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Predicting the Structure of Phonological Systems

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Abstract. Do the phonological predictions derived from phonetic models impose restrictions on the definition of 'possible phonological system'? This question is addressed by examining the spectral integration model of vowel perception. The output of the model is investigated under a series of phonetic manipulations and translated into a set of phonological predictions, which are then compared against cross-linguistic patterns in vowel processes and inventories. It is argued that, despite the serious constraints on predictive power imposed by language-specific aspects of phonetic and phonological structure, phonetic models such as the spectral integration model enable us to define the set of phonetically motivated phonological phenomena.

One of the goals of phonological theory is to delimit or define the set of possible phonological systems. Phonetic theory has, in recent years, focused on the development of models of the human speech mechanism. These two goals overlap in that the phonetic models have been used to generate sets of predictions concerning the structure of phonological systems. The present paper considers the possible consequences of this approach for phonological theory by asking whether the predictions derived from phonetic models impose restrictions on the definition of 'possible phonological system'.

In answering this question, this paper examines one specific phonetic model, the spectral integration model of vowel perception. The model is used to generate a set of predictions concerning the effects of five phonetic manipulations – nasal coupling, horizontal tongue body constriction, lip rounding, breathy voice, and creaky voice – on perceived vowel height. The general question of the consequences of phonetic models for phonological theory is then addressed in terms specific to this model: To what extent do the automatic constraints on vowel processing imposed by the spectral integration model translate into phonological predictions concerning the nature of vowel raising and lowering processes and the structure of vowel inventories?

1. Phonetic Modeling

Quantitative models of specific components of the speech process have many applications, one type of which is to phonological systems. Interpreting a phonetic model in terms of its phonological consequences often involves some version of the following three steps: First, the response of the model is investigated under selected phonetic conditions, yielding a set of output conditions. Second, the output conditions are interpreted as a set of predictions concerning the structure or behavior of phonological systems. Third, these predictions are tested against such aspects of phonological systems as features, units, inventories, and processes. The focus in this paper is on predictions as tested against phonological inventories and processes. [Concerning the relation of phonetic models to phonological features and units, see, for example, Stevens, 1983 and 1989, and Browman and Goldstein, 1989, respectively, and also Keating, 1988, for an overview.]

Each of the three steps just described rests on a set of assumptions. The phonetic model itself is of course only an approximation to a component (e.g., the aerodynamic, articulatory, or acoustic component) of the speech process. Thus, in the first step, the validity of the output conditions of the model depends on the adequacy of both the model and the characterization of the input conditions. In the third step, it is the adequacy of the available language data that is potentially problematic. That is, a fundamental assumption is that language data in grammars or other linguistic accounts provide sufficiently detailed and accurate phonetic descriptions to serve as an appropriate test of the model's predictions.

In the second step, phonetic models tend to be interpreted in one of two ways with respect to their phonological consequences. Under one interpretation, the output conditions of the model are viewed as physical limits which have fairly direct consequences for the behavior of speaker-hearers; these phonetic consequences may become incorporated into the phonological system. This approach is represented by the work of Ohala [e.g., 1974, 1981, 1983], who argues that physical constraints result in speaker-induced or listener-induced variation in the speech signal. Such variation may (under appropriate conditions not, for the most part, specified by phonetic models) result in sound change, which is synchronically reflected in phonological processes or the structure of phonological inventories. For example, calculations using models of speech aerodynamics indicate that voicing can be sustained longer in a front-articulated stop than in a back-articulated stop [Ohala, 1983; Keating, 1984]. Phonetically, if preferred closure duration were the same for all places of articulation, back stops might be expected to sporadically devoice. Systematic incorporation of such occasional devoicing into a language should result in allophonic or morphophonemic alternations or, if applied to all instances of a back stop, loss of that stop (e.g., /g/) in the segment inventory. Cross-linguistic phonological patterns support these predictions: devoicing processes appear to be favored in back stops and voiced stop inventories are more likely to lack back stops than anterior ones [Ohala, 1983; Maddieson, 1984].

Under a second interpretation of phonetic models, the output conditions are viewed as default or optimal settings (as opposed to physical limits).

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2. A Phonetic Model: Spectral Integration

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posed to physical limits). This approach assumes that speaking and listening are processes governed in part by the biological principle of least effort and that the development of phonological systems is in part an adaptation to this principle [see, e. g., Lindblom, 1983]. The translation of output conditions into a set of phonological predictions thus requires a definition of 'least effort' for that aspect of the speech system. When applied to speaker-based models, least effort is translated into a model-specific definition of 'ease of articulation'. For example, Westbury and Keating [1986] used a mathematical aerodynamic model to predict patterns in stop consonant voicing and defined least effort as minimal velocity of articulatory transitions. When applied to listener-based models, the principle of least effort is interpreted as 'maximal perceptual contrast', which assumes the listener's task to be easiest when speech sounds are perceptually as different as possible. Assuming this principle, a model which derives acoustic or perceptual distance measures can be used to predict, for example, the relative frequency of certain consonant or vowel inventories in the world's languages [e. g., Liljencrants and Lindblom, 1972; Lindblom, 1986; Wright, 1986]. As it is ultimately the combined motor-perceptual system that is critical here, a principle of overall economy has been proposed in recent applications of phonetic models to phonological systems [e.g., Lindblom and Maddieson, 1988].

2. A Phonetic Model: Spectral Integration

This section presents the spectral integration model of vowel perception as it has been described and developed in the literature and considers its implications for phonological systems. The limitations of this model and approach need to be recognized. The spectral integration model is based on imperfect understanding of both acoustic-to-auditory transformations and the effect of these transformations on the perception of vowel quality. The model is also based for the most part on static characteristics of the vowel spectrum and does not take into account coarticulatory influences on perceived vowel quality. Further, by viewing the spectral integration model in isolation, other phonetic influences on vowel systems are being ignored. The approach taken here is to temporarily minimize these limitations in order to maximize the predictive strength of the model – in effect, to push the model as far as possible (sections 2.1 and 2.2). Phonetic and phonological restrictions on this approach are then discussed (section 2.3), leading to limited predictions which are tested against phonological data (section 2.4).

2.1. Description of the Model

The theory of spectral integration predicts that, when two adjacent peaks in a vowel spectrum are close in frequency, the perception of vowel quality is determined by a weighted average of this region of the spectrum rather than by the frequency of the individual peaks. This theory rests on a perceptual phenomenon first demonstrated by Delattre et al. [1952], who found that perceptually acceptable one-formant approximations to nonfront vowels could be synthesized by a single formant intermediate in frequency between F_1 and F_2 of the

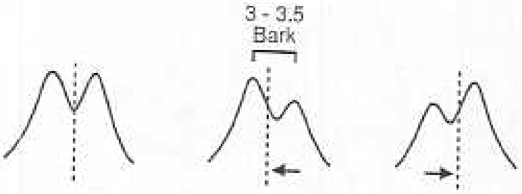

Fig. 1. Schematic representation of the spectral integration phenomenon according to Chistovich's model. When two spectral peaks are within 3–3.5 Bark of each other, the frequency corresponding to the perceptual center of gravity (see text), represented by the dashed line, is an amplitude-weighted measure of the mean frequency of the two peaks.

corresponding naturally produced vowels. Front vowel approximations generally required two formants, with the preferred stimuli having a second formant higher in frequency than that of F_2 of natural front vowels. Given the proximity of F_1 and F_2 in back vowels, and of F_2 and F_3 in front vowels, Delattre et al. [1952] speculated that listeners' responses were governed by formant spacing. This phenomenon of averaging or integration of spectral peaks close in frequency has been substantiated in numerous subsequent experiments [e.g., Miller, 1953; Carlson et al., 1975; Bladon and Fant, 1978; Traunmüller, 1981; Beddor and Hawkins, 1990].

The detailed spectral characteristics under which spectral integration occurs have been investigated by Chistovich and Lublinskaya [1979] and Chistovich et al. [1979] and incorporated into a model of auditory spectrum processing [Chistovich, 1985]. The focus here is on those aspects of the model specifically related to spectral integration. Two aspects are particularly noteworthy. First, based on listener matches for vowel quality between one-formant and two-formant synthetic vowels, the frequency range within which spectral integration occurs was calculated at 3–3.5 critical bands or Bark. Adjacent spectral peaks are perceived as a single 'center of gravity' only when they fall within this critical range. Second, when two formants are within the critical distance, the perceptual center of gravity of that region of the vowel spectrum is influenced by relative formant amplitude. As schematically represented in figure 1, the perceptual center of gravity (i.e., the frequency of the one-formant stimulus that listeners would choose as most similar to the two-formant reference vowel) falls in the middle of the spectral region when the two formants have equal amplitudes, but is closer to the greater-amplitude peak when the formants have different amplitudes. The model defines the centroid, an amplitude-weighted measure of mean frequency in the critical frequency range, as a spectral measure of the effective perceptual center of gravity, according to the formula [based on Chistovich, 1985]

$$X_{CEN} = \sum_{i=1} (X_i Y_i) / \sum_{i=1} (Y_i)$$

where X = frequency (Bark) and Y = response magnitude (variably computed in linear, power, and log scales).

Thus Chistovich's model predicts that spectral smoothing applies within a band of 3–3.5 Bark. The critical distance of roughly 3 Bark is well attested [Bladon, 1983; Syrdal, 1985]. However, recent studies suggest the need to modify Chistovich's formulation of the smoothing function in terms of the relative weighting of formant frequency and amplitude. Klatt [1985] covaried formant amplitude and frequency such that the perceptual center of gravity should re-

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main constant according to Chistovich's formulation and found that the contribution of formant frequency to perceived vowel quality outweighed that of formant amplitude. Beddor and Hawkins [1990] manipulated formant bandwidth and found that formant frequency dominated perceived vowel quality when formant bandwidths were narrow, whereas overall spectral shape exerted more influence when bandwidths were wide.

