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Fronted Velars, Palatalized Velars, and Palatals

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Abstract

Articulatory and acoustic characteristics of various stop consonants in Czech, Hungarian, English, and Russian are compared: velars before back and before front vowels, palatalized velars, and palatals. The articulatory data consist of X-ray tracings and palatograms taken from the literature. The acoustic data consist of LPC spectra of brief intervals at stop release and at vowel onset. These data indicate that all of these consonant types are distinct. Contextual fronting of velars is a gradient effect, less extreme than phonemic palatalization of velars. True palatals are even further forward on the palate and contrast with contextually fronted velars before front vowels. Thus these consonant types should not be collapsed by feature systems.

Introduction

Issues

It has long been observed that velar consonants in front vowel environments tend to be articulated at a more forward position along the palate than velars in back vowel environments [Sapir, 1921, p. 52]. Sapir compared the articulatory positions of the English /k/s in *kin* vs. *cool*, and textbooks since have offered similar comparisons [Heffner, 1950, p. 191; Ladefoged, 1975, pp. 49ff]. Many experimental studies of articulation have provided support for this basic claim. Nonetheless, most sources are not very precise about the segment that results from such contextual velar fronting. Is the segment still a velar, despite its being fronted? Or is it in fact fronted all the way to being a palatal? If a palatal, is it the same kind of segment as other consonants classed as palatals? In either case, is its articulation like that of contrastively palatalized segments? (The term 'palatalized' is used here only to refer to

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surface phonemic contrasts, not to contextual fronting. Following the new IPA conventions, we will symbolize a palatalized velar as [kʲ] and a fronted velar as [k̟].

In one sense, the first two of these questions have a straightforward definitional answer. In traditional terminology, the 'palate' refers to the hard palate, and any sound made on the hard palate is 'palatal'. On this view, any instance of /k/, /g/, etc. articulated on the hard palate is 'palatal', and only instances articulated on the soft palate are 'velar'. (See, for example, Recasens [1990] for this anatomical answer – he refers to fronted velars as 'back palatals', but Gorecka [1989] for a different, phonological, division of articulatory regions.) Since the hard palate is a fairly large portion of the roof of the mouth, palatal articulations may encompass many variants. Thus it may be the case that fronted velars are palatal in this broad usage, but systematically different from other kinds of palatals. The third question above, whether fronted velars or palatalized velars are like other palatals, is then still of interest.

These descriptive questions bear on issues of feature representation. If a feature system is to have some way of representing velar fronting, it should be known whether a fronted velar is the same thing as some other segment type, such as a palatal or a palatalized velar. The system of Chomsky and Halle [*The Sound Pattern of English* (SPE), 1968] forced the strong hypothesis that fronted velars are to be categorized with all other sounds made on the hard palate, including true 'palatals' and palatalized velars, because there is only one set of feature values available for all three of these (supposed) segment types. Under this proposal, the tongue body features High, Low, and Back are used to describe vowels as well as a variety of consonants, including velars and palatals. Velars are high, back segments, and palatals are high, front segments. Below it is shown how values of these features are used to represent velars, palatals, and related segments.

Vowels Consonants	[i], [ɪ] palatals palatalization	[u], [ʊ] velars velarization
High	+	+
Low	–	–
Back	–	+

Under this proposal, velars differ in place from front vowels like [i] in their value for Back. Fronting of a velar by a front vowel can be represented in feature terms by replacing the [+back] value of the consonant with the [–back] value of the vowel. The fronting is then directly expressed in terms of the feature describing location of the tongue body with reference to the palate. The same representation is used for palatalized velars, which are velars on which a high front vowel articulation is superposed: they are [–back], rather than [+back]. Note, however, that this combination of feature values is the same as that for other palatals. Under this analysis, then, fronted velars, palatalized velars, and other palatals are all represented featurally as the same thing[1].

[1] Another phonological sound type that would also be represented by the feature values for palatals would be 'front velars' which contrast with back velars. For example, Yanyuwa [Kirton and Charlie, 1978; see also Ladefoged and Maddieson, 1986, p. 20] contrasts front velars ('palatovelars') with back velars ('dorsovelars') (and also with laminal postalveolar coronals – 'alveopalatals') before /a/ and /u/. These two velars neutralize to the front velar before /i/ (which is the only front vowel in this 3-vowel language). Other nearby languages are reported to have the same contrast: Kirton and Charlie mention Garawa [Furby, 1974] and Djingili [Chadwick, 1975]; as neither source discusses distribution or neutralization facts, we cannot say whether the velars contrast before /i/. Whether these front velars differ phonetically from sound types made on the hard palate in other languages remains to be determined.

This aspect of the SPE representations, which is grounded in the traditional definition of palatal sounds as made on the hard palate, is quite intentional. While in general palatalization is said to leave the primary articulation unaffected, the addition of a vowel type of articulation to a consonant articulated by the tongue body, such as a velar, is seen as shifting the primary place of articulation of the consonant towards that of the vowel, in this case to a palatal. Because the tongue body feature [back] is used for both vowels and consonants, this place shift under fronting or palatalization is an automatic outcome. At the same time, no such place shift occurs for consonants not articulated by the tongue body. This result of the SPE use of the features High, Low, and Back was taken to be an argument for the feature system.

Another consequence of the system is that palatals, fronted velars, and palatalized velars cannot contrast with one another, either underlyingly or on the surface. Again this consequence was taken to be an argument for the feature system. We will claim that surface contrasts are possible, however. There are three potential paired contrasts of these three phonetic categories. The first is palatals vs. fronted velars. As we will see below, languages with palatals do contrast them before front vowels. The second potential contrast is palatals vs. palatalized velars; we know of no contrasts, but as will be seen, they should be possible. The third is fronted vs. palatalized velars. As far as we can tell, it is true that no language contrasts these segment types before a phonetic high front vowel [i], and our data will argue against such a contrast before the mid front vowel in Russian. We will support the SPE position that fronted and palatalized velar articulations are phonetically too similar to contrast.

Since SPE, feature systems and representations have changed quite a bit, particularly with respect to place of articulation. Nonetheless, essentially the same issues remain, since we still do not know how many different types of segments need to be represented. If anything, recent proposals about feature geometry only sharpen our need to understand the relevant articulatory differences. For example, under many proposals since Sagey [1986], a sharp distinction is drawn between dorsal, or tongue body, articulations, and coronal, or tongue blade, articulations. (Lip and tongue root articulations are also distinguished.) Place of articulation is represented in terms of the active articulator of a sound; thus the active articulator must be known for the place of articulation to be represented. We can then ask whether the segment types under discussion – palatals, fronted velars, palatalized velars – are phonetically coronal or dorsal or both.

It is also possible that a sound type which does not contrast lexically, such as contextually fronted velars, could have no distinctive binary featural representation, but instead be represented only later in a derivation, in non-binary terms. In the SPE system, it might be that the feature Back would acquire a particular numerical value in a fronting context. In more recent work in underspecification theory, it is possible for a velar to have no phonological value for this feature, and instead to be fronted or backed entirely according to its context. We will consider this possibility in terms of the model of phonetic underspecification in Keating [1988b, 1990].

Our main point, then, is to clarify the phonetic differences between certain segment types, in a way that is relevant to any version of feature theory. For that reason, we will not present formal proposals about how these sounds might be represented featurally. In particular, since there is currently no agreement as to how the phonetic dimension of tongue body frontness/backness is to be encoded, we will not rely on specific features. Rather we will use general articulatory terms to specify information which might be taken into account under any theory of phonetic representation. Specific proposals can be found in Pulleyblank [1989], Gorecka [1989], Keating [1988a, 1991], Clements [1991], and Lahiri and Evers [1991], inter alia.

In this article we focus on stop consonants in four languages, though other data will be mentioned as well. Czech and Hungarian were selected as languages with contrasting palatal and velar stops. In both of these languages, the palatals alternate with anterior coronals such as /t/, suggesting that the palatals might also be coronal. At the same time, the palatals of these languages are thought to differ, with the Hungarian ones more backed and therefore more prototypically palatal [P. Ladefoged, personal commun.]. In addition, we wanted to know whether the Czech and Hungarian velars are fronted before front vowels as in other languages. If so, this would be a case of a surface contrast of fronted velars with palatals. Russian was selected for its contrasting palatalized and nonpalatalized (velarized) velar stops. English was included for its allophonic velar fronting.

For each of these languages, articulatory data from the literature, and our own acoustic analyses, are used to compare the consonant types. The articulatory data show that all of them are articulated on the hard palate and thus are all 'palatals' in this definitional sense. However, the palatals of both Czech and Hungarian differ from the fronted velars and from some of the palatalized velars in having a clear tongue blade articulation along with the tongue body articulation that all of them evidence. The acoustic data also support this distinction.

Preliminary Terminology

In describing place of articulation, it will be extremely useful to refer to an anatomical distinction for which there are no standard terms. The hard palate extends up and back from the alveolar ridge to the roof of the mouth. For many speakers, the hard palate can be divided into two parts with different orientations: one, a vertical or diagonal sloping section behind the alveolar ridge, the other, a more horizontal section forming (part of) the roof of the mouth. The first, sloping, part is roughly the same as the part with rugae, or ridges. Where possible, then, we will refer to the *corner* of the alveolar ridge, meaning the posterior part of the ridge where the upward slope of the hard palate begins; to the *diagonal* of the hard palate, meaning the basically upward-sloping part of the hard palate, and to the *roof* of the hard palate, meaning the topmost part adjacent to the soft palate. Figure 1 illustrates these. These divisions are similar to Catford's [1988, p. 93]. For Catford, the corner corresponds to 'postalveolar' articulations, 'prepalatal' runs from there back to the highest point of the palate (and so is larger than the diagonal), and 'palatal' is the rest of the hard palate (and so is smaller than the roof). Our divisions perhaps correspond more closely to those of Recasens [1990], for whom prepalatal refers to the diagonal behind the corner, and mediopalatal refers to the roof of the hard palate. However, in general these terms seem not to have a fixed, anatomical meaning. For clarity, then, we use our more pictorial terms diagonal and roof.

Phonologists use the term *anterior* to refer to places of articulation in front of the corner of the alveolar ridge, and *nonanterior* to refer to places of articulation on or behind the corner. This boundary is the same as Catford's [1988] traditional alveolar/postalveolar boundary, but 'anterior' is larger than alveolar, and 'nonanterior' is larger than postalveolar.

