# Experimental approaches in theoretical phonology*

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## 1 Introduction

### 1.1 Overview

This chapter provides an overview of how experiments have informed phonological theories, and vice versa. This chapter starts with some historical overview; when phonology was being established as its own area of research, there was a sharp division between phonetics and phonology. This division was called into question, and the issues on the phonetics-phonology interface are currently extensively pursued by an approach that is now known as laboratory phonology. After the historical overview, I discuss in some detail how phonetic experiments and phonological theories have informed each other.

### 1.2 The tension between phonetics and phonology

When phonology was being established as its own area of research, it was often assumed that phonology and phonetics were independent of one another. For example, Trubetzkoy (1939/1969) stated:

> The speech sounds...possess a large number of acoustic and articulatory properties. All of these are important for the phonetician since it is possible to answer correctly the question of how a specific sound is produced only if all of these properties are taken into consideration. Yet most of these properties are quite unimportant for the phonologists...[p.11]

We still sometimes witness a sharp divide between phonetics and phonology in the current literature: some claim that phonology is an abstract, substance-free computational system, which should be separated out from phonetics: "patterns of phonetic substance are not relevant to phonological theory strictly defined" (Hale & Reiss, 2000, p.158) (see Blaho, 2008 for a recent review of

*Acknowledgements: Thanks to the audiences at Kyoto University, members at Kyuushuu University, especially Toshio Matsuura, and my students in my graduate seminar in Spring 2009 and the graduate phonetics class in Spring 2010 at Rutgers University, especially Aaron Braver, Will Bennett, and Jimmy Bruno. Particular thanks are due to Osamu Fujimura, Beth Hume, Michael Kenstowicz, Marc van Oostendorp, Jaye Padgett, and two anonymous reviewers for their comments on earlier versions of this paper, although they are not responsible for remaining errors. The preparation of this paper is partially supported by a Research Council Grant from Rutgers University.

this position). There has been an uneasiness about integrating phonetics into phonological studies, because there was/is a belief that the phonetic module belongs to performance and the phonological module belongs to competence; i.e. phonetics does not belong to grammar *per se* (see e.g. Blaho, 2008, p.2). An assumption behind this claim is that phonetics involves automatic, universal mechanisms.

However, contrary to the view that phonetics consists of universal implementation rules, experiments have shown that phonetics is neither automatic nor universal; i.e. speakers control their phonetic behaviors and cross-linguistic variation exists in the realm of phonetics (Keating, 1985, 1988a; Kingston & Diehl, 1994, see also section 2.3.1 for more discussion). In this sense, any adequate model of grammar must integrate phonetics as a part of its model.

Phoneticians also responded to the thesis that we can and should study phonology without considering phonetic mechanisms behind phonology (see Diehl, 1991; Lindblom, 1962; Ohala, 1990b, for general discussion).[1] Perhaps the most well-known advocate of the objection is John Ohala (1990b, among many others). His general point is that many phonological patterns can be explained in terms of articulatory and perceptual factors, and therefore purely phonological explanations without considering phonetic substances can be arbitrary, circular and post-hoc. For example, many languages lack voiced stops in their inventory, and one could postulate a redundancy rule [-son, -cont] → [-voice] as in SPE (Chomsky & Halle, 1968) or posit a constraint *[-son, -cont, +voice], but these approaches miss an aerodynamic reason behind the dispreference against voiced stops. In order for speakers to maintain voicing, intraoral airpressure must be lower than subglottal aipressure, but the airflow required for voicing increases intraoral airpressure when the airway is significantly occluded. The increase in intraoral airpressure in turn makes it difficult to satisfy the aerodynamic condition. For this reason, it takes additional articulatory effort—e.g. larynx lowering, tongue advancement, etc—to keep the intraoral airpressure sufficiently low to maintain voicing during stop closure (Jaeger, 1978; Ohala, 1983; Westbury, 1979).

In addition to this kind of articulatory difficulty, perceptual factors demonstrably affect phonological patterns as well. For example, non-low back vowels are usually rounded, and one could postulate a redundency rule [-low, +back] → [+round] or a constraint *[-low, +back, -round], but again these explanations miss a generalization that rounding, by enlarging a resonance cavity, enhances an F2 difference between back and front vowels (Diehl & Kluender, 1989; Diehl, 1991; Stevens, Keyser, & Kawasaki, 1986).

Finally, psycholinguistic factors also seem to play an important role in shaping phonological patterns as well. For instance, word-initial segments provide important cues for word recognition (Hawkins & Cutler, 1988; Nooteboom, 1981). Speakers thus seem to disfavor making phonological changes in word-initial positions, because such changes would result in difficulty in word recognition (J. Beckman, 1997; Kawahara & Shinohara, 2010).

