PRIMARY FEATURES AND THEIR ENHANCEMENT IN CONSONANTS

KENNETH N. STEVENS AND SAMUEL JAY KEYSER

Massachusetts Institute of Technology

Among the distinctive features for consonants, we distinguish a set of primary features that are perceptually the most salient. The strength with which a primary feature is manifested in a given sound is influenced by the secondary features that co-occur with it. The features [sonorant], [continuant] and [coronal] are designated as primary, and this designation applies in all of the eight possible configurations in which they occur. The features [anterior] and [lateral] are also designated as primary, but only under restricted conditions. We examine systematically which combinations of secondary features provide maximal enhancement of the acoustic manifestations of the primary features. This analysis leads to an inventory of eleven preferred feature combinations or segments. There is a close fit between this preferred inventory and a list of the most frequently occurring segments in the languages of the world, based on Maddieson 1984. This match constitutes support for the view that the frequently occurring feature combinations in the languages of the world come about because those combinations maximize perceptual distinctiveness through the mechanism of feature enhancement. It is suggested that these concepts of enhancement and of preferred feature combinations are directly relevant to the notion of markedness.*

1. INTRODUCTION. Though there are a large number of possible speech sounds in the languages of the world, it is well known that a small inventory of sounds appears over and over in language. For example, in the 317 languages listed in Maddieson 1984, about 500 different consonants are listed, but ten of these occur in at least 64% of the languages. These ten consonants are listed in Table 1, together with the percent of languages in which each is observed.[1]

The purpose of this paper is to offer an explanation for the strong preference for this core inventory of consonants. Our argument is an extension of the theory of enhancement introduced in Stevens et al. 1986. The theory of enhancement is based on three hypotheses. The first is that distinctive features constitute the appropriate mode of representation for the sounds of the languages of the world and that groups of features tend to be implemented simultaneously to form segments. The second is that the acoustic manifestations of some distinctive features are more salient than others. We call this particular set of features PRIMARY FEATURES. The third is that a given distinctive feature can be represented in a sound with varying degrees of strength, which in turn can be enhanced by its co-occurrence with other features.

* This work was supported in part by NSF Grant No. BNS-8418733 to the MIT Center for Cognitive Science and in part by NIH Grant No. NS-04332 to the MIT Research Laboratory of Electronics.

[1] In the case of the [+coronal] consonants /t/, /n/, /s/, and /l/, we have included in our count segments labelled by Maddieson either as alveolar or as dental/alveolar, on the assumption that both of these designations could be regarded as [−distributed]. Maddieson (personal communication, 1988) suggests that the majority of the segments he identifies as dental/alveolar are probably apical rather than laminal, thus providing some support for this way of classifying the coronals. If the three groups alveolar, dental/alveolar and dental were combined, then the resulting segments /*t/, /*n/, /*s/, and /*l/ would be higher on the list in Table 1.

SEGMENT	IN MADDIESON
/m/	94
/k/	89
/j/	85
/p/	83
/n/	82
/s/	77
/t/	75
/w/	75
/l/	68
/h/	64

TABLE 1. List of the ten most frequently-occurring consonants in languages surveyed by Maddieson 1984.

We argue that the consonant segments that are most prevalent in language are those that are distinguished from one another by the most salient features, i.e. by the primary features. The remaining, or secondary, features for the preferred segments are selected so as to enhance the strength with which the primary features are implemented, and thereby to maximize the perceptual contrast between the segments.

The notions of enhancement and of maximum perceptual contrast have been discussed by several researchers. Jakobson & Waugh (1979:108–9), for example, point out that redundant features can play the role of reinforcing a distinctive opposition. Liljencrants & Lindblom 1972 have utilized a principle of maximum perceptual distinctiveness to account for the way particular inventories of vowels tend to be distributed. This principle has been refined and extended in a more recent publication by Lindblom (1986).[2] Maddieson 1984 has discussed the problems involved in quantifying perceptual salience and perceptual distance as he seeks a rationale for the patterning of sounds in language.

Our objective in this paper is to explore to what extent it is possible to account for the distribution of preferred sounds in languages of the world based on the concepts of enhancement and perceptual saliency alone. Maddieson's remarks in his important book, together with the extensive data that he presents, have provided a major stimulus for the present paper.

[2] Other principles might be invoked to account for the predisposition of languages to utilize particular segments. One such principle suggests that some segments occur more frequently than others because they are 'easier to articulate'. At the present state of knowledge we question whether 'ease of articulation' can be made into a coherent notion. Consider, for example, the view that obstruents tend to be voiceless because of physiological constraints which make them easier to articulate. A common argument is that the increased intraoral pressure associated with an obstruent consonant causes a reduction in transglottal pressure and hence possible extinction of voicing. It should be noted, however, that, for an obstruent to be heard as voiced, vocal fold vibration is only required in the vicinity of the boundary between the obstruent and the adjacent sonorant, and voicing throughout the obstruent is not needed. Furthermore, the production of a voiceless obstruent generally requires an active abduction of the glottis, whereas a voiced obstruent does not. In view of these observations, one might question whether it is possible to quantify the ease with which these two classes of segments are articulated. Similar ambiguities are evident when one attempts to quantify relative ease of articulation for other pairs of sounds.

2. DISTINCTIVE FEATURES. The distinctive feature is a fundamental unit in the framework that phonologists use to describe utterances. The phonological representation consists of sequences of discrete units, and the items in this sequence are specified in terms of discrete categories. Thus these phonological representations are inherently categorial or quantal, in contrast to the stream of articulatory states and movements and the sound wave or its auditory representation, which are inherently analog in form.

Various proposals have been made concerning the appropriate inventory of features for describing phonetic distinctions across languages. For purposes of the present discussion, we have selected the list of features in Table 2. This inventory is similar to that proposed by Chomsky & Halle 1968, which in turn is a modification of the features originally described by Jakobson, Fant, & Halle 1952. Some of the Chomsky-Halle features were originally defined in terms of articulatory attributes, although the requirement that the features have acoustic or perceptual correlates was always assumed by Chomsky and Halle. In recent years there has been a continuing effort to develop acoustic-perceptual as well as articulatory correlates of the features. This effort has led to some modification of some of the features originally proposed by Chomsky and Halle. Phonological considerations have also led to some adjustments of the feature inventory.

VOCALIC	NONVOCALIC
high	sonorant
low	continuant
back	coronal
round	strident
nasal	consonantal
spread glottis	anterior
constricted glottis	lateral
	distributed
	voice

TABLE 2. List of distinctive features to which reference is made in this paper. The features are organized into two groups: those that are represented in the sound when the vocal tract is relatively open (vocalic), and those that are represented in the sound when the vocal tract is more constricted (nonvocalic).

Thus, for example, our current view is that the feature [+sonorant] should be defined in such a way that it is redundantly [+voice], since this definition can lead to a well-defined and perceptually more reasonable acoustic correlate of the sonorant feature. Another modification of the Chomsky-Halle features involves the features describing the laryngeal configuration. The list in Table 2 includes the features [constricted glottis] and [spread glottis], as well as the feature [voice].[3]

[3] The features [constricted glottis] and [spread glottis] have been discussed in Halle & Stevens 1971. They are intended to provide a framework for classifying obstruents into plain [−spread glottis, −constricted glottis], aspirated [+spread glottis, −constricted glottis], and glottalized [−spread glottis, +constricted glottis]. Other approaches to classifying laryngeal configurations

The features in Table 2 are organized into two sublists depending on the way they are implemented. The features listed in the left-hand column are identified as vocalic. For these features the acoustic manifestation occurs when the vocal tract is relatively unconstricted and the acoustic source that gives rise to the generation of sound is at the glottis. The spectrum of the sound that is generated during time intervals when the vocal tract is relatively unconstricted is characterized by several prominent peaks or formants, particularly in the midfrequency range 700 to 3000 Hz. An additional spectral maximum (or additional maxima) will occur at low frequencies, with a degree of prominence that depends on the glottal and velopharyngeal configuration. For the features in the right-hand column of Table 2, identified as nonvocalic, the acoustic manifestation occurs when the vocal tract is relatively constricted at some point along its length. The source of sound may be at the glottis or it may be in the vicinity of the constriction. The acoustic and articulatory correlates of these features are discussed in other publications, such as Fant 1973 and Stevens 1980, 1983.

