

# Phonetics and phonology: gradience, categoriality, and naturalness\*

*Ioana Chitoran and Abigail C. Cohn*

## 1. Introduction

In this paper, we explore the relationship between phonetics and phonology, in an attempt to broaden the search for possible sources of complexity that arise in sound patterns and sound systems. We propose that complexity may be better understood if one considers phonetics and phonology together in their multi-faceted interaction. Our goal here is to present an overview of the relevant issues in order to help define a notion (or notions) of complexity in the domain of sound systems. Rather than proposing specific measures of complexity, we provide a backdrop to a constructive discussion of the nature of complexity in sound systems.

We begin in §2 by reviewing different notions that have been interpreted as being related to the issue of phonological complexity. Major historical landmarks of complexity in phonetics and phonology are discussed in Pellegrino et al.'s introduction to this volume. From our perspective we organize these earlier endeavors into concerns with: (i) *markedness*, (ii) *effort*, (iii) *naturalness*, (iv) *information content*. We take the time to review them here because they are directly relevant to the relationship between phonetics and phonology and the nature of representations.

In §3 we turn to the details of the relationship between phonology and phonetics. In this regard, we address two main questions that have traditionally played a central part in the understanding of the phonetics-phonology interface. The first of these is the issue of gradience vs. categoriality in the domain of linguistic sound systems, and its implications for the question of an adequate representation of linguistic units.

---

\* We thank the workshop organizers for their initial invitation to present a brief overview of current issues in phonetics and phonology. In doing so they encouraged us to engage in a discussion about the field from a new perspective, that of complexity. This chapter is an attempt to report on our discussion.

In §4 we discuss the second issue: the role of phonetic naturalness in phonology. Both of these questions are major, and we do not attempt to provide a comprehensive treatment here. Rather, our goal is to consider them in framing a broader discussion of phonological complexity.

In §5 we consider the ways in which measures of complexity depend on the type of unit and representation considered. The conclusion of our discussion highlights the multi-faceted nature of phonetics and phonology and therefore of measures of complexity.

## 2. Definitions of complexity

In our survey of earlier implicit and explicit definitions of complexity, we review past attempts to characterize the nature of phonological systems. We discuss earlier concerns with complexity in §2.1; then we turn in §2.2 to the issue of theoretical framing in typological surveys, where we compare two types of approaches: theory-driven and data-driven ones. The first type is illustrated by Chomsky and Halle's (1968) *The Sound Pattern of English* (SPE), and the second by work based on Maddieson's (1984) *Patterns of Sounds* and the UPSID database.

### 2.1. Early approaches to complexity

A concern with complexity in phonetics and phonology can be traced back to discussions of the following related notions in the literature: *markedness*, *effort*, *naturalness*, and the recently reformulated notion of *information content*. While none of these notions taken individually can be equated with complexity, there is an intuitive sense in which each one of them can be considered as a relevant element to be included in the calculation of complexity.

Studies of phonological complexity started from typological surveys, which led to the development of the notion of *markedness* in phonological theory. The interpretation of markedness as complexity is implicit in the original understanding of the term, the sense in which it is used by Trubetzkoy (1939, 1969): the presence of a phonological specification (a Pellegrino et al.'s introduction to this volume).

Later, the interpretation of markedness as complexity referred to *coding complexity* (see Haspelmath 2006 for a detailed review). Overt marking or coding is seen to correspond to higher complexity than no coding or zero

expression. This view of complexity was adopted and further developed into the notion of *iconicity of complexity*, recently critiqued by Haspelmath (2008). What is relevant for the purposes of our paper is noting the actual use of the terms *complex* and *complexity* in this literature. Several of the authors cited in Haspelmath (2006, 2008) use these terms explicitly. Thus, Lehmann (1974) maintains the presence of a direct correlation between *complex* semantic representation and *complex* phonological representation. Givón (1991) treats complexity as tightly related to markedness. He considers complex categories to be those that are “cognitively marked”, and tend to be “structurally marked” at the same time. Similarly, in Newmeyer’s formulation: “Marked forms and structures are typically both structurally more complex (or at least longer) and semantically more complex than unmarked ones” (Newmeyer 1992: 763).

None of these discussions includes an objective definition of complexity. Lehmann (1974) does propose that complexity can be determined by counting the number of features needed to describe the meaning of an expression, where the term *feature* is understood in broad, more or less intuitive terms. The study of complexity through the notions of markedness or iconicity has not been pursued further, and as highlighted by both Hume (2004) and Haspelmath (2006), neither notion constitutes an explanatory theoretical tool.

Discussions of complexity in the earlier literature have also focused on the notion of *effort*, which has been invoked at times as a diagnostic of markedness. It is often assumed, for example, that phonetic difficulty corresponds to higher complexity, and things that are harder to produce are therefore marked (see Kirchner 1998/2001 for one attempt to formalize and quantify the notion of effort). Results of recent experimental work, however, cast doubt on the relevance of effort. Articulatory effort is not necessarily avoided in speech production. Convincing evidence comes from articulatory speech error experiments carried out by Pouplier (2003). Pouplier’s studies show that speech errors do not involve restricted articulator movement. On the contrary, in errors speakers often add an extra gesture, resulting in an even more complex articulation, but in a more stable mode of intergestural coordination.

The role attributed to effort in acquisition has been criticized early on by Jakobson, who rejected the direct interpretation of this idea as the principle of least effort, adopted in linguistics from the 18<sup>th</sup> century naturalist Georges-Louis Buffon:

“Depuis Buffon on invoque souvent le principe du moindre effort: les articulations faciles à émettre seraient acquises les premières. Mais un fait essentiel du développement linguistique du bébé contredit nettement cette hypothèse. Pendant la période du babil l’enfant produit aisément les sons les plus variés...” (Jakobson 1971: 317) [“Since Buffon, the principle of least effort is often invoked: articulations that are easy to produce are supposedly the first to be acquired. But an essential fact about the child’s linguistic development strictly contradicts this hypothesis. During the babbling stage the child produces with ease the most varied sounds...”]<sup>1</sup>

A possible inverse correlation between frequency and effort (see Pellegrino et al.’s introduction) has been criticized by Trubetzkoy (Trubetzkoy 1969, chapter 7). Trubetzkoy advocates instead a more sophisticated approach to frequency count, which takes into account not only the real frequency of a phoneme but also its expected frequency, as determined, for example, from observed restrictions in phoneme occurrence in particular contexts:

“The absolute figures of actual phoneme frequency are only of secondary importance. Only the relationship of these figures to the theoretically expected figures of phoneme frequency is of real value. An actual phoneme count in the text must therefore be preceded by a careful calculation of the theoretical possibilities (with all rules for neutralization and combination in mind)” (Trubetzkoy 1969: 264).

