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A Cross-Sectional View of s, ʃ, θ

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1. Introduction

Articulatory configurations can be described by looking at the vocal organs from two different views, the mid-sagittal and the cross-sectional. A sagittal view of the vocal apparatus is the view of a slice of the head from front to back, as seen from the side. A mid-sagittal view, in particular, is the view of the apparatus when the slice is taken along the mid-line of the head. For example, a mid-sagittal view of the tongue is a trace of the central line of the tongue, which divides its body into two longitudinal halves. A cross-sectional or transverse view is the side-to-side view of the vocal apparatus. In this paper, I will explore the behavior of the front part of the tongue from a cross-sectional view.

Traditionally, articulatory observations in the production of speech are based on a sagittal view of the vocal apparatus. The surface of the tongue, however, is adjustable in both the sagittal and the cross-sectional plane. There seems to be no *a priori* reasons why articulatory descriptions or phonological features that may be based on such descriptions should derive exclusively from the sagittal view. This is particularly true for the fricatives, whose signature property is the presence of a channel which funnels the airstream out of the vocal tract. Obviously this channel can be observed and quantified only by taking a cross-sectional view.

In fact, the phonetic reality of cross-speaker variation in the production of fricatives articulated with the tongue tip-blade appears to be rather puzzling, when one attempts to describe the data by using just the traditional mid-sagittal parameters of the active articulator, specifying whether the sound is formed with the tip or the blade of the tongue, and the place of articulation. For instance, it is known that 50% of Californian English speakers produce [s] as an apical sound and 50% as a laminal one. The same distribution applies to [ʃ]. It also known that the place of articulation of [s] in both English and French varies considerably from

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speaker to speaker, being articulated with a constriction that varies from as far forward as the dental zone to as far back as the post-alveolar zone. Apical or laminal, dental, alveolar or post-alveolar [s] always sounds like an [s] to the ears of English speakers. Ladefoged & Maddieson (1986), based on a cross-linguistic survey of coronal fricative articulations, emphasize the inadequacy of the traditional parameters by writing that "separating apical from laminal articulations does not seem to be as useful in the case of sibilants as it is when distinguishing among stop consonants or liquids" (p. 78), and that "we cannot distinguish different sibilant fricatives from one another by means of the places of articulations used for stops" (p. 93).

Perhaps it is in the acoustic domain where we might be able to extract more reliable phonetic parameters to describe such fricatives in a way that brings order and coherence to our data. Even here, however, things look equally dim. Ladefoged & Maddieson (1986) write:

The acoustic structure of fricatives seems to vary widely from individual to individual, but this really reflects only the unfortunate fact that we do not yet know what it is that we ought to be describing. We do not know how to sum up what is constant, and what is linguistically and perceptually most relevant in acoustic terms. As we do not yet have an adequate model for the acoustics of fricatives, we are in a position comparable to have to describe vowels without having the notion of formants, or at least peaks in the spectrum. (p. 59)

In this paper, pursuing another view of coronal fricatives, I present evidence that the cross-sectional dimension of articulatory control provides a solid basis not only for neatly categorizing different coronal fricatives but also for capturing the phonological contrasts in the coronal fricative inventories of different languages. Specifically, I argue for a distinctive feature, called Cross-Sectional Channel (CSC), defined on the phonetic scale of the area of the fricative channel which is created by the approximation of the tip-blade to the palate. This phonetic scale is divided into three subzones, [wide], [mid], and [narrow], allowing for (at most) a three-way distinction in terms of CSC. English is an example of this three-way distinction in the [θ]-[ʃ]-[s] triad, while other languages, like Chinese and Tohono O'odham, contrast only two values of this feature. One of the strongest arguments for CSC is its ability to make sense of the puzzling speaker-to-speaker variability in the production of coronal fricatives. I will also argue that CSC plays an important role in the phonology of languages in defining natural classes and expressing assimilatory phenomena.

The rest of this paper is organized as follows. Sections 2 to 4 examine the tip-blade fricatives of English, Chinese, and Tohono O'odham from a cross-sectional view. These languages provide the empirical basis on which the proposal for CSC rests. Section 5 sums up the evidence and defines CSC. In section 6, I discuss the issue of speaker-to-speaker variation, and in section 7 I illustrate the phonological relevance of CSC. Finally, section 8 concludes with a summary of the main points.

