A gestural account of the velar fricative in Navajo

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Abstract

Using the framework of Articulatory Phonology, we offer a phonological account of the allophonic variation undergone by the velar fricative phoneme in Navajo, a Southern or Apachean Athabaskan language spoken in Arizona and New Mexico. The Navajo velar fricative strongly co-articulates with the following vowel, varying in both place and manner of articulation. The variation in this velar fricative seems greater than the variation of velars in many well-studied languages. The coronal central fricatives in the inventory, in contrast, are quite phonetically stable. The back fricative of Navajo thus highlights 1) the linguistic use of an extreme form of coarticulation and 2) the mechanism by which languages can control coarticulation. It is argued that the task dynamic model underlying Articulatory Phonology, with the mechanism of gestural blending controlling coarticulation, can account for the multiplicity of linguistically-controlled ways in which velars coarticulate with surrounding vowels without requiring any changes of input specification due to context. The ability of phonological and morphological constraints to restrict the amount of coarticulation argues against strict separation of phonetics and phonology.

1. Introduction

There have been two major themes in the laboratory phonology approach to linguistic sound patterns. The first is a concern with the effects of language use, production, and perception on linguistic structure, and the second is the investigation of how linguistic knowledge affects motor and perceptual patterns (Pierrehumbert et al. 2000). This paper extends research in the second of these major themes. Research in the laboratory phonology framework has shown that languages control many aspects of phonetic behavior (Keating 1985), and a large body of research illustrating this language-specific detail exists (e.g., Öhman 1966; Bradlow 1995). But there is little agreement on *how* languages control physical linguistic behavior. We seek to contribute to this debate

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by proposing a specific task-dynamic mechanism by which languages can control coarticulation.

Using the framework of Articulatory Phonology, we offer a phonological account of the allophonic variation undergone by the velar fricative phoneme in Navajo, a Southern or Apachean Athabaskan language spoken in Arizona and New Mexico. This Navajo fricative strongly co-articulates with the following vowel, varying in both place and manner of articulation. It has been shown that coarticulation between velar consonants and vowels is not a universal motor behavior, but is language-specific (e.g., Butcher and Tabain 2004). Velars often vary in place according to the surrounding vowels (e.g., Jones 1940: 134), but the variation in the velar fricative in Navajo seems to be greater in magnitude and to affect both place and degree of the constriction. It is of further interest in that this variation occurs in the primary position of contrast – the initial position of the stem, the single position in which the full set of Navajo phonemic contrasts is found. The coronal central fricatives in the inventory, on the contrary, are quite phonetically stable, subject only to well-defined phonological processes, such as voicing and consonant harmony. This study of the velar fricative of Navajo thus highlights 1) the linguistic use of an extreme form of coarticulation and 2) the mechanism by which languages control coarticulation.

That the high level of variability of Navajo velar fricatives occurs in the strong position of the stem is surprising, since phonemes in strong positions of contrast are expected to be less likely to show variation than those in weaker positions (Steriade 1994). In general, it is also expected that coarticulation is limited in a consonantal system with a large number of contrasts, such as Navajo (see Table 1), in order to increase distinctiveness (Manuel 1990, 1999). For these two reasons, it is expected that there would be a restriction against a high level of coarticulation for velars in Navajo. The issue of linguistic limitation of the degree of coarticulation is highly relevant to the nature of the interface between phonology and phonetics, since the ability of phonological and morphological constraints to restrict the amount of coarticulation would argue against strict separation of phonetics and phonology. If linguistic constructs are relevant only on one side of the interface and non-linguistic motoric constructs are relevant only at the other side, then Navajo velar fricatives should be as stable as the coronal ones.

