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Features and Sound Inventories

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Summary: Speech sound inventories are structured in terms of distinctive features, not phonetic categories. Five general principles are discussed and exemplified with respect to data drawn from a large sample of phoneme systems.

- *boundedness*
- *economy*
- *markedness*
- *robustness*
- *enhancement*

1. Introduction

1. This paper explores the role of features in the structure of sound inventories
   - Not just any set of consonants and vowels can make up a sound system
   - A central finding of the earliest work in phonology was that sound systems are structured in terms of regular correlations defined in terms of features (e.g. Trubetzkoy 1969/1939, Martinet 1955, Hockett 1955)

2. In recent years the question of inventory structure has been more vigorously debated among phoneticians than among phonologists. This work has tended to minimize the role of features. Examples:
   - adaptive dispersion theory (e.g. Lindblom 1986, Lindblom & Maddieson 1988)
     maximal dispersion
     sufficient dispersion
     articulatory ease
   - gesture economy (Maddieson 1995):
     economize gestures

3. Work in mainstream Optimality Theory has tended to neglect inventory structure, as constraint systems evaluate individual forms rather than system-wide generalizations (McCarthy 2002: 226)
   - see however Boersma (1998) and Flemming (2002) for proposals to incorporate system-level phonetic principles such as dispersion, symmetry and articulatory effort into OT.

4. This paper reviews a range of evidence showing that features play a central role in the structuring of sound systems.
   - it proposes five general principles stated in terms of features, and
   - shows that these principles make testable predictions regarding the structure of sound inventories

2. Features as concrete mental entities

1. Features have been defined from the beginning in concrete physical terms, though linguists have long hesitated between perceptual, acoustic and articulatory definitions.

2. In a current view, features have both articulatory and acoustic correlates, and are constrained in terms of quantal theory (Stevens 1972, 1989; Halle 1983; Carré & Mrayati 1990)

   Articulatory variation within feature boundaries is generally characterized by stable spectral properties, while variation across feature boundaries is marked by rapid spectral shifts.

   example: *pa* vs. *ta*

3. There is considerable evidence suggesting that features are central to speech perception and speech processing. Two basic properties of speech perception:
   - *categorical perception*: adult listeners tend to identify and distinguish stimuli at a higher rate of accuracy across the feature categories of their language than within them (e.g. Liberman et al. 1957, Repp 1984, Harnad 1987)
   - *normalization* (or perceptual constancy): listeners abstract linguistic information from irrelevant acoustic variation (e.g. Kuhl 1979, Eimas et al. 1987)

4. Recent research on early child language acquisition shows that both categorical perception and normalization are present at birth.
   - full-term new-born babies (aged from 2 to 6 days) have been shown to discriminate between the syllables *pa* and *ta* while they are asleep, regardless of whether the stimuli were spoken by the same speaker or by any of four different speakers (Dehaene-Lambertz & Pena 2001; see also Cheour et al. 2002).

5. Feature discrimination -- the ability to distinguish phonetic categories that are distinctive in some languages -- appears to be a neurologically specialized brain function

   Perception of stimuli across feature boundaries triggers qualitatively different electrophysiological response patterns (MMN) from that of perception of stimuli within feature boundaries, in both infants and adults (e.g. Näätänen et al. 1997)

6. The emerging picture:
   - Newborn and very young infants perceive and process speech in terms of broad phonetic categories that correspond closely to the distinctive feature categories of adult sound systems
   - Infants gradually "fine-tune" their perceptual system to that of the ambient language in the course of the first year of life.
   - After this, speech perception is largely, though not entirely, shaped by the distinctive features of the first language.
   - Adults continue to perceive speech largely in terms of the distinctive features of their first language.

7. Summary: there is a considerable amount of evidence suggesting that in cognitive terms, adult phonological representations may have the form of feature-based representations which abstract away from fine phonetic detail.