Based on these findings, the model adopted here assumes that the integration function of 3–3.5 critical bands is an amplitude-weighted frequency measure in which the relative weight assigned to amplitude increases as spectral prominence decreases. While a precise spectral measure of the integration function is lacking, the description is sufficiently detailed to predict the *direction* of a shift in the perceived center of gravity that results from a given spectral manipulation, and in this respect the model can be investigated under a variety of phonetic conditions.

2.2. Output of the Model: Manipulating the Low-Frequency Center of Gravity

This section investigates the consequences of the spectral integration model for perceived vowel height. The perceptual dimension of height is often described as correlating with the frequency of F_1, such that perceived vowel height lowers as F_1 frequency increases [e.g., Peterson and Barney, 1952; Fant, 1960; Lindau, 1978]. The spectral integration model as presented above leads to the expectation that, while this description works well for vowels whose low-frequency spectrum is dominated by F_1, a more general characterization is that perceived height correlates with the low-frequency region of spectral prominence. Under this view, phonetic manipulations which shift the center of gravity of the low-frequency region of prominence in a vowel spectrum are predicted to influence perceived vowel height. Below, the specific consequences of five such manipulations are considered: nasal coupling, horizontal tongue body position and lip position (taken together as oral cavity shape), and breathy and creaky voice (taken together as phonation type).

2.2.1. Nasal Coupling

Coupling the nasal tract to the oral tract in the production of a nasal vowel principally affects the vowel spectrum in the low frequencies, where a pole-zero pair is added in the vicinity of F_1 [Fujimura and Lindqvist, 1971; Stevens et al., 1987]. A consequence of the nasal pole-zero pair is that the low-frequency spectral energy has a low amplitude and is distributed over a broad frequency region relative to the spectrum of the corresponding nonnasal vowel [House and Stevens, 1956; Hawkins and Stevens, 1985]. These changes in spectral shape are generally accompanied by frequency shifts in the center of gravity of this region of the spectrum. The frequency of the first 'oral' formant of the nasal vowel, F_1' is shifted relative to F_1 frequency of the corresponding nonnasal vowel. The frequency of the added nasal formant, F_N, is generally less than that of F_1' in low vowels, but greater than F_1' frequency in high and (higher-) mid vowels [Fant, 1960; Fujimura and Lindqvist, 1971]. These consequences of nasal coupling are illustrated in figure 2 by the vocal tract transfer functions of oral and

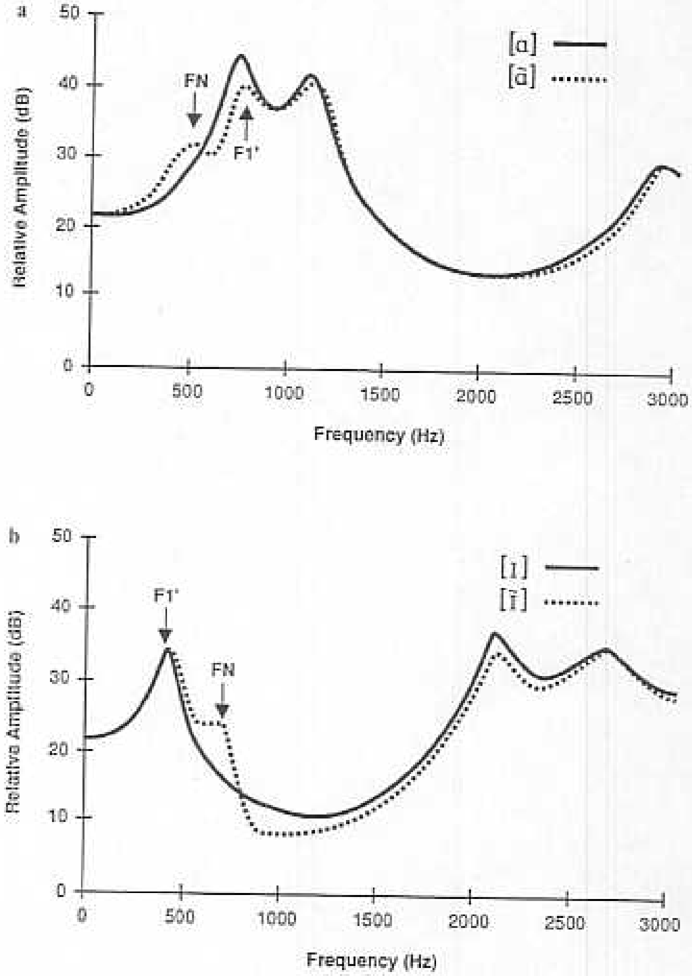

Fig. 2. Transfer functions of articulatorily synthesized oral (solid lines) and nasal (dashed lines) vowels differing in velar port opening. The most prominent nasal formant introduced by port opening is in the F_1 region, F_N frequency being less than F_1' frequency in the low vowel (a) and greater than F_1' frequency in the high vowel (b).

nasal versions of [ɑ] and [ɪ] generated on the Haskins Laboratories' articulatory synthesizer [described by Rubin et al., 1981]. In both nasal vowels, F_N is within 3.5 Bark[1] of F_1', but in the low vowel, addition of a moderate degree of coupling shifted the center of gravity of the low-frequency region slightly downward, while in the high vowel, coupling shifted the center of gravity upward. So, in general, F_N is predicted to lower the low-frequency center of gravity in low vowels and to raise it in high and mid vowels.

That these shifts in the center of gravity due to nasal coupling correlate with shifts in perceived vowel height has been demonstrated experimentally. Using formant syn-

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[1] Here and elsewhere in the paper, Bark values were calculated from Hertz values by the equation provided by Schroeder et al. [1979].

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thesis, Beddor and Hawkins [1990] generated vowel sets in which a nasal vowel standard was paired with a series of oral vowels. The stimuli in each oral vowel series varied in the frequency of F_1, the perceptual effect being variation in vowel height. Listeners, who selected from each set the oral vowel which sounded most similar to the nasal standard, tended *not* to chose the oral vowel in which F_1 frequency was the same as F_1' frequency in the nasal vowel (except for [ĩ], in which F_1'-F_N distance exceeded 3.5 Bark). As predicted by the model, listeners preferred oral vowels in which F_1 frequency fell between F_N and F_1' of the nasal vowel standard.

While the general prediction of the model is that nasalization will lower the perceived height of high and mid vowels and raise that of low vowels, the model can also be shown to predict that the height consequences will differ for back versus front vowels. Because of the proximity of F_1 and F_2 in back but not front vowels (i.e., the low-frequency region of prominence in back nasal vowels often includes not only F_1 and F_N but also F_2), it is not unlikely that the magnitude of the center of gravity shift due to nasalization will be less in back vowels, and the shift in perceived height will be correspondingly smaller. Given that current spectral measures do not accurately describe the perceptual center of gravity of the low-frequency region, this suggested difference is difficult to substantiate. But taking the centroid calculation as a rough description, centroid measures of the spectra of naturally spoken vowels do indicate this front-back asymmetry, the centroids of nonlow front – but not back – nasal vowels being consistently higher than that of corresponding oral vowels [Beddor, 1982].

2.2.2. Oral Cavity Shape: Rounding and Backness

Although lip rounding and front-back tongue body constriction are separable phonetic manipulations, they are considered together here as they interact in their effect on formant proximity in the low frequencies of the vowel spectrum. The principal spectral consequence of lip rounding is to lower formant frequencies, especially F_2–F_4 [Fant, 1960; Ladefoged, 1982]. Horizontal tongue body constriction correlates with F_2 frequency, such that a backed position leads to a maximally low F_2 and a front position to a maximally high F_2 [Fant, 1960; Stevens, 1972, 1983]. When lip rounding and back tongue position co-occur, as they do in most vowel systems of the world's languages, F_1 and F_2 are in relatively close proximity, with F_2 having a wide bandwidth [Stevens, 1989].

The clustering of F_1 and F_2 in back rounded vowels enhances perceived vowel backness [e.g., Lindau, 1978; Ladefoged, 1982; Stevens et al., 1986]. F_1–F_2 proximity is also predicted, according to the spectral integration model, to influence perceived vowel height: for a vowel with a given F_1 frequency, perceived height should be lower when the F_2–F_1 distance is within 3.5 Bark than when it is not. This theoretical prediction is consistent with the empirical findings of Chistovich and her colleagues, although the perceptual consequences of their manipulations of F_2–F_1 proximity are described generally in terms of overall vowel quality. It is more directly supported by Beddor and Hawkins [1990], who describe the acoustic manipulations as influencing perceived height.