Another issue raised by Navajo velar coarticulation is the mechanism by which languages control coarticulation, if indeed they do. It has been argued that coarticulation is not simply a universal motoric act, but is planned (Whalen 1990) and its details are language-specific (Keating 1985; Manuel 1990). Regarding velar coarticulation in general, languages can vary from allowing small effects of vowels on velars as in English, to allowing extensive effects as in Australian languages (Butcher and Tabain 2004). There is little agreement, however, on the mechanism used by languages to control coarticulation. The window model of coarticulation posits that languages specify windows of variability through which interpolation

Table 1. *Navajo consonant inventory in (a) Navajo orthography and (b) IPA transcription (after McDonough 2003; McDonough and Wood 2008).*

(a) Navajo orthography (YM)

Labial	Coronal		Velar	Labialized Velar	Glottal
b	t, d, t’		k, g, k’	kw, gw	’
	ts, dz, ts’	ch, j, ch’			
	tł, dl, tł’				
	s, z	sh, zh	x, gh		h
	ł, l				
m	n				
w		y			

(b) IPA (McDonough 2003; McDonough and Wood 2008)

Labial	Coronal		Velar	Labialized Velar	Glottal
p	tx, t, t’		kx, k, k’	kx^{w}, g^{w}	ʔ
	ts^{h}, ts, ts’	tʃ^{h}, tʃ, tʃ’			
	tł^{h}, tł, tł’				
	s, z	ʃ, ʒ	x, ɣ		h
	ł, l				
m	n				
w		j			

due to context can occur (Keating 1990). The task dynamic model, on the other hand, posits the mechanism of gestural blending, which can be of different types, to control coarticulation (Saltzman and Munhall 1989). We will argue, based on the data from velar coarticulation in Navajo and comparison with other languages, that the mechanism of blending, with its different types, is necessary to account for the multiplicity of linguistically-controlled ways in which velars can coarticulate with surrounding vowels. We believe that the issue of coarticulation is of critical importance in the relation between phonology and phonetics, since establishing the detailed mechanisms of how languages control articulation goes beyond the denial of the dualist view of phonology and phonetics, which holds phonology to be of the mind and phonetics to be of the body, to construct the mechanisms through which it is apparent that they are one and the same. In this paper it will be argued that a unified gestural account can be given to the linguistically-controlled coarticulation of the Navajo velar fricatives with contiguous vowels which could be adapted to account for the different behavior of coronal and velar fricatives. This account is not just an argument against the dualist view; rather it is an instantiation of an explicit testable non-dualist theory. Even though the blending mechanism has been argued to play a role in coarticulation (Fowler and Saltzman 1993), it has never been used before to try to model the variation in amounts and types of coarticulation in different languages. This work is therefore not a straightforward application of task dynamics to velar coarticulation, but a proposed change to the task dynamics model in order to account for language differences at the phonetic level.

We begin by outlining the Navajo phonetic and phonological patterns in Section 2, with a discussion of the phonemic inventory and the morphology. In Section 3, we present the results of acoustic and articulatory studies of the Navajo velar fricative. In Section 4 we will present a linguistically-controlled task-dynamic mechanism to account for the Navajo facts. Section 5 will discuss the relevance of the results for the relation between phonetics and phonology.

2. Outline of Navajo phonology

The full set of Navajo consonantal contrasts is shown in Table 1. The consonant inventory is presented in both IPA and Navajo orthography, since the latter is more familiar to Navajo readers. The orthography is that employed by Young and Morgan (1987, henceforward cited as YM). The voiced allophones of fricatives are included in the listing of consonants, in part since they are written with distinct graphemes in the orthography. The inventory of basic vowels consists of the four vowels /i, e, ɑ, o/ written ‘*i, e, a, o*’. Note that Navajo lacks a high back vowel. Navajo vowels contrast in length and nasality, resulting in 16 distinctions. Vowels also bear high or low tone.

The consonantal inventory is primarily coronal: 22 of the 32 consonantal graphemes in Table 1 represent coronals. Furthermore, the (non-coronal) glides ‘*w*’ (/w/) and ‘*y*’ (/j/) and labial consonants are rare. Thus distinctions between major places of articulation are weakly functional. Because of the morphology, there are few minimal pairs, and the distribution of phonemes is severely constrained by the phonotactics. Stems are the primary morphemes of contrast. Table 1 shows the full consonant inventory in stem onsets, but outside this position phonemic contrasts are severely reduced.

