THE ORGANIZATION OF PHONOLOGICAL INVENTORIES – AN ARTICULATORY APPROACH

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ABSTRACT

The phonological inventories of the world's languages vary remarkably in their size and constituency, when modeled as sets of phonemes or systems of distinctive features. An alternative approach to the analysis of inventories can be made, based on the premise that the phonological primitives represented in the inventory, the lexicon and the speech signal are one and the same – coordinated actions of the vocal tract. Described in articulatory terms, the differences between inventories of different languages may not be as significant as feature and segment-based characterizations suggest.

Comparative estimates of the entropy of different inventory structures suggest that an articulatory model may provide a more parsimonious account of the salient contrasts than a feature-based approach. Under an articulatory account, both consonantal and vocalic inventories can be explained using the same theoretical apparatus, and 'complex' segments can be explained in temporal terms.

Keywords: Phonological inventories, articulatory phonology, gestures, feature sets, entropy.

1. PHONOLOGICAL DIVERSITY

Phonological inventories differ, in some cases quite radically, in three main ways: the total number of phonemes, the ratio of consonants to vowels, and the selection of segments. The UPSID database [1] reveals that some languages use as few as 11 phonemes (Rotokas), while others use as many as 141 (!xõo). The mean number of segments in the survey is 31. 29 languages (6%) use 'sparse' inventories consisting of fewer than 15 phonemes, and another 33 languages (7%) employ 'complex' inventories of 48 phonemes or more. Maddieson identifies 921 distinct phonemes in the UPSID database – 652 consonants and 269 vowels – yet a typical language utilizes only 3% of this potential set of sounds.

It is surprising to find such diversity in a public system, constrained by UG, which relies on parity [2] to ensure successful communication. When languages are modeled as phoneme-based communications systems, it is even more problematic to account for differences between inventories because they exhibit very different properties of entropy and information rate.

Most accounts of the structure of phonological inventories ([3], [4], [5]) are predicated on the assumption that sound systems are "constrained by the fact that speech is perceived and produced in terms of distinctive features" [5]. If on the other hand, contrasts in the speech signal and in the lexicon can be modeled as a discrete set of articulatory entities [6], then we should also be able to analyze phonological inventories, which represent a catalogue of the basic units of contrast of a language, using the same approach.

2. QUANTIFYING INFORMATION IN INVENTORIES

An inventory may be modeled as a discrete combinatorial system whose information potential can be estimated using the concept of entropy [7]. The entropy of S, a set of n distinct, equi-probable symbols, may be quantified in bits (1).

$$H(S) = -\sum_{i=1}^{n} \frac{1}{n} \log(\frac{1}{n}) = \log_2(n) \quad (1)$$

Entropy can be increased either by increasing the number of contrastive elements in a system, or by increasing the number of distinct states which those units can enter into. When all primitives in an inventory may be freely combined, a system S of n freely combinable dimensions $\{d_1, d_2 \ldots d_n\}$ will have a total entropy equal to the sum of the component dimensions (2).

$$H(S) = H(|d_1|) + H(|d_2|) + \ldots + H(|d_n|) \quad (2)$$

An inventory *I* consisting of *P* phonemes, modeled as a combinatorial system *S*, has a utility *U* defined as follows (3).

$$U(S) = \frac{P}{H(S)} \quad (3)$$

An inventory with a utility of 1 therefore makes maximal use of all available contrasts: there will be no gaps in the system. A low utility (→ 0) can indicate either a sparse inventory, or a less parsimonious model of an inventory.

3. MODELING SMALL INVENTORIES

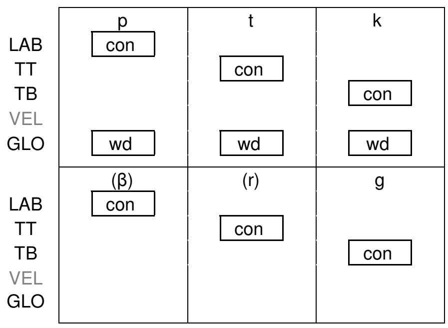
Languages which use a small set of segments are characterized by sparse phonemic inventories and severely underutilized feature matrices. The consonant system of Rotokas, the smallest attested for any language, is illustrated in **Figure 1**.

Figure 1: Rotokas consonant inventory: feature matrix

				cons	sonor	contin	voiced	lateral	nasal
	p	t	k	+	-	-	-	-	-
			g	+	-	-	+	-	-
	β			+	-	+	+	-	-
		r		+	+	+	+	-	-
labial	+	-	-						
coronal	-	+	-						
dorsal	-	-	+						

An examination of the allophony of Rotokas is revealing. The labial fricative is variously realized as [β-m-b], the alveolar stop as [t-s-ts], the rhotic as [r-l-n-d], and the velar stop as any of [g--ŋ] [8]. The degree of constriction is therefore significantly less important than place of articulation and voicing. This suggests that the salient contrasts in Rotokas are being made between three different articulators (lips/tongue tip/tongue body) and two different glottal gestures (voiced/voiceless) – a system which is captured nicely under an articulatory analysis in **Figure 2**.

