Phonetic Evidence for Hierarchies of Features

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1. Introduction

When one attempts to specify the acoustic and articulatory correlates of distinctive features, one is often frustrated by the apparent many-to-one relations that exist between acoustic or articulatory properties and the abstract features which appear to be a part of a speaker/listener's knowledge of language. One step toward resolving this difficulty is to organize the features into hierarchies similar to those used in current approaches to phonology. On the basis of acoustic and articulatory data, the features can be organized roughly into three classes (Halle and Stevens, in press): (1) articulator-free features that indicate whether a narrow constriction is made in the vocal tract, and, if so, whether or not a complete closure is formed and whether pressure is built up behind the constriction; (2) primary articulator-bound features indicating which articulator is active in forming the constriction (whether it be a narrow consonantal constriction or a less severe vocalic constriction), and specifying further details about the placement of the constriction; and (3) secondary articulator-bound features indicating active adjustments of articulators other than the primary ones, such as larynx, the soft palate, and the tongue body. This hierarchical organization can serve as a basis for ordering the identification of features from the acoustic signal, with the more context-independent features being identified first and the more context-dependent features identified later.

A second proposal that may help to clarify the acoustic and articulatory correlates of the features is to give greater attention to the concept of landmarks in the sound that are produced by implementing articulator-free features. The acoustic manifestations of the features for a particular segment occur in the vicinity of these landmarks. The landmarks provide the listener with regions in the signal where attention is to be focussed in order to identify the features for the segments.

Placing emphasis on acoustic landmarks in the sound has implications for models of speech production as well as speech perception. If the acoustic manifestations of the features for particular segments are centered around these landmarks, then the speaker is constrained to coordinate the movements of his/her articulators so that these movements are appropriately represented in the sound near these landmarks.

In this paper we shall first review the articulatory and acoustic manifestations of the features in each of the classes, and we shall attempt to demonstrate the role of acoustic landmarks as events around which the acoustic properties are centered. We shall then consider how this view of features and their correlates places constraints on the control and coordination of the articulatory structures during speech production.

2. Articulator-free features and landmarks

Among the articulator-free features (roughly the mannner features or stricture features of Clements (1985) and Sagey (1986)), we shall focus our attention initially on the features of consonantal segments. When a [+consonantal] segment is produced, a narrow constriction is formed at some point along the midline of the vocal tract above the glottis. The acoustic consequence of manipulating an articulator to form such a narrow constriction or to move away from a constricted position is to introduce a particular type of discontinuity in the acoustic signal. If the constriction is formed or is released adjacent to a vowel or some other sound produced with a vocal-tract configuration that is more open than that of the consonant, then the acoustic discontinuity is characterized by a rapid change in the spectrum shape, with rapid movements of some prominences in the spectrum.

When a segment is [+consonantal], there must always be a specification of the feature [continuant]. If the consonant is [-continuant], then a complete closure is made in the midline of the vocal tract at the point where the consonantal constriction is formed. The feature [+continuant] signifies that the closure at the constriction is not complete.

When a consonantal constriction or closure is formed at some point along the vocal tract, certain additional articulator-free features must be specified. These additional features indicate how the airstream is manipulated when the articulator forms the constriction. For example, it is necessary to specify whether or not the forming of the constriction causes pressure to build up behind the constriction. The buildup of pressure can be prevented if a bypass is provided for the airflow, either by opening the velopharyngeal port or by allowing the flow of air around the sides of the tongue blade. If pressure does build up as a consequence of the consonantal constriction, then the [+consonantal] segment is [-sonorant]. If there is no pressure buildup, then the discontinuity identifies a segment that is [+consonantal, +sonorant].

For a segment that is [+consonantal, +continuant], it may be possible to shape the articulator forming the constriction in such a way that the airstream that passes through the constriction is directed against an obstacle or surface. The consequence of this action is to generate a strong source of turbulence noise – stronger than the source that would be produced without such an obstacle. A consonant produced in this way is classified as [+strident].

