Phonetic explanations for the infrequency of voiced sibilant affricates across languages

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Abstract

This paper shows that several typologically unrelated languages share the tendency for voiced sibilant affricates to be infrequent or missing altogether. Phonological processes examined in the paper illustrate that (1) voiceless stops undergo affrication more readily than voiced ones, and (2) voiced affricates deaffricate more commonly than voiceless ones, thereby contributing to the asymmetry in frequency between voiced vs. voiceless affricates.

Phonetic properties of the sounds may explain these patterns. Affricates in general require complex control over supralaryngeal apertures, and they appear to have long durations in many languages. Long duration and complete oral closure at the beginning of affricates contribute to a buildup of intraoral pressure which impedes phonation. An aerodynamic experiment of obstruents, including affricates, was carried out for Polish and German, languages which differ in their realization of the stop voicing contrast (viz., voicing vs. aspiration). Voiced affricates in Polish had significantly longer voicing than in German; in medial position, they also had shorter durations and lower peak pressure values. We suggest that languages having voiced affricates in their phoneme inventory may tend to limit duration and intraoral pressure buildup in these sounds to allow vocal-fold vibration to continue.

1. Introduction

To explain cross-linguistic patterns in phonological systems, researchers have frequently appealed to phonetic factors, seeking to ground classical phonological notions of markedness (e.g., Jakobson 1972 [1941]; Chomsky and Halle 1968) in phonetic characteristics. This general approach to phonological systems is reflected in the works of Liljencrants and Lindblom (1972) and Stevens (1972); see also review by Schwartz et al. (1997). In this tradition, various types of gaps in phonemic inventories of the world's languages have been accounted for by

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considering aspects of the production or perception of the sounds in question. For example, cross-language data show that the voiced velar stop /g/ occurs less frequently in phonemic inventories than its voiceless counterpart /k/ (Maddieson 1984; Boersma 1998). As discussed in more detail below, Ohala (1983) related this relative rarity of /g/ to the difficulty of maintaining the aerodynamic requirements for phonation when the cavity behind the supraglottal constriction is short.

This paper will likewise consider how phonetic considerations, including aerodynamic ones, may help account for the rarity of another sound type, namely voiced affricates. We will show that voiced affricates represent a specific gap in many coronal inventories, and give examples of phonological processes showing that voiced affricates are less frequently created, and more likely to be deaffricated, than their voiceless counterparts. We will then present aerodynamic data on affricates in Polish and German which may provide some explanations for their infrequency across languages.

A basic assumption behind seeking explanations for phonemic gaps is that phonological systems tend towards symmetry, such that contrastive features will tend to be used in parallel across the inventory. The general expectation of symmetry in phonological systems can be observed, for example, in classical distinctive feature theory (e.g., Jakobson, Fant, and Halle 1952; Jakobson and Halle 1956; Chomsky and Halle 1968; Clements 1985; Hall 2001), which placed a premium on maximizing the use of a small set of distinctive features (e.g., Clements 2003). For example, if a language uses a voicing contrast for an obstruent at one place of articulation, one generally expects to observe voicing contrasts for other places of obstruent articulation. Thus, differences in sound frequencies, including phonemic gaps, call for explanations, and we expect that sounds that are lower in frequency (or which represent systematic gaps) may have aspects of production and/or perception that make them “difficult.” This issue has been widely discussed in phonetic approaches to vowel inventories (cf., e.g., Schwartz, Boë, and Abry 2007, and citations therein). Lindblom and Maddieson (1988) have argued that consonant systems are shaped by factors similar to those that have been discussed for vowel systems, such as maintaining perceptual distinctiveness at “minimum articulatory cost.”