3. Method

1. Evidence is drawn primarily from the expanded UPSID data base (Maddieson & Precoda 1989)
   - contains 451 phoneme inventories (representing 6-7% of the world's languages)
   - geographically and genetically balanced
   - electronic database facilitates rapid searches
   - results can be independently verfied by others

2. Problems with the data base (Basbøll 1985, Maddieson 1991, Clements 2003) include
   - inevitable genetic skewing (e.g. Niger-Congo = 55 languages, Basque = 1 language)
   - heterogeneity of sources, disagreements in analyses
   - inclusion of some allophonic details but not others
     e.g. dental vs alveolar stops, but not apical vs laminal stops
   - many coding errors

   To a considerable exent, these problems are alleviated by the sheer size of the sample; however, caution is called for in interpreting results

3. Statistical evaluation (chi square testing for significance of trends)
   - most of the trends discussed below prove to be highly significant ($p < .001$)

4. Boundedness

Features bound the number of *sounds* and the number of *contrasts* that a language may have.

1. Features set an upper limit on the number of sounds a language may have. Thus, given a set of *n* features, a language may have at most 2^n sounds. For example:
   - a language using 3 features can have up to eight sounds (2^3)
   - one using 4 features can have up to thirty-two sounds (2^4), etc.

2. Features also make predictions about *types* of sounds.
   - The sounds of a language (at the levels of lexicon and phonology) are defined by its active features and their possible combinations.
   - Since the total number of features is rather small, and many feature combinations are strongly disfavored, certain types of sounds recur commonly from one language to another

3. Features make strong predictions about the number and types of *contrasts* a language may have. Example: "major place of articulation" in coronal sounds is defined by two features:

   [anterior/posterior]: dental, alveolar vs. postalveolar, retroflex, palatal

   [apical/distributed]: apical (including retroflex) vs. laminal ("extended contact")

4. These two features define four major categories:

	apico-anterior	lamino-anterior	retroflex	postalveolar/palatal
posterior	-	-	+	+
distributed	-	+	-	+

5. Phonetic theory, by providing a much larger set of different place distinctions within this region (at least seven: "apico-dental", "apico-alveolar", "lamino-dental", "lamino-alveolar", "palato-alveolar", "retroflex", and "palatal"), projects a much larger number of contrasts:

	Max(sounds)	Max(contrasts)
a. feature theory	4	6
b. traditional phonetic theory	7	21

Table 1. Maximum number of sounds and contrasts predicted by (a) a feature system recognizing two coronal features, and (b) a traditional phonetic theory recognizing seven coronal categories. Contrasts = (S * S-1) / 2, where S = number of sounds.

6. All 6 contrasts projected by feature theory are attested in both simple plosives and affricates (strident plosives):

contrast:	example:	found in e.g.:
apical anterior *vs.* laminal anterior	apical *t* *vs.* laminal *t*	Temne
apical anterior *vs.* apical posterior	apical *t* *vs.* retroflex *ʈ*	Yanyuwa
apical anterior *vs.* laminal posterior	apical *t* *vs.* palatal *c*	Arrernte
laminal anterior *vs.* apical posterior	laminal *t* *vs.* retroflex *ʈ*	Arrernte
laminal anterior *vs.* laminal posterior	laminal *t* *vs.* palatal *c*	Hungarian
apical posterior *vs.* laminal posterior	retroflex *ʈ* *vs.* palatal *c*	Sindhi

N*o other primary coronal contrasts* were discovered in either plosives or affricates in a survey of several hundred languages (Clements 1999).

5. Economy

1. F*eature economy* is the tendency to maximize feature combinations (Clements, 2003a,b, after sources in de Groot 1931, Martinet 1955, 1968). This principle can be observed in most speech sound inventories, regardless of size.

2. Illustration: a standard variety of English

pʰ	tʰ		tʃʰ	kʰ	
b	d		dʒ	g	
f	θ	s	ʃ		
v	ð	z	ʒ		
m	n			ŋ	
w	l r		y		h

- [+voiced] cross-classifies oral stops and fricatives to double the number of obstruents
- [+continuant] creates two full fricative series
- [+nasal] creates nasal stops at three places of articulation

3. Feature economy can be quantified in terms of a measure called the *economy index*. Given a system using F features to characterize S sounds, its economy index *E* is given by the expression

$$E = S/F$$

4. Example: English has 24 consonants and requires 9 features to distinguish them:

   labial, dorsal, continuant, voiced, glottal, strident, posterior, nasal, lateral

   The economy index of the English consonant system is 24/9, or 2.67

5. Feature economy can be defined as the tendency to maximize *E*. This goal can be accomplished by:
   - increasing the number of sounds S, and/or
   - decreasing the number of features F

6. A testable prediction of feature economy is *Mutual Attraction*

   A given speech sound will have a higher than expected frequency in inventories in which all of its features are distinctively present in other sounds.