2. English

Dart (1991) has shown that in a sample of 20 speakers of American English the fricatives /s, z/ were 42.50% apical and 57.50% laminal (the same distribution in terms of

A CROSS-SECTIONAL VIEW OF s, ʒ, ʝ

apicality/laminality obtains for each of the two fricatives¹). Two descriptive parameters were used by Dart to categorize the data. The first parameter is the part of the tongue involved in the constriction. When the constriction is formed with contact of the tongue tip only, the articulation is called apical. When contact is only with the tongue blade, the articulation is called laminal; when both the tip and the blade make contact, the articulation is called apicolaminal. The second parameter is the place of articulation. Dart recognizes six distinct places of articulation (categories 1-6 from front to back). The Dental place corresponds to categories 1 and 2, with 1 being a forward dental and 2 a somewhat more retracted dental articulation. The alveolar place corresponds to 3 and 4, and post-alveolar to 5 and 6, the first number again corresponding to the more forward and the second to the more retracted articulation. The following table reproduces the distribution of the data reported in Dart's study, along the two dimensions just described.

1. Variability in place of articulation and apicality-laminality for [s,z]

POA	Apical [s]	Laminal [s]	Apical [z]	Laminal [z]
1	Apical [s]	Laminal [s]	Apical [z]	Laminal [z]
2	Apical [s]	Laminal [s]	Apical [z]	Laminal [z]
3	Apical [s]	Laminal [s]	Apical [z]	Laminal [z]
4	Apical [s]	Laminal [s]	Apical [z]	Laminal [z]
5	Apical [s]	Laminal [s]	Apical [z]	Laminal [z]
6	Apical [s]	Laminal [s]	Apical [z]	Laminal [z]

Key to the table above

Cell	Tokens	Cell	Tokens
Apical [s]	1	Apical [z]	6-10
Laminal [s]	2-5	Laminal [z]	11-15

This variability in the [s] data is consistent with results from previous studies (e.g. Bladon & Nolan 1977). A similar variation has also been reported for [ʒ], a sound which is usually described as a 'laminal postalveolar' (see for example, Recasens 1990: 289, 270). Ladefoged & Maddieson (1986) have found that in a set of sixteen speakers of Californian English, eight speakers produced [ʒ] as apical and eight as laminal. The apicality-laminality and the place of articulation parameters, then, are not very useful in describing the production characteristics of [s], [ʒ]. In particular, it is not at all obvious what kind of articulatory feature

¹ Each speaker produced a word-initial and word-final version of each fricative (as in *a sap, a pass*), resulting in 40 tokens for each fricative. Except for one speaker who made a consistent distinction between an apical word-initial articulation and a laminal word-final articulation, speakers did not vary their productions of the fricatives in terms of apicality/laminality in the two different environments.

could provide a basis for the contrast between these two sounds.

It is widely recognized, however, that the *shape* of the tongue plays an important role in the articulation of fricative sounds (Pike 1943, Malmberg 1963, Ladefoged & Maddieson 1986). The main source of the acoustic energy of fricatives is the turbulence produced by the airstream going through a channel created by the approximation of the tongue to some area on the palate. The shape characteristics of this channel do seem to be different for different fricatives. For example, many writers describe [s] as having a characteristic groove running midsagittally along the length of the tongue. The sides of the tongue are elevated laterally and the airstream is directed into a channel that is formed between the palate and the tongue at the place of the main constriction. Other fricatives, like [θ], are described as being flat in contrast to the grooved shape of [s].

Despite the general feeling that shape is important, there is some confusion in the literature as to what the exact classification of [ʃ] would be in terms of such a parameter. For example, while MacKay (1987:96) writes that [s], [z] are produced with the tongue slightly grooved as opposed to [θ], [ʃ] which are articulated with a flat tongue, Clark & Yallop (1990:87) have [s], [ʃ] as grooved and [θ] as flat. Nevertheless, groove is a good candidate as an articulatory basis for fricative distinctions. In fact, a feature [groove] has been proposed by Halle & Stevens to distinguish between the 'palato-alveolar' fricative [ʃ], which would be [+grooved], from the 'palatal' fricative [ç] which would be [-grooved] (Halle & Stevens 1979: 347). In taking [ʃ] to be [+grooved], Halle & Stevens apparently follow Smalley (1989), who characterizes [s], [ʃ] as grooved and [θ] as flat (like Clark & Yallop 1990).

