CHAPTER 3

Patterns of Perceptual Compensation and Their Phonological Consequences

Patrice Speeter Beddor

Department of Linguistics
University of Michigan
Ann Arbor, Michigan 48109

Rena Arens Krakow

Department of Communication Sciences
Temple University
Philadelphia, Pennsylvania 19122

Stephanie Lindemann

Department of Linguistics
University of Michigan
Ann Arbor, Michigan 48109

I. Introduction
II. Vowel-to-Vowel Coarticulation
A. Perception of Vowel-to-Vowel Coarticulatory Effects
B. Linking Perception of Vowel-to-Vowel Coarticulation to Vowel Harmony Systems
III. Nasal Coarticulation
A. Perception of Coarticulatory Vowel Nasalization
B. Linking Perception of Nasal Coarticulation to Phonological Patterns
IV. Concluding Remarks
Acknowledgments
Notes
References

The Role of Speech Perception in Phonology

I. INTRODUCTION

This chapter takes as its starting point the well-attested notion that perceptual factors play an important role in shaping phonological systems. Other chapters in this book provide strong evidence of the pervasiveness of perceptual influences. The focus of our investigation is *how* perceptual phenomena become part of, or are incorporated into, phonological systems, and whether the results of experimental work in speech perception might help us identify specific conditions that facilitate such incorporation.

Experimental data delineate the types of information that listeners extract from the acoustic signal, and the conditions under which listeners are better or worse at extracting and using this information. One type of information to which listeners are particularly sensitive is coarticulatory variation. Listeners use coarticulatory variation as information about sounds that are further up or down the speech stream. A strong measure of listeners' use of coarticulatory variation is that, in some instances, this variation is sufficient for listeners to recover deleted portions of an acoustic signal. For example, Alfonso & Baer (1982) and van Heuven & Dupuis (1991) found that listeners, presented with the initial V_1C from original V_1CV_2 sequences, could identify the deleted second vowel on the basis of coarticulatory information in the first vowel. Listeners apparently attributed some aspect(s) of the acoustic signal of a target segment to the coarticulatory influence of an upcoming segment, which helped them identify that (experimentally deleted) segment. Other studies have shown that coarticulatory information speeds listeners' reaction times in identifying other portions of the signal, or in word recognition. In these studies, listeners responded faster, and often with fewer errors, when identifying stimuli containing coarticulatorily appropriate information than when identifying stimuli lacking this information (e.g., Martin & Bunnell, 1982; Fowler, 1984; Whalen, 1984; Manuel, 1987; Nguyen & Hawkins, 1999).

If listeners more accurately and more rapidly identify an influencing segment when given information about its coarticulatory influence on a target segment, then we might expect that listeners would also compensate for the acoustic effects of coarticulation on a target segment when judging the nature of that segment. Indeed, experimental evidence shows response patterns indicating that listeners attribute the acoustic effects of a coarticulatory context on a target sound not to the target but rather to the context. Consider, for example, evidence from the nasal coarticulation literature. Kawasaki (1986) applied varying degrees of attenuation to the nasal consonants of [mĩm], [mɑ̃m], and [mõm] and showed that English-speaking listeners heard the nasal vowels as relatively oral when the nasal consonants were clearly audible, but as increasingly nasal with decreasing intensity of the nasal consonants. Krakow *et al.* (1988) found that listeners (again, English-speaking) misjudged the height of nasal vowels when they were in an oral consonant context ([bɛ̃d]), but not when the same vowels were in a coarticulatorily appropriate nasal consonant context ([bɛ̃nd]). Manuel (1995) investigated carryover nasalization of /n/ on /ð/ (in sequences such as *win those*) and obtained perceptual responses consistent with the view that listeners heard contextual nasalization of /ð/ as due to the flanking nasal consonant. In all three cases, listeners used the nasal consonant context in making judgments about a segment that was modified by that context, and their response patterns indicated that listeners ascribed the acoustic consequences of coarticulation to their source (but cf. Kingston & Macmillan, 1995). Such response patterns have been found for a range of segmental and prosodic properties (e.g., Kunisaki & Fujisaki, 1977; Mann, 1980; Mann & Repp, 1980; Fowler, 1981, 1984; Whalen, 1981, 1989; Petersen, 1986; Silverman, 1987; Fowler *et al.*, 1990; Xu, 1994; Pardo & Fowler, 1997; Fowler *et al.*, 1999).

What might be the consequences of listeners' perception of the acoustic effects of coarticulation for phonological systems? Ohala (1981, 1986, 1993) has proposed that, if listeners fail to detect the source of coarticulatory variation (or if, for example, learners are relatively inexperienced in dealing with contextual variation), they might perceive the variation as intrinsic to the target segment. Systematic misperceptions along these lines could lead to phonologization of the variation (e.g., failure to detect the nasal consonant in [ṼN] could result in the well-attested change VN → Ṽ). In other words, this account suggests that perceptual compensation should, under most circumstances, minimize the phonological consequences of coarticulation because, in attributing the variation to its source, the listener correctly identifies the intended utterance. But if the conditioning environment is not clearly detected for some reason, or not associated with the coarticulatory effects, perceptual compensation is effectively ruled out.

The position we take here regarding perception of coarticulatory variation assigns yet a more prominent role to the listener, one in which coarticulatory variation might have phonological consequences even in the context of a detected coarticulatory source. This position is based on our investigation of two types of coarticulation: vowel-to-vowel coarticulation and nasal coarticulation. For both types of coarticulation, coarticulatory context was manipulated in order to investigate the conditions under which listeners were more and less successful at attributing the acoustic effects of coarticulation to their coarticulatory source. The general experimental approach involved the use of naturally produced utterances to which we applied excising and cross-splicing techniques that placed vowels into coarticulatorily inappropriate as well as appropriate contexts, allowing us to test listeners' sensitivity to the presence versus absence of appropriate coarticulatory information. We intentionally chose coarticulatory effects known to have consequences for phonology; hence we studied vowel-to-vowel coarticulation because of its relation to vowel harmony, and nasal coarticulation because of its relation to distinctive vowel nasalization and nasal harmony.

We will show that the results contribute to the literature on how speech perception patterns help to shape phonological systems in two ways. First, the general pattern of results that emerges from the experimental data is that coarticulatory compensation is not "perfect." Listeners do compensate for the acoustic effects of coarticulation, indicating that they associate (at least some portion of) these effects with their coarticulatory source. However, even in the context of a clearly audible coarticulatory source, listeners do not fully compensate for the acoustic consequences of coarticulation. It is this partial compensation for coarticulatory variation that leads us to assign a relatively prominent role to the listener in terms of potential consequences for phonology. Partial compensation means that perceptual association of coarticulatory effects with their source may not fully disambiguate the nature of an intended target segment. The second contribution to the literature on the role of perception in phonology will be to show that the detailed patterns of partial compensation for coarticulation correspond to patterns of change and patterns of contrast in phonological systems.

II. Vowel-to-Vowel Coarticulation

A. Perception of Vowel-to-Vowel Coarticulatory Effects

We investigated listeners' use of vowel-to-vowel coarticulatory effects using a discrimination paradigm similar to that used by Fowler (1981). The original stimuli, produced by a female speaker of American English, were two-syllable utterances of the form ['bV_1bV_2], where the vowels were [i e a o u]; multiple repetitions of all possible combinations of the five vowels (e.g., ['biba], ['bube], ['baba]) were recorded. Acoustic measures of this speaker's disyllables showed extensive carryover effects of V_1 on V_2. (See Beddor *et al.*, 2000, for a full-scale presentation of the experimental methods.)