As a starting point for discussion, Figure 1 shows the number of voiced and voiceless stops, fricatives, and affricates from the P-base database (Mielke 2007). This database contains data from 548 typologically different languages (if varieties of a language are included, the database expands to 627 phonemic inventories). To maximize typological variation, this figure excludes language varieties. For simplicity, it also excludes consonants with secondary articulations.[1] Finally, these data are restricted to coronal places of articulation. Two considerations justify this last restriction, both related to the purposes of the current work. First, we are interested in the characteristics of strident affricates, and in contemporary phonological theory stridency or sibilance is only distinctive at coronal places of articulation; thus, e.g., /θ ð/ are [−strident] whereas /s z/ are [+strident] (Lahiri and Evers 1991;

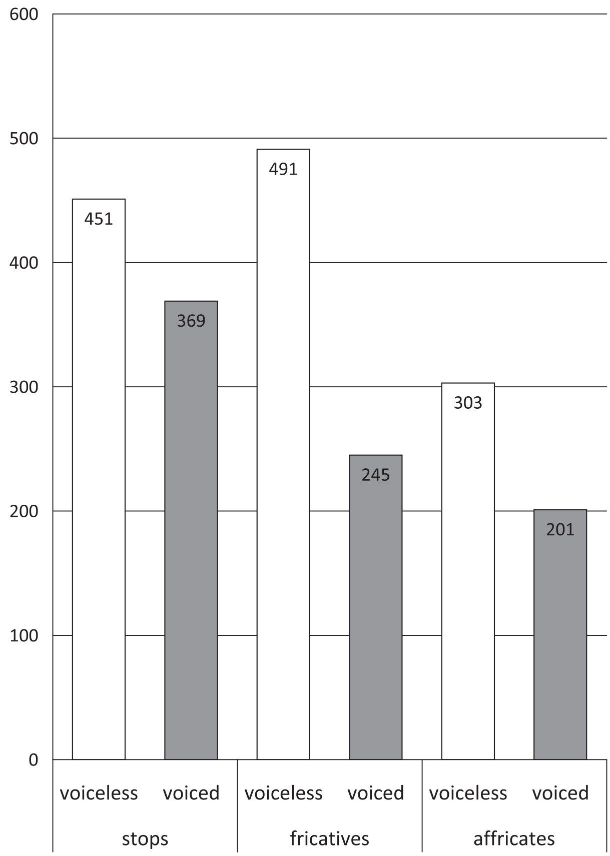

Figure 1. *Frequency of occurrence of coronal voiced and voiceless obstruents based on P-base (Mielke 2007).*

Shaw 1991; Hall 1997).[2] Secondly, we are specifically interested in the voicing characteristics of strident affricates, and, as explained in section 3, place of articulation has implications for the length of time that phonation can be maintained.

Figure 1 illustrates two general points: First, for all three consonant types (stops, fricatives, affricates), voiced obstruents are less frequent than their voiceless counterparts. That is, these data are in accord with the traditional claim that voiced obstruents are marked relative to voiceless ones (e.g., Trubetzkoy 1958 [1939]; Greenberg 1966; Chomsky and Halle 1968; Lombardi 1991, 1995, but see also Vaux and Samuels 2005 for a view that aspirated stops are the least marked segments).[3] The voicing asymmetry is most extreme in the fricatives (245 vs. 491), and Maddieson (1984: 47) states that "generally, the existence of a given voiced fricative in the inventory implies the presence of a voiceless counterpart in the inventory." Secondly, affricates, on the whole, are less frequent than stops or fricatives. According to Greenberg (1963: 3), "There is an implicational universal that an alveolar affricate such as /ts/ always implies the presence of /s/ in a language but not vice versa. [. . .] There are no languages with /ts/ that lack /s/." Jakobson (1972 [1941]: 74) similarly states that the number of affricates in a given language never exceeds the number of fricatives in the same language. He also adds that the phoneme pair /t-ts/ implies the presence of the phoneme /s/ in a given language. With the combination of lower frequencies of voiced obstruents overall, and lower frequencies of affricates overall, we see that voiced affricates are the least common of all six obstruent types.

It should be emphasized that affricates are created from other sounds, mainly stops (Maddieson 1984), and there are language-specific factors that contribute to creating new contrasts out of previously established contrasts, and that may play a decisive role in asymmetries noted in a given inventory. For example, if /t͡s/ is emerging from /t/ in a given language but the inventory does not contain /d/, then asymmetry in the affricates is to be expected.

The paper is organized as follows: in section 2 we present results of a cross-linguistic survey of phonemic coronal inventories to show that voiced sibilant affricates represent a gap in several unrelated languages. In section 2.2.1 we review typological studies which show that there is an asymmetry in the *inputs* of affrication processes in the sense that the voiceless stops /t/ and /k/ undergo affrication more readily than their voiced counterparts. In section 2.2.2 we provide examples of deaffrication processes which affect voiced but not voiceless affricates. In section 3 we outline the aerodynamic requirements of obstruent voicing, and compare affricates to fricatives and stops. Section 4 presents data from an aerodynamic experiment including Polish and German affricates, fricatives, and stops suggesting that aerodynamic and durational considerations can help explain why voiced affricates are often missing in phonemic inventories, and are less frequent outputs of phonological processes. Section 5 concludes.