The link between the discrete representation in the mind of the listener and the analog domain of articulation, sound, and peripheral auditory responses consists of specifications of articulatory, acoustic, and auditory correlates of distinctive features. In describing relations between phonological features on the one hand and articulatory, acoustic, and auditory representations on the other, we need to introduce two concepts. First we need the concept of a THRESHOLD. If a continuous modification of the articulation or of the sound were made from patterns representing one value of a feature to patterns representing the other value, the pattern of articulation or of auditory response reaches a point where a new process or mechanism comes into play. There is, in a sense, a natural threshold or dividing line between two regions within the range of values of an articulatory or acoustic parameter. (See, for example, Stevens 1972, Stevens 1989). Thus, for example, the articulatory correlate of the feature [−back] is that the tongue body is in a fronted position in the vocal tract, and the acoustic correlate is that the second formant (*F2*) is close to the third formant (*F3*). There is, presumably, a threshold phenomenon that occurs when *F2* is displaced upward in frequency to become close to *F3*. This phenomenon has been discussed by Chistovich and her coworkers (1979) and by Syrdal & Gopal 1986. When *F2* and *F3* are sufficiently close together, some aspect of the listener response interprets the two-peaked spectral prominence in terms of a single broad prominence with a center of gravity. Separation of *F2* and *F3* beyond a certain critical distance leads to an auditory representation with two separate prominences. We assume that the perceptual correlate of each of the features can be described in terms of a threshold phenomenon of this type, and that the human perceptual system is equipped with fifteen to twenty of these threshold processes corresponding to features of the kind listed in Table 2.

have also been proposed (e.g. Catford 1977; Ladefoged 1971), but we suggest that the differences are not sufficient to influence significantly the present arguments concerning enhancement. We omit from consideration here the features [stiff vocal folds] and [slack vocal folds] proposed by Halle and Stevens, but we retain the feature [voice] to make the distinction between voiced and voiceless consonants.

Once the appropriate threshold has been achieved, the acoustic property that is manifested can be present with various DEGREES OF STRENGTH beyond this threshold. Thus, in terms of the example just noted, *F2* can be maneuvered closer to *F3*, and the two-peaked spectral prominence can be made even more prominent. Presumably, enhancing the strength of the acoustic and auditory representation of a feature will make that property perceptually more salient and more distinct, and will increase the probability that that property will be detected and the corresponding feature identified.

3. SALIENCY. We begin with the hypothesis that not all distinctive features are equally salient from a perceptual point of view. That is, the contrasting acoustic properties associated with the presence or absence of some features provide a stronger auditory response than those associated with other features.

For example, consider the pairs /t, s/ and /t, t̪/. The members of the first pair are distinguished by the feature [continuant], whereas the members of the second pair are distinguished by the feature [distributed]. We postulate that one of these features is more salient than the other—in particular, that [continuant] is more salient than [distributed]. There is, in the acoustic/auditory domain, a striking difference between the properties that characterize these two features. For a segment that is [−continuant], there is an abrupt onset of energy over a range of frequencies preceded by an interval of silence or of low amplitude. This acoustic property leads to a distinctive response in the auditory system. A segment that is [+continuant] has a less abrupt onset for two reasons: there is acoustic energy during the interval preceding the release, and even if this energy were weak or not present the increase in amplitude at the release is less abrupt. On the other hand, for the feature [distributed] the contrasting acoustic correlate is thought to be the presence or absence of a single brief transient at the consonantal release.[4] Our intuition is that if one compares the difference in the acoustic/auditory domain for minimally distinct utterances involving these features, one finds that the contrast is greater for the feature [continuant] than for the feature [distributed]. It is for this reason that we suppose [continuant] to be more salient than [distributed]. We cannot, at this point, quantify the saliency of individual features in terms of auditory response mechanisms. Consequently, the persuasiveness of our hypothesis must depend upon other kinds of data.

Evidence in support of the conclusion concerning the features [continuant] and [distributed] is that the contrast defined by the pair /t, s/ is almost universal in language whereas that defined by the pair /t, t̪/ is rare. Maddieson 1984 asserts that out of the total of 317 languages that he surveys, only 8% (24

[4] Consonants classified as [+distributed] are produced with a constriction that is longer than that for [−distributed] consonants. A consequence is that at the release of a [+distributed] consonant there is a less rapid change in the spectrum as the consonant is released. A clear definition of the acoustic correlate of this feature and, indeed, the status of the feature itself, is still under discussion.

guages) have both alveolar and dental stops, whereas 84% (266 languages) exhibit /s/ and virtually all of the 317 languages surveyed exhibit an alveolar or dental stop. We suppose that distributions like this can be explained in terms of the saliency hypothesis. In short, we take contrasts that are universally instantiated to reflect an important property of the perceptual system—namely, that just those contrasts are perceptually the most robust.

4. The primary features. We postulate that there is a set of distinctive features for consonants that are the most salient; these are the features [continuant], [sonorant] and [coronal]. We call these features primary,[5] and they lead to the eight possible combinations listed in Table 3.

	Continuant	Sonorant	Coronal	Segment type
(1)	+	+	+	J
(2)	+	+	−	W
(3)	+	−	+	S
(4)	+	−	−	F,H
(5)	−	+	+	N,L
(6)	−	+	−	M
(7)	−	−	+	T
(8)	−	−	−	P,K

Table 3. Three primary features and their combinations.

There are several reasons for the selection of this particular set of features as primary. To begin with, among the ten or so features that are represented in the sound during or immediately adjacent to the constricted interval for a consonant, each of these three primary features can be implemented independently of the presence or absence of other features. That is, generation of the acoustic property associated with each of the primary features does not require that some other feature or features have specific values. The remaining or secondary consonantal features, however, are more restricted in that their values may depend upon the values of the primary features with which they are combined. In a sense, the acoustic correlates of each of the secondary features are modulations on the acoustic properties associated with the three primary features. Once the primary properties are present, these secondary features can then operate to modify the way the primary features are implemented. The secondary features can, of course, also operate in their own right to make distinctions in language.

An example of a secondary feature is the feature [distributed] discussed above. Whereas consonants that are [+coronal] can assume either value of [distributed], this is not true of velar and uvular consonants, which are always [+distributed]. As another example, we observe that the feature [+strident] can be implemented only if [−sonorant] is specified. Furthermore, most views

[5] The classification of these features as primary is unrelated to other groupings of features that have been proposed, such as 'major class' features in Chomsky and Halle 1968, or features within a particular tier in current views of feature geometry (Clements 1985).

of feature systems also require that stridency is only relevant for segments that are [+continuant]. That is, the feature [+strident] cannot be implemented simultaneously with [+sonorant] or with [−continuant].

Other reasons for the special status that we give to the three primary features in Table 3 are based on an examination of their acoustic and perceptual manifestations. While all of the features appear to be based on some distinctive aspect of the auditory response to sound, the three primary features seem to be especially closely tied to fundamental capabilities of the auditory system for processing temporal and spectral aspects of sound. For example, a consonantal segment with the feature [+sonorant] is characterized by continuity of the spectrum amplitude at low frequencies in the region of the first and second harmonics—a continuity of amplitude that extends into an adjacent vowel without substantial change. This property is a consequence of the fact that there is essentially no obstruction to the airflow in the airways above the larynx, and the vocal folds can continue to vibrate in a normal manner, so that the low-frequency amplitude in the radiated sound remains unchanged. Implementation of [−sonorant] gives rise to a reduced spectrum amplitude at low frequencies. The acoustic correlate of the feature [−continuant] is an abrupt increase (or decrease) in amplitude over a range of frequencies (excluding the low-frequency region associated with sonorancy), preceded (or followed) by an interval of relatively weak amplitude. It is known that the peripheral auditory system shows an enhanced response immediately following an abrupt increase in amplitude and a depressed response immediately following an abrupt decrease in amplitude (Smith 1979, Delgutte & Kiang 1984). The articulatory correlate of a [−continuant] consonant is a complete closure at some point along the midline of the vocal tract. The abruptness occurs at the release or implosion of this closure.[6] For the feature [+coronal], the acoustic correlate is a greater spectrum amplitude at high frequencies than at low frequencies, or at least an increase in spectrum amplitude at high frequencies relative to the high-frequency amplitude at immediately adjacent times. A [+coronal] consonant is produced by raising the tongue blade and placing some part of it in contact with the hard palate or upper teeth to form a narrow constriction.[7]

Thus, the three primary features are associated with three basic properties which appear to produce distinctive patterns of response in the auditory system. These properties are illustrated in Figure 1, in which spectrograms of the two utterances [ata] and [awa] are displayed. In the figure, the feature combination [−sonorant, −continuant, +coronal] is illustrated by [t] and the combination [+sonorant, +continuant, −coronal] by [w]. The primary features indicate (1) whether or not there is continuity in amplitude at low frequencies, (2)

[6] An abrupt increase in spectrum amplitude is usually observed at the release of a lateral consonant, which we classify as [−continuant], although for a post-vocalic lateral in English the [−continuant] feature is not always implemented.