If increased proximity of F_2 to F_1 lowers perceived vowel height, then phonetic ma-

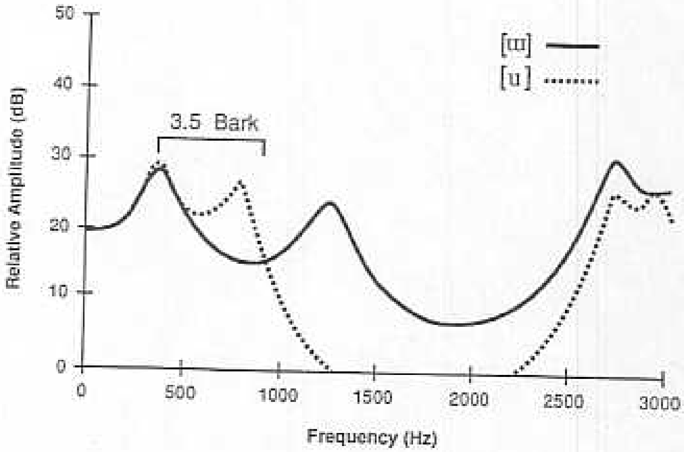

Fig. 3. Transfer functions of articulatorily synthesized high back vowels differing in lip protrusion. F_2–F_1 distance is 5.9 Bark in the spread vowel (solid line) and 3.3 Bark in the rounded vowel (dashed line).

nipulations which affect this proximity, such as lip rounding or unrounding and tongue body backing of fronting, might be expected to influence not only perceived roundness or backness, but also to shift perceived height. This claim has not been investigated experimentally, but acoustic measures of naturally spoken vowels show that linguistic use of rounding and backness have the expected effect on formant proximity. For example, acoustic measures of high back rounded [u] and unrounded [ɯ] in Turkish show that F_1 and F_2 are generally within about 3 Bark for [u], but are separated by about 7 Bark for [ɯ] [based on Selen, 1979, and Ergenç, 1989]. Manipulation of lip rounding by means of articulatory synthesis has a similar, albeit smaller, effect on F_2–F_1 separation. The vocal tract configurations corresponding to the transfer functions in figure 3 differ only in lip protrusion, the main spectral difference being in F_2 frequency. Lip protrusion reduced F_2–F_1 separation to within the critical distance, which raised the low-frequency center of gravity, and is predicted to lower perceived vowel height.

Similarly, languages which contrastively manipulate the front-back dimension in vowels appear to exhibit the critical separation or proximity of formant frequencies. For example, some speakers of French maintain a distinction between two low unrounded vowels, central [a] and back [ɑ]. Measures of formant frequencies show that F_1 and F_2 are within 2.1–2.9 Bark of each other for [ɑ], but are 3.4–5.6 Bark apart for [a] [Debrock, 1974; Mettas, 1979]. Although these French vowels may also differ somewhat in height and lip rounding, these factors were controlled for in articulatorily synthesized versions of [ɑ] and [a] represented by the transfer functions in figure 4. Fronting of the tongue body center from [ɑ] to [a] caused the F_2–F_1 separation to exceed the critical distance, so that in [a] the low-frequency center of gravity is determined exclusively by F_1 (as opposed to a weighted F_1–F_2 average in [ɑ]), which is predicted to raise perceived vowel height.

In contrast, the addition of lip rounding to front vowels, or the backing of front vowels to a more central configuration, does not generally place F_1 and F_2 within the critical distance for spectral
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2.2.3 Phonation Type:
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place F_1 and F_2 within the critical distance for spectral integration. The F_2–F_1 distance for the front rounded vowels of Swedish [Fant, 1969; Linker, 1982] and French [Mettas, 1979], for example, exceeds 6.0 Bark. This distance is of course smaller in central vowels, but is still greater than 4.0 Bark in, for example, the short central rounded vowel [ɵ] of Swedish [Linker, 1982]. Therefore, based on the assumption that perceived height will shift only if the low-frequency center of gravity shifts, the spectral integration model predicts that variation in lip rounding and horizontal tongue body position will affect the perceived height of back vowels but not that of front vowels. The situation with central vowels is more complex, with lip rounding predicted to have little or no effect, and tongue backing predicted to affect only the low vowels (due to relatively high F_1 frequency) and rounded vowels (due to relatively low F_2 frequency).

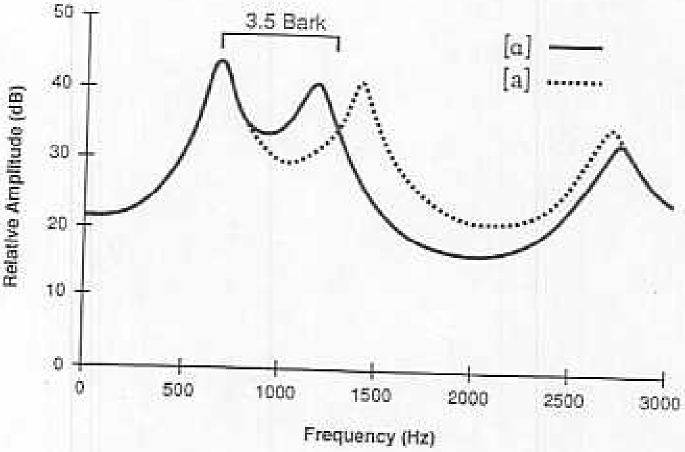

Fig. 4. Transfer functions of articulatorily synthesized low unrounded vowels differing in tongue body backness. F_2–F_1 distance is 3.0 Bark in the back vowel (solid line) and 4.2 Bark in the central vowel (dashed line).

2.2.3 Phonation Type: Breathy and Creaky Voice

The phenomenon of spectral integration occurs not only when two formants are in close proximity, but more generally when adjacent spectral peaks are within the critical range. Of particular importance is that spectral averaging has been demonstrated for the first harmonic, F_0, and F_1 [Fujisaki and Kawashima, 1968; Carlson et al., 1975], and F_0–F_1 proximity has been shown to influence perceived vowel height [Traunmüller, 1981].

The phonatory manipulations considered here are breathy voice, in which the vocal folds are abducted relative to unmarked or modal voicing, and stiff or creaky voice, in which the vocal folds are relatively adducted. Based on a quantitative model of the vocal folds, Stevens [1988] reported that the low-frequency spectral consequences of breathy phonation are increased bandwidth of F_1 and increased amplitude of F_0, resulting in F_0 amplitude being substantially greater than F_1 amplitude. In contrast, the vocal fold configuration in creaky voice (Stevens' 'pressed' voice) leads to a decreased bandwidth of F_1 and increased amplitude of F_1 relative to that of F_0.

These predicted spectral effects have been found in naturally produced vowels of

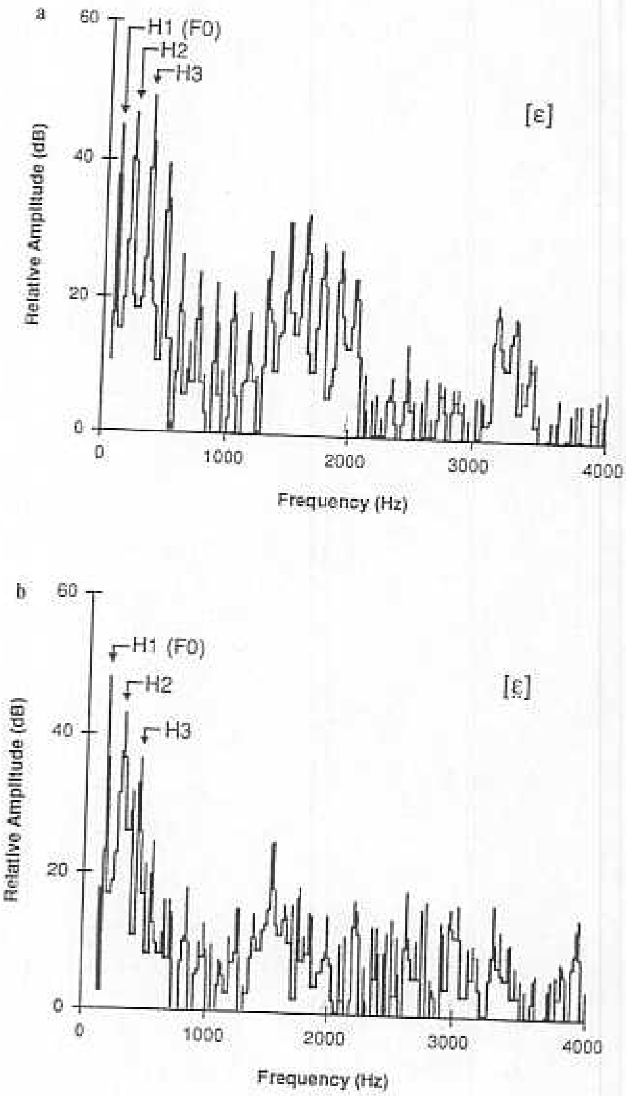

Fig. 5. FFT spectra of nonbreathy voice (**a**) and breathy voice (**b**) vowels produced by a speaker of Dinka illustrating the influence of breathiness on the relative amplitudes of F_0 and F_1 (see text). The vowels are from a recording provided by Keith Denning.

languages in which breathiness or creak has a contrastive function. For example, in Jalapa Mazatec, which contrasts modal, creaky, and breathy vowels, F_0 amplitude is less than F_1 amplitude in creaky vowels and more than F_1 amplitude in breathy vowels, with the general finding being that the value (in dB) of the amplitude difference between F_0 and F_1 increases from creaky to modal to breathy voice [Ladefoged et al., 1988]. This generalization also holds for the breathy–nonbreathy distinction in Gujarati [Fischer-Jørgensen, 1967], !Xóõ [Ladefoged and Antoñanzas-Barroso, 1985] and Dinka [Denning, 1989]. The Dinka contrast, as produced by a speakter of the Bor dialect,

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is illustrated by the FFT spectra in figure 5. In nonbreathy [ɛ], F_0 amplitude is less than F_1 amplitude (the third harmonic carrying most of the energy due to F_1); this amplitude relation is reversed in breathy [ɛ̤].

Within the spectral integration model, the effect of these manipulations is for breathy voice to lower, and for creaky voice to raise, the center of gravity of the low-frequency region. (Possible accompanying differences, such as changes in pitch are being ignored. While such differences sometimes co-occur with phonation differences in languages, they need not.) Consequently, the perceived height of breathy voice vowels is predicted to be higher than their nonbreathy counterparts and that of creaky voice vowels to be lower than their noncreaky counterparts.