2. Voiced affricates in phonology

Phonologically, affricates have been represented in several different ways (cf. Hall and Żygis 2010 for a review). Some authors have proposed feature designations in which affricates are represented as being more complex than corresponding stops. For instance, it has been argued that in contrast to stops which are specified as [−continuant] and fricatives which are [+continuant], affricates should be represented as having both [−continuant] *and* [+continuant] components, either linearly ordered (Sagey 1986) or unordered (Lombardi 1990). Insofar as more complex (marked) segments are expected to be less frequent across languages, these feature systems appear to accord better with the typological data. Yet other representations do not provide such an explanation. For example, some scholars represent affricates as being [+strident] whereas the corresponding stops are [−strident] (Jakobson, Fant, and Halle 1952; LaCharité 1993; Rubach 1994; Clements 1999; Kehrein 2002). In these systems, affricates are not more complex since the feature [strident] is present in both sound classes; it is only the value of the feature that differs. If one accepts a phonological representation whereby affricates, fricatives, and stops are equally complex from a featural point of view, an explanation for the infrequency of affricates must be sought in phonetic properties of the sounds.

Virtually all phonological approaches to voicing contrasts, including those dealing with features, make no distinction in how they represent the voicing contrast in affricates, fricatives and stops (see, e.g., Lombardi 1994, 1999; Iverson and Salmons 1995, 2003; Steriade 1997; Avery and Idsardi 2001; Wetzels and Mascaró 2001; Kehrein 2002). To explain the differences in degree of the voiced-voiceless asymmetry among different kinds of obstruents evident in Figure 1, it appears we must again consider phonetic aspects of these sounds. Several authors have appealed to aerodynamic factors to explain the markedness of voiced obstruents in general (e.g., Ohala 1983; see longer review below), and Ohala has also addressed differences between stops and fricatives in this regard. To the best of our knowledge, however, the aerodynamic characteristics of voiced affricates have not been explored. In this study we present such data to gain more insight into the asymmetry of occurrence of voiced vs. voiceless affricates in comparison to that in stops and fricatives.

2.1. *Phonemic inventories*

Table 1 presents data from a sample of languages that show a voicing contrast in stops and fricatives, but have only voiceless affricates. To simplify the presentation, and following the justification laid out for the dataset shown in Figure 1, the phonemic inventories are limited to coronal obstruents. These examples show that voiced affricates represent a specific gap in languages of many families: Bantu (Kinyarwanda; Table 1a); Niger-Congo (Icen and Jiru; Tables 1b, 1c); Mongolic (Buriat; Table 1d); Sino-Tibetan (Bisu and Sema; Tables 1e, 1f); South American (Quechua; Table 1g); and Indo-European (German, Yiddish, Czech, Bulgarian, and Russian; Tables 1h–1l).[4] One can also observe that the asymmetry appears in languages with varying degrees of complexity in their obstruent systems; compare, for example, the simple coronal inventories of Sema and Icen with the more complex ones of Bulgarian and Russian. Indeed, voiced affricates are missing in some languages whose coronal inventories are quite complex. Two examples of these are Kashmiri, an Indo-Aryan language spoken in India and Pakistan, and Lezgian, a language spoken in southern Dagestan and northern Azerbaijan. The Kashmiri inventory consists of /t tʰ tʲ tʲʰ ʈ ʈʰ ʈʲ ʈʲʰ d dʲ ɖ ɖʲ s sʲ z zʲ t͡s t͡sʰ t͡sʲ t͡sʲʰ/ (cf. Wali and Koul 1997: 294ff).[5] The Lezgian inventory contains the obstruents /t̪ d̪ t̪ʷ t̪ʰ t̪ʰʷ t̪ʼ t̪ʼʷ t̪͡s̪ t̪͡s̪ʷ t̪͡s̪ʰ t̪͡s̪ʰʷ t̪͡s̪ʼ t̪͡s̪ʼʷ t͡ʃ t͡ʃʰ t͡ʃʼ s̪ s̪ʷ z̪ z̪ʷ ʃ ʒ/ (Haspelmath 1993: 34).

