FORMANT INTEGRATION AND THE PERCEPTION OF NASAL VOWEL HEIGHT

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Abstract. Research on oral vowels has shown that vowel perception involves integration of adjacent spectral components such that perceived height correlates with the center of the first region of spectral prominence or "center of gravity". This study investigated the center-of-gravity effect in nasal vowels and asked whether formant integration in vowel perception extends to the first oral formant, F1, and the first nasal formant, FN. Five nasal vowels, [I ə ǝ ɔ ɔ̃], were synthesized. For each nasal vowel, a continuum of synthetic oral vowels was generated by manipulating the frequency of F1. Five vowel sets were constructed by pairing the nasal vowel standard with each member of the corresponding oral vowel continuum; listeners selected the "best-match" pair for each set. Listeners chose the oral-nasal pairs with the same F1 frequency in vowel set i only. For ɛ, ɐ, a, and o, listeners' matches depended on the relative position of F1 and FN in the nasal vowel: when FN frequency was less than F1, as in [ɔ̃] and [ɔ̝], the best oral match had a relatively low F1 frequency; when FN frequency exceeded F1, as in [ɔ̝] and [ɔ̃], the oral match had a high F1. These perceptual data indicate spectral averaging of adjacent oral and nasal vowel formants, thereby demonstrating the center-of-gravity effect in the perception of nasal vowels.

This paper reports the results of a study of the acoustic features determining perceived height in nasal vowels. Most previous research of the perception of vowel height has dealt with oral vowels. Phoneticians generally acknowledge that the perceptual dimension of height in oral vowels is inversely correlated with the frequency of the first formant, such that height perceptually lowers as first formant frequency increases (Fant, 1960; Joos, 1948; Ladefoged, 1982; Peterson & Barney, 1952). But despite this correlation, the frequency of the first formant is not the sole determinant of perceived vowel height.

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Experimental evidence indicates that the first formant does not acoustically specify height in oral vowels when the frequencies of the first two vowel formants are relatively close together, as in back vowels. Studies with synthetic vowels have shown that perceived height in back vowels is determined not only by the first formant (F1), but also by the second formant (F2). In experiments where one formant vowel approximations were perceptually matched to two-formant back vowel stimuli, the frequency of the single formant was not matched to F1 or F2 of the two-formant stimulus, but was instead located between F1 and F2 (Bedrov, Chistovich, & Sheikin, 1978). Similarly, Delattre, Liberman, Cooper, and Gerstman (1952) found that reduction in F1 amplitude perceptually lowered back (but not front) vowels, while reduction in F2 amplitude perceptually raised back vowels, leading to the speculation that "the ear effectively averages two vowel formants which are close together" (1952, p. 203).

Perceptual averaging of vowel spectrum components that are relatively close in frequency is not restricted to F1 and F2, but also occurs for F2 and F3 (Bladon & Fant, 1978; Carlson, Fant, & Granström, 1975; Carlson, Granström, & Fant, 1970; Miller, 1953) as well as for the first harmonic and F1 (Carlson, Fant & Granström, 1975; Fujisaki & Kawashima, 1968; Traummüller, 1981). A substantial body of data therefore indicates that perception of vowel quality involves calculation of a weighted mean of adjacent spectral prominences rather than merely extraction of the frequencies of the spectral peaks. That is, when two spectral prominences fall within some critical frequency range, vowel quality is determined by the "center of gravity" of the region of prominence (Chistovich & Lublinskaya, 1979; Chistovich, Sheikin, & Lublinskaya, 1979). The center-of-gravity effect disappears when the distance between spectral peaks exceeds 3.0 to 3.5 Bark (Chistovich & Lublinskaya, 1979; Syrdal & Gopal, 1983).¹

