a que des différences” (1972: 166) – “in language there are only distinctions.” Mayrhofer (1986: 98) in his monumentally meticulous work on PIE phonology echoes similar sentiments when he emphasizes that one need not choose between different reconstructions if they differ only in subsegmental details, because “die Gleichungen bleiben dieselben... Zahl und Oppositionsverhältnis der Phoneme ändern sich nicht” – “the correspondences remain the same... the number of phonemes and their contrastive relationships do not alter” (similarly Penney 1998: 154). Speculation on proto segmental content has never been absolutely excluded by Indo-Europeanists, but as seen in quotations like these, there has been an understandible reluctance to expect much fruit from the exercise (cf. Kaye 1997: 529). The tracking of segmental oppositions over time is relatively well understood, but how could proto content ever be realistically reconstructed?

Understood purely in terms of abstract segmental oppositions, the synchronic phonology of a proto language is no more than a tally of algebraic symbols representing proto segments, a set of symbol groupings representing proto phonological classes, and occasionally a few rules where classes interact. There is nothing typologically unusual about the abstract tally, map, or rules that one would uncover for PIE by studying only abstract segmental oppositions; many other languages have about the same number of segments and at least the same number of classes and rules. But viewed at the subsegmental level, PIE presents problems that have perplexed historical linguists for nearly as long as the discipline has existed. It is no surprise that intuitive concern for the phonetic content of phonemic categories has long been treated as an important factor in the reconstruction process (Fox 1995: 81). Only the development of phonetically informed theories of subsegmental phonological categories (feature theories) in the last several decades has made possible a formal and systematic, rather than intuitive and fundamentally inconclusive, approach to these problems.

By feature theory I refer here not simply to the study of abstract contrast specifiers in particular languages, but to the wider study of phonetic cues and the various phonological roles they play. Feature theory serves as a formal way to investigate how phonetic properties associate with phonological categories; these associations are not random and unconstrained, any more than indiscriminate groups of segments can make phonological inventories. Feature co-occurrence trends have proven highly restricted by articulatory and other performance-related factors. Knowledge of these restrictions provides guidance as we explore not only the patterns of synchronic sound systems but also the evolution of sound systems over time – the paths of sound change (Stuart-Smith 2004: 1-7, cf. Anttila 1971: 649).

From the investigation in this chapter and the previous ones, it appears that the long-standing difficulty in reconstructing the PIE stop system has been due to the comparatively high number of relevant restrictions on feature patterns which were previously little understood. Antagonisms between voice and oral air pressure buildup and between voice and vocal fold abduction, particularly in stops with their unique aerodynamics, make possible asymmetric consonant systems that are highly sensitive, meaning that relatively few associations between phonetic correlates and phonemic categories can be changed without unacceptably disturbing the rest of the system. Until these repulsions and attractions are identified at the subsegmental level, attempts to characterize such a system are unhelpfully coarse and are likely to make very limited sense. But a systematic typology of possible reconstructions using a cross-linguistically informed understanding of how phonological categories are mapped to phonetic correlates radically changes the situation, boosts the process of elimination, and in the case of PIE reveals that the space of viable solutions is remarkably small. Specifically, a plausible reconstruction of PIE seems to be found in a system with three stop series contrasting in voice and (non-)explosion, with the subsequent merger of /b/ and /ɓ/ in five of the daughter branches and more general mergers of /D/ and /$D^{<}$/ in the other branches effacing the traces of original /ɓ/.

7 Conclusion

We have explored in detail how phonetic correlates map to feature categories, how such correlate bundles interact in commonly reported feature co-occurrence trends, and the implications of these patterns for grammar design and sound change. Rather than deriving these highly specific patterns from abstract structure hardwired in cognition, this work has identified plausible non-cognitive sources for them. Consequently it seems that innate cognitive stipulations for these patterns are redundant and that the highly specific content which OT's universal constraint set aims to capture can be derived more efficiently and with arguably greater neural plausibility in a model where learners construct grammatical representations of phonological patterns on a language-specific basis. A corollary is that sound change generally involves reanalysis of phonetic data rather than altering the organization of any cognitively inherited phonological categories – a fact important for the methodology of diachronic reconstruction, as we saw in a fresh assessment of one of the oldest unsolved problems in historical linguistics, the evolution of laryngeal distinctions in the Indo-European stops.

This work contributes to a growing body of research focused on removing innate/learnable duplication problems. While most language-specific phonological information seems best removed from the innate endowment, I have not concluded that phonetic content and phonological cognition never interact directly. In each of the three main dimensions of this work – developing phonological profiles of specific sound types, exploring implications for grammar design, and historical problem solving – I have argued that cognition maintains extensive awareness of the phonetic values of the variables it manipulates.

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