Testing Opposing Phonetic Structural Principles: Polarization and Gestural Economy

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1. Introduction. This study examines an aspect of the relationship between phonetics and phonology: the influence of phonological patterns on phonetic implementation. Specifically, the matter under focus here is whether the number of phonological contrasts along a given phonetic continuum affects the articulation of those contrasts. The larger goal is to contribute to our understanding of the ways in which physical and abstract representations of language sounds are connected. The approach taken to consider this question is the use of instrumental articulatory evidence from a language which employs varying numbers of contrasts in different phonotactic positions, and so is suited for such an analysis. We take as specific starting points for the investigation two desirable but opposing structural principles of articulation: *polarization* and *gestural economy*.

1.1. Polarization. The original purpose of the polarization principle (Keating 1984) was to explain the differing behavior of segments belonging to the same phonetic categories, in different languages. In treating the implementation of Voice Onset Time (VOT) across languages, Keating noticed that firstly, three and only three VOT categories seemed to exist across languages which had been described: {voiced}, {voiceless unaspirated}, and {voiceless aspirated}. Secondly, adjacent categories were always employed by a given language. Thus, Keating suggested that along a given phonetic continuum, phonological oppositions are instantiated by a fixed number of phonetic categories. Moreover, phonological oppositions can be mapped to different phonetic categories in different languages. Keating observed that English and Polish word-initial stops both employ two of the three contrastive types along the VOT continuum, and both make use of the {voiceless unaspirated} category. However, in Polish the opposing stop is in the {voiced} category, whereas in English the opposing stop is in the {voiceless unaspirated} category, as shown schematically for labials in Figure 1.

Voice Onset Time continuum--->

Phonetic Category	*{voiced}*	*{voiceless unaspirated}*	*{voiceless aspirated}*
Polish	b	---->p	
English		b<---	p^h

Figure 1: Schematized VOT in Polish and English word-initial labial stops

Crucially, polarization states that once phonetic categories have been chosen to instantiate the phonological oppositions in a language, actual phonetic values will be widely separated within those categories, so as to maximize the difference between the contrastive segments. (In this respect, polarization is a subset of *dispersion theory*, Lindblom 1986, 1990; Flemming 1997, to appear.) Thus, the stops in the {voiceless unaspirated} category in English and Polish are not identical, but are displaced with respect to each other, as shown in Figure 1. This has the effect of maximizing the difference with the other member of the contrastive pair; {voiced} in the case of Polish, and {voiceless aspirated} in the case of English.

Note that polarization implicitly places a higher value on perceptual ease in distinguishing among contrasts than on articulatory ease in producing them, in the sense that articulations will be polarized even if this means more extreme

articulations, or means storing more than one motor implementation program for a contrast.

1.2. Gestural Economy. Another possible view of the relationship between phonetics and phonology involves a theory of articulation called *gestural economy* (Maddieson 1996.) The ideas of gestural economy emerge from concepts entertained in Lindblom and Maddieson, 1988. Gestural economy implicitly acknowledges that there must be a balance between articulatory and perceptual ease. Maddieson notes that it is necessary and desirable to maintain sufficient perceptual distinctiveness among contrastive segments. However, given sufficient distinctiveness, the desiderata of gestural economy are two-fold. First, languages place high value on the use of efficient gestures; those gestures which show "economy of kind". Secondly, languages place high value on re-use of these efficient gestures, so that speakers need not internalize more motor programs than necessary to convey the phonological oppositions of their language. This principle constitutes "economy of number."

Maddieson presents instrumental evidence for *economy of kind* from Sele and Ewe, two languages of West Africa. Sele employs a single labiodental fricative which does not contrast with another labial fricative. Ewe, on the other hand, places a labiodental fricative in contrast with a bilabial fricative. On the continuum of upper lip height, Maddieson establishes instrumentally that in the Sele labiodental, the upper lip is in a neutral position, neither lowered nor raised. Elsewhere, Maddieson (1984) gives evidence that labiodental fricatives are frequent members of consonant inventories, and proposes that this is because they require "precise positioning of only one active articulator" and "a relatively small movement" while remaining acoustically distinct from other fricatives (Maddieson 1996).