   Example: a stop with given laryngeal features L should occur more frequently in systems having other stops with the same laryngeal features.

7. Results of an examination of stop types in UPSID languages:

P^{-} vs. T^{-}	P^h vs. T^h	P’ vs. T’
P^{-} vs. K^{-}	P^h vs. K^h	P’ vs. K’
T^{-} vs. K^{-}	T^h vs. K^h	T’ vs. K’
B vs. D	B^h vs. D^h	$B^<$ vs. $D^<$
B vs. G	B^h vs. G^h	$B^<$ vs. $G^<$
D vs. G	D^h vs. G^h	$D^<$ vs. $G^<$

Table 2. Comparisons of pairs of stops sharing all manner features, but differing in place. Symbols: P^{-} T^{-} K^{-} = plain voiceless, P^h T^h K^h = voiceless aspirated, P’ T’ K’ = ejective, B D G = voiced unaspirated, B^h D^h G^h = voiced aspirated, and $B^<$ $D^<$ $G^<$ = implosive.

- *All* comparisons prove positive at a very high level of significance ($p<.0001$). That is, languages having one member of each pair tend overwhelmingly to have the other.

8. Another prediction: a language having the sounds P T K, B D G, and F S X will tend to also have the sounds V Z Ɣ, maximizing the use of [+voiced] and [+continuant].

   Result:
   - voiced labial fricatives V are considerably more frequent than expected in UPSID languages also having P, B, and F
   - analogous results hold for Z and Ɣ
   - these trends are significant at the .0001 level in all cases

6. Markedness

1. *Markedness* is understood here as the systematic avoidance of certain widely disfavored feature combinations (see esp. Trubetzkoy 1939, Jakobson 1941, Greenberg 1968, Chomsky & Halle 1968, Kean 1980, and Calabrese 1994, as well as Rice 2002 for a recent overview).

2. Markedness counteracts the free operation of feature economy.
   - in the absence of markedness, sound systems making use of *n* features would be expected to display the theoretical maximum of 2^n sounds
   - but no languages come anywhere close to approaching this maximum; instead, segments characterized by marked feature combinations tend to be absent

3. Feature economy also counteracts markedness. Example: voiced fricatives
   - voiced fricatives combine the marked features [+voiced] and [+continuant]
   - these features are marked in fricatives because they are inconsistent with the buildup of supraglottal air pressure required to produce the turbulence noise characteristic of obstruents (Stevens 1983)
   - voiced fricatives are absent in roughly half the world's languages
   - however, due to the effect of feature economy, if a language has one voiced fricative, it is *twice* as likely to have another:

4. Occurrence of voiced fricatives in UPSID:

[labial]	overall:	32.6 %
	in languages also having a nonlabial voiced fricative:	60.2
[coronal]	overall:	38.8
	in languages also having a noncoronal voiced fricative:	74.2
[dorsal]	overall:	15.5
	in languages also having a nondorsal voiced fricative:	29.1

5. Phonetic approaches to markedness

   Ideally, one would like to be able to predict the degree of markedness of any given feature combination from the general phonetic (i.e., biological, acoustic, aerodynamic) conditions that underlie the human capacity for speech production.

   The problem is that phonetics provides an extremely rich set of interacting principles which frequently lead to conflicting expectations.

   Consider, for example, the feature [±voiced]. Which value of this feature is marked in stops?
   - [+voiced] is marked in stops because it requires supplementary maneuvers to maintain the aerodynamic conditions required for vocal cord vibration during stop closure
   - [-voiced] is marked in stops because it requires a precise temporal coordination of independent articulatory structures (laryngeal and oral)

   No independently-motivated general principle appears to exist that would allow us to predict the preference for one of these statements over the other in all cases.

