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A COARTICULATORY PATH TO SOUND CHANGE

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Although coarticulatory variation is largely systematic, and serves as useful information for listeners, such variation is nonetheless linked to sound change. This article explores the articulatory and perceptual interactions between a coarticulatory source and its effects, and how these interactions likely contribute to change. The focus is on the historical change VN (phonetically, ṼN) > Ṽ, but with more general attention to how a gesture associated with a source segment comes to be reinterpreted as distinctively, rather than coarticulatorily, associated with a nearby vowel or consonant. Two synchronic factors are hypothesized to contribute to reinterpretation: (i) articulatory covariation between the duration of the coarticulatory source (here, N) and the temporal extent of its effects (Ṽ), and (ii) perceived equivalence between source and effect. Experimental support for both hypotheses is provided. Additionally, the experimental data are linked to the historical situation by showing that the contextual conditions that trigger (i) and (ii) parallel the conditions that historically influence phonologization of vowel nasalization.*

Keywords: sound change, coarticulation, nasalization, phonologization, speech perception, articulatory covariation

1. Introduction. Coarticulation introduces context-dependent variation into the acoustic realization of phonological segments. The variation, which follows from the acoustic theory of speech production (Fant 1960), is lawful and systematic. As would be expected, listeners have knowledge of these acoustic consequences of coarticulation. Nonetheless, coarticulatory variation has been implicated in numerous sound changes, suggesting that listeners do not necessarily arrive at an interpretation of the coarticulated utterance that corresponds to a speaker's intent. This article explores the phonetic underpinnings of a subset of sound changes: those in which the source of coarticulation is apparently lost in the transmission from speakers to listeners, but its coarticulatory effects remain. I offer a theory of the articulatory and perceptual relations between coarticulatory source and effect that could underlie these changes, and provide experimental and historical evidence in support of the theory.

It has long been recognized that the systematic variation introduced by coarticulation has a role in sound change. Paul (1888 [1886]) emphasized that small articulatory deviations are candidates for sound change if they systematically 'incline to one side or the other' of (as opposed to randomly vary around) the target or intended sound. For Paul, such inclinations included the assimilatory influences of one sound on another within a 'sound group' that yield a 'more convenient' articulation (1888 [1886]:45–46). Baudouin de Courtenay also considered changes resulting from discrepancies between the speaker's intention and actual realization, distinguishing between 'conditions which favor the manifestation of the properties of a given phoneme and those which prevent it' (1972 [1895]:172–73). Favorable or unfavorable conditions are determined in part by 'accommodation' of a target phoneme to its phonetic context, giving rise to condi-

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tioned variants that may constitute minute 'embryonic' alternations or may involve more perceptible variants (1972 [1895]:174–75).

Capitalizing on the deeper understanding of variation afforded by phonetic experimentation, Ohala (1981, 1993) developed a more explicit theory of the mechanisms by which coarticulatory variation could lead to sound change. Although Paul (1888 [1886]:53–54) and Baudouin de Courtenay (1972 [1895]:174) both considered the transmission from speaker to learner/listener in establishing the link between articulatory variants and sound change, Ohala's work placed the focus more directly on the listener's task of dealing with a less-than-ideal transmission line. Substantial evidence shows that listeners accommodate or compensate for the acoustic effects of coarticulation. Listeners' responses to experimental tasks suggest that they perceptually reduce and in some cases eliminate the effects of the coarticulatory context on a target segment (Mann & Repp 1980, Kawasaki 1986, Manuel 1995, Mitterer 2006, among many others). Ohala postulated that, while listeners correctly attribute coarticulatory variation to its source under usual circumstances, inexperienced listeners (learners) or experienced listeners who did not detect the coarticulatory trigger might not make appropriate adjustments. That is, these listeners might not normalize the coarticulated input signal. Consequently, they might perceive the coarticulated property as inherent rather than derived, and arrive at a linguistic representation of the relevant sound sequence different from that of the speaker. Listeners might, for example, interpret [Ṽn] as /Ṽ/ (e.g. Ohala 1981) or [iC_iu] as /iCy/ (Ohala 1994; the subscript indicates the coarticulatory effects of the first vowel on the second). In effect, a 'mini sound change' might occur. Perceptual data consistent with Ohala's theory include Krakow and colleagues' (1988) finding that English-speaking listeners perceive nasal vowels in nonnasal contexts as differing in height from their oral counterparts (in keeping with the spectral consequences of nasal coupling), but they correctly resolve perceived height when the same nasal vowels occur in a coarticulatorily appropriate ([_n]) context. More recently, Blevins's EVOLUTIONARY PHONOLOGY (2004:33, 2007) adopts an approach similar to Ohala's with regard to imperfect transmission and learning of coarticulated variants.

Lindblom's hyper- and hypo-articulation (H&H) theory of speaker-listener interactions takes a different approach to coarticulation and, consequently, to its role in sound change (Lindblom 1990, Lindblom et al. 1995). In H&H theory, motor control is purpose-driven: coarticulation is an economical form of motor behavior (hypospeech) to which the articulatory system defaults when unconstrained. However, coarticulation, which may render contrastive differences less distinct, is avoided in listener-oriented speech (hyperspeech)—that is, speech in which listeners' informational needs are estimated to be high. Lindblom and colleagues (1995) share with Ohala the assessment that unnormalized coarticulated variants can serve as the raw material for sound change, but they differ in that attention to such phonetic detail need not be the result of misperception or listener inexperience. Rather, listeners may occasionally be aware of the unnormalized or unprocessed acoustic form of the input signal, such as when informational needs are low or when these needs are perhaps less important than the sociolinguistic information encoded in the phonetic detail. In this approach, the listener-turned-speaker may purposefully produce the new variant, although the listener-speaker NEED not produce it since the original speaker's intent was correctly apprehended. Thus it is listeners' sporadic access to the unprocessed phonetic form that yields new pronunciations and puts language users in a 'state of readiness' for phonological innovations (Lindblom et al. 1995:13). Whether the new variant is accepted and used by others is viewed as dependent on a combination of articulatory, perceptual, and social factors.

In this article, I argue for yet another account of the role of coarticulatory variation in sound change. The insights outlined above serve as the foundation of this account, which assumes that coarticulated variants are the raw material for certain types of change. At the same time, the approach is firmly grounded in the view that the systematic acoustic consequences of overlapping articulations are perceptually informative variants. That is, coarticulation structures the acoustic signal in ways that assist listeners in determining what speakers are saying and in making linguistic decisions. This view is broadly consistent with perceptual theories in which the acoustics of coarticulation provides perceptual coherence (Strange 1989, Hawkins 2003) and enables listeners to assign a gestural parse to the acoustic signal (Liberman & Mattingly 1985, Fowler 1996). The view is supported by evidence that coarticulatory cues speed listeners' responses (e.g. Martin & Bunnell 1982, Nguyen & Hawkins 1999, Fowler 2005) and serve as information about their coarticulatory source (e.g. Alfonso & Baer 1982, Mitterer 2006).

How do coarticulated variants function both as the phonetic material for sound change and as structured information that facilitates perception? That is, if coarticulation introduces perceptually INFORMATIVE variation, how do listener's and speaker's grammars come to DIFFER with respect to coarticulatory source and effect? As discussed above, in Ohala's theory, an important mechanism of change is perceptual error (such as failure to detect the conditioning context leading to 'innocent misapprehension' of the contextual variant as a distinctive property). In contrast, although the current approach is open to misperception of coarticulation leading to sound change,[1] the emphasis is instead on the potential for change even when listeners are accurate perceivers of the input signal. In this respect—that is, in viewing change as not tightly linked to misperception—my perspective is similar to Lindblom and colleagues' (1995) application of H&H theory to sound change. Because Lindblom's and the current theoretical approaches differ fundamentally in whether or not coarticulated variants are useful for listeners, however, they also differ in their views on the mechanisms of change. According to Lindblom and colleagues, the mechanism is the 'decontextualized' or unnormalized perception of coarticulated variants that might occur, for example, when intelligibility demands are low. In comparison, in the approach argued for here, it is precisely because listeners are consistently sensitive to the acoustic consequences of coarticulation, and are extracting those regularities from the acoustic input, that certain types of sound changes have the potential to occur.

The goal of this article is to articulate a theoretical model of the listener's role in sound change in which the listener attends to the dynamics of coarticulation and correctly perceives the input signal, yet the listener's grammar can come to differ from the speaker's with respect to coarticulatory source and effect. The account of how these differences can arise will crucially appeal to the precise nature of coarticulatory variation, and especially to interactions between coarticulatory source and effect. As is shown below, while coarticulation is systematic, its temporal and spatial extent can be highly variable and language-specific. I assume that listeners arrive at (possibly

[1] Because the acoustic signal does not always uniquely specify the corresponding articulatory configuration, perceptual errors can occur. The previous illustration of the effects of nasalization on perceived vowel height is a possible example. Even if listeners correctly detect the nasal consonant that is the source of coarticulatory nasalization, they may fail to assess with complete accuracy the relative contributions of the nasal and oral cavities to the vowel spectrum. In that situation, vowel height might be misperceived (Beddor et al. 1986).

context-dependent) phonological representations that encompass a range of variants. I argue that, because multiple representations are consistent with the variants found in everyday communicative interactions, a given listener need not arrive at the same representation—and/or need not arrive at the same perceptual weighting of the acoustic properties that map to a representation—as that of other listeners, or as that of the speaker.

The current study targets anticipatory vowel nasalization and its relation to the historical change from VN (phonetically [ṼN]) to Ṽ, whereby the lowered velum becomes a required configuration for the vowel rather than being coarticulatorily linked to the consonantal closure. I hypothesize that the process of phonologization of vowel nasalization involves a stage of coarticulatory variation in which the duration of the coarticulatory source (the nasal consonant) is inversely related to the temporal extent of its coarticulatory influences (vowel nasalization). That is, because the historical situation effectively involves reinterpretation of the lowered velum gesture associated with a consonantal constriction as instead being linked to the vowel, the prediction is that, in languages in which vowel nasalization is not phonologized, the gesture itself would be relatively stable but its alignment with the oral articulators might be variable. This production hypothesis is supported by experimental evidence of covariation between nasal consonant duration and the temporal extent of vowel nasalization: shorter nasal consonants cooccur with more extensively nasalized vowels (§2). I further hypothesize that the perceptual counterpart to covariation in production is perceived equivalence between the coarticulatory source and its effects. The perception hypothesis is supported by experimental results showing that many listeners, in making judgments about VNC (phonetically [ṼNC]) as compared to VC sequences, attend less to the nasal consonant than to total nasalization across the syllable rhyme (§§4, 5). Importantly, the contextual conditions that trigger covariation in production and equivalence in perception between coarticulatory source and effect parallel the contexts known to influence phonologization of vowel nasalization (§6). These parallels lead me to postulate a causal link between the phonetic conditions and the phonological patterns of change. Although the focus is on coarticulatory vowel nasalization, it is expected that future work will show that the relations established here hold for certain other coarticulatory phenomena.

2. Covariation in production between coarticulatory source (n) and effect (ṽ). Coarticulatory vowel nasalization varies systematically in temporal and spatial extent depending on the phonetic context in which the nasal consonant source occurs (e.g. Fujimura 1977, Cohn 1990, 1993, Busà 2007, Delvaux et al. 2008), the quantity and quality of the vowel (Whalen & Beddor 1989, Bell-Berti 1993, Delvaux et al. 2008), prosodic context (Vaissière 1988, Cohn 1990, 1993, Krakow 1993, 1999), and speaking rate (Solé 1995). Of particular interest here is evidence in the literature that certain contexts that give rise to relatively extensive vowel nasalization also involve short nasal consonants. For example, Cohn's (1990) nasal airflow measures of English speakers' productions of tautosyllabic /Vnt/ and /Vnd/ showed shorter or absent nasal consonants and a greater likelihood of fully nasalized vowels in prevoiceless (/Vnt/) sequences. Raphael and colleagues (1975) measured N duration in English /Vnt/ and /Vnd/ sequences and found especially short N in /Vnt/ stimuli. They also tentatively observed that /Vnd/ tokens with unexpected short /n/ showed extensive vowel nasalization. In Italian, nasal consonant shortening is especially likely to occur before voiceless fricatives, where vowel nasalization is extensive (Busà 2003, 2007; see §2.2 for more discussion). Along similar lines, in Japanese a nasal triggers partial vowel nasalization when followed by an oral stop, but the nasal is largely absent and the vowel more fully nasalized when followed by a voiceless fricative (Hattori et al. 1958).

2.1. Covariation linked to coda voicing. Evidence of covariation between vowel nasalization and nasal consonant duration suggests that speakers might produce a roughly constant-sized nasal gesture across VNC contexts, but variably align that gesture relative to the oral articulators due to the influences of C. The upper panel of Figure 1 schematically represents overlapping vowel, nasal (lowered velum), and oral-cavity closure gestures for VNC_{voiced}, superimposed over the acoustic waveform of a token of [bɛ̃nd] with partial vowel nasalization. (The dashed vertical lines show acoustic segmentation of V, N, and C.) If, as in the lower panel, timing remains constant in $VNC_{voiceless}$ except for earlier onset of the (same-sized) lowered velum gesture, the outcome would be temporally more extensive vowel nasalization (shown by greater overlap of the lowered velum gesture with the vowel gesture), a shorter acoustic nasal consonant (b–c), and a longer postnasal oral constriction (c–d).

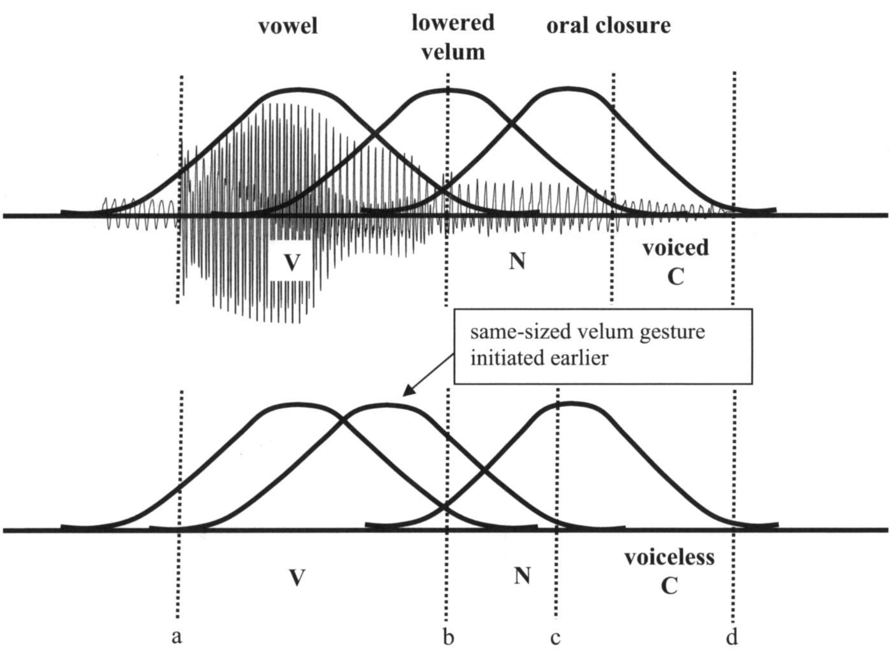

Figure 1. Schematic representation of the consequences for vowel nasalization, the nasal consonant, and the postnasal oral constriction if the velum gesture is initiated earlier in voiceless (bottom) than in voiced (top) contexts. Dashed lines indicate acoustic segmentation.