To explore listeners' sensitivity to the carryover effects, we selected the disyllables with the most salient effects, based on a combination of formant measures and pilot perceptual assessment of second syllables excised from their original context. (The excised syllables consisted of V_2 plus the preceding [b], including stop closure and any burst.) In creating the test stimuli, the excised [bV_2]s selected on the basis of pilot testing were cross-spliced into either another token of the original context (so that all test stimuli underwent splicing) or into a different [bV_1_] context. The cross-splicing was constrained such that the original and 'replaced' V_2s were phonologically the same (e.g., /a/s always replaced /a/s, /i/s replaced /i/s, and so on). Figure 3.1 gives sample original and cross-spliced utterances. The subscript notation indicates the original vowel context in which the cross-spliced vowel was produced (i.e., [$_i$a] = /a/ from original [biba] and [$_a$a] = /a/ from original [baba]).

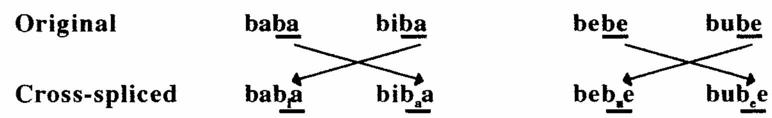

Figure 3.1. Examples of cross-splicing for vowel-to-vowel carryover coarticulation.

We paired the manipulated stimuli using a 4IAX discrimination task in which each trial consisted of two pairs of stimuli. In all trials, the V_2s of one pair were acoustically different (due to different coarticulatory effects) and the V_2s of the other pair were acoustically identical; all V_2s in a trial were phonologically the same. In the *control* trials, only [bV_2] was manipulated and the context was held constant. For example, in control trial [bib$_i$a–bib$_i$a]/[bib$_i$a–bib$_a$a], all V_2s occur in the V_1 context [i]. The control trials were included to verify that listeners could detect the V_2 differences (e.g., [$_i$a] versus [$_a$a]).

For each *test* trial, the V_2s of one pair were acoustically different (due to the coarticulatory influences of V_1), and both were in coarticulatorily appropriate contexts; the V_2s of the other pair were acoustically identical, but one was in a coarticulatorily *in*appropriate context. Two test trial types are illustrated in Table 3.1. Notice that for each pairing of acoustically different vowels in appropriate contexts (left side of table) there are two possible pairings of identical vowels (right): one in which V_2 comes from a disyllable in which V_1 and V_2 were

TABLE 3.1

Sample Discrimination Test Trials for the Vowel-to-Vowel Coarticulation Experiment

		Acoustically different V_2s		Acoustically identical V_2s
V_1 = /i/, V_2 = /a/	Prototypical	bib$_i$a–bab$_a$a	/	bib$_a$**a**–bab$_a$a
	Non-prototypical		/	bib$_i$a–bab$_i$**a**
V_1 = /u/, V_2 = /e/	Prototypical	bub$_u$e–beb$_e$e	/	bub$_e$**e**–beb$_e$e
	Non-prototypical		/	bub$_u$e–beb$_u$**e**

Bold vowels are coarticulatorily inappropriate; all others are appropriate to their context.

(phonologically) identical (i.e., V_2 was produced in the context of itself; [$_a$a] or [$_e$e] in the top row of each section), and the other in which V_2 comes from a disyllable in which V_1 and V_2 were phonologically distinct (i.e., V_2 was produced in the context of a different vowel; [$_i$a] or [$_u$e] in the bottom row of each section). Our acoustic measures suggest that vowels produced in the context of themselves are more prototypical or canonical versions of these vowels (closer, for example, in formant values to the less coarticulated V_1 versions); we propose below that a theory of coarticulatory compensation predicts that listeners will respond differently to the prototypical, as compared to the non-prototypical, pairings.

The test design shown in Table 3.1 was applied to nine different V_1–V_2 pairings: *i–a*, *i–o*, *e–a*, *e–o*, *a–o*, *o–a*, *o–e*, *u–a*, and *u–e*. There were three different tokens of each pairing. As indicated above, corresponding to each test pairing was a control trial in which context was held constant. For all trials, listeners were asked to choose the pair in which the second vowels sounded *more different*. (Therefore the correct responses in Table 3.1 would always be the left pair, although the order of pair presentation was of course balanced in the actual test.) The listeners were 16 native speakers of American English.

Before turning to the results, we consider the predictions of a theory of compensation for coarticulation. The theory predicts that listeners will consistently choose the wrong pair member for the test trials. This is because listeners should hear acoustically different vowels that are both in coarticulatorily appropriate contexts as similar: the coarticulatory variation that distinguishes the vowels is attributed to the vowel context. For example, in the pair [bib$_i$a–bab$_a$a], if listeners (correctly) hear the fronted and raised [$_i$a] as due to the preceding /i/, then [$_i$a] should sound similar to (unfronted and unraised) [$_a$a] in the /a/ context. In addition, listeners should hear acoustically identical vowels, one of which is in an *in*appropriate context, as different because listeners would compensate for coarticulatory effects only for the vowel in the appropriate context. For example, in the pair [bib$_i$a–bab$_i$a], the fronted and raised quality of [$_i$a] would be attributed to context only in the first pair member, and the two (identical) [$_i$a]s would sound different.

A second prediction is that listeners should compensate more — which in this experimental paradigm means that they would make more mistakes — on trials with non-prototypical effects than on trials with prototypical effects. Compare two representative trials from Table 3.1:

Prototypical:	bib$_i$a–bab$_a$a /	bib**$_a$a**–bab$_a$a
Non-prototypical:	bib$_i$a–bab$_a$a /	bib$_i$a–bab**$_i$a**

As we have just seen, compensatory responses in part involve hearing identical vowels, one of which is in an inappropriate context (i.e., the vowel in bold in each trial), as different. An inappropriate non-prototypical effect should be easy for listeners to detect: such acoustic patterns normally occur only as the result of

coarticulation; they are highly unexpected (and sound unusual) when removed from their original context. Consequently, although [$_i$a] in [bib$_i$a] sounds natural, [$_i$a] in [bab$_i$a] does not, resulting in an identical vowel pairing which is likely to mislead listeners. In comparison, inappropriate prototypical effects — such as [$_a$a] in [bib$_a$a] — should be more difficult for listeners to detect because these effects are roughly equivalent to lack of coarticulation. This situation should be close to careful productions that might occur in natural speech situations. In this prototypical case, then, the identical vowels will sound relatively natural in both contexts; hence listeners will be less likely to incorrectly select this pair as more different. The resulting order of difficulty predicted by a theory of compensation for coarticulation is control (least difficult), then prototypical, then non-prototypical (most difficult) trials.