In Ewe, the bilabial fricative shows upper lip lowering as both lips approach each other for the constriction. However, even though it contrasts with the bilabial, the Ewe labiodental fricative is not appreciably different from the Sele labiodental. (The distribution of these segments is schematized in Figure 2.) Maddieson argues that this is because /f/ is qualitatively economical. In Ewe a more efficient segment is used over a potentially more distinctive segment; gestural economy outweighs maximal distinctiveness. Recall that under polarization, one would expect that the Sele and Ewe labiodentals would differ; the Ewe labiodental would involve a higher lip position, in order to maximize its difference from the bilabial.

Upper lip height---------->

Phonetic Category	*{low}*	*{neutral}*	*{raised}*
Sele		f	
Ewe	ɸ	f-->f̟	

Figure 2: Schematized upper lip height positions for Sele and Ewe labial fricatives. (Outlined symbol shows position under polarization.)

Maddieson cites the re-use of efficient places of articulation across different manners to illustrate *economy of number*. The fact that languages very commonly have stops, nasals and laterals reoccuring at the same places of articulation is, in Maddieson's view, an indication that efficient component gestures are being re-used to minimize the number of articulatory motor programs needed for phonological contrasts. However, here Maddieson's evidence comes from the UCLA Phonological Segment Inventory Database (Maddieson 1984) in which segments are categorized *phonologically;* phonetic detail is purposely underplayed. Thus, it remains an empirical question for the majority of languages whether stops and

nasals for instance, are actually articulated identically, or whether they are simply categorized together phonologically.

	p	t	k
√	m	n	ŋ
*	ɱ	ɳ	ɴ

Figure 3: Economy of number vs use of different gestures for stops and nasals

2. Predictions. The issue under focus in this study is that polarization and gestural economy make different predictions about the impact of phonological structure on phonetic implementation. Specifically, in a single language in which different numbers of contrasts operate in different environments, polarization predicts that phonetic realization will be affected by the different numbers of contrasts, while gestural economy predicts that segments will not polarize when contrasts are added.

The language examined here was Western Arrernte, an Arandic language of Central Australia, which makes use of four contrastive coronal places of articulation in the stops, nasals, laterals and prestopped nasals. Coronals are those sounds made by an articulation of the tongue tip and/or blade with the upper surface of the vocal tract. Common auditorily-based descriptions of tongue configurations for these four places of articulation are shown in Figure 4, and involve two tip articulations (apicals) contrasting in place, as well as two blade articulations, (laminals) contrasting in place. Intervocalically, the four-way contrast holds. However, in word-initial position, there is no place contrast between the apicals.

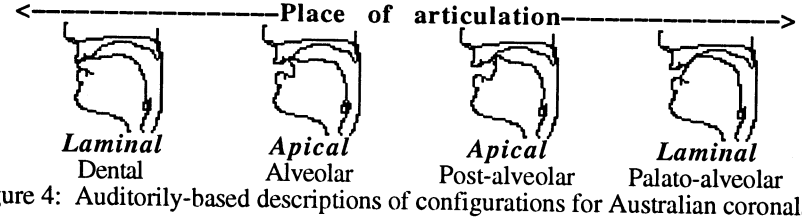


Figure 4: Auditorily-based descriptions of configurations for Australian coronals

Fig. 5 shows examples for stops. "T" is used to refer to the non-contrastive apical.