There are four fricatives in the phonemic inventory, two central fricatives ‘*s*’ and ‘*sh*’ (/s, ʃ/), a lateral fricative ‘*ł*’ (/ɬ/) and the velar fricative, transcribed as /x/ and variously written ‘*x, h, gh, w*’ or ‘*y*’ in the orthography. The voiced variants of /x/ are written as ‘*y*’ before ‘*i*’ or ‘*e*’, as ‘*w*’ before ‘*o*’ and as ‘*gh*’ before ‘*a*’. The voiceless variants of this phoneme are all written as ‘*h*’ or ‘*x*’ (YM: xii–xv). The voicing distinction among fricatives is contextual; they are normally voiced intervocalically or after a voiced segment (Sapir and Hoijer 1967; Kari 1976; YM).[1]

Examples of the variants of /x/ in Navajo verbs are illustrated in (1) and (2) below. In each case, the consonant in the onset of the final syllable is the fricative phoneme under discussion. In (1) are verb forms with the stem *GHÁÁSH*, /xɑ́ːʃ/ 'to boil, bubble', and in (2) forms with the stem *YEED* /xeːt/ 'to move rapidly, fall stiffly'. The variant of /x/ in each case is shown in phonetic transcription. In (1a) and (1c) are examples of the velar fricative in the variants that occur before the low vowel '*a*' and in (2a) and (2c) the variants that occur before the front vowels '*i*' and '*e*'. These two verb stems, as is characteristic of the stem morphemes in Athabaskan, exhibit aspectual variation expressed in part by a change in vowel quality. In both (1b) and (2b) the stem is realized with a round vowel alternant, allowing the surfacing of the back fricative reflex '*w*'. In (1c) and (2a, b) voiceless alternants of /x/ occur.

(1) *GHÁÁSH*, /xɑ́ːʃ/ 'to boil, bubble' (YM: g329)[2]
   a. *hanilgháásh* (Imperfective)
      /xɑnɪl[ɣ]ɑ́ːʃ/
      'It is brought to a boil' (YM: d413)
   b. *háánílwosh* (Repetitive)
      /xɑ́ːníl[w]oʃ/
      'It is repeatedly brought to a boil'
   c. *hanishháásh*
      /xɑnɪʃ[x]ɑ́ːʃ/
      'I bring it to a boil'

(2) *YEED* /xeːt/ 'to move rapidly; to fall stiffly' (YM: g350)
   a. *ch'íníshyeed* (Imperfective)
      /tʃ'íníʃ[ç]eːt/
      'I went running out'
   b. *yishwoł*
      /jɪʃ[w]oɬ/
      'I'm running along'
   c. *naa'iishheed*
      /naːʔiːʃ[ç]eːt/
      'I fell over stiffly'

3. Navajo fricatives

3.1. *Acoustic data*

Spectral properties of the fricatives in Navajo were described in McDonough (2003), and more details can be consulted there. The coronal fricatives '*s*, *sh*', and

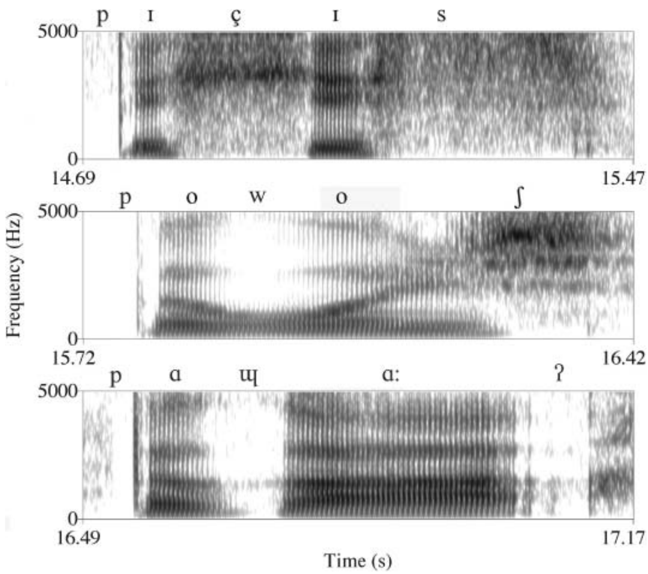


Figure 1. *Spectrograms of three variants of the back fricative in intervocalic position in the onset of noun stems before front, round and low vowels respectively: top to bottom;* bihis *[pɪçɪs] '3SG-POSS-pus',* biwozh *[powoʒ] '3SG-POSS-cactus',* bagháá' *[paɰáːʔ] '3SG-POSS-wool'. Note that harmonization of the prefix vowel is sometimes reflected in the orthography.*

'*ł*' (/s, ʃ, ɬ/) are largely consistent in their acoustic pattern across a variety of contexts. As already noted, the velar fricative /x/ shows the variability illustrated in (1) and (2) above. Some of the corresponding acoustic patterns are exemplified in the spectrograms in Figure 1 (from McDonough 2003: 148), which illustrates three variants of /x/, before front, round, and low vowels respectively. These examples are taken from tokens of prefixed noun stems: the '*bi*' [pɪ] prefix is the 3rd singular possessive 'her/his/its'.