This study extends investigation of the center of gravity effect to nasal vowels. The acoustic theory of vowel nasalization predicts that velopharyngeal coupling of the nasal tract to the main vocal tract adds pole-zero pairs and shifts formant frequencies of the transfer function of the coupled system (i.e., nasal vowel) relative to the transfer function of the uncoupled (non-nasal) system. Especially important to this study of nasal vowel height is that the main acoustic effect of nasal coupling is in the region of F1, where F1 of the non-nasal vowel is replaced in the nasal vowel by two poles and a zero (Fant, 1960; Fujimura & Lindqvist, 1971; Hamada, 1983; Stevens, Fant, & Hawkins, in press). The two poles are the first nasal formant and the first oral formant, the latter typically being shifted in frequency, with a wider bandwidth and lower amplitude than the first formant of the non-nasal vowel (Delattre, 1954; House & Stevens, 1956; Mrayati, 1975). Thus the low-frequency region of nasal vowel spectra is characterized by a relatively flat, wide distribution of acoustic energy (see Maeda, 1982). Some of these spectral properties of nasal vowels are illustrated in Figure 1 by the spectrum of a Hindi speaker's nasal [ə] (solid curve), superimposed on the spectrum of Hindi oral [e] (dashed curve). Note that the low-frequency spectral energy of [ə] is spread across two broad spectral prominences while [e] has a single narrow low-frequency spectral peak.

The present study asks if formant averaging in vowel perception generalizes to adjacent oral and nasal vowel formants. Our purpose was to determine whether the perception of height in nasal vowels involves spectral integration of the first oral formant, F1, and the first nasal formant, FN.
Figure 1. LPC spectra of nasal [ə] (solid curve) and oral [e] (dashed curve) produced by a Hindi speaker. The nasal vowel spectrum has two broad spectral prominences in the low-frequency region while the oral vowel spectrum has a single narrow low-frequency spectral peak.

The oral vowel studies reviewed above might lead us to expect F1-FN averaging since the distance between F1 and FN in many nasal vowels is less than 3.5 Bark, i.e., less than the critical distance found for spectral integration of oral vowel components. (For example, the distance between the first two spectral peaks of nasal [ə] in Figure 1 is roughly 2.8 Bark.) Previous nasal vowel research also points toward possible F1-FN integration. Joos (1948) suggested that French /ɛ/ sounded like [ə] because the average frequency of F1 and FN in nasal /ɛ/ corresponds to F1 in oral /æ/. Similarly, Fant (1960) and Wright (1980) speculated that shifts in perceived vowel height accompanying nasal coupling might be due to the additional low-frequency nasal resonance.

Method

Stimulus Materials

The stimulus materials were five sets of nasal and oral vowels generated on the Haskins serial software formant synthesizer. Each 360-ms stimulus consisted of steady-state vowel formants, with fundamental frequency and amplitude decreasing over the final 120 ms.

The five nasal vowel stimuli, [ɪ ʌ ɐ ɑ ɔ], were synthesized by adding a pole-zero pair in the vicinity of the first pole to the five-pole transfer function for an oral vowel. The spectral characteristics of the synthetic nasal vowels were based on FFT and LPC analyses of natural vowel tokens from several languages (Beddor, 1983). Autoregressive LPC spectra of the synthesized nasal vowels are shown in Figure 2, along with the measured frequencies of the first two spectral peaks. The labels assigned to these peaks are to be interpreted with caution, since identifying the "first oral formant" and the
Figure 2. Spectra of the five synthetic nasal vowel stimuli.
extra "nasal formant" of nasal vowels is a terminological problem (see Stevens, Fant, & Hawkins, in press). The convention adopted here is to label as "F1" the first peak in the high and mid nasal vowels, [I], [E], and [O], and the second peak in the low nasal vowels, [a] and [A] (these "F1" values being close to typical F1 frequencies for the oral vowels [i], [e], [o], [a], and [a]). That is, F1 frequency was less than FN frequency in high and mid vowels and greater than FN frequency in low vowels, which is consistent with the acoustic theory of vowel nasalization (Fant, 1960; Fujimura and Lindqvist, 1971) as well as previous analyses of natural nasal vowel tokens (e.g., Fujimura, 1961; Wright, 1980). The added zero was set between the first oral pole and the additional pole for all nasal vowels except high [I], where the zero separated the additional pole and the second oral pole (see Fujimura, 1961; Maeda, 1982).

