Coarticulatory influences on the perceived height of nasal vowels

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Certain of the complex spectral effects of vowel nasalization bear a resemblance to the effects of modifying the tongue or jaw position with which the vowel is produced. Perceptual evidence suggests that listener misperceptions of nasal vowel height arise as a result of this resemblance. Whereas previous studies examined isolated nasal vowels, this research focused on the role of phonetic context in shaping listeners' judgments of nasal vowel height. Identification data obtained from native American English speakers indicated that nasal coupling does not necessarily lead to listener misperceptions of vowel quality when the vowel's nasality is coarticulatory in nature. The perceived height of contextually nasalized vowels (in a [bṼnd] environment) did not differ from that of oral vowels (in a [bVd] environment) produced with the same tongue–jaw configuration. In contrast, corresponding noncontextually nasalized vowels (in a [bṼd] environment) were perceived as lower in quality than vowels in the other two conditions. Presumably the listeners' lack of experience with distinctive vowel nasalization prompted them to resolve the spectral effects of noncontextual nasalization in terms of tongue or jaw height, rather than velic height. The implications of these findings with respect to sound changes affecting nasal vowel height are also discussed.

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INTRODUCTION

Acoustic analyses have revealed a resemblance between certain spectral effects of nasalizing a vowel and those of modifying the vowel's height. In particular, movements of the velum that result in vowel nasalization, like movements of the tongue and jaw that alter vowel height, have their primary effect on the $F1$ region of the vowel spectrum. Perceptual findings that vowel height judgments can be influenced by nasalization (Wright, 1975, 1986) seem firmly rooted in the similarity between the acoustic consequences of these different articulatory events. This acoustic and perceptual link provides the basis for a phonetic account (Chen, 1971; Ohala, 1974; Wright, 1975; Beddor, 1982) of the widely attested sound changes leading to raising and lowering of nasal vowels in languages of the world (Schourup, 1973; Bhat, 1975; Foley, 1975; Ruhlen, 1975; Beddor, 1982).

Whereas previous perceptual studies of nasal vowel height focused on isolated vowels, the present study is primarily concerned with the influence of context on the perception of nasal vowels. We believed that the perceived quality of nasal vowels could not be determined solely by their spectral shape. Instead, we expected to find that nasal vowels, like oral vowels [cf. Fowler, 1981; (see Ohala, 1986)] are perceived in relation to the phonetic context in which they are produced. This hypothesis was tested by comparing listeners' perception of nasal vowels in the presence and absence of an adjacent nasal consonant. We also investigated the possible influence of different degrees of nasalization on perceived vowel height. Although such variations are commonly found across speakers and utterances, their perceptual consequences have not been assessed in earlier work. In what follows, we review the previous acoustic, perceptual, and phonological findings that together have shaped the hypotheses tested here.

Acoustically, the main effect of nasal coupling is in the vicinity of the first formant ($F1$), the frequency of which bears an inverse relation to vowel height. Thus nasalization might lead to listener misperceptions due to its spectral consequences in the frequency region associated with vowel height. In particular, acoustic theory of nasalization predicts that the first formant ($F1$) of the oral vowel is replaced in the nasal vowel by a shifted oral formant ($F1'$), a nasal formant (*FN*), and a zero (*FZ*) (Fant, 1960; Fujimura and Lindqvist, 1971; Stevens *et al.*, 1986). In the nasal vowel, $F1'$ is shifted upwards in frequency, reduced in intensity, and increased in bandwidth relative to $F1$ in the oral vowel (House and Stevens, 1956; Mrayati, 1975; Hawkins and Stevens, 1985). As a result of the upwards shift in $F1'$ frequency, nasalization might be expected to lower perceived vowel height (Ohala, 1986). Perceptual findings have indicated lowering of high vowels and some mid vowels due to nasalization; however, they have also indicated raising of low vowels and other mid vowels (Wright, 1975, 1986). A possible explanation for bidirectional shifts in perceived nasal vowel height lies with the additional pole (*FN*) in the low-frequency region of the nasal vowel spectrum, and the reduced prominence of $F1'$ due to the presence of a low-frequency zero (*FZ*). The prominence of *FN* is affected by the magnitude of coupling; at low degrees of coupling, *FN* is almost

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canceled by *FZ*, while at higher degrees, *FN* increases in prominence (Fujimura and Lindqvist, 1971). A raising effect of nasalization on vowel height could result when *FN* (if prominent) in the nasal vowel is lower in frequency than $F1$ in the corresponding oral vowel. Acoustic theory predicts this relative ordering of the first nasal and oral poles for low vowels. For high and mid vowels, *FN* is predicted to be higher in frequency than $F1$, a factor that could lead to perceptual lowering.

In Wright's investigation of perceived nasal vowel height (1975, 1986), the speaker produced corresponding oral and nasal vowels by first raising, then lowering the velum, while maintaining a constant tongue configuration. All possible pairings of oral and nasal vowels were presented to listeners who judged the similarity of the members of each pair. Consistent with the hypothesis that the location of *FN* affects perceived nasal vowel height, the perceptual vowel space constructed from listener responses showed a contraction along the height dimension of the nasal vowels relative to the corresponding oral vowels. The low nasal vowels were perceptually raised, and the high nasal vowels, perceptually lowered. Perceptual lowering was also characteristic of mid nasal vowels, although raising of some mid back vowels was obtained. These findings provide an indication that listeners have difficulty assessing the individual contributions of oral tract configuration and velopharyngeal coupling to the spectral shape of a nasal vowel.

Perceptual differences in oral and nasal vowel height may, in turn, lead to articulatory differences, and possibly to sound change, if listeners incorporate the perceived modifications of nasal vowel height into their productions. Ohala (1981, 1986) has argued that listener misperceptions underlie a number of sound changes that have occurred in languages of the world, including those affecting the height of nasal vowels. Indeed, data showing perceptual shifts in nasal vowel height converge with diachronic evidence of height shifts to support the hypothesis that the listener has played a critical role.

Cross-language phonological studies comparing the height of oral and nasal vowels have found that differences frequently occur, and that the differences tend to be quite systematic across geographically distant and genetically unrelated languages. These phonological patterns, which include lowering of high nasal vowels, raising of low nasal vowels, and front–back asymmetries in mid vowel shifts (see Beddor, 1982), generally correspond to the perceptual effects reported by Wright.

The perceptual and phonological evidence support the hypothesis that listeners can be misled by the resemblance between the spectral effects of velopharyngeal coupling, and the effects of certain tongue and jaw movements. However, the present study examines the hypothesis that perceived nasal vowel height is not entirely determined by the spectral shape of the nasal vowel, but rather that the context in which the nasal vowel occurs can affect the way in which the nasalization of that vowel is perceived. The spectral effects of nasalization on a vowel could theoretically be perceived as due to velic lowering in one instance, but as due to tongue–jaw movement in another. Thus, for example, the American English-speaking listeners who were the subjects in Wright's studies may have been prompted to perceive the spectral effects of nasalization in terms of an acoustically compatible tongue or jaw gesture because of their lack of experience with nasalization on a vowel in the absence of a nasal context.[1] However, a very different result might be obtained if such listeners were presented with contextually nasalized vowels, i.e., vowels whose nasalization is a result of coproduction with an adjacent nasal consonant. In fact, English, like many other languages, exhibits substantial anticipatory nasalization (cf. Malecot, 1960; Moll, 1962; Ali *et al.*, 1971; Clumeck, 1976). Presented with a vowel followed by a nasal consonant (as opposed to an isolated nasal vowel or a nasal vowel in an oral context), American listeners might attribute the spectral effects of vowel nasalization to an anticipatory velic gesture for the nasal consonant. We would, in this case, expect a more accurate assessment of vowel configuration than when no conditioning environment is detected. Support for this hypothesis, which the present study tests, is provided by previous perceptual findings indicating that perceptual processes take account of the gestural overlap characterizing speech production.

