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**APPROACHES TO
PHONOLOGICAL COMPLEXITY**

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Complexity in 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 determine possible sources of complexity that arise in sound patterns and sound systems. We propose that in order to understand complexity, one must consider phonetics and phonology together in their interaction. We argue that the relationship between phonology and phonetics is a multi-faceted one, which in turn leads us to a multi-faceted view of complexity itself. 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, and to provide a backdrop to a constructive discussion of the nature of complexity in sound systems.

We begin in §2 by considering possible definitions of phonological complexity based on the different interpretations that have been given to this notion. The issue of complexity has previously been addressed, implicitly or explicitly, through notions such as *markedness*, *effort*, *naturalness*, *information content*. Concerns with a measure of phonological or phonetic complexity are therefore not new, even though the use of the term “complexity” per se to refer to these questions is more recent. In this section we survey earlier endeavors in these directions.

We then turn to the multi-faceted nature 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 relationship. The first of these, addressed in §3, 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.

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

In §5 we return to the question of complexity and consider the ways in which measures of complexity depend on the type of unit and representation considered. The conclusion of our discussion highlights the multifaceted nature of complexity. Thus more than one type of unit and more than one type of measure are relevant to any characterization 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 Maddieson's (1984) *Patterns of Sounds*.

2.1. Early approaches to complexity

A concern with complexity in phonetics and phonology can be traced back to discussions of several related notions in the literature: *markedness*, *effort*, *naturalness*, and more recently, *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 mark) corresponds to higher complexity in a linguistic element. Thus, to take a classic example, voiced /d/ is the more complex (marked) member of an opposition relative to the voiceless (unmarked) /t/.

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 (to appear). 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; to appear) 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. Only Lehmann (1974) proposes 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 very 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. While many such efforts are informal, see Kirchner (1998/2001) for one attempt to formalize and quantify the notion of effort. Ironically, however, Jakobson himself criticized the direct interpretation of this idea as the principle of least effort, adopted in linguistics from the 18th 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...”]¹

Jakobson's critique is now substantiated by experimental work showing that 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.

Similarly, Trubetzkoy cautions against theories that simply explain the high frequency of a phoneme by the less difficult production of that phoneme (Trubetzkoy, 1969, chapter 7). He advocates instead a more sophisticated approach to frequency count, which takes into account both the real frequency of a phoneme and its expected frequency:

“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).

We return to this view below, in relation to Hume's (2006) proposal of information content as a basis for markedness.

In general, however, 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 served to show, 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.

Information content is proposed by Hume (2006) as an alternative to markedness. In her proposal she accepts 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 marked-

ness 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.² While the exact nature of these factors, their interaction, and the specific definition of probability require further empirical investigation, it is plausible to hypothesize a relationship between complexity and probability. For example, 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 information rate (the quantity of information per unit per second) may turn out to be more relevant than, or closely related to information content (the quantity of information per unit).

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 o/, 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.

A data-driven study of phonological complexity is Maddieson’s (1984) *Patterns of Sounds* and the UPSID database that it is based on. The database focuses on the segment, so the implicit measure of complexity involves counting segments. This 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” (Maddieson, 1984:6). The representative allophone is determined by weighing several criteria: (i) the allophone with the widest distribution, when this information is available; (ii) the allophone most representative of the phonetic range of variation of all allophones; (iii) the allophone from which the others can be most easily derived. Maddieson thus codifies an atheoretical, descriptive definition of the segment, adopting a somewhat arbitrary, 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).

Following Maddieson’s example, linguists have continued to make sophisticated use of typological surveys for many purposes, including that of evaluating complexity (e.g., Lindblom and Maddieson, 1988; Vallée, 1994; Vallée et al., 2002; Marsico et al., 2004).

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, 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? The question about the nature of segments 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 phonetics, 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.

First, 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 emerges in the phonetics, in the sense that phonological contrast is physically realized.

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 |

The correlations in (1) suggest the following relationships:

- | | |
|-------------------------------------|----------------------------------|
| (2) a. Categorical phonology | b. Gradient phonology |
| c. Categorical phonetics | d. Gradient phonetics |

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 (a) and gradient phonetics (d). 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. On the other hand, perhaps there is in fact nothing privileged about this correlation. 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 (steady state) 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 under-specification.