Hume (2006) takes up Trubetzkoy’s challenge, trying to determine a measure of the probability of a phoneme, rather than just its frequency of occurrence. She argues that what lies at the basis of markedness is *information content*, a measure of the probability of a particular element in a given communication system. The higher the probability of an element the lower its information content, and conversely, the lower its probability the higher its information content. Markedness diagnostics can thus be replaced by observations about probability, which can be determined based on a number of factors.<sup>2</sup> Hume hypothesizes a relationship between complexity and probability. If low probability correlates with higher information content, then it may in turn correlate with higher complexity. At the same time, a related hypothesis needs to be tested, one signalled by Pellegrino et al. (2007): it is possible that lower rate (the number of syllables per second) may also correlate with higher information content (the average information per syllable), and thus with syllabic complexity. According to this hypothesis, the information rate would result from a trade-off between the

articulation rate and the information density of the syllables (estimated with Shannon's entropy).

In general the usefulness of insights gained by considering speculative notions such as effort, described in either physical or processing terms, has been limited. Nevertheless these attempts have at least shown, as Maddieson (this volume) points out, that: "difficulty can itself be difficult to demonstrate".

Another markedness diagnostic that has been related to complexity is *naturalness*. Even though the term *naturalness* is explicitly used, it overlaps on the one hand with the diagnostic of effort and phonetic difficulty, and on the other hand with frequency. The discussion of *naturalness* can be traced back to Natural Phonology (Donegan and Stampe 1979, among others). A natural, unmarked phenomenon is one that is easier in terms of the articulatory or acoustic processes it involves, but also one that is more frequent. In the end it becomes very difficult to tease apart the two concepts, revealing the risk of circularity: processes are natural because they are frequent, and they are frequent because they are natural. Thus none of these notions in and of itself offers an adequate characterization of complexity.

## **2.2. Theory-driven vs. data-driven approaches**

Overall we identify two main types of studies of phonological complexity, which we refer to as theory-driven and data-driven, respectively.

The theory-driven approach is well illustrated by Chomsky and Halle's (1968) *SPE*, where counting distinctive features is considered to be the relevant measure of complexity, not unlike Lehmann's (1974) proposal, albeit restricted to phonology. In chapter 9 of *SPE*, Chomsky and Halle develop a complexity metric. Starting from the assumption that a natural class should be defined with fewer distinctive features than a non-natural (or less natural) class, Chomsky and Halle observe some contradictions. For example, the class of voiced obstruents is captured by more features than the class of all voiced segments, including vowels. Nevertheless, the first class is intuitively more natural than the second one, and would therefore be expected to have the simpler definition. The solution they propose is to include the concept of markedness in the formal framework, and to "revise the evaluation measure so that unmarked values do not contribute to complexity" (Chomsky and Halle 1968: 402). This adjustment allows them to define complexity, and more specifically the complexity of a segment

inventory, in the following way: “The complexity of a system is equal to the sum of the marked features of its members” (Chomsky and Halle 1968: 409), or in other words, “related to the sum of the complexities of the individual segments” (Chomsky and Halle 1968: 414). Thus, a vowel system consisting of /a i u e o/ is simpler (and therefore predicted to be more common) than /æ i u e o/. By counting only the marked features, the first system has a complexity of 6, while the second one has a complexity of 8. The authors themselves acknowledge the possible limitations of their measure: summing up the marked features predicts, for example, that the inventory /a i u e o/ is as simple and common as /a i u e ə/, both with a complexity of 6. One potentially relevant difference between these systems, which the measure does not consider, is the presence vs. absence of symmetry, the first inventory being more symmetrical than the second one. In general in theory-driven approaches, complexity is defined through a particular formal framework, and thus the insights gained are inevitably limited by the set of operational assumptions.

Data-driven studies of phonological complexity are illustrated by the body of work relying on or inspired by Maddieson’s (1984) *Patterns of Sounds* and the UPSID database that it is based on. Linguists have made sophisticated use of these typological surveys to evaluate complexity (e.g., Lindblom and Maddieson 1988; Vallée 1994; Vallée et al. 2002; Marsico et al. 2004). The UPSID database itself focuses on the segment, but measures of complexity have not been restricted to counting segments. The question of the relevant unit raises the crucial issue of *representation*, which we will return to later. In Maddieson’s survey “each segment considered phonemic is represented by its most characteristic allophone” as determined by weighing several criteria (Maddieson 1984: 6). Maddieson codifies an atheoretical, descriptive definition of the segment, adopting an intermediary level of representation between phonology and phonetics, that is, in-between the underlying contrastive elements, and the phonetic output characterizable as a string of phones. The database captures the output of the phonology, a discrete allophonic representation, which is neither purely phonemic nor purely phonetic, and described as: “phonologically contrastive segments (...) characterized by certain phonetic attributes” (Maddieson 1984: 160).

### **2.3. Summary**

Both theory-driven and data-driven approaches can offer useful insight in the nature and organization of phonological systems. It is also important to bear in mind the implicit assumptions even in what are taken to be “data-driven” approaches. (See also Hayes and Steriade’s 2004, pp. 3-5 discussion of inductive vs. deductive approaches to the study of markedness.)

One critical aspect of these efforts is the question of the relevant linguistic units in measuring complexity. This question is addressed explicitly by Marsico et al. (2004) and Coupé et al. (this volume). Feature-hood and segment-hood can both tell us something about complexity. But neither concept is as clear-cut as often assumed. Under many views (such as *SPE*), features are taken as primitives. Segments are built out of bundles of features. Other views take the segment to be primary, or even suggest that segments are epiphenomenal, as is argued by some exemplar theorists. We take the view that in adult grammar, both segments and features have a role to play in characterizing the inventories and patterns of sound systems.

As seen above, the question of the nature of segments is also a complex one: do we mean underlying contrastive units, do we mean something more concrete, such as Maddieson’s surface allophones? This particular type of unit served as a useful starting point for a measure of phonological complexity because it is non-committal. It circumvents the phonetics-phonology distinction. Subsequent studies (e.g., Maddieson, this volume) however, have considered different types of units and have explicitly addressed the relationships between them. At this stage in the research program on complexity it is necessary to consider all different types of units.

The question about the nature of units of representation leads to broader questions about the nature of phonology and phonetics and their relationship. In the next section, we turn to this relationship.

### **3. The relationship between phonology and phonetics**

Chomsky and Halle provided an explicit answer about the nature of representations, drawing a distinction between underlying representations, captured in terms of bundles of binary feature matrices, and surface forms, which were the output of the phonology. At this point in the derivation a translation of binary values to scalar values yielded the phonetic transcription. They assumed a modular relationship between phonology and pho-

netics, where phonology was categorical, whereas phonetics was gradient and continuous. It was also assumed that phonology was the domain of the language specific and phonetics the domain of universal (automatic) aspects of sound patterns. Research since that time has investigated this relationship from many angles, enriching the view of phonetics in the grammar, showing that the dichotomy between phonology and phonetics is not as sharp as had been assumed. (See Cohn 1998, 2006a & b for discussion). We briefly review the nature of this relationship.