Kawasaki (1986) reported that listeners are sensitive to a coarticulatory relationship between a phonemically oral vowel and adjacent nasal consonants. The degree of perceived nasality of the vowels in naturally produced [mṼm] sequences was increased by attenuating the surrounding nasal consonants. This finding suggests that listeners recognized the nasalizing influence of those consonants upon the adjacent vowel. There is, however, no indication in Kawasaki's study of whether vowel quality judgments would be more accurate when the spectral effects of nasalization have an apparent coarticulatory source than when they do not.

Listeners' ability to disentangle the spectral influence of an adjacent oral consonant when judging the quality of a vowel was examined by Ohala *et al.* (see Ohala, 1986) in a study that showed that listeners recognized the coarticulatory fronting influence of apical consonants on back vowels. Vowels ranging from [i] to [u] were more often labeled as back (/u/) when flanked by apical (/s_t/) than by labial (/f_p/) consonants. Other studies have suggested that perceptual processes take account of coarticulatory effects not only of consonants on vowels, but also of vowels on consonants (e.g., Kunisaki and Fujisaki, 1977; Mann and Repp, 1980; Whalen, 1981; Fowler, 1984) and of vowels on vowels (Fowler, 1981; Fowler and Smith, 1986). These data all suggest that sensitivity to coproduction of phonetic units influences speech perception (see Fowler, 1983; Liberman and Mattingly, 1985), at least by native listeners.

The present research tested the hypothesis that such sensitivity might enable American listeners to distinguish the effects of nasal coupling from those of vowel height on the spectrum of a contextual nasal vowel. The perceived height of contextual nasal vowels was predicted to be similar, if not identical, to that of corresponding oral vowels. In contrast, the perceived height of noncontextual nasal vowels was predicted to differ from that of their oral counterparts because the acoustic effects of nasalization cannot be perceived as due to an adjacent consonant, and, therefore, may be perceived as a change in tongue or jaw height. The possibility of context influencing the perceived quality of nasal vowels was also raised by Ohala (1986). He suggested that the presence of an adjacent nasal consonant may cause listeners to be "alerted to try to factor out some of the distortions" of the vowel due to the nasalizing context (p. 395). Rather than viewing coarticulatory effects as distortions of the signal that pose a problem for the listener, we believe that the gestural overlap characterizing speech production facilitates speech perception. Nonetheless, Ohala, also, had predicted that listeners are more likely to misperceive the height of nasal vowels in the absence of an adjacent nasal consonant.

Our study also examined the perceptual consequences of varying the magnitude of velopharyngeal coupling with which nasal vowels can be produced, since such variations are commonly observed across vowel tokens, types, contexts, and speakers (cf. Ohala, 1971; Ushijima and Sawashima, 1972; Clumeck, 1976; Benguerel *et al.*, 1977; Henderson, 1984). We thought that listeners' experience with this sort of variability might be reflected in fairly accurate height judgments of vowels whether produced with weak, moderate, or heavy contextual nasalization. We, therefore, presented listeners with contextual nasal vowels synthesized with five different velar port openings that provided a range of nasalization, perceptually, from slight to heavy. If listeners lack perceptual "flexibility" in relation to such variability, then we would expect this to manifest itself as listener misperceptions at the extremes. Thus, for example, heavy nasalization on a contextually nasalized vowel could lead to perceptual shifts in vowel height if listeners attributed only some of the effects of nasal coupling to the nasal consonant, and the rest to the oral tract shape for the vowel. Perceptual shifts could also result from overcompensation by listeners for slight contextual nasalization, as suggested by Ohala (1986). Alteratively, listeners' experience with the variable extent to which vowels are influenced by adjacent nasal consonants might allow them to accurately assess the height of slightly, moderately, and heavily contextually nasalized vowels.

I. METHOD

A. Stimuli

Stimuli were generated by means of articulatory synthesis. Haskins Laboratories' articulatory synthesizer allows specification of a midsagittal outline of the vocal tract by means of articulatory parameters that allow independent positioning of the jaw, hyoid bone, tongue body, tongue tip, lips, and velum. An area function is computed, corresponding to the specified vocal tract configuration, and then an acoustic transfer function is calculated. Speech is obtained after source information, specified acoustically, is supplied as input to the acoustic transfer function (see Abramson *et al.*, 1981; Rubin *et al.*, 1981).

The American English /ɛ/–/æ/ contrast was selected for study, and the end-point vowels [ɛ] and [æ] were generated first. The tongue body in [æ] was both lower and more retracted than that in [ɛ]. Five intermediate shapes between these two end-point vowels were calculated by linear inter-

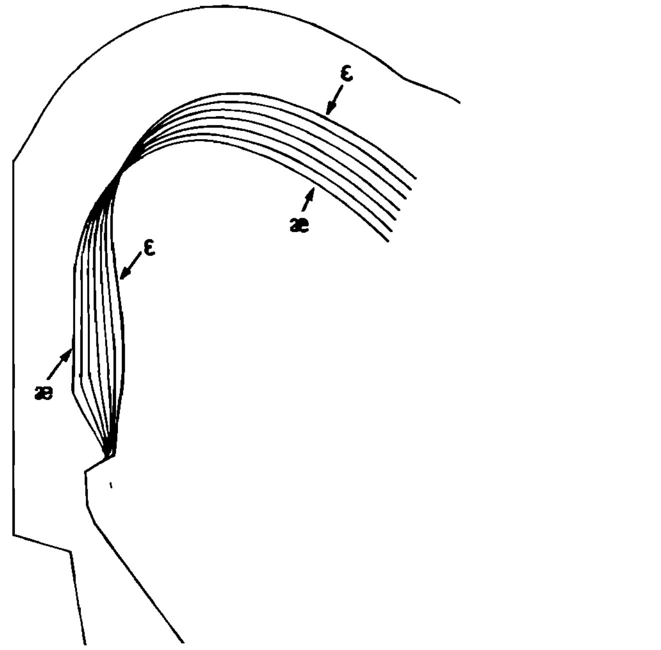

FIG. 1. Vocal tract outlines of the two end-point vowels, [ɛ] and [æ], and the five intermediate configurations obtained by lowering and retracting the tongue body in equal steps between the end points.

polation of the tongue body parameters yielding a seven-step vowel continuum from [ɛ] to [æ], as shown in Fig. 1. The formant frequencies and bandwidths of the transfer functions generated by the synthesizer for these shapes are given in Appendix A.