Another articulator-free feature that is appended as a modifier to the feature [+consonantal] is [lateral] (which is specified for segments that are [+sonorant, -continuant in English]). For a consonant that is [+lateral], the airstream is directed around one or both sides of the tongue blade.

In summary, then, it is postulated that there are four articulator-free features that can operate when a [+consonantal] segment is formed, i.e., when a narrow constriction is made in the vocal tract. Not all combinations of these features are possible, however. For example, [+sonorant] is incompatible with [+strident], and [+strident] consonants are always [+continuant]. The five combinations that are possible are displayed in Table 1. In this table, we place in parentheses the entries for which the feature is constrained to take on just one value. At the top of each column is an example of a consonant that has the given combination of articulator-free features.

The acoustic manifestation of the production of the implosion or release for a consonant is an event that can take several forms depending on whether the consonant is sonorant or continuant, and depending on the state of the glottis. In general, however, the acoustic event must satisfy three requirements: (1) the spectrum should remain relatively constant or change only slowly within the constricted interval adjacent to the implosion or release; (2) a rapid change in the spectrum amplitude should occur over at least some part of the frequency range as the constriction is formed or as it is released; and (3) there should be a rapid change in the frequency of one or more peaks in the spectrum at these points. The first of these requirements indicates that, when the articulator is in the constricted configuration, the vocal-tract shape anterior or posterior to the constriction will tend not to change enough to cause a significant modification of the spectrum shape or the amplitude. The second and third requirements are a consequence of the fact that an articulator is moving toward or away from a constricted configuration, resulting in changes in some natural frequencies of the system and an abrupt shift in the acoustic source (e.g., from a glottal source to frication noise) and/or the acoustic path through the system (e.g., from mouth to nose output).

In the case of segments that are [-consonantal], any constriction that is formed above the glottis is not sufficiently narrow to build up pressure or to create a rapid spectrum change. For [-consonantal] segments, therefore, it is not necessary to specify additional articulator-free features. A discontinuity in the spectrum that is a consequence of adduction or abduction movements of the glottis or constrictions formed in the lower pharynx does not qualify as a consonantal event. Such a discontinuity is not characterized by a rapid movement of a spectrum prominence, although there may be a rapid change in spectrum amplitude over some part of the frequency range.

Examples of some acoustic discontinuities that mark consonantal events are shown in Fig. 1. The figure also gives some examples of acoustic discontinuities that would not qualify as consonantal events at a prevocalic or postvocalic position. Several consonantal discontinuities are evident on the spectrogram. For example, at around 400 ms, a labial closure is produced. Immediately prior to the closure, there are rapid downward movements of the first three formants. The amplitude drops abruptly at the instant of closure, and the spectrum remains weak and constant during the closure interval, except for a brief interval of weak glottal vibration immediately following the implosion. Another example of an implosion and a release for a stop consonant is at about 580 and 680 ms.

At time 1180 ms, a closure is made by raising the tongue body to form a velar nasal, leading to an abrupt change in spectrum amplitude at mid and high frequencies. In this case, the consonant is sonorant, and this fact is represented in the sound by continuity in the amplitude of the first harmonic at low frequencies. A postvocalic fricative consonant is initiated at about 1500 ms, with a relatively stationary spectrum shape in the few tens of milliseconds following the beginning of frication noise.

In the time interval centered around 260 ms, there is aspiration noise which excites all of the formants. This fact, together with the observation that there are no rapid changes in formant frequencies, is evidence that a constriction is formed in the laryngeal region. Thus there is no [+consonantal] segment in this region.