The hypothesis of variable temporal alignment of an otherwise (roughly) stable velum gesture was tested for voiced and voiceless obstruent contexts in English. Because the pattern of more extensively nasalized vowels cooccurring with shorter nasal consonants has already been reported in the literature on English and other languages, the current focused, small-scale experiment explored this pattern in depth for a single vowel context. Nine native American English-speaking members of the University of Michigan community read a randomized word list consisting of multiple repetitions of C(C)V(N)C words where V = /ɛ/, N = /n/, and coda C = one of /t d s z/ (e.g. *bet*, *bent*, *bed*, *bend*). Data from only six speakers, however, are reported because three speakers fully nasalized all vowels (and, in some cases, the initial CV) followed by N, suggesting a categorical rather than coarticulatory process of nasalization for these speakers (Solé 1992, Ohala 1993).[2] /ɛ/ was chosen because of the relatively large set of English words with this vowel having the crucial V(N)C structures. Table 1 gives the word list. Participants were recorded in a sound-attenuated room reading each word embedded in the context 'Say __ quickly'. Stimuli were sampled at 44.1 kHz and filtered at 22 kHz. Only C(C)VNC words were acoustically analyzed; C(C)VC words served as filler items.

$\mathrm{C(C)VNC}_{\mathrm{voiceless}}$	$\mathrm{C(C)VNC}_{\mathrm{voiced}}$	$\mathrm{C(C)VC}_{\mathrm{voiceless}}$	$\mathrm{C(C)VC}_{\mathrm{voiced}}$
bent	bend	bet	bed
sent	send	set	said
spent	spend		sped
lent	lend	let	led
rent	rend		red
sense	lens	less	
hence	hens		
dense	dens		

TABLE 1. Word list for the small-scale production experiment. Speakers read from a list consisting of five to six randomized repetitions of each word.

Temporal measures of the VNC sequences were vowel duration, duration of vowel nasalization, nasal consonant duration, and, for stop-final words, duration of the postnasal oral constriction. Vowel, nasal consonant, and postnasal oral constriction durations were determined from a combination of acoustic waveform and wideband spectrographic displays. Using GWI's SoundScope and Praat software packages, acoustic onset of vowel nasalization was assessed by inspecting FFT spectra (with a 25 ms analysis window) in 10 ms increments beginning at vowel onset. Nasalization onset was identified as the first spectrum with an identifiable nasal formant in the vicinity of F1 (which increased in amplitude in subsequent spectra) and/or a lowering of F1 amplitude accompanied by broadening of F1 bandwidth (Maeda 1993, Stevens 1998). To illustrate, Figure 2 gives four consecutive FFT spectra, two oral (a, b) and two nasalized (c, d), taken from the middle portion of the vowel *bent* produced by one of the speakers. Identification of nasalization onset based on FFT spectra was confirmed against the corresponding spectrographic and waveform displays. The latter often showed a marked decrease in overall vowel amplitude at the onset of vowel nasalization. To establish the reliability of the measurement technique, a second experimenter measured vowel nasalization and nasal consonant duration for all tokens produced by one of the speakers. Seventy percent of the measures of the second experimenter fell within one pitch pulse, and 92% within two pitch pulses, of the measures of the original coder.[3]

[2] Similar to the three speakers excluded here, the speakers whose productions were analyzed by Solé (1992, 1995) fully or nearly fully nasalized all vowels. While complete vowel nasalization is clearly a fairly common pattern in American English, it is not one of direct interest for this production study given its focus on VARIATION in temporal alignment of the velum gesture.

[3] No single spectral criterion for identifying vowel nasalization onset could be applied to the tokens of all speakers. For each individual speaker, however, one or two well-defined criteria were applied, such as a decrease of x dB in the amplitude of the most prominent harmonic of F1 or a maximum y dB difference in the amplitude of the most prominent harmonics of F1 and FN (see also Chen 1997). For the discrepancies between the two coders' measures that were greater than one pitch pulse, the only systematic difference was that one coder was slightly more conservative than the other in measuring the duration of N (as opposed to pulsing for [d]) in the voiced context. Despite this difference, both coders' measures showed an inverse correlation between N duration and vowel nasalization duration within each voicing context.

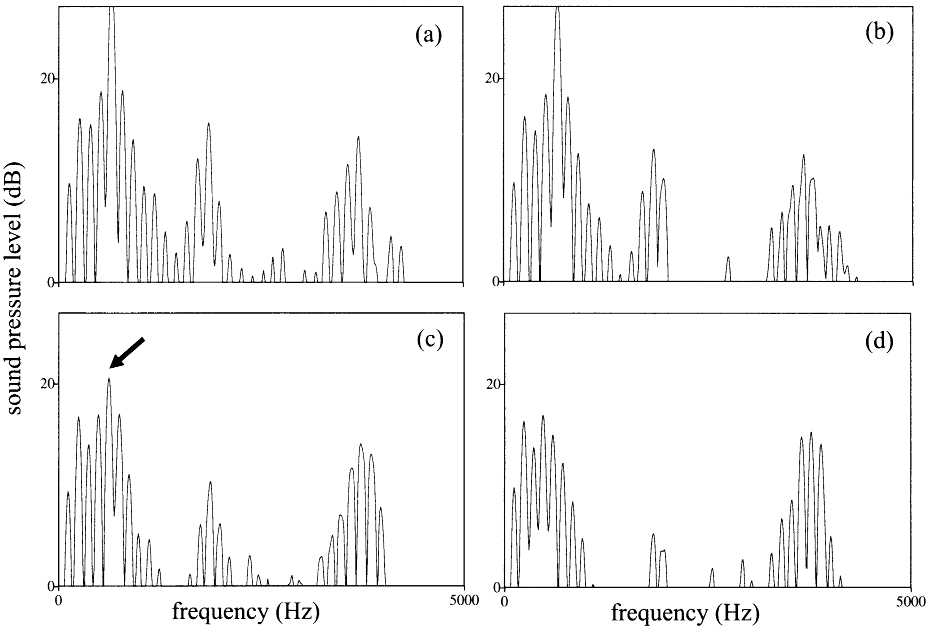

FIGURE 2. Four consecutive spectral sections (a–d) in 10 ms increments for [ɛ̃] from *bent* produced by a male speaker of American English. Onset of acoustic nasalization occurs in spectrum (c), where the arrow indicates reduced F1 amplitude (especially the fifth harmonic). Further flattening of the spectrum in the F1 region occurs as the vowel becomes more nasalized, as shown in spectrum (d).

As stated above, speakers' VN productions are predicted to show an inverse relation between the duration of N and the temporal extent of anticipatory vowel nasalization. Figure 3 plots the relation between N duration and duration of vowel nasalization for the $\mathrm{VNC_{voiced}}$ and $\mathrm{VNC_{voiceless}}$ productions of the six speakers. /h/-initial words were excluded for all speakers, and /r/-initial and /l/-initial words for two speakers, because the following vowels were fully nasalized (i.e. nasalization began during the initial consonant). It may well be that these words show the predicted covariation, but the acoustic criteria for nasalization onset, which are defined for vowels, are difficult to apply to consonant spectra. Final analyses included fifty to sixty tokens per speaker.

The scatter plot in Fig. 3 shows that, overall, longer N durations cooccurred with temporally less extensive vowel nasalization. To determine the significance of the correlation, three LINEAR MIXED MODELS of vowel nasalization on nasal consonant duration were computed, one across voicing contexts, one within the voiceless context, and one within the voiced context. The speaker intercept was treated as a random variable. R^2 was calculated by comparing the residuals from the full model with a reduced model that excluded nasal consonant duration, in order to determine the proportion of within-speaker variance that is explained. The regression line corresponding to R^2 for each model is given in the figure. The model across voicing contexts yielded $R^2 = 0.33$, which was highly significant ($t = 12.46$, $p < 0.0001$). (The t-test was calculated in R version 2.9.0 using Markov chain Monte Carlo estimation; Baayen 2008.)

Because N duration varies within as well as across contexts, the inverse relation between the duration of vowel nasalization and the duration of the nasal consonant should hold not only for contextually conditioned variants but also for within-context variation. The results of the linear mixed model computed on each voicing context again showed a significant correlation: for the voiceless context, $R^2 = 0.13$ ($t = 4.84$,

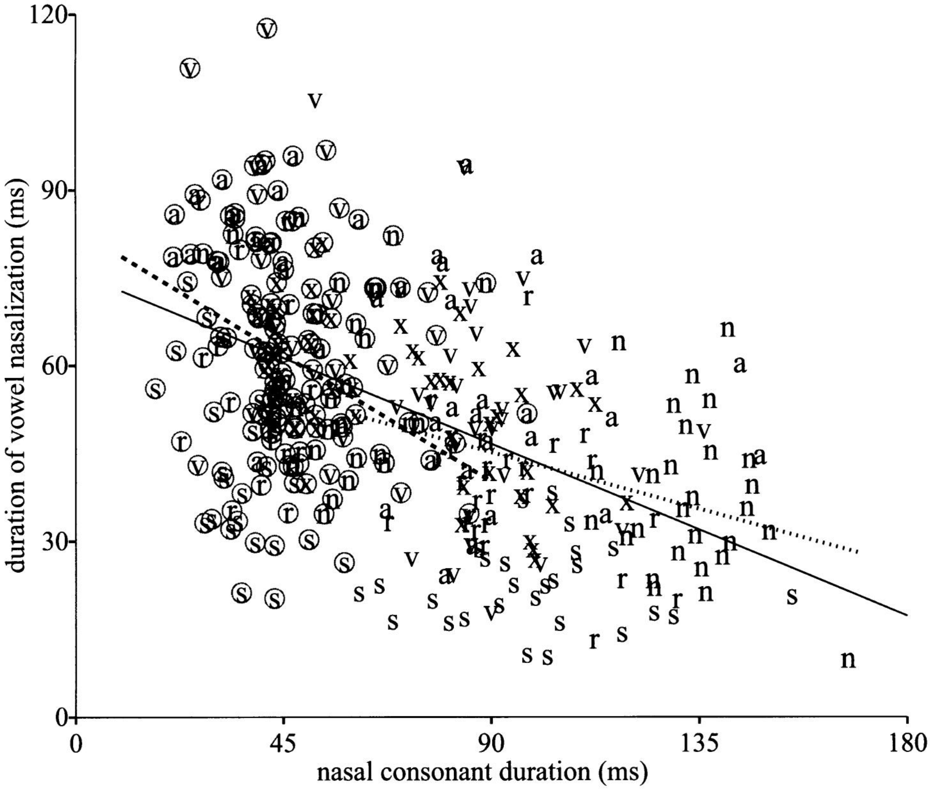

FIGURE 3. Scatter plot showing the inverse relation between nasal consonant duration and vowel nasalization duration for $VNC_{voiceless}$ (circled letters) and VNC_{voiced} (plain letters) produced by six American English speakers. Letter type designates tokens from Speaker A, N, R, S, V, or X. Regression lines correspond to R^2 for each of the three statistical models described in the text (solid line = across contexts, dashed line = voiceless context, dotted line = voiced context).

$p < 0.0001$); and for the voiced context, $R^2 = 0.06$ ($t = 3.27$, $p < 0.005$). The correlation within each voicing context is weaker than that across contexts for reasons that emerge more clearly in the scatter plots for the productions of individual speakers in Figure 4. In the voiceless context, some speakers show more variation in vowel nasalization than expected given fairly restricted variation in N duration; the productions of Speakers R and X are especially clear instances of this 'vertical variation' pattern. Such apparently unconditioned variation can be seen as consistent with the view that the vowel is phonologically unspecified for nasality (e.g. Huffman 1990, Keating 1990). In the voiced context, that same pattern also emerges for some speakers' productions (e.g. Speaker N), but for other speakers (especially Speaker S) we find instead considerably more variation in N duration (i.e. more 'horizontal' variation) than expected on the basis of tightly clustered vowel nasalization durations. While there is clearly much temporal variation that is not accounted for by the model, nonetheless the predicted inverse relation holds for all conditions tested. Busà's (2007) aerodynamic measures exhibit a similar inverse relation for American English $VNC_{voiceless}$ sequences (VNC_{voiced} were not investigated in that study; see §2.2).