		Coronal places of articulation				
	Bilabial	*Laminal* Dental	*Apical* Alveolar	*Apical* Post-alveolar	*Laminal* Palato-alveolar	Dorsal Velar
Stops	**p**	**t̪**	**t**	**ʈ**	**c**	**k**
Word-initially	**pəṯə** *pouch (n)*	**t̪əmə** *grind (vt)*	**Təpə** *back (n)*		**c̪ənə** *friend (n)*	**kəpə** *firestick (n)*
Between vowels	**mapə** *many (n)*	**aṯə** *I (pr, tr.)*	**l̪atə** *today (n)*	**kwaʈə** *egg (n)*	**kwac̪ə** *water (n)*	**makə** *elbow (n)*

Figure 5: W. Arrernte stops, word-initially and between vowels

2.1. Predictions of Polarization. The different predictions that the two principles make are as follows. Under a polarization scenario, the two contrastive apicals will be widely distributed on the place continuum with respect to the noncontrastive apical, in order to maximize distinctions between them. The advantage here is that listeners economize on perceptual effort in recognizing the contrastive segments.

The disadvantage, however, is that speakers must control three different motor programs for apicals, which violates economy of number.

Place dimension ---------->

Non-contrastive	T
Contrastive	t <---------- • ----------> ʈ

Figure 6: Arrernte Polarization Scenario--contrastive vs non-contrastive apicals

A second scenario involving polarization compares stops at each place of articulation with their corresponding nasals. On the assumption that nasals are less perceptually robust than stops because they do not have as many acoustic cues, it may be that nasals are articulated more divergently on the place continuum than stops, in order to maximize perceptual distances among them. Anecdotal evidence for such a possibility has been observed in Malayalam, a Dravidian language of India which, like Arrernte, employs four contrastive oppositions for tongue-palate articulations in both stops and nasals. Ladefoged and Maddieson (1996) observe that for a few speakers of Malayalam, dental nasals are articulated as interdentals, while dentals stops are articulated as post-dentals. For these speakers, dental nasals are articulated further forward on the place continuum than dental stops. In Figure 7, positions for the other stops and nasals have been hypothesized, although only the dentals are explicitly mentioned by Ladefoged and Maddieson.

Place of articulation continuum---------->

Phonetic Category	*{dental}*	*{alveolar}*	*{postalveolar}*	*{palatal}*
Stops	t̪	t	ʈ	c
Nasals	n̪	n	ɳ	ɲ

Figure 7: Schematized places of articulation in Malayalam

2.2. Predictions of Gestural Economy. Gestural economy of number dictates that an articulation will be re-used in both contrastive and non-contrastive environments. That is, an articulation representing the non-contrastive apical will reappear as one of the contrastive apicals, as shown in Figure 8.

Place dimension ---------->

Non-contrastive	T
Contrastive	t |----------| ʈ

or

Non-contrastive	T	
Contrastive	t	ʈ

Figure 8: Arrernte Gestural Economy Scenario--contrastive vs non-contrastive apicals

The advantage here is that speakers economize on motor programming; only two articulations exist for apicals. However, the disadvantage is that the contrastive articulations are not so widely divergent on the place continuum, which violates maximal distinctiveness.

Gestural economy also dictates that nasals will differ from stops in the position of the velum, but will be identical in terms of the gestures used to achieve the oral configuration.

Place of articulation continuum----------->

Phonetic Category	{dental}	{alveolar}	{postalveolar}	{palatal}
Stops	t̪	t	ʈ	c̱
Nasals	n̪	n	ɳ	ɲ̱

Figure 9: Schematized coronal places of articulation in Arrernte: gestural economy

3. Method. In order to empirically investigate how W. Arrernte resolves these conflicting structural principles, direct instrumental articulatory data for tongue-palate contact patterns was collected using a method called static palatography, described in detail in Ladefoged (1997). Briefly, a speaker's tongue is painted with a non-toxic marking material, in this case a mixture of olive oil and digestive charcoal. The speaker utters a word containing the segment of interest, and inserts a mirror into the mouth to reflect the contact area on the palate. The contact area is videotaped (see Figure 10) and the speaker rinses his or her mouth with water.

