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# *Phonological underspecification and speech motor organisation\**

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## **1 Introduction**

Over the last few years, much work in phonology has been devoted to exploring the way features are specified for segments; in particular, to what extent feature specification may be underlyingly present and/or acquired by rule or default in the course of a derivation. While a number of proposals have been made attributing various degrees of underspecification to abstract levels of the phonology (Kiparsky 1985; Steriade 1987; Archangeli 1988), it has been generally assumed that where phonetic implementation comes into play, i.e. at the end of the derivation, segments are exhaustively specified.

This view stands in contrast to that adopted in much of the literature on speech motor control, where the necessity of accounting for coarticulation across multisegmental spans has led researchers to assume that the input to the motor plan leaves a good deal of phonetic detail unspecified. Motor implementation in these models is assumed to proceed by direct translation of specified features into articulatory/acoustic targets, leaving the position of articulators during an unspecified segment open to influences from the surrounding context. Thus, coarticulation is viewed as assimilation of specified features from surrounding segments onto an unspecified target. As a practical matter, researchers in the field have assigned feature specification for this purpose from: (i) surface phonological contrast and (ii) required articulatory/aerodynamic configurations. If neither source mandates specification, the segment is assumed to be unspecified for that feature and thus to have no independent target.

For example, [+nasal] and [–nasal] are feature values that characterise English stops at the surface level, and therefore these consonants are taken to require a relatively low or relatively high velum position,

respectively. At the same time, because English vowels lack a surface contrast in nasality and because nasalisation of vowels is articulatorily possible (while a nasal /s/ is not), coarticulation researchers have assumed that English vowels are unspecified for nasality (e.g. Moll & Daniloff 1971; Kent *et al.* 1974). Note that, in this view, English vowels and consonants have the same [nasal] specification status underlyingly as at the surface. The case is different for a segment such as /s/. On the one hand, it is presumed to have the surface feature value [-nasal] because a high velum is required to produce the necessary aerodynamic conditions for high-intensity frication. On the other hand, English fricatives do not contrast with respect to nasalisation so that specification of [nasal] for /s/ may be lacking at more abstract levels of the derivation.

In English, as in other languages, some amount of nasalisation is generally present on vowels preceding nasal consonants (Clumbeck 1976). In analogy to phonological analyses of assimilation processes such as vowel harmony, many studies of this phenomenon (Moll & Daniloff 1971; Kent *et al.* 1974; Hammarberg 1976) have treated the presence of even minimal acoustic or articulatory indicators of nasalisation as showing the spread of the feature specification [+nasal] into an unspecified domain. It was assumed that the intermediate level of implementation typical of the data came from an inability of the articulators to achieve opposite target configurations instantaneously; that is, it was assumed that the vowels acquired a full [+nasal] target but could not fully implement it, rather than that the vowels had independent but intermediate targets (see Kent *et al.* 1974 for further discussion).

In a seminal paper, Keating (1988b) examined theories of underspecification as they exist both in the motor control literature and in the phonological literature, in an attempt to reconcile the two. She accepted the motor control notion that there are phonetically unspecified segments, and that these segments have no inherent targets, but argued that, rather than indicating the presence of feature spread, the presence of intermediate levels of articulatory/acoustic implementation (e.g. slight lip protrusion for rounding in the context of a [+round] segment, or the presence of a weak nasal formant in the context of a [+nasal] segment) could be taken to indicate persistence of underspecification into the motor planning level. Further, she suggested that if a segment normally analysed as unspecified for a particular feature showed an apparent target, i.e. showed apparent full implementation for that feature, a phonetic rule must have applied to supply that target. She proposed that segments are not exhaustively specified at the end of the derivation, and most radically, and interestingly, that phonetic data can be used to make inferences about the lack of specification at higher levels of the derivation.

In this paper, we examine some of Keating's arguments and introduce data of our own indicating that certain of her conclusions may be premature and/or insufficiently detailed. In particular, we attempt to show that, although Keating's basic insight remains viable, much of her argument suffers from the nature of her assumptions about the phonetic

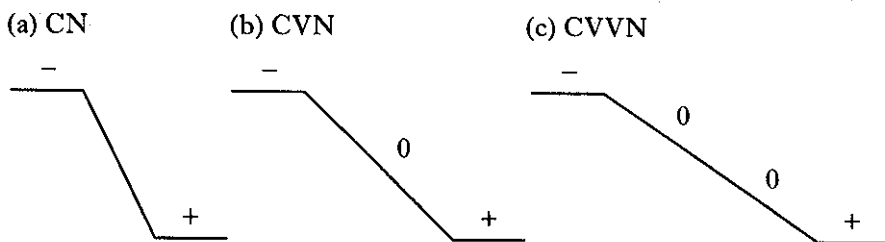


Figure 1

Schematic diagrams showing transitions between fully specified segments separated by (a) no segments; (b) one unspecified segment; (c) two unspecified segments. In this example, [+ ] and [ - ] values refer to the feature specifications for [nasal] and the trajectory corresponds to vertical velum displacement, with high velum positions at the top and low velum positions at the bottom.

implementation of targets, and that a greater attention to phonetic detail, and in particular to the variable of timing, is required in order to eliminate other interpretations of phonetic data. In opposition to Keating's point of view, we present evidence to show that segments which lack specification by contrast criteria or by aerodynamic/articulatory criteria nevertheless exhibit characteristic articulatory positions associated with those features. Our data will focus on the features [round] and [nasal].