6. A statistical approach to markedness

An alternative approach is to define markedness in statistical terms (e.g. Kean 1980). A likely (more probable) specification of a feature in a segment is termed an *unmarked* specification, an unlikely (less probable) one is a *marked* specification.

As pointed out by Greenberg (1966) and others, markedness is reflected in frequency differences at many levels: marked values tend to be less frequent

- in the lexicon
- in running texts
- in early stages of language acquisition
- in given adult sound inventories
- across sound inventories.

Although a statistical approach does not explain why some segments are more frequent than others, it has the advantage of relating markedness to observable frequency distributions that can be readily extracted by language learners. Frequency can be considered a diagnostic of markedness.

7. Universal occurrence: a feature is unmarked if it appears in the sound inventories of all languages; otherwise it is marked. Examples (from UPSID):

all languages have:	*some lack:*	*marked feature (in consonants):*
obstruent consonants	sonorant consonants	[+sonorant]
coronal consonants	labial,[1] dorsal,[2] pharyngeal, or laryngeal consonants	[labial], [dorsal], [pharyngeal]
oral consonants	nasal consonants[3]	[+nasal]
stop consonants	continuant consonants[4]	[+continuant]
unaspirated stops	aspirated consonants	[spread glottis]
nonglottalized stops	glottalized consonants	[constricted glottis]
anterior coronal stops	posterior coronal stops	[+posterior]
nonstrident coronals	strident coronals	[+strident]
simple consonants	consonants with secondary articulations	features of secondary articulation

Remarks:

1. Wichita (Keresiouan) lacks labial consonants (though it has labialized k^w and the glide *w*)
2. Vanimo (Papua New Guinea) lacks dorsal consonants
3. Ewe, Kpelle, Bwamu, Barasana, Tucano, and Warao lack (phonemic) nasal consonants
4. Auca, Maxakalí, Iate (Yate), Dera, Angaatiha, and Ekari lack (phonemic) continuant consonants

8. Wider Occurrence: a feature is unmarked if it occurs in the sound inventories of more languages than its contrary; otherwise, it is marked. Consider the feature [voiced]:

- voiceless obstruents occur in 99.1% of UPSID languages, while voiced obstruents are found in only 84.3%. [-voiced] is unmarked, [+voiced] is marked

9. Prediction: Given a pair of sounds S', S differing only in that S' bears a marked feature lacking in S,

a) S' is the more likely to be absent in a given inventory,

b) if S' is present, S is likely to be present too

Genuine counterexamples consist of statistically significant countertrends (see section 8).

10. The following table shows the distribution of four types of voiceless dorsal stops represented in UPSID. It confirms prediction (9) for these sounds (see unfilled cells).

Languages with:	and lacking: K^{w}’	K’	K^{w}	K
K^{w}’	-	0	0	0
K’	45	-	43	1
K^{w}	46	44	-	0
K	417	373	371	-

Table 3. Distribution of voiceless dorsal (velar and uvular) stops in UPSID. Key: K^{w}’ = labialized ejective (T = 23), K’ = plain ejective (T = 68), K^{w} = plain labialized stop (T = 69), K = plain stop (T = 441).

7. Robustness

1. *Robustness* holds that features are organized in terms of a hierarchy which is similar across languages, and that in the composition of sound inventories, higher-ranked features are made use of before lower-ranked features. (Sources include: Jakobson 1968, Jakobson & Halle 1956, Chomsky & Halle 1968: 409-410, Kean 1980, Stevens & Keyser 1989, Dinnsen 1992, Calabrese 1994).

2. The idea underlying robustness is that certain marked features have a higher "survival value" across time and space, and are accordingly commoner in sound inventories.
   - robust features are, in general, those that are mastered fairly early in the process of language production -- one criterion of articulatory ease -- and that allow one sound to be easily distinguished from another, even in rapid speech and under conditions of noise
   - they are the features that tend to be used most commonly across the languages of the world

3. Some examples of more vs. less robust feature contrasts:

robust:	*less robust:*
sonorant vs. obstruent	apical vs. laminal
labial vs. coronal vs. dorsal	palatalized vs. nonpalatalized
nasal vs. oral	aspirated vs. nonaspirated
stop vs. continuant	glottalized vs. nonglottalized
voiced vs. voiceless	implosive vs. explosive

4. Unlike markedness, which characterizes sounds, the robustness hierarchy involves *contrasts*: those involving the most robust features are found in most or all languages, while those involving less robust features are found in fewer languages. For example:
   - almost languages all have a contrast between sonorant and obstruent consonants
   - considerably fewer have a contrast between central and lateral liquids.

