THE PERCEPTION OF NASAL VOWELS

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1. INTRODUCTION

The experimental study of the perception of nasal vowels spans a period of over 30 years and has focused on acoustic–perceptual relations. Characterization of these relations, however, entails an understanding of complex articulatory–acoustic relations, as the effects of nasal coupling on the vowel spectrum vary to some extent with degree of coupling and with oral cavity configuration. Characterization of acoustic–perceptual relations also requires an understanding of complex interactions of the feature [nasal] with other vowel properties. Accordingly, manipulation of selected acoustic consequences of nasal coupling for perceptual study has been shown not only to influence perceived nasality but to affect simultaneously other aspects of perceived vowel quality.

This chapter addresses two fundamental questions concerning the perception of nasal vowels: first, What spectral property, or set of spectral properties, correlates with perceived nasality in vowels? and second, What other aspects of perceived vowel quality are influenced by the spectral effects of vowel nasalization? The acoustic–perceptual relations proposed in answer to these questions involve interactions between nasality and the inherent vowel properties of height, backness, duration, and phonation type, as well as extrinsic factors relating to vowel context. In a final section of this chapter, further support for such interactions is drawn from cross-language phonological data.

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Nasals, Nasalization, and the Velum

2. PERCEPTUAL CORRELATES OF THE ORAL–NASAL DISTINCTION IN VOWELS

2.1. Acoustic–Perceptual Effects of Nasalization

Is there a vowel-independent and language-independent spectral correlate of nasality that listeners use to differentiate the class of nasal vowels from that of oral vowels?

2.1.1. Vowel Independence

The acoustic consequences of coupling the nasal cavity to the oral cavity include the addition of pole–zero pairs to the vowel spectrum and accompanying shifts in the frequencies, intensities, and bandwidths of oral formants (e.g., Fant, 1960; Fujimura & Lindqvist, 1971). For most vowels, the greatest effect is in the vicinity of F1, where the added pole–zero pair results in a low-frequency spectral prominence in a nasal vowel which typically has a wider bandwidth and lower amplitude than that of the corresponding oral vowel (Delattre, 1954; Hawkins & Stevens, 1985; House & Stevens, 1956; Maeda, 1982; Stevens, Fant, & Hawkins, 1987). However, the detailed characteristics of the low-frequency region of nasal vowels vary with the frequency of the first oral resonance and the magnitude of nasal coupling (House & Stevens, 1956; Maeda, 1982, this volume; Takeuchi, Kasuya, & Kido, 1975).

Delattre (1954, 1965) proposed that perception of vowel nasality was determined primarily by the intensity of F1, with weakening of F1 (by means of the Pattern Playback synthesizer) being a sufficient manipulation to trigger nasal judgments by French listeners. Whether reduction of F1 intensity is a vowel-independent correlate is unclear from Delattre's studies, however, as his investigations were restricted to the low and lower mid nasal vowels of French. House and Stevens (1956) used an articulatory synthesizer to generate vowels of different heights and coupling sizes and elicited nasality judgments from American English listeners. They found that although low vowels required more coupling than high vowels to be labeled as nasal, such differences could be explained in terms of the effects of coupling on F1 intensity: listeners' nasality judgments correlated with the magnitude of F1 amplitude reduction and bandwidth increase. Similar results with articulatorily synthesized nasal vowels were reported by Maeda (1982, this volume), who concluded that the vowel-independent acoustic correlate of vowel nasalization was low-frequency spectral flattening or spreading. Using formant synthesis, Huffman (1990) found that decreasing F1 prominence of a vowel (by increasing F1 bandwidth) generally increased listener judgments of the vowel as nasal. Studies involving manipulation of natural vowels, however, have found spectral manipulations in the higher frequency regions to influence, and in some cases even be necessary for, the perception of nasality in high vowels (Hattori, Yamamoto, & Fujimura, 1958; Takeuchi et al., 1975).

Hawkins and Stevens (1985) acoustically synthesized oral and nasal versions of [i e ɑ o u] by manipulating the frequencies and spacing of a low-frequency nasal pole–zero pair. Listener identification responses to the five oral–nasal continua (of the form [t̪V–t̪Ṽ]) showed similar 50% crossover points from oral to nasal responses. (Pole–zero spacing for the stimulus closest to each crossover point fell between 75 and 110 Hz.) Inspection of the vowel spectra showed that the acoustic consequence of this spacing was a broad low-frequency prominence (compared to the narrow F1 peak of the oral endpoint spectrum) consisting of two fairly close peaks or a single lower amplitude peak. Hawkins and Stevens speculated that the acoustic property corresponding to perceived nasality is the degree of spectral prominence in the F1 region.

Most studies of the perception of nasality in vowels, then, agree that despite the variable acoustic characteristics of nasal vowels of different heights, there appears to be a vowel-independent spectral correlate: the relative prominence or flatness of the low-frequency region of the vowel spectrum. Recent studies are moving toward quantitative specification of a prominence measure. For example, Maeda (this volume) proposed the distance between two low-frequency peaks in the vowel spectrum as a measure of spectral spread and found that, in general, listener judgments of a vowel as nasal increased as this distance increased. This measure worked less well for high back [u], however, in which manipulating degree of nasal coupling had relatively little effect on peak distance. But spectra of natural tokens of back nasal vowels often show a flattened low-frequency peak relative to their oral counterparts (flattening of F2 being typical for [ũ]; Beddor, 1982). If such spectral differences are indeed characteristic of nasal versus oral back vowels, it may be that a spectral distance measure fails to capture some aspect of spectral flatness relevant to the perception of nasality in vowels. (But see Maeda, this volume, for a different approach to the problem of [u].)

2.1.2. Language Independence

Do the spectral properties used by listeners to differentiate the class of nasal vowels from that of oral vowels reflect a universally human auditory capability, or are the relevant properties influenced by listeners' linguistic experience? The linguistic experience in this case is shaped by both the phonological and phonetic behavior of nasal vowels in the native language of the listeners. A fundamental difference across languages is the phonological status of nasal vowels. In many, and possibly all, languages, vowels are allophonically nasalized to some degree in the context of a nasal consonant. In addition, in some 20–25% of the world's languages, vowels not in the immediate context of a nasal consonant are phonemically or distinctively nasalized (Maddieson, 1984; Ruhlen, 1978). Phonetically, languages may differ in degree of vowel nasalization (as measured by magnitude and timing of velic lowering). For example, Clumeck (1976) reported considerable cross-language variation in timing of anticipatory velopharyngeal port opening in vowels preceding nasal consonants, and this variation was not closely linked to the distinctiveness of vowel nasalization in these languages. It is possible that cross-language differences in both phonetic and phonological factors influence the spectral properties used by speakers of those languages to distinguish oral and nasal vowels. To date, cross-language perceptual studies of nasal vowels have focused primarily on the factor of phonological status.