The percentage correct responses to the discrimination test for vowel-to-vowel coarticulation are given in Figure 3.2, pooling across the responses of the 16 American English listeners. The abscissa indicates the nine types of vowel pairings. Four pairings tested sensitivity to carryover coarticulatory effects of front vowels

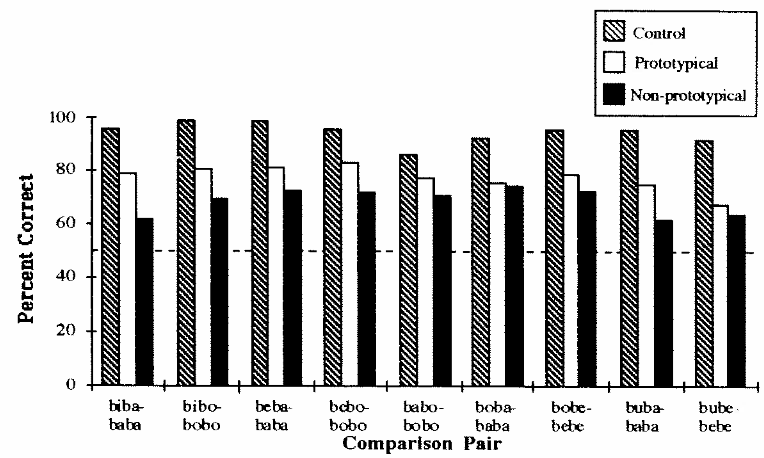

Figure 3.2. Pooled percentage correct responses of 16 listeners to the discrimination test for vowel-to-vowel coarticulation, according to type of V_1–V_2 pairing. Bar type indicates the trial type for each pairing: hatched = control, open = prototypical, and solid = non-prototypical. For example, for the left-most *i–a* pairing:

hatched = bib$_i$a–bib$_a$a / bib$_i$a–bib$_i$a
open = bib$_i$a–bab$_a$a / bib$_a$a–bab$_a$a
solid = bib$_i$a–bab$_a$a / bib$_i$a–bab$_i$a

(Recall that listeners chose the pair in which the *second* vowels sounded more different.) The dashed horizontal line indicates chance (50%) performance.

on non-front vowels (*i–a, i–o, e–a, e–o*), two tested the effects of non-front vowels on front vowels (*o–e, u–e*), and three looked at non-front vowel pairings (*a–o, o–a, u–a*). The three trial types for each pairing — control trial, prototypical trial, and non-prototypical trial — are represented by the different bar types.

The vowel pairings in Figure 3.2 all show similar patterns of results. In all cases, listeners were able to accurately identify the "different" pair in the control trials (as high as 99% for the *i–o* and *e–a* pairings); only in one case did control trial performance fall below 90% (86% for *a–o*). Performance accuracy dropped by an average of 17% from the control to the corresponding prototypical trial (range 8–25%). This drop was significant for all but the *a–o* pairing. In addition, for all pairings, the non-prototypical trials yielded the poorest performance of all trial types, with an average decrease of 9% from the prototypical trials (range 2–18%). The overall decrease in accuracy from the prototypical to the corresponding non-prototypical trials was highly significant; statistical comparisons for the individual pairings showed the decrease to be significant for the majority, but not all, of the nine vowel pairings (decreases of 9% or more were significant). Note, however, that performance was above chance (50%) for all vowel pairings and trial types.

These results are consistent with expectations: the predicted order of difficulty — control, then prototypical, then non-prototypical — was obtained for all vowel pairings. The prototypical/non-prototypical difference indicates that listeners were more often misled by identical vowel pairings when one of the vowels was in a highly unexpected coarticulatory context, which we take as evidence that listeners' responses exhibited *coarticulatory* influences rather than purely auditory contrast effects (cf. Lotto *et al.*, 1997; Lotto & Kluender, 1998).

That performance on even the non-prototypical trials remained above chance means that, although listeners often gave responses consistent with coarticulatory compensation (in that coarticulatory appropriateness of vowel differences often overrode acoustic vowel identity), they did not *consistently* select the (incorrect) compensatory response. Such incomplete or partial compensation is also consistent with previous investigations along these lines. Aspects of this experiment were modeled after Fowler's (1981) study of perception of anticipatory and carryover effects of flanking vowels on unstressed /ə/. In that early study of compensation, Fowler's emphasis was on whether compensation would occur, rather than on whether it was complete. For trials similar to our non-prototypical trials, Fowler found that, although compensation did occur, listeners often did not select the compensatory response.[1]

B. *Linking Perception of Vowel-to-Vowel Coarticulation to Vowel Harmony Systems*

What are the implications of these findings for natural communicative interactions? The compensatory perceptual responses that are errors in this experimental paradigm would not be errors in real-life interactions: attributing coarticulatory variation to the source of the variation facilitates perception and hence should reduce the chances of such variation becoming phonologized, as noted by Ohala (1981). On the other hand, partial compensation for coarticulation — here, attributing some but not all of the acoustic effects of V_1 on V_2 to V_1 — means that there is a detectable coarticulatory "residue" on V_2 that the listener does not attribute to context. As a result, the relevant acoustic properties are divided between the context and the target sound. We have suggested elsewhere (Beddor & Krakow, 1998) that such an outcome is not unexpected within an approach to perception which recognizes that contextual information is only one of many types of information available to listeners in making perceptual decisions (e.g., Hawkins, 1995), and an approach to coarticulation, which recognizes the considerable variability in extent of coarticulation across speakers, rate, and prosodic and segmental contexts.

A likely phonological consequence of hearing the effects of vowel-to-vowel coarticulation as belonging to both the source of coarticulation and the target vowel is vowel harmony. In languages exhibiting vowel harmony, only a restricted set of vowels sharing one or more features (e.g., degree of rounding, backness, or height) can co-occur within a specified domain, usually a word. For example, in harmony systems in which the harmonic feature is backness, vowels within a word are usually either front or non-front, with most front–back combinations being disallowed.

Ideally, in assigning the listener a role in the development of vowel harmony systems, we seek to relate patterns in the perceptual results to specific patterns observed in vowel harmony systems. For example, in stress-dependent harmony systems, harmony is triggered by the stressed vowel of a word. Majors (1998, 1999) explored the possible phonetic basis for such systems, showing that (English) stressed vowels exert greater coarticulatory influences on unstressed vowels than vice versa, and that these effects on unstressed vowels were sufficiently large for listeners to detect. (The effects on unstressed vowels were presumably easier to detect than the weaker effects on stressed vowels, although this was not tested.)

A pattern in vowel harmony systems that is potentially relevant to our perceptual data concerns neutral vowels, that is, vowels in a harmonic domain that neither harmonize nor spread their own harmony. In backness harmony systems, high front [i] and, to a lesser extent, mid front [e] are often neutral to harmony, as is the case in many Uralic and Altaic languages (Goldsmith, 1985; van der Hulst & Smith, 1986; Farkas & Beddor, 1987; Harms, 1987; van der Hulst & van de Weijer, 1995). Table 3.2 provides illustrative examples from Hungarian. Most native roots in Hungarian obey backness harmony, and suffix vowels are either front or back depending on root vowel backness, as in Table 3.2a. However, Hungarian long and short /i(:)/ and /e(:)/ are neutral. As shown in Table 3.2b, the backness of suffix vowels, such as dative [nak]/[nek], is unaffected by a preceding

TABLE 3.2
Hungarian Vowel Harmony

		root + dative	gloss
a. Harmonic roots	back	va:ros + nak	'city (dative)'
	front	öröm + nek	'joy (dative)'
b. Roots with neutral vowels	back-neutral	papi:r + nak	'paper (dative)'
	front-neutral	rövid + nek	'short (dative)'

high (or mid) unrounded front vowel. If vowel-to-vowel coarticulation is the phonetic source of vowel harmony, neutral vowel behavior leads us to expect relatively weak coarticulatory effects of back vowels on [i] and [e]. Because weaker coarticulatory effects should be less perceptible than stronger ones, listeners should be relatively insensitive to the carryover acoustic effects of V_1 on V_2 when V_2 is [i] or [e].