[7] A precise definition of the extent of contact that defines a [+coronal] segment is difficult to formulate at this stage. As indicated in fn. 8, there are acoustic grounds for classifying palatals (including /j/) as [+coronal], so that the articulatory correlate of the feature should encompass this group of segments.

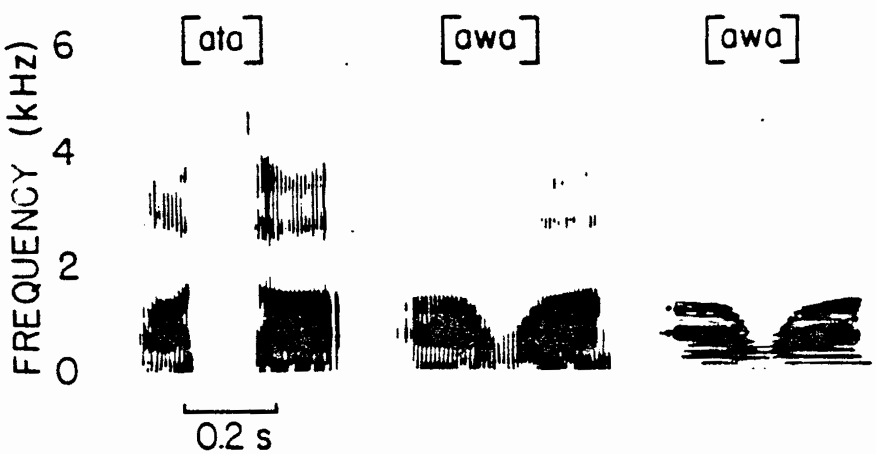

FIGURE 1. Spectrograms of the utterances [ata] and [awa]. Both wide-band and narrow-band spectrograms are shown for [awa]. These spectrograms are intended to illustrate the acoustic manifestations of the three primary features [continuant], [sonorant], and [coronal]. Two extremes of continuancy are the abruptness of the consonantal offset and release for [t] and the smoothness of amplitude changes for [w]. The implementation of [+sonorant] for [w] is best seen in the narrow-band spectrogram, where there is continuity in the low-frequency harmonics with essentially no change in their amplitudes. The low-frequency energy drops essentially to zero in the closure interval for [t]. Coronality is manifested in [t] by a greater high-frequency amplitude in the burst and in the initial part of voicing than in the following vowel. The lack of any high-frequency energy for [w] is evidence for the feature [−coronal].

whether or not there is an abrupt change in amplitude at higher frequencies, and (3) whether or not the speech stream is punctuated by a region in which the high-frequency energy (as represented in the auditory system) stands out from its immediate context.

Still another reason for selecting these three features as primary is that, among the features that are available for signalling phonetic contrasts during consonantal intervals in the speech stream, these three features are used distinctively in a large majority of languages. The distinctive use of secondary features is less frequent in language. We return to this point in our later discussion.

The symbols in the rightmost column of Table 3 represent the segment type that is defined by each row. No row uniquely defines any specific segment, however, and each row may be understood as specifying a class of segments. For example, the fifth row is compatible not only with /n/, but also with a dental /n̪/ as in English *tenth*, a palatalized /nʲ/ as in Russian *nyet*, the lateral /l/ in certain of its various manifestations (for example, a laryngealized /l̰/ or a retroflex /ɭ/) and so on. Similarly, one could elaborate each of the rows in the table. Nonetheless, we have not chosen the symbols in the rightmost column randomly. Rather our contention is that the combinations of features represented by those symbols are, in fact, combinations which, when fully specified, maximize the strength of the properties that are acoustic correlates of the three

primary features [continuant], [sonorant], and [coronal]. For the time being, however, we can regard these symbols as aids in identifying the various combinations of features we will be discussing.

5. ENHANCEMENT OF THE PRIMARY FEATURES. We now examine the secondary features when they are implemented in combination with the three primary features. In particular, we show that the strength with which each of the primary features is represented in the sound is influenced by the combination of secondary features that co-occur with the primary features. We consider each of the secondary features in turn, in order to determine which value of the feature is to be preferred in terms of its effect in strengthening each primary feature. An outcome of this exercise is a specification of a number of feature combinations or segments that are in some sense optimal, since they provide the strongest representation of the contrast defined by each of the three primary features. While all of the arguments for enhancement are grounded in theories of acoustics and perception, some are more speculative than others. Nevertheless, we believe that the sum total of these arguments is sufficiently convincing to warrant serious consideration of enhancement as a linguistic principle.

In this discussion we postpone consideration of [anterior] and [lateral] until the very end, since, as we will see, these features have special properties. Aside from these two features, there is no significance in the order in which we take up the secondary features.

5.1. VOICE. We begin with the feature [voice]. It is evident that the features [sonorant] and [voice] are linked together in the sense that [+sonorant] is enhanced by [+voice] while [−sonorant] is enhanced by [−voice]. In fact, as we mentioned in §2, we believe that [+sonorant] consonants are redundantly [+voice]. Although the feature [+voice] can be implemented together with [−sonorant], as in a voiced stop or fricative consonant, the sound that results necessarily has low-frequency energy, a property which it shares with [+sonorant], though this low-frequency energy is weaker in a voiced obstruent than in a [+sonorant] segment. Consequently, making a [−sonorant] segment [+voice] has the effect of weakening the acoustic manifestation of the [−sonorant] feature. We conclude, then, that the feature [voice] should take on the same value as the feature [sonorant] if the latter feature is to be implemented with maximum strength. This conclusion does not hold for the features [continuant] and [coronal], whose strength appears to be unaffected by the value of [voice].

5.2. CONSONANTAL. The articulatory correlate of the feature [+consonantal] is a narrow constriction at some point along the length of the vocal tract. This constriction is sufficiently narrow that, when the consonant is released into the following vowel, there is a rapid movement of some of the formants, particularly those associated with the part of the vocal tract posterior to the constriction. The result of this formant movement is a rapid change in the spectrum over at least some part of the frequency range. Examination of the ws in Table 3 indicates that six of the eight combinations are redundantly specified for the feature [consonantal]. For example, the combination [+continuant, +sonorant] implies that there is no narrow vocal-tract constriction, and hence this combination is redundantly [−consonantal]. Of the remaining combinations, those that are [+coronal] are redundantly [+consonantal], since these combinations imply a narrow constriction formed by the tongue blade. Likewise, the combination [−continuant, +sonorant, −coronal] is redundantly [+consonantal].

Of the remaining two combinations (rows 4 and 8 in Table 3, identified as [−sonorant, −coronal]), both [+consonantal] and [−consonantal] segments are possible. In the case of the [+continuant] version (row 4) we have at present no strong reason for selecting either value of the feature [consonantal] in terms of its effect on the saliency of the three primary features. (Further discussion of this point will be given in §6.1 below.) On the other hand, for the [−continuant] version (row 8), the strength of all three of the primary features would appear to be enhanced by the feature [+consonantal]. That is, the lack of a rapid spectrum change and of a noise burst near the release for the [−consonantal] segment /ʔ/ leads to a weaker instantiation of [−continuant], [−sonorant] and [−coronal] than in a stop consonant produced by forming a constriction in the vocal tract proper.

5.3. Distributed. The feature [−continuant] in rows 5 through 8 of Table 3 is enhanced if the length of the consonantal closure in the vocal tract is short and if the release is rapid. These attributes will give rise to an abrupt onset of acoustic energy at the release of the consonant. This requirement dictates that the feature combinations in these four rows should be [−distributed] in order to enhance [−continuant]; that is, they should be produced with a short constriction at the tongue tip or at the lips.