As discussed by Cohn (2006b), there are actually two distinct ways in which phonology and phonetics interact. A distinction needs to be drawn between the way phonology affects or drives phonetics—what Cohn terms *phonology in phonetics* and the way that phonetics affects phonology—what Cohn terms *phonetics in phonology*. In the first, the nature of the correlation assumed by *SPE*, that is, that phonology is discrete and categorical, while phonetics is continuous and gradient – is important. In the second, the place of naturalness, as internal or external to the grammar, is central. From both of these perspectives, we conclude that phonology and phonetics are distinct, albeit not as sharply delineated as implied by strictly modular models.

### **3.1. Phonology in Phonetics**

Phonology is the cognitive organization of sounds as they constitute the building blocks of meaningful units in language. The physical realization of phonological contrast is a fundamental property of phonological systems and thus phonological elements are physically realized in time. Phonology is thus embodied in the phonetics.

This then is the first facet of the relationship between phonology and phonetics: the relationship between these cognitive elements and their physical realization. Implicit in the realization of phonology is the division between categorical vs. gradient effects: phonology captures contrast, which at the same time must be realized in time and space. This leads to the widely assumed correlations in (1).



- (1) The relationship between phonology and phonetics:  
phonology = discrete, categorical  
≠  
phonetics = continuous, gradient

If the correlation between phonology and categoriality on one hand and between phonetics and gradience on the other were perfect, we would expect there to be only categorical phonology and gradient phonetics. There are reasons why the correlation might not be perfect, but nevertheless strong enough to re-enforce the view that phonology and phonetics are distinct. In §3.2, we review the evidence for categorical phonology and gradient phonetics. We consider categorical phonetics and gradient phonology in §3.3.

### 3.2. Categorical phonology and gradient phonetics

A widely assumed modular view of grammar frames our modeling of more categorical and more gradient aspects of such phenomena as belonging to distinct modules (e.g. phonology vs. phonetics). We refer to this as a mapping approach. Following a mapping approach, categorical patterns observed in the phonetics are understood to result from either lexical or phonological specification and gradient patterns are understood to arise through the implementation of those specifications.

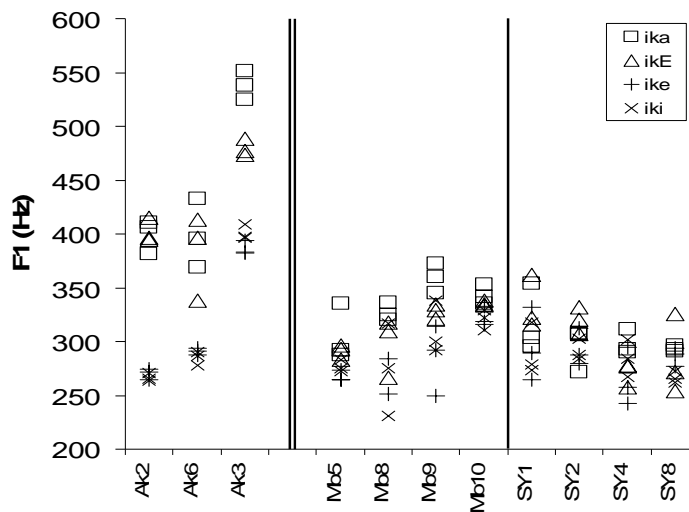
Growing out of Pierrehumbert's (1980) study of English intonation, gradient phonetic patterns are understood as resulting from phonetic implementation. Under the particular view developed there, termed *generative phonetics*, these gradient patterns are the result of interpolation through phonologically unspecified domains. Keating (1988) and Cohn (1990) extend this approach to the segmental domain, arguing that phenomena such as long distance pharyngealization and nasalization can be understood in these terms as well. Within generative phonetics, the account of gradience follows from a particular set of assumptions about specification and underspecification.

It is generally assumed that categoriality in the phonology also follows directly from the nature of perception and the important role of categorical perception. The specific ways in which perception constrains or defines phonology are not yet fully understood, although see Hume and Johnson (2001) for recent discussions of this relationship.

A modular mapping approach has been the dominant paradigm to the phonology-phonetics interface since the 1980's and such approaches have greatly advanced our understanding of phonological patterns and their realization. The intuitive difference between more categorical and more gradient patterns in the realization of sounds corresponds to the division of labor between phonology and phonetics within such approaches and this division of labor has done quite a lot of work for us. Such results are seen most concretely in the success of many speech synthesis by rule systems in their modeling of both segmental and suprasegmental properties of sound systems. (See Klatt 1987 for a review.)

A modular approach also accounts for the sense in which the phonetics, in effect, acts on the phonology. In many cases, phonological and phonetic effects are similar, but not identical. This is the fundamental character of what Cohn (1998) terms phonetic and phonological *doublets*, cases where there are parallel categorical and gradient effects in the same language, with independent evidence (e.g., from speaker awareness, rule interaction) suggesting that the former are due to the phonology and the latter result from the implementation of the former. For example, this is seen in patterns of nasalization in several languages (Cohn 1990); palatalization in English (Zsiga 1995); vowel devoicing in Japanese (Tsuchida 1997, 1998).

The differences between coarticulation and assimilation are also clearly demonstrated in work comparing vowel harmony with effects of vowel-to-vowel coarticulation, as shown in work on Turkish (Beddor and Yavuz 1995) and Yoruba (Przedziecki 2005). Consider an example from Yoruba comparing three dialects where the phonological patterns of vowel harmony differ. In the Àkùrẹ̀ dialect, there is anticipatory [ATR] vowel harmony affecting both mid and high vowels; thus in a V<sub>1</sub>CV<sub>2</sub> form, a mid or high V<sub>1</sub> will agree in [ATR] with the following V<sub>2</sub>. In comparison, in the Mòbà dialect, vowel harmony is active in mid, but not high vowels; and in Standard Yoruba (SY), synchronically vowel harmony is no longer active.



**Figure 1:** From Przeddziecki (2005, Figure 4.62, p. 225)

“F1 values of /i/ measured in the middle of the first vowel (V1) in individual tokens of four VCV contexts: *ika*, *ikẹ*, *ike*, *iki* in speakers of Àkùrẹ̀, Mòbà, SY”

Przeddziecki compares the effects of vowel harmony in high vowels in Àkùrẹ̀ (Ak), where robust differences in F1 are seen, with the effects of vowel-to-vowel coarticulation for four speakers in Mòbà (Mb) and four speakers of Standard Yoruba (SY), where smaller differences going in the same direction as Àkùrẹ̀ are seen for some speakers, but the difference is not of the magnitude of that seen where vowel harmony is active in high vowels. Thus we see a difference between the realization of vowel harmony and effects of vowel-to-vowel coarticulation.