One issue relating to the distinctiveness of vowel nasalization is whether vowel nasality functions as an independent perceptual parameter for listeners whose native language lacks oral–nasal vowel contrasts. That is, do nasal vowels function perceptually as a class, distinct from nonnasal vowels, even if the oral–nasal difference is not contrastive in a language? Results of multidimensional scaling studies provide evidence of such parameterization, as shown for American English by Wright (1986) and for German by Butcher (1976). Furthermore, labeling tasks with listeners whose native language lacks distinctive nasal vowels show that most listeners are able to consistently divide oral and nasal vowel stimuli into two categories (Beddor & Strange, 1982; Hawkins & Stevens, 1985).

But do speakers of different languages use the same spectral properties to cue the oral–nasal distinction? If so, one would expect listeners labeling oral and nasal vowel stimuli to exhibit the same 50% crossover point from oral to nasal regardless of the phonological status of nasalization in their native language. Beddor and Strange (1982) compared the identification responses to oral and nasal vowels of native speakers of American English and Hindi, the latter language having distinctive vowel nasalization. In that study, [ba–bã] continua were articulatorily synthesized by systematically increasing the size of velopharyngeal port opening. The across-continuum variation was in overall range of port opening. The language groups showed small differences in the location of the crossover boundary on each continuum, but across continua there was no consistent difference in identification responses between the Hindi and American English listeners.

The listeners in the study by Hawkins and Stevens (1985; see Section 2.1.1) were native speakers of American English, Gujarati, Hindi, or Bengali, the last three languages having phonemic nasal vowels. Across the five vowel types studied, no overall difference in identification crossover points for the different language groups was found. Similarly, Stevens, Andrade, and Viana (1987) found that English, French, and Portuguese listeners gave similar vowel nasality judgments to acoustically synthesized versions of [ʌ] differing in the amount (in terms of pole–zero spacing) and duration of vowel nasalization. Cross-language data from *labeling* tasks, then, strongly suggest that listeners respond to the same acoustic properties in distinguishing oral and nasal vowels, regardless of the phonological status of nasalization in their native language.

Studies of listeners' abilities to *discriminate* differences between oral and nasal vowels suggest that these abilities are more closely linked to linguistic experience. In general, listeners for whom the distinction is phonemic exhibit categorical-like discrimination functions, with good discrimination of differences which cross the oral–nasal boundary and poor discrimination of within-category differences. In contrast, listeners for whom the distinction is allophonic show good discrimination of both within- and across-category differences, especially for differences within the oral category (Beddor & Strange, 1982; Hawkins & Stevens, 1985). However, this enhanced discriminability within the oral vowel region does not seem to hold for mid vowels (Hawkins & Stevens, 1985).

One interpretation of the cross-language differences in discriminability of vowels differing in nasality is that listeners whose native language lacks distinctive vowel nasalization are responding phonetically, while listeners whose native language contrasts oral and nasal vowels are responding phonemically, and a phonemic response "mode" reduces intracategory discriminability. But there is perceptual evidence that this two-way distinction between distinctive and nondistinctive nasalization is overly simplistic. In many languages, oral–nasal vowel contrasts are accompanied by other differences in vowel quality. In French, for example, certain oral–nasal vowel pairs such as /ɛ/–/ɛ̃/ are very similar in oral cavity configuration, but other pairs such as /a/–/ɑ̃/ differ in tongue/jaw height, tongue backness, and lip rounding (Strenger, 1969; Zerling, 1984).[1] Thus French listeners responding to a synthetic [a–ã] continuum in which the only variation is vowel nasalization are responding to a property that is distinctive in their language for some vowel oppositions but covaries with other properties for this particular vowel. French listeners asked to discriminate one of the [ba–bã] continua used by Beddor and Strange (1982) responded as shown in Figure 1. Hindi and American English results from that study are included for comparison. French listeners, like American English listeners, accurately discriminated vowels within the oral category. (The 50% crossover point from oral to nasal was close to stimulus 5 for all language groups.) On the basis of the interpretation given above to differences in the shape of the American English and Hindi listeners' discrimination functions, French listeners appear to be responding phonetically: while labeling responses indicate the vowels are heard as oral and nasal, the vowels would seem not to be equated with French /a/ and /ɑ̃/. Some support for this view is provided by French listeners' responses to a more appropriate [ba–bɑ̃] continuum. The articulatorily synthesized stimuli again involved variation in velopharyngeal port opening, but

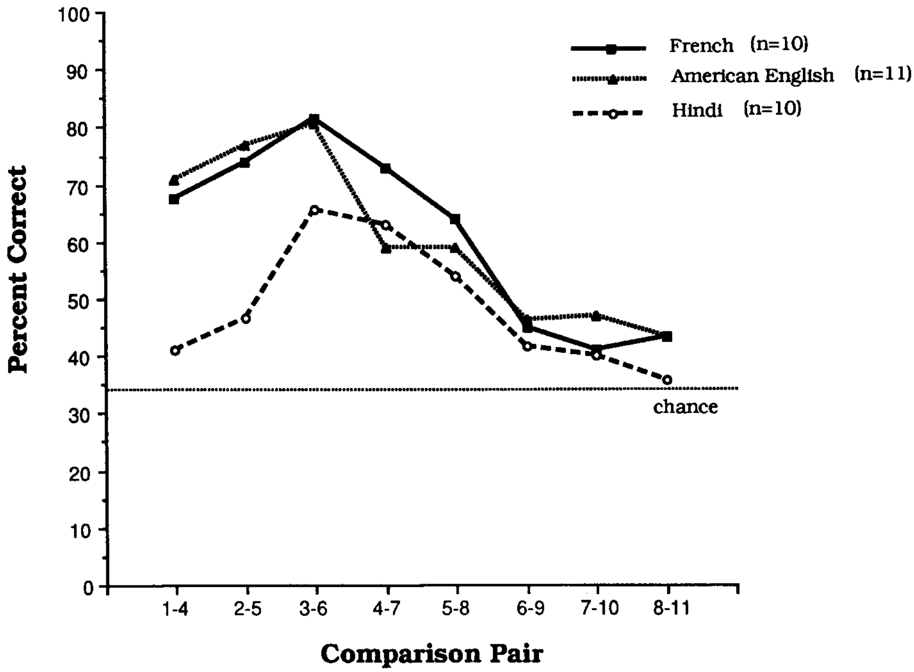

Figure 1. Discrimination functions for French, American English, and Hindi speakers for an articulatorily synthesized vowel continuum, [ba–bã], in which stimuli varied only in the size of velopharyngeal port opening. The French function is similar to the American English function toward the oral end of the continuum.