On the other hand, the combinations in rows 1 and 2, which are [+continuant, +sonorant] should be implemented with a slower release. This kind of release is achieved by forming a longer constriction, that is, with the feature [+distributed].[8] In the case of the continuants in rows 3 and 4, we will see below

[8] Our point of view with regard to the glides /w/ and /j/ is that the former is [+anterior, −coronal] and the later is [−anterior, +coronal]. In the case of /w/, therefore, we consider the labial articulation to be primary (with a secondary velar constriction), and a [+distributed] manifestation is achieved by rounding. There is no implication, however, that rounded consonants are necessarily [+anterior] or [+distributed], since rounding is usually considered to be a secondary articulation. Our representation of /j/ as [+coronal] differs from the classification proposed by Chomsky & Halle 1968. This modification is based in part on acoustic grounds (relative prominence of high-frequency spectrum energy) and in part on a view that a raised tongue blade is used to produce this glide, in common with other [+coronal] segments. It should be noted here that in some recent formulations of feature geometry (Sagey 1986), there are restrictions on the co-occurrence of certain features. In particular, the features [anterior] and [distributed] are assumed in those formulations to apply only to consonants that are [+coronal]. In the present discussion, we do not make these restrictions a priori. We recognize, however, that the features [anterior] and [distributed] are rarely if ever distinctive for noncoronal consonants, and that they act to enhance other, primary, features in those situations. (See, however, later discussion of [anterior].)

that implementation of the feature [strident] is crucial and that the status of the feature [distributed] is irrelevant.

5.4. Strident. Since the feature [+strident] can only occur if frication noise is generated at a constriction, all [+sonorant] segments are redundantly [−strident], as we have noted earlier. This rule applies to rows 1, 2, 5, and 6 of Table 3. Among the stop consonants (rows 7 and 8), our view is that adding the feature [strident] would require that the segment be complex, with a [+continuant] as well as a [−continuant] component (see Clements & Keyser 1982). That is, a segment that contains [+strident, −continuant] is an affricate. For such a complex segment it would appear that the strength of the feature [−continuant] would be weakened, since the rate of release of the closure would be limited by the fact that a narrow constriction needs to be maintained after the release. Consequently, the feature combinations for the stop consonants in rows 7 and 8 are most strongly represented if they are combined with [−strident]. Finally, we turn to rows 3 and 4, which are [+continuant, −sonorant]. The implementation of [+continuant] is clearly strengthened if the frication noise is of high intensity. This condition is achieved for rows 3 and 4 by directing the airstream against the lower teeth or against the upper lip, that is, by the feature [+strident].

5.5. Nasal. The feature [nasal] is implemented with the velum lowered to produce a velopharyngeal opening. In addition to modifying the acoustic properties of the system, this opening permits all or a part of the air from the glottis to flow through the nasal cavity. When the velopharyngeal port is open, there is essentially no pressure buildup above the glottis when the vocal folds are vibrating, and the result is a sonorant segment. During a voiceless nasal consonant (which is [−sonorant] in our system of classification), the airflow is greater than it is for a voiced sound, and some turbulence noise is generated in the airway. The pressure increase in the oral cavity remains small, however, and, as a consequence, the noise is weak. Implementation of the features [continuant] and [coronal], then, is weak for a voiceless nasal consonant, unless a sonorant interval occurs before release of the consonant. We conclude that [+nasal] should be implemented with [+sonorant] in order to enhance the acoustic manifestation of [continuant] and [coronal].

In the case of a sonorant consonant that is [+continuant] (rows 1 and 2 of Table 3), realization of the coronal/noncoronal distinction requires that the formant frequencies and bandwidths be adjusted to yield the appropriate falling (for [−coronal]) or rising (for [+coronal]) spectrum shape. These spectrum shapes are achieved by positioning the second formant *F2* low and close to *F1* for the [−coronal] consonant and by positioning *F2* and *F3* high and close to *F4* for the [+coronal] consonant, together with widening of some formants. (See later discussion in §6.2.) Nasalization of these sonorant consonants will tend to perturb the ideal rising or falling spectrum shapes by shifting some formants from their extreme positions (for example, the lowest resonance will increase in frequency) and by introducing additional peaks in the spectrum.

We conclude, then, that for [+continuant, +sonorant] consonants, the feature [coronal] is more strongly implemented when accompanied by the feature [−nasal]. Another reason for favoring [−nasal] in this environment is that opening of the velopharyngeal port will result in a greater low-frequency amplitude during the consonant, thus causing less of a dip in energy. An energy dip is required to preserve the nonsyllabic nature of the consonant.

For the [−continuant, +sonorant] pair in rows 5 and 6 of Table 3, the situation is quite different. The only ways in which a complete closure can be made in the midline of the vocal tract (to implement the feature [−continuant]) with no pressure increase above the glottis is by opening the velopharyngeal port or by creating a passage for airflow around a lateral edge of either the blade or the dorsum of the tongue. Release of the closure with the nasal opening results in a significantly greater increase in spectrum amplitude over a wide frequency range than does the release of a lateral consonant. This difference can be shown theoretically as well as observed experimentally (at least for coronal laterals and nasals). The abrupt change in spectrum amplitude is a consequence of the rapid switching from nose output to mouth output immediately following the release. Evidently, then, the representation of [−continuant] is enhanced for the [+nasal] versions of the combination of primary features in rows 5 and 6 of Table 3. Enhancement of the abruptness of the release presumably also enhances the representation of the feature [coronal] when [+nasal] is implemented.

5.6. Laryngeal features. We turn next to laryngeal features and we examine the interaction between the primary features and the features [spread glottis] and [constricted glottis]. These laryngeal features, together with the feature [voice], are responsible for sounds that are described as aspirated, breathy, glottalized, and laryngealized.[9] While it is not particularly common for these features to operate distinctively in the languages of the world, it is less evident why this might be so from the point of view of enhancement. One possible argument is that positive values for these features detract from both [+sonorant] and [−sonorant].

Consider first the implementation of the feature [+sonorant] with these laryngeal configurations (rows 1, 2, 5, and 6 in Table 3). When there is a narrow constriction in the airways above the larynx, the maintenance of vocal-fold vibration is less reliable when the glottis is spread than when it is in a normal configuration. Thus, for example, if the glide [w] is produced with a breathy voice, it can be argued that the resulting sound is less sonorant since the greater airflow associated with breathy voicing is likely to create a pressure drop across

[9] We have discussed the feature [voice] separately in §5.1. Our point of view here is that the features [spread glottis] and [constricted glottis] are laryngeal features in the sense that they involve direct manipulation of the laryngeal configurations. Implementation of the feature [voice], for which the acoustic correlate is the presence or absence of glottal vibration, requires appropriate manipulation of supraglottal as well as laryngeal structures, particularly in the case of obstruents. In this sense, the feature [voice] might be classed as a manner feature. The arguments about enhancement that form the basis for the present paper are not, however, dependent upon this particular point of view with regard to the laryngeal features.

the constriction and to generate turbulence at the point of constriction. The resulting decrease in transglottal pressure will tend to decrease the amplitude of the glottal pulses and hence to weaken the acoustic manifestation of sonorancy.

The implementation of the feature [+constricted glottis] weakens the acoustic manifestation of [+sonorant] for a different reason. Constricting the glottis leads to glottal pulses for which the amplitude of the first harmonic is reduced relative to that for modal voicing, thereby weakening the sonorant character of the consonant. Sonorancy depends upon maintenance of the amplitude of the fundamental component through the consonantal interval into the adjacent vowel.

The laryngeal configurations [+spread glottis] and [+constricted glottis] appear to be neutral with respect to the strength of implementation of the feature [−sonorant] and, in fact, may even enhance that feature. That is, these laryngeal configurations will tend to inhibit voicing and hence to weaken the low-frequency spectrum amplitude for consonants. However, for these [−sonorant] consonants the spread and constricted glottal configurations lead to aspirated and ejective or glottalized consonants, respectively. When the glottis is in one of these states at the release, there is a delay of 10 msec or more before the onset of voicing (Catford 1977), and presumably a further delay while the glottal state changes to a modal configuration, during which time there is a change in the spectrum of the glottal output. Identification of consonantal place of articulation is aided if the spectrum of the consonantal release is interpreted in relation to the spectrum of the onset of the following vowel. The spectrum at voicing onset appears to aid in this interpretation. It is expected, then, that a change in glottal spectrum in the time interval immediately following the release will detract from this interpretation. Consequently, these laryngeal features will weaken the implementation of the feature [coronal], which relies on examination of the consonant spectrum in relation to the following vowel (Kewley-Port 1983, Lahiri et al. 1984). In other words, obstruents are best realized with a glottal configuration that is neither spread nor constricted. Exceptions are obstruents which are produced exclusively with a constriction at the glottis, which, as we have seen, are [−consonantal].[10]

6. Other salient features: anterior and lateral. Up to this point we have considered two kinds of features, which we have called primary and secondary features. The three primary features have the unique properties that they are orthogonal (i.e., they can occur in any combination) and they can achieve perceptual saliency for any of their eight combinations, depending on the values of other features with which they are implemented. On the other

[10] As noted in §2, we have chosen to define sonorants to be redundantly [+voice]. Consistent with this definition, and in contrast to the definition in Chomsky & Halle 1968 and elsewhere, we classify /ʔ/ and /h/ as being [−sonorant]. We regard this classification to be consistent with the articulatory correlate of [−sonorant], that is, the formation of a constriction above the glottis. In the case of /ʔ/ and /h/, this contribution is at the level of the false vocal folds. Again, however, these details of particular feature definitions should not influence the main premise of this paper, which is concerned with processes of enhancement.

hand, the secondary features are restricted in the environments in which they can occur and can signal phonetic distinctions, and they are less salient than the primary features. These secondary features differ in the degree to which they enhance the acoustic properties that are correlates of the primary features.