Figure 1(a,b) illustrates, in schematic form, what we take to be the essentials of Keating's model for articulation. What is sketched is the time course of velum movement, which is considered to be a fairly direct index of the feature [nasal] (Keating 1988a).<sup>1</sup> Here, feature specification translates into targets for articulators, and the motor program moves between targets by simple linear interpolation.<sup>2</sup> When two segments with opposite specifications occur in sequence, the transition between their opposite (and relatively extreme) articulator positions is necessarily speedy and steeply pitched (Fig. 1a). Unspecified segments, while introducing an additional timing unit, have no targets and therefore 'when phonetic rules build trajectories between segments, an unspecified segment will contribute nothing of its own to the trajectory' (Keating 1988b: 281). Keating thus predicts that, in these cases, interpolation between [+ ] and [ - ] segments will take longer and be less steep than when the two specified segments are immediately adjacent. In essence, the transition between immediately adjacent segments is 'stretched' when they are separated by one or more unspecified segments (Fig. 1b,c).

Patterns resembling the 'stretched' transitions predicted by Keating's model are easily found in acoustic and articulatory data of all kinds.<sup>3</sup> Keating argues that apparent examples of stretched transitions provide evidence for phonological underspecification continuing to be present at the end of the phonological derivation, i.e. the input to the motor plan. In essence, her argument is as follows: if a segment shows what looks like a target, then it is safe to assume that it enters the motor program with

categorical specification (i.e. either [+ ] or [- ]). If, on the other hand, the data show smooth interpolation-type transitions between specified segments, then it is safe to infer that the intervening segments have no targets. If they have no targets, then they are unspecified at the level where phonological representation is translated into a motor program. In what follows, we will refer to Keating's model as the TARGET EQUALS SPECIFICATION hypothesis, or TES.

If we accept Keating's reasoning, there are several tests that can be done to determine the validity of this model. First, because the TES theory crucially depends on unspecified segments having no target for the feature of interest, it is necessary to establish in any particular case that there is no evidence of such a target. (It is always possible, for instance, that an apparently smooth transition is passing through a target.) There are a number of reports in the literature indicating that for many segments, although contrast arguments and articulatory/aerodynamic arguments for specification do not exist, characteristic articulatory targets may be observed across contexts. It is well known, for example, that the English consonants /r/, /s/ and /ʃ/ often show rounding (Brown 1981). Similarly, the vowels of English are well known to show positions of velum height that are midway between the very high and very low positions of oral and nasal consonants, respectively, and that differ as a function of vowel height (e.g. Ohala 1971; Bell-Berti *et al.* 1979). If such findings are typical, then sequences of the type Keating discusses may show evidence of independent targets. One way to test this is by comparing the segment in minimally contrastive contexts, i.e. varying the specification of flanking segments one segment at a time.

## 2.1 Minimal contrasts

An example from Keating (1988b) may make this procedure clearer. Although other fricatives in Russian show a surface contrast for palatalisation, /x/ does not. Thus, it should be unspecified for the feature [back]. Figure 2 reproduces spectrograms from Keating (1988b) showing /x/ in the context of two back vowels, /axa/, plus the complementary back and front contexts, /axi/ and /ixa/.

Noting that the second formant (which reflects tongue positioning in the front-back dimension) appears to be in continuous movement through the occluded portion of /ixa/ (from the high position for /i/ to the low position for /a/), Keating argues that /x/ cannot have a target and thus must be underspecified at the motor implementation level. This case contrasts with that for /axi/, where the second formant reaches an /i/-like steady state midway through the occluded portion of /x/. Keating argues that, in the case of /axi/, a context-sensitive phonetic rule has applied, spreading the [-back] specification of /i/ into /x/.

Crucially, the TES (Target Equals Specification) hypothesis requires that underspecified segments contribute nothing to the articulatory plan (that is, with regard to the feature of interest). In order to establish that,