The predicted shifts in perceived height depend on the assumption that F_0 and F_1 are within an integration band of 3–3.5 Bark. However, F_0–F_1 spacing does not satisfy this condition for all vowel heights and pitch ranges. (For example, given a vowel with an F_0 of 130 Hz, F_1 is within 3.5 Bark only if it has a frequency of less than 500 Hz.) This suggests that the predicted effect of breathiness and creak on perceived height is, in general, restricted to nonlow vowels. On the other hand, even in low vowels, phonation type influences F_1 bandwidth (which is broad in breathy vowels and narrow in creaky vowels) and F_1 bandwidth can affect perceived vowel height [Beddor and Hawkins, 1990]. The effect of increased bandwidth appears to be to increase the influence of the spectral envelope (as opposed to peak frequency) on perceived height. The prediction of the spectral integration model concerning height shifts in low nonmodal vowels therefore depends in part on the shape of the spectrum of the F_1 region. Whether breathiness or creak has a consistent effect with respect to this spectral property is unclear from the literature and hence, based on current descriptions, there are no predictions concerning the direction of shifts in the perceived height of low vowels due to phonation type.

Table 1. Predicted height effects of changes in oral cavity shape

	Tongue body backness		
	front	central	back
Retraction	–	↓ (round or low only)	↓
Fronting	–	–	↑
Rounding	–	–	↓
Unrounding	–	–	↑

For each manipulation, ↑ indicates a predicted raising effect, ↓ indicates lowering, and – indicates that no height shift is predicted.

Table 2. Predicted height effects of nasalization and phonation type

	Tongue body height	
	high / mid	low
Nasalization	↓ (especially front)	↑
Breathiness	↑	?
Creak	↓	?

Symbols are as in table 1; ? indicates that the direction of the expected height shift is unclear from available acoustic data.

2.2.4 Summary of the Height Shifts Predicted by the Model

The spectral integration model has been interpreted here as predicting that a shift in the low-frequency center of gravity will influence perceived vowel height. Based on what is known about the consequences of nasal coupling, oral cavity shape, and phonation type in the low frequencies of the vowel spectrum, it is predicted that these manipulations will shift perceived height as summarized in tables 1 and 2. The height effects of oral cavity shape (table 1) depend on vowel backness, with effects being restricted to back vowels (and to a subset of central vowels in the case of retraction). On the other hand, the height effects of nasalization and phonation type (table 2) are primarily conditioned by vowel height, with the height effects of nasalization being more pronounced in front vowels.

2.3. Translation into Phonological Predictions

It is emphasized that, if we accept the model's representation of vowel precessing, the predicted shifts in perceived height *automatically* follow. (The exact mechanisms of this automaticity are not directly relevant to this paper.) How, then, are these automatic consequences of vowel processing translated into predictions for phonological systems?

2.3.1. Articulatory Consequences of Perceptual Constraints

The translation here of perceptual constraints into phonological predictions follows a view of the contribution of the listener to phonological change (and hence synchronic phonological patterns) that is implicit in the work of Sweet [1888] and Paul [1891], and made explicit by Ohala [e.g., 1981, 1989]. Within the context of height effects, the view is that, if a listener (presumably, the language learner) perceives a vowel as being relatively high or low – for example, if a breathy voice vowel is heard as higher than its nonbreathy equivalent or a nasal vowel is heard as lower than its oral equivalent – then the learner will in turn *produce* that vowel with a relatively high or low tongue body configuration. That is, the shift in perceived vowel height that results from a shift in the low-frequency center of gravity is reinterpreted by the learner in terms of tongue body height [see Ohala, 1981, and Beddor et al., 1986, for further discussion]. Thus the interpretation here of the spectral integration model with respect to its phonological consequences parallels the first approach described in section 1.[2] That is, the constraints on vowel processing imposed by the model are interpreted as perceptual limits having direct consequences for the behavior of speaker-listeners – consequences which become incorporated into the phonological system.

The question of how the shifted vowel articulations of individual speaker-listeners are incorporated into the phonological system as a stable pattern is in large part a sociolinguistic one. However, if the perceptual height effects of such processes as, say, breathy voice and nasalization are indeed automatic consequences of vowel process-

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[2] This is not to say that the spectral integration phenomenon is not compatible with the second interpretation. For example, the spectral integration model could be viewed as generating auditory vowel spectra that serve as input to a perceptual distance metric [e.g., Lindblom, 1986]. However, this approach involves additional considerations that go beyond the scope of this paper.

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2.3.2. Limitations on the
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ing, then we would expect shifted articulations of breathy or nasal vowels (at least in the speech of language learners) to be the norm rather than sporadic variants. Under this view, it would appear that the output of the spectral integration model should translate into strong predictions concerning vowel raising or lowering patterns in phonological systems, such that languages with breathy vowels, nasal vowels, and so on, are *expected* to exhibit the height patterns described above.

2.3.2. Limitations on the Consequences of Auditory Constraints for Phonological Systems

But such expectations are not satisfied by cross-linguistic study of the relevant phonological patterns. For example, Ruhlen's [1978] survey of 155 languages with distinctive nasal vowels found no reported differences (other than nasality) between the oral and nasal vowel inventories of half of the languages. While the inventories of many of the remaining languages did exhibit height differences (and while some of the other inventories may have had height differences that went unreported), it seems that height shifts in phonological systems are not *necessary* consequences of vowel nasalization. However, given that nasalization can be shown to influence perceived height under a variety of experimental settings [Wright, 1986; Krakow et al., 1988; Beddor and Hawkins, 1990], there would appear to be a discrepancy between the automatic constraints imposed by the spectral integration model and the phonological instantiation of these constraints. Put another way, the strength of our phonological predictions appears to be weaker, in terms of the likelihood of occurrence in a given phonological system, than might be expected on the basis of laboratory findings.

Many factors may account for this difference. One general factor which potentially influences whether the constraints imposed by the model are manifested in a given phonological system is phonetic variation. Languages may differ, for example, in the size of the shifts in the low-frequency center of gravity caused by changes in nasalization, oral cavity shape, and phonation type. Consequently, in some languages, the center of gravity shift might not be of sufficient magnitude to effect a phonological height shift. That is, if the perceived differences are quite small, shifted articulations on the part of language learners are expected to be more sporadic, and the likelihood of the shift becoming a stable phonological pattern is lessened. For example, the combined effects of backness and rounding result in an F_2-F_1 separation of less than 3.5 Bark in Turkish /u/, but this separation exceeds the critical distance in American English /u/ [Syrdal, 1985]. (This difference is consistent with the informal observation that Turkish /u/ is more rounded than that of American English.)

Languages apparently differ not only in the magnitude but also in the nature of the acoustic consequences of manipulations that are described as rounding, breathiness, and so on. For example, the vowel systems of the related West Nilotic languages of Dinka and Acholi are both described as having a breathy–nonbreathy voice distinction, but Denning's [1989] acoustic analyses of 2 speakers of each of these languages showed that the expected F_0-F_1 amplitude differences were present only in the Dinka vowels. Physiological studies of the two languages might explain this result, but of im-

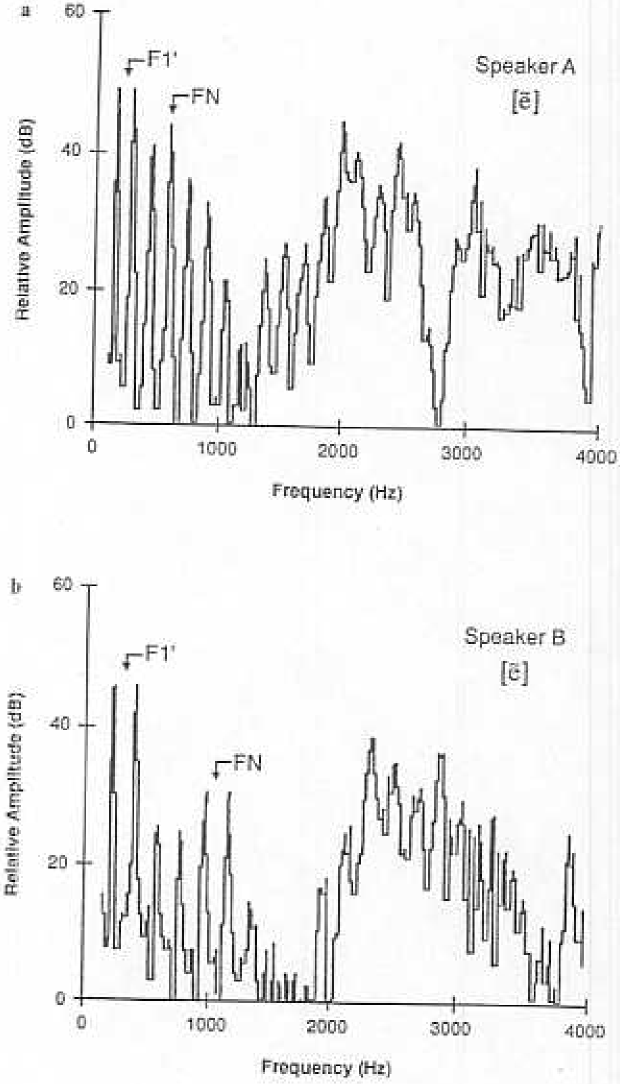

Fig. 6. FFT spectra of nasal [ẽ] produced by 2 speakers (**a, b**) of Hindi illustrating speaker differences in $F_1'–F_N$ spacing (see text).

portance here is that what is labeled breathy voice in these languages has different acoustic manifestations, leading to different predictions as derived from the model.

Phonetic variation introduced by individual speakers of a given language can also have critical consequences for the model's predictions. Figure 6 shows FFT spectra of two tokens of [ẽ] produced by 2 speakers of Hindi. $F_1'–F_N$ spacing is within the critical distance only for the vowel of

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speaker A. Analysis of additional tokens of [ẽ] showed this to be a consistent difference between these speakers: $F_1'-F_N$ distance was within 3.5 Bark for speaker A's vowels and exceeded 4.5 Bark for speaker B's.[3] Once again, these differences lead to different predictions: [ẽ] should be perceptually lower than [e] when produced by speaker A, but not speaker B.