For each nasal vowel, a continuum of oral vowels was constructed by omitting the extra pole-zero pair. Within each oral continuum, stimuli were identical to each other except for the frequency of F1, which was systematically varied as shown in Table 1. F1 step-size in each continuum was approximately 10% of the average F1 frequency for that vowel set. (Thus step sizes were larger for lower vowels, e.g., F1 step-size was 32 Hz for i, 45 Hz for e, and 60 Hz for a.) The F1 range of each oral continuum included two vowels of special interest. One of these oral vowels was an "F1 match": the frequency of its first formant was the same as the F1 frequency of the corresponding nasal vowel. (This can be seen by comparing the oral vowel F1 values designated by * in Table 1 with the nasal vowel F1 values in Figure 2.) A second oral vowel from each of the five series was a "centroid match" (** in Table 1); this stimulus matched the corresponding vowel on a specific measure of center of gravity.

The centroid of a vowel is a measure of the center of gravity calculated from the LPC spectrum of that vowel. The centroid (CEN) function computes the mean frequency of the area under the spectral curve within specified frequency and magnitude ranges according to the formula

$$X_{CEN} = \frac{\sum_{i=1}^{n} (X_i Y_i)}{\sum_{i=1}^{n} Y_i}$$

where \(X\) = frequency (Hz) and \(Y\) = log magnitude (dB). Figure 3 demonstrates the operation of the centroid function for nasal [E]. The left and right vertical bars delimit the frequency range of 100-1100 Hz and the connecting horizontal bar sets the lower magnitude limit. The spectral curve forms the upper magnitude limit. The center frequency or centroid of this area, 526 Hz, is shown by the dashed vertical line. The frequency and magnitude ranges selected in this study were based on analyses of over 800 natural-speech tokens of oral and nasal vowels (see Beddor, 1983, for discussion of these ranges). The frequency range of 100-1100 Hz was used for all vowel stimuli except for the low central vowels, for which the upper limit was extended to 1400 Hz. The lower magnitude limit was determined separately for each stimulus and was set just below the lowest point in the 100-1100 (or 1400) Hz portion of the spectral curve. The area measured by the centroid function included F1 in all vowels, but also FN in the nasal vowels and F2 in the non-front (oral and nasal) vowels.
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Table 1

F1 values (in Hz) for the oral vowel sets.

<table>
<thead>
<tr>
<th>Stimulus</th>
<th>Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>i</td>
<td>1 253  295*  327  359  391**  423</td>
</tr>
<tr>
<td>e</td>
<td>275  320  365  410*  455  500  545**  590  635  680</td>
</tr>
<tr>
<td>e</td>
<td>390  450  510**  570  630  690*  750  810</td>
</tr>
<tr>
<td>a</td>
<td>420  490  560**  630  700  770*  840  910</td>
</tr>
<tr>
<td>o</td>
<td>300  340  380  420*  460  500**  540  580</td>
</tr>
</tbody>
</table>

* = F1 match  ** = Centroid match

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Figure 3. Illustration of the centroid function using the mid front nasal vowel stimulus, [ê]. The figure indicates the region of the spectrum analyzed by the centroid function: the vertical bars delimit the 100-1100 Hz frequency range, the horizontal bar sets the lower magnitude limit, and the spectral curve forms the upper magnitude limit. The dashed line marks the center frequency or centroid of this region.
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Figure 4 compares the stimuli designated "F1 match" and "centroid match" from vowel set a. In the upper panel, the F1 match, we see that the frequency of the first peak in the oral vowel spectrum (dashed curve) and the frequency of the second peak in the nasal vowel spectrum (solid curve) are the same. In contrast, in the centroid match in the lower panel, the first peak in the oral vowel straddles the two low-frequency peaks of the nasal vowel; while these two spectra share no peak frequency in the first region of spectral prominence, the center frequency of this region is the same in the two spectra.

Figure 4 also shows that, in vowel set a, the oral vowel of the centroid-matched pair has a lower F1 frequency than the oral vowel of the F1-matched pair. This is also true of the low vowel set a, as indicated by the values in Table 1. In contrast, in the non-low vowel sets, i, e, and o, the centroid match has a higher F1 frequency than the F1 match. This is due to the location of the first nasal formant relative to the first oral formant in the nasal vowels (see Figure 2): when FN frequency is less than F1 frequency, as in low nasal vowels, FN pulls down the center of gravity; when FN is greater than F1, as in high and mid nasal vowels, FN pulls up the center of gravity.