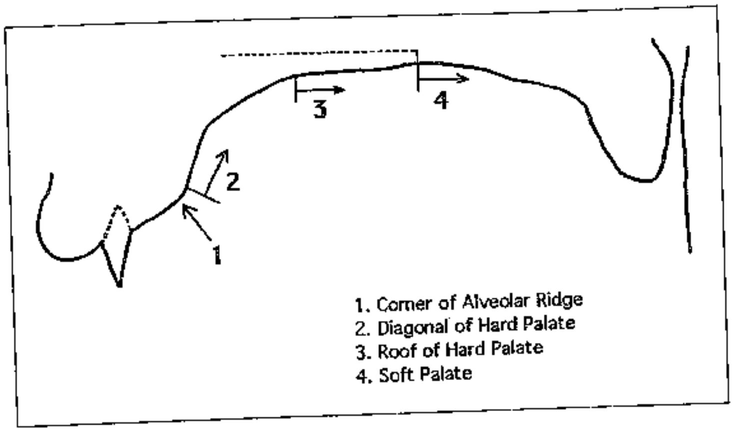

Fig. 1. Schematic of relevant anatomical landmarks and terms.

With respect to active articulators, we distinguish between the tongue blade and the tongue body or dorsum. (In anatomical usage dorsum refers only to the cover of the tongue. Hence Öhman's [1966] distinction between 'dorsal' – for consonants – and 'vowel' channels of articulation. We follow current linguistic practice in using dorsum to refer to the entire body, for both vowels and consonants.) In phonology, sounds with the blade as their active articulator are called *coronal*, and sounds with the tongue body as their active articulator are called *dorsal*. Following Keating [1991], we take the blade to include, conservatively, the tip of the tongue and the first 2 or 3 cm beyond the tip (roughly, the part of the tongue, in front of the anterior genioglossus, which at midline feels less firm to the touch). Some investigators, especially in a European tradition, define the blade as the movable end of the tongue not attached to the floor of the mouth, or roughly 1 cm. The reason to prefer a definition giving a longer blade is that consonants which are clearly 'coronal' phonologically are often formed more than 1 cm behind the tip. Stops made at the corner of the alveolar ridge (postalveolars) are typically made 2–3 cm back on the tongue. Furthermore, Dart [1991] shows that even alveolars may be articulated this far back on the tongue, when they are made with the blade of the tongue. Since alveolar consonants must be 'coronal' for the term to be of any use to linguists, then operationally the blade must go back at least that far. Such an operational definition also has a physiological basis. A length of 2–3 cm corresponds to the back of Stone's [1990] 'anterior' tongue segment. Stone identifies four functionally independent sagittal segments of the tongue: anterior, middle, dorsal, posterior (plus one or more tongue root segments, not studied). Our 'blade' includes the first of these, which Stone estimates to be about 2.5 cm long from the tip. Thus we expect this 2- to 3-cm segment of the tongue to function as an articulator independent of the rest of the tongue body. Our blade, then, is somewhat longer than in the European tradition, but shorter than in the American tradition [Keating, 1991]. The other segments in Stone's model fall together as the tongue body in phonological terms.

In this article, then, 'coronal' refers to the first 2–3 cm of the tongue, and 'dorsal' to the tongue behind that point. Furthermore, a sound can be made with more than one tongue segment at once, so that a sound can be, for example, simultaneously coronal and dorsal. In phonology, single segments made by more than one of the active articulators specified in the theory are called 'complex segments', following Sagey [1986]. Any sound which involves two articulators is thus phonologically complex, even if it is not physically difficult. (For example, [w] is complex because it involves the lips and the tongue body, yet this is a very common sound across languages.) A sound using two adjacent parts of the tongue might be physically easy to make, yet if those parts of the tongue are phonologically distinct – the body and the root, or the body and the blade – then the sound is phonologically complex. Phonologically complex sounds are expected to behave like simple sounds made with each of the given active articulators. [For more discussion of complex segments see Maddieson and Ladefoged, 1989.]

We will have occasion to discuss lateral tongue contact as well. By this we mean contact between the sides of the tongue and the sides of the palate, usually along the teeth. The length of lateral contact in the front-back dimension can be distinguished from the amount of lateral contact in the side-to-side dimension. It is important to note that such lateral contact is not what is involved in the production of 'lateral' segments. Lateral segments involve escape of air around the lowered side(s) of the tongue, whereas lateral contact, with the tongue sides raised, precludes such airflow. In phonological representations of active articulations, the sides of the tongue have no special status; contact with the side(s) of the blade would be coronal activity, while contact with the side(s) of the body would be dorsal activity.

Next, it is important to review how terms for consonantal places of articulation are used here. There are several nonanterior coronal consonant categories in the IPA. Of these, palatoalveolars and retroflexes are made in about the same area at or behind the corner of the alveolar ridge, with the palatoalveolars laminal and the retroflexes apical or sublaminal. In this system English [ʃ] is palatoalveolar, though it is often called palatal in American usage. IPA palatals are distinct from both palatoalveolars and retroflexes, with the IPA chart suggesting that the palatals' place of articulation is further back. A wide range of palatal consonant types – stops [c] and [ɟ], fricatives [ç] and [ʝ], the corresponding affricates, nasal [ɲ], lateral [ʎ], and glides [j] and [ɥ] – is recognized in the IPA.

In addition, the IPA alphabet – though not the main consonant chart – contains 'alveolopalatal' fricatives [ɕ] and [ʑ]; affricates [tɕ] and [dʑ] are also commonly transcribed. Thus there is a distinction in the IPA between palatal and alveolopalatal fricatives and affricates; however, no similar distinction is made for nasals or other sonorant consonants. Furthermore, even for obstruents, alveolopalatals are not always consistently recognized in phonetic descriptions [Maddieson, 1984]. As a result, the IPA palatal symbols often span both phonetic categories.

The intended difference between IPA palatals and alveolopalatals seems to be that alveolopalatal fricatives are sibilants while palatal fricatives are not. The articulatory basis of this acoustic difference is left unspecified. Recasens [1990] treats the articulatory distinction as a more or less straightforward difference in place of articulation: alveolopalatal constrictions are on the back half of the alveolar zone plus the front half of the prepalatal zone (or even further back), while palatal constrictions are on the backer part of the hard palate. We believe the major difference instead to be one of amount of raising of the tongue body behind the constriction, with palatals having much more extensive raising (and therefore lateral contact) than alveolopalatals, but with the tongue tip more consistently behind the lower teeth.

However, for the purposes of this article, the issue of how IPA palatals are to be distinguished from IPA alveolopalatals can be left aside, since the comparisons of interest here are between these sounds and ones made further back on the palate. We will refer to 'palatals' without further elaboration to mean sounds whose primary constriction is mainly on the diagonal of the hard palate. These palatals will be seen to be very different from consonants formed on the roof of the palate. These latter will be treated as front velars and as such represented with IPA [k̟] and [x̟], even though palatal symbols such as [c] and [ç] are often used for such sounds as well.

Articulatory Comparisons

Method

The data to be considered consist primarily of published tracings of midsagittal X-rays. Sources were located largely by examining the listings in Dart [1987]. In each case the available tracings were inspected to determine where the greatest constriction was formed, and by what part of the tongue, and also the general position of the blade of the tongue. When a source indicates the division between the hard and soft palates on the roof of the mouth, constrictions are described relative to that point. In addition, if palatograms and linguograms are included in the source, they were also examined for information about any contact between active and passive articulators. (It must be kept in mind that each such display probably comes from a different token.) This study is thus similar in scope and method to Recasens [1990] and Keating [1991].

A few words are in order about limitations on inferences from such sources of data. With respect to published X-ray tracings, there are three major difficulties. First, tracings are difficult to make and therefore not entirely reliable, especially when viewed only in reproduction. Second, the tracing is taken either from a still X-ray, in which case the speech sample is artificial, or from a cine X-ray, in which case it may not show the desired moment in a rapidly changing speech event. Third, it may not be clear whether the tracing shows central or lateral contact. With respect to static palatograms, problems arise with consonants in /i/ and /e/ contexts, since these vowels themselves may have extensive palatal contact. The static palatogram shows the combined contacts of all the segments in the speech sample. The palatograms are then valid only with respect to a stop consonant's central occlusion.

Czech

Several sources on Czech phonetics include X-rays of oral and nasal palatal stops. However, it appears that several of these sources rely on the same original study; in all there are probably at most 3 or 4 different speakers represented. (Various reports from Hála's group are apparently all based on Polland and Hála [1926a, b]. These early X-rays are stills; in some of the sources, some of the articulatory profiles shown are not from X-rays at all, but are reconstructed from palatograms [as in Hála, 1923]. In Hála [1962], the X-rays and palatograms are probably from different sources. In another source [Pacesová, 1969], some figures are from Hála sources and some are apparently from her own cine film.)

The X-ray tracings of oral palatal stops in Daneš et al. [1954] are typical of those available for Czech. (This source is based on Polland and Hála [1926a, b] and therefore shows tracings from still X-rays, along with labiograms, linguograms, and palatograms. The hard-soft palate boundary is shown. No information is given about the speech items.) Figure 2 is derived from one of these. These tracings show long contact from the corner of the alveolar ridge back onto the roof, though not covering all of the hard palate. Palatograms show wide contact all along the sides, but a stop occlusion only at the front of the palate, probably on the corner and part of the diago-

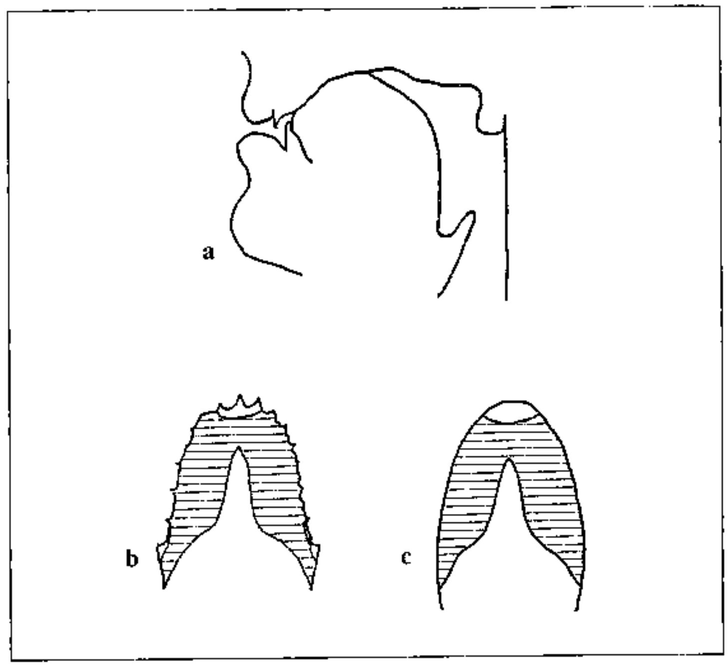

Fig. 2. Articulatory data on palatal stops in Czech [after Daneš et al., 1954]. **a** Tracing of sagittal X-ray, showing lateral tongue-palate contact. **b** Tracing of palatogram, contacted area shaded. **c** Tracing of linguogram, contacted area shaded.

nal. It covers about the same total area as the area of an alveolar plus the area of a palatoalveolar combined. Linguograms strongly suggest that the central contact of this occlusion is made with the blade, not the tip or body, of the tongue, though we cannot be entirely sure since the scale of the figures is not specified. They also show lateral contact extending far back on the tongue. That is, the palatograms and linguograms make clear that the long contact seen in the X-rays is most likely lateral contact only, not central contact [though see Straka, 1965, p. 157 for the possibility of long central contact]. The tip of the tongue is down and the whole tongue is pulled forward, with the pharynx quite wide as a result. As no information is given about the speech items recorded, the contribution of the vowel context to the overall tongue position cannot be determined. The nasal stop is similar to the oral ones, but with a shorter occlusion which does not extend as far forward on the palate or tongue, and lateral contact that, in the X-ray tracing, does not extend as far back.