Figure 2: Rotokas consonant inventory: articulatory model



Each segment is represented on a gestural score [9], in which the activity of each vocal organ (LIPS, TONGUE TIP, TONGUE BODY, VELUM, GLOTTIS) is illustrated. The gestural score indicates the target constriction for each participating organ, the activation time, and the temporal coordination of each of the constituent gestures which make up that phoneme. The production of a voiceless alveolar stop, for example, involves the synchronous coordination of a tongue-tip closure (TT:CLO) and a wide glottal gesture (GLO:WD).

Although the dynamic behavior of the articulators involved will vary continuously, the system may be modeled as discrete combinatorial system at the level of planning [10], so we can approximate the entropy of the system by calculating the number of gestures which are recruited, and the number of contrastive types of gesture which they can form (**Figure 3**).

Figure 3: Entropy of the articulatory system in **Figure 2**

Organ	State		n	H(n)
Lips	constricted	wide	2	1
Tongue Tip	constricted	wide	2	1
Tongue Body	constricted	wide	2	1
Velum	closed		1	0
Glottis	narrow	wide	2	1
Contrasts			16	4

An articulatory model can capture the variety of different ways in which languages with small inventories combine gestures to create contrast, which is not always the case with distinctive features. The consonantal inventory of Hawaiian is illustrated in **Figure 4**.

Figure 4: Hawaiian consonant feature matrix

					cons	sonor	contin	voiced	lateral	nasal
	p		k	?	+	-	-	-	-	-
	m	n			+	+	-	+	-	+
				h	+	-	+	-	-	-
	w				+	+	+	+	-	-
		l			+	+	+	+	+	-
labial	+	-	-	-						
coronal	-	+	-	-						
dorsal	-	-	+	-						

Hawaiian is famous for its rare coronal-dorsal alternation (/k/~[k,t] /n/~[n,ŋ]), and the allophony of the labial stop /p/~[p,b] shows that voicing is not used phonologically. We can therefore analyze this inventory as consisting of a triplet of stops, a pair of nasals, and a triplet of continuants (**Figure 5**).

Figure 5: Hawaiian consonants: articulatory analysis

	p	k	ʔ
LAB	clo		
TT		clo	
VEL			
GLO	wd	wd	clo
	w	l	h
LAB	nrw		
TT		nrw	
VEL			nrw
GLO			
	m	n	
LAB	clo		
TT		clo	
VEL			
GLO	wd	wd	

The entropy of this model (**Figure 6**) is significantly lower than that of the unconstrained feature matrix (9bits), since it is a combinatorial system inherently constrained by the articulatory possibilities of the participating organs:

Figure 6: Entropy of the articulatory system in **Figure 5**

Organ	Constriction Type			n	H(n)
Lips	clo	nrw	wd	3	1.58
Tongue	clo	nrw	wd	3	1.58
Velum	clo		wd	2	1.00
Glottis	clo	nrw		2	1.00
Contrasts				36	5.17

Articulatory analysis also more accurately models the way in which the glottis is used in Hawaiian. In a generative framework, the glottis is treated as a sound source, and is not easily modeled as a place of articulation. Under an articulatory framework, there is no division of articulators into source/place categories – each organ can enter into a variety of salient configurations, a subset of which are used contrastively by each language.

4. REPRESENTING FINER CONTRASTS

Small inventories such as these primarily utilize a limited set of constriction types and discrete organs, however larger inventories make use of more places of articulation than there are contrastive organs. We can model these inventories using the notion of tract variables [6], which introduce more entropy into the system by contrasting constriction location and constriction degree for a given articulator. The fricatives and approximants of American English, modeled as a system of tract variables, are illustrated in **Figure 7**.

Figure 7: American English continuant consonants: articulatory analysis using tract variables

	f	θ	s	ʃ	h
LA	crit				
TTCL		dent	alv		
TTCD		crit	crit		
TBCL				pal	
TBCD				crit	
GLO	wd	wd	wd	wd	wd
	v	ð	z	ʒ	
LA	crit				
TTCL		dent	alv		
TTCD		crit	crit		
TBCL				pal	
TBCD				crit	
	w		l	r	j
LA	nrw			nrw	
TTCL			alv	pal	
TTCD			nrw	nrw	
TBCL	uvu		uvu		pal
TBCD	nrw		nrw		nrw

The entropy of the complete English consonant system calculated using this model (**Figure 8**) proves to be a significantly more parsimonious system than the 13 bits needed using distinctive features.