   From this we may conclude that the feature [±sonorant] is more robust than the feature [±lateral].

5. Commonest consonant contrasts in UPSID, in approximate order of frequency:

	contrast	example	% (UPSID)	feature
a.	sonorant vs. obstruent	N / T	98.9	[±sonorant]
	dorsal vs. coronal obstruent	K / T	99.6	[dorsal], [coronal]
	labial vs. coronal obstruent	P / T	98.7	[labial], [coronal]
	labial vs. dorsal obstruent	P / K	98.7	[labial], [dorsal]
	labial vs. coronal sonorant	M / N	98.0	[labial], [coronal]
b.	oral vs. nasal sonorant	L / N	92.2	[±nasal]
	continuant vs. stop obstruent	S / T	91.6	[±continuant]
	consonantal vs. vocoid	J / T	89.1	[±vocoid] / [±consonantal]
c.	voiced vs. voiceless obstruent	D / T	83.4	[±voiced]
d.	glottal vs. non-glottal consonant	H / T	74.5	[glottal]
e.	strident vs. nonstrident coronal stop	TŠ / T	60.7	[±strident]
	central vs. lateral approximant	R / L	60.5	[±continuant] / [±lateral]

6. A language having just the contrasts in (17) would typically include the consonants and glides shown below (assuming default realizations), among others:

P	T	TŠ	K	
B	D		G	
	S			H
M	N			
	L R			
W	J			

7. These are the fifteen commonest consonant types in UPSID:

sound type	feature code	percent	typical phonetic values
T	obs stop vl cor not strid	98.2	t c
K	obs stop vl dor	97.8	k q
N	son nas cor	95.7	n ɲ
M	son nas lab	94.7	m
P	obs stop vl lab	90.2	p
S	obs cont vl cor	88.9	s θ ʃ
J	voc oral cor	84.0	j
L	cons son oral cor stop	81.4	l ʎ
W	voc oral lab	74.3	w
R	cons son oral cor cont	73.8	r
B	obs stop lab vd	71.4	b
D	obs stop vd ant (cor)	70.3	d
H	glot asp	64.7	h
G	obs stop vd dor	63.2	g
TŠ	obs stop vl cor strid	60.6	t^s $t^ʃ$

8. A proposed robustness scale for consonants
    a. [±sonorant], [labial], [dorsal], [coronal]
    b. [±nasal], [±continuant], [±vocoid]
    c. [±voiced]
    d. [glottal]
    e. [±strident]
    f. others (such as [±posterior], [±distributed], [±lateral], etc.)

9. Prediction: Inventories will make crucial use of lower-ranked features on the robustness hierarchy only if they also make use of higher-ranked features.

10. Like markedness statements, the robustness scale represents a preferred, but not exceptionless trend. Example: French makes use of [±lateral] but not [glottal].

8. Enhancement

1. Enhancement is the name given to the reinforcement of weak acoustic contrasts by increasing the acoustic differences between their members (Stevens & Keyser 1989, 2001).

   Two forms of enhancement:

   - *phonological enhancement*, in which a redundant feature is introduced to reinforce a contrast
     example: [+back] vowel → [+rounded]
   - *phonetic enhancement*, in which reinforcement is achieved by a supplementary articulation at the phonetic level.
     example: posterior fricatives such as [ʃ] tend to be somewhat rounded in many languages to enhance the acoustic contrast with anterior fricatives such as [s]

   We consider phonological enhancement here.

2. Phonological enhancement can be characterized as the introduction of a marked feature to reinforce an existing contrast between two sounds or sound classes. Reinforcement may be achieved:
   - along a single acoustic dimension (as in the examples given above)
   - along a separate acoustic dimension.