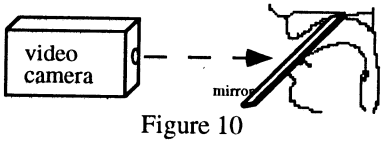


Figure 10

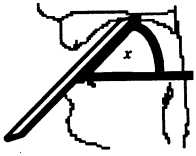
3.1. Data Set. To the extent possible, it is important to choose words containing only low vowels and labials in addition to the coronal of interest, in order to avoid confounding effects of other tongue-palate contacts. The data set used for this experiment is shown in Figure 11.[1]

	Laminal Dental	*Apical* Alveolar	*Apical* Post-alveolar	*Laminal* Palato-alveolar
Stops Between Vowels	**'pə̪tə** *pouch (n)*	**'matə(ɹə)** *cloud (n)*	**'pəʈə** *rock (n)*	**'peʈəmə** *is coming(vi)*
Stops Word-initially	**'t̪əmə** *grind (vt)*	**'Təpə** *back (n)*		**'c̱apə** *grub (n)*
Nasals Between Vowels	**ip'məɳə** *grandmother (n)*	**'manə** *money (n)*	**'məɳə** *veg. food (n)*	**'mpəɲ̱ə** *crumb (n)*
Nasals Word-initially	**'n̪əmə** *rain is falling (vt)*	**'Nəmə** *is sitting (vi)*		**'t̪n̪əmə** *is falling (vi)*

Figure 11: Data set for W. Arrernte static palatography

3.2. Image Processing.

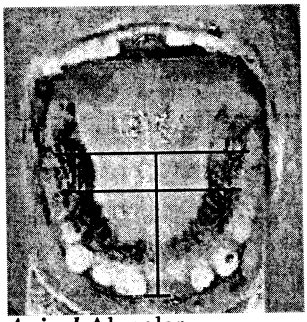
For each token, the relevant video clip was digitized into a computer file from which a high-quality still frame was chosen for analysis. The still frame was corrected for angular distortion caused by slight differences in the angle at which the mirror was placed in the mouth relative to the occlusal plane (angle *x*, left.) For each still frame, vertical and horizontal planes were corrected independently, based on actual millimeter measurements from lifesize palatal plaster casts.



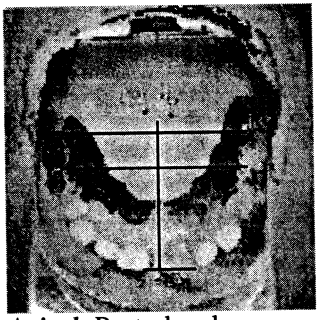
To obtain the horizontal correction factor, a horizontal calibration measure was taken at a line just forward of the left and right first molars (line "h", Figure 13.) This measure was taken on the lifesize plaster cast as well as on the still frame in question, and the ratio of the two was used as the correction factor.

To obtain the vertical correction factor, a vertical calibration measure was taken at a line drawn from the front edge of the front incisors to the horizontal calibration line (line "v", Figure 13.) Again, this measure was made on both the lifesize plaster cast and on each still frame, to produce a correction factor for each vertical measurement on a given still frame.

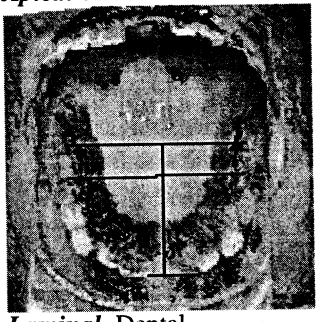
4. Analysis. Figure 12 shows, for one speaker, a sample still frame for each of the four categories of contrastive stop. In each case, upper teeth are shown at the top of the photograph, and are also reflected at the bottom.