Figure 8: English consonant inventory: entropy of an articulatory model

Organ	TV	Constriction Type				n	H(n)
Lips	LA	clo	crit	nrw	wd	4	
	LP	-				1	
						4	2.00
Tongue	TTCL	dent	alv			2	
	TBCL	pal	vel	uvu		3	
	TxCD	clo	crit	nrw	wd	4	
						20	4.32
Velum	VEL	clo			wd	2	1.00
Glottis	GLO			nrw	wd	2	1.00
Contrasts						320	8.32

5. UNIFYING INVENTORIES

Another advantage of an articulatory analysis is that it offers a unified framework under which to model both consonantal and vocalic inventories. 19 features are required to differentiate the complete inventory of American Spanish (**Figure 9**), many of which are specific to either the consonantal or vocalic sub-systems. These 19 features are capable of contrasting over 500,000 phonemes, of which Spanish uses only 22 - a utility of just 0.004%. Under an articulatory analysis, the same set of primitives is used to model both consonants and vowels (**Figure 10**).

Figure 9: American Spanish inventory: feature matrix

										cons	sonor	contin	voiced	nasal	del rel	trill	lateral	high	low
p		t̪				k				+	-	-	-	-	-	-	-	+	-
b		d̪				g				+	-	-	+	-	-	-	-	+	-
m			n		ɲ					+	+	-	+	+	-	-	-	-	-
				tʃ						+	-	-	-	-	+	-	-	-	-
	f		s			x				+	-	+	+	-	-	-	-	-	-
			r							+	+	+	+	-	-	+	-	-	-
			ɾ							+	+	+	+	-	-	-	-	-	-
			l		ʎ					+	+	+	+	-	-	-	+	-	+
							i		u	-	+	+	+	-	-	-	-	+	-
							e		o	-	+	+	+	-	-	-	-	-	-
								a		-	+	+	+	-	-	-	-	-	+
+	+	-	-	-	-	-	-	-	-	labial									
-	-	+	+	+	+	-	-	-	-	coronal									
-	-	-	+	+	-	-	-	-	-	strident									
-	+	+	+	-	-	-	-	-	-	anterior									
-	-	+	-	+	-	-	-	-	-	distrib.									
-	-	-	-	-	+	+	+	+	+	dorsal									
-	-	-	-	+	-	-	-	-	+	round									
-	-	-	-	-	-	-	-	+	+	back									
-	-	-	-	-	-	-	+	-	+	ATR									

Figure 10: American Spanish: articulatory model

	p	t̪	k	f	s	tʃ	x	
LAB	clo			crit				
TT		clo			crit	clo		
TB			clo			crit	crit	
VEL								
GLO	wd	wd	wd	wd	wd	wd	wd	
	b	d̪	g	r	ɾ	l	ʎ	
LAB	clo							
TT		clo		trill	nrw	nrw		
TB			clo			nrw	nrw	
VEL								
GLO								
	m	n	ɲ	i	e	a	o	u
LAB	clo			nrw			pro	pro
TT		clo						
TB			clo	pal-nrw	pal-mid	pha-mid	uvu-mid	uvu-nar
VEL	wd	wd	wd					
GLO								

Once again, the entropy of the articulatory model is significantly smaller because it does not over-generate, being constrained by the organization of articulators inherent in the model.

Figure 11: Entropy of the articulatory model in **Figure 10**

Organ	TV	Constriction Type	n	H(O)
Lips	LA	clo crit nrw wd	4	
	LP	pro -	2	
			8	3.00
TTip	TTCL	alv palv	2	
	TTCD	clo crit nrw trill wd	5	
			9	3.17
TBody	TBCL	pal vel uvu phar	4	
	TBCD	clo crit nrw mid wd	5	
			17	4.09
Velum	VEL	clo wd	2	1.00
Glottis	GLO	nrw wd	2	1.00
Contrasts:			4896	12.26

6. MODELING LARGE INVENTORIES

One additional way in which languages can increase the entropy of an inventory is to utilize finer temporal contrasts. The 4 laryngeal contrasts used in the Hindi stop system for example, can be modeled in terms of asynchronous coordination of oral and glottalic release gestures. Each asynchronous coupling relationship adds another bit of information to the system, so Hindi augments its stop system by another 2.58 bits of temporal entropy, producing a system capable of creating 144 distinct phonemes.

7. DISCUSSION

More work is required to refine these models, however the concept of entropy has proven to be a valuable tool in the typological analysis of inventories and for the comparison of systems of representation. Under an articulatory approach, the diversity in phonological systems is not as large as it seems when segments are modeled as phonemes or bundles of features.

The trend observed in the UPSID database is that languages add complexity to their inventories according to a hierarchy of contrasts, starting with the most salient primitives: languages first utilize contrasts between organs, then distinctive regions of articulators, additional types of constrictions and constriction locations, and finally, temporal contrasts other than synchronous coordination.

8. REFERENCES

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