A second general factor that influences the potential phonological effects of perceptual constraints is that listeners appear to compensate for certain predicted perceptual consequences in ways possibly linked to the phonological structure of their native language. The claim that a phonetic manipulation which shifts the low-frequency center of gravity affects perceived vowel height assumes that, in some instances, listeners may exhibit imperfect knowledge of the spectral consequences of that phonetic manipulation. This claim is based for the most part on listener responses to isolated vowels. Vowels embedded in a phonetic context, however, are judged relative to their coarticulatory context [Lindblom and Studdert-Kennedy, 1967; Strange et al., 1976; Fowler, 1981], and the nature of the contextual influence suggests that listeners' sensitivity to coarticulatory patterns enables them to correctly assess the articulatory configuration which generated the acoustic pattern. How this sensitivity comes about is controversial, but when a listener succeeds in identifying the articulatory source of a given vowel spectrum, there will be no shift in articulation when the listener produces that vowel, and hence no potential for phonological change [Ohala, 1981, 1986].

Listeners apparently compensate for spectral integration in certain circumstances. For example, the perceptual data reported in Krakow et al. [1988] indicate that, under appropriate conditions, listeners adjust for the effects of a shift in the low-frequency center of gravity on perceived vowel height. In that study, listeners identified articulatorily synthesized oral vowels (in a [bVd] context), noncontextually nasalized vowels ([bṼd]), and contextually nasalized vowels ([bṼnd]). The low-frequency spectral effect of velar port opening was to raise the center of gravity in the nasal vowels relative to that of the corresponding oral vowel. American English subjects' judgments showed that, when comparing vowels generated with the same tongue configuration, the perceived height of oral and contextually nasalized vowels was the same, but that of noncontextually nasalized vowels was lower, indicating that the perceived height of nasal vowels is not entirely a function of their low-frequency center of gravity. When listeners are provided with an appropriate context for vowel nasalization, as in the [bṼnd] context for English, they are apparently able to correctly assess the relative contribution of nasal coupling and tongue body configuration to perceived vowel height. It is expected that similar restrictions apply to the perceived height effects of the other phonetic manipulations discussed above, and hence whether these manipulations result in phonological shifts in vowel height in a given language should depend in part on the phonological structure of that language.

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[3] The difference in F_1-FN spacing was presumably due at least in part to the degree of nasalization, speaker A's nasal vowels being less nasalized (as determined perceptually) than those of speaker B.

2.3.3. The Nature of Phonological Predictions Based on the Spectral Integration Model

It follows from the limitations just considered that, although the phenomenon of spectral integration imposes automatic constraints on vowel processing, the consequences of this phenomenon for perceived vowel height do not necessarily entail consequences for a given phonological system. The first factor (i. e., phonetic variation in parameters influencing the center of gravity) shows that strong phonological predictions would require detailed descriptions of spectral structure that are generally not available. Although such descriptions could, in principle, be obtained through appropriate phonetic analyses, the second factor (i.e., listeners' perceptual strategies) shows that even detailed spectral descriptions would not be sufficient, as spectrally identical vowels can elicit different percepts depending on the context in which they occur. Such problems in the translation of the model's output into phonological consequences are consistent with certain of the arguments offered by Ladefoged [1984, 1989] concerning the limitations of phonetic explanation.

Given the current understanding of spectral integration and the factors contributing to perception of vowel height, and the phonetic and phonological limitations just discussed, the spectral integration model cannot be interpreted as predicting that all languages will manifest height effects of spectral integration, nor which languages will manifest such effects. However, as interpreted here, the spectral integration model both predicts that languages will exhibit correlations between nasalization, tongue body backness, rounding, breathiness, or creak on the one hand and tongue body height on the other, and specifies the nature of these correlations. That is, the model is interpreted as predicting, for languages exhibiting a shift in vowel height correlating with one or more of these properties, the direction of that shift. The final step in the application of the spectral integration model to phonological systems is to test these predictions against phonological data.

2.4. Phonological Verification

Ideally, phonological testing of the model's predictions should involve selection of a sufficiently large, genetically balanced language sample and analysis of the vowel inventories and processes (and, if available, historical vowel shifts) of the selected languages in terms of the height effects of nasalization, oral cavity shape, and phonation type. But phonological descriptions differ considerably in purpose and theoretical orientation, and only a subset provide detail sufficient for these purposes. In practice, then, the size and balance of such surveys are seriously limited by the scarcity of appropriate sources [for further discussion of this problem see, e.g., Maddieson, 1984]. The survey presented here is even more limited in that investigation of the phonological consequences of the spectral integration phenomenon is an ongoing project and hence preliminary in some areas.

For the reasons discussed in the preceding section, phonological testing of the spectral integration model is restricted to languages in which vowel height appears to interact with nasalization, backness, rounding, breathiness, or creak. Such testing

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yields both supporting and conflicting language data. In the interest of space, however, language-specific descriptions are not presented; rather, the results are stated below in terms of general cross-linguistic patterns of vowel raising and lowering.

2.4.1. Height Effects of Nasalization

The phonological effects of nasalization on vowel height are relatively well established due to several cross-linguistic surveys. Beddor [1982] analyzed allophonic and morphophonemic processes of nasal vowel raising and lowering in 75 languages and found that oral-nasal height differences reflected the following tendencies: (a) Nasalization raises the height of low vowels. (b) Nasalization lowers the height of high – especially front – vowels. (c) Distinctive nasalization lowers the height of mid – especially front – vowels. (d) Allophonic nasalization raises the height of mid – especially back – vowels. These patterns are generally consistent with the diachronic height shifts reported by Schourup [1973] and Bhat [1975], and the oral and nasal vowel inventory differences discussed in Ruhlen [1978].

The phonological data closely parallel the predictions based on the spectral integration model in two respects: the contraction of the height dimension due to nasalization (i.e., lowering of high and mid vowels and raising of low vowels) and the more pronounced lowering effect of nasalization on front than on back vowels. A third aspect, the different consequences of distinctive as opposed to allophonic or contextual nasalization for mid vowel height was not predicted by the model.

The raising effect of contextual nasalization may be linked to temporal factors. Historically, phonemicization of vowel nasalization is usually accompanied by loss of an adjacent nasal consonant and compensatory vowel lengthening [de Chene and Anderson, 1979; Clements, 1982]. Contextual nasal vowels may therefore be shorter than their noncontextual counterparts and experimental evidence indicates that short vowels are perceived as higher [Krakow et al., 1988] and less nasal [Whalen and Beddor, 1989] than the corresponding long vowels. Alternatively, Ohala [1986] has suggested that the raising effects of contextual nasalization might be due to listener overcompensation. Although the presence of a nasal consonant normally should enable a listener to correctly assess the contribution of nasal coupling to perceived vowel height, the listener might overestimate the contribution of nasal coupling, thereby raising vowel height [see Krakow et al., 1988, for evidence consistent with this view as well].

2.4.2. Height Effects of Oral Cavity Shape

In a preliminary effort to determine whether phonological patterns of vowel raising and lowering are linked to vowel rounding or backing, I inspected the vowel inventories of the 317 languages in the UCLA Segment Inventory Database (UPSID) as reported by Maddieson [1984]. If the lowering effect of rounding on the perceived height of back vowels predicted by the spectral integration model has phonological consequences, then languages with a rounding contrast in back vowels should exhibit asymmetries such that the rounded vowels are lower than their unrounded counterparts. Similarly, if tongue body retraction lowers the perceived height of nonfront (rounded or low) vowels, then vowel inventories with a central-back contrast should also show height differences, with the central vowels being higher than their back equivalents.

The first hypothesis of a correlation between rounding and height was not supported by the UPSID vowel inventories. Of the 27 languages which had both back rounded and unrounded (nonlow) vowels, the majority had rounded and unrounded vowels of the same height. In the 11 languages which showed height asymmetries in the back vowel system, there was no obvious pattern in the height differences attributable to lip rounding.

The hypothesis that backness correlates with height fared somewhat better. Only 9 languages in the UPSID sample had plain central rounded vowels, and 5 of these had back rounded vowels of the same height as the central ones. But in the other 4 languages, the back vowel was lower than its central counterpart (e.g., both Mongolian and Somali have high central /ʉ/ as opposed to lower-high back /ʊ/).

Assessment of the phonological height effects of rounding or backness is limited using this approach given the relatively small number of languages having back unrounded or central rounded vowels. Analysis of the *combined* effects of rounding and backness offers more compelling results. Since both lip rounding and retracted tongue position are predicted to lower vowel height, comparison of back rounded and front unrounded vowel systems should show the expected height differences. Such comparison encompasses over 98% of the UPSID languages. In the vast majority of these languages, the height of the highest back rounded vowel was the same as that of the highest front unrounded vowel (i.e., /u/ and /i/). However, when the heights differed, a lower back vowel was nearly 4 times more likely than a lower front vowel. Specifically, the highest front unrounded vowel was lower than the highest back rounded vowel in 8 languages, the pattern in all 8 being /ɪ u/. Twenty-nine languages had the reverse height difference, with the patterns including relatively low back vowels (i.e., not only /i ʊ/, but also /i o/, /ɪ o/, and /i ɔ/). The frequent absence of /u/ relative to /i/ in vowel systems has been previously noted [e.g., Crothers, 1978; Disner, 1984].