What these cases and many others have in common is that the patterns of coarticulation are similar to, but not the same as, assimilation and that both patterns cooccur in the same language or closely related dialects. The manifestations are different, with the more categorical effects observed in what we understand to be the domain of the phonology and the more gradient ones in the phonetic implementation of the phonology. To document such differences, instrumental phonetic data is required, as impressionistic data alone do not offer the level of detail needed to make such determinations.

Following a mapping approach, assimilation is accounted for in the phonological component and coarticulation in the phonetic implementation. Such approaches predict categorical phonology and gradient phonetics, but do they fully capture observed patterns? What about categorical phonetics and gradient phonology?

### 3.3. Categorical phonetics and gradient phonology

We understand categorical phonetics to be periods of stability in space through time. These result directly from certain discontinuities in the phonetics. This is precisely the fundamental insight in Stevens’s (1989) Quantal Theory, where he argues that humans in their use of language exploit articulatory regions that offer stability in terms of acoustic output.<sup>3</sup> There are numerous examples of this in the phonetic literature. To mention just a few, consider Huffman’s (1990) articulatory landmarks in patterns of nasal-

ization, Kingston's (1990) coordination of laryngeal and supralaryngeal articulations (binding theory), and Keating's (1990) analysis of the high jaw position in English /s/.

There are many ways to model steady-state patterns within the phonetics without calling into question the basic assumptions of the dichotomous model of phonology and phonetics. To mention just one approach, within a target-interpolation model, phonetic targets can be assigned based on phonological specification as well as due to phonetic constraints or requirements (e.g., Keating 1990). Such cases then do not really inform the debate about the gray area between phonology and phonetics.

The more interesting question is whether there is evidence for gradient phonology, that is, phonological patterns best characterized in terms of continuous variables. It is particularly evidence claiming that there is gradient phonology that has led some to question whether phonetics and phonology are distinct. The status of gradient phonology is a complex issue (for a fuller discussion see Cohn 2006a). Cohn considers evidence for gradient phonology in the different aspects of what is understood to be phonology – contrast, phonotactics, morphophonemics, and allophony – and concludes that the answer depends in large part on what is meant by *gradience* and which aspects of the phonology are considered. The conclusions do suggest that strictly modular models involve an oversimplification.

While modular models of sound systems have achieved tremendous results in the description and understanding of human language, strict modularity imposes divisions, since each and every pattern is defined as either X or Y (e.g., phonological or phonetic). Yet along any dimension that might have quite distinct endpoints, there is a gray area. For example, what is the status of vowel length before voiced sounds in English, *bead* [bi:d] vs. *beat* [bit]? The difference is greater than that observed in many other languages (Keating 1985), but does it count as phonological?

This leads to the broader issue of how much phonetics there is in phonology, that is, to what extent phonetic detail is present in phonological alternations and representations. Three main views have been developed in this respect:

- (i) phonetic detail is directly encoded in the phonology (e.g., Steriade 2001; Flemming 1995/2002, 2001; Kirchner 1998/2001);
- (ii) phonetic detail (phonetic naturalness) is only relevant in the context of diachronic change (e.g., Ohala 1981 and subsequent work; Hyman 1976, 2001; Blevins 2004);

(iii) phonetic detail is indirectly reflected in phonological constraints, by virtue of *phonetic grounding* (e.g., Hayes 1999; Hayes and Steriade 2004).

While there is general agreement on the fact that many phonological processes are natural, that is, “make sense” from the point of view of speech physiology, acoustics, perception, the three views above are quite different in the way they conceptualize the relationship between phonetics and phonology and the source of the explanation. We pursue these three approaches in the next section on naturalness.

No matter what approach, an adequate theory of phonology and phonetics needs to account for the relationship between phonological units and physical realities, the ways in which phonetics acts on the phonology, as well as to offer an account of phonetics in phonology. We turn now to the nature of phonetics in phonology and the sources of naturalness.

#### **4. Naturalness**

In this section we consider different views of the source of naturalness in phonology (§4.1). We then present evidence from consonant timing in Georgian stop clusters (Chitoran et al. 2002; Chitoran and Goldstein 2006), bearing on this question (§4.2).

##### **4.1. Sources of naturalness**

Many understand naturalness to be part of phonology. The status of naturalness in phonology relates to early debates in generative phonology about natural phonology (Stampe 1979, Donegan and Stampe 1979). This view is also foundational to Optimality Theory (e.g. Prince and Smolensky 2004), where functional explanations characterized in scalar and gradient terms are central in the definition of the family of markedness constraints. Contrary to the view that “the principles that the rules subserve (the “laws”) are placed entirely outside the grammar [...] When the scalar and the gradient are recognized and brought within the purview of theory, Universal Grammar can supply the very substance from which grammars are built.” (Prince and Smolensky 2004: 233-234.) Under such approaches the explanations of naturalness are connected to the notion of markedness.

A significant group of researchers working within constraint-based frameworks has pursued the view that there is not a distinction between

constraints that manipulate phonological categories and those that determine fine details of the representation. This is a unidimensional approach, one that assumes no formally distinct representations or mechanisms for phonology and phonetics, often interpreted as arguing for the position that phonology and phonetics are one and the same thing.<sup>4</sup>

It is sometimes argued that explicit phonological accounts of naturalness pose a *duplication* problem. Formal accounts in phonological terms (often attributed to Universal Grammar) parallel or mirror the phonetic roots of such developments, thus duplicating the phonetic source or historical development driven by the phonetic source (see Przewdziecki 2005 for recent discussion). We return to this point below.

Naturalness can also be understood as being expressed through diachronic change. This is essentially approach (ii), the view of Hyman (1976, 2001). Hyman (1976) offers an insightful historical understanding of this relationship through the process of *phonologization*, whereby phonetic effects can be enhanced and over time come to play a systematic role in the phonology of a particular language. Under this view, phonological naturalness results from the grammaticalization of low-level phonetic effects. While a particular pattern might be motivated historically as a natural change, it might be *un-natural* in its synchronic realization (see Hyman 2001 for discussion). Phonetic motivation is also part of Blevins's (2004) characterization of types of sound change. According to this view only sound change is motivated by phonetic naturalness, synchronic phonology is not. A sound change which is phonetically motivated has consequences which may be exploited (*phonologized*) by synchronic phonology. Once phonologized, a sound change is subject to different principles, and naturalness becomes irrelevant (see also Anderson 1981).

Hayes and Steriade (2004) propose an approach offering middle ground between these opposing views, worthy of close consideration. They argue that the link between the phonetic motivation and phonological patterns is due to individual speakers' phonetic knowledge. "This shared knowledge leads learners to postulate independently similar constraints." (p. 1). They argue for a deductive approach to the investigation of markedness:

"Deductive research on phonological markedness starts from the assumption that markedness laws obtain across languages not because they reflect structural properties of the language faculty, irreducible to non-linguistic factors, but rather because they stem from speakers' shared knowledge of the factors that affect speech communication by impeding articulation, perception, or lexical access." (Hayes and Steriade 2004: 5).