In summary, there seem to be phonetic and/or psycholinguistic reasons behind many if not all phonological patterns. Therefore, according to Ohala, purging phonetic and psycholinguistic factors from phonological theory seems misguided.

## 1.3 Current situation

Thus, on the one hand, there has been some reluctance to incorporate phonetic (and psycholinguistic) factors into phonological explanations. On the other hand, phonetics does seem to offer

[1]The tension between phonetics and phonology existed before the inception of generative phonology in 1968 (Chomsky & Halle, 1968). See Ohala (1990b, 1999) for reviews of the history.

some insights into phonological patterns. For this (and perhaps other) reason(s), there has been some unfortunate intellectual tension between phonetics and phonology, which Ohala describes as a "turf war" (1990b, p.168) where people from each discipline felt that they had to delineate and defend their own territory.[2]

The situation, however, has been changing, as we witness the rise of a general approach which has come to be known as "laboratory phonology" ("LabPhon" for short) (see Cohn, to appear for sociological aspects of the development of laboratory phonology in the field of general linguistics). The following quote from Beckman & Kingston (1990) succinctly summarizes the spirit of this approach:

> We believe that the time has come to undo the assumed division of labor between phonologists and other speech scientists; we believe this division of labor creates a harmful illusion that we can compartmentalize phonological facts from phonetic facts. At the very least, we maintain that the endeavor of modeling the grammar and the physics of speech can only benefit from explicit argument on this point [p.5].

As the following discussion shows in more detail, many experimental studies have contributed to theoretical debates. The rest of the discussion proceeds as follows. In section 2, I discuss how experimental approaches have informed phonological theories. In section 3, I reverse direction and discuss cases in which theories have informed experiments. Although I try to be comprehensive in my review, there is necessarily a limit. For further examples and discussion, readers are referred to contributions in the Laboratory Phonology series (Kingston & Beckman, 1990, *et seq*.) as well as in other volumes and papers devoted to this issue (Coetzee, Kager, & Pater, 2009; Diehl, 1991; Hayes, Kirchner, & Steriade, 2004; Kingston, 2007; Ohala, 1986b; Ohala & Jaeger, 1986; Solé, Beddor, & Ohala, 2007).

# 2 How experiments have informed theory

## 2.1 Beyond introspection-based data

In generative linguistics, native speakers' intuition—or introspection—is the primary source of data, because "the set of grammatical sentences cannot be identified with any particular corpus of utterances obtained by the linguist in his field work" (Chomsky, 1957, p.15). Since generative phonology aims to study competence—what speakers know about their language—rather than performance—how speakers use the language, the only way to assess competence, it was believed, was introspection (though see Schütze, 1996 for critical discussion). Contrary to this research tradition, phonetic and psycholinguistic experiments have been offering important insights into knowledge of grammar.

### 2.1.1 Wug-tests

The first good example of experiments that have complemented the introspection-based approach is a wug-test. In wug-tests we ask native speakers to pronounce novel words. A wug-test is named after an experiment by Berko (1958). Berko tested whether English-speaking children

[2] An anonymous reviewer pointed out that there may also be "punting" when people say that some other subfield is responsible for a phenomenon that they cannot account for.

acquire a rule of voicing assimilation in the English plural and other suffixs. The finding was that given nonce-words like *wug*, most children pluralize it as wug[z], not as *wug[s], showing that English-speaking children know that the plural suffix and the stem-final consonant must agree in voicing. In this way, a wug-test has been used as a litmus test for the productivity of a phonological generalization. We witnessed a renewed interest in wug-tests in recent years, which has provided some important insights into phonological knowledge, as summarized in (1).

(1) a. A standard assumption in generative phonology is that speakers assign a simple dichotomous grammatical/ungrammatical judgment to linguistic structures. In other words, speakers should treat all attested structures as equally good, and treat all ungrammatical structures as equally bad. However, several wug-tests revealed that speakers can distinguish the grammaticality of two (un)grammatical structures (Shinohara, 2004; Zuraw, 2007).

b. More generally, results of wug-tests often show stochastic, rather than dichotomous, patterns (Albright & Hayes, 2003; Hayes & Londe, 2006).

c. Some experiments showed that the probability of speakers' applying a certain phonological process in a wug-test reflects the frequency of the items that undergo that phonological process in their language (Albright & Hayes, 2003; Bybee, 1999; Ernestus & Baayen, 2003; Hayes & Londe, 2006; Hayes, Zuraw, Siptár, & Londe, 2009; Zuraw, 2000).