The experimental results given in Figure 3.2, combined with the results of the pilot testing leading up to this experiment, suggest possible links between perception of the effects of vowel-to-vowel coarticulation and neutral vowels in backness harmony systems. With regard to pilot testing, recall that, in designing stimulus materials that would explore listeners' sensitivity to the acoustic effects of coarticulation in different vowel contexts, we selected effects large enough to be reliably detected in the control trials (where context was held constant). Although the original recorded stimuli involved all possible pairings of [i], [e], [a], [o], and [u], pilot testing showed that none of the pairings with [i] in V_2 position (*a–i*, *o–i*, *e–i*, and *u–i*) yielded sufficiently large carryover effects; the same result held for two of the pairings with [e] in V_2 position (*a–e* and *i–e*).[2] Thus, our pilot tests indicated that listeners were insensitive to the coarticulatory effects of a preceding vowel on [i], and to a lesser extent [e], which parallels the phonological situation with neutral vowels. (Acoustic studies of vowel-to-vowel coarticulation have also noted that [i] is particularly resistant to coarticulation; Magen, 1984; Recasens, 1987, 1989; Farnetani, 1990; Beddor & Yavuz, 1995.)

Our main perceptual test results in Figure 3.2 provide further evidence along these lines. The two pairings with [e] in V_2 position that were included in the test design were among the pairings for which listeners were least sensitive to contextual effects (i.e., the differences between listener responses to the prototypical and non-prototypical trials were not significant for *u–e* or *o–e*). Consequently, we would argue that listener inability to systematically detect the small effects of vowel-to-vowel coarticulation on [i] and [e] plays a role in backness harmony

systems.[3] More generally, our across-the-board finding of partial compensation for vowel-to-vowel coarticulation, coupled with the systematic differences between prototypical and non-prototypical pairings, suggest that there is a coarticulatory residue that listeners attribute to the target. It is reasonable to speculate that this residue, if phonologized, could result in vowel harmony.

III. Nasal Coarticulation

A. Perception of Coarticulatory Vowel Nasalization

In studying nasal coarticulation, we used a discrimination paradigm similar to that for vowel-to-vowel coarticulation. However, in this case, we systematically manipulated the consonantal, rather than the vocalic, context in which the vowels occurred. In addition, whereas we focused in the other experiment on carryover effects, here we examined bidirectional effects on vowels from preceding and following nasal consonants. (A detailed report of this experiment is provided in Beddor & Krakow, 1999.)

The original stimuli for this experiment were produced by a male speaker of American English and included oral vowels in oral consonant contexts and nasal vowels in nasal consonant contexts, specifically *bode*, *moan*, *bed*, and *men*. The oral and nasal vowels were cross-spliced into either a different token of the original context or into the context having the "opposite" nasality. Thus, with respect to the latter manipulation, nasal [õ] from *moan* was spliced into the oral context [b_d] from original *bode* and oral [o] from *bode* was spliced into the nasal context [m_n] from original *moan*. The vowels from *bed* and *men* were cross-spliced in the same fashion. In addition, we included vowels excised from their original contexts to be played to listeners in isolation. Isolated vowel conditions were investigated because we aimed to test listener sensitivity to vowel nasality under a variety of contextual conditions, and a pilot study had indicated that American English listeners might be more sensitive to nasal vowels in isolation than in an oral consonant context. Examples of both cross-spliced and excised stimulus types are shown in Figure 3.3 for the /o/ stimuli.

Our main interest was in determining listeners' sensitivity to vowel nasality in and out of a nasalizing context. As in the previous experiment, we tested sensitivity using a 4IAX discrimination paradigm in which trials had one pair with acoustically different vowels — here, one oral and the other nasal — and another pair with identical vowels, either both oral or both nasal. In the control trials, context was held constant and only vowel nasality varied (e.g., [bod–bõd]/[bod–bod]; [mon–mõn]/[mõn–mõn]).

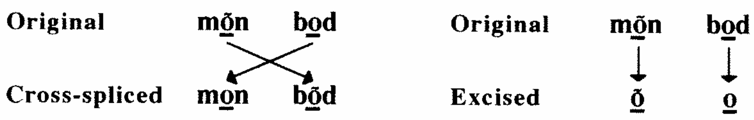

Figure 3.3. Examples of excising and cross-splicing for nasal coarticulation.

The design for the test trials, in which both context and vowel nasality were manipulated, is given in Table 3.3. Four test trial types paired vowels in an oral consonant context with an isolated vowel (top two sections); four additional trial types paired vowels in a nasal consonant context with an isolated vowel (third and fourth sections); and two trial types paired vowels in oral and nasal consonant contexts (bottom section). For the last trial types (bottom section), we used the same design as for the earlier study: in the pair with identical vowels, one vowel was in a coarticulatorily inappropriate context; in the pair with different vowels, both were in appropriate contexts. (This aspect of the experimental design was not possible for isolated nasal vowels, which are coarticulatorily inappropriate in English.) Similar to the first study, the nasal vowels in oral contexts might be

TABLE 3.3
Sample Discrimination Test Trials for the Nasal Coarticulation Experiment

		Acoustically different Vs		Acoustically identical Vs
Oral context–isolation	Oral	bod–õ	/	bod–o
	Nasal		/	bõd–õ
	Oral	bõd–o	/	bod–o
	Nasal		/	bõd–õ
Nasal context–isolation	Oral	mõn–o	/	mon–o
	Nasal		/	mõn–õ
	Oral	mon–õ	/	mon–o
	Nasal		/	mõn–õ
Oral context–nasal context	Oral	bod–mõn	/	bod–mon
	Nasal		/	bõd–mõn

The same design was also applied to the /e/ stimuli.

viewed as non-prototypical effects, and oral vowels in nasal contexts as prototypical effects. However, unlike vowel-to-vowel coarticulation where, for example, [bib$_a$a] would be close to a careful production, [mon] is not possible in American English, making the prototypical/non-prototypical distinction not entirely parallel.

The test design in Table 3.3 was applied not only to the stimuli created from original *bode* and *moan*, but also from original *bed* and *men* (using two tokens of each original word). In each trial, listeners were asked to identify the pair in which the vowels sounded "more different." Listeners were 16 native speakers of American English, none of whom had participated in the first experiment.

The predictions of a compensation hypothesis correspond to those we described for the stimuli investigating vowel-to-vowel coarticulation. Performance on control trials should be accurate. For test trials with a nasal vowel in a nasal consonant context, compensation predicts that listeners will systematically make the wrong choice. For example, if listeners hear the nasalization in [mõn] as belonging to the nasal consonants, then the nasal [õ] in [mõn] should sound similar to the non-nasal [o] in [bod]. In contrast, listeners should be accurate on trials *not* involving the nasal consonant context because there would be no context that would trigger compensation. Compensation does not make clear predictions about accuracy for oral vowels in a nasal consonant context ([mon]); whether listeners compensate for expected, but missing, coarticulatory nasalization is an open question.

We report the results for the combined data obtained on the /ɛ/ and /o/ stimulus sets, which overall showed highly similar patterns. The control data showed that listeners were highly accurate at identifying the pair with the "more different" vowels, with performance ranging narrowly from 95 to 98%. In contrast, the test pairings resulted in a range of performance from near chance to well above. The results for the test pairs are shown in Figure 3.4. Performance on each non-identical (oral–nasal) vowel pair is plotted along the abscissa as a function of the corresponding identical vowel pair, either two oral or two nasal vowels (shown by bar type). Each pair of bars in Figure 3.4 corresponds to one cell in Table 3.3.