In contrast to proposals that consider shape to be important, Catford (1977) is unique in pointing out that with respect to the acoustics it is not the actual shape of the tongue that is the crucial characteristic of fricatives but the cross-sectional area of the channel between the tongue and the palate. In his own words:

Some writers (for example, Pike 1943) have used the terms *groove(d)* and *flat* or *slit* to characterize different transverse shapes of the articulatory channel. According to this terminology [θ] is flat and [s], for example, is grooved. However, it is probable that the crucial characteristic here is not the transverse shape of the channel, but its cross-sectional area. Thus [θ], irrespective of the *shape* of its channel, has a channel area that is three or four times that of [s], and this means that for a given volume-velocity the velocity of air-flow through the [s] channel is three or four times that of flow through the [θ] channel, and it is this velocity difference which is crucial. (p. 153)

Although Catford seems convinced of the significance of the [s]-[θ] distinction in terms of the cross-sectional area, he goes on to write that "it is just possible that, on the average, the channel area of [ʃ] is somewhat larger than that of [s], although there is not much evidence for this" (p. 154).

With this in mind, I will now proceed as follows. First, I confirm the irrelevancy of the actual shape of the channel parameter for the articulation of English [ʃ], eliminating the confusion about whether [ʃ] is flat or grooved. It can be either. Then, I provide evidence that the correct dimension of distinction among all three fricatives, [s]-[ʃ]-[θ], is indeed the cross-sectional area. This will serve as the basis of contrast between the English coronal fricatives,

and for the coronal fricatives of other languages as well, as the following sections will argue.

Consider first the assumption of Halle & Stevens that [ʃ] is grooved. Ladefoged & Maddieson (1986: 67) show a transverse view of the shape of the tongue for [ʃ] which is in fact convex (i.e. arched). If the tongue were grooved, then the expected shape would be concave (i.e. depressed or sunken), not convex. However, the portion of the tongue whose cross-sectional shape is pictured in Ladefoged & Maddieson (1986) is just below what seems to be the postalveolar part of the palate, while the main constriction seems to be right at the alveolar ridge. Perhaps, then, a groove could exist in the part of the tongue under the alveolar place of articulation.

The situation is clarified in Stone et al. (1992). Using ultrasound, Stone et al. were able to produce images of the tongue's surface by scanning the soft tissue with an ultra-high-frequency wave. This technique is particularly informative for the kind of information we are seeking here. The subject of this study produces [s] with a mid-sagittal groove along the entire length of the tongue. For [ʃ], however, only the posterior part of the tongue was grooved mid-sagittally, while the dorsal and anterior parts were oblique, creating a parasagittal air channel, directing the airstream more out of one side of the tongue than out of the other. Schematically, the different shapes of [s] and [ʃ] channels can be represented as in (2) below. The lines depict the cross-sectional outline of the surface of the anterior tongue, as seen from the frontal view. The anterior part of the tongue corresponds roughly to the part under the alveolar place of articulation, that is, the tip-blade of the tongue.



It is thus clear that grooving is not a characteristic of this [ʃ]. However, when the cross-sectional channel areas of the two fricatives are compared, a consistent relation emerges. Stone et al. note that although [ʃ] did not have a groove anteriorly its "air channel, created by a parasagittal depression, was quite deep (7.2 mm)" (p. 260), while [s] had a groove of 5.9 mm. Stone et al. do not report width measures, but it is clear from (2) above, which preserves the relative lengths from the ultrasound images of Stone et al., that the width for [ʃ] is greater than for [s]. The estimates I have computed from the ultrasound images are 20 mm for [s] and 35 mm for [ʃ]. Combining the width and depth measures of the channel, it is clear that the cross-sectional channel area of [ʃ] is considerably larger than that of [s].

To compute the approximate measure of the channel area above, I have multiplied channel depth by channel width. This approximation involves two simplifications. First, I view the channel as a triangle. Two such triangles are shown in (2) above: the channel with the mid-sagittal groove corresponds to an isosceles triangle, and the parasagittal channel corresponds to a right triangle. In the actual shape of the channel, the two sides of the triangle corresponding to the raised sides of the tongue will not be straight but curved, as will also be the base of the channel corresponding to the usually convex surface of the palate. The second simplification is that I ignore the constant factor of $\frac{1}{2}$, which actually is involved in the calculation of a triangle's area. For current purposes, however, these simplifications

suffice in providing us with rough estimates of the actual channel areas, given that what is important here is the area difference between different sounds, and not the precise areas of the individual sounds.