Subjects

Twenty paid student volunteers participated in the experiment. All were native speakers of American English with no known hearing loss and no expertise in phonetics. Although several of the subjects had studied a language in which the oral-nasal contrast in vowels is distinctive (e.g., French, Polish), this background had no apparent effect on their results.

Procedure

Test sequences for the five vowel sets consisted of pairs of oral and corresponding nasal vowels. For each set, two types of ordered sequences were made: ascending sequences (i.e., each oral stimulus from 1 through n paired with the nasal standard) and descending sequences (i.e., oral-nasal pairs from n through 1). A pilot study in which listeners selected the "best-match" oral-nasal pair from these sequences showed that matches tended to fall in the middle of the vowel set. To eliminate clustering of responses in the center of each vowel set, three truncated ordered sequences for each vowel set were constructed from the full ascending and descending sequences. The truncated sequences contained the following oral stimuli (paired with the corresponding nasal vowel): i: 1-5 (twice), 2-6; e: 1-8, 2-9, 3-10; a: 1-7 (twice), 2-8; a: 1-6, 2-7, 3-8; o: 1-6, 2-7, 3-8. The three truncated versions of each of the five vowel sets were arranged in random order, for a total of 15 trials. The inter-stimulus interval between members of an oral-nasal pair was .5 s and the interval between pairs in the ordered sequences was 1 s; subjects controlled intervals across sequences and trials.

Before testing, subjects were given a brief description of the kinds of vowel stimuli to be presented. Subjects were told that they would hear 15 sets of vowels, each set consisting of several vowel pairs. They were informed that the first member of each pair varied across the series while the second member stayed the same and that these pair members were "oral vowels" and "nasal vowels," respectively. It was explained that nasal vowels usually
occur in English in the context of m or n, e.g., mom (versus the oral vowel in Bob), man (versus bad), and moan (versus boat).

Figure 4. Spectra of the F1-matched stimulus pair (upper panel) and the centroid-matched stimulus pair (lower panel) for the low front vowel set æ.
Subjects were tested individually in a sound-attenuated booth. Stimuli were presented binaurally over TDH-39 earphones with an interactive computer program. At the onset of each of the 15 trials, the program presented the ascending and descending truncated sequences for that vowel set. (The relative order of ascending and descending sequences was counter-balanced across trials.) The subject could then request repetitions of either of the sequences or of individual oral-nasal pairs from the sequence. For each trial, a subject was instructed to select that pair in which the oral vowel was the most similar to the nasal standard; this "best-match" pair was circled on a printed score sheet. A subject was encouraged to listen to the sequences and to individual pairs as many times as needed to feel confident about the best-match decision. Average testing time was approximately 45 minutes.

Results

The histograms in Figure 5 show subjects' responses to the five vowel sets, i, e, a, â, and o. As there was no apparent effect of truncation, responses to the three truncated versions of each vowel set were pooled. The data therefore represent 60 responses (20 subjects X 3 truncations) per vowel set. Oral vowel stimulus number is on the ordinate and percent best-match responses on the abscissa. The F1 match in each vowel set is indicated by * and the centroid match by **.

Figure 5 shows that subjects' best-match responses to each vowel set are spread over several stimulus pairs. Of special interest here are the F1- and centroid-matched pairs. It was hypothesized that if perceived nasal vowel height was determined by center of gravity, then the perceptually most similar oral-nasal pair in each vowel set would be the centroid-matched pair. If, however, perceptual integration of F1 and FN did not occur, then the most similar pair might be expected to be the F1-matched pair.

As seen in Figure 5, the F1-matched oral-nasal pair in vowel set i accounted for over 70% of subjects' responses. But in the remaining four vowel sets, subjects perceived the F1-matched pair as the most similar pair only 2% to 12% of the time. For each of the five vowel sets, a t-test of the difference between the stimulus number of the F1 match and the mean stimulus value of each subject's responses showed that responses differed significantly from the F1-matched vowel pair, i, t(19) = 2.68, p < .05; e, t(19) = 11.87, p < .01; a, t(19) = 15.88, p < .01; â, t(19) = 14.45, p < .01, and o, t(19) = 10.97, p < .01. These findings are consistent with the data of Wright (1980), which showed that perceptual effects of nasalization on vowel height were not always a function of acoustic effects of nasalization on first formant frequency.