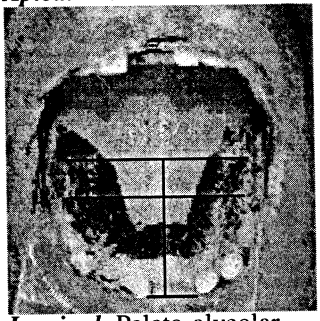
Apical Alveolar



Apical Post-alveolar



Laminal Dental

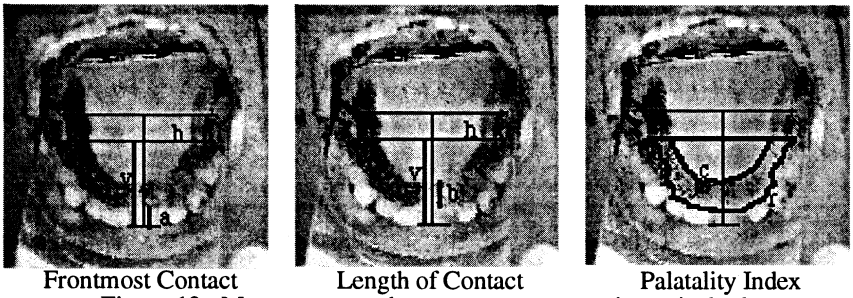


Laminal Palato-alveolar

Figure 12: Tokens of the medial stops for one speaker

After examining still frames for several speakers, measurements were chosen that would yield fruitful ways of differentiating among the five place categories.

4.1. Frontmost Contact. Comparative inspection of frames showed that *frontmost contact* on the palate in the midline was likely to yield differences among categories. Indeed, this metric has been used before by Butcher (to appear), Dart (1991) and others, as a index of place of articulation.[2] Note that in Figure 12 the laminal dental shows contact on the surfaces of the incisors. The apical alveolar begins further back, clear of the teeth in the case of this token, and frontmost contact for the apical postalveolar and laminal palatoalveolar begin appreciably further back than the apical alveolar. Frontmost contact was quantified by measuring from a line drawn at the base of the teeth back to the front edge of the contact pattern, in the midline (line a, Figure 13).



Frontmost Contact Length of Contact Palatality Index

Figure 13: Measurements shown on non-contrastive apical token

4.2. Length of Contact. The apical/laminal distinction itself leads us to expect differences between apicals and laminals based on length of contact from front to back in the midline. However, there may be significant differences among each of the place categories, or indeed between stops and nasals in a single category, in addition to the apical/laminal distinction. Observe that the laminal dental and laminal palatoalveolar in Figure 12 are very broad in their contact area from front to back, although it is not possible to tell from these tokens which may be broader or whether there is a significant difference between them. The apicals, as expected, are much narrower in midline contact. Like frontmost contact, this metric has been used before (Butcher, to appear), and has expected acoustic correlates.[3] Length of contact was measured by drawing a line from the front to rear of the contact in the midline (line b, Figure 13.)

4.3. Palatality Index. Having considered the space in front of the constriction and the length of the constriction itself, we considered differences in the amount of empty space that remained behind the constriction, which is affected by raising of the sides of the tongue body and how far back the midline constriction extends. The more contact on the palate, the smaller this space will be. Here the clearest difference is between the apical alveolar and the laminal palatal, both because of the rear point of midline contact, and the extent of lateral contact on the sides of the palate. Since this space reflects cavity size behind the constriction, we again expect acoustic concomitants.[4] To quantify the palatality index, an area bounded by the horizontal calibration line and the rear contact line was measured. (This area is shown as the inner outlined area "c" in Figure 13.) Analogous to the linear measurements described above, these area measurements were corrected by reference to a calibration area. In each case the calibration area was defined by the

horizontal calibration line and the juncture of the teeth with the gumline. (This area is the outer reference outlined area "r" in Figure 13.)

Incidentally, Figure 13 a, b, and c show a token of the non-contrastive apical for the same speaker, for purposes of comparison with Figure 12. Recall that we wish to categorize non-contrastive stops and nasals in terms of the three measurements described above, to determine how or if they differ from the contrastive apical categories. If the non-contrastive apical has characteristics of an alveolar or a postalveolar, gestural economy is indicated. If it has intermediate characteristics, this would indicate polarization of the contrastive apicals with respect to the non-contrastive apical.

5. Results

5.1. Stops vs Nasals. Let us first consider results of the three metrics for stops and nasals at each place category. Statistical analysis of variance (ANOVA) showed that stops and nasals at any given place of articulation were indistinguishable from each other along all of the measures taken here.