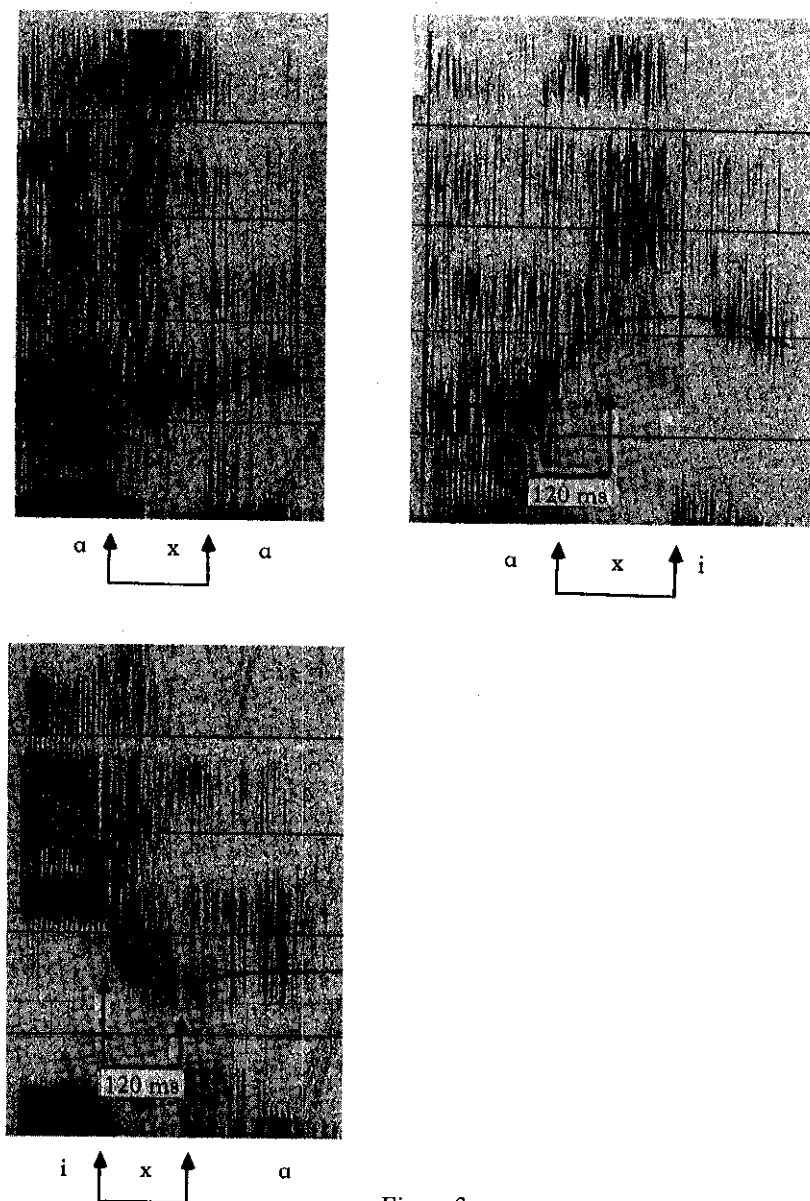


Figure 2

Spectrograms adapted from Keating (1988b) showing formant tracks for Russian /axa/, /axi/, /ixa/. The time course of the second formant, which is considered a reasonable index of tongue constriction along the front/back dimension, is traced by a solid line. The figures are modified from Keating's originals by inclusion of brackets indicating (i) beginning and end of the occlusion period for the /x/, and (ii) beginning and end of the second formant transitions between vowel steady states. The horizontal dimension of the latter brackets indicates 120 ms.

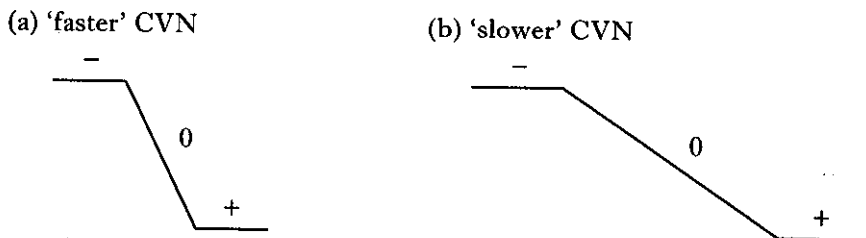


Figure 3

Schematic diagrams showing transitions between fully specified segments separated by one unspecified segment at (a) faster; and (b) slower rates. [+ ] and [- ] values refer to the feature specifications for [nasal] and the trajectory corresponds to vertical velum displacement, with high velum positions at the top and low velum positions at the bottom.

in /axi/, the high second formant seen during the occluded portion of the signal is due to a [-back] specification copied from the /i/, it is necessary to show that /x/ does not normally show a high second formant in other, non-fronted contexts. On the other hand, if /x/ is unspecified, the model predicts that the interpolation between two [+back] vowels will be a straight line. Keating's data for /axa/, where the flanking vowels have [+back] specifications, in fact show that /x/ in this context has a low second formant similar to the formants for the two /a/s. This is consistent with her claim that the unspecified segment /x/ has no target.

One problem with the conclusion that a feature copying rule has applied, however, is that the slopes of the transitions between /a/ and /i/ in /axi/ and between /i/ and /a/ in /ixa/ are too similar to correspond to the predictions of the TES model. In Keating's analysis, the /x/ of /ixa/ is unspecified while the /x/ of /axi/ is specified. Thus, formant movement in the two cases should correspond to the schemata of Fig. 1b and 1a, respectively, in that the transition for /ixa/ should be longer and less steep than that for /axi/. Although for /ixa/ the second formant transition between /a/ and /i/ takes place largely during the occluded portion of /ixa/, and for /axi/ is divided between the final portion of the /a/ and the occluded portion, the actual durations of the transition are almost identical. This is hard to reconcile with the TES model, where the presence of an unspecified segment, by leaving the tongue with no target articulation, necessarily causes it to move more slowly between specified segments. We suggest an alternative explanation, i.e. that the timing of movement for the tongue (resulting in movement of the second formant) is similar in the two cases, but merely starts earlier in the first vowel for /axi/.<sup>4</sup> This may have the effect of fronting /x/ (and giving the listener the perception that a phonetic rule fronting /x/ was intended by the speaker), but is not an example of feature copying in the sense in which Keating uses it.

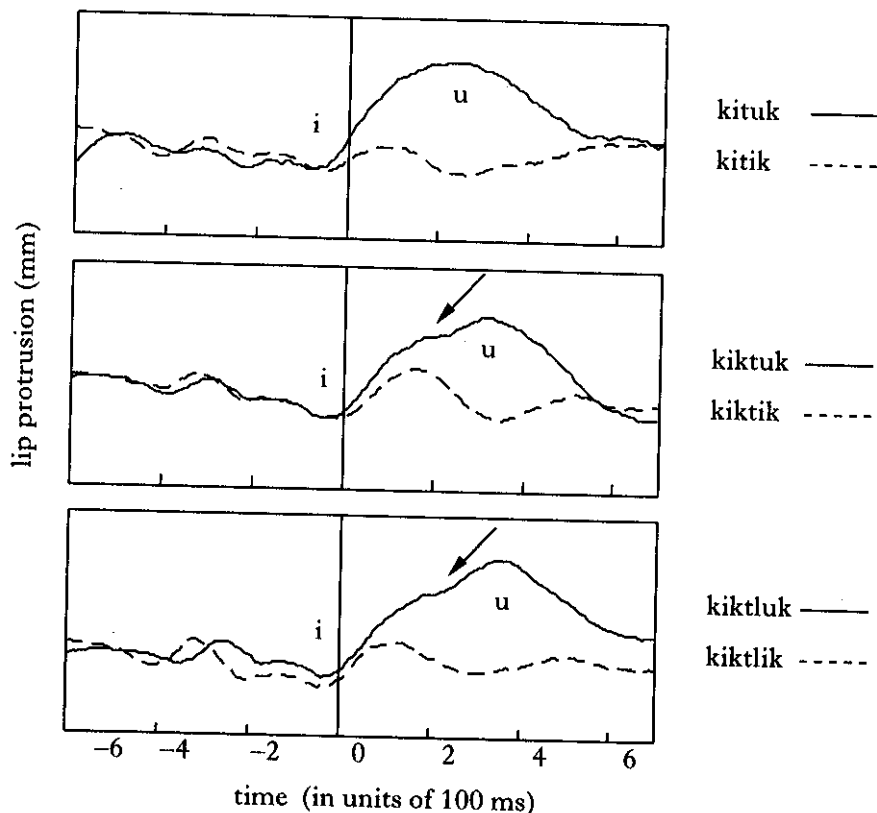
As far as they go, these data concerning Russian /x/ suggest that /x/ is indeed unspecified with regard to [back]. It is still possible, however, that