3. Articulator-bound features

As we have observed, the articulator-free features associated with consonantal segments indicate that a particular type of constriction has been formed in the vocal tract. The articulator-bound features that characterize a segment with a specified set of articulator-free features are of two types. One of these specifies which articulator is active in producing the constriction, i.e., which articulator is responsible for the acoustic discontinuity that occurs at the formation or release of the constriction. For consonantal segments, any one of three different articulators can be the active articulator: the lips, the tongue blade, and the tongue body. This first type of articulator-bound feature indicates how the primary articulator is to be shaped or located to produce the constriction. In terms of the geometrical arrangement of features proposed by Sagey (1986)(based on the original proposal of Clements (1985)), the primary articulator characterizes the node to which the pointer from the stricture features is directed. The second type of feature specifies how other articulators are to be manipulated in coordination with the primary articulator. These secondary articulators do not form the constriction that gives rise to the acoustic discontinuity; rather, they modulate the acoustic pattern in the vicinity of the discontinuity.

Some examples of this division of the articulator-bound features into these two classes are given for several different consonantal segments in Table 2. The articulator-free features are listed at the top. Below this is the list of the three primary articulators, any one of which can be active in producing the consonantal constriction. A partial list of the articulator-bound features constitutes the remainder of the table. Some of these articulator-bound features are enclosed in boxes. These are the features that specify how the primary articulators are to manipulated. The remaining articulator-bound features are the secondary group. The features that specify velopharyngeal, pharyngeal, and laryngeal configurations and states are always in the secondary class for consonant segments, whereas those associated with the lips, tongue blade and tongue body can be either primary or secondary. For example, for the lateral consonant in Table 2, the tongue-body features are secondary.

In the case of nonconsonantal segments, a primary articulator is also designated, but, in contrast to consonantal segments, the primary articulator can be drawn from a wider inventory.[1] Table 3 lists some nonconsonantal segments, and gives for each segment the primary articulator, the features specifying the manipulation of this articulator, and the secondary articulator-bound features. For vowels the primary articulator is always the tongue body, whereas for the glides it can be the tongue blade (for /j/), the lips (for /w/), or the glottis (for /h/). A nasal glide, for which the soft palate is the primary articulator, appears also to be possible (Trigo, 1989). As with consonantal segments, other secondary articulator-bound features can be specified for nonconsonantal segments.

There appear to be some features that specify the state of an articulator rather than its movement or position. These are features that characterize the stiffness or slackness of the vocal folds or of the laryngeal or pharyngeal surfaces immediately above the glottis. The acoustic correlates of these features are the changes in fundamental frequency of vocal-fold vibration and, for obstruents, the inhibition or facilitation of glottal vibration during the obstruent interval. These features are never in the class of primary articulator-bound features.

[1] The convention that a primary articulator is designated for every segment, whether consonantal or nonconsonantal, was proposed by Morris Halle (1991).

4. Acoustic manifestation of articulator-bound features for consonantal segments: the role of acoustic landmarks

We have seen that the acoustic consequence of the articulator-free features for a consonantal segment is a particular type of discontinuity in the signal. The properties of the sound that signal which articulator is responsible for this discontinuity and how this articulator is to be placed are located in regions of the sound immediately adjacent to the discontinuity. These are the regions of the sound where the primary articulator is moving toward or away from the constricted configuration, or has achieved the constricted state. The literature contains a wealth of information indicating that the acoustic properties signalling the secondary articulator-bound features are also concentrated in the vicinity of the consonantal landmarks. Thus, for example, information about the laryngeal state or the state of the velopharyngeal opening for a consonant is located in regions near the acoustic landmarks that are correlates of the articulator-free features.

In a sense, the acoustic discontinuities produced by forming a constriction with the primary articulators constitute the glue that binds together the various features of a consonant to constitute a "segment." The acoustic manifestation of each of the features for the consonant segment normally appears in the vicinity of this discontinuity.