Although listeners generally did not match oral and nasal vowels on the basis of first formant frequency, they also tended not to choose the centroid-matched pairs as perceptually similar. In the mid and low vowel sets, the most frequently-chosen oral-nasal pair fell between the F1 and centroid pairs. This modal best-match response was closer to the centroid for mid front e, but closer to F1 for the low vowels â and a. However, due to the centroid skew of the â, a, and o distributions, subjects' mean response (given in Figure 5) was closer to the centroid than to F1 for all four non-high vowel sets. A t-test for each vowel set compared the difference between the stimulus number of the centroid match and each subject's mean response to the difference between the F1 match and mean responses. The analyses showed that
Figure 5. Percent "best-match" responses to the oral-nasal vowel pairs for the vowel sets i, e, æ, a, and o, where * = F1-matched pair and ** = centroid-matched pair.
perceptually-similar pairs of oral and nasal vowels were significantly closer to the centroid-matched pair than to the F1-matched pair in the four non-high vowel series, e, a, o, t(19) = 3.27, 3.41, 4.87, respectively, p < .01; and a, t(19) = 2.24, p < .05. Only in the high vowel set i were listeners’ responses significantly closer to the vowel pair matched for F1 frequency, t(19) = 18.15, p < .01.

Discussion

The purpose of this experiment was to determine whether spectral integration of the first oral and nasal formants occurs in the perception of nasal vowels such that perceived nasal vowel height correlates with the center of the first region of spectral prominence rather than with the frequency of the first formant. The method used to elicit height judgments from phonetically-naive subjects required listeners to select from a continuum of oral vowels the vowel that was perceptually most similar to a nasal vowel standard. Since the oral stimuli differed from the nasal standard only in low-frequency spectral characteristics, the selected oral match was taken as an indication of the perceived height of the nasal vowel. The results suggest that perception of nasal vowel height, as measured by this paradigm, involves integration of low-frequency spectral prominences. Perceived nasal vowel height was not determined solely by the first formant: with the exception of high [I], F1 accounted for very few of the listeners’ responses. Rather, listeners’ responses showed very consistent deviations from F1: when the frequency of FN was less than the frequency of F1, as in low [â] and [ã], the closest oral match had a relatively low F1 frequency; when FN frequency was greater than F1 frequency, as in mid [ê] and [œ], the selected oral match had a relatively high F1. In all four of these vowel sets, the selected F1 frequency of the oral vowel was intermediate relative to the F1 and FN frequencies of the nasal vowel. Even for high [I], over 80% of the non-F1 responses were pulsed in the direction of the nasal formant. Thus our data provide empirical support for previous speculations that the relative positions of the first oral and nasal formants might influence perceived nasal vowel height (Fant, 1960; Joos, 1948; Wright, 1980).