d. In some experiments, speakers either fail to replicate some statistical patterns in the lexicon (Becker, Ketrez, & Nevins, 2008) or at least show bias against reproducing some arbitrary, though statistically significant, patterns in the lexicon (Hayes et al., 2009).

e. Some phonological patterns are not productive (at least under a wug-test), which leads to the suspicion that they are not a part of the speakers' grammar. Patterns whose productivity wug-tests failed to reveal include English velar softening (Ohala, 1974, though see; Pierrehumbert, 2006), Japanese verb conjugations (Vance, 1987, chapter 12), and Polish raising (Sanders, 2001) (see also Zimmer, 1969 for a test of morpheme structure conditions in Turkish).

### 2.1.2 Wellformedness judgment studies

Another type of experiment which complements generative phonology's introspection-based approach is wellformedness judgment experiments. In these experiments we ask native speakers to judge the naturalness of particular words or phonological processes (they can also take the form of word-likeliness judgments). These experiments, as with wug-tests, reveal, for example, that speakers can distinguish the grammaticality of two (un)grammatical structures (Coetzee, 2008; Pertz & Bever, 1975) and show that grammatical patterns exhibit a stochastic, rather than a simple dichotomous grammatical/ungrammatical, distinction (Albright & Hayes, 2003; Fanselow, Féry, Vogel, & Schlesewsky, 2006; Hayes, 2000). Wellformedness judgments are also known to reflect the frequency of the target items (e.g. Frisch, Large, & Pisoni, 2000).

## 2.2 Addressing the quality of phonological data

### 2.2.1 Re-evaluating phonological data

Experiments have also reevaluated what is phonological and what is not. Phonetic experiments have shown that many textbook examples of "phonological patterns" do not involve categorical changes but instead involve gradient changes, suggesting that they might be phonetic processes. For example, English was thought to have a vowel nasalization rule before a nasal consonant, as in [bĩn] 'bean' and [dĩn] 'dean'. Cohn (1993) however, based on an instrumental study measuring patterns of nasal airflow, showed that English nasalization differs from contrastive nasalization in French in that, within a nasalized vowel, the closer to the nasal consonant, the more nasal airflow was detected. English nasalization is therefore gradient rather than categorical, in the sense that it does not alter the whole segment but instead the degree of nasalization changes within a segment. For this reason, Cohn concluded that English nasalization belongs to phonetics. Many other examples of phonological patterns have been argued to show similar gradient properties, which I list in (2):[3]

(2) a. Arabic tongue backing (emphasis) spreading (Keating, 1990, and references cited therein)
b. English [l] velarization in coda (Sproat & Fujimura, 1993)
c. English flapping (de Jong, 1998; Fox & Terbeek, 1977)
d. English phrasal nasal assimilation (Gow, 2002; Nolan, 1992) (but cf. Ellis & Hardcastle, 2002)
e. English phrasal palatalization (Zsiga, 1995)
f. English and French schwa deletion (Davidson, 2006b; Fougeron & Steriade, 1997)
g. Japanese tonal spreading in unaccented words (Pierrehumbert & Beckman, 1988)
h. Russian vowel reduction in second pretonic syllable (Barnes, 2002) (though cf. Padgett & Tabain, 2005)

The abundance of such examples led Hayes to state "I occasionally wondered, 'Where is the normal phonology that I was trained to study?"' (Hayes, 1995, p.68).

The list in (2) shows that many patterns that have been believed to be phonological turned out to be phonetic. A more complex example comes from the domain of intonation. In Japanese and many other languages, the height of tones generally decline toward the end of an utterance. The question arose whether this pattern of declination is due to phonetics or phonology. One could posit that this declination is phonetic (Fujisaki & Sudo, 1971) (see Poser, 1984, p.200 for more references); for example, subglottal air pressure decreases toward the end of an utterance, and the height of tones naturally drops. On the other hand, McCawley (1968) proposed a phonological rule in Japanese that changes a high tone to a mid tone after another high tone within a phrase. It turned out that it would be most fruitful to approach intonation from both perspectives. Poser (1984) argued that Japanese has both local lowering of H after another H(L)—which seems

[3]Davidson (2006a) demonstrated that a 'schwa' inserted in English speakers' production of non-native clusters differs from a lexical schwa. She argued that this 'schwa' results from gestural mis-coordination, and hence differs from phonological epenthesis (see also Hall, 2006, for related cross-linguistic phenomena). However, within the framework of Articulatory Phonology (Browman & Goldstein, 1986), she also proposed that gestural mis-coordination arises in the phonological component, rather than in phonetic component.

phonological—as well as gradient, steady declination throughout the utterance, which is phonetic.[4] Beckman & Pierrehumbert argued that a similar hybrid approach accounts for the complex pattern of intonation in both English and Japanese (M. Beckman & Pierrehumbert, 1986; Pierrehumbert & Beckman, 1988).