The phonological changes described in Labov et al. [1972] also suggest an influence of vowel backness and rounding on vowel height. Their analysis of ongoing chain shifts in the vowels of various English dialects, combined with study of completed shifts in other languages, showed that the fronting of back tense (rounded) vowels in such shifts may be accompanied by a raising movement. In contrast, front vowel chain shifts, which primarily involve the height dimension, do not show a height-backness (or height-rounding) interaction. [Other phonetic factors, of course, may be involved here; see Goldstein, 1983, for another view.]

Thus preliminary data from vowel inventories and historical change are generally consistent with the claim that the combination of backing and rounding lowers vowel height and the combination of fronting and unrounding raises vowel height. Additional cross-linguistic analysis is needed not only to provide further support for these tentative patterns, but also to differentiate the relative contributions of rounding and backness to phonological shifts in vowel height.

2.4.3. Height Effects of
Creaky Voice

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[i̤ e̤ o̤ ṳ] have breathy
tongue root position, and
and [ɪ̰ ɛ̰ ɔ̰ ʊ̰ a̰] have creak
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Drawing on allophonic v
vowel inventories, histo
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between vowel height a
greater vocal fold laxne
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(b) greater vocal fold ten
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It should be noted that
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However, when the heights
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ely than a lower front vowel,
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l in 8 languages, the pattern
ɪ u/. Twenty-nine languages
height difference, with the
ing relatively low back vow-
y /i ʊ/, but also /i o/, /ɪ o/,
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g., Crothers, 1978; Disner,

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2.4.3. Height Effects of Breathy and Creaky Voice

This section is based on the phonological data reported in Denning [1989], which examined evidence from 50 languages exhibiting an interaction between vowel height and phonation (taken to include phonation type, pitch, and voicing in adjacent consonants). In over half of these languages, the interaction involved the phonation types of breathy or creaky voice, sometimes co-occurring with other differences, such as pitch or tongue root position. For example, in Acholi, the breathy-nonbreathy distinction correlates with consistent differences in vowel height: breathy [i̤ e̤ ə̤ o̤ ṳ] and nonbreathy [ɪ ɛ a ɔ ʊ]. But the set of interacting factors may be quite complex, as in some dialects of Akan, where the vowels [i̤ e̤ o̤ ṳ] have breathy voicing, advanced tongue root position, and a lowered larynx, and [ɪ̰ ɛ̰ ɔ̰ ʊ̰ a̰] have creaky voicing, normal tongue root position, and a raised larynx. Drawing on allophonic variation, phonemic vowel inventories, historical change, and phonetic analyses, Denning [1989] concluded that, in languages with a correlation between vowel height and phonation: (a) greater vocal fold laxness (as in breathy voicing) is associated with higher vowels; (b) greater vocal fold tension (as in creaky voicing) is associated with lower vowels.

It should be noted that the patterns in (a) and (b) are consistent with the predictions of the spectral integration model. The phonological patterns, however, would appear to be more general than expected in that the model makes no clear predictions concerning low vowels. It may be that, phonologically, low nonmodal vowels are less likely to shift height than nonlow ones. While the high and mid vowels in the languages cited by Denning consistently exhibit the predicted height effects of phonation type, the low vowels in several of the languages either fail to have a phonation contrast (as in the Akan example above) or show no height difference between modal and nonmodal vowels. Yet it is also the case that, in other languages, low vowels exhibit a clear effect of phonation type on vowel height. Noting the frequent interaction of phonation type, voicing, and tongue root position in these languages, Denning [1989] suggested that the shifts in tongue body height might be the result of aerodynamic and neuromuscular factors, as well as biomechanical linkages involving tongue root retraction, laryngeal height, and vocal fold tension. It may well be that differences in the relative amplitudes of F_0 and F_1 interact with differences in F_1 frequency resulting from changes in articulatory configuration to enhance the perceptual effect of raising or lowering.

3. Discussion and Conclusion

This paper has focused on the interpretation of the spectral integration model in terms of its phonological consequences as a detailed illustration of one approach to the application of phonetic models to phonological systems. Using evidence from articulatory modeling and acoustic measures of naturally produced vowels, it was shown that manipulation of nasalization, oral cavity shape, and phonation type resulted in shifts in the low-frequency center of gravity of the vowel spectrum. Investigation of these spectral shifts in terms of the spectral integration model indicated that their perceptual consequence was to raise or lower perceived vowel height, depending on the direction of the center of gravity shift. But while these changes in perceived height are automatic consequences of (the model's characterization of) vowel processing, the translation into phonological consequences was shown to be mediated by both phonetic and phonological considerations, yielding restricted predictions concerning the phonological effects of nasalization, backness, rounding, breathiness and creak on vowel height. Furthermore, even these restricted predictions (taken to apply not to all languages, but only to those exhibiting a correlation between vowel height and one or more of these properties) must be viewed as the output of a single component of the speech mechanism, and hence as predictions that could in principle be outweighed by other forces.

However, despite these limitations, the height shifts predicted by the model were generally borne out by phonological patterns of height differences between oral versus nasal vowels, back rounded versus front unrounded vowels, and modal versus nonmodal vowels. (That certain other height effects not predicted by the model were also found is not surprising since, as noted, viewing the model in isolation ignores influences other than spectral integration.) The overall parallel, then, both supports the validity of the assumptions underlying the current approach and leads to the conclusion that the phonetic motivation for diverse phonological processes of vowel raising and lowering is, at least in part, the phenomenon of spectral integration.

Before considering what the consequences of this conclusion might be for phonological theory, it is noted that the limitations on the translation of the model's output into phonological predictions are not unique to the spectral integration model, nor even to listener-based models in general. Of the models presented in the literature, neither those interpreted as generating default settings [e.g., Lindblom, 1983, 1986; Westbury and Keating, 1986] nor those viewed as imposing physical limits [e.g., Ohala, 1981, 1983] derive exceptionless predictions for phonological systems. It would appear that only constraints of the type 'the human vocal mechanism cannot produce the sound X' or 'the human auditory system cannot differentiate between the sounds X and Y' would yield such predictions. Yet to the extent that such constraints are known [see, e.g., Catford, 1977], they fall considerably short of characterizing the vowel or consonant space utilized by the world's languages [Lindblom, 1983, 1990; Ladefoged, 1985].

Of what value to phonological theory, then, are phonological predictions of the type generated by the spectral integration model? Taking one of the goals of phonological theory to be the delimination of the set of possible phonological systems, the answer is that such predictions enable us, in principle, to delimit the set of possible phonetically motivated phonological phenomena. The qualification 'in principle' is needed because, in most cases, a given model provides information concerning only one component of the speech process. So, for example, the spectral integration model as interpreted here identifies only a particular class of perceptually motivated vowel height phenomena. In reality, then, predictions that delimit the more general set of 'phonetically motivated' phonological phenomena will depend on the convergence of the output of models of all speech

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components. Fortunately, phonetics research would appear to be moving in the direction of such convergence: not only do phonetic studies extend to virtually all components of the speech process [Ohala, 1990], but there is increasing emphasis on their interactions [Stevens, 1972, 1989; Lindblom, 1983; Lindblom and Maddieson, 1988].

Implicit in this view of the contribution of phonetic modeling to phonological theory is the assumption that it is desirable to be able to determine whether or not a phonological phenomenon is motivated by phonetic factors. Inasmuch as this is essentially equivalent to saying that it is desirable to be able to explain phonological phenomena, this assumption is taken to be uncontroversial. To quote Anderson [1981, p. 497]: 'it is still very much part of the business of phonologists to look for "phonetic explanations" of phonological phenomena'. In the approach taken here, the offered explanations or predictions fall short of the deductive-nomological form required by Dinnsen [1980] since the model cannot be interpreted as *necessitating* phonological shifts in vowel height. Rather, the spectral integration model achieves what Ohala [1987] has referred to as deductive-probabilistic explanations.

In concluding, it is emphasized that there is considerable potential for strengthening the contribution of phonetic models to phonological theory. Although certain limitations are inherent in the approach, others can be addressed by further study. One rectifiable limitation is the scarcity of adequate descriptive accounts of diverse phonetic and phonological structures. Also, as noted, manipulation of models of isolated components of the speech mechanism needs to be supplemented with study of possible interactions. The output of different components may be in conflict [Lindblom, 1990] or may enhance each other [see, e.g., section 2.4.3 and Stevens et al., 1986] with respect to a particular property, but in both cases knowledge of their interaction should improve the 'fit' between the predictions derived from phonetic theory and observed phonological phenomena.

Finally, interpreting the output of phonetic models in terms of phonological consequences is hindered by lack of knowledge concerning the nature of certain phonetic-phonological interactions. Within listener-based models, for example, perhaps the strongest limitation on translating the perceptual effects predicted by the model into phonological consequences is evidence that, under certain conditions, listeners are able to adjust or compensate for otherwise expected perceptual consequences. But relatively little is known about the conditions which facilitate such compensation. In particular, little is known about the extent to which compensatory abilities are influenced by knowledge of a particular phonological system. Krakow et al. [1988], for example, suggested on the basis of judgments by American English listeners that, for vowels, such abilities depend in part on the phonological appropriateness of the context in which the vowel occurs, but cross-linguistic investigation is needed to support this position.

It is hoped, then, that further investigation will enhance our understanding of the conditions under which perceptual compensation does or does not take place and, more generally, shed light on the conditions under which a particular phonetic constraint becomes a stable phonological pattern. However, while further study might enable us to better characterize these appropriate or prerequisite conditions, serious constraints on the predictive power of phonetic models will remain. Interpretation of the spectral integration model was restricted here to predictions concerning the direction of height shifts in languages exhibiting a correlation between vowel height and certain properties. Given that other phonetic and nonphonetic forces may counteract the predictions of an isolated model, this approach encounters exceptions (although inspection of exceptional languages should indicate, in some cases at least, the nature of the countervailing forces). Thus, for current phonetic models, predictive power may be limited to the claim that there is a greater-than-chance tendency for phonological systems to reflect a given model's constraints. Yet the consequences of such limited predictions for phonological theory should not be minimized. Phonetic models cannot predict the structure of phonological systems, but they enable us to predict which phonological structures recur across languages and provide explanations for their occurrence.