We shall consider here some examples of the acoustic correlates of articulator-bound features for consonants. The acoustic manifestations of these features often reside in the sound on both sides of an acoustic discontinuity. When a consonantal constriction is formed with the primary articulator, this constriction in effect divides the lumen of the vocal tract into two parts: a portion anterior to the constriction and a portion posterior to the constriction. The acoustic attributes that signal the identity and positioning of the primary articulator and of the other articulators will be different when the constriction is in place than when the articulator is moving toward or away from the constricted position. For example, for an obstruent consonant the acoustic signal can potentially provide information only about the portion of the vocal tract anterior to the constriction during the constricted interval when turbulence noise is being generated in the vicinity of the constriction.[2] In the case of a nasal consonant, information about the vocal-tract configuration during the closure interval is sampled, in effect, by observation of the sound passing through the velopharyngeal opening and radiated from the nose, whereas the mouth output provides this information after the consonant is released. Similar kinds of statements can be made for a lateral consonant.

Reports in the literature describe a variety of acoustic and perceptual data indicating the importance and diversity of the components of the acoustic pattern on the two sides of the discontinuity in providing cues for place of articulation of a consonant. We shall not review all of this evidence, but we shall discuss just two examples: the acoustic patterns following the release of unaspirated alveolar and velar stop consonants.

It is well known that both the spectrum of the burst and the time course of certain formant frequencies contribute information about the consonantal place of articulation. At the release of each of these two types of consonants there is a burst of turbulence noise that is spectrally shaped or filtered by the acoustic cavity anterior to the constriction. After the onset of vocal-fold vibration following the release, the formants are evident as prominences in the spectrum. The frequencies of these formants are determined by the acoustic cavities both posterior and anterior to the constriction. Just after the release, some of these formants are associated with the cavity anterior to the constriction and some are associated with the posterior cavity. The frequency of the lowest spectral prominence in the burst is, of course, determined by the dimensions of the front cavity.

[2] An exception to this statement is that the presence or absence of glottal vibration during the constricted interval can be observed in the sound that is radiated from the neck.

In Fig. 2 we plot on the ordinate the frequency of the lowest spectral prominence for the burst when these two consonants are released into several different vowels. The data are for one male speaker, and averages are taken separately over five front vowels, two unrounded back vowels, and four rounded back vowels. In addition to a frequency scale, the ordinate is labeled with a rough estimate of the length of the front cavity. This length is given by $\frac{c}{4f}$, where c is the velocity of sound and f is the frequency of the spectral prominence.[3] The abscissa is the frequency of $F2$ or $F3$ at the onset of the transition into the vowel. When the length of the front cavity is relatively short, as it is for an alveolar or a labial consonant, then the cavity behind the constriction is long enough that $F2$ and $F3$ are resonances of this back cavity. The sloping line in the figure marks points where the burst frequency and $F2$ or $F3$ are equal. A point on this line signifies that the front-cavity is sufficiently long that its resonance for this consonant is $F2$ or $F3$. For a release that leads to a point below the line in the $F2$ region, then $F2$ is a back-cavity resonance. Similarly if the point is below the line in the $F3$ region, that formant is also a back-cavity resonance.

The data in Fig. 2 show that alveolar consonants are consistently characterized by points below the line in the $F2 - F3$ region, indicating that the frequency of the spectral prominence in the burst for [d] is always well above $F2$ and $F3$ at the onset of the vowel, i.e., the front-cavity resonance is above $F2$ or $F3$. On the other hand, for velar consonants the frequency of the burst is always a front-cavity resonance identified with either $F2$ or $F3$. When the velar consonant precedes a back vowel, the front-cavity resonance is $F2$, whereas when it precedes a front vowel, that resonance is $F3$. The figure shows that the frequency of the major spectral peak for the burst for an alveolar consonant before a rounded back vowel is not too different from the burst frequency for a velar consonant before a front vowel. However, the starting frequencies for $F2$ and $F3$ are quite different following a velar adjacent to a front vowel than they are following an alveolar consonant adjacent to a back rounded vowel.

[3] This estimate of front cavity length is an especially poor approximation when the lips are rounded, and hence there is a significant deviation from a uniform front-cavity shape.