The test trial results show that several factors influence listeners' sensitivity to the acoustic differences between oral and nasal vowels. First, the presence of a nasal consonant context significantly reduces the accuracy of judgments of oral–nasal vowel differences. Discrimination is highly accurate (around 90%) when the pairings do not include a vowel in a nasal consonant context (two left sets of bars) and performance drops by 7–11% when the oral vowels are placed in a nasal consonant context (NVN–Ṽ pairings). Second, accuracy is again significantly reduced (by another 13%) when the vowel in the nasal consonant context is a coarticulatorily appropriate nasal vowel (NṼN–V pairings). Third, as predicted, performance is worst (significantly so; at or somewhat below chance) when the nasal vowel in the nasal consonant context is paired with an oral vowel in an oral consonant context (NṼN–CVC pairings). Finally, for all comparisons, accuracy

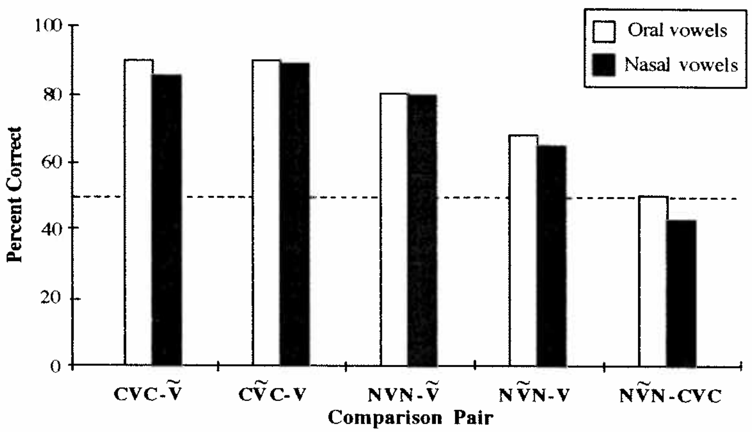

Figure 3.4. Pooled percentage correct responses of 16 listeners to the discrimination test for nasal coarticulation, according to context and type of oral–nasal (i.e., different) vowel pairing. Bar type indicates the identical vowel pairing: both oral or both nasal. Each pair of bars corresponds to a cell in Table 3.3. For example, for the left-most CVC–Ṽ pairing: open = CVC–Ṽ/CVC–V; solid = CVC–Ṽ/CṼ–Ṽ.

was somewhat (although in most cases only marginally and not significantly) reduced when the matched vowels were nasal than when they were oral (compare filled bars to unfilled bars). Whether this difference is an effect of the phonological status of vowel nasalization in American English or an effect of acoustic/auditory properties is unclear.

This pattern of performance provides insights concerning listeners' ability to disentangle (or compensate for) coarticulatory effects of adjacent segments on a target sound. A compensation hypothesis predicts that the listener will attribute vowel nasality in English to an audible nasal consonant context. That nasal vowels in nasal consonant contexts are the hardest to discriminate and most likely to lead to errors (i.e., compensatory responses) is consistent with this claim. Importantly, however, the data show that compensation for coarticulatory nasalization is *partial* rather than complete. Listeners respond as though they are aware of the presence of some nasality on the vowel; they do not provide a pattern of responses indicating that they hear the contextually nasalized vowel as fully "oral." Neither do they respond as though it sounds fully "nasal."

The evidence for partial compensation for coarticulatory nasalization is thus consistent with that for vowel-to-vowel coarticulation. However, it does appear that, in this study, listeners compensated more for nasal coarticulation than

for vowel-to-vowel coarticulation, because performance dropped to chance only in the nasal study (albeit only on the NṼN–CVC comparisons). One possible explanation is that the coarticulatory effects in the nasalization study were greater than those in the vowel-to-vowel experiment; greater effects should be more perceptible and, as a result, should more consistently lead to compensation. Another possibility is that listeners compensated more in the nasal study because we selected a context that provided listeners with two influencing segments (N_N) to which to attribute the coarticulatory effects. Our experimental design does not allow us to tease apart these accounts.

B. Linking Perception of Nasal Coarticulation to Phonological Patterns

The results obtained for the nasal coarticulation data also provide insights into the relation between patterns of partial compensation on the one hand, and the historical development of distinctive nasal vowels and phonological constraints on oral–nasal vowel contrasts on the other. One of the most robust patterns in the perceptual data is listeners' difficulty in determining the nasality of vowels in a nasal consonant context: nasal vowels in nasal consonant contexts do not sound fully oral or nasal. Interpreted in terms of its possible phonological consequences, this experimental finding suggests that distinctive nasal vowels might emerge in contexts in which they were previously contextually nasalized, and this is, in fact, the most common historical source of distinctive nasal vowels in the world's languages (Entenman, 1977; Hajek, 1997; among others).[4]

That nasal vowels in a nasalizing context sound neither fully nasal nor oral, combined with the finding that oral vowels in a nasal consonant context are also not heard as fully oral, indicates that it would be difficult to maintain a phonological contrast between oral and nasal vowels in a nasal consonant context. The phonological evidence shows that languages rarely preserve such contrasts *before* a nasal consonant; in this regard, note the frequent historical loss of a following nasal consonant with distinctive vowel nasalization (Ohala, 1993). Although less common, some languages do not preserve the oral–nasal vowel contrast *after* a nasal consonant (Kawasaki, 1986), a situation that is also linked in some languages to the historical evolution of nasal vowels. For example, Hyman (1972) argued that distinctive nasal vowels in the Kwa languages evolved from earlier /NV/ sequences. Neutralization of the oral–nasal vowel distinction in nasal consonant contexts can also result from nasal harmony, as in Gokana, where nasal consonants trigger both rightward spreading of nasality through vowels (and consonants if the nasal consonant is initial; Hyman, 1982; see also Piggott, 1988). Furthermore, languages that contrast /V/ and /Ṽ/ may (partially) denasalize nasal consonants next to an oral vowel, or partially nasalize oral stops next to a nasal vowel (as in Apinaye; Hyman, 1975; Kawasaki, 1986). Such phonological patterns support the experimentally based notion that the contrast between a nasal and an oral vowel is difficult to maintain in a nasal consonant context.

Although the experiment reported here does not directly speak to this issue, as we have just noted, oral–nasal vowel distinctions are more likely to be lost before rather than after a nasal consonant, and we believe that production and perception data on coarticulation provide some insight into this difference. In comparing our data on nasal coarticulation with both our data and Fowler's (1981) on vowel-to-vowel coarticulation, we argued that one interpretation of the three studies taken together was that, the more robust the coarticulatory effects in production, the more robust the compensatory responses of listeners. We argued this on the basis of greater compensation for bidirectional than unidirectional coarticulatory effects. However, in addition to differences between bi- versus unidirectional effects, effects can be stronger in one direction than the other. For example, Fowler (1981) found stronger carryover than anticipatory vowel-to-vowel effects in English and relatedly greater compensation for carryover than anticipatory coarticulation. Although we did not compare here compensation for anticipatory versus carryover coarticulation, we would expect greater compensation for anticipatory effects of nasalization since syllable-final nasal consonants are associated with lower positions of the velum and longer durations of low positioning (Krakow, 1999).[5] This would suggest that listeners are likely to have more problems maintaining a distinction between oral and nasal vowels before than after a nasal consonant, which is consistent with the phonological evidence.