hyoid bone position (pharyngeal cavity size increased from oral to nasal) and lip position (rounding increased from oral to nasal) were also manipulated, to approximate the French contrast. The discrimination functions for French, Hindi, and English listeners' responses to this continuum are given in Figure 2. In this case, French performance is more similar to that of the Hindi listeners than the American English listeners. Apparently, discriminability of oral and nasal vowels is linked to the linguistic appropriateness of the vowels in terms of not only vowel nasality, but also other aspects of vowel quality.

Listeners' judgments of the naturalness of vowel nasalization are also language-dependent. Stevens, Andrade, and Viana (1987) reported that, when rating stimulus goodness or naturalness, French, Portuguese, and English listeners preferred different amounts and temporal patterns of nasalization. These cross-language differences in perceptual ratings were found to be consistent with acoustic measures of nasalization in these languages.

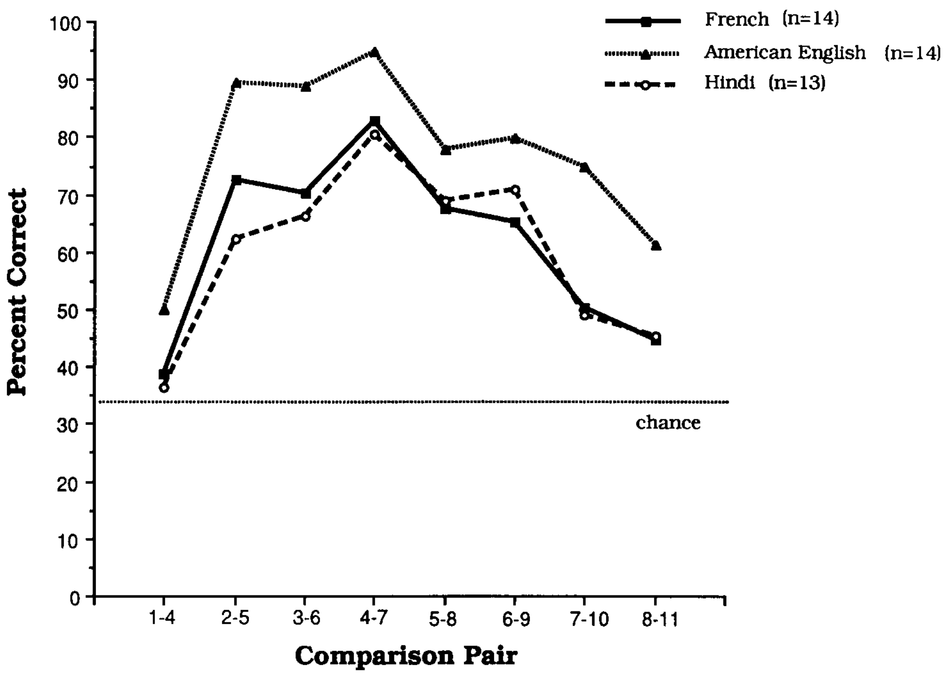

Figure 2. Discrimination functions for French, American English, and Hindi speakers for an articulatorily synthesized vowel continuum, [ba–bɑ̃], in which stimuli varied in size of velopharyngeal port opening, hyoid bone position, and lip position (corresponding to the French distinction between /a/ and /ɑ̃/). In contrast to Figure 1, the French function is more similar to the Hindi function than to the American English one.

In summary, identification of oral and nasal vowels is remarkably similar across languages, but discrimination and naturalness judgments of these vowels show language-specific differences which appear to interact in complex ways with the phonological and phonetic appropriateness of the stimuli. Understanding the nature of these interactions will require more cross-language studies, extended to other languages and eliciting other types of nasality judgments.

2.2. Other Vowel Properties Influencing Perceived Vowel Nasality

The evidence presented above suggests that the vowel-independent and language-independent spectral correlate of perceived vowel nasality is some (not yet fully quantified) measure of low-frequency spectral prominence. However, certain other spectral, temporal, and contextual manipulations also appear to influence judgments of vowel nasality.

2.2.1. Vowel Height

Two types of experimental findings suggest a relation between vowel height and perceived nasality. First, studies using natural speech stimuli have found that low vowels are more likely to elicit nasal percepts than are nonlow vowels in the same contexts (e.g., Ali, Gallagher, Goldstein, & Daniloff, 1971; Brito, 1975; Lintz & Sherman, 1961). Second, studies with synthetic speech have shown that low vowels require more nasal coupling than high vowels to elicit nasal percepts (e.g., Abramson, Nye, Henderson, & Marshall, 1981; House & Stevens, 1956; Maeda, 1982). Although the results of these two types of study seem to be in conflict, the apparent contradiction is likely due to stimulus differences in velic height. In natural speech, low vowels tend to be produced with a somewhat lowered velum even in oral contexts (e.g., Czermak, 1857; Fritzell, 1969; Henderson, 1984; J. Ohala, 1971); hence the low vowels in studies using natural vowel tokens were most likely produced with more velic lowering than were the high vowels. In the synthetic speech studies velic height was controlled, and the differences in perceived nasality linked to vowel height appear to be attributable to corresponding differences in spectral prominence, such that a given degree of nasal coupling reduces low-frequency prominence more in high vowels than in low vowels (House & Stevens, 1956; Maeda, 1982).

Studies have not shown whether vowel height affects perceived nasality independent of intrinsic velic height and degree of spectral prominence. Given that the main effect of tongue body height is to shift the frequency of F1, and that the main effect of vowel nasalization is also in the region of F1, it may be that shifts in F1 frequency alone influence perceived nasality. Hawkins and Stevens (1985) found that, under conditions of ambiguous nasality, listeners' nasality judgments of the [o–õ] continuum were largely dependent on differences in perceived vowel height, but systematic study of the effect on perceived nasality of manipulating F1 frequency has not been undertaken.

