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*Introduction: phonological models and experimental data**

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> Under traditional conceptions of linguistics, the phonology of a language … is restricted to a generally finite set of facts … However, once linguistics is regarded as (and not merely called) cognitive psychology, phonology, even the phonology of the word, ceases to be a finite domain: the range of data is limited only by the investigator's imagination in devising tasks that tap into his subjects' phonological knowledge and is not limited to the existing vocabulary of the language.
>
> (McCawley 1986: 38)

James McCawley's 'Today the world, tomorrow phonology' appeared in Volume 3 of this journal, whose first half was a special issue on 'The validation of phonological theories', edited by John Ohala. Both McCawley and Ohala (1986), in his own contribution to the volume, saw the widespread use of experimental methodologies in phonology as a yet-to-be-achieved state of affairs. Some twenty years later, we can say that McCawley's 'tomorrow' has arrived: laboratory experimentation is just as much a part of the phonologist's toolkit as is the analysis of cross-linguistic corpora collected using just ordinary phonetic transcription. We offer the present issue as evidence of the current high level of integration of experimental methodology and phonological theory, and

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especially as a report on important new developments in both methodology and theory.[1] As we discuss in what follows, the papers collected here both use the laboratory to test predictions derived from phonological theory, and also develop phonological theory so that it can better deal with data collected in experiments.

In the course of providing some context for the papers, we briefly consider how and why the status of experimental phonology has changed so dramatically since 1986. Alongside the efforts of Ohala and colleagues, which might be called the first wave of experimental phonology (see also Ohala & Jaeger 1986), the subsequent establishment of the Laboratory Phonology conference and book series (starting with Kingston & Beckman 1990) has clearly played a major role in promoting the use of experimental techniques in the study of phonological knowledge and processing (see Pierrehumbert *et al.* 2000 for an overview). It is also clear that developments in phonological theory itself have contributed to the heightened productive interplay with experimentation.

First, phonological theory has become increasingly grounded in phonetics, both in articulation (e.g. the feature geometry of Clements 1985, Sagey 1986 and the articulatory phonology of Browman & Goldstein 1986) and in perception (see e.g. Hume & Johnson 2001, Boersma & Hamann, to appear). Recent collections on phonetically driven phonology appear in *Phonology* 18:1 (Gussenhoven & Kager 2001) and in Hayes *et al.* (2004). Not all of this research is itself experimental, but it has increased the phonological community's interest in the mechanisms of articulation and perception, which are of course studied experimentally.

A second development in phonological theory, which greatly aids its experimental investigation, is the increased use of mathematical formalism and computational methods. These have been applied in developing explicit models of the mapping from categorical phonological representations to the continuous domain of phonetic implementation, and also in the creation of models of phonology which themselves employ numerical formalisation. Experimental data are by their very nature quantitative, which entails that predictions or interpretations based on phonological theory must be given a quantitative formulation. In addition, data from experiments can be gradient in ways that are difficult to line up with a theory that only provides a categorical distinction between well-formed and ill-formed structures. One of the main contributions of the present issue is its presentation of a series of virtuosic displays of both of these applications of mathematics to phonological theory, which use the

[1] A little (admittedly selective) quantitative evidence for a change in the relationship between experimental and theoretical phonology between 1986 and now: of the ten dissertations completed in phonology at the University of Massachusetts, Amherst in the ten-year period ending in 1986, none used laboratory methods. Of the 13 completed in the ten-year period ending in 2008, eight did. The field of dissertations was determined by the label they bore at http://web.linguist.umass.edu/research/dissertations.php in January 2009. Only ones explicitly labelled as 'phonology' were included, which likely results in an overly conservative measure of the degree of change.

resulting models to predict and interpret experimental data. Similar virtuosity is also displayed in a number of the papers' statistical analyses of their data.

Jason Shaw, **Adamantios I. Gafos**, **Philip Hoole** and **Chakir Zeroual** test two competing hypotheses about the syllabification of initial consonant clusters in Moroccan Arabic: that they are syllabified as a complex onset to a single syllable with a vocalic nucleus, or as a sequence of syllables, the first of which is headed by a consonant. To do so, they draw on work in articulatory phonology that has shown that patterns of relative temporal stability across segmental strings depend on the syllabification of the segments. Quantitative predictions are thus made on the basis of different categorical phonological representations. To test these predictions, Shaw *et al.* use precise articulatory measures collected by means of Electromagnetic Articulometry. While the bulk of the data supports the syllabic sequence analysis, under certain conditions, the data seem to support the complex onset analysis. Through computational modelling of the mapping from phonological structure to temporal implementation, Shaw *et al.* go on to provide an account that is consistent with the hypothesis that the phonological structure uniformly consists of syllabic sequences.