The same sources include velar consonants as well, and so we can compare palatals and velars. Since the contacts for velars shown in these sources are made only on the soft palate, there is no overlap at all between palatals and velars in this sample. The occlusions for velars are slightly longer than those for palatals.

Based on these data, the Czech palatal stop looks like a long coronal stop (extending over anterior and nonanterior areas) combined with the lateral contact of a [j]. It is therefore useful to compare these palatal stops with the Czech palatal glide /j/. Palatal glides in general show lateral contact only, basically a long narrowing along the hard palate. In Czech the profile of the tongue seen in the X-ray tracings is very similar for the stops and the glide, but the glide of course does not show the central contact seen with the stops. Correspondingly, the palatograms show lateral contact for the glide which extends as far forward along the teeth but which is slightly less extensive from side to side, indicating that the tongue body is less raised. (This contact for the glide is at the same time much more extensive than for the nonpalatal coronal consonants.) This difference suggests that with the stops, the goal of stop occlusion leads to extreme tongue raising. Otherwise, the stops are quite comparable to the glide in tongue body position. In some palatograms, the greatest constriction in the glide is at about the corner of the alveolar ridge; others show no point of greatest constriction. Straka [1964, 1965] provides interesting palatographic data on the relation of the Czech palatal stops and glide. Straka [1965, p. 157] shows that as the stop /c/ is pronounced more energetically, the lateral contact becomes more extensive so that the central occlusion becomes longer and more of the hard palate is contacted. Straka [1964. p. 96] shows that for the glide /j/, an emphatic pronunciation results in so much lateral contact that there is almost a central occlusion, and this near-occlusion is in the same location as for the stop occlusion. This finding supports the parallel treatment of the Czech stops and glide as both consisting of a coronal (laminal nonanterior) component together with a dorsal component. The two types differ, however, in how the two components are combined. It might be said that for the stops, the coronal component dominates the articulation and is thus primary, with the dorsal component secondary, while for the glide the dorsal component dominates and is thus primary, with the coronal component secondary. In both cases, the secondary component becomes stronger in emphatic pronunciation.

In sum, the palatal stop in Czech has a coronal occlusion and a secondary tongue body articulation.

Hungarian

Bolla discusses X-rays of Hungarian in various sources; we refer here primarily to Bolla [1980] because there he gives continuous tracings of the tongue's shape and location, rather than schematics based on a few points, as in some of his other publications[2]. The palatals (and velars as well) were all before/after a low back vowel, except one palatal /c/ before /u/. It is thus possible that all might be somewhat backed in their place of articulation relative to the palatals of Czech, which are almost surely in an /i/ context, but we have no relevant articulatory data on coarticulation of palatals with vowels to clarify this possibility. Figure 3, based on Bolla, shows a Hungarian palatal stop articulation. The voiced stop and nasal of Hungarian are similar to each other, with contact largely on the diagonal nearer the roof. This contact is somewhat longer than that for velars shown in the same source. The tracing of the voiceless stop shows no occlusion at all; the near-occlusion shown is on the diagonal of the palate. The palatograms and linguograms for all three show occlusions over a large area of the hard palate, but not using the first centimeter or two of the tongue blade. The occlusion seems to be made behind the blade; the blade is involved in noticeable lateral contact in front of the occlusion. The central contact is not as long as the lateral contact, but it extends quite far back on the tongue. Bolla [1981a] shows schematic displays of positions of individual points on the tongue over time. While such dis-

[2] The data in Bolla [1980] are palatograms, linguograms, tracings of frames from a cine X-ray, and other kinds of data; the tracings shown are from the 'pure phase of articulation' of the segments. Sometimes the side and center of the tongue are distinguished. The hard-soft palate boundary is not shown. Original frames from five points in time are also reproduced in miniature. Several words were recorded for each segment. The palatograms do not necessarily correspond to the X-ray tracings with which they are paired.

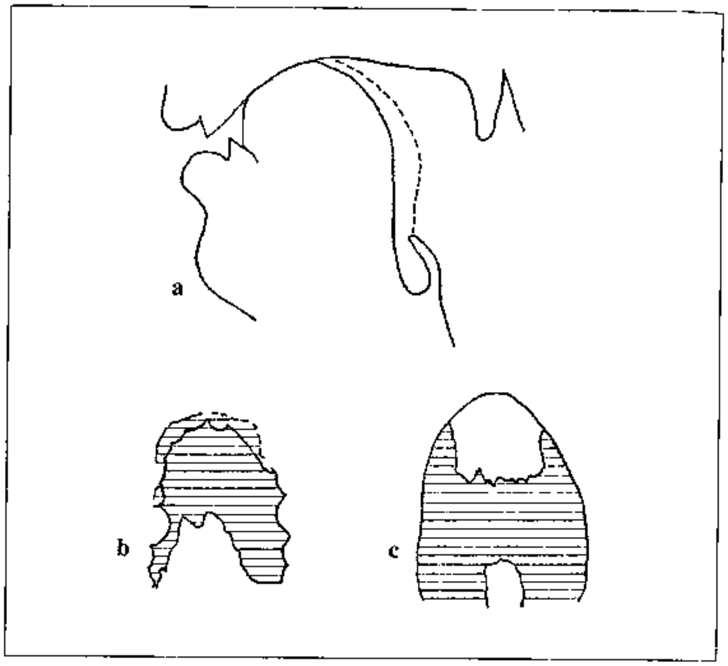

Fig. 3. Articulatory data on palatal stops in Hungarian [after Bolla, 1980]. **a** Tracing of sagittal X-ray. **b** Tracing of palatogram, contacted area shaded. **c** Tracing of linguogram, contacted area shaded.

plays do not detail contact areas, they do show overall changes in tongue position. These displays for palatals in Bolla [1981a] show that the palatals have their first contact more to the back of the palate and slide it forward onto or towards the diagonal; if this is correct, then the palatograms show a composite of total contact areas during the articulation. Indeed, the central contact for the occlusion is longer in the palatogram than in the linguogram.

None of these palatals overlap at all in place of articulation with the palatoalveolars or velars shown by Bolla [1980]. The consonants transcribed as palatoalveolars (fricatives and affricates) are apical and postalveolar, made in front of the palatals; they show less side-to-side lateral contact than do the palatals. The velars are entirely on the roof, with their central contact on the soft palate. The palatograms and linguograms of the palatals and velars indicate that the contacts are in quite different regions. In terms of the overall shape of the front of the tongue, as seen in the X-ray tracings, for the palatals the tongue is bunched forward so that the blade comes to the lower teeth and the diagonal. For the velars, the tongue is also bunched up, but is not thrust forward to the teeth/diagonal; its shape is instead rather symmetrical.

The glide /j/ in Hungarian is not quite like the palatal stops. Bolla's X-ray tracing shows a glide which is rather back, on the roof, and has no obvious blade involvement. The palatogram shows no single point of constriction, and the linguogram shows a consistent lateral contact along the tongue. The glide and stops are similar in terms of their rearward lateral contact, but the glide lacks the forward central constriction. In these respects the glide is like the Hungarian palatal fricative, which also has only lateral contact. As in other languages in the literature, the Hungarian palatal fricatives have longer lateral contact than do the stops – from the diagonal over the entire hard palate, and even onto the soft palate. A wide passage remains open along the center of the tongue, as for [i] vowels. That is, the glide and the fricative constrictions extend further back than does the stop, and the stop is not strongly coronal.

Although Icelandic is not one of our primary languages of investigation here, Pétursson's [1974] X-ray study of that language provides additional information about palatals not available from the studies of Czech and Hungarian. In this study, superposed frames from different time points in palatal stops before front vowels clarify the time course of the lateral articulation (which, it will be recalled, is what X-rays primarily reflect for palatals). These figures indicate that neither the contact nor the release is made all at once, but instead often proceeds from small to large to small contact, with a more fronted contact at the release. It is certainly plausible that the same holds in Czech and Hungarian; the back-to-front movement of contact has already been mentioned for Hungarian. At the same time, it must be noted that Recasens [1990] found that the alveolopalatal nasal of Catalan is released from front to back (alveolar contact released first).

In Hungarian, then, a palatal stop has a long occlusion on the hard palate, together with additional forward and rearward lateral contact. The stop occlusion probably slides during closure, but its location lies between that of the postalveolar and velar consonants. The palatal glide and fricative have lateral contact all along the tongue but the tongue shows no particular point of constriction. The Hungarian palatals are thus somewhat different from those in the Czech sources. In both languages the tongue is raised and pulled forward with the tip behind the lower teeth, so that there is extensive lateral contact between tongue and palate for palatal stops and glides. (Czech has no palatal fricatives to compare with Hungarian.) The palatal stops in the two languages differ in where central contact is made – it is more forward, and definitely coronal, in Czech. The Hungarian stops are only marginally coronal even under our definition of the blade, and more likely dorsal. The palatal glides in the two languages differ in the X-ray tracings, with the Hungarian glide showing less constriction along the diagonal, but in the linguograms the Hungarian glide shows more contact. From these sources, however, it is impossible to say whether the palatals of the two languages are systematically different, since we do not know what vowel contexts the Czech palatals were produced in. If, as seems likely, they were largely front vowel contexts, then we would expect the Czech palatals to differ from the Hungarian ones, produced in back vowel contexts. We will return to this point in 'Acoustic Comparisons'.

In sum, based on the articulatory data, the Hungarian palatal stop has an occlusion made primarily or only with the tongue body, and additional lateral laminal constriction forward of that, in these back vowel contexts.