In addition to helping us to decide whether patterns under discussion are phonological or phonetic, some studies called into question the existence of some phonological patterns *per se*. Based on the traditional description of Tswana, Hyman (2001) discussed a case of post-nasal devoicing, but Gouskova, Zsiga, and Tlale (2006) argued based on a production experiment that Tswana may not have a process of post-nasal devoicing after all. A later study showed, however, that some, though not all, speakers do show evidence for post-nasal devoicing (Coetzee, Lin, & Rigardt, 2007). A general lesson we can draw from this series of studies is that careful instrumental experiments help us to ask whether phonological patterns under discussion really exist.

### 2.2.2 Incomplete neutralization

While it is standardly assumed that phonological processes involve categorical changes (see subsections 2.2.1 and 2.3.2), some experiments called that assumption into question. Port & O'Dell (1985) reported a production experiment on German where they found some acoustic differences between underlying voiceless stops and "voiceless" stops that are underlyingly voiced but devoiced by coda devoicing. They found appreciable differences between these two categories in terms of preceding vowel duration, closure voicing duration, closure duration, and aspiration duration. Further, they demonstrated that listeners can detect the differences between the two categories at more than chance frequency. They argue therefore that coda devoicing in German is incomplete.

Subsequent studies found other cases of incomplete neutralization in many languages, including Cantonese (Yu, 2007), Catalan (Dinnsen & Charles-Luce, 1984), Dutch (Ernestus & Baayen, 2006, 2007; Warner, Good, Jongman, & Sereno, 2006), English (Fourakis & Port, 1986; Ohala, 1986a), Japanese (Mori, 2002), Lebanese Arabic (Gouskova & Hall, 2009), Polish (Slowiaczek & Dinnsen, 1985; Slowiaczek & Szymanska, 1989), and Russian (Chen, 1970; Dmitieva, 2005; Padgett & Tabain, 2005). Some studies argued however that these experimental results are largely or entirely due to extra-grammatical factors such as speakers' familiarity with English, orthographic influences and hyperarticulation in a laboratory setting (Fourakis & Iverson, 1984; Jassem & Richter, 1989; Warner et al., 2006). The status of incomplete neutralization is much debated in the literature (see Port & Leary, 2005; Warner, Jongman, Sereno, & Kemps, 2004, for recent reviews), but these experiments at least showed that we need to be careful when we talk about the categoricality of phonological changes.[5] See subsection 2.3.2 for more on the discussion on the categorical nature of phonological alternations.

[4]Downstep may apply iteratively (Kubozono, 1988; Poser, 1984), the result of which can result in a quasi-gradient behavior. See subsections 2.2.1 and 2.3.2 for the categorical nature of phonological patterns.

[5]Some phonologists admit that some phonological changes are incomplete and propose a model of phonology that handles incomplete neutralization (Gouskova & Hall, 2009; van Oostendorp, 2008). Others consider the results of neutralization as lacking phonological/phonetic specifications (Steriade, 1995, 1997), following the theory of phonetic underspecification (Keating, 1988b) (also Hsu, 1996 cited in Steriade, 1995, 1997). Yet others consider these incomplete neutralization patterns to be implemented in the phonetic component (Fourakis & Port, 1986).

## 2.3 Bearing on the architecture of the grammar

Not only have experiments served to evaluate the quality of phonological data, some phonetic studies have provided important insights into the general architecture of the grammar.[6]

### 2.3.1 Against universal phonetics

In SPE (Chomsky & Halle, 1968), the output of phonology was considered to be "the phonetic transcription" (p. 293), which lacked "properties of the signal that are supplied by universal rules" (p. 235). Keating (1985, 1988a) characterizes this view as phonetics involving universal, automatic rules (see also Kingston & Diehl, 1994, subsection 1.2). Phonetic studies soon showed that this view is too simplistic. For example, Chen (1970) compared durations of vowels before voiced consonants and those before voiceless consonants in seven languages (English, French, Russian, Korean, German, Spanish and Norwegian), and showed that different languages show different degrees of lengthening before voiced consonants. Keating (1979) (reported in Keating, 1985) followed up on this result and showed that neither Czech nor Polish shows a reliable effect of voicing on preceding vowel duration. It therefore seems that the degree of lengthening before voiced consonants is language-specific. Similarly, an acoustic experiment by Port, Al-Ani, and Maeda (1980) showed that in Japanese, vowel durations are heavily affected by the duration of adjacent consonants, but in Arabic such patterns are not evident, concluding that rhythmic compensation is not universal. These examples show that phonetic implementation is neither automatic nor universal. See Port & Leary (2005) for more recent summaries of language-specific phonetic patterns.