3. Example of the latter: enhancement of [+posterior] coronal stops with [+strident] (realized as high-frequency, high-amplitude turbulence noise)
   - this enhancement does not merely add more of a quantity along a single dimension, since [+posterior] and [+strident] have different acoustic attributes
   - the addition of [+strident] nevertheless enhances the distinction between anterior and posterior coronals by increasing the auditory distance between them
     - e.g. [t] is more distinct from strident [tʃ] than it is from nonstrident [t̠] or [c]

4. Enhancement creates a class of regular exceptions to the predictions of markedness, in which marked values are more frequent than corresponding unmarked features in enhancement contexts.

5. Examples of enhancement effects involving both uniform and nonuniform acoustic dimensions:

in the class of:	*more frequent:*	*less frequent:*
a. coronal stops coronal fricatives	t [-strident] (450) s [+strident] (397)	tʃ [+strident] (291) θ [-strident] (105)
b. anterior coronal stops posterior coronal stops	t [-strident] (450) tʃ [+strident] (235)	ts [+strident] (148) c [-strident] (138)
c. vowels obstruents sonorants	a [-nasal] (451) t [-nasal] (451) n [+nasal] (445)	ã [+nasal] (102) nt [+nasal] (57) l [-nasal] (428)
d. labial stops labial sonorants labial fricatives	p [-labiodental] (446) β [-labiodental] (34) v [+labiodental] (199)	pf [+labiodental] (7) ʋ [+labiodental] (7) ɸ [-labiodental] (82)
e. low vowels mid/high front vowels mid/high back vowels	a [-rounded] (448) i [-rounded] (449) u [+rounded] (444)	ɒ [+rounded] (22) y [+rounded] (33) ɯ [-rounded] (62)

6. Sound inventories tend to conform to the enhancement preferences shown in (5).

9. Illustrations

1. Let us see how feature economy, markedness, robustness, and enhancement interact to distinguish likely from unlikely consonant systems. A number of unlikely systems are shown below.

2. System A: violates Feature Economy ("maximize feature combinations")

p	t	tʃ	k	
ɓ				
	t^h			
		dʒ		
			k’	
m				
	l			
		j		
			x	
				h

- economy index: 1.1 (13/12)

3. System B: violates Markedness ("avoid marked feature combinations")

p	t	k	ʔ
$p^{w’}$	$t^{w’}$	$k^{w’}$	
b	d	g	
v	z	ɣ	
m̥	n̥		
	r, ʎ		
w	j		

- voiced fricatives but no voiceless fricatives
- voiceless nasals without voiced nasals
- labialized ejectives without plain labialized and plain ejective stops
- posterior lateral without anterior lateral

4. System C: violates the Robustness scale ("select higher-ranked features first")

p	t	tʃ	k		
b	d	dʒ	g		
f	s	ʃ	x		
v	z				
				h	ʔ

- lacks the robust obstruent/sonorant contrast

5. System D: violates Enhancement ("enhance weak contrasts with marked features")

p	t	**t̠**	k	
b	d	**d̠**	g	
ɸ	θ	ç	x	
β	ð			
w	l			h

- bilabial fricatives [ɸ β] instead of the preferred labiodentals [f v]
- nonsibilant fricatives [θ ð] instead of the preferred sibilants [s z]
- nonsibilant posterior stops [**t̠ d̠**] instead of the preferred sibilants [tʃ dʒ]
- oral sonorants [w l] instead of nasals [m n]

8. Discussion: the role of phonetics in constraining sound inventories

1. Summary: The principles of Boundedness, Economy, Markedness, Robustness, and Enhancement operate together to exclude many imaginable, but unlikely sound systems.

   It appears that nothing much more complicated than a ranked list of features indicating marked values, together with principles of feature economy and enhancement, can predict the statistically preferred design features of sound inventories to a good first approximation.

2. Two ways in which phonology can be understood as constrained by phonetic factors:
   - a "direct access" theory, in which phonological generalizations make direct access to the vast number of articulatory and acoustic parameter values provided by phonetic theory
   - a "feature-mediated" theory, in which phonetics constrains phonology through the mediation of the phonetic definitions associated with the small set of universal features.

   This paper has offered support for the second of these views: the major generalizations governing sound inventories appear best captured in terms of principles stated over the features of which speech sounds are composed.

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