In some other languages, there are reasons for considering voiced affricates to have marginal status in the phonemic inventory. In German (Table 1h), the voiced

Table 1. *Coronal obstruent inventories of several languages with no voiced affricates.*

1a. *Kinyarwanda (Bantu, spoken in Rwanda; Walker, Byrd, and Mpiranya 2008: 501).*

	alveolar		retroflex	
fricative	s	z	ʂ	ʐ
stop	t	d		
affricate	t͡s		t͡ʂ	

1b. *Icen (also known as Etkywan, Niger-Congo, spoken in Nigeria; Shimizu 1980: 72).*

	dental/alveolar*	
fricative	s	z
stop	t	d
affricate	t͡s	

* Shimizu (1980) does not specify the exact place of articulation for /s z t d/; dental/alveolar is supplied here as the most likely set of options.

1c. *Jiru (also known as Wuyar, Niger-Congo, spoken in Nigeria; Shimizu 1980: 82).*

	dental/alveolar*		postalveolar/alveolo-palatal**	
fricative	s	z	ʃ/ɕ	ʒ/ʑ
stop	t	d		
affricate	t͡s			

* Since the exact place of articulation for /s z t d t͡s / is not specified by Shimizu (1980), we put dental/alveolar as the most likely option.
** Shimizu (1980) uses the symbols ⟨sh⟩ and ⟨zh⟩ and specifies them in IPA terms as being variably [ʃ]~[ɕ] and [ʒ]~[ʑ], respectively.

1d. *Buriat (the so-called Russian Buriat, Mongolic, spoken in Russia along the northern border of Mongolia; Poppe 1960).*

	dental/alveolar*		postalveolar	
fricative	s	z	ʃ	ʒ
stop	t	d		
affricate	t͡s		t͡ʃ	

* Poppe (1960) does not specify the exact place of articulation for /s z t d/; dental/alveolar is supplied here as the most likely set of options.

1e. *Bisu (Sino-Tibetan, spoken in China and Thailand; Shixuan 2001: 19).*

	alveolar*			alveolo-palatal		
fricative	s		z	ɕ		ʑ
stop	t	t^{h}	d			
affricate	t͡s	t͡s^{h}		t͡ɕ	t͡ɕ^{h}	

* Shixuan (2001) classifies alveolar phonemes into apical / t͡s t͡s^{h} t͡ɕ t͡ɕ^{h}/ and laminal /t t^{h} d/.

Table 1. *(Continued)*

1f. *Sema (Sino-Tibetan, spoken in India; Sreedhar 1980: 19, 28–33, 36–38).*

	dental	
fricative	s̪	z̪
stop	t̪	d̪
affricate	t͡s̪	

1g. *Imbabura Quechua (South American, spoken in Ecuador; Cole 1985: 199).*

	alveolar*		postalveolar	
fricative	s	z	ʃ	ʒ
stop	t	d		
affricate	t͡s		t͡ʃ	

* Cole (1985: 199ff) characterizes /s z t d t͡s/ as apico-alveolar and /ʃ ʒ/ as dorso-postalveolar.

1h. *German (Indo-European, Germanic branch; Hall 1992: 21)*

	dental		postalveolar*	
fricative	s̪	z̪	ʃ	(ʒ)**
stop	t̪	d̪		
affricate	t͡s̪		t͡ʃ	(d͡ʒ)

* Hall (1992) uses the term palato-alveolar for denoting /ʃ ʒ t͡ʃ d͡ʒ/. We changed the term to postalveolar in accordance with IPA.

** ( ) indicates that the sound has marginal status in the language; see text for details.

1i. *Yiddish (Indo-European, Germanic branch; Katz 1987: 29ff)*

	dental/alveolar*		postalveolar	
fricative	s	z	ʃ	ʒ
stop	t	d		
affricate	t͡s			

* Katz (1987) does not specify the exact place of articulation of /s z t d t͡s/. He also uses ⟨sh⟩ and ⟨zh⟩ and describes them as ⟨š⟩ and ⟨ž⟩. We assigned the former sounds a dental/alveolar and the latter a postalveolar place of articulation as the most common option.