In evaluating the generality of the evidence above, we must first consider the fact that the subject produces, perhaps somewhat unexpectedly, a parasagittal channel for [ʃ]. Yet such individual 'peculiarities' in articulation seem to be the canon, as shown by Hamlet (1987) who finds that 37% of 357 subjects produce [s] with an asymmetrical channel, similar to the parasagittal channel for [ʃ] produced by the subject of Stone et al. (1992). Second, the validity of the cross-sectional area difference between [ʃ] and [s] finds additional support in Ladefoged (1957), who reports that in a palatographic survey of 164 speakers of English "for every speaker the articulation of the voiceless fricative in *ship* involves the formation of a narrower channel (which is usually also further forward) than in *ship*."

These results imply that the tentative proposal of Halle & Stevens (1979) for a feature [+/-groove] cannot be maintained. As I pointed out earlier, the feature [groove] was proposed to distinguish between the 'palato-alveolar' [ʃ] which would be [+grooved], and the 'palatal' fricative [ç] which would be [-grooved]. We now know that these two fricatives cannot be distinguished on the basis of this feature, because grooving is not a reliable characteristic of [ʃ]. In the next section, I propose to distinguish them in terms of the different active articulators involved in these two sounds.

Next consider the fricative [θ]. Variation in terms of place of articulation and apicality-laminality can also be found here. According to Catford, one articulation of [θ] is as a 'lamino-dental', where the tip touches the backs or the rims of the lower teeth and the lamina is in contact with the upper teeth (Catford 1977: 152). Another articulation of [θ] is as an 'apico-dental', where the emphasis is on the contact of the tip of the tongue with the upper teeth, irrespective of the fact that there is also some lamino-alveolar contact (p. 151, 154). Yet another articulation is as an 'apico-alveolar', where the contact of the tip is immediately behind the upper teeth on the flat part of the alveolar zone (p. 151). A similar 'apical' articulation is also noted by Ladefoged & Maddieson (1986) 'with the tip of the tongue behind the upper front teeth' (p. 62). Ladefoged & Maddieson (1986) also comment on the term 'interdental' which is typically used for [θ]. They report that 90% of 28 Californian English native speakers produce this sound with the tip protruded between the teeth. Ladefoged & Maddieson choose to call this latter articulation 'laminal', because the constriction is between the lamina and the upper teeth. In a study of 28 speakers of British English, Ladefoged & Maddieson find that only 10% of the speakers have this type of 'interdental' articulation. The other 90% have what has been referred to above as an 'apico-dental' articulation. To sum up, at least four different articulations of [θ] have been noted: [θ] can be produced with the tip protruded between the upper and lower incisors, with the tip behind and in contact with the upper incisors, with the tip behind the lower incisors, and with the tip behind the upper incisors but making no contact with the teeth ridge. No doubt, this sound also shares the same variability in terms of place of articulation and apicality-laminality as I have documented for [ʃ] and [s] above.

Concerning the channel characteristics of [θ], however, there is general agreement

that [θ] has a wider channel than [s] or [ʃ]. As noted, Catford (1977: 153) estimates the channel area for [θ] to be three or four times that of [s] and also significantly greater than that of [ʃ]. Stone & Lundberg (1996) note that [θ] is grooved shallowly throughout, and with the surface of the tongue more laterally spread anteriorly than for any of the other sounds, implying significant differences in channel width. The electropalatographic results from the same study also clearly show a very wide channel for [θ], as compared to the channel of [ʃ] or [s]. (Data are reported from a subject different from that of Stone et al. 1992.)

In short, there is abundant evidence that the three English fricatives [θ], [ʃ], and [s] are distinguished by their cross-sectional area, according to the scale [θ] > [ʃ] > [s].

3. Chinese

Another language of interest is Chinese, which has two fricatives, an "s"-type fricative [s], and a "sh"-type fricative [ʃ]. Data are drawn from Ladefoged & Wu (1984) who provide X-ray photographs and palatographic information from three speakers of Standard Chinese. For all three speakers, [s] is produced with the tip of the tongue raised to form a constriction at some point in the front palate. The characteristic groove of [s] is seen in all three speakers, although as Ladefoged & Wu point out, it is not as deep as that for the English [s]. Finally, the exact location of the channel is different for each speaker, being on the teeth for speaker A, behind the teeth for speaker B, and further back on the alveolar ridge for speaker C. Despite this difference, the cross-sectional areas of the [s] channels of the three speakers turn out to be very similar. Given the data in (3), providing channel width and depth information, I have computed the cross-sectional areas of the channels. It can be seen that the area measurements range from about 3.75 to 4.5 mm².