The top panel of Figure 1 illustrates a variant of /x/ before the front vowel '*i*' (a voiceless palatal fricative in this case). It shows intense energy in the high frequencies, somewhat similar to the coronal fricative at the end of this word, and without clear formant structure. The middle panel shows a variant before the round vowel '*o*'. This variant is the most approximant-like. Very little frication is apparent in the acoustics of this sound; most of the energy in the spectrum is in the lower formants. The bottom panel illustrates a variant before the low vowel '*a*'. This token does not show such a clear formant structure as the variant before the round vowel, nor the frication seen before the front vowel, so is intermediate between an approximant and fricative (McDonough 2003: 153). In each panel, /x/ is in intervocalic position, normally the voiced position for Navajo fricatives, but only the [w] variant is fully voiced in these tokens.

We draw two conclusions from the analysis so far. First is that the realization of velar fricatives is highly variable in Navajo stems. Although comparing across consonant classes is problematical, the range of variability of Navajo /x/ appears higher than that reported for velar stops in English (e.g., Dembowski et al. 1998) or in some Australian languages (Butcher and Tabain 2004). The Navajo velar fricative may display more variation in constriction degree as well as in constriction location than velar stops in other languages. Notably, the vowel context has a very significant effect on both constriction location and degree.

3.2. *Articulatory data*

To determine the extent of contextual variation of production of velar fricatives in Navajo, ultrasound imaging was used to track tongue movement for a female native speaker from the Window Rock area as she produced 11 words containing /x/ in three vowel contexts: /xi/, /xo/, and /xɑ/. The wordlist is given in the Appendix at the end of the paper. Each utterance was repeated at least four times for a total of 54 tokens. The data was collected at Haskins Laboratories on an Aloka SSD-1000 scanner with a hand-held probe. The probe was held by a researcher standing behind the speaker. This position maximized stability of the probe with respect to the speaker's chin without requiring constrictive head restraints. The data was recorded onto a VCR and digitized at 30 frames per second. Tongue edges were extracted using Edgetrak (Li et al. 2005).

The purpose of the articulatory analysis was to determine the variability in the constriction degree (CD) and constriction location (CL) for variants of /x/. Since it was not possible to unambiguously locate the hard palate in all of the ultrasound frames, numbers that correlate with CD and CL were estimated. This was done by superimposing a polar line (Campbell et al. 2010) extending from the center of the probe and passing through the point of maximum constriction in the frame which showed the maximum movement towards the target in each exemplar of /x/. The angle in degrees of the line was used as an estimate of CL, with 0 indicating a vertical line, and the distance from the origin of the line to the intersection with the edge used as an estimate of CD, with a larger distance indicating a closer CD.

As seen in Figure 2, /x/ is, as expected, highly subject to contextual variation in both constriction location and degree. Instances before /i/ have the closest and most forward constriction; those before /o/ are most open and intermediate in location, while those before /a/ have an intermediate amount of opening and are marginally more posterior than those before the round vowel. The conclusions we draw from the articulatory data reflect that seen in the acoustic patterns; as expected, a large amount of variability was found in the articulation of the back fricative contrast, but this variability is strongly associated with the following vowel context.