2.2.2. Vowel Duration

Phonological evidence of a link between vowel duration and nasalization (see Section 4.1) has led to experimental manipulation of vowel duration to determine its effects on perceived nasality. Delattre and Monnot (1968), using the Pattern Playback system, synthesized nine versions of a CVC syllable differing only in vowel duration. French and American English listeners identified the shorter vowels as oral and the longer ones as nasal. In that study, vowel nasalization was held constant and was intermediate between that of an oral vowel and that of a nasal vowel in terms of F1 amplitude. More recently, Whalen and Beddor (1989) co-varied vowel duration and vowel nasalization. Using articulatory synthesis, the vowels /a/, /i/, and /u/ were each generated with five vowel durations and varying degrees of velopharyngeal port opening. American English listeners judged the stimuli with greater port opening as more nasal but also consistently judged the longer stimuli as more nasal, indicating that increased duration enhanced perceived vowel nasality. This relation appears to be vowel-independent.

The effect of vowel duration on perceived nasality also appears to be language-independent. For French listeners, that longer vowels are perceived as more nasal is not surprising, as French nasal vowels are longer than their oral counterparts (Delattre & Monnot, 1968). For American English listeners, however, the perceptual effect runs counter to reported duration differences between English oral and nasal vowels, vowels in nasal contexts being shorter than vowels in corresponding oral contexts (e.g., Krakow, Beddor, Goldstein, & Fowler, 1988).

2.2.3. Vowel Context

Perceived vowel nasality is also influenced by the phonetic context in which the vowel occurs. For example, American English listeners judge nasal vowels as sounding more nasal when in (inappropriate) nonnasal contexts than when in (appropriate) nasal contexts. Kawasaki (1986) found that perceived vowel nasality was enhanced as adjacent nasal consonants were attenuated (i.e., [NṼN] → [Ṽ]). Similarly, Krakow and Beddor (1991) found that nasal vowels were more often correctly judged as nasal when spliced out of nasal contexts and presented in isolation ([Ṽ]) or in an oral context ([CṼC]) than when in their original nasal context ([NṼN]).

One interpretation of these results is that listeners' knowledge of coarticulatory overlap leads them to attribute vowel nasalization to adjacent nasal consonants, thereby hearing nasal vowels in a nasal context as nonnasal. Generally consistent with this view are the results of Lahiri and Marslen-Wilson's (1991) gating study using nasal vowels of British English and Bengali. Both languages nasalize vowels preceding nasal consonants; this contextual nasalization is allophonic in English and neutralizing in Bengali (i.e., oral and nasal vowels contrast only in nonnasal contexts in Bengali). When asked to identify the words presented, listeners from both language groups usually responded to gatings of the [CV] portion of [CVC] tokens with words of the form CVC, but CVN responses also occurred, indicating that oral vowels were not interpreted as incompatible with following nasal consonants. Furthermore, Bengali listeners tended to respond to gatings of the [CṼ] portion of [CṼN] tokens with words of the form CṼC rather than CVN, suggesting that vowel nasality is not interpreted as a cue to the presence of a nasal consonant in a language with distinctive vowel nasalization.

On the other hand, there is also evidence that the claim that nasal vowels in nasal contexts are perceived as oral, or nonnasal, is too strong. First, Krakow and

Beddor (1991) found that although the nasality of vowels in nasal contexts was not very accurately judged, such vowels were not consistently judged as oral, indicating listeners were uncertain as to vowel nasality in nasal contexts. Second, the nasality of nasal vowels in that study was better perceived in isolation than in oral contexts, suggesting that the distinction between "appropriate nasal" and "inappropriate nonnasal" contexts is insufficient to describe how context influences perceived vowel nasality. Determination of precisely which parameters are relevant, however, awaits further study.

3. THE EFFECTS OF NASALIZATION ON PERCEIVED VOWEL QUALITY

Coupling the oral tract to the nasal tract in the production of nasal vowels not only affects the shape (i.e., relative flatness) of the low-frequency spectrum, but also shifts the overall frequency of the first region of spectral prominence. When two adjacent peaks in a vowel spectrum are close in frequency, perceived vowel quality is determined by some weighted average, or center of gravity, of this region of the spectrum rather than by the frequency of individual peaks (e.g., Chistovich & Lublinskaya, 1979). In nasal vowels, the lowest frequency formant falls between F1 of the uncoupled oral tract and the lowest resonant frequency of the nasal tract when closed at the coupling end (in the region of 200–400 Hz; Fujimura & Lindqvist, 1971; Stevens, Fant, & Hawkins, 1987). So in low vowels, in which F1 of the oral system has a relatively high frequency, the lowest frequency formant is FN, which generally results in a lower frequency center of gravity for low nasal vowels than for corresponding oral vowels. In nonlow nasal vowels, FN frequency is typically higher than F1 frequency, and the frequency of the center of gravity is consequently higher than that of nonlow oral vowels. In recent years, experimental studies have investigated whether the influence of nasalization on the frequency of the first region of spectral prominence affects perceived vowel height and other aspects of perceived vowel quality.

3.1. Vowel Height

Perceptual findings indicate that the perceived height of nasal vowels differs from that of oral vowels in ways consistent with oral–nasal differences in the low-frequency center of gravity of the vowel spectrum. Using optical palatography to verify tongue body position, Wright (1986) produced oral and nasal versions, differing only in velum position, of the American English vowels /i e ɛ æ a o ʊ u/. All possible pairings of these vowels were presented to listeners for similarity judgments. Listener responses yielded a perceptual vowel space in which the height of nasal vowels differed consistently from that of corresponding oral vowels: high and mid nasal vowels were lower, and low nasal vowels were higher, than their oral counterparts. These perceptual differences did not always correlate with the acoustic difference between oral and nasal vowels in F1 frequency, leading Wright to speculate that the position of FN relative to F1 might influence perceived height. This speculation, reformulated in terms of the low-frequency center of gravity of oral and nasal vowels, was directly addressed by Beddor and Hawkins (1990). In that study, formant synthesis was used to generate five nasal vowels, [ĩ ẽ æ̃ ɑ̃ õ], and five corresponding continua of oral vowels in which F1 frequency was varied. The perceptual effect of manipulating F1 in the oral continua was to change vowel height. For each oral–nasal vowel set, American English listeners selected the oral vowel which sounded most similar to the nasal standard. Listeners rarely chose the oral vowel in which F1 frequency was the same as that of the nasal vowel but rather preferred oral vowels in which F1 frequency fell between FN and F1 of the nasal vowel standard (except for [ĩ], in which F1–FN separation exceeded the 3.5 Bark critical distance proposed by Chistovich & Lublinskaya, 1979). Although a precise acoustic measure predictive of listeners' perceptual choices has yet to be quantified, these results indicate that shifts in the low-frequency center of gravity due to nasalization influence perceived vowel height.