a target for /x/ exists, but is not visible in the time course of the second formant because the tongue 'en route' to /a/ or /i/ does not have time to show this independent target. A good way to test for such a target is to insert additional 'unspecified' segments to see whether the transition between the flanking specified segments becomes lengthened and less steep. (Keating makes no mention of her expectations for instances in which the number/duration of 'unspecified' segments is increased; in fact, the contribution of time to the model is not addressed.) Thus, test sequences should be constructed so as to maximise the opportunity for articulatory/acoustic behaviour to show itself. This is schematised in the series a-b-c of Fig. 1. Note that while the slope of the transition should change, the transition itself should remain smooth. Another, equally valid, test is to decrease speaking rate (i.e. slow down). This likewise, by increasing the time gap between specified segments with opposing values, ought to lead to lengthened and more gradual, but smooth, transitions (see Fig. 3a, b).

In what follows, we will test these notions using data from two articulators, the lip and the velum, as related to rounding and nasalisation, respectively. We will show, by adding time to the trajectories via segment addition and speech rate manipulation, that evidence for underspecification of the type Keating discusses may be more apparent than real. Further, we will advance a very different argument about what appear as smooth trajectories through 'unspecified' segments. Our claim is that, at least for these data, independent targets for so-called 'unspecified' segments exist, although temporal constraints may prevent them from being visible in the acoustic or articulatory signal.

## 2.2 Adding time by adding segments

We begin by examining data on lip protrusion for rounded vowels in American English from a larger study reported in Boyce (1988, 1990). In this study, an optoelectronic tracking system (modified Selspot) was used to track the horizontal movements of a light-emitting diode (LED) attached to the vermilion border of the lower lip. Four native speakers of American English produced fifteen tokens, at a normal rate, for each of a set of nonsense words with various combinations of /k/, /t/, /l/, and the vowels /i/ and /u/. Each was embedded in the carrier phrase 'It's a \_\_\_ again'. Words with /i/ and /u/ vowels (/iC<sub>n</sub>u/) were chosen to illustrate the case where a segment with [-round] specification (/i/), and a segment with [+round] specification (/u/), are separated by a segment or segments with no specification for [round]. (Again, specification here refers to surface specification.) Words with two /i/ vowels (/iC<sub>n</sub>i/) were chosen to illustrate the minimal contrast condition whereby segments with no predicted specification for [round] are nevertheless examined for evidence of rounding. Words with two and three intervocalic consonants were chosen to test the prediction, derived from the TES hypothesis, that a longer time interval between [-round] and [+round] segments would

*Figure 4*

Lower lip protrusion traces for Subject 1's productions of /kituk-*kitik*/, /kiktuk-*kiktik*/, /kiktluk-*kiktlik*/, aligned at the beginning of the intervocalic consonant closure. Upward movement indicates increased protrusion. Arrows are used to indicate the location in the protrusion trace where a local peak emerges before the protrusion peak for the /u/.

result in a longer, more gradual transition. The three panels of Fig. 4 show movement traces for, respectively, the nonsense word-pairs /kituk-*kitik*/, /kiktuk-*kiktik*/, /kiktluk-*kiktlik*/.<sup>5</sup> The traces shown belong to single tokens typical of one speaker's production.

We will examine the results of /iC<sub>n</sub>u/ words first. As any model of motor control would predict, each of the words in Fig. 4 shows clear, relatively extreme, protrusion peaks associated with the [+]-valued /u/, and local valleys with the [-]-valued /i/. For the word /kituk/, we observe a smooth transition from the [-round] /i/ to the [+round] /u/ through the /t/. This is consistent with Keating's conjecture of linear interpolation between [-] and [+]-valued segments through segments with unspecified features. The pattern seen for /kiktuk/ and /kiktluk/, in which the trajectory has acquired local peaks preceding the larger peaks associated with the /u/, is not predicted.