1j. *Czech (Indo-European, West Slavic branch; Kučera 1961: 30)*

	dental/alveolar*		postalveolar	
fricative	s	z	ʃ	ʒ
stop	t	d		
affricate	t͡s		t͡ʃ	

* Kučera (1961: 30) denotes /t d/ as apico-dental, /s z t͡s/ as apico-alveolar, and /ʃ ʒ t͡ʃ/ as apico-alveo-palatal. He uses /š/, /ž/, and /č/ for /ʃ/, /ʒ/, and /t͡ʃ/, respectively.

Table 1. *(Continued)*

1k. *Bulgarian (Indo-European, South Slavic branch; Scatton 1993: 191)*

	dental*	postalveolar
fricative	s̪ s̪ʲ z̪ z̪ʲ	ʃ ʒ
stop	t̪ t̪ʲ d̪ d̪ʲ	
affricate	t͡s̪ t͡s̪ʲ	t͡ʃ d͡ʒ

* Scatton (1993) uses alveolo-dental for /s s′ z z′ t t′ d d′ c c′/ and alveolo-palatal for /š ž č ǯ/ which we changed to IPA dental and postalveolar accordingly.

1l. *Russian (Indo-European, East Slavic branch; Timberlake 1993: 829; Padgett and Żygis 2007: 296).*

	dental*	retroflex	palatoalveolar
fricative	s̪ s̪ʲ z̪ z̪ʲ	ʂ ʐ	
stop	t̪ t̪ʲ d̪ d̪ʲ		
affricate	t͡s̪		t͡ʃʲ

* Timberlake (1993) only differentiates between the dental and palatal place of articulation for the sounds presented in this table. Padgett and Żygis (2007) use IPA symbols and in addition they include /ɕː/ and /ʑː/ but state that the phonemic status of these segments is not clear.

affricate /d͡ʒ/ (and the fricative /ʒ/) only occur in words of foreign origin and /d͡z/ is not attested at all. In Slovene, the palatoalveolar /d͡ʒ/ is only found in words of foreign origin, and as such its phonemic status is questionable or even rejected by some scholars (see, e.g., Dalewska-Greń 2002: 95). Similarly, in Bulgarian, /d͡z̪/ and /d͡z̪ʲ/ are not part of the phonemic inventory and /d͡ʒ/ is found in a few words of foreign origin, cf. Table 1k (Scatton 1993: 191).

Besides the examples presented in Table 1, there are also many languages in which the obstruent inventories lack not only voiced affricates but other voiced obstruents as well. Such examples show the typological dominance of voiceless obstruents; however, since markedness of voiced stops and fricatives has been discussed in past work, we will provide only a few brief examples of this kind.

In Galician, voiced affricates and voiced fricatives are not attested (/t d s ʃ t͡ʃ/). In Castilian's coronal inventory of /t d s t͡ʃ d͡ʒ/, /z/ is missing, and the phonemic status of /d͡ʒ/ is a matter of debate and "by no means securely established in the system" (Green 1988: 80). The Rumanian coronal inventory lacks the voiced counterparts of fricatives and /t͡s/, and the system contains the following obstruents: /t d s ʃ t͡s t͡ʃ d͡ʒ/ (Mallinson 1988). Similarly, in Northern Sotho, spoken in the South African provinces of Gauteng, Limpopo Province, and Mpumalanga, voiced affricates as well as /d/ and /z/ are not attested, whereas four voiceless affricates are part of the phonemic inventory /s ʃ ʒ t tʰ t͡s t͡sʰ t͡ʃ t͡ʃʰ/ (see Louwrens, Kosch, and Kotzé 2006).

In summary, an investigation of sibilant inventories of several typologically different languages points to a phonemic gap: Voiced affricates are not attested despite the presence of their voiceless counterparts as well as voiced and voiceless stops and fricatives. In many other languages voiced affricates have a very limited distribution and/or marginal phonological status. Several other languages have a more general restriction against voiced obstruents, lacking not only affricates but also voiced fricatives and/or stops.