The seven vowel shapes were used as a basis for three synthetic continua: oral [bɛd]–[bæd], noncontextual nasal [bɛ̃d]–[bæ̃d], and contextual nasal [bɛ̃nd]–[bæ̃nd]. To construct these continua, each of the seven vowel shapes was first embedded in a /bV(n)d/ context by specifying schematized (straight-line) movement patterns of the synthesizer's model articulators appropriate to an initial bilabial closure and to a final alveolar closure. Additional modifications of velar port opening and the duration of final alveolar closure were used to differentiate the three continua. Input parameters were chosen so that the resulting speech was perceptually convincing, and so that its durational properties matched real speech exemplars, namely an American English speaker's productions of "bed," "bad," "bend," and "band." For this particular speaker, vowels in the context of the nasal consonant were, on the average, 50 ms shorter than those in the oral context. In order to control for and examine any effects of vowel duration on perceived oral and nasal vowel height, we synthesized long and short versions of each of the three continua. Long versions had steady-state vowels that were 50 ms longer in duration than the vowels in the short versions.

Figure 2 shows the time-varying values of the input parameters (as well as the synthetic waveform) for the [ɛ] end point of each of the three continua used in the experiment: oral (top panel), noncontextual nasal (middle panel), and contextual nasal (bottom panel). The trajectories shown here are for the long versions of these utterances. For ease of

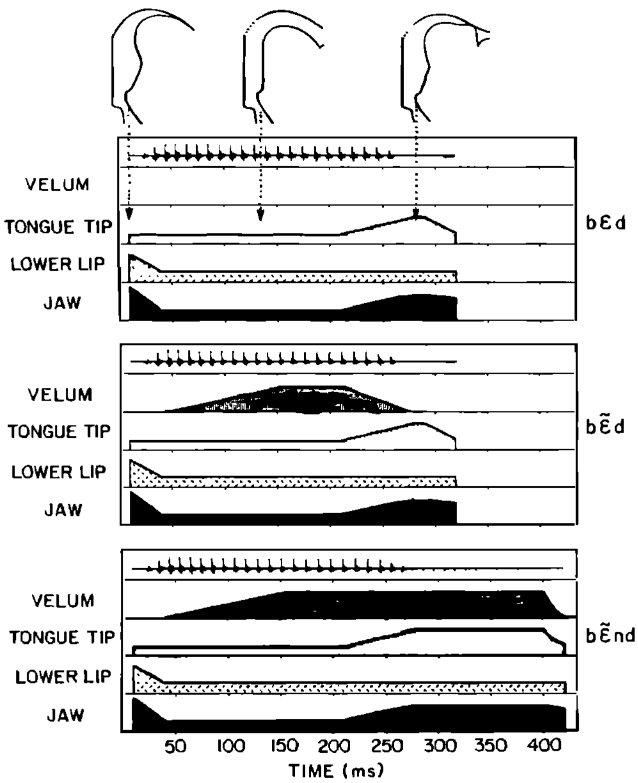

FIG. 2. Time-varying articulatory parameters used to synthesize the [ɛ] end point of the oral, noncontextual nasal, and contextual nasal continua. At the top of the figure, the oral tract shapes produced by these parameters are shown for three points in time: during bilabial closure, during the steady-state vowel, and during the alveolar closure. Maximum and minimum values covered by the ranges displayed are as follows: velum (24-mm^2, 0-mm^2 velar port opening), tongue tip (0.8-, −0.3-rad elevation above horizontal), lower lip (7.14-, 1.79-mm height above the lower teeth), jaw (−0.2-, −0.4-rad angle with respect to horizontal).

reference, the vocal tract shapes produced by the specified parameters are shown at the top of the figure for three points in time: during the bilabial closure, during the steady-state vowel, and during the alveolar closure. (The shapes at these points in time are identical for all three continua, except for velar port opening.) The time-varying articulatory parameters included velar port opening, tongue tip elevation, lower lip height (relative to the jaw), and jaw opening. Tongue tip extension also varied, but its trajectory over time was identical to that of tongue tip elevation, and is not plotted separately. The release of the initial bilabial closure involves lowering of the lower lip and opening of the jaw. The final alveolar closure involves raising both the jaw and the tongue tip. The articulatory parameters for these gestures are identical for all continua, as can be seen in Fig. 2. The noncontextual nasal continuum (middle panel) differs from the oral continuum (top panel) only in the addition of the opening and closing gestures of the velar port. The contextual nasal continuum (bottom panel) shows the same port opening gesture as the noncontextual continuum, but differs from both of the other continua in having a lengthened final alveolar closure, which is accompanied by continued port opening. Release of the final alveolar closure in each of the three continua involves lowering of the tongue tip and jaw.

The maximum velar port opening in Fig. 2 has a value of 16.8 mm^2. We also synthesized the contextual and noncontextual nasal continua using four other degrees of velar port opening: 7.2, 12.0, 24.0, and 36.0 mm^2. This manipulation was intended to reflect inter- and intraspeaker variability in the extent to which vowels are nasalized, and to allow examination of the effects of this variability on perceived vowel height. These values were selected on a perceptual basis. That is, they were judged by the experimenters as providing a range of perceived nasalization from slight (7.2 mm^2) to moderate (12.0 and 16.8 mm^2) to heavy (24.0 and 36.0 mm^2). The effect of these various degrees of port opening on the calculated transfer function for each of the seven tongue configurations is given in Appendix A. Note that while we varied the peak opening value of the velar port, the duration of velic lowering and raising gestures and of the steady-state plateau of velic opening were constant across the degree of port opening.

The fundamental frequency ($F0$) of all utterances was 100 Hz at onset and fell linearly to 85 Hz after 150 ms. Oral and noncontextual nasal stimuli remained at 85 Hz until the end of the utterance, while the contextual nasal stimuli were found to sound more natural if $F0$ was allowed to increase back to 100 Hz for the nasal murmur. This upward $F0$ movement began simultaneously with upward movements of the tongue tip and jaw for alveolar closure, and reached 100 Hz when maximum articulatory closure was achieved. In addition to the main experiment reported here, a second smaller experiment, in which $F0$ contours were identical across conditions, was also conducted. The results of the second experiment (reported along with its methods in Appendix B) indicated that this $F0$ difference did not have important consequences with respect to the results of the main experiment.

Our stimuli consisted of 154 synthetic utterances in all, divided among the six sets as shown in Table I. An audiotape was made for each stimulus set that consisted of ten randomized repetitions of all utterances in that set. Fifteen utterances randomly selected from each set provided practice trials for that condition. Test utterances were blocked into groups of 20, with an 8-s ISI intervening between blocks. Within a block, utterances were separated by a 2-s ISI.

TABLE I. Six sets of synthetic stimuli generated by means of articulatory synthesis for perceptual judgments by 12 native speakers of American English.

Stimulus sets
1. short oral [bɛd]–[bæd] (seven vowel shapes)
2. long oral [bɛd]–[bæd] (seven vowel shapes)
3. short noncontextual nasal [bɛ̃d]–[bæ̃d] (five degrees of coupling × seven vowel shapes)
4. long noncontextual nasal [bɛ̃d]–[bæ̃d] (five degrees of coupling × seven vowel shapes)
5. short contextual nasal [bɛ̃nd]–[bæ̃nd] (five degrees of coupling × seven vowel shapes)
6. long contextual nasal [bɛ̃nd]–[bæ̃nd] (five degrees of coupling × seven vowel shapes)

B. Procedure

Subjects were tested in small groups ranging in number from 1 to 4. Testing of each group occurred over three 1-h sessions in a sound-attenuated room. Stimuli were presented binaurally over headphones. The order of presentation of the six tapes was counterbalanced across subjects. Each trial in the oral and noncontextual nasal sets consisted of a /bṼd/ sequence ([bVd] in the oral condition and [bṼd] in the noncontextual nasal condition) following which the subject was required to make a forced choice between "bed" and "bad." (The subjects had no difficulty with this labeling of the noncontextual nasal utterances.) Each trial in the contextual nasal condition consisted of a [bṼnd] sequence and the choice between "bend" and "band." Printed answer sheets were provided with the choices listed for each trial. Subjects were required to place a check next to their selection. They were told to respond to all utterances and to guess when uncertain. Brief rest periods intervened between the presentation of the individual tapes.