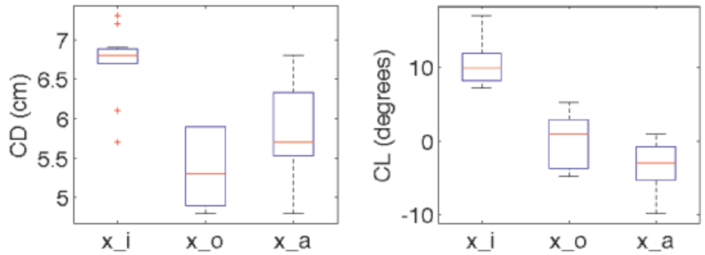


Figure 2. *Constriction Degree (CD) and Constriction Location (CL) estimates from ultrasound data. The central mark is the median, the edges of the boxes are the 25th (Q1) and 75th (Q3) percentiles, and the whiskers indicate one and a half standard deviations. Crosses indicate outliers. These accounted for 7.4% of the data, but all were for CD of /i/. Data is considered to be an outlier if larger than Q3 + 1.5 (Q3 − Q1) or smaller than Q3 − 1.5 (Q3 − Q1).*

4. Task dynamic account

In the task dynamic model introduced by Saltzman and Munhall (1989), each contrast unit carries a specific target for a constriction location task and a constriction degree task (the stiffness parameter will not be discussed here). The tasks constitute the gestures for the formation and release of constrictions at specified locations (Browman and Goldstein 1989) that are the primitives of Articulatory Phonology. In the model, the abstract constriction location and constriction degree tasks control the movement of the model articulators. For instance, in the Navajo case, velars are predicted to have a defined target for Tongue Body Constriction Location (TBCL) and Tongue Body Constriction Degree (TBCD), which is distinct from those of the three vowels, each of which have their own targets. These targets are defined independently for each of the contrastive units (phonemes) and allow these phonemes to be distinguished from each other. In addition, in the Navajo consonant inventory, /x/ contrasts with the rich set of coronals which are specified for TTCL and TTCD tasks of their own in the anterior tongue tip region. Note that for /x/, we posit a single fricative TBCD target and a single velar target for TBCL. It is crucial for this discussion that this is not a window of targets (cf. Keating 1990), but rather a single inherent specification of the segment.

In the task dynamic model the target parameters specified for a contrastive unit such as /x/ serve as the constant parameters of a dynamical system whose continuous solution in time directs the motion of articulators in the vocal tract (Saltzman and Munhall 1989). The set of constant parameters (constant within a segment) serve as the units of contrast, which upon solving the dynamical equations, yields the continuous evolution in time of the dynamical system for each task (CL or CD) for – in this case – the Tongue Body articulator. In this account, the same target specification that allows the velars to contrast with the coronals also serves the purpose of determining articulator motion through the implementation of the dynamical system. It is due to this that Articulatory Phonology is an account of the phonological contrasts (constant coefficients) and articulator motion (solutions to a dynamical equation, whose coefficients are the contrastive parameters).

In this model, however, the units of contrast are not sequenced as a string of items. They are allowed to be transmitted in parallel, or overlapped. When the two target gestures for two different segments, like /x/ and the front vowel /i/, overlap, they simultaneously influence the vocal tract shape by jointly determining the target for the task that is active for the two contrastive units. This is a process termed *blending*. In addition to their articulatory CL and CD parameters, a number α specifies the strength of each of the co-active contrastive units. The unit with a larger α value has a greater effect on the model articulators' movement towards the task target during the time that the tasks for both units are simultaneously active. For instance, if the consonant's TBCL is assigned a large α and the vowel's is assigned a small α, the blending process will favor the target of the consonant, whereas if the consonant and vowel are assigned the same α, the target for TBCL will be the average of the two targets. The blending mechanism therefore allows for the prediction of variability at the level of articulator motion despite the invariant contrastive target sets. Different tasks contrast by having different targets, but the mechanisms of blending and overlap mean that the same target specification can result in variable articulator movements. One example provided by Saltzman and Munhall (1989) is of velar to vowel coarticulation in English. The data show that the locations of the constrictions of the vowel and an adjacent velar consonant mutually influence each other, while the constriction degrees that are produced are close to their canonical values. This is accomplished in the model in the following way: the TBCL target for the vowel and the consonant are averaged by setting α to be the same for the TBCL of the vowel and of the consonant. However, α for the TBCD of the consonant is set to be high, while the TBCD for the vowel is given a low α value. The result is what is expected in English (e.g., Öhman 1966): the vowel influences the location of the constriction for the velar, but not the degree of constriction. The stop remains a stop.

In this work we propose that the blending parameter is language-specific. Saltzman and Munhall (1989) and the discussion of blending by Fowler and Saltzman (1993) do not raise the possibility that blending is language-specific. But work on language variation within the Articulatory Phonology framework (Browman and Goldstein 1991) has proposed that gestural timing and the task parameters themselves are the aspects that could differentiate one language from another.