As Shaw *et al.* emphasise, the question of how different syllable structures map to different patterns of temporal stability is a relatively new area of research. The type of phonology–phonetics mapping investigated by **Amalia Arvaniti** and **D. Robert Ladd** has a much longer history of study: that of the realisation of categorical autosegmental specification of intonational melodies as continuous pitch contours. Arvaniti & Ladd defend the autosegmental position that tonal specifications are relatively sparse, consisting of targets distributed to a subset of the syllables in a string, with intervening specifications supplied by interpolation. This position is contrasted with theories of intonation that specify targets for all syllables, or that specify contour shapes that are superposed on the syllabic string. From the autosegmental model and a theory of interpolation, Arvaniti & Ladd derive a series of precise predictions about the shape of F0 contours in Greek wh-questions. Acoustic analyses of experimentally elicited data confirm the predictions of the autosegmental model, and pose problematic for the alternative theories. This paper provides further demonstration of how phonological theories supplemented with explicit models of the phonology–phonetics interface can profitably be put to experimental test.

Adam Albright's contribution proposes an elaboration of phonological theory that itself employs numerical formalism: a model of phonotactics that assigns probability to segmental sequences based on their featural make-up. The special issue of this journal published in 1986 provides some historical context for this study. Amongst the examples of phonological experimentation that Ohala (1986) reviews is Ohala & Ohala's (1986) study of nonce word judgements by native speakers of English, which supports some predictions made by Greenberg & Jenkins' (1964) neighbourhood density model over those of the phonological model of gradient phonotactics in Chomsky & Halle (1968: 417). Ohala (1986: 14) goes on to note that:

> An important aspect of the [Greenberg & Jenkins] model is that it requires only the lexicon (plus a means of accessing its contents) and some very general data processing mechanisms … The data processor does not contain and need not contain any abstracted ('derivative') knowledge about language-specific or language-universal sound patterns … It is interesting to speculate how much of speakers' phonological knowledge … may be based only on their knowledge of the lexicon plus the possession of very general cognitive abilities.

Although phonologists usually assume that knowledge of phonotactics should be represented in terms of a phonological grammar, there has been until recently little attempt to justify this assumption experimentally. As the references in Albright's paper show, this is currently a rapidly growing area of research; see further Coetzee (2008) and the work cited therein. In Albright's theory, knowledge of phonotactics is 'derivative' in Ohala's terms, as it involves abstraction from the lexicon, rather than a direct calculation of similarity to lexical items. While Albright's formalisation of grammatical knowledge in probabilistic terms does depart from most generativists' conceptions of phonological grammar (though see the review in Pierrehumbert 2003), it shares with other research in generative phonology the use of a set of distinctive features and natural classes – it is over these representations that probabilities are calculated. Albright follows Ohala & Ohala's (1986) precedent in pitting different models of phonotactics against experimental data. The newer study differs in that rather than developing experiments to test particular predictions, it seeks to determine the overall relative fit of the models to existing judgement data. Albright's conclusions are quite nuanced: he finds support for a model of phonotactics that makes use of phonological features, but also evidence for a more coarse-grained analysis in terms of segmental sequence probabilities.

Data from speech errors, collected naturalistically and through experimentation, have long been used as evidence bearing on phonological theory (for an overview and collection of recent work, see Schütze & Ferreira 2007). **Matthew Goldrick** and **Robert Daland** address a challenging issue for the interpretation of speech-error data in terms of phonological theory. They point out that speech errors generally respect the phonotactics of the speakers' language, and have also been shown to tend toward universally unmarked outcomes. However, neither of these are absolute restrictions: errors can violate language-specific phonotactics, and can make changes that increase rather than decrease markedness. Goldrick & Daland's solution to this problem adopts a standard connectionist approach to the modelling of speech errors: the addition of noise to the weights of network connections. Their innovation is to apply this noise to weights of connections of a network that realises the phonological grammar of the language, as in Harmonic Grammar (Smolensky & Legendre 2006; see also the review in Pater, this issue). Goldrick & Daland clearly illustrate, and rigorously prove, how the resulting model predicts the observed tendencies.

Goldrick & Daland's contribution connects with another development in phonological theory since 1986 that has contributed to the increased attention to experimental research: the introduction of Optimality Theory (OT; Prince & Smolensky 1993). This statement may well be controversial. After all, Prince & Smolensky and most subsequent researchers using their theory do not rely at all on data gathered in the laboratory, and also adopt the standard generative assumptions about the structure of lexical representations that have led many experimental phonologists to argue in favour of analogical/usage-based/exemplarist alternatives (see e.g. Bybee 2001, Bybee & Hopper 2001, Gahl & Yu 2006). Furthermore, in proposing constraint ranking as an alternative to Harmonic Grammar's weighted constraints, Prince & Smolensky (1993) also explicitly reject a numerical formalisation of their theory of grammar, which may well allow for simpler and more explicit models of the relation between grammatical knowledge and the behaviour measured in the laboratory. Nonetheless, there are several features of this framework that have had a positive impact on the fate of experimental phonology. Since the OT-experimental phonology connection is not an obvious one, and since several papers in this volume expand on it, we here take some space to briefly explain each of these features.