Russian

Several published sources provide data on Russian velars, usually in comparisons of palatalized with nonpalatalized velars. However, minimal pairs are not often given, since isolated native words do not provide them. Palatalized velars occur mainly before front vowels, and nonpalatalized velars mainly before back vowels. (According to Jones and Ward [1969], palatalized /kʲ/ occurs before back vowels only in borrowings, and nonpalatalized /k/ occurs before front vowel phonemes /i/ and /e/ only in combinations of the preposition /k/ with words beginning with those vowels. In these cases the phoneme /i/ is realized as a retracted allophone. Thus nonpalatalized /k/ is not found at all before a phonetic [i] and

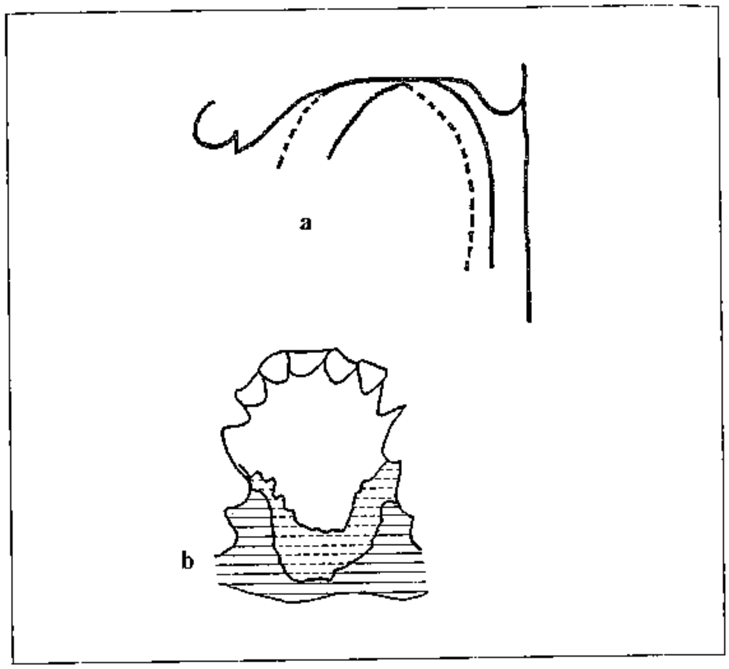

Fig. 4. Articulatory data on palatalized and nonpalatalized velar stops in Russian [after Skalozub, 1963].
a Superimposed tracings of sagittal X-rays of nonpalatalized (plain line) and palatalized (dashed line) stops.
b Superimposed tracings of palatograms of nonpalatalized (plain-line shading) and palatalized (dashed-line shading) stops.

is found before /e/ only across a word boundary.) Therefore, sources tend to give palatalized velars in a front vowel context and nonpalatalized velars in a back vowel context; other sources give no information about vowel context. Nonetheless, minimal pairs are most helpful for our purposes, and some studies use minimal nonsense syllables. Sources showing minimal pairs include Koneczna and Zawadowski [1956], Skalozub [1963], and Fant [1960][3]. Figure 4 shows a palatalized vs. a nonpalatalized velar before /a/ based on Skalozub [1963].

Skalozub [1963] compares velars between /a/ vowels for 3 speakers. In these X-ray tracings, for 2 of the speakers [Skalozub, 1963, fig. 100, 102], the /k/ and /kʲ/ are extremely different in place of articulation, with no overlap at all and contact on soft vs. hard palates. For the other speaker [Skalozub, 1963, fig. 101], the /k/ and /kʲ/ are much more similar; the nonpalatalized /k/ is clearly on the soft palate, while the palatalized /kʲ/ is just in front of it, at the border of the two palates. However, this speaker does have a clear distinction between /g/ and /gʲ/ in a palatogram [Skalo-

[3] Koneczna and Zawadowski [1956] show tracings from still X-rays along with palatograms from other sources. Four speakers produced nonsense and real words, but tracings of velars are limited to 1 speaker. The hard-soft palate boundary is shown; the sides and center of the tongue are distinguished. Skalozub [1963; data reproduced also in Skalozub, 1966, Bulanin, 1970, and possibly Akishina and Baranovskaja, 1980] shows originals and tracings of still X-rays, palatograms and odontograms (lower teeth contact), of nonsense items for 4 speakers. Fant [1960] presents still X-rays for which the entire surface of the tongue has been highlighted and in which the sides and center of the tongue are distinguished; 1 speaker produced monosyllables.

zub, 1963, fig. 105]. A greater difference between /g/ and /gʲ/ than between /k/ and /kʲ/ seems to be a general pattern in most palatograms and X-rays [Skalozub, 1963, fig. 104–107] and is due to the fact that /g/ is more back than is /k/. (The same can be seen in the palatograms reproduced in Koneczna and Zawadowski [1956]). Bulanin [1970] reproduces one pair of X-ray tracings from Skalozub [1963] and describes the articulation of the nonpalatalized consonants as being on the soft palate near the border between the two palates and of the palatalized consonants as being on the hard palate near the border between the two palates. He also notes that different points on the tongue form these articulations. However, in both kinds of velars, the contour of the tongue is rounded, with the blade not raised to the palate; odontograms (lower teeth contact) show contact between the tongue (tip) and the lower teeth.

Koneczna and Zawadowski [1956] show /ka/, /kʲa/, /ga/, and /gʲa/ for 1 speaker, plus /ka/ and /kʲi/ for another speaker, and palatograms, also probably not minimal pairs, from still another speaker. In the minimal pairs, the palatalized velars are well forward on the roof of the hard palate, while the nonpalatalized velars span the hard-soft palate boundary. Also, in the palatalized velars the tongue is somewhat raised in front of the constriction. The constriction after stop release is probably quite long, like that for [xʲ].

Fant [1960, p. 186] gives very small tracings of /ka/ and /kʲa/. The nonpalatalized velar has the longest contact seen in any source for any oral velar; it appears to cover the entire soft palate including the uvula. (Fant [personal commun.] attributes this feature to the style of speech used for the still X-rays.) The palatalized velar has a much shorter contact (though one which is still longer than in any other source), probably on both the hard and soft palates. (The boundary between them is not shown, and the palate is quite domed; the contact is along the dome.)

Other sources for Russian velars, which do not show minimal pairs, include Oliverius [1974] and Bolla [1981b, 1982]). Dem'janenko [1966] and Matusevic and Ljubimova [1964] present data from several different publications. From sources such as Oliverius [1974] and Bolla [1982], as well as from Koneczna and Zawadowski [1956], the articulation of a palatalized velar in a front vowel context can be examined. In the latter source, the X-ray contact seen for /kʲ/ is longer before /i/ than before /a/. Since one palatogram shows long central, as well as lateral, contact, the X-ray might also be reflecting both of these. (Recall that in front vowel contexts, static palatograms will probably show the lateral contact associated with the vowel and are reliable only with respect to the central stop contact.) The X-ray tracings in Oliverius [1974] show contact entirely on the hard palate; the accompanying palatogram shows that both central and lateral contact are more fronted than for the plain velar in back vowel contexts; that is, the whole tongue, except for the tip, is moved forward, as for the vowel. Bolla's [1981b, 1982] X-ray tracings are point schematics and therefore not precise with respect to contact, but the accompanying palatograms and linguograms are useful and show an occlusion rather far back on the tongue, and probably on the soft palate – that is, the least far forward palatalized velars seen in the sources.

The same sources generally also show tracings of palatalized vs. nonpalatalized labials and coronals. Such tracings indicate that palatalization quite generally involves a forward raising of the entire tongue blade, body, and root, with the body approaching the roof of the hard palate. Palatalized velars can be seen to have this same basic articulation, where fronting of the tongue body necessarily affects the location of the consonantal constriction.

Russian also has a glide /j/, and the relation between its articulation and palatalization is a key question. Skalozub's [1963] X-ray tracing and palatogram of /j/ before /a/ shows that it is much like the vowel [i] but with greater narrowing at the diagonal/roof border, along with an expanded pharynx, and greater side-to-side lateral contact – thus, presumably, a more raised and fronted tongue body and blade. Fant's [1960] X-ray tracing shows long palatal contact, which is surely lateral, not central, and the blade clearly raised up. Bolla's [1982] palatogram of /j/ before /u/ shows an even lateral contact all along the molars. Thus some but not all of these tokens of /j/ appear to have a coronal component. At the same time, however, the X-ray sources by and large do not show blade raising in /kʲ/ as they do for /j/. Also, the pattern of lateral contact for the palatalized velars in the sources is more variable, since the vowel context is variable. In an /a/ context they show either no lateral contact in front of the occlusion [Skalozub, 1963] or lateral contact only along the molars [Oliverius, 1974], but in /i/ contexts the palatograms show (as expected) a great deal more lateral contact, almost as much as for /j/. In the /i/ context, of course, the palatograms confound the consonant and vowel articulations. That is, there is no clear evidence for extensive lateral contact or for a coronal articulation in the palatalized velars, unlike for /j/.

A recent electropalatographic (EPG) study of Irish consonants [Ni Chasaide and Fealy, 1991] provides data on another contrast between palatalized and nonpalatalized velars. Not much can be said about the difference in overall contact for Irish /gʲ/ vs. /g/ because the EPG pseudopalate does not extend far enough back on the speaker's palate to record much /g/ contact. What can be seen is that early in closure both /g/ and /gʲ/ are fronted between /i/s, compared to between /a/s and /u/s, and that for /gʲ/ the front of the tongue is also raised. However, this difference between the /i/ context and the other contexts is not seen just prior to release of closure. By that point, all are equally fronted. The velars start out fronted in the /i/ context, but become fronted only during the closure in the other contexts. Such fronting will be discussed in more detail in the next section.

Taking into account all of these sources, the general pattern in Russian is that the contact for palatalized velars is just in front of that for nonpalatalized velars. The nonpalatalized velar is usually articulated toward the front of the soft palate, and the palatalized velar is usually articulated toward the back of the hard palate. Both the lateral and the central contacts are shifted forward for the palatalized velar. Furthermore, the entire tongue is shifted forward, giving a larger pharyngeal cavity for the palatalized velar. The contact for the palatalized velar is usually the same length in the sagittal dimension as the contact for the nonpalatalized velar, but the lateral contact may be longer. Palatalized velars involve a fronted tongue, but not generally a raised tongue blade.

English

Surprisingly little data on velar fronting is available for English. MacNeilage and DeClerk [1969] collected EMG and X-ray data for /g/ before the vowels /i, u, æ, ɔ/. They show one figure from the X-ray data, combining tracings for the four contexts. However, these are from 100 ms before the /g/ release, which is before the stop closure; this means that stop contact cannot be seen in the figure. Judging from this figure, it appears that /g/ will have its contact in similar locations before /u, æ, ɔ/, and more than a centimeter in front of that before /i/. However, unpublished X-ray microbeam data made available by Mary Beckman suggests a more forward release before /æ/ than before /a/. Figure 5 shows our estimates of contact for /g/ before /i/ vs. /ɑ/.