If perceptual integration of spectrally adjacent formants operates at the level of auditory processing (e.g., Chistovich, 1985; Syrdal, 1985), it would be expected that consequent shifts in the height of nasal vowels are language-independent. While cross-language phonological patterns of shifts in nasal vowel height are consistent with this view (see Section 4.2), there is perceptual evidence that, under certain conditions, listeners adjust or compensate for the height effects of a change in the low-frequency center of gravity. Krakow et al. (1988) articulatorily synthesized three types of continua: oral [bɛd–bæd], noncontextual nasal [bɛ̃d–bæ̃d], and contextual nasal [bɛ̃nd–bæ̃nd]. Within each continuum, the variation was in tongue body height; across continua, tongue body height manipulations were identical, but the two nasal continua differed from the oral in velopharyngeal port opening. The low-frequency spectral effect of port opening was to raise the center of gravity of the nasal vowel relative to that of the oral vowel with the same tongue body height. In the noncontextual nasal vowels, the perceptual effect of this spectral shift was to lower perceived vowel height, as shown by an earlier 50% identification crossover from /ɛ/ to /æ/ (i.e., more /æ/ responses) in the [bɛ̃d–bæ̃d] than in the [bɛd–bæd] continuum. However, there was no shift in the location of the 50% crossover due to contextual nasalization (i.e., although the vowels in the two nasal continua were identical, the contextual nasal identification function was more similar to the oral function than to the other nasal function). Krakow et al. concluded that, provided with an appropriate coarticulatory context for vowel nasalization, American English listeners are able to correctly judge the relative contributions of nasal coupling and tongue body height to the vowel spectrum.

Given that appropriateness of a given context for vowel nasalization is language-dependent, this conclusion is consistent with the view that the effect of nasalization on perceived vowel height depends in part on listeners' linguistic experience. However, support for this view awaits extension of this research to languages other than American English, especially languages with distinctive vowel nasalization.

3.2. Vowel Backness

The acoustic consequences of vowel nasalization, together with current understanding of the acoustic correlates of the perceptual dimension of backness, lead to the expectation that nasalization would influence the perceived backness of certain vowels. Perception of backness correlates with F1–F2 distance, such that the smaller the distance, the greater the perceived backness (e.g., Ladefoged, 1982; Lindau, 1978; Stevens, 1989). The spectral changes in the vicinity of F1 due to nasalization might be expected to have a negligible effect on the perceived backness of front vowels, in which F1–F2 distance is relatively large. But in back vowels, these low-frequency spectral changes influence the entire F1–F2 region. For example, Beddor (1982) analyzed the acoustic characteristics of oral and nasal vowels produced by speakers of Hindi, Turkish, Igbo, and English and found that, in the nonfront vowels /a o u/ of these languages, nasalization resulted in an increase in F1–F2 proximity. This greater proximity might be expected to lead to perceptual retraction in back nasal vowels as compared to their oral counterparts.

The predicted shifts in perceived vowel backness, however, are not well supported by the oral and nasal perceptual vowel spaces reported by Wright (1986), in which the main perceptual shift along the front–back dimension was in the front vowel pair [i–ĩ]. In general in that study, the nonlow front nasal vowels [ĩ ẽ ɛ̃] were perceived as more back than their oral counterparts. The back vowels did not exhibit a uniform shift: while [õ] was perceived as more front than [o], [ũ] and [ʊ̃] were heard as being slightly more back than their oral partners. Presumably this particular pattern of results can be explained by examining the spectral consequences of velic lowering in the specific vowels used in Wright's study. (For example, the nonlow front vowels in that study generally showed a decrease in F2 frequency from oral to nasal, consistent with perceptual backing.) But overall, in comparison to vowel height, there is relatively little experimental evidence of an effect of nasalization on perceived vowel backness.

3.3. Vowel Distinctiveness

The preceding sections indicate that the perceptual effects of vowel nasalization are to lower nonlow vowels, raise low vowels, and, to a lesser extent, retract front vowels. These effects amount to a contraction of the perceptual vowel space and lead one to expect that, when nasal vowels are compared to each other, the perceptual distance between any two nasal vowels would be less than that between the corresponding two oral vowels. Consistent with this suggestion is the finding by Bond (1975) that vowels excised from nasal contexts are more often misidentified than are vowels from oral contexts. In a more direct assessment of perceptual distance between vowels, Mohr and Wang (1968) asked American English listeners to rate the similarity of naturally produced vowels and found that nasal [ĩ ã ũ] were judged to be closer to each other than were oral [i a u]. Similar ratings of oral and nasal versions of [ɛ ɑ ɔ] have been reported for German and French adult listeners (Butcher, 1976). Further, Wright (1986) found, for a much larger set of articulatorily equivalent vowels, that the perceptual distance between members of nasal vowel pairs was consistently less than that between oral vowels. Clearly, nasalization decreases the perceptual distinctiveness of vowels.

The decreased perceptual distinctiveness appears to correlate with a reduction in spectral contrast among vowels, due to the introduction of nasalization. Early acoustic studies of nasal vowels noted that the frequency of the first spectral peak showed little variation across different vowels (Delattre, 1958; Hattori et al., 1958). This acoustic closeness is borne out by measures of acoustic distance applied to the overall vowel spectrum. For example, using a critical band-based measure of acoustic distance, Lindblom (1975) found greater acoustic similarity among the synthetic nasal vowels used by House and Stevens (1956) than among the oral vowels of that study.

In summary, perceptual studies have shown vowel nasalization to influence aspects of vowel quality other than nasality. Spectral shifts in the low-frequency center of gravity correlate with shifts in perceived vowel height and, to a considerably lesser extent, vowel backness. The direction of the shifts is such that the overall perceptual space defined by nasal vowels is a contraction, especially in the height dimension, of the oral vowel space.