Constraint universality : The notion of a universal constraint set is not unique to OT; it is adapted from Chomsky's (1981) Principles and Parameters framework, in which there is considerable work in phonology, starting with Hayes (1980). However, OT has succeeded in pushing the UG agenda quite far, since the violability of OT's constraints have allowed analyses of a broad range of phenomena, using relatively general, plausibly universal, constraint sets. The use of universal constraints to study linguistic typology does not necessarily entail the cognitive hypothesis that these constraints are literally present in the minds of speakers of all languages (see Ellison 2000 for discussion), but OT has generally been interpreted as making that claim. A benefit of interpreting universality as a cognitive hypothesis is that it can be used to generate testable predictions, which have been investigated in a wide range of experimental research, mostly in studies of the acquisition of both of natural and constructed languages (see Barlow & Gierut 1999, Boersma & Levelt 2003 and Kager *et al.* 2004 for overviews of OT research on natural language acquisition, and Moreton 2008 for an overview of recent work on artificial language learning). Constraint universality is crucial to Goldrick & Daland's model of the tendency of speech errors to result in decreases along universal scales of markedness (though not necessarily to their account of the tendency of errors to respect language-specific phonotactics), and it forms the basis of the experimental hypotheses in Berent *et al.*'s paper in this issue, discussed below.

Theories of learning: OT's theory of grammar is accompanied by explicit theories of learning (see especially Tesar & Smolensky 2000, Boersma & Hayes 2001), which can be used to make predictions for experimental research. Coetzee's paper in this issue, introduced below, tests a prediction of an elaborated version of Tesar & Smolensky's learning algorithm.

Extensions to non-categorical data: The original OT grammar model produces only a single grammatical output for a given input, and does not distinguish between degrees of well-formedness across grammatical outputs for different inputs, or between degrees of ill-formedness between ungrammatical forms. Partly because of OT's connectionist roots, it is relatively amenable to elaboration as a model that has a stochastic component and thus generates a probability distribution over outputs for an input, and as a model that ranks outputs for their degree of well-formedness (for overviews of such models, see Coetzee & Pater, to appear and Coetzee & Pater 2008 respectively). This property of OT greatly increases its utility in generating experimental predictions, and in constructing interpretations of data. This is demonstrated at length in Goldrick & Daland's paper, and Berent *et al.* also sketch an OT-based model of how perception can be influenced stochastically by grammar.

Andries W. Coetzee investigates a specific prediction of the subset principle, which states that learners acquire the most restrictive grammar compatible with the learning data. He points out that some instantiations of a restrictive learner for OT predict that in the absence of evidence, learners will assume that the morphemes of their language do not alternate. He then shows that when the grammatical model and the learning theory are provided with a mechanism designed to handle exceptions (lexically specific constraints) a new prediction is generated: that even when a language does generally permit alternation, learners should display a bias toward non-alternation in individual morphemes. Coetzee finds evidence for this prediction across a series of experiments, and also finds that the frequency of alternation in the language being learned affects the subjects' propensity to assume that the morphemes alternate. As well as providing an example of how phonological theory can be used to generate predictions suitable for experimental investigation, Coetzee's study also shows how experimentation can distinguish between alternative analyses of linguistic data obtained through traditional methods.

Iris Berent, **Tracy Lennertz**, **Paul Smolensky** and **Vered Vaknin-Nusbaum** investigate constraint universality in a study of speech perception. They show that once one develops a sufficiently explicit model of the role of phonological grammar in perception, universality predicts that listeners should respond differently to structures that differ in markedness, even if they do not occur in the listeners' native language. Berent *et al.* study nasal-initial onset clusters, which do not occur in English, the native language of their experimental participants. Berent *et al.* find that their participants respond more accurately to rising sonority sequences than to falling sonority sequences, as predicted by their model of the role of phonological grammar in perception. They go on to address and rule out various alternative explanations for their data, highlighting a methodological rigour that we hope continues to find its way into phonology.

In sum, we think that we see in this issue of *Phonology*, and more generally in the state of the field as a whole, a third wave of experimental phonology, in which experimental methods are fully the partner of more traditional approaches in advancing our understanding of the phonological component of language.

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