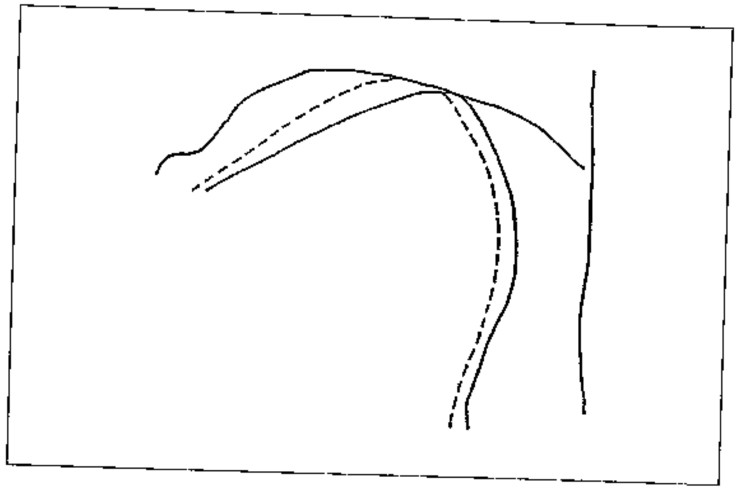

Fig. 5. Estimated superimposed tracings of sagittal X-rays of velar stops in English before /u/ (plain line) vs. /i/ (dashed line), estimated after data in MacNeilage and DeClerk [1969].

Similarly, Ladefoged [1982; p. 58] shows palatograms for [ki] and [ku], along with inferred sagittal sections; however, it must be borne in mind that static palatograms confound information from vowel and consonant. In an EPG study, Dagenais and Critz-Crosby [1991] showed that for 12-year-olds the frontmost midline contact is about 8 mm forward for velars before /i/ compared to before /ɑ/. A similar result was found by Fletcher [1989] in an EPG study with adult speakers.

Another source of data, one which focuses on the time course of articulation, is Houde's [1967] X-ray comparison of /g/ between /i/, /ɑ/, and /u/. (In this study, pellets were attached to the midline of the tongue body, and their positions were measured over time from the frames of a cine film (100 frames/s). The overall tongue contour was also visible. VCVCV utterances combined the vowels /i, ɑ, u/ with /g/ or with /b/, under different rate and stress conditions.) While he does not reproduce tracings of the tongue as a whole, he does reproduce, and discuss, several figures which show just the tongue dorsum and palate at different points in VCVCV sequences, as well as measurements of pellet location. Again, the contact locations vary along the palate over about 8 mm, with /igi/ having the most forward location. The contact for /igi/ does not overlap with those for /ɑgɑ/ and /ugu/, whereas these two backer contacts do overlap in location. In these three sequences, where the velars are between two like vowels, there are two distinct /g/ movements seen, one vertical and one horizontal. First, tongue movements from vowels to velars show mainly a raising motion: the tongue retains the front-back position from the vowel, and raises to form the closure. Thus the location of the initial palatal contact for /g/ varies according to the vowel context. Second, there is a forward and backward horizontal movement of the tongue, which Houde [1967] calls a 'palatal closure-related perturbation'. During the closure, the body moves forward along the palate, and after the release it moves downward and backward in the oral cavity. The horizontal movement component is larger (up to about 6 mm) when the context vowels are low. Houde [1967] is unsure whether this component is actively controlled by the speaker, or is passive. (Ohala [1983] interprets the closure-induced fronting of /g/

in Houde's data as an active voicing-facilitating mechanism of back-cavity expansion. Houde also considers this interpretation but finds it less convincing, and in the case of /b/ argues directly that the expansion is passive, not active.) Regardless, the effect is that the location of the tongue body for /g/ varies throughout its duration.

In VCVCV sequences in which the vowels are not the same, an additional movement component is seen during /g/. There is a vowel-to-vowel gesture whose direction depends on the frontness/backness of the vowels, so that it can be either front to back, or back to front. This gesture is executed simultaneously with the vertical vowel-to-velar gesture, so that the two are effectively added together. Houde [1967] refers to these two gestures as the 'target-directed component' of the velar movement; these are components directed towards the velar target and the vowel target. The vowel-to-vowel movement is seen both as the tongue is raised toward the palate, and during the closure interval.

The vowel-to-vowel gesture from a front to a back vowel is obscured during /g/, however, because in those cases its effect is countered by the independent forward perturbation during stop closure. The two horizontal components – forward for the /g/, backward for the second vowel – can simply cancel each other out. On the other hand, when the vowel-to-vowel gesture is from back to front, the two horizontal components are in the same direction, and when added together result in a very pronounced forward movement of the tongue. The largest changes in contact location for /g/, up to 1 cm, are seen in these cases.

Houde's [1967] analysis of observed movements of the tongue body for velars is thus that they are the sum of three components: the vowel-to-vowel gesture (if any), the vertical velar gesture, and the closure-related forward/backward perturbation.

What is important here for our purposes is that these data indicate that velar fronting, at least in English, is a more or less continuous process during closure. The forward movement of the tongue is distributed over time. It is not the case that the entire velar contact is equally fronted before a front vowel; rather, it becomes more front during the closure, so that by the moment of release it is noticeably fronted. In a similar vein, Öhman [1966] claims that in Swedish /ygɑ/ the position for the /g/ slides from front to back during contact, but no data or detailed discussion are presented. (Houde [1967] cites this result as agreeing with his own.)

Such articulatory gradience has been hypothesized to be a characteristic of surface underspecification by Keating [1988b, 1990]. In this view, the fact that the backness of velar contact varies during closure according to vowel context is taken to show that the velar itself is relatively unspecified on this dimension. That is, the velars of English and Swedish would be specified as being articulated by the raised tongue dorsum, but the tongue's position would not be specified as back or front. The location of the velar contact would be determined by the phonetic context and thus would vary over the hard and soft palates as for vowels. If surrounding vowels have the same position on the palate, the velar would share that position; if surrounding vowels differ, then the velar will coincide with vowel-to-vowel movement.

We should note that this kind of underspecification of tongue body backness is a property of most consonants, not just of velars. For example, the X-ray tracings of /t/ before different vowels in Perkell [1969] show marked variation in tongue body position during consonant closure. Labials probably show even more variation in tongue body position across vowel contexts. That is, context effects on tongue body position are probably quite general.

What is special about velars in this regard is that the tongue body is the primary articulator, so that variation in tongue body position is also variation in the stop constriction location. For velars, variation in tongue body location affects the size of the resonating cavity in front of the constriction and thus affects the audible characteristics of the consonant noise. For labials and coronals, tongue body movement does not affect the size of the front cavity, and therefore does not affect the release acoustics as much.

Many sources in the literature, on a variety of languages other than English, provide examples of velars in various vowel contexts, usually /i,a,u/. Besides Öhman [1967], these include Wierzchowska [1980] for Polish; Dukelski [1960] for Rumanian; Miletič [1960] for Serbian; Sovijärvi [1963] for Finnish; Warnant [1956] for Wallon; Chlumsky [1938], Straka [1965], Simon [1967] and Dem'janenko [1966] for French; Botherel [1982] for Breton; Hiki and Itoh [1986] for Japanese; Farnetani [1988] for Italian (these last two being EPG studies). A few sources show velars in five different vowel contexts [e.g. Dukelski, 1960; Miletič , 1960]. These data, with more vowel contexts, show that the central contact for velars varies in location according to the frontness of the contextual vowel. The more front the vowel, the more front the velar. It would be helpful to know whether these fronted velars consistently have lateral contact in front of the central occlusion, but such information cannot be gleaned from X-rays and static palatography. Dagenais and Critz-Crosby [1991] did find such lateral contact before /i/ with 12-year-old English speakers, but it is not the focus of their study. Similarly, it cannot be determined from published data whether the point of contact changed during the occlusion interval.

In sum, velar fronting results in a constriction at the rear of the hard palate; in this respect contextually fronted velars are much like contrastively palatalized velars. Movement of the stop contact during the closure interval would seem to be an important feature of velar-vowel coarticulation in English, and as noted above, in Irish, for palatalized as well as nonpalatalized velars.

Discussion and Comparisons

All of the sound types discussed above – palatals, palatalized velars, and fronted velars – are articulated on the hard palate. Thus all of them can be said to be 'palatal' in the traditional sense [Recasens, 1990]. However, the palatals of Czech and Hungarian have a much more forward articulation on the hard palate, and contact more of its surface. It also makes sense to reserve the term 'palatal' for this sort of articulation, as is often done in more phonemically oriented descriptions of languages.

Fronting of velars between or before front vowels appears to be a robust general trend across the languages surveyed here. Although details differ across languages, back vowel contexts generally give rise to velar articulations on the soft palate, while front vowel contexts generally give rise to velar articulations on the hard palate. The precise location of the contact varies with vowel frontness. Crucially, this influence of vowel on consonant appears to be temporally gradient. In English and Swedish, when two different vowels flank the velar consonant, then the velar contact moves between the locations of the two vowels during its closure interval. We expect that this is more generally the case across languages.

Following Keating's surface underspecification approach [Keating 1988b, 1990], we hypothesize that fronting of velars is not indicative of a specified feature value for frontness (e.g. [-back] or coronal) on the velar. Instead, velars, like other consonants, are generally unspecified for the relevant feature, with a range ('window') of possible tongue positions that is about the same as the front-back dimension of the vowel space. Observed fronting arises from phonetic implementation of the specified vowel-unspecified velar-specified vowel sequence, as described by Houde [1967]. This analysis is necessarily tentative, since the data come only from sagittal X-rays. We hope that further relevant data on the time course of overall velar contact will emerge via other techniques.

A corollary of this account of velar fronting is that there is no sense in which back velars are basic and front velars special; all are equally dependent on context. That is, it would appear that there is no reason we should speak of velar 'fronting' (but not 'backing') in the first place. We can think of two reasons why fronting might appear more salient than backing to introspective linguists. The more obvious reason is the closure-related fronting for velars described by Houde [1967], a fronting that is enhanced by vowel-to-vowel fronting but potentially canceled by vowel-to-vowel backing. The less obvious reason is that front velars might have a special kind of release due to their lateral contact. Nonlow front vowels, and especially [i], generally have lateral contact, and introspection suggests that this contact is probably coarticulated with an adjacent velar as well. If this is so, the release of the velar consonant could be central only, with the lateral contact held from the consonant into the vowel. Such a release will entail a smaller-than-expected front cavity (because of the long central channel in front of the occlusion) plus a good chance of affrication (because of the small opening). This sort of coarticulated release would be a special characteristic of [ki] (and presumably [ci] as well). This idea is completely speculative on our part, since evidence from X-rays and static palatography does not bear on this point.