This view relies on the Optimality Theoretic (OT) framework. Unlike rules, the formal characterization of an OT constraint may include its motivation, and thus offers a simple way of formalizing phonetic information in the grammar. Depending on the specific proposal, the constraints are evaluated either by strict domination or by weighting. Phonetically grounded constraints are phonetically “sensible”; they ban structures that are phonetically difficult, and allow structures that are phonetically easy, thus relying heavily on the notion of “effort”. Such constraints are induced by speakers based on their knowledge of the physical conditions under which speech is produced and perceived. The link between the phonological system and phonetic grounding is *phonetic knowledge* (Kingston and Diehl 1994). Consequently, while constraints may be universal, they are not necessarily innate. To assess these different views, we consider some evidence.

#### 4.2. Illustrating the source of naturalness and the nature of sound change: Georgian consonant clusters

We present here some evidence supporting a view consistent with phonologization and with the role of phonetic knowledge as mediated by the grammar, rather than being directly encoded in it. We summarize a recent study regarding patterns of consonant timing in Georgian stop clusters.

Consonant timing in Georgian stop clusters is affected by position in the word and by the order of place of articulation of the stops involved (Chitoran et al. 2002; Chitoran and Goldstein 2006). Clusters in word-initial position are significantly less overlapped than those in word-internal position. Also, clusters with a back-to-front order of place of articulation (such as *gd*, *tp*) are less overlapped than clusters with a front-to-back order (*dg*, *pt*).

##### (2) Georgian – word-initial clusters

Front-to-back		Back-to-front	
<b>b</b> gera	‘sound’	<b>g-ber</b> -av-s	‘fills you up’
<b>p<sup>h</sup>t<sup>h</sup></b> ila	‘hair lock’	<b>t<sup>h</sup>b</b> -eb-a	‘warms you’
<b>dg</b> -eb-a	‘stands up’	<b>gd</b> -eb-a	‘to be thrown’

The authors initially attributed these differences to considerations of perceptual recoverability, but a subsequent study (Chitoran and Goldstein 2006) showed that this explanation is not sufficient. Similar measures of

overlap in clusters combining stops and liquids also show that back-to-front clusters (*kl, rb*) are less overlapped than front-to-back ones (*pl, rk*), even though in these combinations perceptual recoverability is not at stake. The stop release is not in danger of being obscured by a high degree of overlap from a following liquid, and liquids do not rely on their releases in order to be correctly perceived. The timing pattern observed in stop-liquid and liquid-stop clusters is not motivated by perceptual recoverability. Consequently, the same explanation also seems less likely for the timing of stop-stop clusters. It suggests in fact that perceptual recoverability is not directly encoded in the phonology after all, but rather that the systematic differences observed in timing may be due to language-specific coordination patterns, which can be phonologized, that is, learned as grammatical generalizations.

Moreover, in addition to the front-to-back / back-to-front timing patterns, stop-stop clusters show overall an unexpectedly high degree of separation between gestures, more than needed to avoid obscuring the release burst. Some speakers even tend to insert a brief vocalic element in back-to-front stop clusters, the ones with the most separated gestures. While this process of epenthesis is highly variable at the current stage of the language, it occurs only in the “naturally” less overlapped back-to-front clusters, suggesting a further step towards the phonologization of “natural” timing patterns in Georgian.

The insertion of epenthetic vowels could ultimately affect the phonotactics and syllable structure of Georgian. This would be a significant change, especially in the case of word-initial clusters. Word-initial clusters are systematically syllabified as tautosyllabic onset clusters by native speakers. The phonologization of the epenthetic vowels may lead to the loss of word-initial clusters from the surface phonology of the language, at least those with a back-to-front order of place of articulation.

Although the presence of an epenthetic vowel is not currently affecting speakers’ syllabification intuitions, articulatory evidence shows that the syllable structure of Georgian is being affected in terms of articulatory organization.

In the model developed by Browman & Goldstein (2000) and Goldstein et al. (2006) syllable structure emerges from the planning and control of stable patterns of relative timing among articulatory gestures. A hypothesis proposed in this model states that an onset consonant (CV) is coupled in-phase with the following vowel. If an onset consists of more than one consonant (CCV), each consonant should bear the same coupling relation to



the vowel. This would result in two synchronous consonants, which would make one or the other unrecoverable. Since the order of consonants in an onset is linguistically relevant, it is further proposed that the consonants are also coupled to each other in anti-phase mode, meaning in a sequential manner. The result is therefore a competitive coupling graph between the synchronous coupling of each consonant to the vowel, and the sequential coupling of the consonants to each other. Goldstein et al. (2007) examined articulatory measures (using EMMA) which showed that in Georgian, as consonants are added to an onset (CV – CCV – CCCV) the time from the target of the rightmost C gesture to the target of the following vowel gesture gets shorter. In other words, the rightmost C shifts progressively to the right, closer to the vowel. This is the predicted consequence of the competitive coupling.

In this study, two Georgian speakers produced the triplet *rial-i* ‘commotion’ – *k’rial-i* ‘glitter’ – *ts’k’rial-a* ‘shiny clean’. One of the speakers shows the rightward shift of the [r], as expected. This effect has previously also been observed in English, and is known as the ‘c-center’ effect (Browman and Goldstein 1988, Byrd 1996). The second speaker, however, did not show the shift in this set of data. This speaker produced an audible epenthetic vowel in the back-to-front sequence [k’r] in all forms. This suggests that [k’] and [r] do not form an onset cluster for this speaker, and in this case no rightward shift is predicted by the model. The rightward shift is absent from this speaker’s data because the competitive coupling is absent. Instead, [r] is coupled in-phase with the following [i], and [k’] is coupled in-phase with the epenthetic vowel. Thus, in a C1<sup>v</sup>C2V sequence with an emerging epenthetic vowel the two consonants are no longer relatively timed as an onset cluster, rather C1 is timed as a single onset relative to the epenthetic vowel (Goldstein et al. 2007).

The longer separation observed in Georgian back-to-front clusters may have been initially motivated by phonetic naturalness (perceptual recoverability in stop-stop clusters). But the generalization of this timing pattern to all back-to-front clusters, regardless of segmental composition, and the further development of epenthetic vowels in this context can no longer be attributed directly to the same phonetic cause. An appropriate conclusion to such facts is the phrase coined by Larry Hyman: “Diachrony proposes, synchrony disposes” (Hyman 2005). Once phonologized, synchronic processes become subject to different factors, therefore the study of phonetic naturalness is relevant primarily within the context of diachronic change. Phonology is the intersection of phonetics and grammar (Hyman 1976).

The naturalness of phonetics (in our example, the reduced gestural overlap in back-to-front clusters) thus interacts with grammatical factors in such a way that the phonetic naturalness observable in phonology (the insertion of epenthetic vowels) is not the direct encoding of phonetic knowledge, but rather phonetic knowledge mediated by the principles of the grammar. This suggests that, as with the case of phonology in phonetics, here too, phonetics and phonology are not reducible to one and the same thing.