3. [s]	<i>Width</i>	<i>Depth</i>	<i>Channel area</i>
Speaker A	< 3.75 mm	1 mm	< 3.75 mm ²
Speaker B	4.5 mm	1 mm	4.5 mm ²
Speaker C	3.75 mm	< 1 mm	< 3.75 mm ²

Turning to the "sh"-type fricative [ʃ], all three speakers produce this sound with the upper surface of the tip. The constriction location is more consistent than for [s], being around the center of the alveolar ridge for all three speakers. It is clear from the X-ray photographs in Ladefoged & Wu that this sound is different from a typical apical sound. In fact, different classifications of this sound have been given in different studies. For example, while Ladefoged & Wu write that it is formed "with the upper surface of the tip of the tongue" (p. 271) and avoid labelling it as either apical or laminal, Ladefoged & Maddieson (1986: 71) call it laminal. Perhaps, the most descriptively accurate characterization would be in terms of the 'upper apical' category proposed in Dart's study discussed below. But whatever the exact characterization of that sound may be in terms of the part of the tongue involved, it is clear that no useful distinction between [s] and [ʃ] in Chinese can be drawn in terms of the apical vs. laminal parameter, exactly as was the case with English [s] and [ʃ].

Turning to cross-sectional area, however, the same relationship established between English [s] and [ʃ] obtains here between Chinese [s] and [ʃ]. Although Ladefoged & Wu do

not give all the necessary information for the [ʃ] channel measures they do remark that “both the height and the width of the channel are greater than in [s]”. It follows that the area of the channel for [ʃ] is consistently greater than for [s] for all three speakers.

Chinese has another fricative [ç] for which there are no available channel measures. For this fricative the tongue is at a much higher and more retracted position than for [s] or [ʃ], hence Ladefoged & Wu’s characterization of this sound as a ‘palatalized postalveolar’. From the X-ray photographs provided in Ladefoged & Wu it appears that this sound belongs to the category of sounds known as ‘front palatals’ (Recasens 1990), such as the approximant [j] in English *you* and the voiceless fricatives of Japanese *hito* and German *ich*. These sounds are produced under the regime of another articulator, which includes the pre-dorsum and the medio-dorsum (in Recasens’ terms), as opposed to the tip-blade articulator employed for [s] and [ʃ]. I assume that a different active articulator suffices to provide the needed distinction between [ç], on the one hand, and [s]-[ʃ], on the other hand, the latter two fricatives being distinguished by the proposed feature of cross-sectional area.

The last point takes us back to the proposal by Halle & Stevens (1979) discussed in the previous section. Halle & Stevens used the feature [groove] to distinguish between [ç] and [s]-[ʃ], although apparently also aware of some differences in terms of the active articulator. As argued in the previous section, grooving is not a reliable characteristic of [s]-[ʃ] (or [ʃ]), and thus it cannot be employed as a phonological feature². The proposed new distinction in terms of the cross-sectional area of the channel is relevant to fricatives produced with the tip-blade articulator only. Other distinctions between fricatives are to be drawn in terms of the active articulator.

4. Tohono O’odham

Formerly known as Papago, Tohono O’odham is an Uto-Aztecan (Tepiman) language of Arizona. My data come from the linguagraphic and palatographic study of eight speakers in Dart (1991, 1993). O’odham has two coronal fricatives, an “s”-like [s], and another sound which is somewhat ‘intermediate’ between an “s” type and a “sh” type, labeled [ʃ]. In the table in (4) shown in the next page I have reproduced Dart’s results, in the following format. For every speaker (1-8) there are four cells. In the [s] and [ʃ] columns, the top two cells indicate whether [s], [ʃ] are formed by an apical or a laminal constriction, and the bottom two cells give the corresponding places of articulation. The definitions of apical and laminal are the same as those given in the discussion of English in §2.

Reviewing the results in this table, five out of eight speakers produce [s] with a laminal constriction and three of them produce it with an apical constriction. On the other hand, six out of eight speakers produce [ʃ] with an apical constriction at the postalveolar zone, while speaker 7 forms the apical constriction at the alveolar zone, as he does for [s], but with [ʃ] articulated slightly farther back. The last speaker made no distinction in terms of

² See Lahiri & Blumstein (1984) and Keating (1988) for discussion of other aspects of Halle & Stevens (1979).

Dart's parameters, with both fricatives being apical alveolar, but again [s] was formed at the front edge and [ʃ] at the farthest back edge of the alveolar region, the distance between the two points of articulation being 5-6 mm.