As is apparent in Fig. 1, if the covariation between N duration and vowel nasalization duration is the result of variable alignment of a roughly constant-sized velum gesture relative to the oral configuration, then not only should Ṽ and N durations be inversely

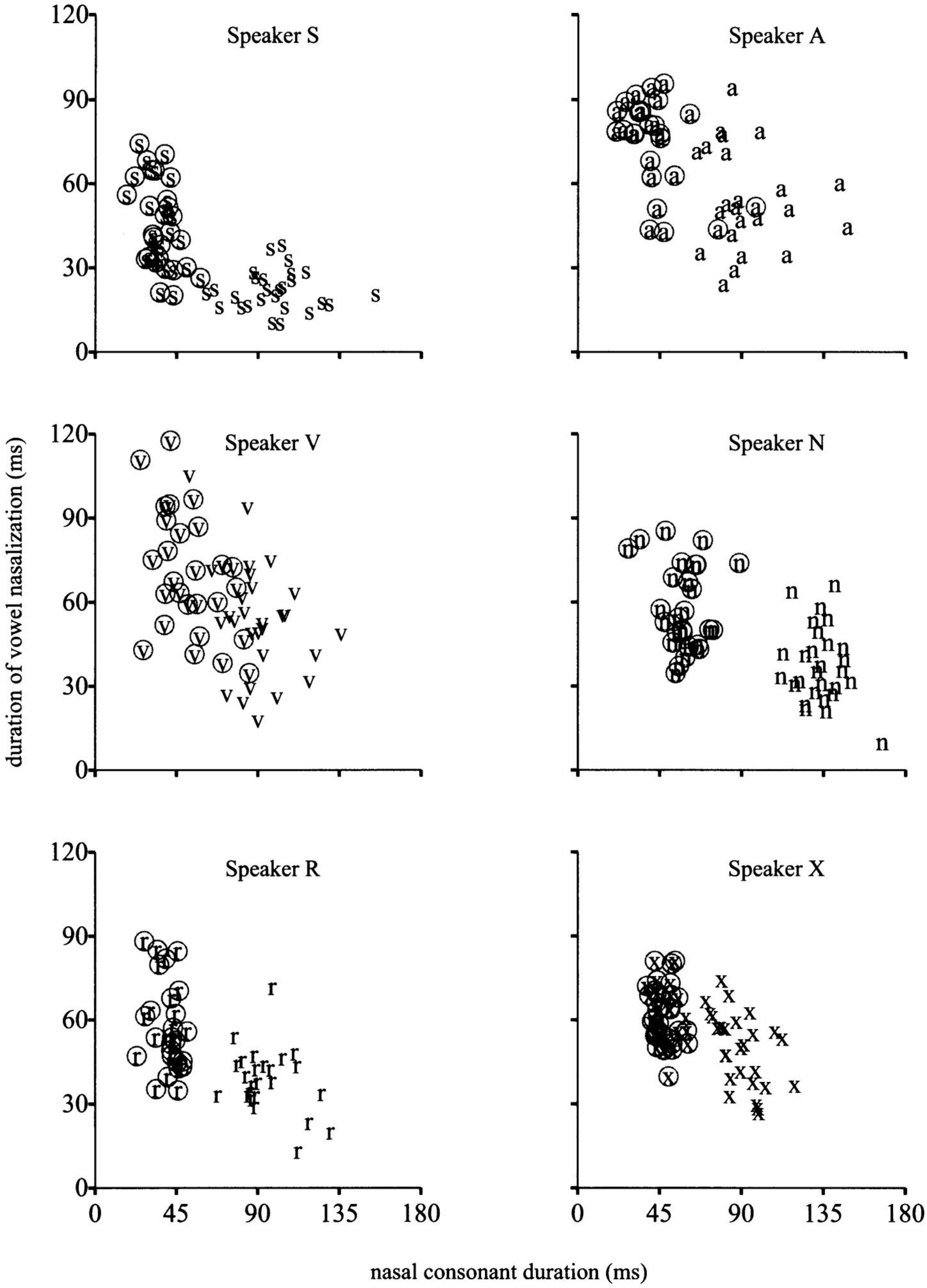

FIGURE 4. Scatter plot of the relation between nasal consonant duration and vowel nasalization duration for $VNC_{voiceless}$ (circled letters) and VNC_{voiced} (plain letters) for each of the six speakers.

related, but so should N and C durations. That is, shorter nasal consonants (and longer nasalized vowel portions) should cooccur with longer postnasal oral constrictions. To test this prediction, these constrictions were measured for words ending in a voiceless stop (/t/) and, for each token, oral stop closure duration was compared against N duration. The prediction was not tested ACROSS voicing contexts because voiceless stop closures are generally longer than voiced (Lisker 1957, Suen & Beddoes 1974), regardless of context. (That is, across voicing contexts, the prediction could have been upheld for reasons not linked to timing of the nasal gesture.) Figure 5 plots the relation between N duration and voiceless C closure duration for five of the six speakers. Data from one speaker, who glottalized most final /t/s, were excluded because absence of spectrally visible release bursts made it impossible to acoustically measure C closure. Consistent with the prediction, the results of a linear mixed model of voiceless C closure duration on N duration showed a highly significant correlation, $R^2 = 0.48$ ($t = 9.50$, $p < 0.0001$).

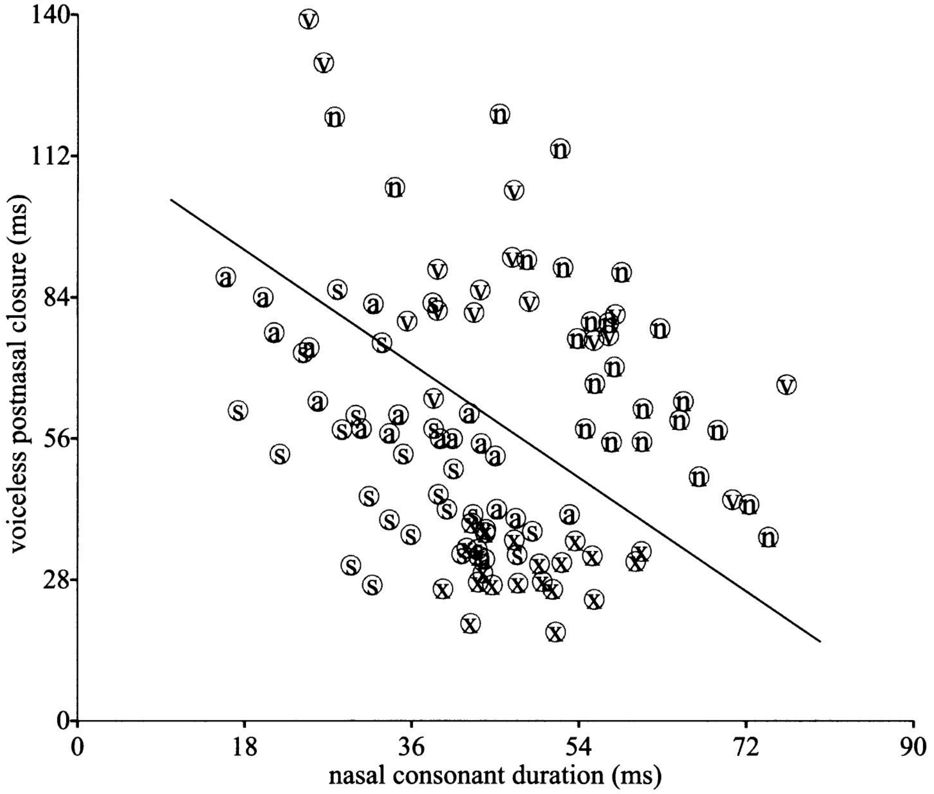

FIGURE 5. Scatter plot showing the inverse relation between nasal consonant duration and duration of postnasal oral closure for words with /Vnt/ sequences produced by Speakers A, N, S, V, and X. Regression line corresponds to R^2 from the statistical model described in the text.

To summarize, temporal measures of nasal consonants and nasal portions of vowels in English VNC sequences provide evidence of covariation in production between the coarticulatory source and its effects. Furthermore, the relation between nasal consonant duration and duration of the postnasal oral stop suggests that the covariation involves velum and alveolar closure gestures that are fairly stable in duration but are more tightly aligned (i.e. overlap more) in some productions than in others.

The duration of the velum gesture, however, is not absolutely constant within or across voicing contexts. The across-context measures of the temporal consequences of coda voicing in this study show that the schematic representation in Fig. 1, in which gestural durations but not their alignment remain absolutely constant across voicing contexts, is an oversimplification. Rather, the vowel, velum, and alveolar constriction gestures are all moderately longer (as measured acoustically) when the coda is voiced. The average increase across speakers from voiceless to voiced contexts is 24% for vowel duration, 32% for the acoustic duration of nasalization ($\tilde{V}$ + N), and 19% for alveolar closure (N + C_{stop}) duration. Thus, at least across contexts, the temporal magnitude of the velum gesture appears to stretch or shrink very roughly in proportion to the magnitude of the other gestures in the syllable. (Although on average the velum gesture increased more than the others in duration, this pattern does not hold for the productions of all speakers.) It is expected that more extreme overall duration differences, such as those induced by speaking rate, would give rise to yet greater variation in the temporal extent of the velum gesture.

Clearly, though, the 20–30% increase in gestural durations from voiceless to voiced contexts is small in comparison to the 125% increase in N duration from $VNC_{voiceless}$ to VNC_{voiced}. This substantial segmental difference is thus largely the result of the different temporal ALIGNMENT of the velum and oral consonant constriction gestures in these contexts. Early onset of the velum gesture in prevoiceless position can be attributed to a combination of auditory and aerodynamic factors. Voiceless obstruents have high-intensity noise cues, and the pressure buildup needed for these cues is not compatible with a lowered velum, likely leading speakers to resist velic leakage to retain the voiceless percept (Ohala & Ohala 1991, 1993). In contrast, voicing is facilitated by nasal leakage until complete velum closure is achieved; it is facilitated as well as by continued raising of the velum after closure, which expands the oral cavity (Hayes & Stivers 2000, Solé 2007).

2.2. COVARIATION LINKED TO OTHER PHONETIC CONTEXTS. While the main focus of the production investigations in this article is the influence of coda voicing on timing in VNC sequences, the hypothesis that $\tilde{V}$ and N covary is a more general prediction. Consequently, there should also be evidence of a stable velum gesture in other contexts in which nasal consonants are relatively short or long. Two such contexts are coda manner and vowel length.

In VNC sequences, the manner of the C influences N duration, albeit in different ways in different languages. Busà (2007) studied airflow patterns in /VnF/ (F = voiceless fricative) and /Vnts/ productions by speakers of Northern Italian, Central Italian, and American English. She found that N duration was shorter before (voiceless) fricatives (/VnF/) for speakers of both dialects of Italian, whereas N duration was shorter before (voiceless) stops (/Vnts/) for American English speakers' productions. Consistent with the predictions, however, speakers of all three language varieties nasalized vowels more extensively in the context with the shorter nasal consonants (that is, longer vowel nasalization in /VnF/ sequences for Italian and in /Vnts/ sequences in American English).[4]

[4] Busà's findings for American English are further substantiated by the acoustic measures from this study. Analysis of the duration measures in Fig. 3 according to stop versus fricative contexts (rather than voiceless versus voiced) reveals that nasals are shorter, and vowels more nasalized, in prestop than in prefricative position, although this generalization is stated tentatively for these results given that stops were more heavily represented than fricatives in this dataset.

Vowel length can also systematically influence the duration of a following nasal consonant. In many languages, shorter vowels cooccur with longer postvocalic consonants (e.g. Broselow et al. 1997 for Levantine Arabic, Pind 1999 for Icelandic, van Leyden 2002 for Norwegian, Yu 2008 for Washo). Thai exhibits this cooccurrence for nasal coda consonants. Onsuwan (2005), for example, found that nasal codas were 60% longer after phonologically short than after phonologically long vowels (see also Abramson 1962, Roengpitya 2001). Additionally, Onsuwan's acoustic measures of anticipatory vowel nasalization in CV(:)N sequences produced by Thai speakers showed the by now familiar inverse relation to N duration: vowel nasalization was temporally less extensive before longer N. For Thai, the temporal stability of the lowered velum gesture in the syllable rhyme is such that there was no significant difference in total nasalization in V:N compared to VN: contexts.

Nonlow tense and lax vowels in English also systematically differ in duration. Sefton (2005) analyzed the temporal characteristics of American English CVN words, where V was one of relatively long tense /i e/ or shorter lax /ɪ ɛ/ and N was /m/ or /n/ (e.g. *deem*, *dim*, *Dane*, *den*). Acoustic measures showed that N was significantly longer after lax /ɪ ɛ/ than after tense /i e/. Correspondingly, the duration of vowel nasalization was significantly shorter for the lax than the tense vowels. Although the Ṽ and N trade-off was not perfect, with total nasalization (Ṽ + N) in VN sequences being on average 21 ms longer in tense than in lax vowel contexts, the predicted covariation held for each of the five speakers whose productions were investigated.

2.3. Assessment of covariation in production. The production hypothesis stated in the introduction postulates that a precursor to the historical process of phonologization of vowel nasalization—a process whereby the lowered velum position associated with the consonant constriction is reinterpreted as being associated with the vowel—is a stage of temporal covariation between the nasal consonant and its coarticulatory effects. The experimental data were predicted to provide evidence of a roughly constant-sized lowered velum gesture that was variably aligned relative to the oral articulators (as in Fig. 1). The new findings reported here show that there is much variation in the timing of the velum gesture that is not accounted for by the hypothesis of covariation. Nonetheless, covariation consistently emerges in these data and in nearly all of the relevant data in the literature. In general, the phonetic contexts that give rise to systematic differences in nasal consonant duration also give rise to inversely related differences in the extent of coarticulatory vowel nasalization. A possible exception to this pattern emerges in x-ray microbeam data for an American English speaker's productions of *lent* and *lend* (Vaissière & Amelot 2008), where velum lowering in both words coincided with release of [l], resulting in a longer velum gesture in *lend* than in *lent* (albeit with more rapid velum lowering in *lent*). More data would be needed to determine whether these results are exceptional or whether this speaker, like three of the original nine speakers recorded here, systematically nasalizes all vowels in VNC sequences.

An account of articulatory covariation should explain both why certain contexts trigger N shortening and why N shortening is accompanied by realignment of the velum gesture as opposed to a temporally less extensive velum gesture. It was suggested above that the impetus for the early velum gesture—and consequent short N duration—in prevoiceless contexts might be a combination of auditory and aerodynamic factors. These same factors are likely responsible for the early onset of velum lowering in prefricative contexts, inasmuch as both obstruent contexts require relatively intense noise cues. Moreover, much (although not all) of the evidence of prefricative nasal consonant shortening involves voiceless fricatives (Busà 2007 for Italian, Hattori et al. 1958 for Japanese; see also §6.1), which are characterized by particularly high-intensity noise. Thus, while manner and voicing appear to interact with nasality differently in different languages—a not surprising outcome given language-specific coarticulatory patterns for nasalization (Cohn 1990, Solé 1995, Beddor & Krakow 1999, Manuel 1999)—both of their influences on the velum gesture may stem from the constraints imposed by the requirement of intense turbulence (e.g. Ohala & Ohala 1993). In contrast, the factors underlying nasal consonant shortening before obstruents would appear to be distinct from those underlying shortening after long vowels. In the latter context, nasal coda shortening after long vowels does not involve early velum raising relative to an oral consonantal constriction, but rather involves shortening of that constriction without concomitant shortening of the lowered velum gesture. (Oral-constriction shortening reduces syllable duration and maintains a more nearly constant duration or weight for stressed syllables; Broselow et al. 1997.)

Because a strategy that would seem to be available to speakers would be to shorten N in these contexts without realigning the velum gesture, the relative stability of the velum gesture still requires explanation. Focusing on the VNC_{voiced} and $VNC_{voiceless}$ contexts of particular interest here, a plausible account of the across-context pattern would seem to be that speakers are maintaining roughly the same proportional gestural durations across contexts. Proportional duration is not, however, obviously responsible for covariation within a voicing context. Although within-context covariation is a weak pattern in these data that must be interpreted cautiously, a possible account of both the within- and across-context patterns is that speakers purposefully maintain a somewhat stable velum gesture so that, as N shortens, listeners will still have sufficient information about nasality. Such an account is consistent with the central tenet of Lindblom's (1990) H&H theory that speakers adjust their productions in keeping with their estimation of listeners' informational needs. The account, however, differs from the usual enhancements cited by H&H theorists in that providing additional information for listeners results not in reduced coarticulation but rather greater coarticulation.[5] Currently, the data needed to resolve these or other alternatives are not available, although an ongoing study in our laboratory is investigating the effects of listener-directed (clear) speech on nasal and oral airflow patterns in voiced and voiceless contexts.

A velum gesture that is variably aligned relative to the oral configuration and results in covariation between N and Ṽ has implications for the perception of nasals and nasalization, and potentially for a listener's phonological grammar. The focus of the article is now shifted to the listener's interpretation of covariation between a coarticulatory source and its effects.