C. Subjects

Twelve Yale University students served as subjects and were paid for their participation. All subjects reported that they were native speakers of American English having no history of hearing impairment.

II. RESULTS

The identification functions in Fig. 3 summarize the main results of our study. We show here the percentage of /ɛ/ responses as a function of stimulus number, for long and short vowels, collapsed over degree of nasalization (for the nasal stimuli). This figure, like all subsequent figures and tables of vowel height judgments, depicts the pooled responses of 12 listeners to ten tokens of each utterance. As can be seen from these data, there were fewer /ɛ/, and, therefore, more /æ/, responses to the noncontextual nasal vowels (circles) than to the oral vowels (triangles). That is, the noncontextual nasal vowels were perceived as lower in quality than the oral vowels. But, the functions for the contextual nasal vowels (squares) showed no such lowering. This pattern was consistent at both vowel durations.

All statistical analyses were performed on values obtained as a result of Probit Analysis (Finney, 1971) for the 50% crossover from /ɛ/ to /æ/ calculated for each subject's judgments of the vowels in each of the six continua. Crossover values were based on a scale of 1 to 7, corresponding to the seven vowel configurations: 1 corresponded to the [ɛ] end point of the continuum and 7, to the [æ] end point. Thus higher crossover values (that is, crossovers closer to the [æ] end point) indicated a greater number of /ɛ/ responses. The crossover values corresponding to the identification functions in Fig. 3 are shown in Table II. We discuss below the statistical analyses performed on the crossovers obtained in each of the conditions in our experiment.

The first ANOVA focused on the responses to the nasal stimuli and examined the within-subjects effects of degree of nasalization (five velar port openings), vowel duration (short versus long), and vowel context (presence versus ab-

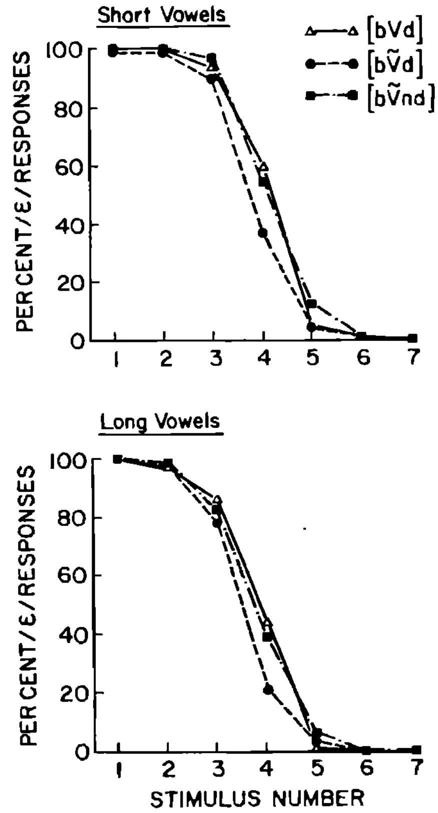

FIG. 3. Identification responses to the oral [bVd], noncontextual nasal [bṼd], and contextual nasal [bṼnd] continua for two different vowel durations.

sence of a nasal consonant) on the crossover from /ɛ/ to /æ/. There was a significant main effect of context, $F(1,11) = 15.82, p < 0.01$, due to the greater number of /æ/ responses to the noncontextual nasal vowels than to the contextual nasal vowels. This result supported the hypothesis that the perceived height of nasal vowels is not solely a function of the vowels' spectral characteristics. That is, although acoustically identical in the central region of the vowel and the transition to that region, the noncontextual nasal vowels were perceptually lower in quality than the contextual nasal vowels.

There was also a significant main effect of degree of nasalization, $F(4,44) = 60.47, p < 0.01$. This effect reflected a shift in the /ɛ/–/æ/ crossover toward the [ɛ] end point (i.e.,

TABLE II. Crossover values (50%) corresponding to the identification responses to the [bɛd]–[bæd], [bɛ̃d]–[bæ̃d], and [bɛ̃nd]–[bæ̃nd] continua.

Utterance	Crossover values for stimulus sets, Vowel duration: Short	Long
[bVd]	4.14	3.85
[bṼd]	3.79	3.49
[bṼnd]	4.10	3.78

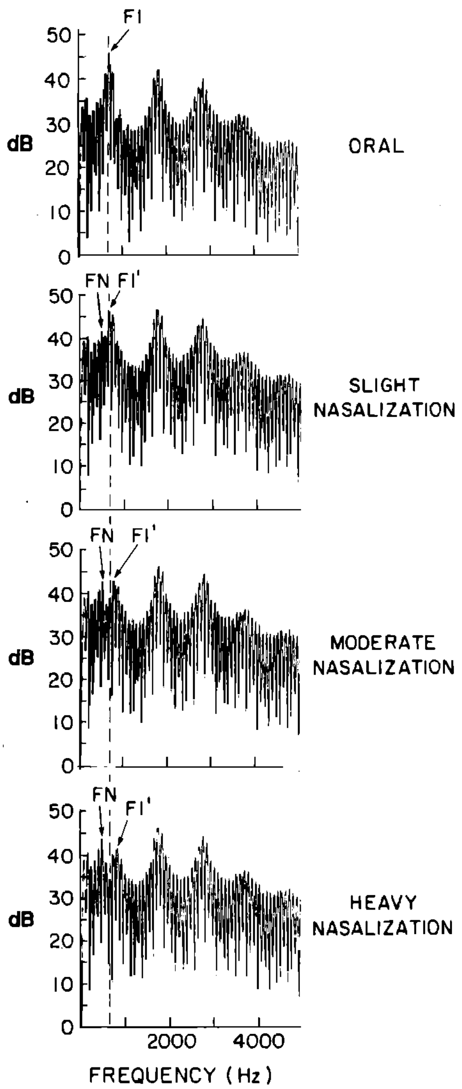

FIG. 4. Spectra of the middle vowel configuration (number 4) in the /ɛ/–/æ/ continua synthesized without nasal coupling (i.e., oral), and with slight (7.2-mm^2 velar port opening), moderate (16.8 mm^2), and heavy (24.0 mm^2) nasalization. Each spectrum is the result of a discrete Fourier transform sampled over a 40-ms Hamming window during the steady-state portion of the vowel.