What seems to be clear from this table is that [ʃ] is consistently apical. However, [s] is not consistently laminal or apical, and seems to be formed somewhat further forward than [ʃ]. Also, the place of articulation of [ʃ] is not consistently postalveolar (witness the data on speakers 7, 8). These problems are by now familiar. We saw that variation in the place of articulation was also found in the productions of [s] by three speakers of Chinese, and in the productions of [s], [ʃ] by twenty speakers of American English (Ladefoged & Wu 1984, Dart 1991). Variation in the apical-laminal parameter was found in the productions of [s], [ʃ] by sixteen speakers of Californian English, and in the productions of [s], [z] by twenty speakers of American English and twenty-one speakers of French (Ladefoged & Maddieson 1986, Dart 1991).

4. Eight O'odham speakers' characteristics of [s], [ʃ]

☺	[s]	[ʃ]	☹	[s]	[ʃ]
1	laminal alveolar	apical postalv	5	apical alveolar	apical postalv
2	laminal alveolar	apical postalv	6	laminal alveolar	apical postalv
3	laminal alveolar	apical postalv	7	laminal alveolar	apical alveolar
4	laminal dental	apical postalv	8	laminal alveolar	apical alveolar

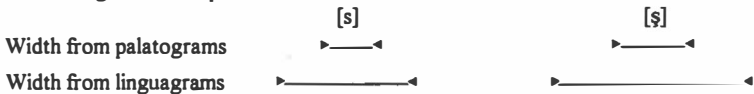
I now turn to examine the cross-sectional area differences between these two sibilants, which will turn out to be more meaningful. Dart provides measurements of the channel width, given in the table in (5) below.

5. Channel width measurements (in mm) for [s], [ʃ] (from the palatographs)

☺	[s]	[ʃ]	☹	[s]	[ʃ]
1	7	15	5	3	13
2	4.5	5	6	8.5	9
3	8	10	7	8	8
4	6.5	6.5	8	5	6

Except for speakers 4 and 7 who have the same channel width, all speakers exhibit greater channel width for [ʃ] than for [s]. It is crucial to point out that this channel width is measured from the palatograms, not from the linguagrams³. Dart carefully observes an important difference between the palatograms and the linguagrams. Looking only at the linguagrams a “wider channel appeared to occur for all the speakers” (Dart 1993: 32, emphasis DG). However, when the palatograms are examined some speakers have quite comparable, indeed equal width spans. This situation is depicted schematically in (6) below. The widths of the palatograms are shown on the top, and are indicative of the widths of the cross-sectional channels of [s] and [ʃ], indeed relatively similar in span. This much of the palate, outlining the upper boundary of the channel, was not contacted by the tongue. In contrast, the linguagrams show a marked difference in span length, which comprises the parts of the tongue forming both the lower and the lateral parts of the channel.

6. Inferring channel depth



This difference between the palatograms and the linguagrams allows us to infer, as Dart does, that there is a much deeper channel in the tongue for the articulation of [ʃ] than for [s]. Given that the cross-sectional area is the product of channel width by channel depth, it follows that the area of [ʃ] is larger than that of [s]. Crucially this is true even for speakers 4 and 7 who have equal palatographic widths for [ʃ] and [s], because according to Dart all speakers had a substantially wider linguagrammatic width, and thus deeper channel, for [ʃ] than for [s].

This suffices to establish once again that there is a consistent relation between the cross-sectional areas of the channels for [ʃ] and [s], with [ʃ] > [s]. Although the same contrast appears to be widespread in aboriginal Californian languages, the lack of available data unfortunately precludes an extension of this result to these other languages as well.

5. The Feature Cross-Sectional Channel

The previous sections have examined data from different languages which include three cases of “s” fricatives, [s] of English, [s] of Chinese, and [s] of O’odham, and three cases of “sh” fricatives, [ʃ] of English, [ʃ] of Chinese, and [ʃ] of O’odham. I have noted that within each language there is often a puzzling cross-speaker variation in shape, place of articulation, and/or apicality-laminality for each individual sound. However, there is significant

³ A palatogram or a linguagram is taken by painting a subject’s palate or tongue with a dark liquid, and having the subject utter a test word, containing only one consonant which requires contact of the tongue with the palate. Immediately after the word is produced the subject sticks his/her tongue out, and a photograph is taken of either the area of the palate that has come in contact with the painted part of the tongue, producing a palatogram, or the part of the tongue that has come in contact with the painted palate, producing a linguagram. See Ladefoged (1968: xv), Dart (1991: 11) for precise descriptions of these methods of investigation, and Abercrombie (1957) for the history of this over a hundred years old technique.

evidence to support the claim that in the examined languages the “sh”-like fricatives consistently have a greater cross-sectional area than the “s”-like fricatives. Moreover, in English the cross-sectional area of [θ] is also consistently greater than that of [ʃ].