3. Perceived equivalence between coarticulatory source (N) and effect (ṽ). A fundamental task of the listener is to assign a linguistic message to the input acoustic signal, that is, to determine the speaker's intended utterance. While the lis-

[5] The theoretical approach to perception of variation adopted here shares with H&H theory the notion that listeners aim at 'making sense of' variability (Lindblom 1996:1684). With respect to perception of coarticulatory variation, however, the current approach differs from H&H theory in that a decrease in coarticulation is not predicted to be the intended result in listener-directed speech. The results of several listener-directed or clear-speech studies bear on these different approaches. Consistent with H&H theory, studies consistently find less reduction in clear speech than in more casual speech (see, for example, Lindblom 1990 and 1996 for discussion). In contrast, several recent studies have failed to find less coarticulation in clear speech (e.g. Matthies et al. 2001, Bradlow 2002, Scarborough 2004; see Beddor 2009 for more discussion).

tener's efforts are often characterized as being largely successful 'despite' variation in the signal (e.g. Ladefoged 2001:251, Tatham & Morton 2006:42), I approach the perceptual process as one that takes advantage of the variation afforded by the acoustics. As is well known, acoustic variation provides sociolinguistic as well as phonetic-phonological information (e.g. Labov 1966, 2007, Lindblom et al. 1995, Pierrehumbert 2001, among others), although it is the latter that is explored here.

Suppose the input signal is a production of English *bent* with a short nasal consonant and extensive vowel nasalization. The listener must determine whether the speaker's intention was /bɛt/ or /bɛnt/ or, especially if the listener is also a learner of English, /bɛ̃t/. In actuality, of course, the listener's task is more complex, since the listener is potentially also making decisions about, for example, coda voicing (/bɛnt/ or /bɛnd/) and vowel quality (especially /ɛ/ or /æ/). (Both of these judgments are partly informed by the flanking nasal, as shown in Raphael et al. 1975 and Krakow et al. 1988.) A listener making the determination among CVC, CVNC (voiced or voiceless coda), and (for learners) CṼC will, in the course of a conversation with that speaker, hear a range of ṼN variants, even within a voicing context.

The listener presumably formulates a phonological representation of *bent* that encompasses the range of variants. I hypothesize that listeners use the COVARYING information in the signal in determining the acoustic properties that access this representation, and quite possibly in determining the representation itself. Specifically, that nasalization across the ṼN sequence provides acoustic evidence of a relatively stable lowered velum gesture leads me to postulate that at least some listeners will attend to 'nasal', rather than /ɛ̃/ or /n/, as the critical information differentiating, for example, *bent* and *bet* (or *bend* and *bed*). English listeners who attend primarily to 'nasal' in the syllable rhyme should, in an experimental setting, be insensitive to whether nasality is primarily on the vowel or the consonant and should instead treat these two sources of nasality as perceptually equivalent. If these listeners have arrived at 'nasal' as the distinctive property differentiating *bent* and *bet*—that is, if this property's perceptual weight is mirrored in the phonological representation—such listeners would be accurate perceivers of the input signal, yet would have arrived at a phonological representation that differs from that of a speaker who intended /bɛnt/. (See §5.5 and §6 for fuller discussion.)

Two experiments, both using the trading-relations paradigm, were conducted to test the hypothesis of perceptual equivalence. In the trading-relations paradigm, two acoustic properties that typically cooccur in the distinction between target speech sounds (e.g. F2 transition and release burst properties in differentiating stop place of articulation) are independently varied to assess whether a change in one property can be offset by an opposing change in the other, yielding a constant phonetic percept (Pisoni & Luce 1987). A successful trade-off demonstrates perceptual coherence among the relevant parts of the signal. Here, this paradigm was extended to test the coherence and equivalence of coarticulatory source and effect. Listeners were presented with ṼN stimuli in which the duration of the nasal consonant and the temporal extent of vowel nasalization were covaried. The first experiment (§4) tested the basic prediction of perceptual equivalence between Ṽ and N. The second experiment (§5) tested the more specific prediction that, because English listeners are exposed to different ṼN patterns in voiceless and voiced contexts, their patterns of perceptual equivalence would likewise be context-dependent.

4. PERCEIVED EQUIVALENCE BETWEEN Ṽ AND N IN ṼNCV STIMULI. The current approach to coarticulatory source and effect predicts that a perceptual consequence of articulatory covariation between Ṽ and N is that listeners are relatively insensitive to differences in the duration of N or of the nasal portion of the vowel, and are more sensitive to differences in total nasalization (Ṽ + N) across the syllable rhyme. This prediction is first tested for a context in which N does not become extremely short in production. That is, I wanted a context in which Ṽ and N covary in natural productions, but not to the extent that N is sometimes absent in production and Ṽ is the only manifestation of nasality. (The latter situation is tested in §5.)

4.1. Methodology. The original stimuli were natural productions of [gaba] and [gãma], with coarticulatory nasalization of the initial stressed vowel, produced by a female native speaker of Botswanan Ikalanga (see n. 6). Despite not being English productions, the stimuli sound like perfectly good English sequences (albeit nonsense items) and the listeners who were queried after testing reported that they thought the items were produced by a native English speaker. Waveform editing techniques were applied to the original utterances to create a [b] – [mb] continuum and a vowel nasalization continuum. The resulting stimuli were varying forms of [gã(m)ba].

The [b] – [mb] continuum consisted of nine steps ranging from 0 to 70 ms of [m] murmur and, conversely, 90 to 20 ms of postnasal [b] closure. That is, each increment of [m] involved same-sized decrements in [b]. This manipulation is consistent with medial [b] and [mb] in natural speech, in which the postnasal oral closure of [VmbV] is substantially shorter than the oral closure of [VbV] (in keeping with a single labial gesture; Browman & Goldstein 1986). The first four increments of [m] involved adding one nasal period (6 ms) and subsequent increments added two nasal periods (11–12 ms), excised from [m] onset to offset. Step sizes were smaller toward the [b] endpoint in keeping with just noticeable differences being smaller at shorter durations. The [m] portion of the stimuli was taken from original [gãma] rather than [gãmba] to ensure that all consonantal pitch pulses were nasal.

To create the vowel nasalization continuum, portions of oral [a] from [gaba] were replaced with same-sized portions of nasal [ã] from [gãma], yielding a four-step continuum ranging from 0% (oral vowel) to 52% nasalized. However, only two steps, 20% (5 nasal pulses = 30 ms) and 52% (13 nasal pulses = 76 ms) nasalized, were used in the tests reported here.[6] The splicing procedure included two types of manipulations. First, to ensure that the entire vocalic portion extracted from [gãma] was nasalized, three noncontiguous pitch pulses near the end (i.e. closest to [m]) of that vowel were repeated. Second, minor adjustments to the amplitude contour were made at the locations of the splices. (No fundamental or formant frequency adjustments were made, although the tokens were selected from a larger set to provide a close match for these spectral characteristics.) There were no audible discontinuities in the cross-spliced stimuli. Vocalic and nasal murmur portions were orthogonally varied and embedded in [g__a], for a total of eighteen [gã(m)ba] variants (nine [b] – [mb] durations × two degrees of vowel nasalization) tested in the current study. For all stimuli, medial (N)C

[6] The study reported here is part of a larger cross-language study (including Botswanan Ikalanga) testing listeners' perception of the relation between Ṽ and N. This larger study investigated carryover as well as anticipatory vowel nasalization. Because speakers of these languages differ in the extent to which vowels are nasalized, I used a wider range of Ṽ step sizes, and a wider range of ṼN pairing, than would have been used if only English were under investigation. Thus listeners were tested on a relatively large set of conditions. All results reported here were obtained in a single testing session, although the entire series of tests required two sessions.

closure duration was held constant at 90 ms and initial vowel duration (V + Ṽ portions) was 145 ms.

Stimuli were paired in same-different discrimination trials in a variant of a task developed by Fitch and colleagues (1980; see also Best et al. 1981). In the 'same' pairs, each stimulus was paired with itself. 'Different' pairs were of three types, as shown in Table 2. All 'different' pairs involved a four-step difference in [m] duration (and, correspondingly, in the duration of the [b] closure), resulting in five pairings across the [b] – [mb] continuum. Because continuum step sizes were smaller toward the [b] endpoint, the difference in [m] duration between pair members increased across the five pairings (the rows in Table 2), but the same difference holds for all three 'different' pair types (the columns). NASAL-ONLY pair members, [gã$m_S$ba] – [gã$m_L$ba] (where [m_S] = shorter and [m_L] = longer N), differed in N duration but not vowel nasality. DIFFERENT-NASALITY pairings, [g$ã_S m_S$ba] – [g$ã_L m_L$ba] (where [$ã_S$] = less nasalized and [$ã_L$] = more nasalized V), differed in Ṽ and N, with one pair member having slight vowel nasalization and shorter N and the other heavier nasalization and longer N. SIMILAR-NASALITY pairings, [g$ã_L m_S$ba] – [g$ã_S m_L$ba], also differed in Ṽ and N but with the opposite pairing of these portions of the signal so that total nasalization was more nearly constant across the ṼN sequence. A spectrographic illustration of the durations of Ṽ and N portions, as well as of the inverse relation between [m] and [b] durations, is given in Figure 6 for one different-nasality pair (top) and one similar-nasality pair (bottom) from the series.

	NASAL-ONLY	DIFFERENT-NASALITY	SIMILAR-NASALITY
	$ã_S m_S$ – $ã_S m_L$	$ã_S m_S$ – $ã_L m_L$	$ã_L m_S$ – $ã_S m_L$
Pair 1,5	$ã_{30ms}m_{0ms}$ – $ã_{30ms}m_{24ms}$	$ã_{30ms}m_{0ms}$ – $ã_{76ms}m_{24ms}$	$ã_{76ms}m_{0ms}$ – $ã_{30ms}m_{24ms}$
Pair 2,6	$ã_{30ms}m_{6ms}$ – $ã_{30ms}m_{35ms}$	$ã_{30ms}m_{6ms}$ – $ã_{76ms}m_{35ms}$	$ã_{76ms}m_{6ms}$ – $ã_{30ms}m_{35ms}$
Pair 3,7	$ã_{30ms}m_{12ms}$ – $ã_{30ms}m_{46ms}$	$ã_{30ms}m_{12ms}$ – $ã_{76ms}m_{46ms}$	$ã_{76ms}m_{12ms}$ – $ã_{30ms}m_{46ms}$
Pair 4,8	$ã_{30ms}m_{18ms}$ – $ã_{30ms}m_{58ms}$	$ã_{30ms}m_{18ms}$ – $ã_{76ms}m_{58ms}$	$ã_{76ms}m_{18ms}$ – $ã_{30ms}m_{58ms}$
Pair 5,9	$ã_{30ms}m_{24ms}$ – $ã_{30ms}m_{70ms}$	$ã_{30ms}m_{24ms}$ – $ã_{76ms}m_{70ms}$	$ã_{76ms}m_{24ms}$ – $ã_{30ms}m_{70ms}$

TABLE 2. Nonidentical pairs for the same-different discrimination task with [gã(m)ba] stimuli. (Order of pair members was counterbalanced across the multiple repetitions of each pair type in the test sequence.)

Listeners were twenty-eight native speakers of American English, all undergraduate students who were paid for their participation. They were seated in front of a laptop computer in a sound-attenuated room and heard the stimuli presented over headphones. For each trial, they selected 'same' or 'different' from the computer display by a mouse click. A short (several item) session that familiarized listeners to a randomly selected subset of the stimuli was followed by the test session, in which listeners heard, in random order, four instances of each same or different trial. Thus for the test items reported here (see n. 6), there were 132 trials (60 different (15 pair types × 4 repetitions) + 72 same (18 pair types × 4 repetitions)). Order of the pair members in the different trials was counterbalanced.

4.2. PREDICTIONS. Corresponding different- and similar-nasality trials (i.e. in a given pair row in Table 2) have the same-size acoustic differences between pair members: in both, one pair member has [$ã_S$] and the other [$ã_L$] and one pair member has [m_S] and the other [m_L]. Nasal-only trials, which hold vowel nasality constant ([$ã_S$]), have smaller acoustic differences. If listeners attend primarily to the acoustic characteristics of the stimuli, they would be expected to have greatest difficulty with the nasal-only pairs.

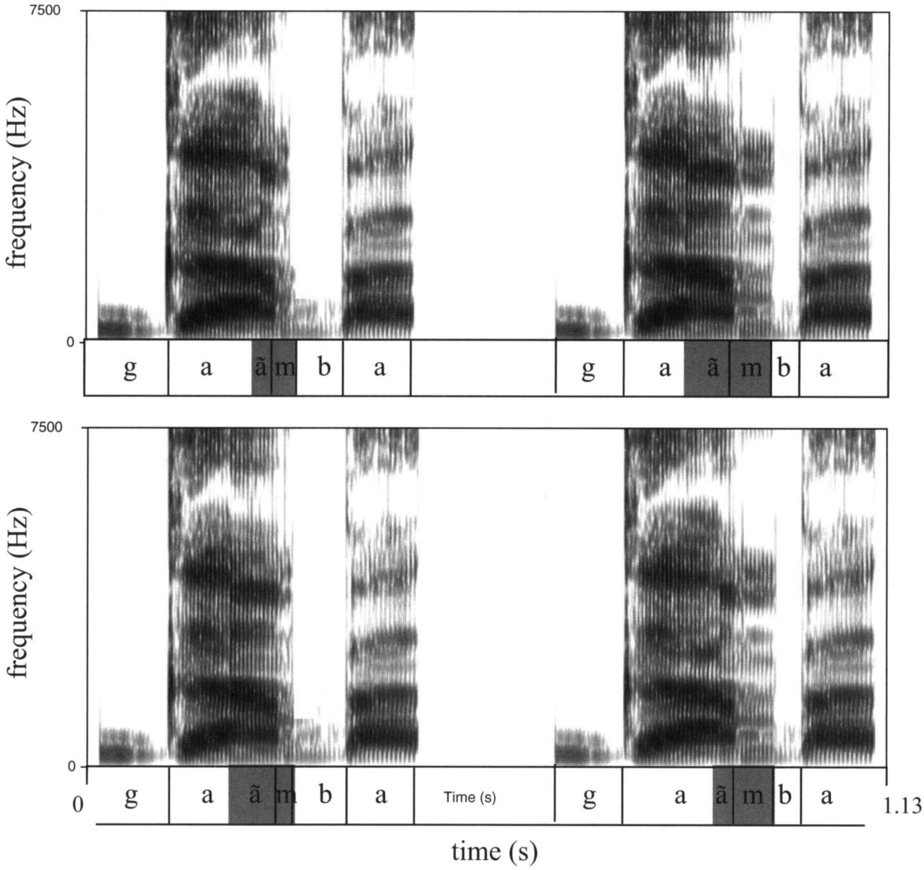

FIGURE 6. Illustrative different-nasality (top) and similar-nasality (bottom) pairs. The shaded portions of the transcription grids indicate the nasal (Ṽ and N) portion of each pair member.