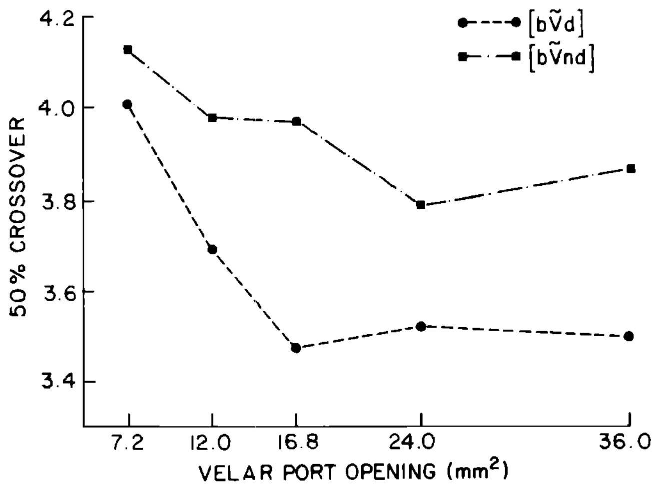

FIG. 5. Effects of the size of velar port aperture on the 50% crossover point from /ɛ/ to /æ/ for the noncontextual [bṼd] and contextual nasal [bṼnd] continua.

an increase in /æ/ responses as the velar port opening increased in size). Figure 4 shows the effects of relatively slight, moderate, and heavy nasalization (12.0-, 16.8-, and 24.0-mm^2 coupling, respectively) on the spectrum of the vowel in the middle stimulus (number 4) of the [bɛ̃(n)d]–[bæ̃(n)d] continua. The spectrum of the corresponding oral vowel is shown at the top. This figure shows that with slight nasalization, *FN* is barely in evidence and $F1'$ is shifted only slightly upwards in frequency relative to $F1$ of the oral vowel. But, as nasalization increases, *FN* becomes increasingly prominent, and $F1'$ is shifted further upwards in frequency.

The perceptual consequence of increasing nasalization was to lower perceived vowel height. Presumably this was a result of the rising frequency of $F1'$ in the nasal vowels relative to $F1$ in the corresponding oral vowels. However, there were differences in the perceptual effects of degree of nasalization as a function of the presence versus absence of a nasal consonant, as indicated by a significant interaction between degree of nasalization and vowel context, $F(4,44) = 3.0$, $p < 0.05$. Figure 5 shows the effects of degree of nasalization on the crossovers for the noncontextual and contextual nasal conditions collapsed across vowel duration. The difference in the slope of the two functions indicates greater lowering in the noncontextual nasal condition than in the contextual nasal condition as nasalization increased. In a subsequent analysis, discussed below, we analyzed each degree of nasalization separately.

The perceived height of the nasal vowels was significantly affected not only by context and degree of nasalization, but also by vowel duration, $F(1,11) = 60.47, p < 0.01$. More nasal vowels were perceived as /æ/ in the long conditions than in the short conditions. This result parallels the tendency for lower vowels to be longer in duration than higher vowels in natural speech (Lehiste, 1970). The duration effect was consistent across both nasal contexts and across the five degrees of nasalization; there were no significant interactions involving vowel duration.

To determine whether the effects of vowel duration were consistent in the oral condition with those in the contextual and noncontextual nasal conditions, a two-way ANOVA compared the within-subjects effects of utterance type (oral, contextual nasal, noncontextual nasal) and vowel duration (short versus long). For the purposes of this analysis, crossovers were collapsed across the five degrees of nasalization within each of the two nasal conditions. As shown in Fig. 6, the crossover values were greater for the short vowels than for the long vowels for each utterance type, indicating that the short vowels were consistently perceived as higher than the corresponding long vowels, whether oral or nasal. Consistent with the observed differences, the results revealed a significant main effect of vowel duration, $F(1,11) = 35.63$, $p < 0.01$. The lack of a significant interaction with utterance type, $F(2,22) < 1.0$, confirmed that the duration effect was constant across oral, contextual nasal, and noncontextual nasal conditions. The results also revealed a significant main effect of utterance type on perceived vowel height,

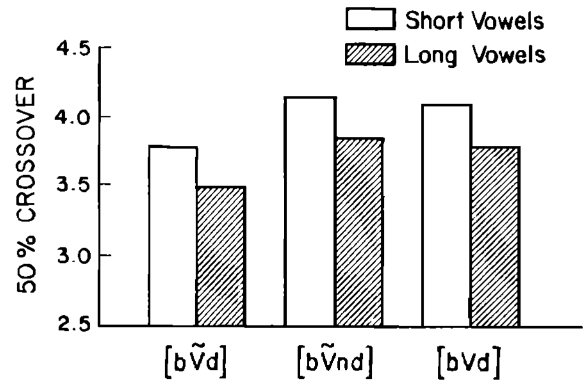

FIG. 6. Influence of vowel duration on the /ɛ/–/æ/ crossover for the noncontextual nasal [bṼd], contextual nasal [bṼnd], and oral [bVd] continua.

$F(2,22) = 8.91, p < 0.01$. (This result was expected since in the previous analysis in which the two nasal conditions were compared, a significant main effect of utterance type emerged.) The means from this analysis indicated that the perceived height of our contextual nasal vowels was similar to that of the oral vowels (as can be seen in Figs. 3 and 6), and that these functions differed from those obtained with the noncontextual nasal vowels. Our interest in the effects of degree of nasalization on perceived vowel height combined with the obtained interaction between degree of nasalization and context led us to analyze each degree of nasalization separately.

Figure 7 shows the percent /ɛ/ responses for the two nasal conditions at each of the five degrees of nasalization, collapsing the responses across vowel duration. The identification function for the oral condition is plotted in each graph for comparison. The effects of noncontextual and of contextual nasalization on perceived vowel height at each degree of nasalization were assessed with paired *t* tests. Five (two-tailed) *t* tests (one at each degree of nasalization) compared the crossovers for the noncontextual nasal utterances to the crossovers for the oral utterances. Five additional *t* tests made the corresponding comparison between the contextual nasal utterances and the oral utterances. The results of these analyses, which are shown in Table III (oral versus noncontextual nasal) and Table IV (oral versus contextual nasal), indicated that, in general, nasalization had a significant effect on the perceived height of noncontextual, but not on contextual nasal vowels. Perceptual lowering due to noncontextual nasalization was significant at all but the lowest degree of nasalization, which was presumably nasalized so weakly that it was perceived much like an oral vowel. In contrast, the perceived height of the contextual nasal vowels, whether slightly, moderately, or heavily nasalized, never differed significantly from that of the oral vowels produced with the same oral tract shapes. These results provide additional support for the hypothesis that perceptual processes take account of the overlap of articulatory gestures characterizing speech production. Furthermore, the analyses indicate a high degree of flexibility on the part of listeners in relation to variability in the magnitude of velopharyngeal coupling with which a contextual nasal vowel can be produced. It is worth noting, however, that at high degrees of contextual nasalization (24- and 36-mm^2 coupling), the figures reveal some perceptual lowering of the contextual nasal vowels, although it is not statistically significant. Furthermore, we observe slight raising at the lowest degree of contextual nasalization (7.2-mm^2 coupling) that approaches, but also does not reach significance. Thus, there are some suggestions of both "under" and "over" compensation, but they are relatively weak.