The palatalized velars of Russian are generally like very fronted velars. They have similar points and lengths of occlusion involving similar parts of the tongue. Their X-ray profiles are like those of velars before [i] in other languages. On the other hand, the palatalized velars before [a] seem not to show the pattern of extensive lateral contact seen before [i] and also in consonant [j]. There is no way to tell from the available data whether the lateral contact seen in /k^ji/ comes from the [i] or the [k^j] or both, or whether other vowel contexts pattern like [i]. We suspect that [i] is special in this respect, but cannot pursue the question.

Palatal stops – by which we mean stops of the type discussed here for Czech and Hungarian – are consistently articulated on the hard palate with both the blade and the body of the tongue. The contact seen in X-rays is very long (about three times that seen for velars), but that contact is mainly lateral contact extending back from the stop occlusion onto the tongue body. Comparison of the palatograms and linguograms for Czech and Hungarian indicates that the stop occlusion might be somewhat backer and longer in Hungarian than in Czech, extending further back on the hard palate and involving less of the tongue blade. The lateral contact in the two languages' palatals appears quite similar in the palatograms, but perhaps less extensive in Hungarian according to the X-rays. We have raised the possibility that these differences are due to different vowel contexts in the two language samples, with the probable /i/ context in Czech resulting in more tongue blade raising. Nonetheless, the palatals of both languages have a more forward articulation than for even palatalized or fronted velars. The stop occlusion is much further forward on the hard palate (on the diagonal rather than on the roof), and the lateral contact is much more extensive. For velars, the blade at most contributes lateral contact in front of the occlusion, while the body forms the occlusion. For palatals the blade forms the occlusion while the body contributes lateral contact behind the occlusion. The degree of tongue body raising seen in these palatals is extreme compared to other nonanterior coronal sounds and probably is done to facilitate the combination of a laminal constriction with tongue tip lowering.

Thus we have seen that these palatal stops, but not fronted or palatalized velars, have a coronal component. In Czech, the occlusion itself is coronal, while in Hungarian only the lateral contact is clearly coronal. In both languages the X-rays and the pattern of side-to-side contact show extensive raising and fronting of the tongue body in the hard palate region. This articulation corresponds to a [j] or to palatalization and is in addition to the more forward coronal articulation. It is possible to articulate sounds that do not combine these separate components [Keating, 1991]. Therefore, unlike Recasens [1990], we do not take one component to be a passive consequence of the other. Instead, we consider these sounds to be instances, at least in a fully specified surface representation, of complex segments in the sense of Sagey [1986] and subsequent work. In the articulation of the Czech segments, there is a primary coronal component and a secondary tongue body component; in Hungarian, the situation seems to be reversed.

The status of these palatals as complex segments is in the end something of a side issue here. (Equally so are other differences with Recasens [1990].) The main point is that these sounds have very little in common with palatalized or fronted velars, even when these 'velars' are articulated on the hard palate, a point made also by Recasens [1990] as well as our own earlier work.

Acoustic Comparisons

General Considerations

We turn now to the acoustic characterization of the three consonant types. The first question of interest is whether the fronted velars are acoustically distinct from the palatals. The second question of interest is whether the fronted velars are acoustically distinct from the palatalized velars. Our acoustic data are spectra of the stop consonant release.

Method

Acoustic data were collected from 1 male speaker of each of the languages under consideration (Hungarian, Czech, Russian, English). The Hungarian sample is the one used by Blumstein [1986]. Palatals and velars were recorded for Hungarian and Czech; plain and palatalized velars for Russian, and velars for English. The consonants are voiceless in all cases; though there is more aspiration in English than in the other three languages, all are sufficiently aspirated that there is no voicing source at the release. Five following vowel contexts were used, broadly /i,e,a,o,u/. Different numbers of repetitions were available for each language: five in Czech and Hungarian, four in Russian, and three in English. The Russian speaker recorded was one who had no objections to producing the combination plain /k/ plus /i/ (phonetically [kɨ] and plain /k/ plus /e/, as if it were the first syllable of the preposition /k/ followed by a vowel-initial word. The speech samples were digitized at 10 kHz and filtered at 4.8 kHz, and autocorrelation LPC spectra were computed with a 25.6-ms full-Hamming window and 14 coefficients. One spectrum was computed for the consonant release by centering the window at the burst onset [so that half the window, or 13.2 ms, spans the burst, as in Blumstein and Stevens, 1979]; another was computed for the vowel onset by positioning the left edge of the window at the beginning of the first full glottal pulses. These two spectra for each CV were then displayed together; relative amplitude is preserved within a CV token. The data are presented in figures 6-9 as superposed tracings of the two spectra for all the repetitions: plain velars in figures 6-8, palatalized velars in figure 6, and palatals in figure 9. In all figures, the solid lines are spectra at

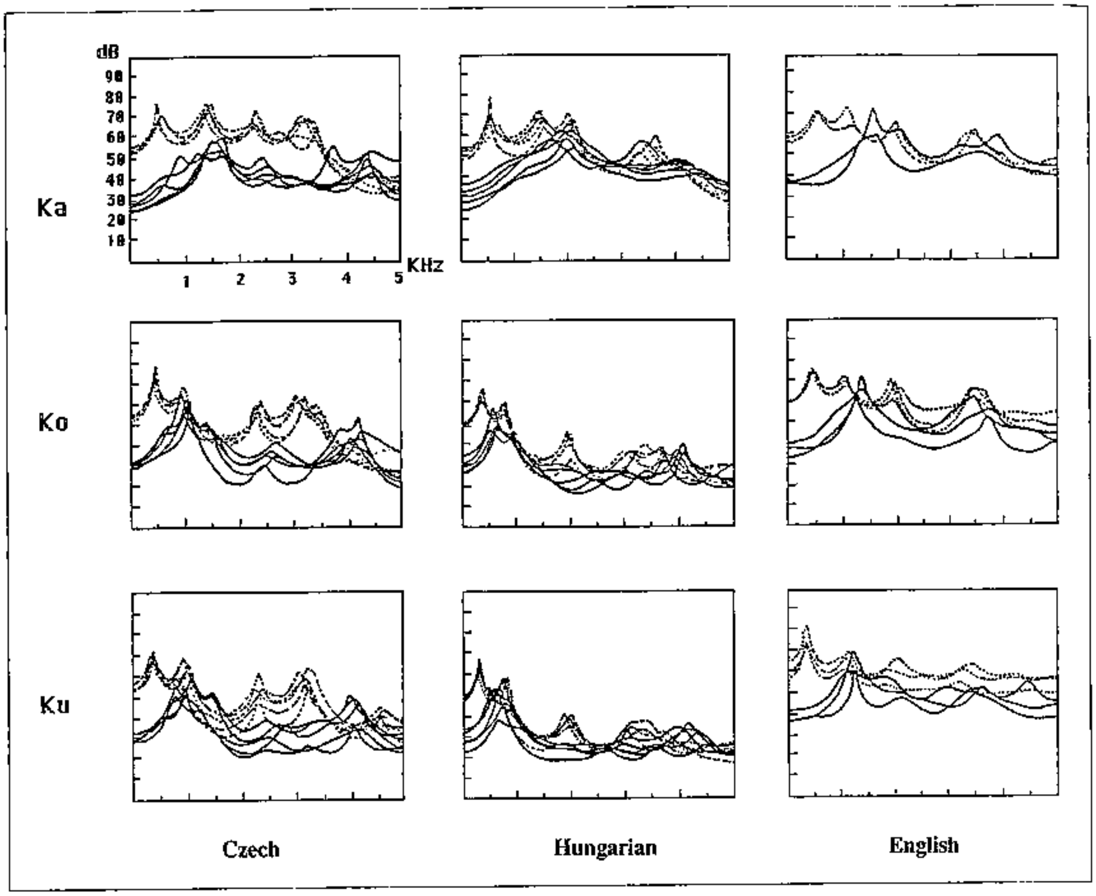

Fig. 6. LPC spectra for stop release burst (solid lines) and vowel onset (dashed lines) of velars before back vowels in Czech, Hungarian, and English. Individual spectra for each token are superimposed.

consonant releases, and dotted lines are at voiced vowel onset.

Spectra can be characterized as compact, with a main spectral peak at mid (to low) frequencies, or as diffuse, with energy more evenly distributed [Jakobson et al., 1963]. The dominant peak in a compact spectrum (or the highest-energy peak in a diffuse spectrum) can be further characterized in terms of its frequency location and in terms of its correspondence to resonances in, e.g., a following vowel [Fant, 1960]. The consonant spectrum can also be characterized relative to a following vowel in terms of overall distribution of energy and changes in that distribution [Kewley-Port, 1983; Lahiri et al., 1984; Stevens and Keyser, 1989; Halle and Stevens, 1989]. Our discussion of the data focuses on the first two of these[4]. The advantage of looking at alignment of consonant peaks with vowel formants is that it provides an informal method of cross-speaker comparison, unlike absolute frequency values. In each display of an individual CV token pairing a consonant and a vowel spectrum, we

[4] Another way of looking at spectra is discussed by Stevens and Keyser [1989], in terms of F_2 and the feature Back. Within a segment, an F_2 raised near F_3, possibly merging with it auditorily, is the main acoustic correlate of the feature value [-back]. The feature Back is used to represent, roughly, the difference between soft palate vs. hard palate tongue body artic-

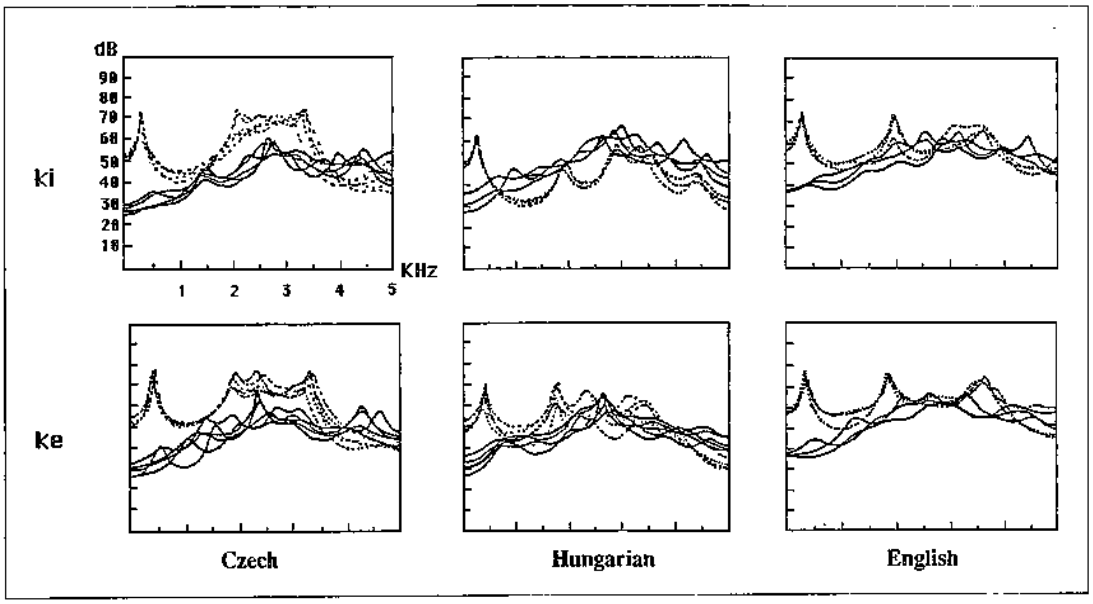

Fig. 7. LPC spectra for stop release burst (solid lines) and vowel onset (dashed lines) of velars before front vowels in Czech, Hungarian, and English. Individual spectra for each token are superimposed.

note the formant peaks in the vowel spectrum and the strongest peak in the consonant spectrum, and which vowel formant peak is nearest to the consonant peak. (Printouts of frequency values of peaks helped in this.) If the consonant peak is within about 200 Hz of a vowel formant, it is said to align with that formant, otherwise it is said to be between two formants.