Processes may be natural in terms of their motivation. In terms of their effect they can be more categorical or more gradient. Studies such as the one outlined above suggest that examining phonetic variability, both within and across languages, may reveal additional facets of complexity, worthy of investigation. This brings us back to the two facets of the relationship between phonology and phonetics.

As discussed above, it is not the case that coarticulation and assimilation are the *same*, since these patterns are not identical and the coarticulatory effects are built on the phonological patterns of assimilation. It is an illusion to say that treating such patterns in parallel in the phonology and the phonetics poses a *duplication problem* as has been suggested by a number of researchers focusing on the source of naturalness in phonology. Rather the parallel effects are due indirectly to the ways in which phonology is *natural*, not directly in accounting for the effects through a single vocabulary or mechanism. Thus we need to draw a distinction between the source of the explanation, where indeed at its root some factors may be the same (see Przedziecki 2005 for discussion), and the characterization of the patterns themselves, which are similar, but not the same.

Since assimilation and coarticulation are not isomorphic, an adequate model needs to account for both of them. As seen for example in the Yoruba case, while assimilation might arise historically through the process of phonologization, there is evidence in many cases that the patterns of assimilation and coarticulation are not reducible to the same thing, thus we need to understand how the more categorical patterns and the more gradient patterns relate. In the following section we consider how the issues discussed so far relate to the question of the relevant units of representation.

## 5. The multi-faceted nature of complexity

Based on the richness of the representational structures often characterized as phonology or phonetics, it becomes increasingly clear that the notion of

complexity needs to be multi-faceted. As discussed in this chapter highlights, and as also proposed by Maddieson (this volume), Marsico et al. (2004) and subsequent work, different measures of complexity of phonological systems can be calculated, at different levels of representation, notably features, segments, and syllables. The question of the relevant primary units is therefore not a trivial one, as it bears directly on the question of the relevant measure of complexity. Moreover, it brings to the forefront the triad formed by perception units – production units – units of representation. The following important questions then arise:

- in measuring complexity, do we need to consider all three members of the triad in their interrelationship, or is only one of the three relevant?
- does the understanding of the triad change depending on the primary categories chosen?

In this section we briefly formulate the questions that we consider relevant in this respect, and we provide background to start a discussion.

We distinguish here between units at two levels: units at the level of cognitive representation, and units of perception. The fact that these two types of representations may or may not be isomorphic suggests that a relevant measure of complexity should not be restricted to only one or the other. We propose that the choice of an appropriate unit may depend on whether we are considering: (i) representations, (ii) sound systems, or (iii) sound patterns. For example, when considering exclusively sound systems, the segment or the feature has been shown to be appropriate (Lindblom and Maddieson 1988; Maddieson 2006; Marsico et al. 2004), but when considering the patterning of sounds within a system, a unit such as the gesture could be considered equally relevant.

The number of representation units proposed in the literature is quite large.<sup>5</sup> So far, concrete measures of complexity have been proposed or at least considered for *features*, *segments*, and *syllables*. The most compelling evidence for units of perception has been found also for *features*, *phonemes*, and *syllables* (see Nguyen 2005 for an overview). A clear consensus on a preferred unit of perception from among the three has not been reached so far. The evidence suggests that all three may have a role to play. In fact, recent work by Grossberg (2003) and Goldinger and Azuma (2003) suggests that different types of units, of smaller and larger sizes, can be activated in parallel. Future experiments will reveal the way in which multiple units are needed in achieving an efficient communication process. If this is the case, then multiple units are likely to be relevant to computations

of phonological complexity. Obviously, this question cannot be answered until a fuller understanding of the perception of the different proposed units has been reached.

We focus our discussion on the subset *features*, *segments*, and *syllables*, which overlaps with that of plausible perception units. The relevance of features for complexity has already been investigated. Marsico et al. (2004) compare measures of complexity based on different sets of not so abstract phonetic dimensions, for example features of the type “high”, “front”, “voiced”, etc. Distinctive features as such have not been considered in calculations of complexity, but their role has been investigated in a related measure, that of *feature economy* (Clements 2003). The hypothesis based on feature economy predicts that languages tend to maximize the number of sounds in their inventories that use the same feature set, thus maximizing the combinatory possibilities of features. Clements’ thorough survey of the languages in the UPSID database confirms this hypothesis. Speech sounds tend to be composed of features that are already used elsewhere in a given system. The finding that is most interesting relative to complexity is that feature economy is not a matter of the total number of features used per system, but rather of the number of segments sharing a given feature. This is interesting because feature economy can be seen as a measure of complexity at the feature level. Nevertheless, this measure makes direct reference to the *segment*, another unit of representation. This again brings up the possibility that more than one unit, at the same time, may be relevant for computations of phonological complexity. As pointed out by Pellegrino et al. (2007), the relevance of segments is hard to ignore. While the authors agree that the cognitive relevance of segments is still unclear, they ask: “if we give up the notion of segments, then what is the meaning of phonological inventories?” Thus, at least intuitively, segments cannot be excluded from these considerations. As discussed earlier, this is the level of unit used by Maddieson (1984), and has been the level at which many typological characterizations have been successfully made. More recent approaches to complexity have considered the third unit, the syllable. Maddieson (2007; this volume) has studied the possible correlations between syllable types and segment inventories, and tone contrasts.

Other units have not yet been considered in the measure of complexity. Their relevance will depend in part on evidence found for their role in perception and cognitive representation. In addition to this aspect, we believe that relevant measures will also depend on the general context in which the interaction of these units is considered: sound inventories or phonological

systems including processes. Moreover, within processes, we expect that the measures will also differ depending on whether we are considering synchronic alternations or diachronic change. Finally, we believe that understanding phonological complexity may also require an understanding of the relevance of phonetic variation, for example the phoneme-allophone relation. In this respect we echo John Ohala's call (this volume) to not ignore what he calls "the devilish details in the implementation of phonological contrasts". Phonetics and phonology empirically defy a reductionist characterization privileging one level or one unit over another. At this stage of the inquiry we advocate considering all the different types of units within the contexts in which they were proposed, and to seriously entertain the possibility that complexity ultimately requires attention to multiple units and multiple levels.