I therefore propose a new feature, which I will call cross-sectional channel (CSC), to express the contrasts among these fricatives. CSC is defined on the phonetic scale of the cross-sectional area of the fricative channel. As with any phonetic scale, there is a continuum of cross-sectional area values. This continuum appears to be divided into three subzones, giving rise to a three-way categorical distinction among [wide], [mid], and [narrow] cross-sectional channels. Some languages, like English, employ the full triad of contrasts, with [θ] corresponding to the [wide] value of CSC, [ʃ] to the [mid], and [s] to the [narrow], as shown in (7) below.⁴

7. CSC scale: [wide] > [mid] > [narrow]
 θ ʃ s

Other languages, like Chinese and O’odham, employ only two values from this scale, presumably [wide] and [narrow], although there is not much evidence as to which pairs of values on the scale are being contrasted.

6. Speaker-to-Speaker Variation

CSC enables us to come to terms with the puzzling cross-speaker variability noted in previous sections. We saw, for example, that in a study of 20 speakers of English it is found that the ‘alveolar laminal’ [s] and its voiced counterpart [z] are produced at a total of six distinct places of articulation, and 42.50% of the time as apical and 57.50% of the time as laminal. This variability in the data is the sort of thing for which phonology is typically considered not responsible, its accounting being relegated to ‘low-level phonetic rules’ which take the phonological output and map it onto the physical world. Irrespective of one’s general position on the latter view, this is not an option for the case at hand. For, in the production of English [s], the variability manifests itself precisely in terms of the same parameters used in the phonological specification of [s]. This indicates that the problem lies in what we consider to be the parameters of [s]’s phonological specification.

The proposed solution to the variability problem is to elevate the search for invariance to a more abstract level. At that level, the roles of the descriptive parameters of shape of the articulator, place of articulation, and apicality-laminality are secondary in the sense that they are engaged in a synergistic way to effect the realization of the phonological contrast in terms of the CSC. Specifically, consider the variability in terms of each of the descriptive parameters. First, there is variability in terms of the actual shape of the channel. Some speakers of English, e.g. the subject studied in Stone et al. (1992), implement the [mid] value of CSC for [ʃ] by a para-sagittal channel, instead of forming a symmetric hollowing of the tongue by raising both of its sides. By the definition of CSC, the actual shape of the channel,

⁴ See the arguments in Ladefoged (1988) that distinctive features can be multivalent. Fant (1973: 175) also points out that distinctive features need not be binary.

para-sagittal or mid-sagittal, is irrelevant, as long as the channel area difference is attained faithfully. The second type of variability is in terms of place of articulation. For example, the three speakers of Chinese studied in Ladefoged & Wu (1984) had slightly different places of articulation for [s], and Dart's 21 speakers of English articulated [s] at up to six different places covering the entire area from the dental to the back of the postalvelolar zone. The third type of variability is in terms of the apicality-laminality parameter. English speakers produce apical and laminal versions of [s] and [ʃ] (Dart 1991, Ladefoged & Maddieson 1986). O'odham [s] is produced as laminal by five speakers and as apical by three speakers. The conclusion is inescapable that the exact place of articulation and apicality-laminality of the fricative gestures are not essential. What matters is the formation of a channel, the definitional characteristic of fricatives, whose cross-sectional area must be made significantly different for two contrastive fricatives for the same speaker.

This is not to say that apicality-laminality and place of articulation can vary freely. A salient statistical trend in the data is that "sh"-like fricatives tend to be formed farther backward than "s"-like fricatives and with blade of the tongue making contact at some point in the alveolar and/or post-alveolar zones (Ladefoged 1957; see also the results reported in Dart 1991 reproduced here in the section on English). There seems to be a simple interpretation of this tendency in terms of the CSC feature. The tongue's width narrows towards its front end. The formation of a wider and deeper channel requires a greater tongue width, because laterally the tongue raises symmetrically or asymmetrically to form the sides of the channel, hence the more retracted and usually laminal articulations of the "sh"-type fricatives. However, these tendencies are merely statistical and as such they cannot be elevated individually to the status of phonetic properties implementing a phonological contrast. Their exceptions will be the norm because individuals' oral morphology differences, in terms of dentition, palate height and asymmetry, tongue length and width, are the norm (see Best & Queen 1989, and the earlier discussion of Hamlet 1987).