Results

The data for nonpalatalized velars can be seen in figures 6 and 7. For example, the top left box in figure 6 shows the tokens of /ka/ in Czech. The dotted lines, for the vowel onsets, are fairly consistent, with F_1 at about 500 Hz, F_2 at about 1,500 Hz, F_3 at about 2,500 Hz, and F_4 under 3,500 Hz. The solid lines, for the consonant releases, are not quite so consistent; the strongest peak is at about 1,500 Hz, with another peak at 3,500–4,500 Hz, and sometimes other weaker peaks in addition. The strongest consonant peak, then, aligns with the vowel's F_2. In contrast, in Hungarian the strongest peak in the release of /ka/ is at or near F_3 (with another peak at or above F_4), and in English it is at 1,500 Hz, between F_2 and F_3 in the vowel. Within the panel for each language, the effects of different vowel contexts can be seen. Thus, for example, in Hungarian the /a/ context shows a decidedly higher peak frequency than do the rounded vowel contexts.

In our data, as in many previous studies, the spectrum at release of a velar typically is com-

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ulations. Therefore we would expect all but the nonfronted velars to show this kind of raised F_2 merged with F_3. However, this acoustic correlate cannot be applied to consonant release spectra, since these show primarily the resonances of the cavity in front of the constriction, and either F_2 or F_3 will be a back cavity resonance in the velar region.

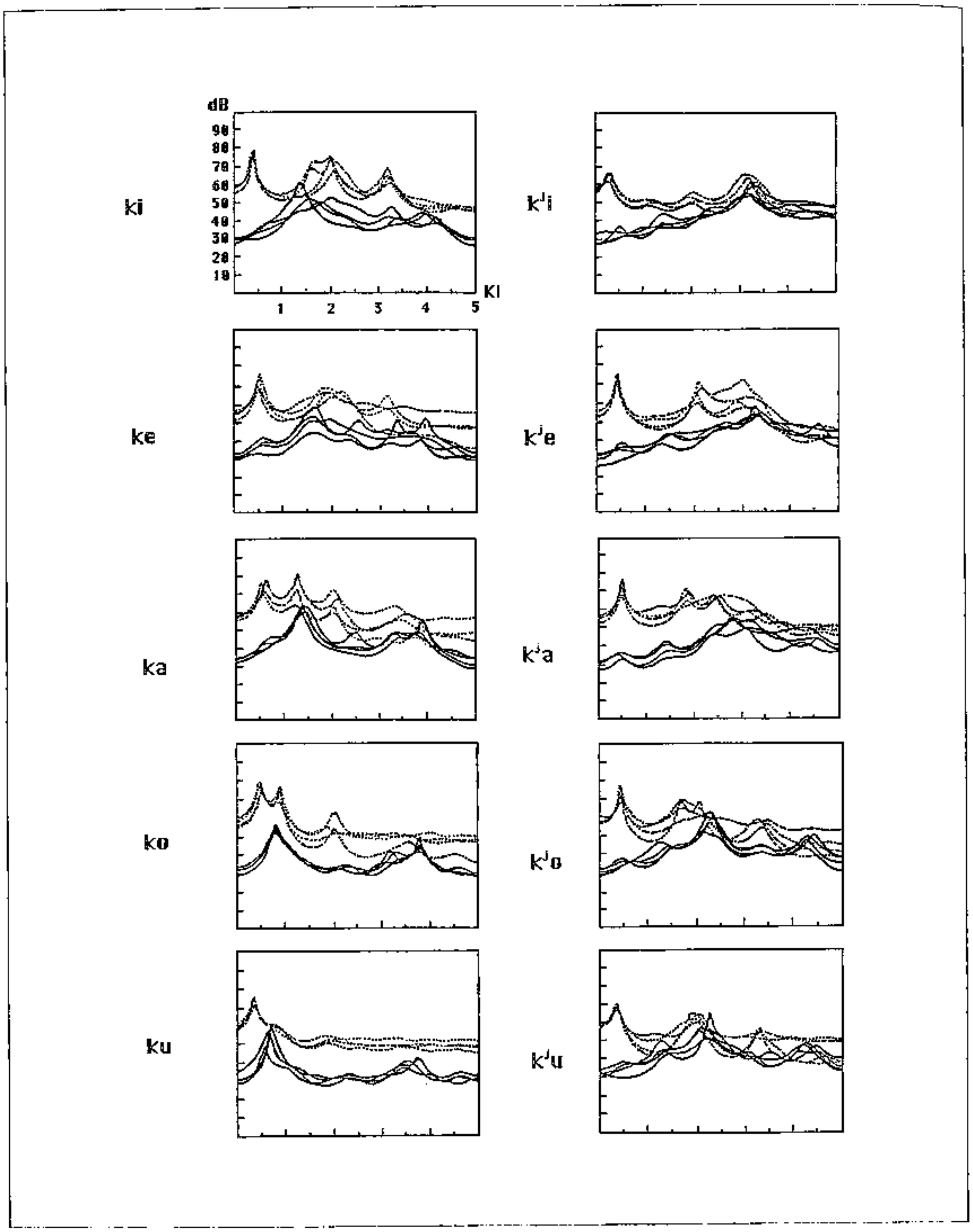

Fig. [illegible] spectra for stop release burst (solid lines) and vowel onset (dashed lines) of velars before five vowels in Russian. *Left panel* Nonpalatalized stops. *Right panel* Palatalized stops. Individual spectra for each token are superimposed.

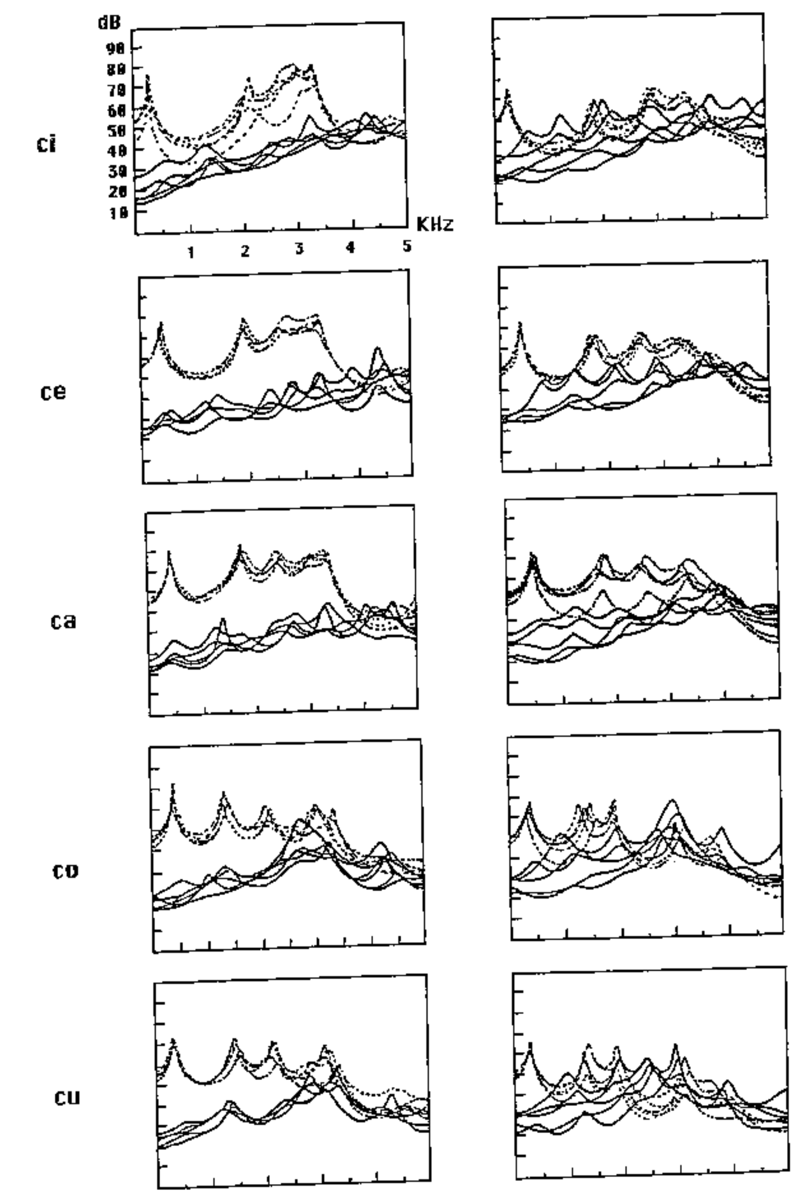

Fig. 9. LPC spectra for stop release burst (solid lines) and vowel onset (dashed lines) of palatals before five vowels in Czech *(left panel)* and Hungarian *(right panel)*.

pact, with a prominent peak at about the second or third formant frequency of, and at a similar intensity as, the following vowel. In a truly compact spectrum, the strongest peak stands out clearly from any other peaks, dominating the spectrum. In real data, however, spectra may be more or less compact. For example, English /ku/ in figure 6 shows an assortment of peaks in the release spectra. In any event, almost all velar spectra show a peak at or above about 3,500 Hz (at or above F_4 of the vowel) which is generally ignored in discussions of 'compactness', being considered out of the crucial frequency range.

The main peak in a consonant release spectrum is a front cavity resonance whose frequency value largely depends on the following vowel. Thus the velar spectra are expected to differ according to the vowel context. This is true not only in terms of absolute frequency values, but also in terms of the correspondence between the consonant peak and formants of the following vowel. Velars in front vowel contexts, seen in figure 7, have their strongest peaks higher than the vowel's F_2 but lower than the vowel's F_4. (Russian patterns differently and will be discussed below.) The overall shift up in frequency of the strongest peak in the release spectra is clear when figures 6 and 7 are compared. In Czech the peaks in /ki/ and /ke/ fall at around 2,800 and 2,500 Hz, respectively, and often correspond to the vowel's F_3. In Hungarian peaks at 3,000 and 2,700 Hz sometimes lie above the vowel's F_3. Velars before /i/ and /e/ in English generally have peaks at or below F_3. Comparing figures 6 and 7, in these three data sets the velars before front vowels differ from the velars before back vowels in this respect. In back vowel contexts, the strongest consonant peak usually lies at or below F_2 of the vowel, while in front vowel contexts it is consistently higher, and for central /a/ it is in between F_2 and F_3. The difference is less in English than in Czech or Hungarian, but on average it holds.