The values for α chosen to fit the English data have not been further tested on other languages. This implies a hypothesis about the uniformity of coarticulation, whose adequacy can be tested by asking if alternative values for α for velar coarticulation yield the facts for other contexts or other languages. Such a test requires us to generate the factorial typology of velar-vowel blending and to

a)
b)

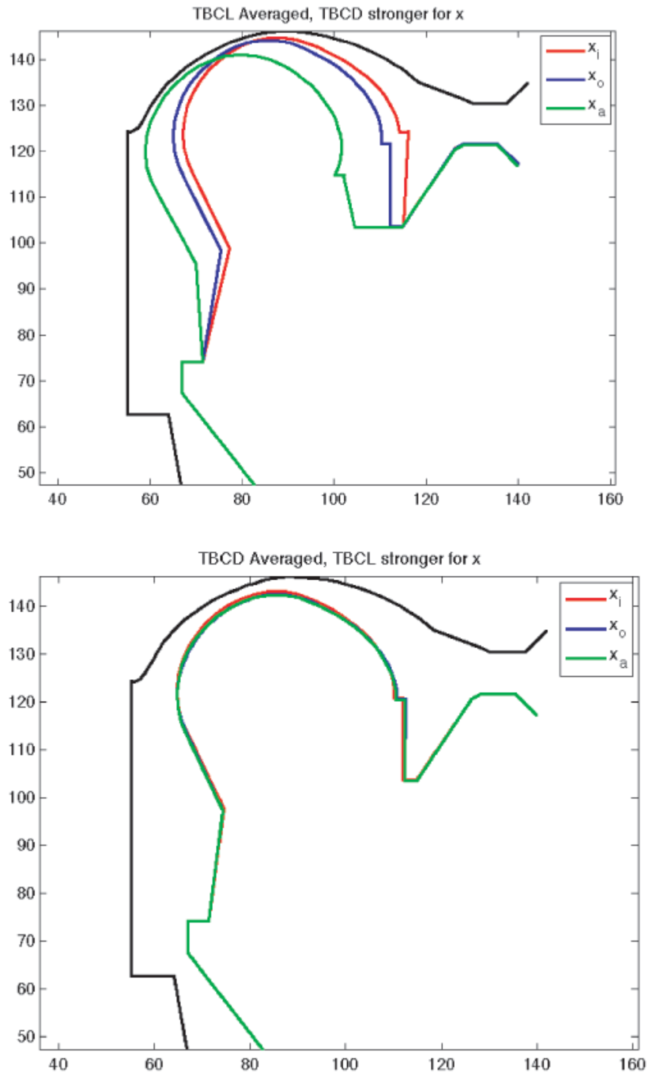
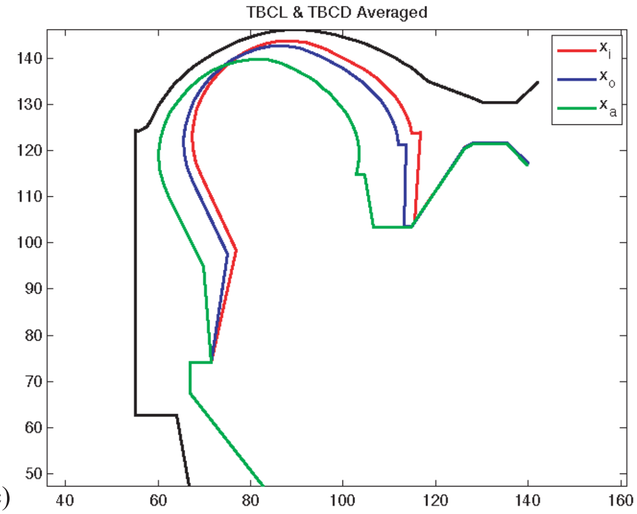


Figure 3. *TADA simulations for a) CL-only coarticulation, b) CD-only coarticulation, and c) CD & CL coarticulation.*

determine whether different languages make use of a typology parameterized by the dynamics of blending. Therefore, we performed simulations using the TADA (Task Dynamics Application) toolkit (Nam et al. 2004) to generate this typology. These simulations allow us to predict the shape of the vocal tract when the equations of task dynamics are solved with particular contrastive units and their gestural scores and blending values as input. The hypothesis being tested is that Na-



c)