The final analysis involved a direct comparison between

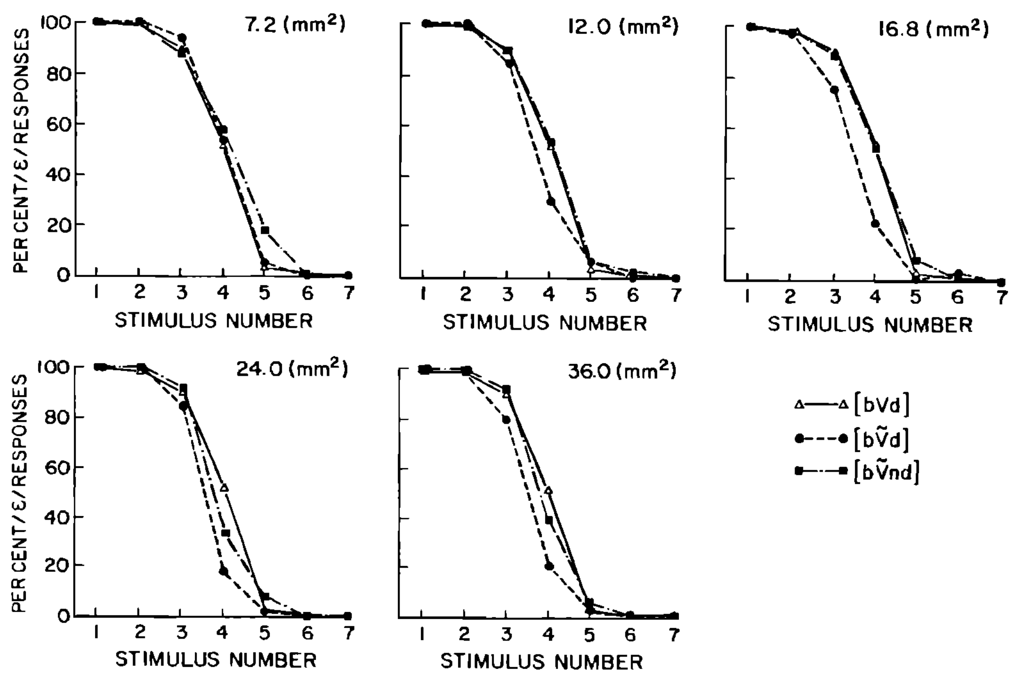

FIG. 7. Identification functions for the noncontextual [bṼd] and contextual nasal [bṼnd] continua synthesized with five different degrees of nasal coupling. The identification function for the oral continuum is reproduced in each of the panels for reference.

TABLE III. Results of t tests ($df = 11$, two tailed) assessing the effects of noncontextual nasalization on perceived vowel height at each of five degrees of velar port opening.

Effects of noncontextual nasalization on perceived vowel height		
Velar port opening	t statistic	Probability
7.2	0.89	0.39 (ns)
12.0	5.07	<0.01 (**)
16.8	5.66	<0.01 (**)
24.0	3.97	<0.01 (**)
36.0	5.07	<0.01 (**)

the perceived height of the *short* contextual nasal utterances ([bṼnd]) and the *long* oral utterances ([bVd]) since this comparison reflects the 50-ms vowel duration difference in the natural productions obtained as models for the synthetic vowels. The identification functions for these two continua are found in Fig. 8, which shows more /ɛ/ responses to the short contextual nasal vowels than to the long oral vowels. The results of a one-way ANOVA (collapsing judgments across the degrees of nasalization in the contextual nasal condition) revealed a main effect of utterance type (contextual nasal versus oral) on perceived vowel height, $F(1,11) = 14.58$, $p < 0.01$, due to perceptual raising of the contextual nasal vowels. This finding indicates that the perceived height of contextual nasal vowels and oral vowels can indeed differ significantly from one another under certain circumstances. Our data indicate that this difference stems from durational, rather than spectral factors. The lack of spectral influence on this height shift was indicated by the finding that when vowel duration was held constant, there was no significant effect of contextual nasalization on perceived vowel height. Thus it is important to consider the role that durational factors may play in perceptual shifts in nasal vowel height, as well as in sound change.

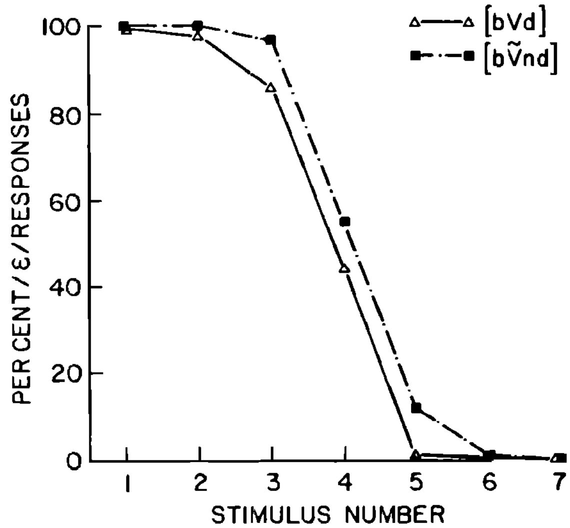

FIG. 8. Identification responses to the contextual nasal [bṼnd] continuum produced with short vowels and the oral continuum [bVd] produced with long vowels.

III. DISCUSSION

The present results support previous findings that nasalization can affect perceived vowel height. As in prior work, the effects of noncontextual nasalization on perceived vowel height were correlated with the acoustic consequences of nasalization in the spectral region (i.e., the vicinity of $F1$) associated with vowel height. Perceptual lowering of the noncontextual nasal vowels obtained in our study was consistent with a higher frequency $F1'$ in the nasal vowel spectra than $F1$ in the corresponding oral vowel spectra. These findings suggest that listeners can be misled by the resemblance between the spectral effects of velopharyngeal coupling and those of a modification of oral tract configuration. The use of articulatory synthesis in the present study enabled us to specify identical oral tract configurations for corresponding oral and nasal vowels. Thus our results provide a clear demonstration that perceived vowel height can be affected by manipulating velopharyngeal coupling. While these results are dependent, in part, on the validity of the synthesis model, they dovetail nicely with studies like those of Wright (1975, 1986) that employed naturally produced speech. It is also clear from our results, however, that the perceived height of nasal vowels is not solely a function of their spectral shape. That is, as we varied the context in which the nasal vowels were embedded (i.e., [bṼnd] vs [bṼd]), but held all other articulatory variables constant, perceptual differences emerged. In contrast to the results obtained with the noncontextual nasal vowels, the perceived height of the contextual nasal vowels never differed significantly from that of the oral vowels (of the same duration). Thus listeners who had difficulty assessing the relative contributions of oral tract configuration and velic height to the spectral shape of noncontextual nasal vowels had no such difficulty when a coarticulatory source for vowel nasalization was apparent.

The present finding that listeners are sensitive to the coarticulatory spectral influence of a nasal consonant on an adjacent vowel adds to a growing set of results indicating that vowels are not perceived independently of their phonetic context. Given the complexity of the spectral effects of nasalization on a vowel, our findings provide strong evidence that listeners are sensitive to the ways in which gestures overlap in speech. Here we do not attempt to provide a specific account of how this sensitivity comes about in listeners' processing. The results are clearly compatible with the-

TABLE IV. Results of t tests ($df = 11$, two tailed) assessing the effects of contextual nasalization on perceived vowel height at each of five degrees of velar port opening.

Effects of contextual nasalization on perceived vowel height		
Velar port opening	t statistic	Probability
7.2	2.12	0.06 (ns)
12.0	0.38	0.71 (ns)
16.8	0.35	0.73 (ns)
24.0	1.31	0.22 (ns)
36.0	0.74	0.47 (ns)

ories that take the talker's articulatory gestures to be the (more or less) immediate products of their speech perception mechanism (e.g., Liberman and Mattingly, 1985; Fowler, 1984). Alternatively, it is possible that some kinds of auditory contrast or anchoring effects may mediate this sensitivity to gestural overlap. Further experiments would be necessary to sort out the different hypotheses.