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 well 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 gra-

dient 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 both in their modeling of 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 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); as well as vowel harmony vs. vowel-to-vowel coarticulation and vowel harmony, investigated by Beddor and Yavuz (1995) in Turkish and by Przewdziecki (2005) in Yoruba. (See Cohn, 2006b for fuller discussion of this point.)

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. The manifestations are different, with the more categorical effects observed in what we independently 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) Quan-

tal Theory, where he argues that humans in their use of language exploit articulatory regions that offer stability in terms of acoustic output.³ There are numerous examples of this in the phonetic literature. To mention just a few, consider Huffman's (1990) articulatory landmarks in patterns of nasalization, 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. 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?

An alternative to the types of approaches that assume that phonology and phonetics are distinct and that there is a mapping between these two modules or domains are approaches that assume that phonology and phonetics are understood and modeled with the same formal mechanisms—what we term *unidimensional* approaches. A seminal approach in this regard is the theory of Articulatory Phonology, developed by Browman and

Goldstein (1992 and work cited therein), where it is argued that both phonology and phonetics can be modeled with a unified formalism. This view 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. This approach has served as fertile ground for advancing our understanding of phonology as resulting at least in part from the coordination of articulatory gestures.

More recently, 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 another type of approach 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.

The controversy here turns on the question of how much phonetics there is in phonology, 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 most 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.

The first view proposes a unidimensional model, in which sound patterns can be accounted for directly by principles of production and perception. One argument in favor of unidimensional approaches is that they offer a direct account of naturalness in phonology, the second facet of the relationship: *phonetics in phonology*, a topic we will turn to in §4. Under the second view the effect of naturalness on the phonological system is indirect. Under the third view, some phonological constraints are considered to be phonetically grounded, but formal symmetry plays a role in constraint

creation. The speaker/learner generalizes from experience in constructing phonetically grounded constraints. The link between the phonological system and phonetic grounding is *phonetic knowledge* (Kingston and Diehl, 1994).

An adequate theory of phonology and phonetics, whether modular, unidimensional, or otherwise 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 bearing on this question (§4.2). The case we examine concerns patterns of consonant timing in Georgian stop clusters (Chitoran et al., 2002; Chitoran and Goldstein, 2006).

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.

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 de-

velopment driven by the phonetic source (see Przedziecki, 2005 for recent discussion). We return to this point below.

Others understand naturalness to be 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 pro-

duced and perceived. 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

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 (like *gd*, *tp*) are less overlapped than clusters with a front-to-back order (*dg*, *pt*).

(3) Georgian – word-initial clusters

Front-to-back		Back-to-front	
b gera	‘sound’	g-ber -av-s	‘fills you up’
p^ht^h ila	‘hair lock’	t^hb -eb-a	‘warms you’
dg -eb-a	‘stands up’	gd -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 the stop release is no longer in danger of being obscured by a high degree of overlap, 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 coor-

dination 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 an epenthetic vowel 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 a $C1^VC2V$ sequence with an 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).

In the model recently 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 (i.e., the center) 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.

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* thing, 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 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 Przewdziecki, 2005 for discussion), and the characterization of the patterns themselves, which are similar, but not the same.

Since assimilation and coarticulation are distinct, an adequate model needs to account for both of them. The view taken here is that while assimilation might arise historically through the process of phonologization, there is ample evidence 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 our discussion of the relationship between phonetics and phonology, it becomes increasingly clear that the notion of complexity in phonology must be a multi-faceted one. 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.⁴ 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. This 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.

Although more representation units have been proposed in the literature, other than *features*, *segments*, and *syllables*, we will limit our discussion to this subset, 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, to return to the interaction between phonetics and phonology, the topic with which we started this paper, we believe that understanding phonological complexity may also require an understanding of the relevance of phonetic variation – for example the phoneme-allophone relation – for a measure of phonological complexity.

Notes

1. Authors' translation.
2. See Jurafsky et al., (2001) for discussion of the role of predictability of language processing and production.
3. Pierrehumbert et al., (2000) make similar observations.
4. Here we only consider 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 it is not easy to tell what, in an exemplar model, could be included in a measure of complexity.

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