Figure 3 *(Continued)*

vajo velar–vowel coarticulation is obtained by a different setting of the parameters than those used for English. To test this hypothesis we generated gestural scores for the three possible settings: 1) TBCL targets for consonant and vowel averaged (i.e., α is set the same for consonant and vowel) and TBCD is strongest for consonant (α larger for consonant); 2) TBCL target is strongest for consonant and TBCD is averaged; 3) Both TBCD and TBCL are averaged. Our hypothesis, based on the fact that vowel context affects both CL and CD, is that Navajo adopts the third strategy, averaging of both TBCL and TBCD targets.

Figure 3 shows simulation outputs for /x/ before /i/, /o/, and /a/ under three conditions. In Figure 3a TBCL α is the same for the vowel and the consonant but TBCD α is stronger for the consonant; In Figure 3b TBCL α for the consonant is high, but TBCD target is averaged; In Figure 3c both TBCD and TBCL targets are averaged. The targets for the consonants and the vowels and the amount of overlap are held constant in all of the simulations. That is, the same velar contrast parameters are used for all three cases: what varies is the relative strength of the parameters for the consonant with respect to their values for the following vowel. /a/ and /o/ were given the same TBCD in the three simulations, and no attempt was made to control the lips for /o/, since we did not measure lip motion to check against the model.

In the first case we see that coarticulation averages the TBCL targets of the vowel and consonant, but the TBCD target is determined by the consonant. This is the English-like case, except that the consonant is a fricative, not a stop. In the second case the TBCL target is determined by the consonant only, but the TBCD target is co-determined by the vowel and consonant. This is the case for languages with velar spirantization; that is /g/ → [ɣ], when the CD of the vowel has a marked effect on the CD of the consonant. In the third case, both TBCL and TBCD targets are averaged. We argue that this is the case for Navajo /x/, with its wide variability. Moreover, the simulation in Figure 3c predicts the pattern of CD and CL found in the data in Figure 2: /o/ forces the intermediate location and widest constriction on the velar unit. For the /a/ context, the CD seems to be underestimated in the model, but that is probably due to the shape of the hard structures assumed, which likely underestimate the extent to which the uvular area is enlarged when the velum is high. Figures 3a and 3c both show high levels of variation between vowel contexts, but it can be seen that case 3c is more predictive of the Navajo case, since it involves CD variability as illustrated in Figures 1 and 2. Therefore, the TADA typology of blending allows us to model possible CD and CL variations in different velar segments as required by English and Navajo. We call this classification a typology, since it presents a linguistically parameterizable dynamical principle that posits the similarities (principle) and differences (particular parameters) between languages.

In the simulations presented here, "stronger" means setting α for the stronger unit to be 10 times that for the weaker one. Our initial settings may involve larger differences than would be found with more direct measures of spoken language. However, experience with other parameters, such as gesture phasing, has been that only two or three values out of the infinite range that is theoretically available are in fact used. It may, for instance, be that the case of dorsal coarticulation in Australian languages will require one more magnitude of α to be used (Butcher and Tabain 2004). We also predict that related languages would vary in the strength of the vowel, resulting in differing (lesser) kinds of coarticulatory influence of the vowel on the fricative. Evidence of this sort is available. In the McDonough and Wood (2008) study of stop contrasts in seven Athabaskan languages, the stop releases were unusually long and patterned with affricates and ejectives; indeed, /t^h/ and /k^h/ were affricates [tx, kx], with velar fricative releases. However, their study noted that the 'heaviness' of the frication in the release varied. In Tłı̨ Chǫ (Dogrib), for instance, the velar releases and velar fricatives were heavily fricated and showed little coarticulatory influence from the following vowel, more or less the opposite of Navajo. However for the most part, Athabaskan languages exhibit some degree of the coarticulation phenomena we find in Navajo (vowel coarticulation with the velars).

5. Discussion and conclusion

Navajo velar fricatives in the stem-initial position (the single position in the word where they occur) exhibit a great deal of coarticulatory influence from the vowel. Specifically, both CD and CL are affected, with /i/ having the least effect on CD and /o/ having the greatest effect. Here, we showed that the task-dynamic mechanism of blending can predict the pattern of variability seen in Navajo. The Navajo case is a counterexample to the assertion that a language will limit the amount of coarticulation in the strong position (Steriade 1994) – coarticulatory variability is quite extensive for Navajo /x/ in this position.