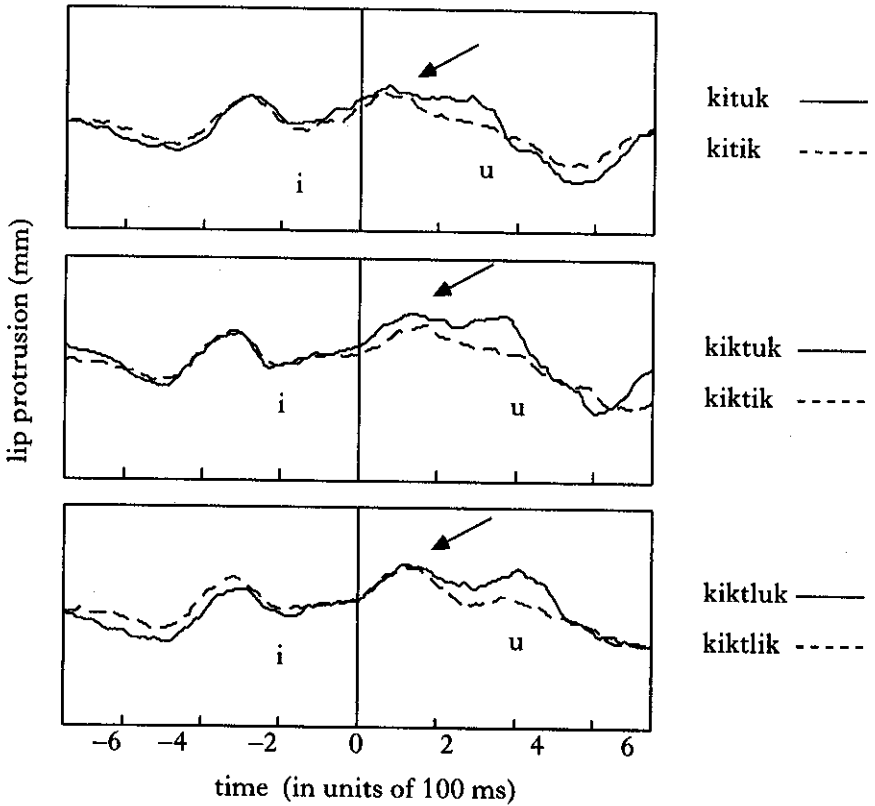


Figure 5

Lower lip protrusion traces for Subject 2's productions of /kituk-kitik/, /kiktuk-kiktik/, /kiktuk-kiktlik/, aligned at the beginning of the intervocalic consonant closure. Upward movement indicates increased protrusion. Arrows are used to indicate the location in the protrusion trace where a local peak emerges before the protrusion peak for the /u/.

If we look at the /iC<sub>n</sub>i/ words, however, we see a possible explanation. Movement traces for /kitik/, /kiktik/ and /kiktlik/ all show local peaks in protrusion (flanked by local valleys due to retraction for /i/ vowels). For the pairs /kiktuk-kiktik/ and /kiktuk-kiktlik/, the peaks in the traces for /iC<sub>n</sub>i/ words correspond in time to local peaks seen in /iC<sub>n</sub>u/ words. For /kituk-kitik/, the local peak in /kitik/ has no obvious correlate in the smooth movement trace of /kituk/.<sup>6,7</sup> The most perspicuous explanation of these facts is that the intervocalic consonant(s) have independent targets for protrusion. These targets, which are best seen in the traces for /kitik/, /kiktik/ and /kiktlik/, are also evident in the local peaks seen in /kiktuk/ and /kiktlik/. These targets are not visible in the shortest /iC<sub>n</sub>u/ word (/kituk/) because there is insufficient time for the intervocalic consonant to show a target independent of the trajectory for the rounded vowel.

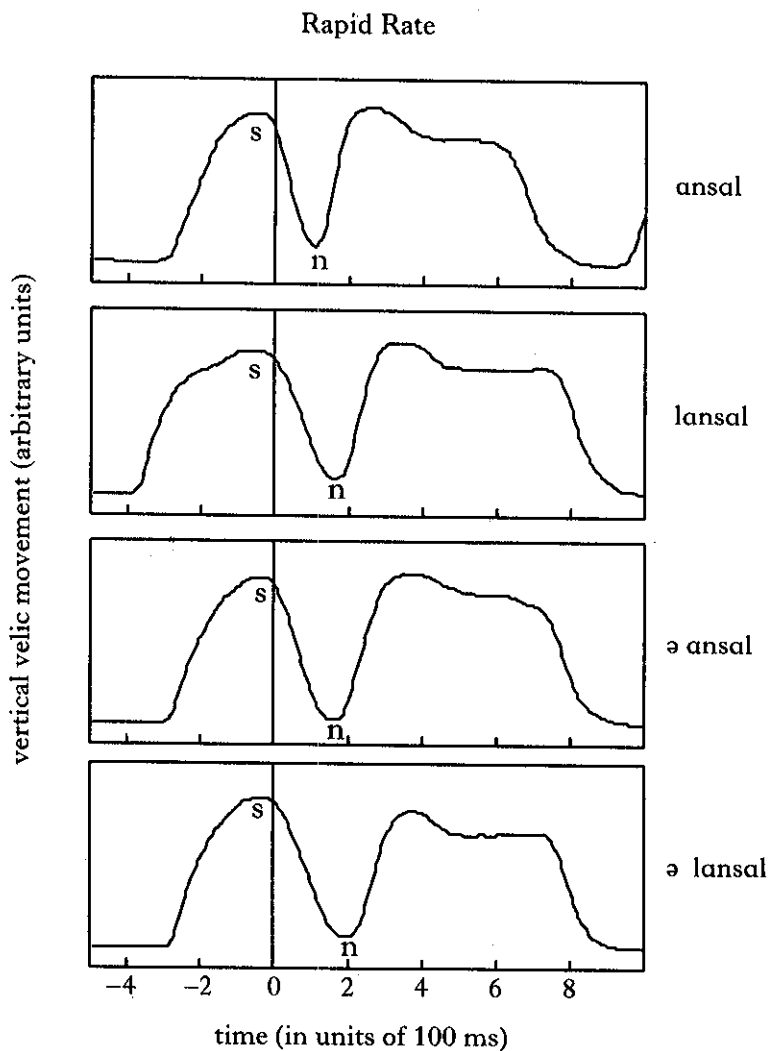


Figure 6

Velum movement traces for /ansal/, /lansal/, /ə ansal/, /ə lansal/ produced at a self-selected rapid rate, and aligned at the offset of an immediately preceding /s/ of the carrier phrase in which they were embedded. Target positions associated with the /s/ of the carrier phrase and the /n/ of the sequence are identified. Downward movement indicates velum lowering (and thus opening of the velopharyngeal port).