Similar analyses can be made to interpret the acoustic properties that exist in the vicinity of a consonantal landmark for other features. Thus, for example, place of articulation for nasal consonants is determined in part by the spectrum of the nasal murmur and in part by the starting frequencies of the formant transitions into the following vowel. Identification of place of articulation can apparently be made more readily if it is first determined that a consonant is a nasal or a stop consonant. It frequently happens that interpretation of the acoustic data for a particular feature is dependent on other features that are manifested in the sound in the vicinity of the acoustic discontinuity. That is, there would appear to be a preferred order or hierarchy for identifying features in the vicinity of a consonantal landmark.

These examples illustrate three different points about the acoustic manifestation of features for consonants. One point is that the acoustic pattern on both sides of the acoustic discontinuity and at the discontinuity itself contribute to identification of articulator-bound features. The second point – which is perhaps of only indirect relevance to the present discussion – is that the diverse acoustic attributes signalling that an articulator-bound feature has been implemented are perhaps most easily interpreted if the relation between articulatory shapes and acoustic outputs for constricted configurations are taken into account. Thirdly, since identification of some features for a segment is facilitated if other features of the segment (such as continuancy or sonorancy) are known, an optimum strategy for a human or machine recognizer of speech is to identify features according to a particular order.

In the case of nonconsonantal segments, no abrupt discontinuity appears in the signal to serve as a focus for implementing the features of the segment. Nonconsonantal segments are characterized by points or regions in time at which certain articulatory structures reach an extreme position or state. At these points in time, some acoustic parameter, such as a formant frequency, achieves a maximum or minimum value, or may remain at a relatively

fixed value over a time interval.[4] It is postulated that this region where a maximum or minimum in the frequency or amplitude of a spectral prominence occurs defines an acoustic landmark for a nonconsonantal segment (cf. the "gestural peak" proposed as a landmark by Huffman (1990)).

Acoustic interpretation of the various articulator-bound features for these nonconsonantal regions involves examining acoustic data in the vicinity of the acoustic landmark defined in this way, as well as changes in the spectrum preceding and following the landmark. The extent to which this view of an acoustic landmark can be applied to nonconsonantal segments is unclear, and requires further study. It is expected, for example, that tongue body movements that are used to produce a labiovelar glide are adjusted to achieve an extreme high back configuration in synchrony with an extreme lip rounding. This synchrony would lead to a minimum in $F1$ and $F2$ and a maximum in the increased $F2$ bandwidth that is characteristic of this glide. On the other hand, there may be other situations in which some asynchrony in the movements of a secondary articulator (such as the tongue root) in relation to the primary articulator may help to enhance the acoustic manifestation of the secondary articulator-bound features. For example, the distinction between vowels in English is carried in part by the way in which the spectrum changes with time. It appears that for some vowels the implementation of a feature specifying the configuration in the pharyngeal region is sequential with the implementation of features indicating the tongue body position. Acoustic studies of vowels in English have consistently shown that accuracy of machine identification of vowels is enhanced by examining formant trajectories over time rather than at a single point in time (Leung, 1989; Huang, 1990).

As with the consonantal segments, the acoustic properties required to identify certain features of nonconsonantal segments appears to be independent of other features for a segment,

[4]For each nonconsonantal segment we might also postulate that there is a primary articulator (and a corresponding feature or features) that acts as a focus for the implementation of the other features that form the segment.

whereas knowledge of context may be needed for identifying others. Thus, for example, the acoustic properties used to identify the feature **nasal** or the feature **tense** are most readily identified if the feature **back** and perhaps **high** and **low** are known.

5. Constraints on the implementation of articulator-bound features

We have presented arguments for the view that there are consonantal landmarks in the speech signal and that the acoustic manifestations of articulator-bound features are represented in the signal in the vicinity of these landmarks. A consequence of this view is that, if the various articulator-bound features are to be represented adequately in the sound, there must be constraints on the timing of the movements of the secondary articulators in relation to the primary articulators. Manipulation of a primary articulator creates an acoustic landmark. The movements of secondary articulators must be coordinated with the primary articulators so that acoustic evidence for the secondary features appears around the landmarks. This principle governing the coordination of different articulators during speech production has been proposed by Kingston (1990), who used the term "articulatory binding" to describe the process. Further discussion of the generality and possible limitations of the principle is given by Ohala (1990), Goldstein (1990) and Huffman (1990).