The finding that perceived nasal vowel height was not determined by the frequency of a single low-frequency spectral peak but rather involved apparent integration of low-frequency spectral components demonstrates the center-of-gravity effect in the perception of nasal vowel height. The high front nasal vowel, however, did not show strong evidence of perceptual integration of F1 and FN: the majority of listeners’ responses to [I] points toward F1 frequency as determining perceived height. A possible explanation for this difference between the high and non-high vowels lies in the distance between F1 and FN frequencies in [I] versus [ê], [ê], [ã], and [œ]. As noted above, Chistovich and Lublinskaya (1979) and Syrdal and Gopal (1983) report that formant integration does not occur in oral vowels (i.e., the center-of-gravity effect disappears) when formant distance exceeds 3.5 Bark. In our stimuli, the separation between F1 and FN in the mid and low nasal vowels was 2.5 and 3.4 Bark, respectively, while the separation for the high nasal vowel was 4.5 Bark. F1-FN integration in the mid and low, but not the high, nasal vowels is therefore consistent with previous oral vowel findings.
While the center-of-gravity effect is apparent in the mid and low vowel data, it is also clear that perceived nasal vowel height did not correspond exactly with our measure of center of gravity, the centroid. Although obtained matches between oral and nasal vowels were significantly closer to the centroid-matched pairs than to the F1-matched pairs, 38% to 75% of the responses to the non-high vowel sets fell between the F1- and centroid-matched pairs. This bias towards F1 in listeners' judgments indicates that, for the centroid to reflect perceived vowel height, F1 should be given more weight than in the current measure. Note, however, that such a revision is not simply a matter of increasing the weight of the lowest-frequency spectral peak, since in low [ə] and [æ], F1 was the second, rather than the first, spectral prominence. Although identification of the spectral prominence corresponding to F1 is problematic in nasal vowels, this problem does not change our finding that subjects' responses were higher than the centroid for low nasal vowels but lower than the centroid for non-low nasal vowels. Furthermore, the F1 bias cannot be accounted for by increasing the weight of the higher-magnitude spectral peak, since the magnitude of the second peak was greater than the magnitude of F1 in mid [ʊ]. It appears, then, that no simple weighting of spectral components in terms of their frequency and magnitude will account for perceived center of gravity in nasal vowels. Whether oral vowels show a similar discrepancy between perceived center of gravity and the centroid is currently under investigation.

In summary, although our measure of center of gravity needs to be revised, the results clearly evidence the center-of-gravity effect in the perception of nasal vowel height. Previous studies with oral vowels have shown that vowel formants are integrated over frequency intervals which are broader than a critical band (Bladon, 1983; Chistovich & Lublinskaya, 1979; Syrdal & Gopal, 1983). Our findings with the first oral and nasal formants of nasal vowels show that nasal vowel formant energy is also integrated over relatively wide frequency intervals. Whether the critical distance for formant averaging is the same in nasal vowels as in oral vowels needs further study. The data presented here, however, are consistent with the critical distance of 3.5 Bark previously reported for oral vowels.

References


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Footnotes

1 The Bark scale divides the audible frequency range into units of critical bands, where 1 Bark equals one critical band. The relationship of Hertz to Bark is expressed in the following equation from Schroeder, Atal, and Hall (1979)

\[ f = 650 \sinh(x/7) \]

where \( f \) is frequency in Hz and \( x \) is frequency in Bark.

2 Since there is a problem in identifying the first oral versus the first nasal formant of nasal vowels, we might ask whether the F1 match indeed matches first oral formant frequencies of the oral and nasal vowels or whether it might be a F1-FN match in some vowel sets. One way to avoid this issue would be to extend the F1 range covered by each oral vowel continuum to include the frequencies of both F1 and FN of the corresponding nasal vowel. However, a pilot study with such extended continua indicated that pairs in which F1 frequency of the oral vowel matched what we have labeled "FN" frequency of the nasal vowel were very poor perceptual matches. Inasmuch as these extended series were unnecessarily long, the "FN" end of the series was omitted in the actual experiment.

3 For all vowel sets, matches between oral and nasal vowels in F1 and centroid values were based on measurements of LPC spectra of these vowels. In the LPC analysis, 14 predictor coefficients were calculated for each oral vowel and 18 for each nasal vowel. To verify the LPC measures, F1 and centroid values were also obtained from FFT spectra of the vowel tokens. These frequencies were within 15 Hz of the LPC measures.

4 For a single frequency range to be applied in each vowel set, a rather broad frequency range was necessitated by the variation in F1 frequency in the oral continua (the F1 frequencies of the endpoint stimuli in a continuum were up to 490 Hz apart). This broad range, however, is not meant to imply that perceivers average spectral information over a 1000 Hz range. A more accurate interpretation is that these frequencies might be relevant to perception of vowel height; additional research is of course necessary to determine the limits of the relevant frequency range.

5 Similarly, Carlson, Fant, and Granström (1975) reported that efforts to calculate F2' as a linearly weighted mean frequency of F2, F3, and F4 were unsuccessful. Their revised formula gave greater weight to F2 when F2 was close to F3 but greater weight to F3 and F4 when F2 and F3 were far apart.