2.2. *Phonological processes*

Several phonological processes have the effect of reducing the frequency of voiced affricates cross-linguistically, in line with data shown in Figure 1. We will focus on two types of data. The first suggests an asymmetry in the inputs to affrication processes: Namely, while voiceless stops change to affricates in certain vocalic contexts, their voiced counterparts do not always follow a parallel pattern (cf. Ohala and Solé 2010). In several cases they change to fricatives or glides instead of affricates, or simply do not undergo any phonological process at all. The second piece of evidence is the observation that voiced affricates, when they occur, seem to be unstable in contrast to their voiceless counterparts. It will be shown that the voiced affricates frequently convert to other sounds, mostly to fricatives and glides.

2.2.1. *Voiced and voiceless coronals and velars in affrication processes* In their typological study, Hall and Hamann (2006) analyze assibilation processes of /t/ and /d/ before /i/ and /j/ in over 30 languages.[6] These authors postulate two universal implicational rules: (a) assibilation cannot be triggered by /i/ unless it is also triggered by /j/, and (b) voiced stops cannot undergo assibilation unless voiceless ones do. Implication (b) is of special relevance for the present study because it shows that voiced and voiceless coronal stops do not always behave in a parallel fashion. Hall and Hamann provide examples of languages in which both /t/ and /d/ assibilate or exclusively /t/ undergoes assibilation. Languages in which only /d/ undergoes assibilation are argued to be unattested.[7]

This asymmetry is also found for velar stops /k/ and /g/. Guion (1998) noted that in several languages only the voiceless velar stops become affricates, while the voiced series remains unaltered. The author drew on Bhat's (1978) typological data on palatalizations, which included ca. 100 examples of palatalization affecting labial, coronal, and velar stops. Based on these data, Guion came to the conclusion that about 60% of the cases of velar palatalization induced by a following front vowel or glide affected both voiced and voiceless stops; 40% of the examples affected only voiceless velars while voiced stops remained intact. No examples were provided by Bhat for a language in which /g/ affricated but /k/ did not. Guion also observed that voiceless velars behave differently in comparison to voiced ones as far as the palatalization output is concerned. By taking into consideration examples from English, Bantu, and Slavic, she showed that voiceless velars are generally more likely to change to affricates, while voiced velars changed to fricatives or glides. For instance in Late Protoslavic, the so-called First Velar Palatalization converted /k g x/ to [t͡ʃ ʒ ʃ] before any front vowel (Guion 1998: 20; Carlton 1991: 113ff).

Telfer (2006), analyzing sound changes of /k/ and /g/ from a cross-linguistic point of view, also confirms that coronalization (affrication) of /k/ implies coronalization of /g/.[8] In his data set (24 typologically different languages), no language changes /g/ to /d͡z/ or /d͡ʒ/ if /k/ is not affected by a parallel process. Telfer (2006: 73) also claims that while voiceless velars tend to become affricates, voiced velars tend to become fricatives or glides or are deleted altogether. The deletion is attested, e.g., in Puglia, Salento, and Lucania dialects of Italian, in which /k/ changes to [t͡s] before /j/ and /g/ deletes in this context (Telfer 2006: 67). When referring to Hamann and Hall's study,[9] Telfer (2006: 84) observes that, like coronalization, assibilation patterns also tend to show differences between the outputs of voiceless and voiced coronal stops: Whereas the former become affricates (t → t͡s), the latter tend to change to fricatives (d → z). He also highlights the fact that no language provided in Hall and Hamann's study shows a reverse pattern, i.e., where assibilation caused spirantization of the voiceless stops (t → s) while at the same time affricating the voiced stops (d → d͡z). Since affrication of stops is the main source of affricates' emergence (see, e.g., Maddieson 1984), the different behavior of voiceless vs. voiced stop inputs provides one explanation for why voiceless affricates are more common than voiced ones.

In summary, the typological studies on both coronal /t d/ and velar /k g/ show that voiced and voiceless stops do not behave in a parallel manner in affrication processes. Namely, voiced stops change to affricates only if voiceless stops are affected by the process. It also appears that when voiceless stops change to affricates, their voiced counterparts change not only to voiced affricates but also to fricatives or glides. This typological asymmetry contributes to the lower frequency of voiced affricates in comparison to their voiceless counterparts.

2.2.2. *Changes affecting voiced but not voiceless affricates* Another supportive piece of evidence comes from synchronic and diachronic phonological processes which show that voiced affricates which are already present in a phonemic inventory are unstable in the sense that they change to other sounds while their voiceless counterparts do not. In the following we will provide some examples where voiced affricates undergo deaffrication, i.e., are converted into a stop or a fricative.