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References

Anderson, S. R.: Why phonology isn't 'natural'. Linguist. Inquiry *12:* 493–539 (1981).

Beddor, P.S.: Phonological and phonetic effects of nasalization on vowel height; PhD thesis University of Minnesota (1982; reproduced by Indiana University Linguistics Club 1983).

Beddor, P.S.; Hawkins, S.: The influence of spectral prominence on perceived vowel quality. J. acoust. Soc. Am. *87:* 2684–2704 (1990).

Beddor, P.S.; Krakow, R.A.; Goldstein, L.M.: Perceptual constraints and phonological change: a study of nasal vowel height. Phonol. Yb. *3:* 197–217 (1986).

Bhat, D.N.S.: Two studies on nasalization; in Ferguson, Hyman, Ohala, Nasálfest, Papers from a Symposium on Nasals and Nasalization, pp. 27–48 (Stanford University, Stanford 1975).

Bladon, A.: Two-formant models of vowel perception: shortcomings and enhancements. Speech Commun. *2:* 305–313 (1983).

Bladon, R.A.W.; Fant, G.: A two-formant model and the cardinal vowels. Q. Prog. Status Rep., Speech Transm. Lab., R. Inst. Technol., Stockh., No. 1, pp. 1–8 (1978).

Browman, C.P.; Goldstein, L.: Articulatory gestures as phonological units. Phonology *6:* 201–251 (1989).

Carlson, R.; Fant, G.; Granström, B.: Two-formant models, pitch, and vowel perception; in Fant, Tatham, Auditory analysis and perception of speech, pp. 55–82 (Academic Press, New York 1975).

Catford, J.C.: Fundamental problems in phonetics (Indiana University Press, Bloomington 1977).

Chistovich, L.A.: Central auditory processing of peripheral vowel spectra. J. acoust. Soc. Am. *77:* 789–805 (1985).

Chistovich, L.A.; Lublinskaya, V.V.: The 'center of gravity' effect in vowel spectra and critical distance between the formants: psychoacoustical study of the perception of vowel-like stimuli. Hear. Res. *1:* 185–195 (1979).

Chistovich, L.A.; Sheikin, R.L.; Lublinskaya, V.V.: 'Centres of gravity' and spectral peaks as the determinants of vowel quality; in Lindblom, Öhman, Frontiers of speech communication research, pp. 143–157 (Academic Press, New York 1979).

Clements, G.N.: Compensatory lengthening: an independent mechanism of phonological change (Indiana University Linguistics Club, Bloomington 1982).

Crothers, J.: Typology and uni
tems; in Greenberg, Fergus
versals of human language,
pp. 93–152 (Stanford Unive
1978).

Debrock, M.: La structure spec
sales. Revue phonét. appl.

de Chene, B.; Anderson, S. R.:
thening. Language *55:* 505–

Delattre, P.; Liberman, A., Co
L.: An experimental study
terminants of vowel colo
one- and two-formant vow
spectrographic patterns.
(1952).

Denning, K.: The diachronic
nological voice quality; P
University (1989).

Dinnsen, D. A.: Phonological r
planation. J. Ling. *16:* 171–

Disner, S. F.: Insights on vowel
son, Patterns of sounds,
bridge University Press, Ca

Ergenç, I.: Türkiye Türkçesini
(Engin, Ankara 1989).

Fant, G.: Acoustic theory of
(Mouton, The Hague 1960).

Fant, G.: Formant frequencies
Q. Prog. Status Rep., Spee
Inst. Technol., Stockh., No
in Fant, Speech sounds and
(MIT Press, Cambridge 197

Fischer-Jørgensen, E.: Phoneti
(murmured) vowels in Guja
71–139 (1967).

Fowler, C. A.: Production and p
ulation among stressed and
Speech Hear. Res. *24:* 127–

Fujimura, O.; Lindqvist, J.: S
ments of vocal-tract chara
Soc. Am. *49:* 541–558 (1971

Fujisaki, H.; Kawashima, T.: T
higher formants in the pe
IEEE Trans. Audio Ele
73–77 (1968).

Goldstein, L.: Vowels shifts an
tic relations; in Cohen, van
10th Int. Congr. Phonet.
(Foris, Dordrecht 1983).

Hawkins, S.; Stevens, K. N.: A

nological and phonetic effects of
vowel height: PhD thesis Uni-
esota (1982; reproduced by Indi-
Linguistics Club 1983).
vkins, S.: The influence of spec-
e on perceived vowel quality. J.
n. *87:* 2684–2704 (1990).
cow, R.A.; Goldstein, L.M.: Per-
ints and phonological change: a
vowel height. Phonol. Yb. *3:*
-
studies on nasalization; in Fer-
Ohala, Nasálfest, Papers from a
Nasals and Nasalization, pp.
d University, Stanford 1975).
ormant models of vowel percep-
ngs and enhancements. Speech
5–313 (1983).
Fant, G.: A two-formant model
al vowels. Q. Prog. Status Rep.
Lab., R. Inst. Technol., Stockh.,
1978).
oldstein, L.: Articulatory gestures
l units. Phonology *6:* 201–251

G.; Granström, B.: Two-formant
and vowel perception; in Fant,
ory analysis and perception of
82 (Academic Press, New York

damental problems in phonetics
sity Press, Bloomington 1977).
entral auditory processing of pe-
spectra. J. acoust. Soc. Am. *77:*

ublinskaya, V.V.: The 'center of
vowel spectra and critical dis-
the formants: psychoacoustical
erception of vowel-like stimuli.
5–195 (1979).
heikin, R.L.; Lublinskaya, V.V.:
ity' and spectral peaks as the de-
vowel quality: in Lindblom,
rs of speech communication re-
157 (Academic Press, New York

ompensatory lengthening: an in-
anism of phonological change
sity Linguistics Club, Blooming-

Crothers, J.: Typology and universals of vowel systems; in Greenberg, Ferguson, Moravscik, Universals of human language, vol. II: Phonology, pp. 93–152 (Stanford University Press, Stanford 1978).

Debrock, M.: La structure spectrale des voyelles nasales. Revue phonét. appl. *21:* 15–31 (1974).

de Chene, B.; Anderson, S.R.: Compensatory lengthening. Language *55:* 505–535 (1979).

Delattre, P.; Liberman, A.; Cooper, F.; Gerstman, L.: An experimental study of the acoustic determinants of vowel colour: observations on one- and two-formant vowels synthesized from spectrographic patterns. Word *8:* 195–210 (1952).

Denning, K.: The diachronic development of phonological voice quality; PhD thesis Stanford University (1989).

Dinnsen, D.A.: Phonological rules and phonetic explanation. J. Ling. *16:* 171–191 (1980).

Disner, S.F.: Insights on vowel spacing; in Maddieson, Patterns of sounds, pp. 136–155 (Cambridge University Press, Cambridge 1984).

Ergenç, I.: Türkiye Türkçesinin görevsel sesbilimi (Engin, Ankara 1989).

Fant, G.: Acoustic theory of speech production (Mouton, The Hague 1960).

Fant, G.: Formant frequencies of Swedish vowels. Q. Prog. Status Rep., Speech Transm. Lab., R. Inst. Technol., Stockh., No. 4 (1969); reprinted in Fant, Speech sounds and features, pp. 94–99 (MIT Press, Cambridge 1973).

Fischer-Jørgensen, E.: Phonetic analysis of breathy (murmured) vowels in Gujarati. Indian Ling. *28:* 71–139 (1967).

Fowler, C.A.: Production and perception of coarticulation among stressed and unstressed vowels. J. Speech Hear. Res. *24:* 127–139 (1981).

Fujimura, O.; Lindqvist, J.: Sweep-tone measurements of vocal-tract characteristics. J. acoust. Soc. Am. *49:* 541–558 (1971).

Fujisaki, H.; Kawashima, T.: The roles of pitch and higher formants in the perception of vowels. IEEE Trans. Audio Electroacoust. *AU-16:* 73–77 (1968).

Goldstein, L.: Vowels shifts and articulatory-acoustic relations; in Cohen, van den Broecke, Abstr. 10th Int. Congr. Phonet. Sci., pp. 267–273 (Foris, Dordrecht 1983).

Hawkins, S.; Stevens, K.N.: Acoustic and perceptual correlates of the non-nasal–nasal distinction for vowels. J. acoust. Soc. Am. *77:* 1560–1575 (1985).

House, A.S.; Stevens, K.N.: Analog studies of the nasalization of vowels. J. Speech Hear. Disorders *21:* 218–232 (1956).

Keating, P.: Physiological effects on stop consonant voicing. UCLA Working Papers Phonet. *59:* 29–34 (1984).

Keating, P.: The phonology-phonetics interface; in Newmeyer, Linguistics: the Cambridge survey, vol. 1: Linguistic theory: foundations, pp. 281–302 (Cambridge University Press, Cambridge 1988).

Klatt, D.H.: A shift in formant frequencies is not the same as a shift in the center of gravity of a multi-formant energy concentration. J. acoust. Soc. Am. *77:* suppl. 1, p. S7 (1985).

Krakow, R.A.; Beddor, P.S.; Goldstein, L.M.; Fowler, C.A.: Coarticulatory influences on the perceived height of nasal vowels. J. acoust. Soc. Am. *83:* 1146–1158 (1988).

Labov, W.; Yaeger, M.; Steiner, R.: A quantitative study of sound change in progress (US Regional Survey, Philadelphia 1972).