Regardless of the particular mechanisms involved, we interpret the results as suggesting that listeners' perception of the nasal vowel spectrum is interwoven with their sensitivity to whether a nasal vowel is phonologically appropriate in a given environment. It seems likely that English speakers' lack of experience with phonemic nasal vowels (i.e., nasal vowels without adjacent nasal consonants) led them to resolve the spectral effects of noncontextual nasalization in terms of an acoustically compatible tongue or jaw gesture. This interpretation predicts that different results would be obtained if we were to examine perceptual judgments of contextual and noncontextual nasal vowels by speakers of a language with phonemic (as well as allophonic, i.e., contextual) nasal vowels.

The findings here, which suggest that listeners are able, under certain circumstances, to make accurate assessments of nasal vowel height, also provide insight into circumstances that might lead to listener misperceptions and sound change. The link between perceptual and phonological shifts in nasal vowel height is assumed to arise when listeners incorporate perceived modifications of oral tract shape into their productions (see also Ohala, 1986). Cross-language evidence attests to widespread phonological effects of nasalization on vowel height that are consistent with the perceptual effects in yielding a contraction of the nasal vowel space along the height dimension. The present study suggests three situations in which phonological shifts in nasal vowel height might emerge.

One source of nasal vowel height shifts may be loss of the conditioning environment (i.e., the nasal consonant) for vowel nasalization. The finding that noncontextual nasalization lowered perceived vowel height indicates that the ability of English speakers to associate the spectral effects of vowel nasalization with a lowered velum breaks down in the absence of a conditioning environment. It is our view that the perceptual lowering in this instance was due to our subjects' lack of familiarity with nasal vowels in oral environments; they, therefore, reconciled the spectral shifts induced by nasality in terms of tongue or jaw height. It is not inappropriate to compare these experimental findings to the historical development of nasal vowels. In the vast majority of languages that have distinctive nasal vowels, these vowels have evolved from earlier sequences of phonemic oral vowels followed or preceded by a nasal consonant, with subsequent nasal consonant loss. Just as our subjects misperceived the height of "unfamiliar" noncontextual nasal vowels, so, in the transition from contextual to distinctive vowel nasalization, might listeners perceive vowel nasalization as vowel raising or lowering. In fact, Beddor *et al.* (1986) provide phonological evidence suggesting the emergence of nasal vowel height shifts around the time of nasal consonant loss.

A second source of height shifts in nasal vowels may be variability in the degree of nasal coupling with which a vowel is produced. In natural speech, such variability is considerable and occurs across vowel tokens, types, and contexts, as well as across speakers and languages. In general, our study indicated that variable amounts of vowel nasalization were not a major source of listener misperceptions. The perceived height of the contextual nasal vowels, whether slightly, moderately, or heavily nasalized, never differed significantly from that of the corresponding oral vowels. But, our figures reveal slight height shifts at the extremes of nasalization. That is, at the two high degrees of nasalization (24- and 36-mm^2 coupling), the functions for the contextual nasal vowels began to approach the functions for the noncontextual nasal vowels, indicating perceptual lowering. Thus, it is possible that, as nasalization became heavy, listeners began to attribute some of the spectral effects of nasalization to a modification of oral tract shape. At the lowest degree of nasalization (7.2-mm^2 coupling), we observed slight perceptual raising, possibly due to listeners' overestimating the contribution of the nasal consonant to the adjacent vowel's spectral shape. Ohala (1986) has suggested that such overcompensation may help explain cross-language diachronic findings showing a tendency for contextual nasal mid vowels to shift upwards when corresponding noncontextual nasal mid vowels shift downwards. Our study suggests that overcompensation may indeed be involved, but that it can be expected to occur only in instances of unexpectedly weak coarticulatory effects of a nasal consonant on an adjacent vowel. Further research with more sensitive measures should be able to address in more depth the influence of variability in degree of coupling (from low to high extremes) on nasal vowel height shifts.

A third possible source of sound changes affecting nasal vowel height stems not from nasalization but rather from the contextual effect of a following consonant cluster on a vowel's duration. Recall that in our model speaker's tokens of "bed" and "bend," the vowel preceding the /_nd/ cluster was shorter in duration than that preceding the single oral stop consonant /_d/. When listeners' judgments of the contextual nasal and oral vowels at their appropriate durations were compared, perceptual raising of the contextual nasal vowels was obtained. This, of course, was in contrast to the result found when vowel duration was held constant, i.e., no effect of contextual nasality on perceived vowel height. Thus a specifically durational effect may play a role in nasal vowel height shifts. This durational effect is of special interest for a number of reasons. First, it suggests that phonetic explanations for nasal vowel height shifts need to consider the temporal as well as the spectral characteristics of nasal vowels. Second, it suggests that while listeners are sensitive to the spectral influence of a nasal environment on a vowel, they do not similarly appear sufficiently sensitive to the temporal influence of the same environment (cf. Nooteboom, 1974). Although this finding is provocative, we must be tentative about our conclusions, because our durational specifications were based on vowel durations obtained from a single speaker. While it is generally expected that vowels will be shorter when preceded by a cluster (e.g., /_nd/) rather than a single consonant (e.g., /_d/), we do not yet know whether the particular differences displayed by our speaker are typical. Interestingly, this finding also bears on the question of why contextual and noncontextual nasal vowels of similar quality sometimes shift in opposite directions. As shown here, certain contexts in which nasal vowels occur apparently exert a shortening influence on the vowels' duration and, as a result, a raising influence on perceived height. The duration of phonemic nasal vowels may, likewise, contribute to perceptual shifts, and, in fact, may predispose them to lowering. Historically, phonemic nasal vowels have evolved out of contextual nasal vowels, as discussed above. The loss of the adjacent nasal consonant, and phonemicization of the vowel's nasality have been thought to coincide with compensatory lengthening of the vowel (Clements, 1982). The increased duration of the phonemic nasal vowel may contribute to the perception of a lowered vowel. Thus, durational differences between contextual and noncontextual (phonemic) nasal vowels may predispose the former to shift upwards and the latter, downwards. These observations further reinforce our view of the necessity to consider temporal influences on nasal vowel height shifts.

We hoped from the beginning that our study would afford insight into the relationship between perceptual and phonological shifts in nasal vowel height. Our results suggest a role for both spectral and temporal characteristics of nasal vowels. But, it is also clear that these factors are only part of the story. When embedded in different phonetic contexts, articulatorily and acoustically identical nasal vowels were judged as different in height. This finding supports the view that the link between the acoustic and perceptual effects of vowel nasalization is mediated by the context in which the nasal vowel occurs.

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APPENDIX A: ACOUSTIC CHARACTERIZATION OF STIMULI

The stimuli for this experiment were specified in terms of the synthesizer's articulatory parameters. For purposes of comparability with other studies, however, it is possible to provide an acoustic characterization of the stimuli. As noted in the text, the vocal tract configuration for each synthesis frame is used to compute an area function, which is, in turn, used to compute an acoustic transfer function. This transfer function is a ratio of two polynomials in Z: The roots of the numerator represent the zeros of the filter, while the roots of the denominator represent the poles of the filter. The frequency locations of these poles and zeros could be used as input values to a terminal analog synthesizer to approximate the stimuli of this experiment.

In Tables AI–AVII, we give the frequencies (in Hz) of

TABLE AI. Stimulus No. 1.