In a more general context, both the variability problem and the proposed solution are signature characteristics of sensorimotor systems of skilled actions. The first goes under the name of 'motor equivalence'. Hughes & Abbs (1976) define this term as "the capacity of a motor system to achieve the same end product with considerable variation in the individual components that contribute to that output" (p. 199). Turvey (1980) identifies the type of solution I proposed as another characteristic property of skilled behavior, which he calls 'indefiniteness of action plans'. According to this property, plans for actions are indefinite in the sense that "they are not 'written' in muscular predicates but in predicates of a more abstract kind" (p. 46). CSC is such an abstract predicate or phonological primitive. Its implementation does not specify the exact values of shape, place, or apicality-laminality, but instead coordinates the aggregate of these attributes into achieving the realization of the phonological contrast in terms of the CSC.

7. Phonology of CSC

CSC plays an important role in capturing natural classes in the phonological organization of languages, ultimately the role of any phonological feature. In a typological study of consonant harmony in Gafos (1996), I have argued that assimilation in terms of the

feature CSC is one case of this phenomenon, attested especially in the languages of the aboriginal North America and Alaska.

I illustrate this phenomenon with Tahltan, an Athabaskan language spoken in Northern British Columbia, in the vicinity of Iskut, Dease Lake and Telegraph Creek⁵ (Hardwick 1984, Shaw 1991). Tahltan, like other Athabaskan languages, has a very rich coronal consonant inventory, containing five distinct series of coronals. Only three out of the five coronal series participate in consonant harmony. Interestingly, these are the three series of fricatives and their affricates, shown in (8) below. The other two coronal series, the coronal stops and the laterals (/d, n, n'/ and /dl, tʰ, tʰ', t, l/), are completely transparent to the harmony process.

8. The three series of harmonizing sounds

θ	s	ʃ
dθ	dz	d
tθ	ts	tʃ
tθ'	ts'	tʃ'
θ	s	ʃ
θ̄	z	ʒ

Examples of the harmony are given below. Underlined in (9), I show the first person singular subject marker /-s-/ surfacing as [θ] if followed anywhere in the word by any member of the [θ] series (9a), as [ʃ] if followed by any member of the [ʃ] series (9b), and as [s] elsewhere (9c). Also the initial /θ/ of the first person dual subject prefix /θi(d)-/ in (10a) surfaces as [s] or [ʃ] before sounds of these two series, as shown in (10b,c) respectively.

9. First person singular /s/

- a. θeθθeɬ 'I'm hot'
deθkʷuθ 'I cough'
eθduuθ 'I whipped him'
mεθeθeθ 'I am wearing'
naθtθ'et 'I fell off (horse)'
- b. hudiʃtʃa 'I love them'
eʃdʒɪni 'I'm singing'
teneʃtʃuuʃ 'I'm folding it'

10. First person dual subject /θi(d)-/

- a. deθigtɬ 'we threw it'
naθibaɑtɬ 'we hang it'
θiitθædi 'we ate it'
- b. deʒidzɛl 'we shouted'
xoʃiidets 'we plucked it'
niʒit'ɑɑts 'we got up'

⁵ I wish to thank Keren Rice for her assistance with various issues on Athabaskan sound structure, and for providing me with Margaret Hardwick's manuscript on Tahltan phonology and morphology.

c.	ešk'aa	'I'm gutting fish'	c.	išitšotł	'we blew it'
	ešda	'I'm drinking'		ušidže	'we are called'
	sešxet	'I'm going to kill it'		tedenešidžut	'we chased it away'
	nešet	'I'm sleepy'			

The Tahltan assimilation is a straightforward case of assimilation in terms of CSC. This feature correctly and directly captures the striking property of this harmony, which singles out the three series of coronal fricatives and their corresponding affricates. The theoretical implications of the CSC proposal for the proper treatment of consonant harmony are explored in detail in Gafos (1996).

8. Conclusion

In this paper, I have explored the behavior of the front part of the tongue in a cross-sectional view. While some traditional beliefs about the importance of the actual tongue shape were found to be factually incorrect, I have identified a phonetic scale, the cross-sectional area of the channel, on which I have defined a new feature, CSC, with three contrastive values [wide], [mid], and [narrow]. CSC provides the needed phonological contrasts among the fricatives of different languages. An important virtue of CSC is its ability to account for the widespread cross-speaker variation observed in terms of the descriptive parameters of place of articulation, apicality-laminality, and shape of the tongue. Finally, CSC also plays a role in phonological patterning by capturing natural classes in the phenomenon of consonant harmony.

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