Scatton (1993: 191) observes that Bulgarian /d͡z/, besides occurring in foreign proper nouns, also appears "in a small number of non-literary, dialectal words, which, if used in the literary language regularly replace /d͡z/ by /z/." For example, /d͡z/ift is pronounced as [z]ift 'tar'. Dalewska-Greń (2002: 96) states that /d͡ʒ/, which is found in foreign words in Standard Bulgarian, changes to [ʒ] in colloquial speech. No changes regarding voiceless affricates are reported.

In the Graulhet dialect of Occitan (Romance, Western Lengadocian, near Tolosa and Albi), [t͡ʃ] and [d͡ʒ] from Standard Occitan merge into a single affricate [t͡s].

Thus, Standard Occitan [d͡ʒorn] ‘day’ is pronounced as [t͡sun] in Graulhet dialect (Lieutard 2004).

In Chitwan Tharu (Indo-Aryan, spoken in Nepal), the lamino-alveolar /d͡z/ converts to the lamino-alveolar [z] intervocalically: hai/d͡z/a ‘malaria’ is pronounced as hai[z]a and so/d͡z/a ‘straight’ as so[z]a. The voiceless lamino-alveolar /t͡s/ does not undergo change to a fricative; e.g., /t͡s/ikata is pronounced as [t͡s]ikata ‘smooth’, and ba/t͡s/a as ba[t͡s]a ‘child’ (Leal 1972: 20f.).

In literary Upper Sorbian, /d̪͡z̪/ is replaced by [z], e.g., in the declension of substantives ending in -ga. For example Jadwi/g/a ‘proper name, nom.sg’ appears as Jadwi[d̪͡z̪]e ‘acc.sg.’ The latter form converts to Jadwi[z]e (see Schuster-Šewc 1999: 38). No changes regarding voiceless affricates are reported.

In Standard Rumanian as well as its southern dialects, /d͡z/ was lost as a phoneme and became /z/ in all environments (Vasiliu 1968). For instance, lucre/d͡z/i ‘you work’ changed to lucre/z/i and /d͡z/ic to /z/ic ‘I say’. The voiced palato-alveolar /d͡ʒ/ also underwent changes but only if followed by back vowels: e.g., /d͡ʒ/ok ‘game’ changed to /j/ok (Vasiliu 1968). The voiceless affricates were not affected.

In Shanghai Chinese, which belongs to the Wu dialect family, a diachronic process of deaffrication took place: The voiced alveolar affricate /d͡z/ changed to /z/ word initially. The variation between [d͡z] and [z] was reported by Edkins (1868: 47, cited in Chen 2003: 131), who observed that /z/ appeared in ‘colloquial form’. For example, ⟨’dzau⟩ [d͡zɔ4] ‘make, manufacture’ (reading form) changed to ⟨’zau⟩ [zɔ4] in colloquial speech. (Note that 4 denotes the falling (4th) tone in Chinese.) The change was accomplished in the 1920s when only /z/ was pronounced (Chen 2003: 179). The process affected neither the alveolo-palatal /d͡ʑ/ nor the voiceless affricates.

In summary, the processes presented above confirm a certain amount of instability of sibilant voiced affricates. Voiced affricates tend to convert to voiced fricatives or to be devoiced while their voiceless counterparts tend to remain intact.

3. Phonetic considerations for voiced affricates

To understand the production requirements for voiced affricates, it is useful first to review the corresponding considerations for voiced stops and fricatives. The most immediate reason for this is simply that affricates can be described as a stop + fricative combination. It is also the case that voiced fricatives and stops have received extensive attention in the literature, so a review of past work on these sound types will serve to lay out the general principles. After the following section on the production of voicing in stops and fricatives, we consider the production requirements for affricates in general and, finally, voiced affricates in particular.