The experimental model of perceptual equivalence, however, predicts that listeners should be poor discriminators of similar-nasality trials, despite the relatively large acoustic differences between their pair members. Listeners are expected to be relatively insensitive to whether nasality occurs primarily during the vowel portion (e.g. [gã$_{76ms}$m$_{18ms}$ba] from Pair 4,8) or the consonant portion (e.g. [gã$_{30ms}$m$_{58ms}$ba]) of ṼN. They are predicted to attend more to differences in total nasalization (Ṽ + N) in the rhyme, resulting in a high percentage of incorrect 'same' responses to similar-nasality trials. A strong version of the perceptual-equivalence hypothesis predicts that listeners would find similar-nasality trials even more difficult to discriminate than the acoustically less distinct nasal-only trials. Thus, although the size of the acoustic differences between pair members is different-nasality = similar-nasality > nasal-only, the predicted order of discriminability (again, within a strong interpretation of equivalence), from most to least accurate, is different-nasality > nasal-only > similar-nasality.

4.3. RESULTS AND DISCUSSION. In this same-different task, listeners' responses to the identical (same) trials were overall 78% correct, while their responses across the nonidentical (different) trials were 58% correct. Thus, as expected, listeners had more difficulty with the nonidentical trials. The prediction is that discriminability of nonidentical trials will depend on trial type, and the results uphold the predicted order of discrimination difficulty: listeners correctly responded ‘different’ 72% of the time to different-nasality trials, 60% to nasal-only, and 41% to similar-nasality. (Chance level is 50%.)

Figure 7 gives the percent correct responses to each of the five stimuli within each trial type, pooled across twenty-seven listeners. (Stimulus pair numbers refer to Table 2.) The results of one listener, who responded ‘same’ to both identical and nonidentical trials with equal frequency, were excluded due to apparent difficulty with the task. As shown in the figure, the difference in discriminability between nonidentical trial types holds across the entire [m] – [mb] continuum. The results of a multivariate repeated-measures ANOVA showed the main effect of trial type to be highly significant ($F(2,25) = 51.62$, $p < 0.0001$). Posthoc pairwise comparisons similarly revealed that each trial type was significantly different from each of the other two ($p < 0.0001$ for each comparison). The same pattern of results held for analyses in which the raw data were transformed into d' scores using Macmillan and Creelman’s (1991:147) independent-observation model ($F(2,25) = 45.62$, $p < 0.0001$, with the same posthoc outcome).[7]

This overall pattern was also representative of the findings of individual listeners. Different-nasality trials were more discriminable than similar-nasality trials for all but one listener who discriminated them equally well. Nasal-only trials were more discriminable than similar-nasality for twenty-two of the twenty-seven listeners. The general decline in discriminability with increasing [m] duration (from left to right in Fig. 7) is likely due to psychoacoustic factors, with temporal resolution and hence discrimination accuracy decreasing with longer durations (despite the moderately larger step sizes at the longer durations).

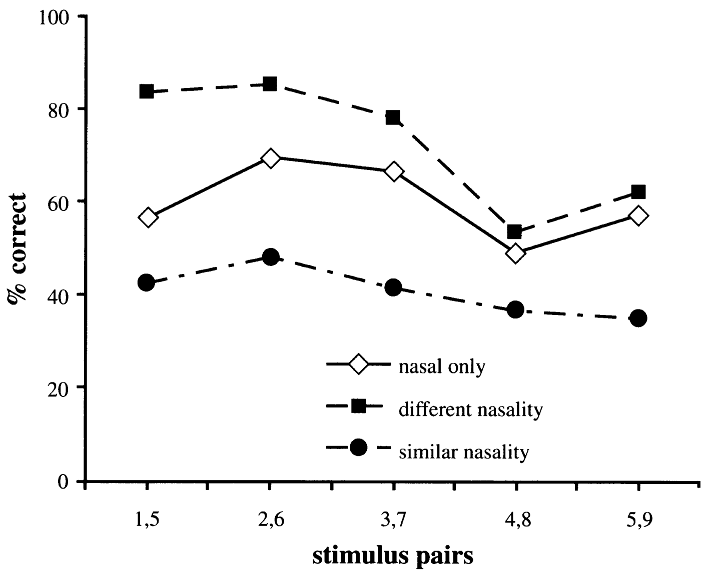

FIGURE 7. Pooled responses of twenty-seven American English-speaking listeners to three types of discrimination trials: nasal-only [gãm$_S$ba] – [gãm$_L$ba]), different nasality ([gã$_S$m$_S$ba] – [gã$_L$m$_L$ba]), and similar nasality ([gã$_L$m$_S$ba] – [gã$_S$m$_L$ba]).

[7] In discrimination testing, we are interested in listeners’ sensitivity to stimulus (or signal) differences. Listeners’ responses are influenced by sensitivity and bias, according to signal detection theory, with bias being the criterion a given listener is adopting to respond ‘same’ or ‘different’. Unlike the more commonly reported percent correct analysis, d' takes into account both hits (detection of different stimuli as different) and false alarms (responses to same stimuli as different), and is independent of the listener’s criterion.

Thus listeners had more difficulty discriminating pairs whose members were similar in total nasalization across the ṼN sequence than they had discriminating (nasal-only) pairs whose members were acoustically more similar. Moreover, listeners' poor performance on similar-nasality pairs held for all pairs of that type (i.e. pairs represented by circles in Fig. 7). Indeed, discrimination was significantly BELOW chance on similar-nasality trials ($t(26) = 2.3, p < 0.015$), indicating that listeners were not simply uncertain as to whether the paired stimuli sounded the same or not. Rather, they were remarkably insensitive to whether most of the nasalization in a ṼN sequence was on the vowel or the consonant, perceptually trading these two sources of nasality. Variation in duration of vowel nasalization interfered with discrimination (relative to nasal-only trials) when that variation was offset by corresponding changes in the duration of the nasal consonant.

I postulated that the perceptual consequence of covariation in production between the duration of a coda nasal and the temporal extent of its anticipatory effects would be that listeners would attend more to the acoustics of the lowered velum gesture than to the precise alignment of this gesture relative to the oral articulators. The discrimination results show that listeners treat vocalic and consonantal nasality as perceptually equivalent and provide strong evidence of the predicted pattern. The historical implications of perceptual equivalence are considered in §6. I turn first to a more detailed test of equivalence that assesses the generality of the finding across contexts that differ in timing of the velum gesture.

5. PERCEIVED EQUIVALENCE BETWEEN Ṽ AND N IS CONTEXT-DEPENDENT FOR SOME LISTENERS. The production data in §2.1 showed covarying realizations of [ɛ̃] and [n] in words of the form $\mathrm{VNC_{voiced}}$ and $\mathrm{VNC_{voiceless}}$. Under the perceptual-equivalence hypothesis, listeners hearing these words should be more sensitive to differences in nasalization across [ɛ̃n] than to differences in specifically [ɛ̃] or [n]. At the same time, the production data also showed that velum lowering generally begins earlier in $\mathrm{VNC_{voiceless}}$ words, resulting in longer vowel nasalization and shorter nasal consonants. The following experiment tests whether coda voicing influences listeners' perceptual judgments of covarying [ɛ̃] and [n]. This question is of particular importance to the goal of experimental investigation of phonologization of vowel nasalization because, historically, VN > Ṽ is more likely to develop when N is followed by a voiceless, as opposed to a voiced, obstruent (e.g. Hajek 1997; see §6 for discussion).

5.1. METHODOLOGY. As in the previous experiment, nasal consonant duration and vowel nasalization duration were orthogonally varied in a trading-relations paradigm to assess the equivalence of coarticulatory source and effect. The original stimuli were natural utterances of *bet*, *bed*, and *mend* produced by a female native speaker of American English and edited to create consonant and vowel continua, resulting in two series, [bɛt] – [bɛ̃nt] and [bɛd] – [bɛ̃nd].

The nasal consonant continuum consisted of ten steps of [n] murmur, excised from *mend*. The first four increments increased by one nasal period (6 ms) and the last five increments by two nasal periods (12 ms), for a total [n] duration range of 0–85 ms. Continuum members were spliced into [bV_t] and [bV_d] carriers by incrementally shortening the [t] and [d] closures from *bet* and *bed*, respectively, such that each 6 or 12 ms increment of [n] replaced 3 or 6 ms, respectively, of [t] or [d] closure.[8] The three-

[8] That the [b] – [mb] series in the earlier experiment replaced equal amounts of [b] closure with [m] closure, but the [t] – [nt] and [d] – [nd] series in this experiment replaced at a ratio of 1 : 2, parallels measures of natural productions: intervocalic [m] and [mb] have nearly the same duration, while coda [nd] and [nt] tend to be longer than coda [d] and [t], respectively.

step oral-to-(partially) nasal vowel continuum was created by cross-splicing portions of [ε] from *bed* and [ε̃] from *mend*. Prior to cross-splicing, [ε] was shortened (by removing several noncontiguous pitch pulses) to a value that fell between durations appropriate for *bed* and (shorter) *bet*. For the nasalized portion of the vowel, *mend* rather than *bent* or *bend* was chosen to ensure that the entire excised portion was nasalized. ([n] was extracted from the same stimulus to preserve naturalness.) The vowel continuum ranged from oral (185 ms of [ε]) to 33% nasalized (124 ms from the onset portion of [ε] followed by 61 ms from the final portion of [ε̃]) to 66% nasalized (61 ms of [ε] + 124 ms of [ε̃]). For all stimuli, the initial [b] was from *bed* so that the voiceless [bεt] – [bε̃nt] and voiced [bεd] – [bε̃nd] series would be identical with the exception of the postnasal closure and the coda release burst. Spectrographic representations of the oral and most nasal endpoint stimuli for each of the series are given in Figure 8.

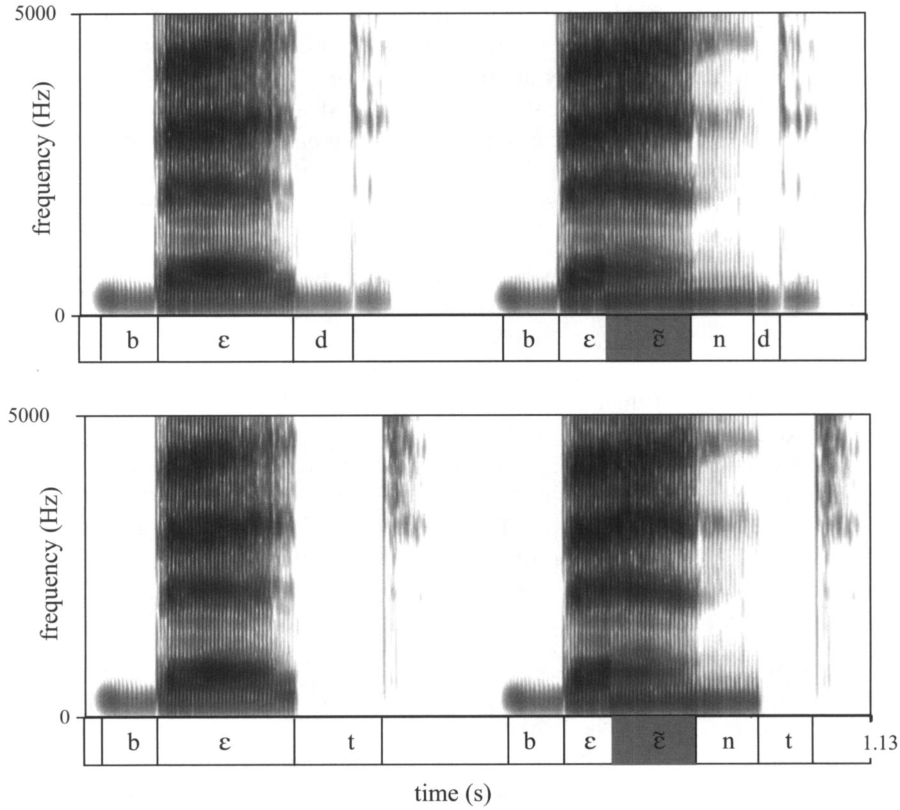

FIGURE 8. Oral and nasal endpoints for *bed–bend* (top) and *bet–bent* (bottom) stimuli. The shaded portions of the transcription grids indicate the region of vowel nasalization.

The resulting sixty stimuli (10 [n] durations × 3 degrees of vowel nasalization × 2 voicing contexts) were presented to listeners in two types of perceptual tests, discrimination and identification. The same-different discrimination task again paired stimuli in three types of trials: nasal-only, different-nasality, and similar-nasality. The trials of primary interest here are those trials that mirror the task used in the earlier experiment, in which all vowels have some nasalization. Nasal-only pairings were [bε̃n$_{S}$t] – [bε̃n$_{L}$t] and [bε̃n$_{S}$d] – [bε̃n$_{L}$d] (vowel nasalization = 33%), different-nasality pairings were [bε̃$_{S}$n$_{S}$t] – [bε̃$_{L}$n$_{L}$t] and [bε̃$_{S}$n$_{S}$d] – [bε̃$_{L}$n$_{L}$d] ([ε̃$_{S}$] = 33% and [ε̃$_{L}$] =

66%), and similar-nasality pairings were [b$\tilde{\varepsilon}_L n_S$t] – [b$\tilde{\varepsilon}_S n_L$t] and [b$\tilde{\varepsilon}_L n_S$d] – [b$\tilde{\varepsilon}_S n_L$d]. For all trials, the difference between [n_S] and [n_L] was a constant 36–37 ms.[9] Table 3 provides details of the stimulus pairs. Listeners heard eight instances of each nonidentical trial (counterbalanced for order of pair members) and five of each identical trial.