### 2.3.2 The phonetics-phonology divide

As briefly discussed in subsection 2.2.1, many experiments identified a crucial difference between phonetics and phonology: phonological patterns involve complete categorical changes, whereas phonetics yield gradient outcomes (Barnes, 2002; Cohn, 1993, 2006; Keating, 1990; Tsuchida, 1997; Zsiga, 1995) . Experimental results played an essential role in establishing this difference. For instance, an electropalatographic study by Zsiga (1995) showed that English possesses two kinds of palatalization: complete palatalization which we find in a morphophonological process, as in *press* [prɛs] vs. *pressure* [prɛʃər], and gradient palatalization which we find across a word boundary, as in *miss you* [miʃju]. Zsiga found that the former [ʃ] is [ʃ] throughout its constriction whereas the latter [ʃ] starts like an [s] and ends like an [ʃ] . An explanation we can give is that the former process involves a categorical phonological change, whereas the latter process is a gradient phonetic gestural overlap.

Pycha (2009) demonstrated another difference: comparing phonological lengthening (i.e. gemination) and phonetic lengthening at phrase-edges in Hungarian, she found that phonological lengthening always targets the closure phase of affricates, whereas phonetic phrase-edge lengthening affects portions that are adjacent to the boundaries. In this way, experiments have identified characteristics of phonetics that distinguish it from phonology. See Keating (1996, p.263) for constellations of other properties that distinguish phonetics and phonology. See also Anderson, 1981 for general discussion on the phonetics-phonology divide.

[6] Another topic that would fit in this subsection is the search for the phonetic basis of distinctive features. Due to space limitation, I cannot provide comprehensive discussion. See Kingston (2007) for recent summaries.

### 2.3.3 The phonetics-morphology interface?

As exemplified by the two palatalization processes in English, morphophonological processes tend to involve categorical changes whereas phonetic processes yield gradient outputs. A general assumption in generative studies is thus that phonology can be sensitive to morphology, but phonetics is not. The inaccessibility of morphological structures to phonetics was assumed in Chomsky & Halle (1968) where morphological boundaries are erased at the end of each transformational cycle (p.15). The Bracket Erasure Convention in Lexical Phonology (Kiparsky, 1982) also removes morphological boundaries after each level of derivation. As a result, word-internal structures are inaccessible to later post-lexical rules or phonetics.

As an illustration, take the case of minimal word requirements. Many languages require (lexical) words to be of certain minimal length, and this requirement is expressed in terms of abstract prosodic units (McCarthy & Prince, 1986), but not in terms of raw phonetic duration (Cohn, 1998). For example, even though English tense [i] is shorter than lax [æ] in raw duration ([i]=100 ms; [æ]=123 ms, according to Strange, Bohn, Trent, & Nishi, 2004), [pi] is wellformed, but [pæ] is not. Therefore, the minimal word requirement operates on abstract, phonological units rather than on raw phonetic duration.This sort of requirement can be sensitive to morphological information. For example, in Yoruba, only nouns are required to be maximally disyllabic (Pulleyblank, 1988, p.250, fn 24). On the other hand, no known languages seem to vary raw phonetic durations depending on morphological categories. Phonological requirements, therefore, may refer to morphological information whereas phonetic implementation cannot.[7] This thesis has been taken for granted and rarely questioned or addressed in the phonological literature.

However, Cho (2001) directly addressed this issue using EMA (electromagnetic articulography), and found that in Korean gestural timing is more variable across a morpheme boundary than within a morpheme and also more variable across a non-lexicalized compound boundary than across a lexicalized compound boundary. Also, Sprout & Fujimura (1993) used X-ray microbeam technology and compared the amount of dorsal retraction of English coda [l] at various boundaries including Level I and Level II boundaries, and they found a difference between these two contexts. These experimental findings suggest that morphological boundaries may be visible to phonetic implementation rules.[8]

Another debate was initiated by Steriade (2000) who challenged the immunity of phonetics to morphological information. She argued that there are cases of phonetic analogy, a requirement that paradigmatically related words be phonetically similar. For example, derived words are required to be identical in raw phonetic duration to their corresponding bases. This phonetic analogy was proposed to explain why flapping applies in words like capi[ɾ]alistic (cf. capi[ɾ]al) whereas it fails to apply in words like militaristic (cf. mili[t]ary) with a similar stress pattern: the applicability of flapping in derived words depends on whether flapping is possible in the base words. However, Riehl (2003) found in a production experiment that the transfer of flapping from a base form to related words was not robustly observed. Based on an acoustic study, Riehl also challenged the assumption that the distinction between [t] and [ɾ] is solely made in terms of constriction duration (see also de Jong, 1998 and Fox & Terbeek, 1977 for the phonetics of flapping).