Ladefoged, P.: A course in phonetics; 2nd ed. (Harcourt Brace Jovanovich, New York 1982).

Ladefoged, P.: 'Out of chaos comes order': physical, biological, and structural patterns in phonetics; in van den Broecke, Cohen, Proc. 10th Int. Congr. Phonet. Sci. (Foris, Dordrecht 1984).

Ladefoged, P.: Introduction (interview with V.A. Fromkin); in Fromkin, Phonetic linguistics, p. 11 (Academic Press, New York 1985).

Ladefoged, P.: Representing phonetic structure. UCLA Working Papers Phonet. *73:* 1–79 (1989).

Ladefoged, P.: Antoñanzas-Barroso, N.: Computer measures of breathy phonation. UCLA Working Papers Phonet. *61:* 79–86 (1985).

Ladefoged, P.; Maddieson, I.; Jackson, M.: Investigating phonation types in different languages; in Fujimura, Vocal physiology: voice production, mechanisms and functions, pp. 297–317 (Raven Press, New York 1988).

Liljencrants, J.; Lindblom, B.: Numerical simulation of vowel quality systems: the role of perceptual contrast. Language *48:* 839–862 (1972).

Lindau, M.: Vowel features. Language *54:* 541–563 (1978).

Lindblom, B.: Economy of speech gestures; in Mac-

Neilage, The production of speech, pp. 217–245 (Springer, New York 1983).

Lindblom, B.: Phonetic universals in vowel systems; in Ohala, Jaeger, Experimental phonology, pp. 13–44 (Academic Press, New York 1986).

Lindblom, B.: On the notion of 'possible speech sound'. J. Phonet. *18:* 135–152 (1990).

Lindblom, B.; Maddieson, I.: Phonetic universals in consonant systems; in Hyman, Li, Language, speech and mind. pp. 62–78 (Routledge, New York 1988).

Lindblom, B.; Studdert-Kennedy, M.: On the role of formant transitions in vowel recognition. J. acoust. Soc. Am. *42:* 830–843 (1967).

Linker, W.: Articulatory and acoustic correlates of labial activity in vowels: a cross-linguistic study. UCLA Working Papers Phonet. *56:* 1–134 (1982).

Maddieson, I.: Patterns of sounds (Cambridge University Press, Cambridge 1984).

Mettas, O.: French oral vowels analyzed from recorded spontaneous conversations; in Lindblom, Öhman, Frontiers of speech communication research, pp. 93–108 (Academic Press, New York 1979).

Miller, R.L.: Auditory tests with synthetic vowels. J. acoust. Soc. Am. *25:* 114–121 (1953).

Ohala, J.J.: Phonetic explanation in phonology; in Bruck, Fox, LaGaly, Papers from the Natural Phonology Parasession, pp. 251–274 (Chicago Linguistic Society, Chicago 1974).

Ohala, J.J.: The listener as a source of sound change; in Masek, Hendrick, Miller, Papers from the parasession on language and behavior, pp. 178–203 (Chicago Linguistic Society, Chicago 1981).

Ohala, J.J.: The origin of sound patterns of vocal tract constraints; in MacNeilage, The production of speech, pp. 189–216 (Springer, New York 1983).

Ohala, J.J.: Phonological evidence for top-down processing in speech perception; in Perkell, Klatt, Invariance and variability of speech processes, pp. 386–401 (Erlbaum, Hillsdale 1986).

Ohala, J.J.: Explanation in phonology: opinions and examples; in Dressler, Luschützky, Pfeiffer, Rennison, Phonologica 1984, pp. 215–225 (Cambridge University Press, Cambridge 1987).

Ohala, J.J.: Sound change is drawn from a pool of synchronic variation; in Breivik, Jahr, Language change: contributions to the study of its causes, pp. 173–198 (Mouton/de Gruyter, Berlin 1989).

Ohala, J.J.: There is no interface between phonology and phonetics: a personal view. J. Phonet. *18:* 153–172 (1990).

Paul, H.: Principles of the history of language; translated by H.A. Strong (1891). Excerpt reprinted in Baldi, Werth, Readings in historical phonology, pp. 3–22 (Pennsylvania State University Press, University Park 1978).

Peterson, G.E.; Barney, H.L.: Control methods used in a study of the identification of vowels. J. acoust. Soc. Am. *24:* 175–184 (1952).

Rubin, P.E.; Bear, T.; Mermelstein P.: An articulatory synthesizer for perceptual research. J. acoust. Soc. Am. *70:* 321–328 (1981).

Ruhlen, M.: Nasal vowels; in Greenberg, Ferguson, Moravscik, Universals of human language, vol. II, Phonology, pp. 203–242 (Stanford University Press, Stanford 1978).

Schourup, L.: A cross-language study of vowel nasalization. Ohio State Working Papers Ling. *15:* 190–221 (1973).

Schroeder, M.R.; Atal, B.S.; Hall, J.L.: Objective measure of certain speech signal degradations based on masking properties of human auditory perception; in Lindblom, Öhman, Frontiers of speech communication research, pp. 217–229 (Academic Press, New York 1979).

Selen, N.: Söyleyis sesbilimi akustik sesbilim ve Türkiye Türkçesi (Ankara Üniversitesi Basimevi, Ankara 1979).

Stevens, K.N.: The quantal nature of speech: evidence from articulatory-acoustic data; in David, Denes, Human communication: a unified view, pp. 51–66 (McGraw-Hill, New York 1972).

Stevens, K.N.: Design features of speech sound systems; in MacNeilage, The production of speech, pp. 247–261 (Springer, New York 1983).

Stevens, K.N.: Modes of vocal fold vibration based on a two-section model; in Fujimura, Vocal physiology: voice production, mechanisms and functions, pp. 357–371 (Raven Press, New York 1988).

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

Stevens, K.N.; Fant, G.; Hawkins, S.: Some acoustical and perceptual correlates of nasal vowels; in Channon, Shockey, Festschrift for Ilse Lehiste, pp. 241–254 (Foris, Dordrecht 1987).

Stevens, K.N.: Keyser, S.J.: Ka
a phonetic and phonologic
dant features; in Perkell, Kl
variability in speech proc
(Erlbaum, Hillsdale 1986).

Strange, W.; Verbrugge, R.R.;
Johnson, T.R.: Consonantal
fies vowel identity. J. aco
213–224 (1976).

Sweet, H.: History of English s
versity Press, Oxford 1888).

Syrdal, A.K.: Aspects of a mo
representation of America
Speech Commun. *4:* 121–13

Traunmüller, H.: Perceptual dim
in vowels. J. acoust. Soc.
(1981).

Westbury, J.; Keating, P.: On

ntributions to the study of its causes,
8 (Mouton/de Gruyter, Berlin 1989).
ere is no interface between phonol-
onetics: a personal view. J. Phonet.
2 (1990).
ciples of the history of language;
by H.A. Strong (1891). Excerpt re-
Baldi, Werth, Readings in historical
pp. 3–22 (Pennsylvania State Uni-
s, University Park 1978).
.; Barney, H.L.: Control methods
udy of the identification of vowels. J.
. Am. *24:* 175–184 (1952).
ear, T.; Mermelstein P.: An articula-
esizer for perceptual research. J.
. Am. *70:* 321–328 (1981).
asal vowels: in Greenberg, Ferguson,
Universals of human language, vol.
gy, pp. 203–242 (Stanford University
ord 1978).
A cross-language study of vowel na-
hio State Working Papers Ling. *15:*
973).
R.; Atal, B.S.; Hall, J.L.: Objective
certain speech signal degradations
asking properties of human auditory
in Lindblom, Öhman, Frontiers of
munication research, pp. 217–229
Press, New York 1979).
leyis sesbilimi akustik sesbilim ve
kçesi (Ankara Üniversitesi Basimevi,
9).
The quantal nature of speech: evi-
articulatory-acoustic data; in David,
nan communication: a unified view,
McGraw-Hill, New York 1972).
Design features of speech sound sys-
cNeilage, The production of speech,
l (Springer, New York 1983).
Modes of vocal fold vibration based
ection model: in Fujimura, Vocal
voice production, mechanisms and
p. 357–371 (Raven Press, New York

On the quantal nature of speech. J.
7: 3–45 (1989).
Fant, G.; Hawkins, S.: Some acous-
rceptual correlates of nasal vowels:
, Shockey, Festschrift for Ilse Le-
1–254 (Foris, Dordrecht 1987).

Stevens, K.N.; Keyser, S.J.; Kawasaki, H.: Toward a phonetic and phonological theory of redundant features; in Perkell, Klatt, Invariance and variability in speech processes, pp. 426–449 (Erlbaum, Hillsdale 1986).

Strange, W.; Verbrugge, R.R.; Shankweiler, D.P.; Johnson, T.R.: Consonantal environment specifies vowel identity. J. acoust. Soc. Am. *60:* 213–224 (1976).

Sweet, H.: History of English sounds (Oxford University Press, Oxford 1888).

Syrdal, A.K.: Aspects of a model of the auditory representation of American English vowels. Speech Commun. *4:* 121–135 (1985).

Traunmüller, H.: Perceptual dimension of openness in vowels. J. acoust. Soc. Am. *69:* 1465–1475 (1981).

Westbury, J.; Keating, P.: On the naturalness of stop consonant voicing. J. Ling. *22:* 145–166 (1986).

Whalen, D.H.; Beddor, P.S.: Connections between nasality and vowel duration and height: elucidation of the Eastern Algonquian intrusive nasal. Language *65:* 457–486 (1989).

Wright, J.T.: The behavior of nasalized vowels in the perceptual vowel space; in Ohala, Jaeger, Experimental phonology, pp. 45–67 (Academic Press, New York 1986).

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