Another aspect of the timing of the low velum position for nasalization — and, we would argue, listeners' perception of these coarticulatory effects — may be associated with yet another set of phonological patterns involving nasality. As pointed out by Hajek (1997), in some languages, including Northern Italian dialects, distinctive nasal vowels evolved in VNC contexts (VNC > ṽC) before they evolved in VN# contexts. In addition, synchronically, some languages with distinctive nasal vowels contrast /ṽ/ and /VN/ (which may be phonetically [ṼN]) word-finally, but neutralize this distinction when N is followed by an oral C, as in French (e.g., /pɛ̃/ 'bread,' /pɛn/ 'pain,' /pɛ̃s/ 'pinch,' but */pɛns/). The articulatory evidence suggests that vowels in CVNC sequences might be more nasal than vowels in CVN sequences. Kent and colleagues (1974), for example, showed that, when a nasal consonant is followed immediately by an oral consonant, the requirement of the high velum in such close proximity to a nasal segment requires a very early onset for the velum raising gesture. This appears to have the effect of an earlier onset for the low velum position. If listeners only partially compensate for coarticulatory effects, such early lowering may lead to yet greater difficulty in maintaining a perceptual contrast between oral and nasal vowels in a nasal consonant context.

IV. Concluding Remarks

The most robust finding in our perceptual investigation of vowel-to-vowel and nasal coarticulation is that, when judging the nature of a target segment, listeners partially compensated for the acoustic effects of a nearby segment on the target. Compensation was measured by the extent to which coarticulatory appropriateness of vowel differences overrode acoustic identity in listeners' judgments of vowel similarity. In both experiments, listeners chose the coarticulatorily appropriate — that is, the compensatory — response often, although not consistently. That listeners are sensitive to coarticulatory variation, and its contextual appropriateness, is consistent with a growing body of perceptual evidence indicating that coarticulatory variation can facilitate listeners' recovery of speakers' intended utterances. At the same time, listeners are far from perfect compensators: apparently, the acoustic signal (at least in these laboratory conditions) does not always provide sufficient information for listeners to correctly attribute all the acoustic consequences of coarticulation to their source. A coarticulatory environment may be unambiguously present; however, the extent to which it influences the target segment may remain unclear to the listener. Factors influencing the extent of compensation include the particular context in which the coarticulated target sound is embedded and the particular contrast with which the listener is faced (e.g., note in Figure 3.4 the increasing compensation from left to right as vocalic contexts and contrasts change).[6]

The parallel patterns of partial compensation for vowel-to-vowel and nasal coarticulation are especially noteworthy as the two kinds of coarticulation involve the influences of different articulators: the relevant articulators for vowel-to-vowel patterns are the tongue, jaw, and lips, whereas for nasal coarticulation the articulator is the velum. Furthermore, taken together, study of these coarticulatory patterns examined effects of consonants on vowels (nasal coarticulation) and of vowels on vowels (vowel-to-vowel coarticulation), as well as the effects of anticipatory coarticulation (for nasal coarticulation) and carryover coarticulation (for vowel-to-vowel and nasal coarticulation).

We have suggested that the finding that listeners compensate for coarticulation, but not perfectly so, is in many respects not surprising once we recognize how variable coarticulation is. For example, in vowel-to-vowel coarticulation, speaker-to-speaker differences are an important source of differing patterns of coarticulation. For the American English speaker whose data were manipulated here, as well as for the productions of the speakers studied by Fowler (1981), carryover effects exceeded anticipatory effects. However, this pattern does not hold for all the speakers whose productions have been examined in our laboratory. Magen (1997) also reports variability among American English speakers in vowel-to-vowel coarticulation, and across-speaker variability has been reported for other languages as well (e.g., Italian; Vayra *et al.*, 1987). The vowel-to-vowel coarticulation literature also provides substantial evidence of variability due to speaking rate, and segmental and prosodic factors (see Farnetani, 1990, for a review; also, Magen, 1997; Majors, 1998). Similarly, sources of variation in nasal coarticulation include segmental structure (Bell-Berti, 1993), as well as such nonsegmental factors as speaking rate and style, in addition to clause, word, and syllable position (for reviews, see Krakow, 1993, 1999). Speaker-to-speaker differences in nasal coarticulation include dialect (Kavanagh *et al.*, 1994) and gender-based (Litzaw & Dalston, 1992) influences. Listeners' considerable experience with native-language coarticulatory structures may well lead them to expect certain general coarticulatory patterns, but the variability in the production of these structures is in keeping with the perceptual finding that there is often a coarticulatory "residue" that listeners do not attribute to context.

Listeners' partial compensation for coarticulatory effects provides a mechanism for the incorporation of perceptually based phenomena into phonological systems. In describing this mechanism, we build on Ohala's insight that listeners' failure to "normalize the variable speech signal" (1993, p. 162) could lead to phonologization of coarticulatory effects. But partial compensation broadens the scope of the conditions under which coarticulatory variation might become phonological patterns over time. If the experimental evidence reflects usual listening conditions, partial compensation may be the norm rather the exception — keeping in mind, of course, that in natural communicative settings listeners have access to other types of information in arriving at perceptual decisions.

Support for our argument that partial compensation for coarticulation plays a role in shaping phonological structure was provided by comparing the detailed patterns of partial compensation with phonological patterns in vowel systems. Compensation for nasal coarticulation, as compared to vowel-to-vowel coarticulation, yielded more variable performance across vowel contexts and paired vowel contrasts, thereby offering more opportunity to explore perceptual–phonological links. However, possible links between perception of vowel-to-vowel coarticulation and vowel harmony systems were also drawn. In addition, for both types of coarticulation, we posited a close relationship between the spatial and temporal extent of speakers' patterns of coarticulation and listeners' patterns of compensation. This relationship means that the relative contributions of the speaker and the listener to the phonology of vowel systems are not always readily disentangled. In the case of vowel-to-vowel coarticulation, this is especially true for /i/ and /e/ — that is, the neutral vowels in many backness harmony systems. As noted, acoustic studies of vowel-to-vowel coarticulation have shown that these vowels, especially /i/, exhibit relatively small coarticulatory effects. This may be due to relatively tight articulatory constraints on the range of palatal constrictions that give rise to an acceptable /i/ (e.g., Fowler, 1993). Alternatively, it may be that palatal constrictions for /i/ are *acoustically* stable, with small changes in front–back constriction having a negligible effect on formant frequencies (Goldstein, 1983; Stevens, 1989); the listener would play a more prominent role in this latter case. A third alternative is that both articulatory and acoustic–perceptual factors are involved. Regardless, it is listeners' inability to systematically detect these small variations that renders these vowels phonologically neutral. More generally, it is the listener who mediates which aspects of coarticulatory variation become part of phonology, and an important component of this mediation process is compensation. In our view, compensation that is partial, and consistently more extensive under some context and contrast conditions than others, is particularly conducive to phonologization of coarticulatory variation. The close parallels between patterns of partial compensation and the phonological data strengthen this claim.

ACKNOWLEDGMENTS

The research reported here was supported in part by NSF Grant SBR 9319597 to Patrice Beddor, NIH Grant NS-131617 to Haskins Laboratories, and a University of Michigan Department of Linguistics/Rackham Graduate School Research Partnership to Stephanie Lindemann and Patrice Beddor. We thank James Harnsberger for assistance in data collection and numerous discussions. Oral versions of this paper benefitted from the comments of the University of Michigan phonetics–phonology discussion group and participants in the ICPhS satellite meeting. An earlier written version also benefitted from the editors' helpful comments.