We turn now to a third type of feature, one which is perceptually salient when implemented with certain of the primary features, but not otherwise. When a feature of this type is implemented with the appropriate combination of primary features, it becomes, in effect, a primary feature. Otherwise, it plays the role of a secondary feature. We have identified two features of this type, although it is possible that others may be added to this group. The features that we focus on are [anterior] and [lateral].

6.1. Anterior as a salient feature. The feature [anterior] indicates where in the vocal tract the constriction is located for a consonant. In fact [anterior] is unique among the features proposed by Chomsky & Halle 1968 in that it is the only feature which refers to a vocal tract location rather than to an articulatory structure or to a manner of articulation.[11] For a segment that is [−anterior], the cavity in front of the constriction is sufficiently long that its natural frequency corresponds to the second or third resonance of the entire vocal tract. That is, the front-cavity resonance is in the frequency range that plays a role in the identification of backness for vowels. For a [+anterior] segment, on the other hand, there is no major spectral prominence in this midfrequency range. The feature [anterior] can be strongly represented in the sound, however, only for obstruent consonants, for which turbulence noise is generated in the vicinity of the constriction. This noise source forms the excitation for the acoustic cavity in front of the constriction, and is only weakly coupled to the rest of the vocal tract. It is only for such excitation of the vocal tract that the presence or absence of major midfrequency spectral prominences that form a continuity with spectral peaks in an adjacent vowel become strongly evident in the sound. For a [+sonorant] consonant, on the other hand, all of the vocal tract resonances are excited by the glottal source, including the first formant, and the spectral peak corresponding to a midfrequency formant becomes less prominent in relation to the entire spectrum shape. The prominence is achieved in this case by arranging for two formants (*F2* and *F3*, or *F3* and *F4*) to be in close proximity.

A prominent spectral peak characteristic of a [−anterior] consonant will be more salient if it is well isolated from other spectral peaks. Since the acoustic correlate of [+coronal] is the presence of significant spectral energy at high frequencies, a midfrequency spectral peak will be less prominent (in the sense of being less well separated from other peaks) for a [+coronal] consonant than for a [−coronal] consonant. We conclude, then, that there are only two combinations of the primary features that permit the feature [anterior] to achieve strong saliency—the combinations identified by [−sonorant, −coronal], i.e.

[11] The feature [anterior] bears a close resemblance to the feature [diffuse] proposed in Jakobson et al. 1952.

the combinations in rows 4 and 8 of Table 3.[12] Rows 4 and 8 of Table 3, then, are each expanded into two rows to include the two values for [anterior], as shown in Table 4.

	Continuant	Sonorant	Coronal	Anterior	Segment type
(4a)	+	−	−	+	F
(4b)	+	−	−	−	X,H
(8a)	−	−	−	+	P
(8b)	−	−	−	−	K,ʔ

Table 4. Combinations of primary features for which the feature [anterior] is salient.

We have already discussed which combinations of secondary features are most effective in enhancing the three original primary features in the different rows of Table 4. For example, for the primary features in rows 4a and 4b we have seen that the optimal secondary features include [−voice, +strident], together with particular laryngeal features. With regard to the feature [consonantal], however, there appeared to be no preference for either value as far as enhancement of the three primary features in row 4b was concerned. (The feature [consonantal] is redundant for [+anterior] in row 4a.) We suggest, however, that there is a preference for [−consonantal] in enhancing the feature [−anterior] for this [+continuant] class of consonants. For these [−sonorant] segments, the [−consonantal] feature implies a source in the vicinity of the glottis, whereas [+consonantal] implies a turbulence noise source in a region along the length of the vocal tract, such as near the soft or hard palate. For the latter source position, only one front-cavity resonance in the range of *F2*, *F3*, and *F4* is excited by the source, whereas when the source is near the glottis all of these resonances are excited, although the excitation for one of the resonances may be stronger than for the others. In any case, there will be more than one midfrequency spectral peak that is continuous with a similar peak in an adjacent vowel for the [−consonantal] implementation. We take this attribute to be an enhancement of the feature [−anterior] by the feature [−consonantal]. In the case of the [−continuant] versions of the consonants in Table 4, we have already noted that the [+consonantal] feature for the combination in row 8b takes preference over [−consonantal]. The positive value of this feature also enhances the representation of [−anterior], since it provides conditions appropriate for generation of a strong midfrequency noise burst.

6.2. Anterior as an enhancing feature. When the feature [anterior] occurs with the six combinations of primary features other than those in Table

[12] This conclusion is in part a consequence of the fact that /ʔ/ and /h/ are classified here as [−sonorant] and [−anterior], for the reasons discussed in fn. 10. It might be argued that the feature [−anterior] can also achieve a degree of saliency when it is implemented with [+coronal, +continuant], since the stridency of the resulting fricative consonant accentuates the spectral peak of the noise in a midfrequency region (the *F3* region) normally associated with [−anterior]. Since this peak is not well separated from a spectral prominence at higher frequencies, we would suggest that this instantiation of [−anterior] does not achieve the status of a primary feature.

4, it can serve to enhance those features. We consider first the influence of [anterior] on the [+continuant] manifestations of [+sonorant] consonants (rows 1 and 2 in Table 3). In the case of [+sonorant, +continuant] consonants, the source of acoustic energy arises from normal glottal vibration rather than from turbulence noise at a constriction. The [+coronal] consonant requires that there be greater amplitude at high frequencies relative to that in the adjacent vowel or relative to the amplitude at low frequencies. Consequently the high-frequency amplitude must be achieved through appropriate shaping of the entire vocal tract, and thereby through appropriate placement of the formant frequencies and adjustment of the formant bandwidths, as we have observed earlier. Significant high-frequency amplitude is realized by adjusting the frequencies and bandwidths of the second, third, and fourth formants such that the fourth-formant peak dominates the spectrum. Raising the tongue blade to make a relatively long constriction between the tongue blade and the palate will cause an increase in *F2* (usually a back-cavity resonance of the widened pharyngeal cavity behind the constriction) and in *F3* (usually a resonance of the narrow front cavity), and will place *F3* close to *F4*. The bandwidth of *F3* will be somewhat greater than that of *F2* and *F4* because of greater losses for the narrow palatal section. The resulting configuration of formants will give the desired spectrum shape in which the fourth-formant peak is dominant. These attributes can be seen in the spectrogram and spectra for the utterance *the yacht* in Figure 2a. This acoustic goal can only be achieved with a [−anterior] or palatal position for the tongue blade. If a [+anterior] position were used, the constriction length would be too short to give a proximity of *F3* and *F4* while maintaining a high *F2*. Thus, the feature [−anterior] will enhance the strength of [+coronal] for the [+sonorant, +continuant] combination. This value for [anterior], permitting a long tongue blade constriction, also enhances the feature [+continuant] since it results in relatively slow movement of the formants as the tongue-blade constriction is released.

The strength with which the feature [−coronal] is represented in the sound for [+sonorant, +continuant] segments is maximized by weakening the relative amplitude of the sound at high frequencies, and by increasing the relative amplitude at low frequencies. This goal is achieved by raising and backing the tongue body and by producing a long and narrow lip opening. The consequence of these maneuvers is a low frequency for both *F1* and *F2*, thereby minimizing the amplitudes of spectral peaks corresponding to higher formants. Furthermore, the bandwidth of *F2* will be relatively large due to losses at the constrictions. The spectrogram and spectra for the utterance *the watt* in Figure 2b illustrate these acoustic attributes. The narrowed lip opening is the articulatory correlate of the feature [+anterior],[13] and the acoustic consequence is a lack of acoustic energy in the middle frequency range where the second and third formants normally occur for vowels. The rounded lips, with the corresponding relatively long labial constriction, give rise to a slow movement of the formants

[13] The classification of /w/ as [+anterior] is discussed in fn. 8.