### **References**

- Anderson, S.  
1981 Why phonology isn't "natural". *Linguistic Inquiry* 12: 493-539.
- Beddor, P. and H. Yavuz  
1995 The relationship between vowel-to-vowel coarticulation and vowel harmony in Turkish. *Proceedings of the 13th International Congress of Phonetic Sciences*, volume 2, pp. 44-51.
- Blevins, J.  
2004 *Evolutionary Phonology. The Emergence of Sound Patterns* Cambridge: Cambridge University Press
- Browman, C. and L. Goldstein  
1988 Some notes on syllable structure in articulatory phonology. *Phonetica* 45: 140-155.  
1992 Articulatory Phonology: an overview. *Phonetica* 49: 155-180.  
2000 Competing constraints on intergestural coordination and self-organization of phonological structures. *Bulletin de la Communication Parlée* 5 : 25-34.
- Byrd, D.  
1996 Influences on articulatory timing in consonant sequences. *Journal of Phonetics* 24. 209-244.
- Chitoran, I., L. Goldstein, and D. Byrd  
2002 Gestural overlap and recoverability: Articulatory evidence from Georgian. In C. Gussenhoven and N. Warner (eds.) *Laboratory Phonology* 7. Berlin: Mouton de Gruyter. 419-48.
- Chitoran, I. and L. Goldstein

Ioana Chitoran and Abigail C. Cohn

- 2006 Testing the phonological status of perceptual recoverability: Articulatory evidence from Georgian. Poster presented at Laboratory Phonology 10, Paris, France, June-July 2006.
- Chomsky, N. and M. Halle  
1968 *The Sound Pattern of English*. New York, NY: Harper and Row.
- Clements, G. N.  
2003 Feature economy in sound systems. *Phonology* 20.3: 287–333
- Cohn, A.C.  
1990 *Phonetic and Phonological Rules of Nasalization*. UCLA PhD dissertation. Distributed as *UCLA Working Papers in Phonetics* 76.  
1998 The phonetics-phonology interface revisited: Where's phonetics? *Texas Linguistic Forum* 41: 25-40.  
2006a Is there gradient phonology? In G. Fanselow, C. Fery, R. Vogel and M. Schlesewsky (eds.) *Gradience in Grammar: Generative Perspectives*. Oxford: OUP, pp: 25-44.  
2006b Phonetics in phonology and phonology in phonetics. To appear in *Working Papers of the Cornell Phonetics Laboratory* 16.
- Coupé, C., E. Marsico, and F. Pellegrino  
this volume Structural complexity of phonological systems
- Donegan, P. and D. Stampe  
1979 The study of natural phonology. In D.A. Dinnsen (ed.) *Current approaches to phonological theory*. Bloomington: Indiana University Press
- Flemming, E.  
2001 Scalar and categorical phenomena in a unified model of phonetics and phonology. *Phonology* 18: 7-44.  
2002 Auditory Representations in Phonology. New York, NY: Routledge. [Revised version of 1995 UCLA Ph.D. dissertation.]
- Givón, T.  
1991 Markedness in grammar: Distributional, communicative and cognitive correlates of syntactic structure. *Studies in Language* 15.2: 335-370.
- Goldinger, S. and T. Azuma  
2003 Puzzle-solving science: the quixotic quest for units in speech perception. *Journal of Phonetics* 31, 305-320
- Goldstein, L., D. Byrd, and E. Saltzman  
2006 The role of vocal tract gestural action units in understanding the evolution of phonology. In M. Arbib (ed.) *From action to language: The mirror neuron system*. Cambridge: Cambridge University Press. pp. 215-249.
- Goldstein, L., I. Chitoran, and E. Selkirk  
2007 Syllable structure as coupled oscillator modes: Evidence from Georgian vs. Tashlhiyt Berber. *Proceedings of the 16<sup>th</sup> International*

*Complexity in Phonetics and Phonology*

*Congress of Phonetic Sciences*, Saarbrücken, Germany, August 6-10, 2007. 241-244.

- Grossberg, S.  
2003 Resonant neural dynamics of speech perception. *Journal of Phonetics* 31, 423-445
- Haspelmath, M.  
2006 Against markedness (and what to replace it with). *Journal of Linguistics* 42:1, 25-70.  
2008 Frequency vs. iconicity in explaining grammatical asymmetries. *Cognitive Linguistics* 19:1, 1-33.
- Hayes, B.  
1999 Phonetically-driven phonology: The role of optimality theory and inductive grounding. In M. Darnell, E. Moravcsik, M. Noonan, F. Newmeyer, and K. Wheatly (eds.) *Functionalism and Formalism in Linguistics, Volume I: General Papers*, Amsterdam: John Benjamins, pp. 243-285.
- Hayes, B. and D. Steriade  
2004 Introduction: the phonetic bases of phonological markedness. In B. Hayes, R. Kirchner, and D. Steriade (eds) *Phonetically Based Phonology*. Cambridge: CUP, pp. 1-33.
- Huffman, M.  
1990 *Implementation of Nasal: Timing and Articulatory Landmarks*. UCLA PhD dissertation. Distributed as *UCLA Working Papers in Phonetics* 75.
- Hume, E.  
2004 Deconstructing markedness: A predictability-based approach. To appear in *Proceedings of The Berkeley Linguistic Society* 30.  
2006 Language Specific and Universal Markedness: An Information-Theoretic Approach. Paper presented at the Linguistic Society of America Annual Meeting, Colloquium on Information Theory and Phonology. Jan. 7, 2006.
- Hume, E. and K. Johnson  
2001 *The Role of Speech Perception in Phonology*. San Diego: Academic Press.
- Hyman, L.  
1976 Phonologization. In A. Juillard (ed.) *Linguistic Studies Offered to Joseph Greenberg*. Vol. 2 Saratoga: Anma Libri, pp. 407-418.  
2001 The limits of phonetic determinism in phonology: \*NC revisited. In E. Hume and K. Johnson (eds.) *The Role of Speech Perception in Phonology*. San Diego: Academic Press, pp. 141-185.  
2005 Diachrony proposes, synchrony disposes – Evidence from prosody (and chess). Talk given at the Laboratoire Dynamique du Langage, Université de Lyon 2, Lyon, March 25, 2005

- Jakobson, R.  
1971 Les lois phoniques du langage enfantin et leur place dans la phonologie générale. In *Roman Jakobson : Selected Writings, vol. 1. Phonological Studies*. 2<sup>nd</sup> expanded edition. The Hague: Mouton. 317-327
- Johnson, K.  
1997 Speech perception without speaker normalization. In K. Johnson and J. Mullinix (eds.) *Talker Variability in Speech Processing*. San Diego: Academic Press, pp. 146-165.
- Jurafsky, D., A. Bell, M. Gregory and W. D. Raymond  
2001 Probabilistic relations between words: Evidence from reduction in Lexical Production. In J. Bybee and P. Hopper (eds) *Frequency and the Emergence of Linguistic Sstructure*. Amsterdam: John Benjamins, pp. 229-254.
- Keating, P.  
1985 Universal phonetics and the organization of grammars. In V. Fromkin (ed.) *Phonetic Linguistic Essays in Honor of Peter Ladefoged*. Orlando: Academic Press, pp. 115-132.  
1988 The window model of coarticulation: articulatory evidence. *UCLA Working Papers in Phonetics* 69: 3-29.  
1990 The window model of coarticulation: articulatory evidence. In Kingston and Beckman (eds.) *Papers in Laboratory Phonology I: Between the Grammar and the Physics of Speech*. Cambridge: CUP, pp. 451-470.
- Kingston, J.  
1990 Articulatory binding. In Kingston and Beckman (eds.) *Papers in Laboratory Phonology I: Between the Grammar and the Physics of Speech*. Cambridge: CUP, pp. 406-434.
- Kingston, J. and R. Diehl  
1994 Phonetic knowledge. *Language* 70: 419-53.
- Kirchner, R.  
1998/2001 *An Effort-Based Approach to Consonant Lenition*. New York, NY: Routledge. [1998 UCLA Ph.D dissertation]
- Klatt, D.  
1987 Review of text-to-speech conversion for English. *JASA* 82.3: 737-793.
- Lehmann, C.  
1974 Isomorphismus im sprachlichen Zeichen. In H. Seiler (ed.) *Linguistic workshop II: Arbeiten des Kölner Universalienprojekts 1973/4*. München: Fink (Structura, 8). 98-123
- Lindblom, B. and I. Maddieson