NOTES

1. In Fowler's (1981) study, unlike the current study, overall performance fell somewhat below chance. We expect that the greater tendency of listeners in that study to judge vowel similarity on the basis of coarticulatory appropriateness rather than acoustic similarity is linked to stimulus differences between the two studies. Fowler's stimuli were trisyllables, with most pairings involving acoustic differences due to both anticipatory and carryover effects. Indeed, Fowler found that the error rate was higher (i.e., more compensatory responses) for pairings involving bidirectional (anticipatory and carryover) influences than those involving unidirectional influences.
2. The only other original vowel pairings that did not yield reliably detectable effects of V_1 on V_2 involved [u] in the V_2 position. We attribute this to the centralized /u/ articulations of this speaker, regardless of vowel context.

3. See Ohala (1994) for a perceptual account of the failure of neutral vowels to trigger their own harmony. See also Harms (1987) for an alternative phonetic account to ours concerning the failure of neutral vowels to harmonize.
4. At first glance, it might seem as though the relatively high rate of compensation for pairings with NṼN would lead to the prediction of a negligible effect on phonological systems since, as argued in section I, more compensation should mean greater ability to disentangle the contribution of the nasal consonant to vowel nasality. Indeed, this should hold if listeners consistently compensated for nasality in NṼN utterances. However, we would argue that, when listeners' performance is close to *chance* (e.g., the NṼN–CVC pairings), the disentanglement remains difficult.
5. The lower position of the velum in VN than NV sequences may be subject to dialectal and cross-language variation. See Chafcouloff & Marchal (1999) for a review of anticipatory compared to carryover effects of nasalization.
6. Theoretically, given variability in coarticulation, the same factors that lead to partial or under-compensation for coarticulatory effects might be expected to lead to over-compensation if listeners' expectations concerning the extent of coarticulation in particular contexts are not met. However, the present experiments were not designed to investigate this possibility.

REFERENCES

Alfonso, P. J., & Baer, T. (1982). Dynamics of vowel articulation. *Language and Speech, 25*, 151–173.

Beddor, P. S., & Krakow, R. A. (1998). Perceptual confusions and phonological change: How confused is the listener? In B. K. Bergen, M. C. Plauché, & A. C. Bailey (Eds.), *Proceedings of the 24th Annual Meeting of the Berkeley Linguistics Society* (pp. 320–334). Berkeley: Berkeley Linguistics Society.

Beddor, P. S., & Krakow, R. A. (1999). Perception of coarticulatory nasalization by speakers of English and Thai: Evidence for partial compensation. *Journal of the Acoustical Society of America, 106*, 2868–2887.

Beddor, P. S., & Yavuz, H. K. (1995). The relation between vowel-to-vowel coarticulation and vowel harmony in Turkish. In K. Elenius & P. Branderud (Eds.), *Proceedings of the 13th International Congress of Phonetic Sciences* (Vol. 2, pp. 44–51). Stockholm: KTH and Stockholm University.

Beddor, P. S., Harnsberger, J., & Lindemann, S. (2000). *Language-specific patterns of vowel-to-vowel coarticulation: Acoustic structures and their perceptual correlates.* Unpublished manuscript.

Bell-Berti, F. (1993). Understanding velic motor control: Studies of segmental context. In M. K. Huffman & R. A. Krakow (Eds.), *Nasals, nasalization, and the velum* (pp. 63–85). New York: Academic Press.

Chafcouloff, M., & Marchal, A. (1999). Velopharyngeal coarticulation. In W. J. Hardcastle & N. Hewlett (Eds.), *Coarticulation: Theory, data and techniques* (pp. 69–79). Cambridge: Cambridge University Press.

Entenman, G. (1977). *The development of nasal vowels.* Unpublished doctoral disssertation, University of Texas, Austin.

Farkas, D. F., & Beddor, P. S. (1987). Privative and equipollent backness in Hungarian. In A. Bosch, B. Need, & E. Schiller (Eds.), *Parasession on autosegmental and metrical phonology* (pp. 90–105). Chicago: Chicago Linguistic Society.

Farnetani, E. (1990). V–C–V lingual coarticulation and its spatiotemporal domain. In W. J. Hardcastle & A. Marchal (Eds.), *Speech production and speech modeling* (pp. 93–130). Dordrecht: Kluwer Academic.

Fowler, C. A. (1981). Production and perception of coarticulation among stressed and unstressed vowels. *Journal of Speech and Hearing Research, 46*, 127–139.

Fowler, C. A. (1984). Segmentation of coarticulated speech in perception. *Perception and Psychophysics, 36*, 359–368.

Fowler, C. A. (1993). Phonological and articulatory characteristics of spoken language. In G. Blanken, J. Dittmann, H. Grimm, J. C. Marshall, & C.-W. Wallesch (Eds.), *Linguistic disorders and pathologies: An international handbook* (pp. 34–46). New York: Walter de Gruyter.

Fowler, C. A., Best, C. T., & McRoberts, G. W. (1990). Young infants' perception of liquid coarticulatory influences on following stop consonants. *Perception and Psychophysics, 48*, 559–570.

Fowler, C. A., Brown, J. M., & Mann, V. A. (1999). Compensation for coarticulation in audiovisual speech perception. In J. J. Ohala, Y. Hasegawa, M. Ohala, D. Granville, & A. C. Bailey (Eds.), *Proceedings of the 14th International Congress of Phonetics Sciences* (Vol. 1, pp. 639–642). Berkeley: University of California Press.

Goldsmith, J. (1985). Vowel harmony in Khalkha Mongolian, Yaka, Finnish, and Hungarian. *Phonology Yearbook, 2*, 253–275.

Goldstein, L. (1983). *Vowel shifts and articulatory-acoustic relations.* Paper presented at the 10th International Congress of Phonetic Sciences, August 1983. Utrecht, The Netherlands.

Hajek, J. (1997). *Universals of sound change in nasalization.* Boston: Blackwell.

Harms, R. T. (1987). What Helmholtz knew about neutral vowels. In R. Channon & L. Shockey (Eds.), *In honor of Ilse Lehiste: Ilse Lehiste Pühendusteos* (pp. 381–399). Dordrecht: Foris.

Hawkins, S. (1995). Arguments for a non-segmental view of speech perception. In K. Elenius & P. Branderud (Eds.), *Proceedings of the 13th International Congress of Phonetic Sciences* (Vol. 3, pp. 18–25). Stockholm: KTH and Stockholm University.

Hyman, L. (1972). Nasals and nasalization in Kwa. *Studies in African Linguistics, 3*(2), 167–205.

Hyman, L. (1975). Nasal states and nasal processes. In C. A. Ferguson, L. M. Hyman, & J. J. Ohala (Eds.), *Nasálfest. Papers from a symposium on nasals and* *nasalization* (pp. 249–264). Stanford: Language Universals Project, Stanford University.

Hyman, L. (1982). The representation of nasality in Gokana. In H. van der Hulst & N. Smiths (Eds.), *The structure of phonological representations*, Part I (pp. 111–130). Dordrecht: Foris.

Kavanagh, M. L., Fee, E. J., Kalinowski, J., Doyle, P. C., & Leeper, H. A. (1994). Nasometric values for three dialectal groups within the Atlantic provinces of Canada. *Journal of Speech and Language Pathology and Audiology*, *18*(1), 7–13.

Kawasaki, H. (1986). Phonetic explanation for phonological universals: The case of distinctive vowel nasalization. In J. J. Ohala & J. J. Jaeger (Eds.), *Experimental phonology* (pp. 81–103). Orlando: Academic Press.

Kent, R. D., Carney, P. J., & Severeid, L. R. (1974). Velar movement and timing: Evaluation of a model of binary control. *Journal of Speech and Hearing Research*, *17*, 470–488.