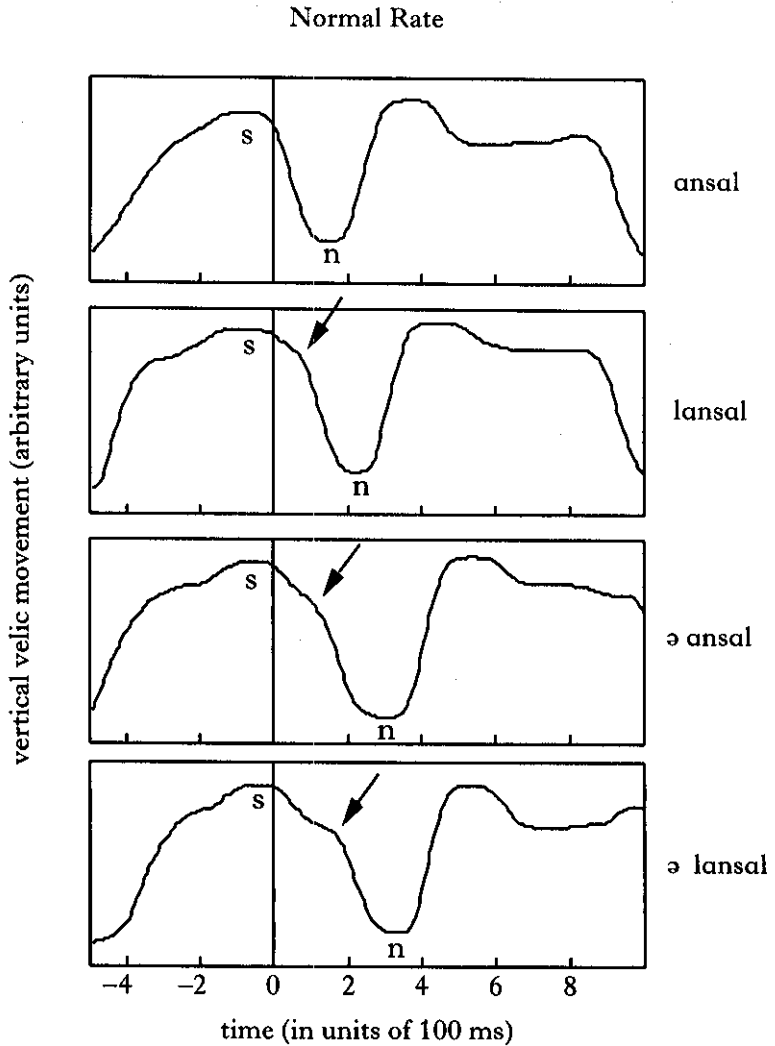
(Note that there remains a slight difference in target position for the consonant(s) in the /iC<sub>n</sub>u/ and /iC<sub>n</sub>i/ words.)

A similar argument can be made in the case of what appears to be feature copying. Figure 5 shows characteristic tokens of the word pairs /kituk-kitik/, /kiktuk-kiktik/ and /kiktuk-kiktik/ for a second speaker.

Here the articulatory pattern shows a peak equal to that for the rounded vowel during the consonant(s) for all three /i-u/ words. Thus, for this speaker, it appears that rounding has occurred on the supposedly unspecified segments. By analogy with Keating's /axi/ example (above), it might seem that the consonants have copied a rounding feature from the following /u/. On this account, speaker 2 has a phonetic rule of feature copying for rounding, and speaker 1 does not. However, both speakers' /iC<sub>n</sub>i/ words show coincident peaks during the consonant interval. Thus, the more likely explanation is that for both speakers, some or all of the 'unspecified' consonants have targets. These targets are different for the two speakers, such that speaker 2's consonant(s) are relatively more protruded when compared with their rounded vowels. It is worthwhile noting that although the TES model (and similar models) can account for the behaviour of Speaker 2, by postulating a default rule assigning rounding to /t/, models of this type have no obvious way of accounting for less than full rounding such as that exhibited by Speaker 1.<sup>8</sup>

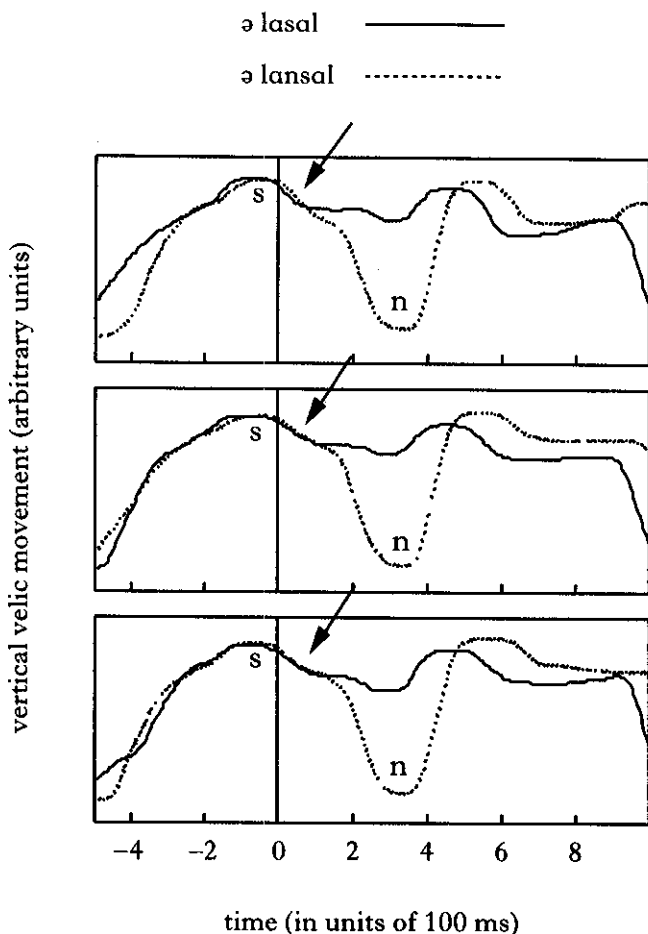
Similar problems arise for the TES model in considering the feature [nasal]. Here we present data from a study of 3 subjects by Bell-Berti & Krakow (1991) that included 12 tokens each of a set of minimally contrastive sequences containing some number of vowels (sometimes in combination with /l/) followed by either another oral consonant (/s/) or a nasal consonant (/n/), including /asal/, /ansal/, /ə#asal/, /ə#ansal/, /lasal/, /lansal/, /ə#lasal/, /ə#lansal/, /se<sup>l</sup> #asal/, /se<sup>l</sup> #ansal/, /se<sup>l</sup> #lasal/, /se<sup>l</sup> #lansal/. Each of these sequences was preceded by an oral consonant, /s/, in the carrier phrase, 'It's — again.' The Velotrace, a mechanical device developed by Horiguchi & Bell-Berti (1987), was used to monitor the vertical movements of the velum with the aid of a modified Selspot system.