In relation to incomplete neutralization discussed in subsection 2.2.2, Ernestus & Baayen

[7] In turn, morphological processes can be sensitive to phonological information (i.e., phonologically conditioned allomorphy (McCarthy, 2002, p.183 for references)), but do not seem to be controlled by phonetic information (though see Bybee, 1999, for a case of a morphological pattern that manipulates a non-contrastive feature.).

[8] A question that remains regarding these results is whether the differences could be attributed to differences in the presence of prosodic boundaries like foot boundaries or prosodic word, which the phonetics is presumably able to see.

(2006, 2007) argued for another case of morphological influence on phonetics. They found that there is slight voicing left in "devoiced" final consonants and they argued that this voicing is due to the activation of morphologically related words with a voiced consonant. In summary, whether phonetics has access to morphological information or not is still under debate; experiments will be able to contribute much to this debate (see Barnes & Kavitskaya, 2003; Bybee, 1999; Davis, 2005; Cohn, 2006; Yu, 2007, for further discussion on the phonetics-morphology interaction and phonetic analogy).

## 2.4 Arguments for/against the psychological reality of grammar

Not only have experiments addressed what grammar should look like, they also have examined whether grammar is psychologically real in speakers' minds. Many experiments have addressed the question of whether the rules, constraints and structures that linguists posit are psycholinguistically real or are merely theoretical devices that help us explain the linguistic patterns (Cena, 1978; Ohala, 1974, 1986a; McCawley, 1986; Zimmer, 1969). A general concern behind this work is that the psychological reality of a grammatical postulate was sometimes confused with the analytical success of that postulate. As McCawley (1986, p.28) put it, "Chomsky's [(1986)] policy that the subject matter of linguistics is psychological in nature does not provide any reason for assuming that the purported facts that linguists have hitherto adduced as evidence for or against particular analyses are psychological in nature, nor even that they are strictly speaking facts." Psychological reality of phonological data should not be taken for granted, and must be explicitly tested. Some wug-tests in fact revealed that some phonological patterns are not reflected in speakers' behaviors (see 1e).

Recent development of experimental techniques has allowed us to address the question of psychological reality from a different perspective. In particular, a number of perception experiments showed that phonological constraints affect speech perception—given ambiguous acoustic signals, speakers are biased against categorizing the stimuli as those not allowed by their phonological grammar (Berent, Steriade, Lennertz, & Vaknin, 2007; Coetzee, 2008; Dupoux, Kakehi, Hirose, Pallier, & Mehler, 1999; Massaro & Cohen, 1983; Moreton, 2002; Pitt, 1998). A classic work by Massaro & Cohen took advantage of word-initial phonotactic restrictions in English where only [ɹ] is allowed after [t], only [l] is allowed after [s], and both are allowed after [p]. They created a continuum from [ɹ] to [l] by varying F3 and presented the continuum in these contexts, and found that speakers judge the continuum as [ɹ] most frequently after [t], less after [p] and least frequently after [s]. These results showed that phonotactic restrictions in speakers' grammars affect how they categorize the speech signals.

Extending this work, some studies showed that some particular phonological hypotheses are psychologically real. For example, in Japanese, only foreign words, but not native or Sino-Japanese words, allow word-final long [aa] and singleton [p] (Itô & Mester, 1995). Moreton & Amano (1999) showed that once listeners hear [p] in the stimuli, cueing foreignness of the stimuli, then they are more likely to judge the word-final [a] as long [aa]. Gelbert & Kawahara (2007) extended this result and showed that as long as we present real foreign words, we observe a similar bias toward allowing word-final long [aa] perceptually, even under the lack of phonological cues to the lexical affiliation. See Gelbert (2005) for similar results from other languages.