4. PHONOLOGICAL CONSEQUENCES OF NASAL VOWEL PERCEPTION

It has been argued that changes in the shape and in the frequency of the low-frequency spectral prominence due to vowel nasalization have different perceptual consequences. Changes in spectral shape correlate primarily with perceived nasality, while changes in frequency correlate with other facets of perceived vowel quality. Such a theory of acoustic–perceptual relations can be tested not only in the phonetics laboratory, but also against phonological data. If the acoustic–

perceptual relations proposed here are correct, then two general types of phonological phenomena might be expected to recur in human languages. First, phonetic manipulations shown to enhance perceived vowel nasality should result in, or facilitate, phonological nasalization. For example, manipulations having spectral consequences similar to those of nasal coupling (i.e., broadening and flattening of the low-frequency spectrum) should result in nasal-sounding vowels and phonologically might give rise to nasal vowels. Second, if shifts in the low-frequency center of gravity due to nasal coupling influence perceived vowel quality, then phonological vowel systems should exhibit consistent differences in the height, backness, and distinctiveness of nasal vowels as compared to their oral counterparts. This section reviews previously reported cross-language studies of phonological patterns in nasal vowel systems in light of these two proposals.

4.1. Phonological Effects of Perceived Nasality

Experimentally, judgments of vowel nasality have been shown to be influenced primarily by degree of low-frequency spectral prominence, but vowel height, vowel duration, and vowel context also have an effect on such judgments. The phonological data presented below indicate that all four of these factors play a role in the historical development and synchronic patterning of vowel systems. These data involve vowel nasalization in nonnasal contexts or facilitation of vowel nasalization in certain nasal contexts. That the triggering or facilitating phonological properties overlap with the factors shown to be relevant in experimental studies is taken as further support for the perceptual correlates of vowel nasality proposed in Section 2.

4.1.1. Vowel Nasalization in Nonnasal Contexts

In the world's languages, allophonically nasalized vowels typically occur in the context of a nasal consonant, and distinctively nasalized vowels almost universally have evolved from vowels in nasal contexts (with subsequent loss of the conditioning nasal consonant). However, there are some well-established cases of "spontaneous" nasalization in nonnasal contexts. One such case is vowel nasalization adjacent to glottal consonants, as in some Indic, Tai, Sinitic, Tibeto-Burman, and Semitic languages (e.g., Matisoff, 1975; J. Ohala, 1974; M. Ohala, 1975; Ohala & Ohala, this volume). For example, in Northeastern Thai, vowels are allophonically nasalized after syllable-initial /h/ (Matisoff, 1975). Following /h/, a vowel is often produced with breathy voicing (Stevens, 1988), and breathy voicing mimics certain of the effects of nasalization on the low-frequency spectrum (J. Ohala, 1975). In particular, breathy voicing, like nasalization, results in a low-amplitude, wide-bandwidth F1 (Ladefoged, Maddieson, & Jackson, 1988; J. Ohala, 1975; Stevens, 1988). It is tempting to conclude that such cases of spontaneous nasalization are due at least in part to these low-frequency similarities, although further phonological study is needed to determine the extent to which these cases are linked to breathiness rather than glottality (cf. Matisoff, 1975).[2]

Another apparent source of spontaneous nasalization is vowel length. In accounting for the development of nasal vowels in nonnasal contexts in Marathi, and in Indo-Aryan more generally, Bloch (1919, 1965) noted the correlation between /Ṽ/ and /V:/ and attributed the nasalization to vowel length. Similarly, in certain Eastern Algonquian languages, long—but not short—Proto-Eastern-Algonquian **a:* became nasal /ã/ in all (i.e., oral as well as nasal) contexts (Goddard, 1965, 1971). These phonological changes are consistent with the perceptual evidence reported in Section 2.2.2 that longer vowels sound more nasal than shorter ones.

4.1.2. Vowel Nasalization in Nasal Contexts

Certain conditions seem to favor the historical development of nasal vowels from oral vowels in nasal contexts as well as the synchronic distribution of nasal vowels. Three conditions are noteworthy here. First, there is sporadic evidence of an effect of vowel duration, in that long vowels in nasal contexts become distinctively nasalized earlier than short vowels in similar contexts, as in the Teke group of Bantu languages (Hombert, 1986).

Second, vowel height influences the phonological development of vowel nasalization. The cross-linguistic data suggest that low vowels tend to distinctively nasalize earlier than nonlow vowels, and high vowels tend to denasalize earlier than nonhigh ones (e.g., Chen, 1972; Ferguson, 1975; Lightner, 1970; J. Ohala, 1974; Ruhlen, 1975; but see Entenman, 1977, for an opposing view). This preference for low vowel nasalization is in keeping with the perceptual finding that low vowels tend to be perceived as more nasal than high vowels. However, as noted above, low vowels are generally produced with a somewhat lowered velum, and therefore the phonetic source of this phonological pattern may be articulatory rather than perceptual. (For further discussion, see Whalen & Beddor, 1989.)

A third condition is that phonological nasalization is subject to certain phonotactic constraints. For example, historically the change from /VN/ to /Ṽ/ occurs more often and earlier when V and N are tautosyllabic than when heterosyllabic (Lightner, 1970; Schourup, 1973). The synchronic reflex of this change is that nasal vowels are more likely to contrast with oral vowels in syllable-final position, with the most common context being word-final position (Ferguson, 1975; Kawasaki, 1986). Also, properties of an oral consonant immediately following the conditioning nasal consonant may influence phonological nasalization. For example, distinctive nasalization accompanied by nasal consonant loss occurs more readily before continuants or voiceless consonants (Lightner, 1970; Malécot, 1960; M. Ohala, 1972, 1983; Schourup, 1973). Further, historical neutralization of the oral–nasal distinction occurs in nasal consonant contexts (Hyman, 1975), so that many languages with nasal vowels fail to contrast them with oral vowels when adjacent to nasal consonants (Beddor, 1982; Kawasaki, 1986). Not all of these contexts have been examined experimentally for their effects on perceived nasality, although it seems clear that, once again, the constraints are not wholly perceptual in origin. For example, the tendency for vowels to distinctively nasalize preceding tautosyllabic nasal consonants is presumably linked to heavier nasalization (due to a difference in the timing of velic lowering) on vowels preceding tautosyllabic nasal consonants than heterosyllabic ones (Krakow, 1989). However, the patterns are generally consistent with the view that perceivers (here, language learners) are uncertain of the status of vowel nasality in nasal contexts and are most certain of vowel nasality in open syllable position, especially when the preceding consonant is oral.