Some variability in the timing of the secondary articulators in relation to the primary ones is possible without doing damage to the ability of a listener to uncover the secondary articulator-bound features. However, too large a deviation in the relative timing will result in an acoustic output that does not provide information about the intended features of the segment, or indicates feature values different from those intended (Goldstein, 1989). In some cases, the influence of a secondary articulation might spread over a sufficiently wide time interval that it appears to be aligned with the landmark of an adjacent segment as well as (or instead of) its parent landmark. Adjustment of the timing and extent of the movement

of secondary articulators can have an influence not only on the secondary features but also on the salience with which the articulator-free and the primary articulator-bound features are represented in the sound.

The potential influences on the sound of the relative timing of the movements of different articulatory structures have been examined for a variety of movement patterns by Browman and Goldstein (1986), although details of the acoustic consequencies of these timing changes were not examined. In the present discussion we consider more closely the acoustic manifestations of these articulatory movements and we attempt to develop some principles, based on acoustics and perception, that might help to delineate constraints on the implementation of the features for an utterance. In this sense, therefore, we are drawing on the work of a number of investigators who have used phonetic data and models to show the kinds of constraints under which speakers operate when they produce an utterance in a given language (Manuel and Krakow, 1984; Manuel, 1990; Ohala, 1983).

Several examples can be cited to illustrate how the movements of secondary articulators need to be properly timed in relation to the primary articulators. (See also Kingston, 1990.) A familiar example is a voiceless aspirated stop consonant such as [p^h]. Here the relevant secondary articulator-bound features are [+spread glottis] and [+stiff vocal folds], using the laryngeal features that are accepted by some phonologists. The feature [+spread glottis] is implemented by adjusting the glottal abducting movement in such a way that the glottis is maximally open at the time of release of the primary articulator (Dixit, 1975, 1989). In this way, the presence of aspiration noise and of a subsequent breathy-voiced onset is evident in the sound in the few tens of milliseconds following the release. Presumably the timing of the glottal adduction following the release is adjusted so that the movement of the supraglottal articulator that forms and releases the constriction is essentially complete by the time glottal vibration begins. The glottal spreading maneuver also contributes to inhibition of vocal-fold vibration immediately following the implosion. The feature [+stiff vocal folds] is implemented within the consonantal closure interval so that vocal-fold vibration does not occur within this interval when there is an increased intraoral pressure, or at the consonant release. Evidence for the feature [+stiff vocal folds] appears not only as inhibition of vocal-fold vibration within the closure interval but also as a raised fundamental frequency at the onset of vocal-fold vibration.

A somewhat more complex example is that of the voiced aspirated stop consonant as it occurs in Hindi and other languages. In this case again, the feature [+spread glottis] must be implemented in a way that shows aspiration noise and breathy onset of vocal-fold vibration following the consonantal release. The glottal spreading need not be as great as it is for a voiceless aspirated consonant since there is not a requirement that vocal-fold vibration be inhibited during the aspiration interval. However, the feature [+slack vocal folds] requires that vocal-fold vibration be evident in the sound prior to the consonant release. Because there is an interaction between the glottal spreading movement and the maintenance of vocal-fold vibration, it is necessary to preserve a reasonably adducted glottis throughout most of the consonantal closure interval, together with a slack state of the vocal folds. Glottal abduction is initiated only toward the end of the closure interval (Dixit, 1975, 1989). Maintenance of glottal adduction and vocal-fold vibration is assisted by a vigorous active expansion of the vocal-tract walls, which helps to keep the supraglottal pressure low and the transglottal pressure high.