Recall the possible Malayalam scenario outlined in section 2.1. Investigators suggested that in order to make weaker nasals more perceptually robust, speakers might articulate them more divergently on the place continuum. However, at least for W. Arrernte, this is found not to be the case. First, perception tests of the stops and nasals with native listeners show that the nasals are as perceptually robust as the stops (Anderson 1997). Second, the manner distinction does not interact with place distinctions in any of our measures of tongue-palate contact. Thus we have the scenario shown in Figure 9. Gestural economy of number is suggested by these results. Though the position of the velum differs for stops and nasals, the same oral gesture is used in both. In the following discussion of results for contrastive and non-contrastive apicals, we will collapse stops and nasals together.

5.2. Contrastive vs Non-contrastive Apicals. Before comparing initial apicals with medial ones, we must first determine whether such a comparison is appropriate. For example, it may be that the segments simply involve positional differences, whether or not they involve different numbers of contrasts. (See Keating et.al., to appear, regarding fortition of initial segments.) Luckily, the laminals provide a way to address this question, because they involve the same numbers of contrasts in initial and medial positions. Results of ANOVA on laminal initials and medials show that initials are not strengthened or weakened vis-a-vis medial segments. Therefore, we will take the comparison between non-contrastive and contrastive apicals to be an appropriate one, and assume that results are not an artifact of position. Moreover, results for initial and medial laminals will be shown together. Let us now consider each measure in turn, comparing non-contrastive and contrastive apicals.

Results for the five place categories were compared, both as raw measurements in millimeters and as proportional measurements reflected as a percentage of the appropriate calibration measurement. Proportional measurements take into account the different mouth sizes of speakers. Quite surprisingly, the use of either raw or proportional measurements yielded the same significance results. Proportional measurements showed slightly greater significance values, and will be reported here. In each case, the summarized results below reflect data from 171 tokens ([7 stops +7 nasals] x 6 speakers x approx. 2 tokens each.) Statistical significance depended on a p value of $\leq .05$.

5.2.1. Frontmost Contact.

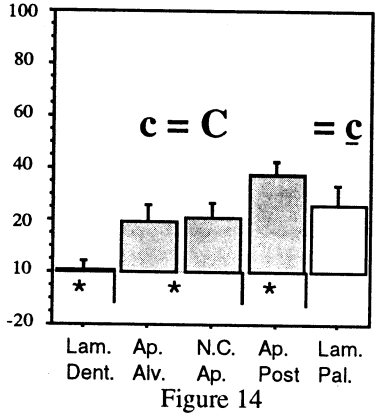


Figure 14

Figure 14 shows results for frontmost contact on the palate in the midline, summed over the six speakers. The x-axis shows the five place categories, with non-contrastive apicals placed between the contrastive ones for ease of comparison. Apical categories are shown with shaded bars. Laminals are included for completeness, and are shown unshaded. Measurements on the y-axis are reported as percent of the vertical calibration line. Lines above bars reflect one standard deviation.

As expected, we find that laminal dentals have the lowest percent values, and thus the furthest frontmost contact of the five segment categories. The non-contrastive and alveolar apical categories are not statistically differentiable; i.e. they behave as a group. Both are statistically differentiable from the postalveolar, which begins significantly further back from the alveolar and non-constrastive segments.[5]

5.2.2. Contact Length

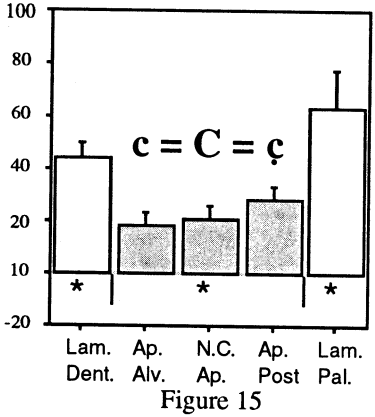


Figure 15

Results are shown in Figure 15. Again, place categories are shown on the abscissa; contact length as a percentage of the vertical calibration line is shown on the ordinate. As expected, we find laminals to be much broader in contact than apicals; these segments have been correctly described in auditory descriptions. However, the laminals do not act as a group. Laminal palatoalveolars are statistically significantly broader than laminal dentals. On the other hand, none of the apicals differ statistically from each other, as we hypothesized would be the case at first glance. Thus, since even the two contrastive apical categories group together, this measure provides no insight into either polarization or gestural economy.