4.2. Phonological Effects of Perceived Nasal Vowel Quality

The phonological data presented above indicate that the factors influencing perceived vowel nasality (detailed in Section 2) also influence phonological vowel nasalization. We now address whether the influence of nasalization on other aspects of perceived vowel quality (presented in Section 3; i.e., distinctiveness, height, and possibly backness) are reflected in historical or synchronic phonological patterns of nasal vowels.

It is widely recognized that nasal vowel systems are phonologically less distinct than oral vowel systems in that, in a given language, the nasal vowels may number the same as or fewer than, but not more than, the oral vowels (e.g., Ferguson, 1963; Ruhlen, 1978; Wright, 1986). Presumably, this synchronic situation is due in part to the typical evolution of nasal vowels from phonemic oral vowels in nasal contexts. However, cross-linguistically, there are patterns in the gaps in nasal vowel systems relative to oral ones, with much of the reduction in nasal systems occurring in the mid vowels (Ruhlen, 1975; Wright, 1986). That such patterns exist suggests that some general principle of perceptual distinctiveness may be operating to maximize the perceived distance between nasal vowels (Hawkins & Stevens, 1985; Lindblom, 1986).

Much of the phonological research on quality differences between oral and nasal vowels has focused on vowel height. Studies have found that the description of cross-language patterns of raising and lowering of nasal vowels involves reference to the high–low dimension (Beddor, 1982; Bhat, 1975; Lightner, 1970;

TABLE 1
LANGUAGES WITH RAISING EFFECTS OF NASALIZATION[a]

High vowels raise		Mid vowels raise		Low vowels raise	
		Ṽ IN CONTEXT OF N			
Havyaka Kannada	(i u)	Basque	(e o)	Danish	(œ)
Iraya Mangyan	(ɨ)	Connaught Irish	(e o)	American English	(æ)
		Havyaka Kannada	(e o)		
		Swahili	(e o)	Toba Batak	(a)
		Scottish Irish	(e o ɔː)	Breton	(a)
				Diola Fogny	(a)
		Bariba	(ɛ ɔ)	Haida	(a)
		Portuguese	(ɛ ɔ)	Havyaka Kannada	(a)
		Tswana	(ɛ ɔ)	Nama	(a)
		Zulu	(ɛ ɔ)	Portuguese	(a)
		Castilian Spanish	(e)	Seneca	(a)
				Wori	(a)
		Texas English	(ɛ)	Zapotec	(a)
		Turkish	(ɛ)	Scottish Irish	(aː)
		Parachi	(ɵː)	Taos	(ɑ)
		Dutch	(ɔ)		
		Djuka	(o)		
		Toba Batak	(o)		
		Nama	(o)		
		Ṽ NOT IN CONTEXT OF N			
Kiowa Apache	(ɪ)	Chipewyan	(e ɛ)	Chatino	(a)
		Maithili	(ə)	Cuicateco	(a)
		Mazahua	(ə)	French	(a)
				Havyaka Kannada	(a)
		French	(ɔ)	Maithili	(a)
		Yoruba	(ɔ)	Nupe	(a)
				Portuguese	(a)
				Seneca	(a)
				Yuchi	(a)
				Taos	(ɑ)

[a]The vowels in parentheses indicate the oral counterparts to the raised nasal vowels. For example, in Connaught Irish stressed /e/ and /o/ are raised to [ĩ] and [ũ] adjacent to a nasal consonant. (See Beddor, 1982, for references.)

Ruhlen, 1978), the front–back dimension (Beddor, 1982; Maddieson, 1984), and the context in which the nasal vowel occurs (Beddor, 1982; Foley, 1975; J. Ohala, 1986; Ruhlen, 1978; Schourup, 1973). As an illustration of these interacting factors, Tables 1 and 2 summarize the height effects of nasalization reported in one

TABLE 2
LANGUAGES WITH LOWERING EFFECTS OF NASALIZATION[a]

High vowels lower		Mid vowels lower		Low vowels lower	
		Ṽ IN CONTEXT OF N			
Tabukang Sangir	(i ɨ u)	Grand Couli	(e o)	Inuit	(a)
Bengali	(i u)	Armenian	(e ə)		
Binumarien	(i u)	Albanian	(e)		
Ewe	(i u)	Campa	(e)		
Gadsup	(i u)	Chitimacha	(e)		
Inuit	(i u)	Dehu	(e)		
Kharia	(i u)	Djuka	(e)		
Mongolian	(i u)	Fore	(e)		
Swahili	(i u)	Gadsup	(e)		
Danish	(i y)	Hawaiian	(e)		
Alabaman	(i)	Kâte	(e)		
Campa	(i)	Tewa	(e)		
Cham	(i)	Wikchamni	(eː)		
Djuka	(i)	Washkuk	(ɛ)		
Fore	(i)	Danish	(øː)		
Kapau	(i)	Maidu	(ɔ)		
Maidu	(i)	Molinos Mixtec	(o)		
Menya	(i)				
Nama	(i)				
Pocomchí	(i)				
Selepet	(i)				
Tewa	(i)				
Vietnamese	(i)				
Yoruba	(i)				
Arabela	(ɪ)				
Coeur d'Alene	(ɪ)				
Pame	(ʊ)				
Parachi	(ʊ)				
Taos	(u)				

(continued)

of these studies. Beddor (1982) surveyed 75 languages exhibiting allophonic or morphophonemic processes involving nasal vowel raising (Table 1) or lowering (Table 2). The tables are organized according to two of the relevant factors, vowel height and context; the third factor, vowel backness, can be extracted by analyzing

TABLE 2

Continued

High vowels lower		Mid vowels lower		Low vowels lower
		Ṽ NOT IN CONTEXT OF N		
Albanian	(i y u)	Konkani	(e o)	
Nupe	(i u)	Maithili	(e o)	
Yoruba	(i u)	Portuguese	(e o)	
Yuchi	(i u)	Seneca	(e o)	
		Shiriana	(e o)	
French	(i y)	Slave	(e o)	
		Yuchi	(e o)	
Maithili	(i)			
Portugueses	(i)	Gbeya	(ɛ o)	
Pame	(ʊ)	French	(e ɛ̃ ø)	
		Hindi	(e)	
		Jicaltepec Mixtec	(e)	
		Kiowa Apache	(eː)	
		Taos	(ɛ)	

[a]The vowels in parentheses indicate the oral counterparts to the lowered nasal vowels. For example, in Campa, /i/ and /e/ are lowered to [ĩ] and [ɛ̃] before a nasal consonant. (See Beddor, 1982, for references.)

the vowels in parentheses. Although there are sporadic exceptions, the patterns exhibited by these data are as follows:

High nasal vowels: Lower

Low nasal vowels: Raise

Mid nasal vowels
- Non-contextual: Lower
- Contextual
  - Back: Raise
  - Front: Lower (unless the mid *back* vowel is raised in that language, in which case *both* front and back vowels raise).[3]

Note that the effect of vowel context is restricted to the mid vowel system. The backness factor, while necessary to describe the height shifts only in the mid vowels, is actually more pervasive, with front vowels generally being more likely to lower than back ones (see Table 2).