The task-dynamic account is able to specify the contrast between the back fricatives and the front fricatives by the former having TBCD and TBCL targets, while the latter have TTCL and TTCD targets. The blending mechanism allows languages to combine their contrastive units in different ways, and varying the strength of the blending parameter predicts three ways in which languages can combine consonants and vowels. For velar coarticulation, it seems that all three types of patterns exist. The first pattern, used in languages like English, is where the location but not the degree of the resulting constriction is determined jointly by the vowel and the consonant. The second pattern is used in spirantization languages like Spanish, where CD is co-determined by the vowel, and the third by languages like Navajo, where both the location and degree of the resulting constriction are determined by the gestures for the vowel and the consonant. In future work, we intend to perform perceptual tests on native speakers of languages in different parts of the typology to examine whether speakers are aware when blending parameters have become less appropriate for this language. This would further the claim that blending is indeed a language-specific mechanism.

The mechanism of blending, which is proposed in this work as an important way in which languages differ, does not impose a window of variability through which interpolation can occur. For the simulations in Figure 3, the contrasts across the simulations are the same and given as single targets, not windows of targets (Keating 1990). Rather, a range of variation *emerges* in the output as a result of a complex interaction between the blending strength, the passive vocal tract constraints of the anatomy of the vocal tract, and active articulator motion. This is therefore a different type of mechanism than the window mechanism. The advantage of the blending approach is that the windows of variability emerge from the invariant gestural specifications, rather than having to be specified explicitly.

The implication of this account for the interface between phonology and phonetics is that it provides a constrained framework where the same parameters serve the purpose of contrast and determining phonetic variability through blending. In this theory there is no assumption of a translation from a cognitive to a physical level. Traditionally it was thought that a phonemic representation is an expression of entities in the cognitive domain, while phonetic units are defined in the physical domain (e.g., Pierrehumbert 1990). The notation we have used, expressing each word in a phonemic and phonetic IPA transcription, is not meant as an endorsement of this underlying philosophy. In this paper, we have relied on, and extended, a dynamic view of phonetics and phonology in which they are highly interlocked aspects of a single representation: 1) The phonological IPA transcription lists the assumed targets for the task variables, which are coefficients of a set of dynamical equations; 2) The phonetic IPA transcription is a broad representation of the articulatory-acoustic solutions to that same set of equations, assuming a blending parameter setting within the equation. In this framework, phonetics and phonology are not two different representations, but specifications of different aspects of one dynamical system.

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Appendix

Word list used in the ultrasound experiment. (This is a subset of the list used in McDonough 2003, compiled with the assistance of Martha Austin of Diné College, Shiprock, NM).

Navajo Orthography	IPA	Gloss	# Repetitions
bihis	pɪxɪs	(3rd pers poss) pus	4
his	xɪs	pus	4
ha'nishheed	xaʔnɪʃxeːt	to start to limp, be lame	6
biyeel	pɪxeːl	(3rd pers poss) fee for services	5
'aniishháásh	ʔaniʃxáːʃ	to administer heat treatment using steam	4
nima hozdoohdi bighan	nɪma xoztoːhtɪ pɪxan	Your mother lives in Phoenix	5
baghaa'	paxaːʔ	(3rd pers poss) wool	4
ghą́ą́'ask'idii	xãːʔask'ɪti	camel	5
yishwoł	jɪʃxoɬ	to be running along (1 actor)	6
hosh	xoʃ	thorn, cactus	5
bowozh	pɪxoʃ	(3rd pers poss) thorns	6

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Notes

1. The phonology of fricative voicing in Navajo has received considerable attention (Holton 2001; Kari 1976; McDonough 1990, 2003; Young and Morgan 1987; Young 2000). For the present, we will assume a voicing/lenition process that normally imparts to the stem-initial fricative the voicing of the preceding segment, but this explanation is incomplete.
2. The grammar and dictionary parts of Young and Morgan (1987) are separately paginated; examples taken from this work are cited with page numbers preceded by 'g' or 'd' for 'grammar' or 'dictionary' respectively.

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