*Complexity in Phonetics and Phonology*

- 1988      Phonetic universals in consonant systems. In C.N. Li and L.H. Hyman (eds.) *Language, Speech and Mind: Studies in Honor of Victoria H. Fromkin*. 62-78. Beckenham: Croom Helm
- Maddieson, I.  
1984      *Patterns of Sounds*. Cambridge: Cambridge University Press  
2006      Correlating phonological complexity: Data and validation. *Linguistic Typology* 10. 108-125  
2007      Issues of phonological complexity: Statistical analysis of the relationship between syllable structures, segment inventories and tone contrasts. In Solé, M-J., P.S. Beddor, M. Ohala (eds.) *Experimental Approaches to Phonology*. Oxford University Press, Oxford and New York
- this volume      Calculating Phonological Complexity
- Marsico, E., I. Maddieson, C. Coupé, F. Pellegrino  
2004      Investigating the “hidden” structure of phonological systems. *Proceedings of The Berkeley Linguistic Society* 30. 256-267
- Newmeyer, F.  
1992      Iconicity and generative grammar. *Language* 68. 756-796.
- Nguyen, N.  
2005      La perception de la parole. In Nguyen, N., S. Wauquier-Graveline, J. Durand (eds.) *Phonologie et phonétique: Forme et substance*. Paris : Hermès. 425-447
- Ohala, J.J.  
1981      The listener as a source of sound change. In C. Masek, R. Hendrick, and M. Miller (eds.) *Papers from the Parasession on Language and Behavior*. Chicago : CLS. 178-203.
- this volume      Languages’ sound inventories: the devil in the details. 49-60.
- Pellegrino, F. , C. Coupé, and E. Marsico  
2007      An information theory-based approach to the balance of complexity between phonetics, phonology and morphosyntax. Paper presented at the Linguistic Society of America, LSA Complexity Panel, January 2007.
- Pierrehumbert, J.  
1980      *The Phonology and Phonetics of English Intonation*. MIT Ph.D. dissertation.  
2001      Exemplar dynamics: Word frequency, lenition and contrast. In J. Bybee and P. Hooper (eds.) *Frequency and the Emergence of Linguistic Structure*. Amsterdam: John Benjamins. 137-157.  
2002      Word-specific phonetics. In Gussenhoven and Warner (eds.) *Laboratory Phonology* 7. Berlin: Mouton de Gruyter. 101-139.
- Pierrehumbert, J. M. Beckman, and D. R. Ladd  
2000      Conceptual foundations in phonology as a laboratory science. In N. Burton-Roberts, P. Carr and G. Docherty (eds.) *Phonological*

Ioana Chitoran and Abigail C. Cohn

- Knowledge: Conceptual and Empirical Issues*, New York: Oxford University Press. 273-304.
- Pouplier, M.  
2003 Units of phonological encoding: Empirical evidence. PhD dissertation, Yale University.
- Prince, A. and P. Smolensky  
2004 *Optimality Theory: Constraint Interaction in Generative Grammar*. Malden, MA: Blackwell.
- Przedziecki, M.  
2005 *Vowel Harmony and Coarticulation in Three Dialects of Yorùbá: Phonetics Determining Phonology*, Cornell University PhD dissertation.
- Stampe, D.  
1979 *A Dissertation in Natural Phonology*. New York: Garland Press. [1973 University of Chicago Ph.D dissertation]
- Steriade, D.  
2001 Directional asymmetries in assimilation: A directional account. In E. Hume and K. Johnson (eds.) *The Role of Speech Perception in Phonology*. San Diego: Academic Press, pp. 219-250.
- Stevens, K.  
1989 On the *quantal* nature of speech. *Journal of Phonetics* 17: 3-45.
- Trubetzkoy, N.S.  
1939 *Grundzüge der Phonologie*. Publié avec l'appui du Cercle Linguistique de Copenhague et du Ministère de l'instruction publique de la République Tchéco-slovaque. Prague  
1969 *Principles of Phonology* [Grundzüge der Phonologie] translated by C. Baltaxe. Berkeley: University of California Press.
- Tsuchida, A.  
1997 Phonetics and Phonology of Japanese Vowel Devoicing. Cornell University, PhD dissertation.  
1998 Phonetic and phonological vowel devoicing in Japanese. *Texas Linguistic Forum* 41. 173-188.
- Vallée, N.  
1994 Systèmes vocaliques : de la typologie aux prédictions. PhD dissertation, Université Stendhal, Grenoble
- Vallée, N., L-J Boë, J-L Schwartz, P. Badin, C. Abry  
2002 The weight of phonetic substance in the structure of sound inventories. *ZAS Papers in Linguistics* 28. 145-168
- Zsiga, E.C.  
1995 An acoustic and electropalatographic study of lexical and postlexical palatalization in American English. In B. Connell and A. Arvaniti (eds.) *Phonology and Phonetic Evidence: Papers in Laboratory Phonology IV*. Cambridge: Cambridge University Press. 282-302

## **Notes**

<sup>1</sup> Authors' translation.

<sup>2</sup> See Jurafsky et al. (2001) for discussion of the role of predictability of language processing and production.

<sup>3</sup> Pierrehumbert et al. (2000) make similar observations.

<sup>4</sup> An earlier, seminal approach which does not draw a sharp boundary between phonetics and phonology is the theory of Articulatory Phonology, developed by Browman and Goldstein (1992 and work cited therein). Under this view phonology and phonetics are both modeled with a unified formalism, but it does not exclude the possibility that there are aspects of what has been understood to be phonology and what has been understood to be phonetics that show distinct sets of properties or behavior.

<sup>5</sup> Here we consider only abstractionist models, acknowledging the importance of exemplar models (Johnson 1997, Pierrehumbert 2001, 2002, among others). At this point in the development of exemplar models the question of complexity has not been addressed, and we do not attempt to characterize what, in an exemplar model, could be included in a measure of complexity.