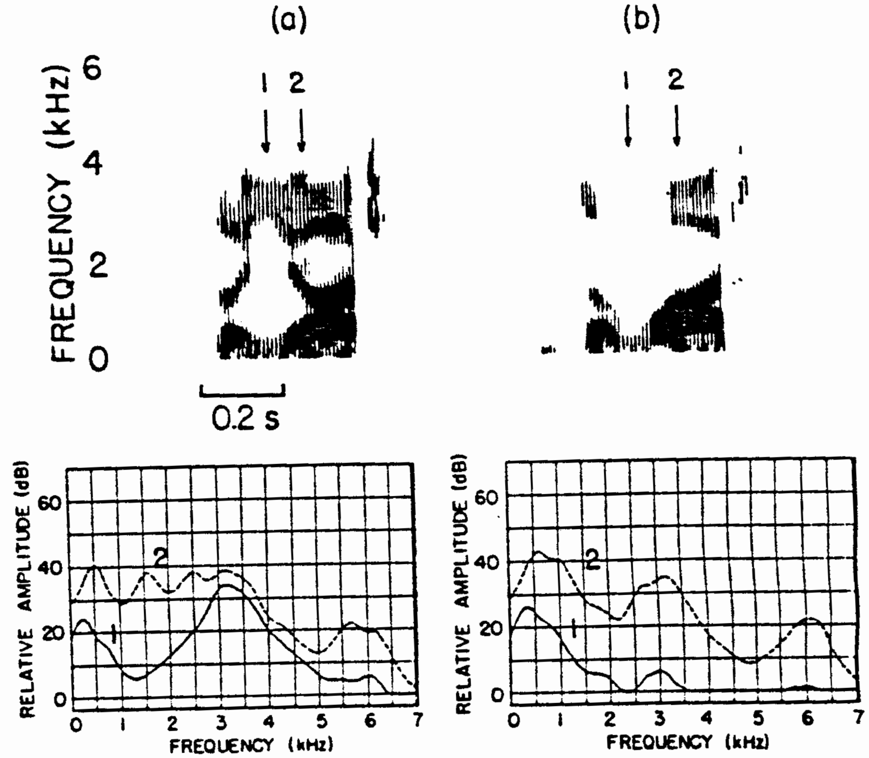

FIGURE 2. (a) A spectrogram of the utterance *the yacht* is shown at the top. Spectra sampled at two points within the utterance (indicated by arrows) are given at the bottom. The spectrum sampled within the consonant interval shows the prominent peak corresponding to *F4*, and can be contrasted with the spectrum in the vowel, where peaks corresponding to several formants are apparent.

(b) Same as (a), except the utterance is *the watt*. In this case, prominences corresponding to formants above *F1* are not evident in the spectrum sampled in the consonant interval. Spectra are preemphasized, and are smoothed discrete Fourier transforms with an effective bandwidth of about 400 Hz.

at the release of this consonant, thereby enhancing the acoustic manifestation of [+continuant]. We conclude, then, that when [+anterior] is implemented with [+sonorant, +continuant, −coronal], the latter two features are enhanced.

For the segments that are [+sonorant, −continuant] (rows 5 and 6 in Table 3), different considerations enter into the selection of the optimal value for the feature [anterior]. For these segments, which are realized most effectively as nasal consonants, there is no generation of turbulence noise in the vicinity of the constriction, and place of articulation is signalled principally by the way the spectrum changes at the instant of release of the closure (or at the instant when the closure is formed). As we have seen, the acoustic property corresponding to the feature [+coronal] is a spectrum amplitude at high frequencies that is large in relation to the amplitude at low frequencies and in relation to the high-frequency amplitude just after the beginning of the adjacent vowel. Presumably it is in the auditory representation that this enhanced high-frequency amplitude occurs, and thus the effects of adaptation following an abrupt onset of energy play a role in this representation (Smith 1979, Delgutte & Kiang 1984). Consequently an abrupt rise in amplitude at high frequencies at the consonantal release gives an enhanced response immediately after the release followed by a decay in response in the next 10–20 msec, thereby signalling the coronality of the consonant. The rise in the high-frequency spectrum amplitude above about 2000 Hz at the release of a [+coronal] nasal consonant is achieved most effectively by making a constriction in the [+anterior] location. A constriction in the [−anterior] position, i.e. a palatal or retroflex position, would result in a spectrum change that is less dominant at high frequencies. The increase in high-frequency amplitude is a consequence of the abrupt shift of the sound output from the nose to the mouth, and the introduction of the short cavity in front of the constriction. Thus, the feature [+anterior] enhances the realization of [+coronal] for these nasal consonants.

In the case of nasal consonants that are [−coronal], an abrupt rise in spectrum amplitude can be realized at lower frequencies (in the vicinity of 1000 Hz) as opposed to high frequencies by forming the constriction at the lips. The increase will be more abrupt and will be at lower frequencies if a labial (i.e. [+anterior]) rather than a dorsal (i.e. [−anterior]) constriction is used. We conclude, then, that [−coronal], like [−continuant], is enhanced by implementing the feature [+anterior] for the nasal consonants.

We consider next how the feature [anterior] can operate to enhance the three primary features as they occur in segments that are [−sonorant, +coronal] (rows 3 and 7 of Table 3). For these consonants, an important aspect of the implementation of the feature [+coronal] is the generation of turbulence noise in the vicinity of the constriction. The noise is either continuous in the case of a fricative consonant (row 3 in Table 3), or in the form of a burst for a stop consonant (row 7). The acoustic correlate of [+coronal] is a noise spectrum which has significant amplitude at high frequencies relative to that at low frequencies. The high-frequency amplitude must reach a value greater than the high-frequency amplitude in the adjacent vowel. The implementation of this feature for [−sonorant] consonants is enhanced if the tongue blade makes contact with the palate in the region of the alveolar ridge rather than at a more posterior palatal location. This constriction position leads to a shorter front cavity and consequently a spectral peak at higher frequencies. Consequently the feature [+anterior] is preferred over [−anterior] as far as the implementation of the feature [+coronal] is concerned for these obstruent consonants. There appears to be no particular preference for either value of [anterior] with respect to the strength of the feature [continuant] for these coronal consonants.

6.3. Lateral as a salient feature. Laterals have the acoustic property that the lowest vocal-tract resonance during the constricted interval is distinctly

higher than it is for other sonorants such as nasals and glides.[14] This first formant location presumably occurs because the constriction for laterals is shorter than it is for the glides, and the volume behind the constriction is smaller than it is for the other sonorants. Both of these factors lead to a low-frequency Helmholtz resonance that is higher for laterals than for nasals and glides. With respect to sonorants, then, the difference between lateral consonants and nonlateral sonorant consonants is similar to the high/nonhigh distinction for vowels. Since this is a salient feature for vowels, we can expect this acoustic correlate to be salient also for sonorant consonants. Consequently the feature [lateral] is expected to be high on the list of salient features.

However, there is a very restricted environment of primary features for which [lateral] is salient. This feature is clearly most effectively implemented as [+sonorant] in order to make the first formant evident in the spectrum. The higher frequency of *F1*, requiring a relatively short constriction, is achieved only if the constriction is formed with the tongue blade, i.e. if [+lateral] is implemented with [+coronal]. Furthermore, the tongue blade must form contact with the palate in the midline, leading to a [−continuant] implementation. Thus, the contrast defined by [lateral] is highly salient only when accompanied by [+sonorant, −continuant, +coronal]. This restriction is in contrast with [anterior], whose saliency requires the primary features [−sonorant, −coronal].

6.4. Lateral as an enhancing feature. In view of the restrictions on the primary features with which [lateral] can be implemented, it plays only a minor role as an enhancing feature. With the combination [+sonorant, −continuant, +coronal] it acts as a salient feature, whereas the features for the only other possible combination, [−sonorant, −continuant, +coronal], are certainly enhanced more strongly by [−lateral] than by [+lateral]. That is, a stop consonant such as /t/ implements these features more strongly than does a voiceless lateral consonant.