In a slightly different line of research, acoustic studies provided evidence for particular prosodic structures (Broselow, Chen, & Huffman, 1997; Frazier, 2007; Maddieson, 1993) or tonal representations (Morén & Zsiga, 2006). Broselow et al. (1997) showed that language particular prosodic

structures, each motivated in terms of stress placement, are manifested in different phonetic implementation patterns. Yet another line of research argued for the psychological reality of underspecification (Archangeli, 1988). For example, a priming study by Lahiri & Reetz (2002) showed that labial and dorsal signals can activate coronal input. They argued that assuming coronals are underspecified in the mental lexicon, all labial, coronal, and dorsal consonants can be matched up with underlying coronals (see also Lahiri & Marslen-Wilson, 1991). These studies aimed to show that theoretical devices that have been proposed, such as lexical stratification, prosodic structure, or underspecification may not merely be abstract theoretical constructs but may be psychologically real, influencing our speech behaviors (see Goldrick (to appear) for recent discussion).

## 2.5 Sources of phonological patterns

Finally, many experiments addressed the issue of sources of phonological patterns. This tradition has most rigorously been pursued by Ohala (Ohala, 1990b, 1983, among many others), but has been taken up by many other researchers. For example, many languages diachronically changed [$k^j$] (or [k] before front vowels) into [tʃ]. The ubiquity of this sound change (and its synchronic correspondence) may be attributed to acoustic affinity between [$k^j$] and [tʃ] (Chang, Plauché, & Ohala, 2001; Guion, 1998; Ohala, 1989; Wilson, 2006). Raising of F2 via palatalization makes [k] sound similar to palatal consonants, and a long aspiration of dorsal [k] makes it sound similar to an affricate. A perception experiment by Guion (1998) in fact demonstrated that listeners often misperceive [$k^j$] as [tʃ], showing that the sound change [$k^j$] → [tʃ] may be due to the acoustic similarity. Furthermore, Chang et al (2001) pointed out that the directionality of the [$k^j$] → [tʃ] change is rarely if ever reversed, and demonstrated through a perception experiment that listeners may confuse [$k^j$] as [tʃ], but not vice versa.

To provide another example, in many languages a vowel must be long after a glide. Traditionally, this restriction was analyzed as a case of compensatory lengthening: a first vowel in vowel sequences obtains a mora by a universal convention, loses its mora when it becomes a glide, and that floating mora is reassociated with the following vowel, resulting in a long vowel (Hayes, 1989). Myers & Hansen (2005) offered an alternative explanation, namely, that given a sequence of two vocoids, the boundary between them is blurry, and listeners may misattribute the gradient transition to the second vowel. The misattribution would result in a percept of long second vowels. Their perception experiments supported their hypothesis: the longer the transition duration, the more likely listeners judge the second vowel to be long.

The list of other experiments which have searched for the basis of phonological patterns would include, but is not limited to, the following (Barnes, 2002; Huang, 2001; Hume & Johnson, 2001; Hura, Lindblom, & Diehl, 1992; Kawahara, 2006; Kawasaki-Fukumori, 1992; Kochetov, 2006; Kohler, 1990; Mielke, 2003; Myers & Hansen, 2007; Ohala, 1990a) as well as those discussed in subsection 3.1. See also Blevins (2004) and Ohala's other work (Ohala & Lorentz, 1977; Ohala, 1981, 1983, among many others) for further cases of phonetic origins of phonological patterns.

# 3 Experiments informed by phonology

So far I have been focusing on how experiments have informed phonological theories. However, the communication is by no means one-way. So we now turn our attention to how phonological observations and theories helped us design phonetic experiments and led to important discoveries.

## 3.1 Motivated by phonological patterns

As discussed in subsection 2.5, many experiments have attempted to make sense of why certain phonological patterns occur. Put in a different perspective, this tradition has allowed us to reveal aspects of our phonetic systems by addressing why phonology works in the way that it does. To illustrate this point with another example, an influential tradition of this line of research is that of Adaptive Dispersion Theory initiated by Björn Lindblom and his colleagues (Diehl, Lindblom, & Creeger, 2004; Lindblom, 1986; Liljencrants & Lindblom, 1972) and pursued by a number of studies (e.g. Boersma, 1998; Flemming, 1995; Padgett, 2002). This theory was set out to address why languages have the sets of vowels that they have. For example, languages that have three contrastive vowels usually have [a,i,u] rather than, say [ə,ɨ,ʌ], and languages that have five contrastive vowels have [a,i,u,ɛ,ɔ] rather than [ə,ɨ,ʌ,ɤ,ɪ]. The general idea is that speakers keep contrasting elements maximally (Liljencrants & Lindblom, 1972)—or sufficiently (Lindblom, 1986)—distinct from one another; this thesis has received support from experimental work (Engstrand & Krull, 1994; Padgett & Tabain, 2005) as well as from corpus-based cross-linguistic analyses (Kingston, 2007). This research tradition shows that an attempt to explain phonological patterns provided important insights into our speech behaviors. In this sense, taken together with the discussion in subsection 2.5, phonological observations and phonetic experiments inform one another.