Oral	*F*1	*F*2	*F*3	*F*4	*F*5
F	580	1886	2765	3705	4804
B	77	113	148	312	403
Nasal	Velar port opening	*FN*	*FZ*	*F*1′	
	7.2	478	~500	~600	
	12.0	482	~530	~675	
	16.8	488	569	~725	
	24.0	490	637	~750	
	36.0	492	704	775	

TABLE AII. Stimulus No. 2.

Oral	*F*1	*F*2	*F*3	*F*4	*F*5
F	618	1860	2772	3696	4785
B	78	112	155	346	467
Nasal	Velar port opening	*FN*	*FZ*	*F*1′	
	7.2	475	~500	~625	
	12.0	490	~530	~650	
	16.8	498	560	~700	
	24.0	502	625	730	
	36.0	504	694	802	

TABLE AIII. Stimulus No. 3.

Oral	*F*1	*F*2	*F*3	*F*4	*F*5
F	657	1830	2785	3688	4756
B	79	115	173	432	587
Nasal	Velar port opening	*FN*	*FZ*	*F*1′	
	7.2	471	~500	649	
	12.0	494	~530	~700	
	16.8	504	550	~750	
	24.0	509	617	769	
	36.0	514	685	819	

TABLE AIV. Stimulus No. 4.

Oral	*F*1	*F*2	*F*3	*F*4	*F*5
F	680	1785	2791	3671	4744
B	99	122	183	407	629
Nasal	Velar port opening	*FN*	*FZ*	*F*1′	
	7.2	469	~500	690	
	12.0	495	~530	721	
	16.8	507	545	755	
	24.0	515	613	790	
	36.0	527	676	843	

TABLE AV. Stimulus No. 5.

Oral	$F1$	$F2$	$F3$	$F4$	$F5$
F	718	1760	2817	3680	4635
B	98	121	185	525	1188
Nasal	Velar port opening	FN	FZ	$F1'$	
	7.2	466	~500	733	
	12.0	496	~530	762	
	16.8	509	541	782	
	24.0	524	608	819	
	36.0	538	667	862	

TABLE AVII. Stimulus No. 7.

Oral	$F1$	$F2$	$F3$	$F4$	$F5$
F	784	1683	2865	3727	~4750
B	82	127	217	633	···
Nasal	Velar port opening	FN	FZ	$F1'$	
	7.2	461	~500	804	
	12.0	495	~530	821	
	16.8	513	536	848	
	24.0	536	598	877	
	36.0	549	658	908	

the poles and zeros for each of the seven vowels, separately for the oral versions and for each of the five degrees of nasalization (listed according to velar port opening, in mm^2). The values given correspond to a point in time (during the vowel) at which both the tongue shape and the velar port opening reach their target values (approximately 160 ms from the beginning of the stimulus). The values are the same for both contextual and noncontextual nasal stimuli, and for both short and long stimuli.

The first part of each table shows the frequencies ($F1$–$F5$) and bandwidths ($B1$–$B5$) of the poles of the oral version of the vowel (the oral versions do not have zeros). The effect of adding nasalization to each vowel is to add a low-frequency nasal pole (FN) and a low-frequency nasal zero (FZ), as well as to shift the frequency of the first formant of the oral vowel ($F1'$). These three values are given for each of the five degrees of nasalization. Additional higher frequency pole/zero pairs are also added as nasalization increases, but the poles and zeros are so close in frequency that they almost completely cancel and have only trivial effects on the transfer function. Likewise, there are some small shifts in the other oral formant poles ($F2$–$F5$) as nasalization increases, but again, effects are quite small and are ignored here.

Finally, it was not possible to solve directly for the roots of the transfer function numerator and denominator, and thus the poles and zeros had to be obtained by finding the peaks in the Fourier transform (FFT) of the two polynomials. Most of the values shown below were obtained by an automatic peak-picking routine. In some instances (typically at low degrees of nasalization), the routine failed to locate one or more of the relevant peaks. When this occurred, the frequency values were estimated graphically; these estimates are preceded by a "~" symbol in the table.

TABLE AVI. Stimulus No. 6.

Oral	$F1$	$F2$	$F3$	$F4$	$F5$
F	752	1724	2841	3664	~4750
B	91	129	205	610	···
Nasal	Velar port opening	FN	FZ	$F1'$	
	7.2	463	~500	771	
	12.0	495	~530	794	
	16.8	512	538	817	
	24.0	532	603	851	
	36.0	544	661	889	

APPENDIX B: $F0$ TEST

The $F0$ test was designed to ascertain whether the difference in the $F0$ contours of the contextual nasal stimuli on the one hand, and the oral and noncontextual nasal stimuli on the other, could have affected the pattern of results obtained in the main experiment. The $F0$ of the contextual nasal stimuli synthesized for the main experiment rose from 85 to 100 Hz during the transition to the nasal murmer. The $F0$ of the oral and noncontextual nasal stimuli, however, remained at 85 Hz from the middle of the vowel through the end of the utterance.

1. Methods

The stimuli consisted of modified versions of all of the "short" contextual nasal utterances (i.e., those with the shorter vowel durations) used in the main experiment, as well as the original "short" noncontextual nasal utterances and the "short" oral utterances. The "long" utterances were not included because there had been no interaction between vowel duration and the factor "utterance type" (oral, contextual nasal, noncontextual nasal). In the $F0$ test, the short contextual nasal utterances were modified so that $F0$, which fell from 100 to 85 Hz after 150 ms, then remained at 85 Hz with no subsequent rise. This manipulation yielded identical $F0$ contours for the three utterance types.

Test tapes were made using the same ordering of stimuli for a given condition as was used in the main experiment. Except for the absence of "long" stimuli, all testing procedures used in the first experiment were also used here. Five subjects participated in the $F0$ test.

2. Results and discussion

We obtained the 50% crossover values (from /ɛ/ to /æ/) for each subject's judgments of the oral, contextual nasal, and noncontextual nasal stimuli. Here, we collapsed the judgments across degree of nasalization within the two nasal conditions. Our statistical analyses consisted of two paired t tests ($df = 4$, two tailed). The first of these compared the perceived height of the oral stimuli to that of the contextual nasal stimuli. The results indicated that utterances in these two conditions were, as in the main experiment, perceptually similar ($t = 0.25, p = 0.8$). The second t test compared subjects' judgments of the noncontextual nasal stimuli to their judgments of the oral stimuli. These results suggested that noncontextual nasalization did have a lowering effect on perceived vowel height, as in the main experiment ($t = 2.26, p < 0.09$), although the effect did not quite reach significance in this experiment, which only involved a small number of subjects. We were, however, satisfied that additional subjects would have provided a better significance level since the oral and noncontextual nasal stimuli used in the $F0$ test were the same as those used in the main experiment, where the larger subject number yielded a significant result.

Based on the results of the $F0$ test, we concluded that the $F0$ difference in the main experiment's stimuli was not likely to have been an important factor with respect to the outcome of that experiment.

[1]Although English does not typically have distinctive nasal vowels before voiced stops, an apparent exception to nondistinctive vowel nasalization in American English occurs before voiceless stops. Malécot (1960) found that nasal consonants before voiceless stops are of extremely short duration, and may possibly be absent for some speakers, suggesting the existence of minimal pairs (e.g., *cat* versus *can't*) differing only in vowel nasality. The same observation was made by Fujimura (1977).

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