7. Summary of primary features and their combinations. At this point we elaborate Table 3 to take into account our discussion of the role of [anterior] and [lateral] as salient features when they occur with particular combinations of primary features. Table 5 is identical to Table 3 with the exception of rows 4, 5, and 8, each of which has been expanded into two rows. Rows 4a, 4b, 8a, and 8b have been shown previously in Table 4. These rows reflect the fact that [anterior] is strongly salient for these combinations of the primary features, and hence both values of [anterior] are retained. Rows 5a and 5b perform a

[14] Laterals share this property with certain other consonants such as English /r/ and uvular consonants. We have chosen here to use the term lateral to identify this class of consonants, recognizing that it may be misleading, and that a different label may be more appropriate. The term liquid is a possible alternative, but we : ·e not prepared at this point to include a discussion of the acoustic properties that are common to liquids, particularly the large variety of r-sounds such as trills, taps, and flaps.

	Continuant	Sonorant	Coronal	Anterior	Lateral	Segment type
(1)	+	+	+			J
(2)	+	+	−			W
(3)	+	−	+			S
(4a)	+	−	−	+		F
(4b)	+	−	−	−		H
(5a)	−	+	+		−	N
(5b)	−	+	+		+	L
(6)	−	+	−			M
(7)	−	−	+			T
(8a)	−	−	−	+		P
(8b)	−	−	−	−		K

Table 5. Primary features, including [anterior] and [lateral].

similar function for [lateral]. Cells that are left blank correspond to features that do not play a primary role.

8. Tongue-body features and rounding: enhancing features for consonants. The features relating to the tongue-body position and lip rounding are [high], [low], [back] and [round]. We have postponed consideration of these features as potential enhancing features until we completed discussion of [anterior] and [lateral] as primary features, since values of the tongue-body features that optimize the implementation of [anterior] and [lateral] tend to be different from those that optimize the major primary features [continuant], [sonorant], and [coronal]. Again our interest is to determine which combination of these tongue-body and rounding features, when implemented with the combination of the features in Table 5 (i.e. the expanded version of Table 3), will potentially give rise to the strongest manifestation of the primary features in the sound.

Implementation of the feature [−anterior] in the case of row 8b requires that the constriction be formed by raising the tongue body to make contact with the roof of the mouth. This maneuver requires implementation of the feature [+high]. Furthermore, the midfrequency spectral prominence that is the acoustic correlate of [−anterior] will be enhanced if the tongue body is in the [+back] position, since this will lead to a prominence that is closer to the center of the midfrequency range. The [+back] position also enhances the feature [−coronal] by avoiding spectral energy at high frequencies. Furthermore, the feature [−round] should be implemented along with [+high, +back] in order to ensure that the frequency of the spectral prominence arising from the front cavity resonance is not too low.

In the case of the combination of features in row 4b of Table 5, there is no strong preference for particular values of the tongue-body and rounding features. All of the primary features can be adequately represented for any configuration of the tongue-body or the lips as determined by these features. However, given that this row contains the feature [−sonorant], certain tongue-body configurations that lead to a relatively narrow vocal tract constriction could result in the generation of turbulence noise at the constriction, and hence

could result in a [+consonantal] implementation of the segment.[15] Either way, the feature [−anterior] is well represented in the sound.

For the combination of features in row 5b, [+lateral] is enhanced if *F2* is positioned relatively close to *F1*. The combination of these two formants produces a perceptual center of gravity that is raised relative to *F1*, thereby enhancing the contrast with sonorant consonants that have a low *F1*. The decreased value of *F2* is achieved with the feature [+back]. For this same combination in row 5b, the feature [+coronal] is usually achieved by bringing *F3* and *F4* closer together, that is, by adjusting the front cavity resonance to be equal to the second resonance of the back cavity. This coincidence is best realized without rounding the lips and by placing the tongue body in a backed position. An increased *F3* (to create proximity with *F4*) can be achieved by narrowing the airway in the upper pharyngeal region.

In the case of the combinations of primary features in rows 1 and 2 of Table 5, we have seen that the [+continuant] feature is enhanced by implementing the feature [+distributed] to form a longer constriction either at the lips (row 2) or with the tongue blade (row 1). The lengthened constriction at the lips is synonymous with the feature [+round] in the case of the labial consonant in row 2, while the constriction with the tongue blade is enhanced by the features [+high, −back]. Furthermore, the contrast between the [−coronal] versions of these glides is enhanced by implementing the features [+high, +back] for row 2 (reducing the frequency of *F2* to bring it closer to *F1*) and [−round] for row 1 (keeping *F2* and *F3* as high as possible and bringing *F3* close to *F4*).

We turn finally to an examination of the role of tongue-body and rounding features for rows 3, 4a, 5a, 6, 7, and 8a in Table 5—that is, for the coronal and labial fricative, nasal, and stop consonants. We observe first that for all of these rows the features [continuant] and [coronal] are represented most strongly (with either their positive or their negative values) if there are no narrow constrictions in the vocal tract other than the constriction formed by the tongue blade or the lips. For example, a narrow constriction behind the point of closure for a [−continuant] consonant can detract from the abruptness of the acoustic change at the release. In the case of obstruent stop consonants, the secondary constriction will limit the airflow that produces the initial transient and the burst, and for nasal consonants the presence of the additional constriction will cause a less abrupt shift in the spectrum in some frequency regions. The [+continuant] obstruents in rows 3 and 4a of Table 5 are best implemented with no secondary constriction, since such a constriction could cause an increase in pressure within the vocal tract and lead to a decrease in the amplitude of turbulence noise at the alveolar or labial constriction. The optimum implementation of the feature [continuant] without a secondary constriction will also enhance the acoustic manifestation of [coronal] by guaranteeing either an abrupt onset or sufficient noise generation at the constriction to carry the requisite

[15] The similarities and differences in the properties of the segment /h/ and of its neighbors, such as /ɦ, X, x and ç/, are not well understood at present. Further work is needed to clarify the discussion of the combination of features in row 4b of Table 5.

-tral characteristics. The amount of secondary constriction will be minimized by implementing the features [−high, −low], i.e. by avoiding palatalization, velarization, or pharyngealization.

For the feature combinations in these same rows (3, 4a, 5a, 6, 7, 8a) the optimal value of the rounding feature is [−round]. In the case of the combinations in rows 3, 5a, and 7, the feature [+coronal] would be weakened by rounding, since a narrowed and lengthened lip opening would lower the natural frequency of the front cavity. For the labial stop consonants (rows 6 and 8a) the abruptness of the release would be weakened by rounding, and noise generation for the labial fricative (row 4a) would be enhanced with [−round] because the labiodental constriction is needed to direct the airstream against the upper lip.

The acoustic manipulation of the feature [coronal] can be enhanced by appropriate selection of the feature [back] in rows 3, 4a, 5a, 6, 7, and 8a. In the case of the three [+coronal] consonants in this group, this enhancement is achieved with [−back]. When the tongue body is in a fronted position, the frequency of *F2* is raised, leading to an increased spectrum amplitude at high frequencies in the vowel immediately following the release of the consonant. Since a spectrum that slopes upward at high frequencies (in relation to its immediate environment) is the mark of a [+coronal] consonant, an increased *F2* carries this property of coronality over into the beginning of the following vowel, thereby providing additional acoustic evidence of its presence. (See Stevens et al. 1986 for more discussion of this point.) The opposite argument can be used to show that [+back] can enhance the acoustic manifestation of [−coronal]. The lowered *F2* associated with [+back] will decrease the spectrum amplitude at high frequencies, so that there is a downward slope in the spectrum immediately following the consonantal release, when this spectrum is compared with the later-occurring spectrum in the vowel. We conclude, then, that the feature [−back] enhances [+coronal] and [+back] enhances [−coronal].

9. Summary of optimal feature combinations. We have argued that there are particular combinations of the secondary features that will result in maximally strong implementation of the primary feature combinations in Table 5, which is an extension of Table 3. Thus, for example, in row 5a of Table 5 the optimal combination of these secondary features is the list given in Table 6. These secondary features, combined with the primary features [−continuant, +sonorant, +coronal, −lateral] in row 5a of Table 5, comprise the segment /n/. This segment is identified in the rightmost column of that table. Needless to say, many of the features in Table 6 are redundant in most languages, in the sense that they do not operate to form a distinction. For some of these features, the redundancy is an automatic consequence of the feature definition (e.g., [+sonorant] implies [−strident]). For others, as we have seen, the feature value is selected so as to enhance the implementation of the primary features.