As another example of acoustic requirements influencing how a secondary articulator is controlled, we consider events at the release of a nasal consonant (cf. Huffman, 1990; Ohala, 1975). The velopharyngeal port is normally caused to close following the acoustic event created by the consonantal release. This temporal sequence guarantees that evidence of the feature [+sonorant] remains represented in the sound. An early closing of the velopharyngeal port, prior to the consonantal release, will result in a buildup of intraoral pressure, and consequent noise generation at the release. Thus a relatively small change in the timing of the

velopharyngeal closure (the velum being a secondary articulator) results in an abrupt switch in the properties of the sound, from characteristics indicating [+sonorant] to [-sonorant].

Not only must the timing of the velopharyngeal opening in relation to the release of the primary articulator closure be appropriately adjusted, but it is probable that the amount of velopharyngeal opening that exists at the instant of the consonant release must be controlled depending on the following vowel (Abramson et al., 1981). When a nasal consonant is released into a high vowel, the velopharyngeal opening should be relatively small compared to the oral constriction for the vowel, to ensure the required rapid shift in output from the nose to the mouth. For a following low vowel, this requirement can be achieved with a larger velopharyngeal opening. Proper selection of the timing and degree of velopharyngeal opening, then, appears to enhance the strength of the acoustic discontinuity that occurs at the consonantal release.

Similar constraints on the timing and degree of movement of secondary articulators appear to play a role in the production of nonconsonantal segments. For example, the amount of lip rounding or spreading that is used to contrast rounded and unrounded vowels is different for different vowel heights and degrees of backness. Presumably the amount of lip rounding is selected to enhance the acoustic and perceptual contrast, and this amount may vary from one vowel to another. Similarly, the area of the velopharyngeal opening that is required to produce a nasal vowel is different depending on the vowel height. Data are needed to determine how the timing of the lip rounding or velum movements are adjusted in relation to movements of the tongue body, which is taken to be the primary articulator for vowels.

These and other examples illustrate how acoustic requirements constrain the coordination of secondary articulators with the primary articulators, particularly for consonants. There are many situations in which the acoustic consequences of manipulation of the timing of the secondary articulators are quantal. When the relative timing exceeds certain limits, there are abrupt changes in the characteristics of the sound in the vicinity of the consonantal landmark. Furthermore, the degree of movement of the secondary articulators appears often to be adjusted so as to enhance the acoustic representation of the various articulator-free and articulator-bound features (Stevens and Keyser, 1989).

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Figure Legends

Fig. 1 Spectrogram of the sentence "The happy boy drank Billy's juice." Various consonantal events and nonconsonantal regions are discussed in the text.

Fig. 2 Illustrating how different kinds of acoustic information on two sides of a consonantal discontinuity can contribute to the identification of features for the consonant. Data are from alveolar and velar stop consonants produced by a male speaker of English in a variety of vowel contexts. The ordinate is the frequency of the major spectral prominence for the consonant burst. The abscissa is the second and third formant frequencies ($F2$ and $F3$) measured at the beginning of voicing in the following vowel. Each point represents average data over several utterances fo either [d] or [g] before four rounded back vowels (**dr** and **gr**), two unrounded back vowels (**db** and **gb**), and five front vowels (**df** and **gf**). A point on the solid line indicates that the burst frequency is equal to $F2$ or $F3$. The dashed line separates $F2$ and $F3$.