	NASAL-ONLY	DIFFERENT-NASALITY	SIMILAR-NASALITY
	$\tilde{\varepsilon}_S n_S$ – $\tilde{\varepsilon}_S n_L$	$\tilde{\varepsilon}_S n_S$ – $\tilde{\varepsilon}_L n_L$	$\tilde{\varepsilon}_L n_S$ – $\tilde{\varepsilon}_S n_L$
Pair 1	$\tilde{\varepsilon}_{33\%} n_{0ms}$ – $\tilde{\varepsilon}_{33\%} n_{36ms}$	$\tilde{\varepsilon}_{33\%} n_{0ms}$ – $\tilde{\varepsilon}_{66\%} n_{36ms}$	$\tilde{\varepsilon}_{66\%} n_{0ms}$ – $\tilde{\varepsilon}_{33\%} n_{36ms}$
Pair 2	$\tilde{\varepsilon}_{33\%} n_{12ms}$ – $\tilde{\varepsilon}_{33\%} n_{48ms}$	$\tilde{\varepsilon}_{33\%} n_{12ms}$ – $\tilde{\varepsilon}_{66\%} n_{48ms}$	$\tilde{\varepsilon}_{66\%} n_{12ms}$ – $\tilde{\varepsilon}_{33\%} n_{48ms}$
Pair 3	$\tilde{\varepsilon}_{33\%} n_{24ms}$ – $\tilde{\varepsilon}_{33\%} n_{60ms}$	$\tilde{\varepsilon}_{33\%} n_{24ms}$ – $\tilde{\varepsilon}_{66\%} n_{60ms}$	$\tilde{\varepsilon}_{66\%} n_{24ms}$ – $\tilde{\varepsilon}_{33\%} n_{60ms}$
Pair 4	$\tilde{\varepsilon}_{33\%} n_{36ms}$ – $\tilde{\varepsilon}_{33\%} n_{72ms}$	$\tilde{\varepsilon}_{33\%} n_{36ms}$ – $\tilde{\varepsilon}_{66\%} n_{72ms}$	$\tilde{\varepsilon}_{66\%} n_{36ms}$ – $\tilde{\varepsilon}_{33\%} n_{72ms}$
Pair 5	$\tilde{\varepsilon}_{33\%} n_{48ms}$ – $\tilde{\varepsilon}_{33\%} n_{85ms}$	$\tilde{\varepsilon}_{33\%} n_{48ms}$ – $\tilde{\varepsilon}_{66\%} n_{85ms}$	$\tilde{\varepsilon}_{66\%} n_{48ms}$ – $\tilde{\varepsilon}_{33\%} n_{85ms}$

TABLE 3. Nonidentical pairs for the same-different discrimination task with [b$\tilde{\varepsilon}$(n)t] and [b$\tilde{\varepsilon}$(n)d] stimuli. (Order of pair members was counterbalanced across the multiple repetitions of each pair type in the test sequence.)

Because listeners in natural conversational settings are exposed to substantial variation in the temporal extent of vowel nasalization, an additional discrimination test was conducted to determine whether changes in [n] duration are less discriminable as vowel nasalization increases. In this task, the difference between [n_S] and [n_L] was again a constant 37–38 ms, but nasal-only pairings tested all degrees of vowel nasalization, although a given pairing held vowel nasalization constant (e.g. [b$\varepsilon_{0NAS} n_S$t] – [b$\varepsilon_{0NAS} n_L$t], [b$\tilde{\varepsilon}_{33\%NAS} n_S$t] – [b$\tilde{\varepsilon}_{33\%NAS} n_L$t]). Listeners heard six instances of each nonidentical trial and five of each identical trial.[10]

The identification test was a four-choice (*bet*, *bent*, *bed*, *bend*) task consisting of a randomly ordered presentation of nine instances of each of the sixty stimuli. The goal of the identification task was to verify that the perceptual trade-off between the nasal consonant and coarticulatory vowel nasalization observed in discrimination also holds for listeners' labeling judgments of these stimuli.

Thirty-two native American English-speaking undergraduate students were paid for their participation. The same testing conditions as described in §4.1 were used. In the main discrimination test, trials were blocked according to coda voicing (with order counterbalanced across listener groups). Presentation was not blocked in the discrimination test in which nasal-only pairs tested all degrees of vowel nasalization. Testing took place in two listening sessions of .75–1.25 hours each.

5.2. PREDICTIONS. Recall that the experimental model of perceptual equivalence predicts that listeners will be relatively insensitive to whether nasality is primarily on $\tilde{V}$ or N, and will instead attend primarily to differences in total nasalization ($\tilde{V}$ + N). This prediction is based on acoustic evidence of temporal covariation between $\tilde{V}$ and N, and the hypothesis that listeners might focus on 'nasal' rather than on its more

[9] Recall that, along the [n] continuum, the first four increments were 6 ms and the last five were 12 ms. To achieve a constant [n_S] – [n_L] difference, two stimuli ([n] = 6 ms and [n] = 18 ms) were omitted from the discrimination task, although all stimuli were presented to listeners for identification.

[10] This secondary test also included different-nasality and similar-nasality pairings in which the more oral pair member had an ORAL vowel and the more nasal member had either 33% or 66% vowel nasalization. These pairings address perceptual questions related to other work being conducted in our laboratory, but are not directly relevant to this study, in which I am investigating coarticulatory patterns similar to those that naturally occur in spontaneous speech. Although those findings are not reported here, they are consistent with the patterns reported below for the main discrimination test.

variable alignment relative to the oral articulators. The prediction was upheld for ṼNCV stimuli (§4.3) as shown by listeners' poor discrimination of similar-nasality trials, and their significantly more accurate discrimination of different-nasality trials. A comparable outcome is predicted for the [bɛ̃(n)d] stimuli in the main discrimination test, with a strong version of the model again leading to the predicted order of discriminability: different-nasality > nasal-only > similar-nasality. (A weaker version predicts different-nasality > similar-nasality, but does not predict that nasal-only trials will differ significantly from the other two trial types.)

For [bɛ̃(n)t] stimuli, perceived equivalence would again be consistent with the production data. Because *bent*-like ($VNC_{voiceless}$) words tend toward quite short [n] and extensive vowel nasalization, however, vowel nasalization should also serve as a very reliable cue in this context. Consequently, it would not be surprising if at least some listeners were especially sensitive to vowel nasalization in [bɛ̃(n)t] stimuli—more so than for [bɛ̃(n)d] stimuli. For any such listeners, it would be the [bɛ̃(n)t] trials that differ in vowel nasalization (i.e. different-nasality and similar-nasality) that would be easiest to discriminate. Thus it is predicted that perceived equivalence will be less likely for [bɛ̃(n)t] than for [bɛ̃(n)d] stimuli and that, for [bɛ̃(n)t], the order of discrimination accuracy may be different-nasality = similar-nasality > nasal-only.

For the nasal-only stimuli in the secondary discrimination task that tested all degrees of vowel nasalization, a given $[n_S] - [n_L]$ pairing should, on psychoacoustic grounds, be most accurately discriminated after an oral vowel and least accurately discriminated after a heavily (66%) nasalized vowel.

Identification patterns should parallel discrimination findings. The identification counterpart to a trade-off in discrimination between Ṽ and N would be that, as vowel nasalization increases, less [n] duration is needed to elicit *bend* (rather than *bed*) and *bent* (rather than *bet*) responses. In an early tape-splicing experiment, Malécot (1960) found that vowel nasalization alone, with the nasal consonant excised, was sufficient to elicit $VNC_{voiceless}$ percepts (e.g. *camp*, *can't*, *tank* rather than *cap*, *cat*, *tack*). This outcome, combined with the production findings, lead to the expectation that a similar result would hold for *bet–bent* stimuli.

5.3. Discrimination results and discussion. The results of the secondary discrimination task upheld the prediction that, the more heavily a vowel is nasalized, the less accurate listeners are in discriminating differences in [n] duration. Summing across voicing contexts, the overall discrimination accuracy of thirty listeners responding to nasal-only $[n_S] - [n_L]$ trials was 59% correct for [n] after an oral vowel, 48% correct for [n] after a moderately (one-third) nasalized vowel, and 43% in the more heavily (two-thirds) nasalized vowel context. (The responses of two listeners are excluded, one due to an intermittent headset signal and the other to apparent difficulty with this test and the main discrimination test, as indicated by chance-level performance.) The main effect of degree of vowel nasalization was highly significant in a multivariate repeated-measures ANOVA ($F(2,28) = 28.63, p < 0.0001$), and pairwise comparisons showed each degree to be significantly different from the other ($p < 0.015$ or better). Overall accuracy (59–43%) was not high because not all $[n_S] - [n_L]$ differences were discriminated equally well; accuracy on individual pairs was as high as 82% in the oral vowel context, but never above 66% after a moderately nasalized vowel nor above 59% after a heavily nasalized one. An implication of this outcome for natural communicative settings is that, even when nasal consonants are clearly articulated, their psychoacoustic salience is diminished after nasalized vowels, possibly leading listeners to attend more to the vowel or to the property 'nasal' than to the phonetic details of the nasal consonant itself.[11]

The main discrimination task tested listeners' perception of nasal-only, different-nasality, and similar-nasality trials. The responses of thirty listeners to the identical (same) trials and nonidentical (different) trials were 86% and 63% correct, respectively, for the [d] context and 83% and 72% correct, respectively, for the [t] context. Thus accuracy was comparable across the voicing contexts for the identical trials, but overall better for the [t] than the [d] context for the nonidentical trials. Of importance here is the relative order of difficulty of the three types of nonidentical trials in each voicing context.

Two multivariate repeated-measures ANOVAs were conducted on the percent correct scores, one for [d]-final and another for [t]-final trials; corresponding ANOVAs were also conducted on d' scores. All tests showed a highly significant main effect of trial type (percent correct scores: $F(2,28) = 15.43$ for [d]-final and 19.65 for [t]-final; d' scores: $F(2,28) = 12.35$ for [d]-final and 13.31 for the [t]-final; $p < 0.0001$). Posthoc comparison results, however, differed for percent correct and d' scores and, because the latter adjust for listener bias (see n. 7), those outcomes are reported here.

Figure 9 gives the d' scores for each of the three types of nonidentical trials for the [d] and [t] contexts, pooled across thirty listeners.[12] (Mean percent correct scores for these trials were, for [d], 73%, 59%, and 57% for different-nasality, nasal-only, and similar-nasality, respectively. The corresponding scores for [t] were 80%, 65%, and 72%.) For [d]-final trials, pairwise comparisons on d' scores showed that listeners were significantly more accurate in discriminating different-nasality than either nasal-only or similar-nasality trials ($p < 0.0001$). They were equally accurate in discriminating nasal-only and similar-nasality [d]-final trials, against the prediction of a strong version of the model ($p = 1.00$). For [t]-final trials, pairwise comparisons on d' scores showed discrimination of different- and similar-nasality trials to be more accurate than that of nasal-only ($p < 0.0001$ and $p < 0.015$, respectively). Discrimination of different- and similar-nasality [t]-final trials did not differ significantly ($p = 0.732$). Thus, statistically, relative difficulty was different-nasality > similar-nasality = nasal-only for [bɛ̃(n)d] stimuli and different-nasality = similar-nasality > nasal-only for [bɛ̃(n)t] stimuli.

The relative difficulty of [bɛ̃(n)t] trials was as predicted based on the production patterns of covariation. Listeners were especially sensitive to vowel nasalization in the voiceless context, as shown by the different-nasality = similar-nasality outcome. Also as predicted, listeners were more likely to treat nasality on the vowel and consonant as perceptually equivalent in [bɛ̃(n)d] stimuli, shown by different-nasality > similar-nasality. Contrary to a strong version of perceived equivalence, according to which listeners should have substantial difficulty on similar-nasality trials (and contrary to the results for the [gã(m)ba] stimuli), listeners judging [bɛ̃(n)d] trials were not less accurate on similar-nasality than on nasal-only trials. An explanation for this outcome

[11] Relatedly, listeners, in attending to 'nasal', may require some minimum RELATIVE increase in total nasalization to detect differences between [$\tilde{V}n_S$] and [$\tilde{V}n_L$]. That is, a 36 ms increase in [n] duration from [n_S] to [n_L] is a proportionately larger—hence more detectable—increase in total nasalization after less nasalized than after more nasalized vowels.

[12] The scale for d' based on the calculation method adopted here (Macmillan & Creelman 1991:147) is 0–4.09 where 0 is zero sensitivity (hit rate = false alarm rate) and 4.09 is a perfect hit rate (= 1) and no false alarms.

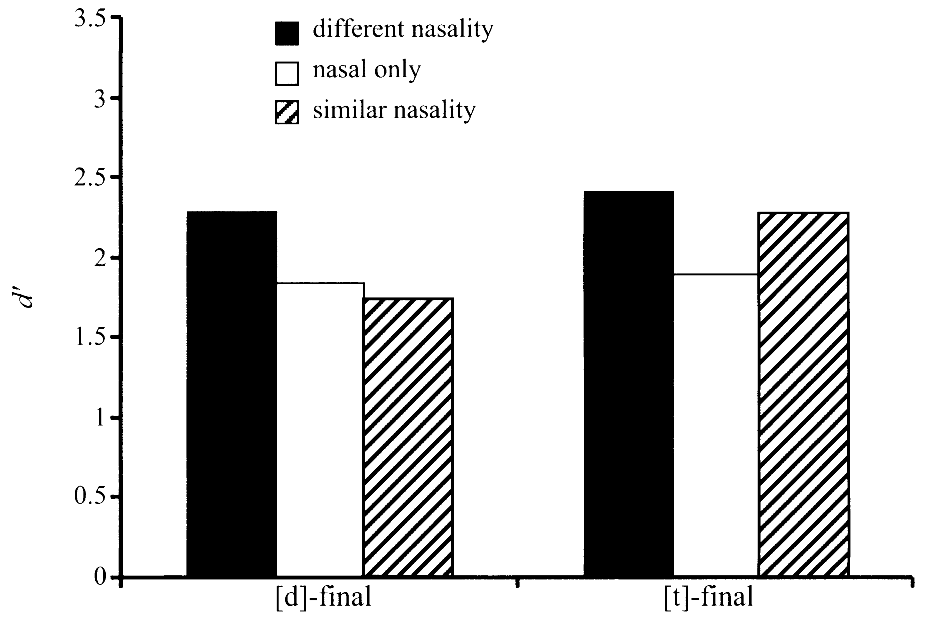

FIGURE 9. Pooled d' scores of thirty American English-speaking listeners for three types of discrimination trials in [d]-final and [t]-final contexts: nasal-only ([ɛ̃n_S] – [ɛ̃n_L]), different-nasality ([$\tilde{ɛ}_S n_S$] – [$\tilde{ɛ}_L n_L$]), and similar-nasality ([$\tilde{ɛ}_L n_S$] – [$\tilde{ɛ}_S n_L$]). All pairwise comparisons within a voicing context were significant except that the nasal-only – similar-nasality comparison was not significant for [d]-final stimuli, nor was the different-nasality – similar-nasality comparison significant for [t]-final stimuli.

emerges from inspection of individual listener's results: the [d]-final pattern in Fig. 9 is not representative of each listener's responses, but rather averages across listeners who found similar-nasality trials to be quite difficult and those who were fairly accurate discriminators of similar-nasality trials. Variation emerges in listeners' responses to [t]-final stimuli as well, but to a lesser extent; that is, the [t]-final pattern in Fig. 9 is more representative.

By way of investigating listener-specific discrimination patterns, each listener was categorized as either a 'perceived equivalence' or 'different = similar nasality' listener on the basis of that listener's relative performance on different- and similar-nasality trials in a given voicing context. The cut-off was the arbitrarily determined, but fairly stringent, criterion of 0.3 d'. A decrease in discriminability of more than 0.3 d' from different- to similar-nasality trials was taken to mean that the listener attended less to vowel or consonant nasality differences in these stimuli and more to total nasalization across the syllable rhyme (hence their poorer performance on similar-nasality trials). This is the 'perceived equivalence' pattern. Highly similar performance in the form of a smaller than 0.3 d' drop, or even a modest increase from different- to similar-nasality trials, is not consistent with perceived equivalence. These 'different = similar nasality' listeners can, almost without exception, be characterized as 'vowel nasalization' listeners because they are more accurate discriminators of stimuli that include differences in vowel nasalization (i.e. similar-nasality and different-nasality trials) than of the nasal-only stimuli.