In this respect, our data on velars are comparable to results of previous studies [e.g. Zue, 1976; Sereno and Lieberman, 1987 on English]. In particular, discussions of velars in Swedish by Fant [1973] and Danish by Fischer-Jørgensen [1954] make similar points about the way in which the major peak in the consonant's release spectrum depends on the adjacent vowel's higher formants, and the way in which the compactness of the spectrum varies across vowel contexts. Minifie [1973] also discusses the fact that the release spectrum for velars will vary along with the contextually determined place of constriction.

A further effect of the front vowel contexts is that the consonant spectrum is less compact. Particularly for Czech /ki/ and /ke/, and Hungarian /ki/, the most prominent peak is still in the mid-frequency range, but this peak does not dominate the spectrum, since surrounding peaks are also at high levels. Also, because the main velar peak is at a higher frequency in Hungarian, it is nearer to the secondary peak above it. This gives the fronted velars in the three languages somewhat different overall spectra, with a more prominent main peak in Hungarian and Czech, and a flatter spectrum around the peak in English.

Russian differs from the other languages with respect to velar fronting. Data for the nonpalatalized velars are presented in the left panel of figure 8. Recall that phonemic /i/ is phonetically [ɨ] here. The only nonpalatalized Russian velar in a phonetic front vowel context is /ke/. This velar is very different from the /ke/ samples in figure 7: the Russian peak is under 2,000 Hz, while the others are well above it. The Russian /ke/ behaves just like nonpalatalized velars before central or back vowels. All of the nonpalatalized velars have their strongest peak in the vicinity of the vowel's F_2. Thus it appears that the Russian nonpalatalized velar is not fronted before the mid front vowel the way the velars of the other languages are, as seen in figure 7.

The data for Russian palatalized velars can be seen in the right panel of figure 8. These look much like the fronted velars in figure 7, with the peak of the consonant release spectrum at or above the vowel's F_3. The difference can only be seen on close inspection: the palatalized velar peaks are higher in frequency. At the same time, the palatalized velars are like plain, backed velars in having decidedly compact spectra, consistently flat around the main peak. Fant [1960] notes that all Russian palatalized consonants have compact spectra. Vowel context effects can also be seen with palatalized velars. Before /i/, the main consonant peak is quite high, aligned with F_4 of the vowel – the only velar of any kind to show such a high correspondence. Otherwise the main consonant peak falls between F_3 and F_4 of the vowel, closer to F_3 in the rounded vowel contexts. Palatalized velars always have a fairly high frequency peak, but it is higher – in terms of frequency and formant correspondence – before front vowels than back.

Data for palatals can be seen in figure 9. Before unrounded vowels (front vowels and /a/), palatals show spectra which slope up to a highest peak at 3–4 kHz or even higher. These spectra do not always have a single dominant peak: there may be a few peaks of similar amplitude which together dominate the spectrum in a single broad region. For these palatals, the energy of the release spectrum is strongly concentrated at higher frequencies, often strongest at the highest frequencies in the display. We consider these spectra marginally compact. Before back rounded vowels, the consonant spectra are quite compact. The main peak for /cu/ and /co/ is usually in the range of 2,500–3,000 Hz, which corresponds roughly to F_3 of the following vowel. The palatals in figure 9 are quite different from the palatalized velars in figure 8. Overall, it can be said that the strongest peak in palatal releases corresponds to a higher formant in the following vowel, thus before /i/ it is at F_4 for the velars and above that for palatals.

In sum, plain velars before back vowels have compact spectra whose main peak is low in frequency and lies near F_2 of the vowel. Plain velars before front vowels have a less compact spectrum whose main peak is higher in frequency and lies near F_3 of the vowel. Palatalized velars have a compact spectrum whose main peak is mid to high in frequency and lies near F_3 (back vowel contexts) or F_4 ([i] context) of the vowel. Palatals before back vowels have a compact spectrum whose main peak is at a mid frequency and lies above F_4 of the vowel. Palatals before front vowels have a somewhat more diffuse spectrum whose strongest peak is high in frequency and lies near F_4 of the vowel. Thus the front velars are distinguished from the palatals by spectral shape and location of main peak. Palatalized velars are distinguished from the palatals in back vowel contexts by the location of the consonant peak, and in front vowel contexts by location of peak and spectral shape: the palatalized velars are compact while the palatals are more diffuse. Thus, when release spectra are considered in relation to vowel onset spectra, all of the phonetic types under discussion can be distinguished.

Discussion

In Hungarian and Czech, velars are in contrast with palatals in all vowel contexts, and thus it is not surprising that there are clear acoustic differences between them. Furthermore, the velars before front vowels are clearly different from the velars before back vowels. Not only is the consonant peak higher in frequency, but it corresponds to a higher formant of the vowel. This difference between velars in front vs. back vowel contexts is greater in Czech and Hungarian than in English. That is, Hungarian and Czech show acoustic evidence of more velar fronting than English. This is perhaps surprising in that in front vowel contexts the fronted velars contrast with palatals; we might have expected the velars to be somewhat less fronted to keep the contrast clear. However, the fact that the spectra do indicate velar fronting in surface contrast with palatals shows clearly that fronted velars cannot be equated with, and represented as, palatals.

In Russian, /k/ before /e/ is not a fronted velar. This result is consistent with the view that Russian nonpalatalized velars have a secondary articulation of their own, namely, velarization, which consists of a mandatory backed tongue body. This articulatory requirement prevents the velars from assuming a fronted position in a front context. This finding clarifies how it is that velars can be velarized, a seeming tautology: velarization of velars is the absence of velar fronting.

The Russian palatalized velars in each front vowel context are clearly more fronted at their release than are velars in the same front vowel contexts in the other languages, especially English. Most striking is the /i/ context. In none of the other three languages does the fronted velar's peak correspond to the vowel's F_4 as it does in Russian /kʲi/. At the point of release, then, the palatalized velars before [i] are apparently more front than are the fronted velars before [i], especially in English. This difference may be related to the claim that only the palatalized velars have a positive feature specification for tongue backness: this results in a clear fronting of the tongue body which reaches a more extreme position in each vowel context.

Because palatalized velars are always fronted, the difference between palatalized and nonpalatalized velars will be largest before back vowels. In back vowel contexts, the distinction can be cast in terms of whether the main spectral peak of the consonant release is at the vowel's F_3 (in which case the consonant is palatalized) or F_2 (in which case the consonant is not palatalized). In front vowel contexts, the distinction would be at best subtle. Presumably because of this difficulty, Russian nonpalatalized velars do not occur before front vowels within words.

General Discussion and Conclusions

Comparison of Articulatory and Acoustic Data

In general terms, the more fronted a constriction in the vocal tract, the smaller the front cavity, and the higher the frequency of its main spectral peak – back velars having their main peak at the frequency of the vowel's (lowered) F_2, palatals having their main peak at the frequency of the vowel's F_4. This relation is orderly in our data, with front velars falling between back velars and palatals. There is, however, one apparent exception – palatalized velars before /i/ have their main spectral peak at the vowel's F_4, like the palatals. From this we can infer that the front cavities of palatalized velars in front vowel contexts are quite small, yet none of the articulatory data suggest very fronted occlusions. Most likely, the front cavity of these velars is decreased in size by lateral contact in front of the occlusion, which is seen in some though not all of the articulatory sources. That is, the sides of the tongue blade may be forming a kind of secondary constriction in front of the stop occlusion. Thus palatalized velars before /i/ may be weakly coronal in articulation, accounting for their acoustic similarity to the coronal palatals.

At the same time, it must be stressed that the palatalized velar spectra with peaks near F_4 are distinct from the palatal spectra. In particular, the main spectral peak is lower in frequency; furthermore, palatalized velar spectra are more compact, with palatals before front vowels generally having more than one high-energy peak in a high-frequency band. It seems clear from the articulatory data that the primary articulatory constrictions are much more front for palatals than for palatalized velars, so it is to be expected that they will be acoustically distinct. What is not clear from the articulatory data is why they are not even more distinct acoustically.

Another question raised by the articulatory data was the possibility that the Czech palatals might be systematically more front than the Hungarian palatals. The acoustic data, where vowel contexts are as matched as possible across the languages, show no obvious difference in this respect. There are noticeable differences between the two panels of spectra in figure 9, but these have to do with the vowels, not with the consonants or with the relation between consonants and vowels. This result lends weight to the alternative suggestion that the articulatory data for Czech came from fronter vowel contexts.

Summary

We have compared articulatory and acoustic data on back velars, contextually fronted velars, palatalized velars, and palatals to determine whether all of these consonant categories can be phonetically distinguished. The data suggest that all of them differ. First, the phonemic palatals have occlusions which are distinctly more fronted than the others and which are made with the tongue blade as well as the tongue body. Neither fronted nor palatalized velars have such a forward occlusion, though palatalized velars, especially before [i], may have quite fronted lateral contact. Acoustically, these palatalized velars show evidence of strong fronting. From these results we conclude that palatals are coronal, front velars are not, and palatalized velars before /i/ may be weakly so.

Second, fronted and palatalized velars are both fronted along the palate, but in different ways. Palatalized velars appear to be more fronted at release than contextually fronted velars. Furthermore, contextual fronting appears to be a continuous, gradient effect of context: the constriction location moves continuously during the closure, from a position more dependent on the preceding segment to a position more dependent on the following segment. We also saw that Russian nonpalatalized velars fail to show evidence of contextual fronting. From these results we conclude that velar stops in Russian have specifications for tongue body frontness or backness, but that velars in other languages, where palatalization is not contrastive, are not specified for front vs. back tongue positions, even in surface forms. Rather, their fronting results from phonetic implementation.

One of our initial questions was whether contextually fronted velars, articulated on the palate, should be (featurally) represented like the palatals of Czech and Hungarian. We showed that such sounds contrast on the surface in Czech and Hungarian, and so cannot be collapsed into a single category. Furthermore, the hypothesis that emerges from this study is that contextual fronting of the tongue body during consonant articulation should not be represented featurally at all, and thus the question is answered negatively. Another question was whether contrastively front velars, such as the palatalized velars of Russian and also other cases (as in footnote 1) should be represented like the Czech and Hungarian palatals. Again the answer is negative, in this case because of clear articulatory and acoustic differences.

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