Figure 6 shows the characteristic patterns of velum movement for four sequences containing the postvocalic nasal consonant /n/ produced at a self-selected rapid speech rate. What appear as smooth interpolation trajectories (of the sort described by Keating 1988b) are clearly seen in these examples. That is, the velum moves smoothly and continuously through a sequence of intervening vowels (with or without an /l/ in the sequence) between the high velum position required for the /s/ of the carrier phrase and the low position required for the /n/. In general, as the string lengthens, the trajectory appears to stretch. From these data, it might be concluded that the smooth movements indicate a lack of specification for the feature [nasal]. (Note that this conclusion, if drawn, must therefore apply to /l/ as well as to the vowels. See also Moll & Daniloff (1971) for data indicating that the behaviour of /l/ resembles that of vowels with respect to velum positioning.)



*Figure 7*

Velum movement traces for /ansal/, /lansal/, /ə#ansal/, /ə#lansal/ produced at a self-selected normal rate, and aligned at the offset of an immediately preceding /s/ of the carrier phrase in which they were embedded. Target positions associated with the /s/ of the carrier phrase and the /n/ of the sequence are identified. Arrows are used to show the location in the lowering movement at which a separation between two components of that movement may be seen. Downward movement indicates velum lowering (and thus opening of the velopharyngeal port).



*Figure 8*

Velum movement traces for paired tokens of /ə#lasal/ (solid lines) and /ə#lansal/ (dotted lines) produced at a self-selected normal rate, and aligned at the offset of an immediately preceding /s/ of the carrier phrase in which they were embedded. Target positions associated with the /s/ of all tokens is shown, as is the target for /n/ in those tokens in which it occurs. The similarity between the early portions of the lowering movement in /ə#lasal/ and /ə#lansal/ can be seen in the area marked by the arrows. Downward movement indicates velum lowering (and thus opening of the velopharyngeal port).

### 2.3 Adding time by slowing the rate of speech

We would, however, like to approach these movements as we have approached the lip rounding data above: that is, by testing the hypothesis that the shapes of the smooth trajectories represent the combined

influences of the sequence of segments during which they are observed. In this case, we claim that the smooth trajectory between /s/ and /n/ is composed of lowering towards specified vowel, /l/- and /n/-related velum targets.

To support this claim, we compare the utterances of Fig. 6 (above), which were produced at a relatively rapid rate, with those in Fig. 7 for the same utterances produced at a somewhat slower rate, i.e. the subjects' self-selected normal rate. Proceeding from the top to the bottom of Fig. 7 we see the effects of adding segments and/or syllables, which results in increasingly clear evidence of an intermediate velum position between the high position of the /s/ and the low position of the /n/. Thus, as we increase the duration of the intervening string between the /s/ and the /n/ (a) by slowing the rate and/or (b) by adding segments/syllables, we begin to see the separate lowering movements that, in faster and shorter sequences, remain merged in the movement trace.

These examples provide evidence of a target between the high position for the /s/ and the low position for the nasal consonant. Given these data, the contributions of the individual intervening segments cannot be separated. Bell-Berti & Krakow (1991), however, showed that additional intermediate vocalic targets are observable in the slowest sequences that they examined with multiple vowels. This is consistent with other studies suggesting that there are characteristic positions of the velum for different vowels (Moll 1962; Ohala 1971; Ushijima & Sawashima 1972; Kent *et al.* 1974; Bell-Berti *et al.* 1979; Henderson 1984).

One question that we have not yet answered is whether the intermediate positions of the velum observed following the /s/ are related in some fashion to the upcoming nasal consonant. To test this possibility, we compared minimally contrastive utterances with and without a postvocalic /n/. An example can be seen in Fig. 8, where three typical tokens of /ə#lansal/ and /ə#lasal/ produced at the self-selected normal rate are paired. The early portion of velar lowering from the high position for the /s/ is much the same across the two contexts, indicating that the intervening string has a specification independent of that for the upcoming oral or nasal consonant. Thus the velum data, like the lip data, indicate that the appearance of smooth trajectories can obscure the presence of specified intervening targets.<sup>9</sup>

### 3 Conclusions

To summarise, the evidence presented here speaks to several issues. Perhaps most importantly, it suggests that segments which lack specification for rounding or nasalisation by contrast criteria or by aerodynamic/articulatory criteria nevertheless may exhibit characteristic articulatory positions. However, these positions may be obscured because of temporal constraints. Experimental manipulations that alter or remove

these constraints (e.g. comparison between minimal contrasts, adding additional unspecified segments, slowing speaking rate, etc.) are necessary to fully evaluate articulatory behaviour that results in a smooth trajectory. Thus, the TES model, in which smooth trajectories are taken as evidence for lack of specification in intervening segments, is not supported. It remains an empirical question, however, whether observed smooth transitions through 'unspecified' segments reflect lack of target specification(s), as appears to be the case for Russian /x/, or a merged and invisible target.