Figure 10 gives the results of this categorization. (One listener's results could not be categorized due to poor performance on all [d]-final trials.) Nine listeners showed the perceived equivalence pattern for both voicing contexts, although as seen in the figure this pattern was more robust for the voiced context. Twelve listeners showed the different = similar nasality pattern for both contexts. Eight 'mixed result' listeners showed one pattern for [bε̃(n)t] stimuli and the other for [bε̃(n)d] stimuli. For six of these eight, the voiced context—as expected—triggered the perceived-equivalence pattern. While the voiceless context unexpectedly triggered the perceived-equivalence pattern for the other two listeners, this was a marginal outcome. Had the criterion been slightly less stringent (0.5 difference in *d′*), these listeners' results would be recategorized as falling into the middle category in Fig. 10.

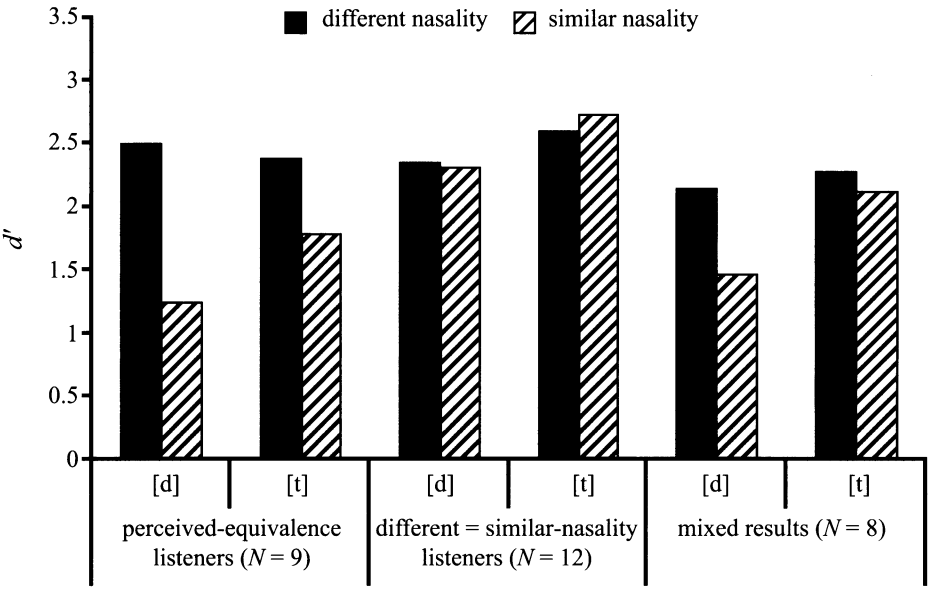

FIGURE 10. *d′* scores of three groups of listeners for the different- and similar-nasality trials, for two voicing contexts. See text for explanation of the listener groups.

That a subset of listeners showed the different = similar nasality (i.e. 'vowel nasalization') pattern for [bε̃(n)d] stimuli, but none did so for [gã(m)ba] stimuli (both of which have VNC_{voiced}), could be due to various factors. One contributing factor may be the difference in lexical status, but another likely factor is that N is shorter and shows more variation in duration in VNC# than in VNCV items (a generalization based on measures of VNCV sequences that have been taken in our laboratory over the years but have not yet been reported; see also Cohn 1990:139–40).

To summarize, when presented with covarying Ṽ + N durations, listeners overall attend more to Ṽ variation in *bent*-like stimuli than in *bend*-like stimuli. For the latter stimuli, they are more likely to perceptually equate Ṽ and N. While these broad perceptual patterns are compatible with the patterns of covariation between Ṽ and N found in production, individual listeners differ in their sensitivity to these characteristics of the signal. Both the overall and listener-specific patterns suggest that American English-speaking listeners accommodate the wide range of Ṽ and N variation that occurs in natural speech by attending less to the details of the nasal consonant and more to relatively stable properties such as nasalization across the syllable rhyme or, especially in voiceless contexts, vowel nasalization. The results of the identification test provide additional evidence of how listeners perceptually assess these coarticulatory and segmental properties.

5.4. Identification results and discussion. Figure 11 gives the pooled responses of the same thirty American English-speaking listeners to the four-choice (*bet*, *bent*, *bed*, *bend*) test. Several patterns are immediately evident. First, listeners need a longer [n] in the voiced than in the voiceless context to identify stimuli as CVNC rather than CVC. When the vowel is oral, on average listeners cross over from responding *bed* to *bend* (i.e. the 50% category boundary) when [n] is 55 ms long, whereas they shift from *bet* to *bent* when [n] is only 25 ms long. A similar-sized boundary difference holds when the vowel is moderately (33%) nasalized. The 30 ms perceptual difference between voicing contexts directly parallels the 30–40 ms average difference in [n] duration between VNC_{voiced} and $VNC_{voiceless}$ for productions of three of the six speakers in the production study. (Measures for the other three speakers showed somewhat larger voiced-voiceless differences in [n] duration.)

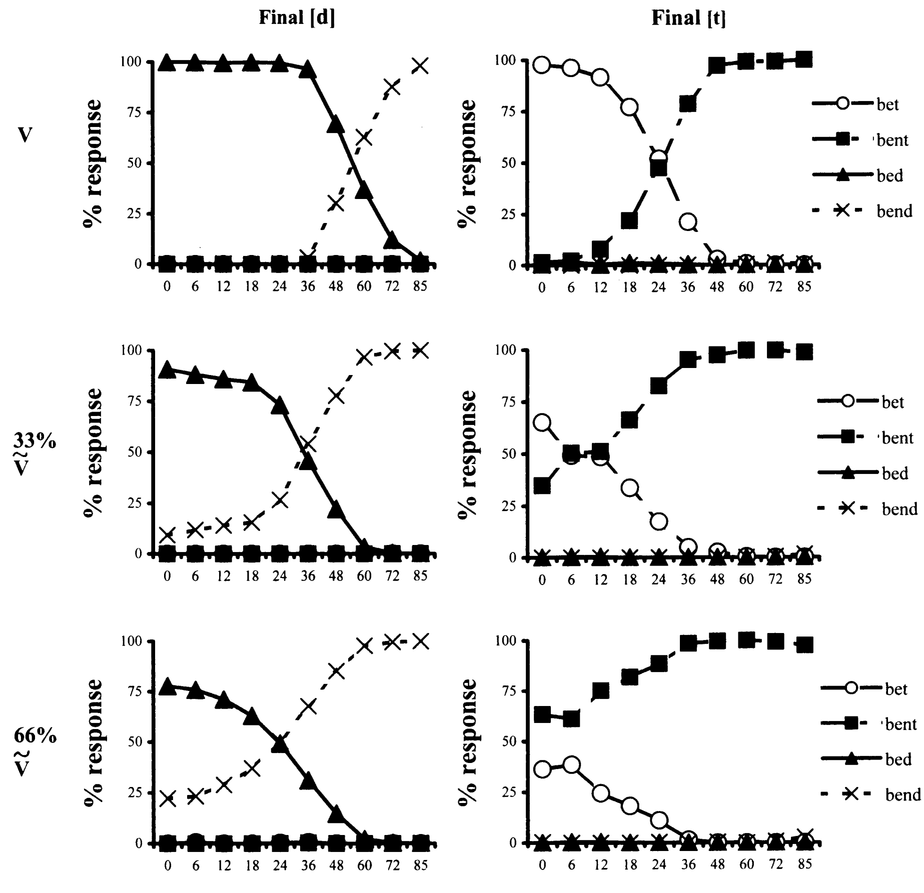

Figure 11. Identification responses of thirty American English-speaking listeners to the *bed–bend* (left) and *bet–bent* (right) series for three degrees of vowel nasalization (increasing from top to bottom).

A second robust outcome is that the segmental and coarticulatory cues trade off in listeners' labeling judgments: the more nasalized the vowel, the shorter the [n] needed to elicit CVNC responses. The 50% *bed–bend* category boundary decreases from 55 to 34 to 24 ms as vowel nasalization increases from 0 to 33% to 66%. For *bet* to *bent*, the boundary decreases from 25 to 6 ms as nasalization increases from 0 to 33%. At 66%, vowel nasalization alone—with no [n] murmur—is sufficient to elicit a majority of *bent* responses.

Third, listeners were highly accurate in their /t/ and /d/ judgments, with less than 1% voicing errors overall. This outcome was not entirely expected because coda voicing systematically influences preceding Ṽ and N durations in production. Raphael and colleagues (1975) found that increasing N duration in CVNC items was sufficient to elicit perceptual shifts from final voiceless to voiced C. The current data show only a hint of this effect: 37% of the 1% voicing errors were incorrect *bend* judgments of the [t]-final stimuli with the longest [n] durations. (This effect is visible in Fig. 11 as a slight decrease in *bent* responses, and a corresponding increase in *bend* responses, toward the right end of the 33% and 66% Ṽ functions.) The accuracy of listeners' voicing judgments in this study is likely due to the robust characteristics of the postnasal [t] and [d] closures and release bursts. In natural speech, final stops are often not audibly released, and [t] and [d] closures may be partially voiced or devoiced, leading me to expect greater voicing ambiguity in natural productions.

The identification patterns coincide with the discrimination results. That Ṽ contributes to an /n/ percept follows from perceived equivalence between Ṽ and N. That Ṽ is sufficient for an /n/ percept before [t] is consistent with the large number of 'vowel nasalization' (different = similar nasality) discriminators in that context. The identification results also parallel discrimination when the responses of SUBGROUPS of discriminators (Fig. 10) are inspected. For example, with moderate vowel nasalization, the 'vowel nasalization' subgroup shifted from *bet* to *bent* responses a full stimulus earlier (along the [n] continuum) than did the 'perceived equivalence' listeners.

While this application of the trading-relations paradigm to the interaction between coarticulatory source and effect gives rise to perceptual outcomes that are generally consistent with those reported in the trading-relations literature, the present findings are distinct from that literature in an important respect. A major outcome of the trading-relations paradigm as standardly applied to two cooccurring properties—but typically not to coarticulatory source and effect—is that the trade-off in identification and (much less investigated) equivalence in discrimination are reported only for phonetically ambiguous stimuli (e.g. Best et al. 1981, Repp 1981, 1982). That is, the cues 'trade' specifically at the point(s) along the continuum where one dimension provides equivocal information about the target categories. This trading restriction does not hold for the current nasalization results. As can be seen in Fig. 11, vowel nasalization influenced identification for most listeners even when the consonantal information was unequivocally oral. Correspondingly, equivalence in discrimination between Ṽ and N (for listeners showing this pattern) held across the entire N series, not just for ambiguous stimuli. Whalen and colleagues' (1993) study of the perceptual trade-off between another coarticulatory source and effect—onset voicing and its influences on vocalic F0—also provides evidence of the coarticulatory effect (F0) influencing judgments of phonetically unambiguous source stimuli. It may be that such robust perceptual tradeoffs, across a wide range of stimulus conditions, are a hallmark of coarticulatory source and effect relations, although much more work would be needed to establish this pattern.

5.5. Perceptual weightings and phonological grammars. In this experimental setting, listeners who based their perceptual decisions on 'nasal' or on vowel nasalization ended up making mistakes on certain types of stimuli or stimulus pairings. Nonetheless, when these perceptual choices are viewed in light of the production patterns, it is clear that listeners were attending to the stable properties in the input signal. Thus the picture that emerges is one of listeners being accurate perceivers of critical signal properties.

Another important aspect of the emerging picture is that some listeners assign more perceptual weight to certain aspects of the input signal than other listeners do, and perhaps more weight than might be expected if we assume the speaker intended /bɛnt/ and /bɛnd/. (Of course, it is not known for certain what the speaker intended; moreover, in this experimental setting the speaker's original productions have been manipulated.) Figure 10 showed that listeners differed in the influence of Ṽ on their same-different judgments of CṼNC stimuli. As observed above, the discrimination differences were mirrored in how these listeners labeled the stimuli. By way of illustration of the listener-specific identification patterns, Figure 12 gives the percent *bent* responses to the *bet–bent* stimuli for four listeners. Two of the listeners were categorized as 'perceived equivalence' listeners (top) and two as 'vowel nasalization' listeners (bottom) based on their discrimination responses. Clearly, different acoustic information signals *bent* for these listeners: several of the stimuli with shorter N durations and moderate to heavy vowel nasalization count as *bet* for Listeners 1 and 2 but as *bent* for Listeners 3 and 4.

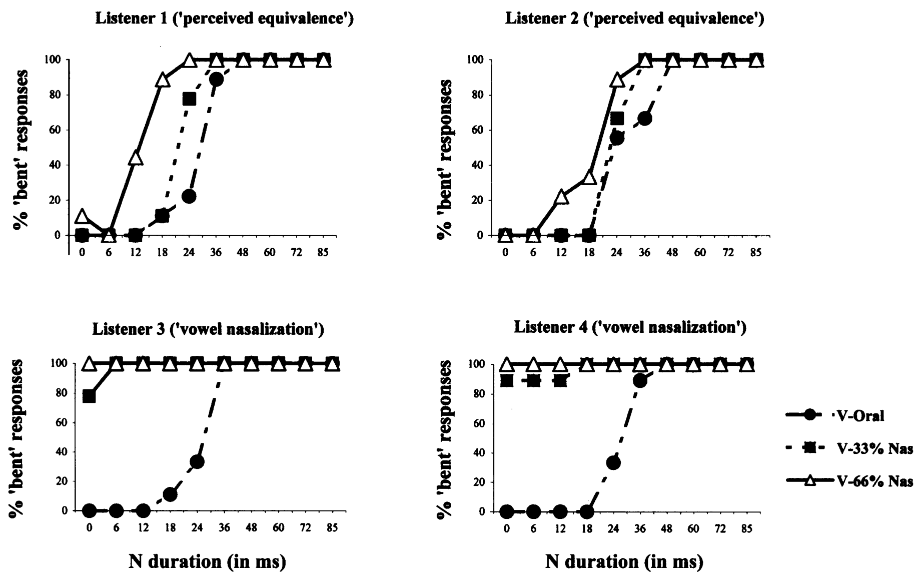

Figure 12. Percent 'bent' identification responses of four listeners (a subset of the original thirty listeners) to the *bet–bent* series for three degrees of vowel nasalization (shown by line type). Categorization as 'perceived equivalence' or 'vowel nasalization' listener is based on that listener's discrimination judgments.