5.2.3. Palatality Index.

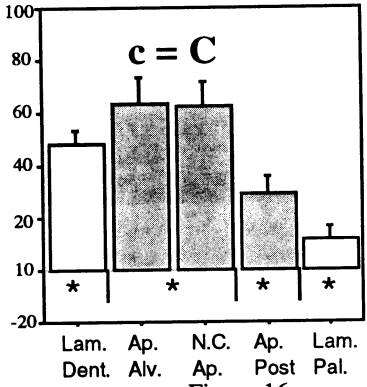


Figure 16

In Figure 16, the x-axis is as above; the y-axis shows percent of *uncontacted* space as a percentage of the calibration area described in 4.3 above. Since a large amount of contact with the palate means a small cavity size, we expect an inverse relationship between the percentage value reported and amount of contact on the palate.

Laminal palatoalveolars have far and away the most contact with the palate, and thus the smallest uncontacted area. This category is quite significantly differentiable from all others, and reflects both the laminality of the midline contact and lateral tongue raising behind the midline constriction.

Alveolar and non-contrastive apicals do not differ at all on this measure. They behave as a group, but are significantly differentiable from every other place category.

6. Summary and Conclusion. In this study we have examined evidence for the phonetic principles of polarization and gestural economy, by quantitatively characterizing the articulation of segments in which we might expect phonological structure to affect phonetic realization of segments. We focused on the coronal stops and nasals in Western Arrernte, which employ different numbers of contrasts initially and medially. Results for three quantitative articulatory measures were shown. Results for *contact length* were compatible with either polarization or gestural economy, and so did not bear on the issue of how these opposing principles may compromise or be weighted. Results for *frontmost contact* and *palatality index* indicate that in terms of both the front and back cavities, alveolar and non-contrastive apicals are identical, which is evidence for re-use of gestures and bears out the predictions of gestural economy of number. Moreover, the fact that the alveolar rather than the postalveolar was used in the greater number of contexts points to gestural economy of kind: use efficient (in this case *less displaced*) gestures.

We also showed that stops and nasals of a given place category do not differ from each other along any of these measures, which indicates economy of number. This result, added to the fact from perceptual work that Arrernte nasals can be differentiated just as well as the stops also gives credence to the idea that "sufficient perceptual contrast" rather than contrast-maximizing principles may be at work.

Polarization and gestural economy are both desirable structural principles of articulatory phonetic implementation. However, in this study we have accrued evidence only for the latter, in both "the number and the nature of the gestures used" (Maddieson 1996).

[1]Two cases require discussion. In the word for cloud, /'matəɹə/, speakers were instructed to omit the final syllable, in order to avoid potential confounding effects of the /ɹ/ on the resulting pattern. Speakers participating in the study were consulted to make sure they were satisfied that their articulation and the resulting portion of the word sounded reasonably accurate. Also, since a word completely lacking other coronals or high vowels could not be found for the laminal palatoalveolar word-initial nasal /n̠/, a prestopped nasal /t̠n̠/ was used.

[2]Moreover, since this measure reflects the size of the cavity in front of the constriction, it can be taken to be associated with acoustic correlates such as spectral shape.

[3]Since this measure is associated with the mass of the articulator, we would expect extent of midline contact to relate directly to relative voice onset time, amount of frication at the burst release, and duration of formant transitions.

[4]For example, transition loci at the onset of the following vowel.

[5]As an aside, the frontmost edge of the apical postalveolar is further back than that of the laminal palatoalveolar. And though the palatoalveolar is statistically distinct from the laminal dental, it is in the realm of the alveolar/non-contrastive apical group, which is unexpected. However, it is harder to maintain that frontmost contact is the optimal measure of intended "place" or "target" in the case of such a broad contact.

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