## 3.2 Motivated by phonological theories

Not only can phonological observations lead to interesting phonetic hypotheses and experiments, sometimes specific phonological hypotheses can provide a guideline for where to look in experimental work. For example, in traditional analyses of Japanese intonation (M. Beckman & Pierrehumbert, 1986; Pierrehumbert & Beckman, 1988; Venditti, 2005) Japanese was not thought to have an Intonational Phrase. Selkirk (2005), however, based on cross-linguistic patterning, proposed a general theory of syntax-phonology mapping where clause edges should generally correspond to Intonational Phrase edges. Guided by this theory, Kawahara & Shinya (2008) investigated the intonational properties of clause edges in Japanese and found evidence for Intonational Phrase edges. In particular, they found that the left edges of clauses show larger initial rises and stronger pitch reset compared to VP-edges, and also characterized by final lowering of tones, final creakiness, and pause at their right edges. This work shows that theories can provide a guideline as to what to look for in phonetic studies.

Another example comes from recent articulatory studies on transparent segments in harmony contexts (Benus & Gafos, 2007; Gick, Pulleyblank, Campbell, & Mutaka, 2006; Walker, Byrd, & Mpiranya, 2008). Several works proposed that autosegmental spreading is strictly local and can never skip a segment (Ni Chiosain & Padgett, 1997; Gafos, 1998; Walker, 1998). Transparent segments in harmony patterns pose a problem for this theory because it looks as though these segments are "skipped". Recent articulatory studies showed, however, that "transparent" segments too undergo harmony (e.g. tongue body backing in back vowel harmony in Hungarian and the tip-blade gesture in Kinyarwanda consonant harmony), without causing much perceptual effect. This outcome was as predicted by strict locality because transparent segments too undergo harmony phonologically. Again the theory of strict locality led to experiments that revealed a non-trivial aspect of transparent segments in harmony contexts. See Hayes (1999) for related discussion on theory-driven experiments.

### 3.3 Testing specific phonological hypotheses and beyond

Specific phonological hypotheses can motivate specific hypothesis testing, which has often resulted in further insights into the intricacy of the phonetics-phonology interface. To take one example, Steriade (1997, 2001/2008) proposed that the less perceptible a phonological contrast is (in a particular context), the more likely it is to be neutralized. Some work showed that indeed, at least some contrasts that are likely to be neutralized are less perceptible than non-neutralizing contrasts (Kawahara, 2006; Kochetov, 2006). Kochetov (2006) however further showed that not all differences in phonetic perceptibility are reflected in phonological patterns. Once again Steriade's specific hypothesis about the interaction between phonetic perceptibility and phonological patterns motivated experimental testing, which revealed the complex interaction between phonetics and phonology.

To take another example, many languages require that lexical words be minimally bimoraic or bisyllabic (subsection 2.3.3). Japanese, however, allows monomoraic lexical words, and Mori (2002) tested if Japanese does indeed violate the minimality requirement. She found that when monomoraic words are pronounced without a case particle, they undergo lengthening, and that longer words do not show such lengthening. In this sense, Japanese does satisfy the minimal word requirement. However, she further found that lengthened monomoraic roots are not as long as bimoraic roots, instantiating a case of incomplete neutralization (subsection 2.2.2).

To summarize, these experiments show that specific phonological hypotheses can inform experiments, which often in turn provide insight into the complex interaction between phonetics and phonology. The list of theories that motivated specific experimentation includes, but is not limited to, sonority sequencing principle (Broselow & Finer, 1991), Optimality Theory's (Prince & Smolensky, 1993/2004) thesis about transitivity of constraints (Guest, Dell, & Cole, 2000), the emergence of the unmarked (Broselow, Chen, & Wang, 1998), and positional faithfulness theory (Kawahara & Shinohara, 2010).

## 4 Summary

Phonetic and psycholinguistic experiments have contributed much to the development of phonological theories, and they should continue to do so. In (3) and (4) I summarize how experiments have informed phonological theories and vice versa.

(3) How experiments inform theory
   a. Provide data beyond those available through introspection.
   b. Reexamine the quality of phonological data.
   c. Address questions about the architecture of the grammar.
   d. Show and examine the psychological reality of the grammar.
   e. Find the sources of phonological patterns.

(4) How phonology informs experiments
   a. Help to find restrictions on—and the nature of—speech through phonological patterns.
   b. Provide a guide as to where and what to look for in phonetic experiments.
   c. Specific phonological hypotheses motivating specific hypothesis testing.

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