Thus different listeners access their representation of, for example, *bent* through systematically differing acoustic signals. Assuming that listeners' responses in experimental settings provide some indication of the acoustic properties they find useful in more naturalistic settings, I take these across-listener perceptual differences as evidence of their different phonological grammars. (Of course, in more naturalistic settings, listeners also have nonacoustic information that could influence the perceptual outcome.) It may be that these differences in listeners' grammars involve different phonological representations for *bent* and other English words having similar structure. Although such differences would not be unexpected, they cannot be determined. Here I use 'grammar' more broadly to include not only the phonological representation but also the perceptual weighting that a particular speaker-listener assigns to the acoustic-auditory properties that map to that representation. (See also, for example, Berent et al. 2007 for discussion of perceptual differences as evidence of grammar differences.) I consider below the implications of across-listener and speaker-listener differences in their grammars of CVNC structures for the historical change VN > Ṽ.

6. Covariation in production, equivalence in perception, and sound change. As outlined in the introduction, my argument concerning a coarticulatory path to sound change has two basic claims. First, I hypothesized that, for some coarticulatory properties, phonologization involves a stage of coarticulatory variation in which the duration of the coarticulatory source and the temporal extent of its influences on nearby segments are inversely related. That is, the target gesture itself remains fairly stable in phonologization. It is the intended alignment of that gesture relative to other articulators that is reinterpreted in the transmission from speaker to listener. The production data presented in §2 establish for nasalization that speakers of some languages do systematically vary the alignment of the velum gesture relative to the oral articulators depending on contextual factors. What remains to be shown is that the contextual factors that trigger earlier onset in production (hence more vowel nasalization) are also involved in phonologization of coarticulatory nasalization. This link is established in §6.1. The second basic claim of the argument is perceptual: phonologization is hypothesized to be further facilitated by listeners perceiving Ṽ and N as equivalent sources of information or, in some cases, perceiving Ṽ as the more salient property. In §6.2 I further articulate a theory of listeners as accurate perceivers who contribute to sound change.

6.1. Contextual influences on covariation in production parallel the phonological evolution of nasal vowels. Fortunately, documentation of the historical development of vowel nasalization includes, especially for the Romance languages, details of the contextual factors that influence phonological vowel nasalization and nasal consonant loss. The three contextual factors shown in §2 to contribute to phonetic covariation between Ṽ and N were postnasal voicing, postnasal frication, and vowel length/duration. The influence of each of these factors on the phonological evolution of nasal vowels emerges in the literature, and the main evidence is reviewed here.

That nasal consonants are preferentially deleted, with vowels becoming nasalized, before voiceless obstruents has been clearly demonstrated for Northern Italian. Sampson's detailed study of vowel nasalization in Romance languages demonstrated the 'broad tendency' (1999:224, 274) of the dialects of Northern Italian and the Alpine region extending into Switzerland to develop nasal vowels in $\mathrm{VNC_{voiceless}}$ sequences, with weakening and often ultimate loss of the nasal consonant (1999:256). Hajek's analysis of vowel nasalization and nasal consonant loss in nine varieties of Northern Italian showed VN > Ṽ in seven varieties for $\mathrm{VNC_{voiceless}}$ contexts. However, this change occurred in only a subset of these varieties in $\mathrm{VNC_{voiced}}$ contexts (1997:141–43; see also Tuttle 1991). Ruhlen (1978) reported that VN > Ṽ took place first before voiceless stops and then later or not at all before voiced stops in Indo-Aryan.[13] Evidence of Ṽ rather than VN in voiceless contexts also emerges in acquisition data. Hernández-Chávez and colleagues (1975) found that two-to-five-year-old monolingual Chicano Spanish speakers often produced $\tilde{V}C_{voiceless}$ corresponding to adult $VNC_{voiceless}$. In contrast, N was systematically present in children's productions of adult VNC_{voiced} words. Similarly, the spelling of six-to-seven-year-old American English speakers and their responses to phoneme-counting tasks suggest that words containing phonological $VNC_{voiceless}$ are sometimes interpreted as $\tilde{V}C_{voiceless}$ (Treiman et al. 1995; see also Bybee 2001:44–45).

Nasal deletion with accompanying vowel nasalization is also a common pattern in prefricative (especially pre-voiceless-fricative) position in Romance. Sampson (1999: 47–48) noted nasal weakening in $VNC_{fricative}$ sequences with likely vowel nasalization in Latin. In Old French, VN > Ṽ appears to have been an especially early development in prefricative position (Sampson 1999:63–64). Comparable conditioning occurred in some Rheto-Romance dialects (1999:220, 224) and in Romanian (1999:302), in which VNF may be realized as ṼF or with heavy coarticulatory vowel nasalization and a weakened N. In some dialects of northern Italy, the outcome in this context is distinctive vowel nasalization (Sampson 1999:256; see also Hajek 1997:141–42). Developments in non-Romance languages also demonstrate the influence of postnasal frication. For example, Polish nasal vowels occur only before fricatives and, less commonly in contemporary Polish, word-finally; in other contexts the nasal consonant is retained (Brooks 1968:13, 36–37). Ohala and Busà (1995) observed that the combined effects of voicelessness and frication are especially likely to lead to N loss and vowel nasalization. They cite evidence from Ila, Western Ossetic, Eastern Ojibwa, and Delaware, among other languages. Nasals were lost before voiceless fricatives in many Germanic languages (de Chene & Anderson 1979, Ohala & Busà 1995, Kavitskaya 2002:62), with nasalization and subsequent denasalization of preceding vowels in several varieties (Campbell 1959:44, 47).

Vowel length is clearly linked to the phonological development of vowel nasalization. A well-known interpretation of long nasal vowels is that lengthening occurs in compensation for nasal consonant loss (e.g. de Chene & Anderson 1979). The compensatory interpretation of long nasal vowels is not strictly consistent with the phonetic data, in which temporally extensive vowel nasalization is reported on longer vowels even in the presence of nasal consonants. Nonetheless, the interpretation is broadly consistent in that, as discussed in §2.2, the phonologically long vowels of, for example, Thai and the relatively long tense vowels of English are followed by shortened nasal codas. An especially close parallel between the phonetic situation and phonological development is again provided by the detailed data available for Northern Italian dialects, in which long vowels were the outcome of degemination. Subsequently, in certain of these dialects, the long vowels—and only the long vowels—followed by N underwent V:N > Ṽ (Hajek 1997:85–86). In Romance languages more generally, Sampson (1999:340) concluded that long vowels are 'more receptive' than short vowels to nasalization. In the Teke languages, the change NC > N (where NC was a prenasalized stop) was

[13] Modern Standard Hindi has $\tilde{V}C_{voiceless}$ but $\tilde{V}NC_{voiced}$, and Ruhlen (1978) cited Hindi as an example of the Indo-Aryan pattern. More recently, Ohala and Ohala (1991) have argued that Old Hindi had $\tilde{V}C_{voiced}$ and N was subsequently reintroduced before voiced stops. At the same time, the reintroduction in only voiced contexts points to the influence of voicing on ṼN patterns.

accompanied by compensatory lengthening of the preceding vowel, and these long vowels subsequently nasalized before short vowels did (Hombert 1986).

That articulatory covariation between Ṽ and N and the phonological evolution of VN > Ṽ are conditioned by the same factors suggests that I may be on the right track in hypothesizing a link between covarying coarticulatory source and effects (in which more extensive effects cooccur with a temporally reduced source) and subsequent phonologization of these effects. In this approach, the listener further contributes to the progression from covarying Ṽ and N, to Ṽ as the distinctive property.

6.2. Perception of coarticulation and sound change. Listeners have knowledge of systematic coarticulatory patterns and they use this knowledge in determining what speakers are saying. One way in which listeners use coarticulatory knowledge is to perceptually attribute coarticulatory effects to their source. For example, listeners assign at least some of the spectral consequences of velum lowering during the vowel to their consonantal source, as suggested by the finding that nasal vowels sound more nasalized when embedded between acoustically weakened nasal consonants than between more salient ones (Kawasaki 1986). Moreover, listeners use knowledge of the specific coarticulatory patterns of their native language(s) to respond to these effects in language-particular ways: the more extensive the coarticulatory overlap for a particular gesture, such as velum lowering, in a language, the greater the perceptual accommodation for that overlap by speakers of that language (Beddor & Krakow 1999).

A tightly linked correlate of attributing coarticulatory effects to their source is that listeners also use the acoustic effects of coarticulatory overlap as information about the source itself. When English-speaking listeners hear fragments of words in which a coda consonant has been removed (e.g. [si] from *seize* or [sĩ] from *seen*), they offer more responses of the form CVN when the fragment ends in a nasal vowel than when it ends in an oral vowel (Lahiri & Marslen-Wilson 1991, Ohala & Ohala 1995). Similarly, English listeners identify N more quickly when the preceding vowel has anticipatory nasalization than when it does not (Fowler & Brown 2000). In the current study, listeners also used anticipatory nasalization in identifying a following consonant, and their perceptual responses within and across voicing contexts mirrored the timing of ṼN in production. The perceptual links between coarticulatory source and effect are such that many listeners treat the two as equivalent sources of information across a remarkably wide range of stimulus conditions.

In using the information in the coarticulated signal to determine what speakers are saying, listeners arrive at phonological grammars consistent with the coarticulated variants and their covarying source. I have argued that these grammars are listener-specific. Listener specificity may be due in part to that listener's linguistic experience, but is arguably also due to different phonological analyses being compatible with the input. Listeners who do not perceptually differentiate coarticulatory source from effect (as shown by their poor discrimination of whether nasality is on the vowel or consonant) may formulate phonological representations in which the distinctive property encompasses both—here, distinctive nasality, but not necessarily Ṽ or N. I have postulated as well that the distinctive property may be context-specific. Although sensitivity to nasality across the syllable rhyme is found to some degree in listeners' responses to all three contexts investigated in this study—VNCV, VNC_{voiced}#, and $VNC_{voiceless}$#—responses especially to the last context show that listeners are more likely to rely on the coarticulatory effect as the dominant property if the coarticulatory source is only variably present in the input. Listeners' reliance on coarticulatory effect is not simply a consequence of that property being systematically present in the signal. As indicated by the results for the nasal-only discrimination condition in §5.3, the psychoacoustic salience of the source (N) diminishes as the extent of its anticipatory influences increases.

The perceptual patterns, in tandem with the production data, provide evidence of how listeners can be accurate perceivers who attend to the information available to them in the input signal and yet arrive at a phonological grammar that may differ from that of the speaker. Multiple grammars are consistent with intended /VN/ input in which Ṽ and N covary and the timing of Ṽ and N systematically differs across voicing contexts. These include VN, 'nasal', Ṽ, or different analyses for different contexts, among others. Listeners who encode 'nasal' as the property corresponding to speakers' intended /VN/ may, in their own productions, largely replicate the input to which they have been exposed. Alternatively, these listeners' productions might exhibit more variation in Ṽ and N durations than is present in their input, while maintaining relative stability in Ṽ + N (i.e. in total nasalization). In the present study, one of the six speakers in the production experiment was also a listener in the *bet–bent* and *bed–bend* perception experiment. (Data collection for the two studies was separated by more than eighteen months, likely ruling out any influence of participation in both.) This participant was a 'perceived equivalence' listener for both voicing contexts, discriminating different-nasality trials more accurately than similar-nasality trials, although he was somewhat atypical in that he was a poorer discriminator than most perceived-equivalence listeners of nasal-only trials. In production, this participant, who was perceptually insensitive to source information except when it covaried with vowel nasality, produced an especially wide range of variation in Ṽ and N durations. For example, in voiceless contexts, this speaker's standard deviations for N were 35% to 130% greater than those of other speakers; Ṽ durations were correspondingly variable. Thus, consistent with Labov's (2007) process of incrementation, this nineteen-year-old speaker appears to be faithfully transmitting the properties present in the input system, but with relatively high variation (nonetheless maintaining relative stability of Ṽ + N). Of course, perception and production data from multiple participants would be needed to systematically study listeners-turned-speakers.

Thus, for VNC sequences, English-speaking listeners assess Ṽ as perceptually equivalent to N or as perceptually more salient than N. Listeners' relative insensitivity to properties of N could lead to a stage in which this coarticulatory source, especially following heavily nasalized vowels, is no longer informative. To the extent that phonological representations reflect the perceptual weighting of acoustic properties that access that representation, at this stage Ṽ rather than N would be the distinctive property. Additionally, the RAW MATERIAL for this type of reinterpretation from one generation of speaker-listeners to the next need not be restricted to language varieties, like American English, with extensive coarticulatory nasalization. Articulatory covariation between Ṽ and N has been observed in a range of languages (see §2), including languages with only moderate anticipatory nasalization. A clear pattern of perceived equivalence between Ṽ and N in VNCV stimuli has also emerged for native speakers of Botswanan Ikalanga, a language in which anticipatory nasalization is considerably less extensive, both temporally and spatially, than in American English (Beddor 2007).

7. CONCLUSION.

This experimental investigation is firmly grounded in the earlier work on coarticulation and sound change of Ohala and Lindblom, in combination with the core assumptions that salient aspects of coarticulatory variation are systematic, and that listeners regularly make use of these systematic variants in perceiving speech. The focus was on a single sound change, VN > Ṽ, albeit one that has recurred in many languages of the world. Over one-fifth of the world's languages have distinctive nasal vowels (Maddieson 1984), and most of these vowels have their origin in earlier VN sequences. I argued that converging articulatory and perceptual factors might lead to reinterpretation of a nasal gesture associated with a consonantal constriction as being associated with a vocalic configuration. The articulatory factor is covariation between Ṽ and N: speakers variably align the nasal gesture relative to the oral articulators. The realignment is triggered by contexts that promote early velum lowering or shortened consonantal constrictions, resulting in an inverse relation between duration of nasal consonants and duration of anticipatory vowel nasalization. Listeners have experience with these covarying properties in the input signal. They perceive nasality on the consonant and vowel as equivalent sources of information (at least in the syllable rhyme) or, in contexts in which nasal consonants are especially short and vowels are especially nasalized, attend primarily to the vocalic information. Consequently, listeners may arrive at a perceptual weighting and phonological interpretation of the signal that differ from a speaker's intended output. Although the present study concentrated on the phonetic underpinnings of distinctive vowel nasalization, the expectation is that articulatory covariation and perceptual equivalence might hold for other coarticulatory sources and their effects. They may therefore underlie other sound changes in which the source is lost and the coarticulated variant becomes distinctive. For example, consonant voicing has systematic influences on the fundamental frequency of a flanking vowel, and these perturbations have been convincingly argued to be linked to the historical development of tones from voicing contrasts (e.g. Hombert et al. 1979). Although I know of no evidence of covariation in production between the consonantal source and the temporal or spatial extent of the vocalic effects, source and effect do perceptually trade with each other as noted in §5.4—indeed, robustly so (Whalen et al. 1993). Moreover, the effects of consonant voicing on an adjacent vowel are temporally extensive in some languages; a perceptual consequence is that the vowel's fundamental frequency can outweigh voice-onset-time information in listeners' consonant judgments (e.g. Kim et al. 2002 for Korean). This relation is viewed as an especially promising area for future investigation of the coarticulatory path for sound change advanced here.

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