Filling in the appropriate values for the above features for each of the remaining rows of Table 5 will also yield precisely the segments indicated in the rightmost column. The eleven rows in Table 5, then, expand into eleven com-

+voice
+consonantal
−distributed
−strident
+anterior
+nasal
−spread glottis
−constricted glottis
−high
−low
−back
−round

Table 6. Combinations of secondary features that are considered to enhance maximally the primary features in Row 5a of Table 5.

binations of features, each of which is optimal in that it represents the most salient or strongest representation of the primary features.

In the rightmost column of Table 7 we indicate the percent of languages in Maddieson's 1984 inventory that contain each of the segments in the rightmost column of Table 5. In the case of the [+coronal] consonants in rows 3, 5a, 5b, and 7, we include in our count segments labelled by Maddieson either as alveolar or as dental/alveolar, on the assumption that both of these designations could be regarded as [−distributed], as discussed earlier in footnote 1.

	Segment	% in Maddieson
(1a)	/j/	85
(2)	/w/	75
(3)	/s/	77
(4a)	/f/	44
(4b)	/h/	64
(5a)	/n/	82
(5b)	/l/	68
(6)	/m/	94
(7)	/t/	75
(8a)	/p/	83
(8b)	/k/	89

Table 7. Frequency of occurrence of optimal feature combinations.

What is noteworthy about these percentages is that, with the exception of /f/, they represent the ten most commonly occurring consonantal segments in the 317 languages surveyed by Maddieson, i.e. the segments originally listed in Table 1. The low percentage occurrence for /f/ is presumably due to the fact that the turbulence noise for a labial fricative consonant is inherently weak, since there is no resonator in front of the constriction to amplify the output of the noise source. We suggest that the frequency of occurrence of the ten remaining segments is due precisely to their being just those segments whose primary feature combinations are maximally enhanced.

In Table 8 we list additional segments that are identified by Maddieson as occurring in at least 34% of the languages in his inventory. The items on this list differ from the segments identified in Table 7 by just one independent secondary feature. Thus, for example, the segments /b, d, g/ in Table 8 differ

	SEGMENT	% IN MADDIESON
(1)	/b/	62
(2)	/g/	55
(3)	/ŋ/	53
(4)	/š/	46
(5)	/ʔ/	46
(6)	/d/	45
(7)	/č/	44
(8)	/ɲ/	34

TABLE 8. Segments occurring in at least 34% of Maddieson's inventory but not listed in Table 7.

from /p, t, k/ in Table 7 by the feature [voice]. The segments /ŋ/ and /ɲ/ are [−anterior] versions of /m/ and /n/, respectively, but with some necessary adjustment of tongue-body features. The segment /ʔ/ is a [−consonantal] version of /k/, again with some necessary adjustment of tongue-body and laryngeal features. The segment /š/ is a [−anterior] version /s/, with an adjustment of tongue-body features to optimize the representation of [+continuant] in the sound. Finally, we suggest that the segment /č/ is simply a [−back] modification of /k/ with some adjustment of the feature [strident] to optimize the representation of the [+continuant] aspect of this consonant. Alternatively, /č/ might be considered as a [−anterior] modification of /t/, similar to the modification of /s/ to /š/.

10. MARKEDNESS. A central concern of phonologists and phoneticians has been the notion of markedness. It has long been noted that certain feature combinations occur more frequently than others in the languages of the world. Some typical observations include the following:

(1) Nonlow back vowels are normally rounded.
(2) Continuant obstruent consonants are normally strident.
(3) Coronal stops are normally anterior.
(4) Nonsonorant consonants are normally voiceless.

Such statements do not, of course, explain why these observations should be so rather than some other formally equivalent set of observations; for example:

(1) Nonlow front vowels are normally rounded.
(2) Continuant obstruents are normally voiced.
(3) Coronal consonants are normally palatal.
(4) Nonsonorant consonants are normally retroflexed.

The present paper is intended to point toward an explanation of why certain combinations occur much more frequently than others. We suggest that this tendency toward particular feature groupings characterizes the languages of the world because of the properties of saliency and enhancement which those groupings exhibit. These combinations occur because, from the listener's point of view, they are maximally distinctive. We anticipate that, as our understanding of the concepts of saliency and enhancement deepens, the relationship between them and notions of markedness discussed in the literature will become clearer.

REFERENCES

CATFORD, IAN. 1977. Fundamental problems in phonetics. Bloomington: Indiana University Press.

CHISTOVICH, LUDMILLA A., and VALENTINA V. LUBLINSKAYA. 1979. The 'center of gravity' effect in vowel spectra and critical distance between the formants: Psychoacoustical study of the perception of vowel-like stimuli. Hearing Research 1.185–95.

CHOMSKY, NOAM A., and MORRIS HALLE. 1968. The sound pattern of English. New York: Harper and Row.

CLEMENTS, GEORGE N. 1985. The geometry of phonological features. Phonology Yearbook 2.225–52.

——, and SAMUEL JAY KEYSER. 1982. CV phonology: A generative theory of the syllable. (Linguistic Inquiry Monograph Series, No. 9.) Cambridge, MA: MIT Press.

DELGUTTE, BERTRAND, and NELSON Y.-S. KIANG. 1984. Speech coding in the auditory nerve, IV. Sounds with consonant-like dynamic characteristics. Journal of the Acoustical Society of America 75.897–907.

FANT, GUNNAR. 1973. Speech sounds and features. Cambridge, MA: MIT Press.

HALLE, MORRIS, and KENNETH N. STEVENS. 1971. A note on laryngeal features. Research Laboratory of Electronics Quarterly Progress Report No. 101, 198–213. Cambridge, MA: MIT.

JAKOBSON, ROMAN; GUNNAR FANT; and MORRIS HALLE. 1952. Preliminaries to speech analysis. (Acoustics Laboratory Report No. 13.) Cambridge, MA: MIT.

JAKOBSON, ROMAN, and LINDA R. WAUGH. 1979. The sound shape of language. Bloomington: Indiana University Press.

KEWLEY-PORT, DIANE. 1983. Time-varying features as correlates of place of articulation in stop consonants. Journal of the Acoustical Society of America 73.322–35.

LADEFOGED, PETER. 1971. Preliminaries to linguistic phonetics. Chicago: Chicago University Press.

LAHIRI, ADITI; LETITIA GEWIRTH; and SHEILA E. BLUMSTEIN. 1984. A reconsideration of acoustic invariance for place of articulation in diffuse stop consonants: Evidence from a cross-language study. Journal of the Acoustical Society of America 76.391–404.

LILJENCRANTS, JOHAN, and BJORN LINDBLOM. 1972. Numerical simulation of vowel quality systems: The role of perceptual contrast. Lg. 48.839–62.

LINDBLOM, BJORN. 1986. Phonetic universals in vowel systems. Experimental Phonology, ed. by John Ohala and Jeri Jaeger, 13–44. Orlando, FL: Academic Press.

MADDIESON, IAN. 1984. Patterns of sounds. Cambridge: Cambridge University Press.

SAGEY, ELIZABETH C. 1986. The representation of features and relations in nonlinear phonology. MIT dissertation.

SMITH, R. LOWELL. 1979. Adaptation, saturation and physiological masking in single auditory-nerve fibers. Journal of the Acoustical Society of America 65.166–78.

STEVENS, KENNETH N. 1972. The quantal nature of speech. Human communication: A unified view, ed. by E. E. David, Jr., and P. B. Denes, 51–66. New York: McGraw-Hill.

——. 1980. Acoustical correlates of some phonetic categories. Journal of the Acoustical Society of America 68.836–42.

——. 1983. Acoustical properties used for the identification of speech sounds. Annals of the New York Academy of Sciences 405.2–17.

——. 1989. On the quantal nature of speech. Journal of Phonetics, to appear.

——; S. JAY KEYSER; and HARUKO KAWASAKI. 1986. Toward a phonetic and phonological theory of redundant features. Invariance and variability in speech processes, ed. by Joseph S. Perkell and Dennis H. Klatt, 426–49. Hillsdale, NJ: Lawrence Erlbaum Associates.

SYRDAL, ANN K., and H. S. GOPAL. 1986. A perceptual model of vowel recognition based on the auditory representation of American English vowels. Journal of the Acoustical Society of America 79.1086–100.

Kenneth N. Stevens
Research Laboratory of Electronics
Massachusetts Institute of Technology
Cambridge, MA 02139

Samuel Jay Keyser
Department of Linguistics & Philosophy
Massachusetts Institute of Technology
Cambridge, MA 02139

[Received 22 March 1988;
revision received 2 November 1988;
accepted 6 November 1988.]