With regard to Keating's original attempt to marry motor and phonological organisation, it is not clear how such characteristic articulatory targets for supposedly unspecified segments should be treated. On the one hand, there seems to be a qualitative difference between the type of specification implied by such targets and specification originating at a deeper phonological level. On the other hand, demonstration of a target of any kind is hard to reconcile with the classic notion of underspecification.

One way to interpret the presence of these characteristic articulatory positions is as support for the notion that segments acquire exhaustive specification, by some phonetic evaluation process, just before input to the motor plan. In this view, the notion of phonetic underspecification would have to be abandoned. However, there is another way in which underspecification may influence production. We might think, for instance, that phonologically underspecified features, while associated (in production) with particular articulatory positions for a particular speaker, may be associated with cross-speaker and cross-dialectal variability. The different degree of protrusion evinced by the two English speakers during unspecified consonants (shown in Figs. 4 and 5) is a case in point. Similar variability in rounding among speakers has been noted by Brown (1981) and by Gelfer *et al.* (1989).

Some of the objections to Keating's (1988b) model described here are met in her 'windows' paper (1988a). In that paper, for example, she proposes limits on velar height for English vowels (in the form of 'windows') to a region (vertical dimension) which allows for substantial variability, but nonetheless excludes the extreme low and extreme high positions that are associated with nasal consonants and oral consonants, respectively. For a given speaker, our evidence suggests that there may be more precise articulatory configurations associated with underspecified segments than that paper implies.<sup>10</sup> But, perhaps, a 'windows' approach may be more easily applied to cross-speaker and cross-dialectal variability in the realisation of phonologically unspecified features. Of course this hypothesis will need to be tested empirically as well.

NOTES

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exploring this link and we have benefited greatly from her comments. We also thank Pat for allowing us to use her spectrograms of the Russian words discussed in her paper and in ours. This work was supported by NIH Grant DC-00121 to Haskins Laboratories and by NIH grant NSO-7040-15 to MIT. Requests for reprints should be addressed to the second author.

- [1] Degree of nasality is ultimately a perceptual quality whose most direct articulatory index is the size of velopharyngeal port opening. The vertical position of the velum reflects velopharyngeal port opening.
- [2] Keating uses linear interpolation in her exposition. She suggests that other types of interpolation may be possible, but their precise manifestation is not explored.
- [3] Although her 1988b paper presents acoustic data only, it is clear from this and other writings (e.g. Keating 1988a) that her hypothesis is a production hypothesis and her conclusions are meant to apply to articulatory data as well.
- [4] It is noticeable that the duration of /a/ is longer than that of /i/ in both /axi/ and /ixa/. This is part of a well-known pattern in which higher vowels have shorter intrinsic durations than lower vowels (Klatt 1975). Also, several researchers have noted a reciprocal temporal relation between adjacent consonants and vowels such that a given consonant is likely to be shorter when its tautosyllabic vowel is longer and *vice versa*. We clearly see this sort of relation in the longer /x/ preceding /i/ *vs.* /a/ (Fowler *et al.* in press). The time course of tongue movement could, in fact, be the same in both cases, but intrinsic duration differences and the compensatory behaviour described might cause the tongue to appear to be moving during the /a/ of /axi/ but during the /x/ of /ixa/. (We are grateful to Sharon Manuel for bringing the issue of timing in these data to our notice.)
- [5] Speakers were provided with the real word model *tactless* for the /ktl/ sequence in these items.
- [6] The extent to which small variations in movement, as seen in the retraction of the lips for /i/, the intervocalic consonant protrusion movements for /iC<sub>n</sub>i/ words, and the early peak in protrusion seen for /iC<sub>n</sub>u/ words, affect the actual perception of features such as [round] cannot be assessed without data from other lip dimensions and/or perceptual data. It should be noted, however, that the range of movement seen for this subject, e.g. 10–12 mm for protrusion related to /u/, and 3–4 mm for intervocalic protrusion in /kiktik/ and /kiktlik/, is quite normal and even large compared to the ranges often reported for /u/-related protrusion in the literature (Lubker & Gay 1982; Engstrand 1981; Perkell 1986). More importantly, if a behaviour is consistent (whether perceptible or not) it is necessary to incorporate it into any theory of how utterances are translated from phonological representation into a motor plan.
- [7] One of our reviewers suggested that the peak in /iC<sub>n</sub>i/ words might represent a return to a neutral position for the lips, from a retracted position for the preceding /i/ vowel. Although difficult to substantiate, this is a very plausible explanation. Note, however, that for the purpose of the argument, the origin of the peak in /iC<sub>n</sub>i/ words does not matter – if a peak, or its effects, are present in contrastive contexts, then that peak represents a target that must be accounted for in the translation from the phonology to a motor plan.
- [8] More extensive data on protrusion for all three intervocalic consonants are reported in Boyce (1988, 1990).
- [9] One reviewer suggested the possibility that underspecification of vowels for the feature [nasal] might manifest itself as a smooth trajectory between flanking oral and nasal consonants with small perturbations due to intrinsic vowel height-velum height relationships. We would like to point out, however, that this hypothesis would not predict such similarity in movement traces in the early portions of /ə#lasal/ and /ə#lansal/.
- [10] Keating also assigns narrow windows of velum height to consonants, one, in the low velum region, for nasal consonants and another, in the high velum region, for oral consonants. The problem with this proposal is that the relatively



large size of the velum window for vowels (as compared to consonants) is derived from combining measures for vowels of different qualities. The question of whether a window for individual vowels is wider than that for individual consonants is an empirical one that has not yet been tested.

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