Comparison of these phonological patterns with the perceptual findings reported in Section 3.1 shows the effect of vowel height to be strongly supported. That is, phonological high vowel lowering and low vowel raising correlate with acoustic–perceptual shifts in the low-frequency center of gravity.

In contrast, the effect of vowel backness in the phonological data does not appear to correlate with the perceptual results, there being no difference in perceived height between front and back nasal vowels reported in studies to date. Yet there is some evidence that this discrepancy between the phonological and perceptual data may be due to the particular stimuli used in the relevant perceptual studies, which were based on English. For example, the pole–zero pair added to the vowel spectrum for [o] by Beddor and Hawkins (1990) resulted in an upward shift in the center of gravity for [õ] relative to [o], which is consistent with acoustic theory and with the effect of nasalization on English /o/. However, languages differ considerably in the degree of retraction of "back" vowels and hence in the proximity of the low-frequency nasal formant and zero to F2. Acoustic measures of the center of gravity in the F1–F2 region of [o] versus [õ], and [u] versus [ũ], showed that while nasalization raised the center of gravity in the back vowels of English, it resulted in either no change or a lowering of this measure for these vowels in Igbo, Turkish, and Hindi, due in part to the proximity of the nasal zero to F2 (Beddor, 1982). On the other hand, the corresponding comparisons for front vowels (in which F2 is not in the region of the low-frequency nasal formant and zero) of these languages showed much more consistent center-of-gravity increases due to nasalization. Therefore, cross-language acoustic measures of front and back oral and nasal vowels are consistent with the phonological effects of backness on nasal vowel height, and further perceptual study may reveal similar backness effects.

With respect to vowel context, the perceptual findings of Krakow et al. (1988) predict that noncontextual and contextual nasalization may differ in their height effects, with the former but not the latter giving rise to shifts in vowel height. This does not entirely parallel the phonological data, in which contextual nasalization gives rise to a reverse (rather than no) height shift in mid vowels. J. Ohala (1986) has proposed that this reversal may be viewed as perceptual in origin if it is assumed that, although a nasal context typically enables listeners to compensate for the height effects of nasalization, such coarticulatory information may result in overcompensation. Consistent with this view is a second finding by Krakow et al. (1988) that weakly nasalized vowels in [b__nd] contexts were perceived as slightly higher than their oral counterparts, although this finding suggests that overcompensation might be restricted to unexpectedly weak coarticulatory effects. (See Beddor, Krakow, & Goldstein, 1986, for further discussion of possible phonological effects of variation in degree of nasal coupling.)

5. CONCLUSIONS

The perceptual distinction between the class of nasal vowels and that of oral vowels, and perceptual distinctions among members of the class of nasal vowels, correlate with the shape and overall frequency of the F1 region of the vowel spectrum. The oral–nasal distinction in vowels correlates primarily with broadening and flattening of the prominence of the F1 region due to nasalization. Distinctions within the class of nasal vowels (compared to the corresponding oral vowel distinctions) are affected by the proximity of formants in the F1 region, which influences the center of gravity of the low-frequency spectral prominence. The claim that the perception of nasal vowels is determined by such properties as the spacing and shape of low-frequency spectral peaks is consistent with a more general theory of vowel perception in which the spectral properties taken to be perceptually relevant are not absolute but are rather relational (e.g., Beddor & Hawkins, 1990; Carlson, Fant, & Granström, 1975; Chistovich, 1985; Ladefoged, 1982; Stevens, 1989; Syrdal, 1985).

That nasalization principally affects the F1 region in vowel spectra also accounts for the interactions attested in perceptual and phonological data between nasality and other properties closely tied to the low-frequency region, such as vowel height, breathiness and, for some vowels, backness. However, certain other properties influencing the perception of nasal vowels are not well understood, with current explanations resting on as yet untested assumptions. Such gaps in our understanding of the perception of nasal vowels have been noted throughout this chapter. One often-cited gap is cross-language support for proposed interpretations. The source of this gap is well known to those who have worked to fill it: differences across languages in degree of vowel nasalization, phonological status of vowel nasalization, phonotactic constraints on nasal vowel distribution, and vowel quality differences accompanying vowel nasalization, to name but a few, pose serious obstacles for the selection of appropriate stimuli for cross-language perceptual study. But the richness of the cross-language variation in nasal vowels is what makes such research potentially so valuable not only to our understanding of the feature nasal, but much more generally to our understanding of phonological–phonetic interactions.

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NOTES

[1] /a/ and /ɑ̃/ are viewed as members of the same oral–nasal vowel pair in French on the basis of morphophonemic alternations (e.g., [plane] *planer* 'to glide, level'; [plɑ̃] *plan* 'level-ADJ'). The symbol /ɑ̃/ is used here in keeping with traditional transcriptions of this vowel, although phonetically [ɔ̃] is more appropriate (Lonchamp, 1979).

[2] If the phenomenon is more generally that spontaneous nasalization develops in glottal contexts, then the explanation would not seem to be perceptual. Following [ʔ], vowels may be produced with creaky or pressed voicing, resulting in a decreased bandwidth and increased amplitude of F1 (Stevens, 1988)—the reverse of the effects of nasalization. However, review of the data cited by Matisoff (1975) suggests that, while [ʔ] is sometimes involved, the phenomenon is more strongly linked to the presence of [h].

[3] For example, of the languages in which both front and back contextual nasal vowels shift height, 9 languages have nasal vowel raising and only 1 language (Grand Couli) has nasal vowel lowering. Of the languages in which only front nasal vowels shift height, 13 show lowering effects, while only 3 (Castilian Spanish, Texas English, and Turkish) show raising effects.

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