Table 1 Listing of possible combinations of articulator-free features. An entry in parentheses indicates that the feature is constrained to take on a particular value. An example of a consonant with the given combination of features is given at the top of each column.

features	t	l	n	s	θ
consonantal	+	+	+	+	+
continuant	-	-	-	+	+
sonorant	-	+	+	(-)	(-)
lateral	(-)	+	-	(-)	(-)
strident	(-)	(-)	(-)	+	-

Table 2 Expansion of Table 1 to include primary articulator-bound categories and articulator-bound features. The features enclosed in boxes are features that specify the placement of the primary articulator.

		t	n	f	g	l
articulator-free features	consonantal	+	+	+	+	+
	continuant	-	-	+	-	-
	sonorant	-	+	-	-	+
	lateral	(-)	(-)	(-)	(-)	+
	strident	(-)	(-)	+	(-)	(-)
primary articulator-bound categories	lips			x		
	tongue blade	x	x			x
	tongue dorsum				x	
articulator-bound features	round			$\boxed{-}$		
	anterior	$\boxed{+}$	$\boxed{+}$			$\boxed{+}$
	distributed	$\boxed{-}$	$\boxed{-}$			$\boxed{-}$
	high				$\boxed{+}$	-
	low				$\boxed{-}$	-
	back				$\boxed{+}$	+
	spread glottis	+		+	-	
	stiff vocal folds	+		+		
	slack vocal folds				+	
	adv. tongue root	-		-		
	const. tongue root					
	nasal		+			

Table 3 Representation of some nonconsonantal segments in terms of two types of categories: articulator-free features and articulator-bound features. The features enclosed in boxes are features that specify the placement of the primary articulator.

		e	u	w	j	h
articulator-free features	consonantal	-	-	-	-	-
	continuant					
	sonorant					
	lateral					
	strident					
articulator-bound categories	lips			x		
	tongue blade				x	
	tongue dorsum	x	x			
	larynx					x
features classifying articulator-bound categories	round		+	$\boxed{+}$		
	anterior				$\boxed{-}$	
	distributed				$\boxed{+}$	
	high	$\boxed{-}$	$\boxed{+}$	+	+	
	low	$\boxed{-}$	$\boxed{-}$	-	-	
	back	$\boxed{-}$	$\boxed{+}$	+	-	
	spread glottis					$\boxed{+}$

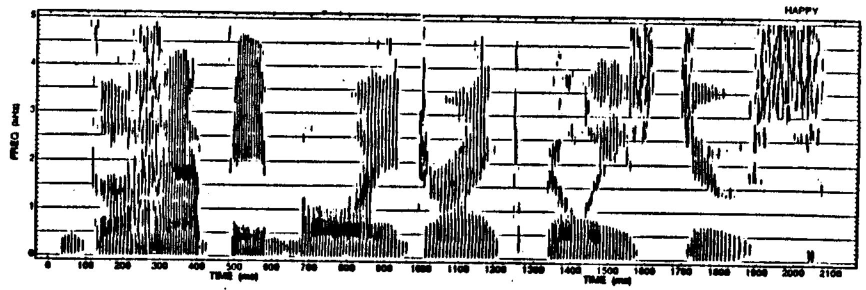

Fig. 1

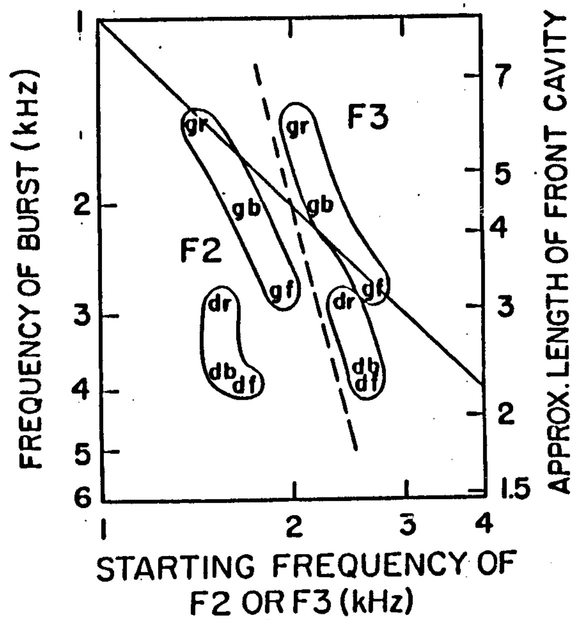

Fig. 2