Kingston, J., & Macmillan, N. A. (1995). Integrality of nasalization and F1 in vowels in isolation and before oral and nasal consonants: A detection-theoretic application of the Garner paradigm. *Journal of the Acoustical Society of America*, *97*, 1261–1285.

Krakow, R. A. (1993). Nonsegmental influences on velum movement patterns: Syllables, sentences, stress, and speaking rate. In M. K. Huffman & R. A. Krakow (Eds.), *Nasals, nasalization, and the velum* (pp. 87–113). New York: Academic Press.

Krakow, R. A. (1999). Articulatory organization of syllables: A review. *Journal of Phonetics*, *27*, 23–54.

Krakow, R. A., Beddor, P. S., Goldstein, L. M., & Fowler, C. A. (1988). Coarticulatory influences on the perceived height of nasal vowels. *Journal of the Acoustical Society of America*, *83*, 1146–1158.

Kunisaki, O., & Fujisaki, H. (1977). On the influence of context upon the perception of fricative consonants. *Research Institute of Logopedics and Phoniatrics Annual Bulletin, University of Tokyo*, *11*, 85–91.

Litzaw, L. L., & Dalston, R. M. (1992). The effect of gender upon nasalance scores among normal adult speakers. *Journal of Communication Disorders*, *25*, 55–64.

Lotto, A. J., & Kluender, K. R. (1998). General contrast effects in speech perception: Effect of preceding liquid on stop consonant identification. *Perception and Psychophysics*, *60*, 602–619.

Lotto, A. J., Kluender, K. R., & Holt, L. L. (1997). Perceptual compensation for coarticulation by Japanese quail. *Journal of the Acoustical Society of America*, *102*, 1134–1140.

Magen, H. S. (1984). Vowel-to-vowel coarticulation in English and Japanese. *Journal of the Acoustical Society of America*, *75*, S41.

Magen, H. S. (1997). The extent of vowel-to-vowel coarticulation in English. *Journal of Phonetics*, *25*, 187–205.

Majors, T. (1998). *Stress-dependent harmony: Phonetic origins and phonological analysis.* Unpublished doctoral disssertation, University of Texas, Austin.

Majors, T. (1999). *Perceptually motivated phonology: The case of stress-dependent harmony.* Poster presented at "The Role of Speech Perception Phenomena in Phonology" Satellite Meeting of the International Congress of Phonetic Sciences, July 1999, San Francisco.

Mann, V. A. (1980). Influence of preceding liquid on stop-consonant perception. *Perception and Psychophysics*, *28*, 407–412.

Mann, V. A., & Repp, B. H. (1980). Influence of vocalic context on perception of the [ʃ]–[s] distinction. *Perception and Psychophysics*, *28*, 213–228.

Manuel, S. Y. (1987). *Acoustic and perceptual consequences of vowel-to-vowel coarticulation in three Bantu languages.* Unpublished doctoral disssertation, Yale University, New Haven.

Manuel, S. Y. (1995). Speakers nasalize /ð/ after /n/, but listeners still hear /ð/. *Journal of Phonetics*, *23*, 453–476.

Martin, J. G., & Bunnell, H. T. (1982). Perception of anticipatory coarticulation effects in vowel–stop consonant–vowel sequences. *Journal of Experimental Psychology: Human Perception and Performance*, *8*, 473–488.

Nguyen, N., & Hawkins, S. (1999). Implications for word recognition of phonetic dependencies between syllable onsets and codas. In J. J. Ohala, Y. Hasegawa, M. Ohala, D. Granville, & A. C. Bailey (Eds.), *Proceedings of the 14th International Congress of Phonetics Sciences* (Vol. 1, pp. 647–650). Berkeley: University of California Press.

Ohala, J. J. (1981). The listener as a source of sound change. In C. S. Masek, R. A. Hendrick, & M. F. Miller (Eds.), *Papers from the parasession on language and behavior* (pp. 178–203). Chicago: Chicago Linguistic Society.

Ohala, J. J. (1986). Phonological evidence for top–down processing in speech perception. In J. S. Perkell & D. H. Klatt (Eds.), *Invariance and variability of speech processes* (pp. 386–401). Hillsdale, NJ: Erlbaum.

Ohala, J. J. (1993). Coarticulation and phonology. *Language and Speech*, *36*, 155–170.

Ohala, J. J. (1994). Hierarchies of environments for sound variation; plus implications for "neutral" vowels in vowel harmony. *Acta Linguistica Hafniensia*, *27*(2), 371–382.

Pardo, J. S., & Fowler, C. A. (1997). Perceiving the causes of coarticulatory acoustic variation: Consonant voicing and vowel pitch. *Perception and Psychophysics*, *59*, 1141–1152.

Petersen, N. R. (1986). Perceptual compensation for segmentally conditioned fundamental frequency perturbation. *Phonetica*, *43*, 31–42.

Piggott, G. L. (1988). A parametric approach to nasal harmony. In H. van der Hulst & N. Smith (Eds.), *Features, segmental structure and harmony processes* (pp. 131–167). Dordrecht: Foris.

Recasens, D. (1987). An acoustic analysis of V-to-C and V-to-V coarticulatory effects in Catalan and Spanish VCV sequences. *Journal of Phonetics*, *15*, 299–312.

Recasens, D. (1989). Long-range coarticulation effects for tongue dorsum contact in VCVCV sequences. *Speech Communication, 8*, 293–307.

Silverman, K. (1987). *The structure and processing of fundamental frequency contours.* Unpublished doctoral disssertation, Cambridge University.

Stevens, K. N. (1989). On the quantal nature of speech. *Journal of Phonetics, 17*, 3–45.

van der Hulst, H., & Smith, N. (1986). On neutral vowels. In K. Bogers, H. van der Hulst, & M. Mous (Eds.), *The phonological representation of suprasegmentals* (pp. 233–279). Dordrecht: Foris.

van der Hulst, H., & van de Weijer, J. (1995). Vowel harmony. In J. A. Goldsmith (Ed.), *The handbook of phonological theory* (pp. 495–534). Cambridge: Blackwell.

van Heuven, V. J., & Dupuis, M. C. (1991). Perception of anticipatory VCV-coarticulation: Effects of vowel context and accent distribution. In *Proceedings of the 12th International Congress of Phonetic Sciences* (Vol. 4, pp. 78–81). Aix-en-Provence: Université de Provence.

Vayra, M., Fowler, C. A., & Avesani, C. (1987). Word-level coarticulation and shortening in Italian and English speech. *Studi di Grammatica Italiano, 13*, 249–269.

Whalen, D. H. (1981). Effects of vocalic formant transitions and vowel quality on the English [s]–[ʃ] boundary. *Journal of the Acoustical Society of America, 69*, 275–282.

Whalen, D. H. (1984). Subcategorical phonetic mismatches slow phonetic judgments. *Perception and Psychophysics, 35*, 49–64.

Whalen, D. H. (1989). Vowel and consonant judgments are not independent when cued by the same information. *Perception and Psychophysics, 46*, 284–292.

Xu, Y. (1994). Production and perception of coarticulated tones. *Journal of the Acoustical Society of America, 95*, 2240–2253.

4

CHAPTER

Markedness and Consonant Confusion Asymmetries

Steve S. Chang, Madelaine C. Plauché, and John J. Ohala

Department of Linguistics
University of California, Berkeley
Berkeley, California 94720

I. Introduction
II. Markedness
A. Study 1
B. Study 2
C. Discussion
III. [ti] versus [tʃi]
A. Study 3a
B. Study 3b
C. Discussion
IV. Conclusions
Acknowledgments
Notes
References

The Role of Speech Perception in Phonology