3.1. *Obstruent voicing, with particular reference to stops and fricatives*

It has long been known that vocal-fold vibration requires a pressure differential across the glottis (e.g., van den Berg 1958; Ishizaka and Matsudaira 1972; Lindqvist 1972; Baer 1975; Titze 1988). This pressure differential ensures sufficient airflow for a transfer of energy to the vocal fold tissues. The threshold value of the pressure differential has been estimated at about 2–3 cm H_2O for typical speech conditions with adducted vocal folds (Ishizaka and Flanagan 1972; Catford 1977). In obstruents, the closure or constriction in the upper vocal tract leads to an increase in supraglottal or intraoral pressure (P_{io}). Assuming that the subglottal pressure (P_{sub}) remains approximately constant, increasing P_{io} will lead to a decreasing transglottal pressure difference (P_{trans}). When P_{trans} falls below the threshold value, voicing will cease. Passive expansion of vocal-tract surfaces can absorb some of this increased P_{io} (Ohala and Riordan 1980). However, aerodynamic modeling (Müller and Brown 1980; Westbury 1983) has suggested that voicing can be sustained throughout the duration of a typical stop closure only if speakers perform compensatory actions to slow the rate of P_{io} increase (i.e., maintain a higher P_{trans}). Such actions may include altering the compliance of the vocal tract walls (Westbury 1983), expanding the supraglottal volume via movements of the larynx and upper articulators (Kent and Moll 1969; Perkell 1969; Bell-Berti 1975; Riordan 1980; Svirsky et al. 1997; Fuchs 2005), and allowing airflow leakage through the velopharyngeal port (Bell-Berti 1975). These studies also suggest that speakers may use combinations of such volume-compensating maneuvers. These considerations provide an explanation for the typological infrequency of voiced obstruents: These sounds require compensatory maneuvers, or greater aerodynamic control, compared to voiceless obstruents, since an oral closure will make continued voicing difficult. Ohala (2011) refers to this effect as the Aerodynamic Voicing Constraint.

Distinctions can also be made among voiced consonants with respect to place of articulation. As indicated in the introduction, in the voiced stop series it is the velar which is most often missing from phonemic inventories. That is, /g/ is not only less common than /k/, but also than /b/ and /d/. This can be related to the possibilities for passive and active vocal tract expansion. As observed by Ohala (1983), velars are characterized by a short posterior cavity. Whereas bilabial and coronal or apical stops allow expansion of the cheeks to regulate P_{io} increases, velars provide less surface area that can provide passive expansion, and may consequently also limit the options for performing compensatory maneuvers. As a result, devoicing is more likely in /g/, and hence it is this place of articulation where voicing contrasts are most often neutralized.

Stop consonants might appear to represent the most extreme case of a voiced obstruent (i.e., the least conducive to phonation) insofar as the vocal tract is completely closed. However, it is evident from Figure 1 above that voiced sibilant fricatives, despite providing a vent for P_{io}, are proportionally less common than voiced coronal stops. Ohala (1983) made a similar observation for voiced fricatives in general and outlined the problems unique to voiced fricatives. Subsequent work has added detail to his general argument. The essence of this argument is that the production of frication noise and the maintenance of phonation present conflicting aerodynamic demands.

Frication, like voicing, requires airflow, in this case through a supraglottal constriction. The oral constriction in fricatives has the effect of creating a pressure differential across the constriction region, analogous to that across the glottis. Solé (1998) laid out a quantification of pressure requirements for voiced fricatives. Assuming a subglottal pressure of 7.6 cm H_2O in the production of a voiced sibilant, and a minimum of 2 cm H_2O as the phonation threshold pressure, the maximum P_{io} that will permit phonation is 5.6 cm H_2O. This places an upper bound on the intraoral pressures speakers can use in voiced fricatives. One can also define a lower bound: It has been estimated that a supraglottal pressure drop of about 3 cm H_2O across the constriction is required to create frication (Catford 1977; Stevens 1998). Together, the pressure requirements for phonation and those for fricative generation yield a restricted aerodynamic range of a few cm H_2O for achieving both together (Solé 1998). Experimental evidence suggests that, at least for some languages, speakers make articulatory adjustments during the production of voiced fricatives to increase airflow and thereby facilitate frication. Specifically, transillumination and electromyographic studies of the larynx suggest that speakers may use slightly more abducted vocal folds for voiced fricatives as compared to vowels or voiced stops (Lisker et al. 1969; Hirose and Gay 1972; Hirose, Yoshioka, and Niimi 1978; Hirose and Ushijima 1978; Fuchs 2005). This has the effect of generating higher airflow rates, and helps to meet the requirement of a smaller supraglottal than glottal constriction in the production of fricatives (cf. Scully et al. 1992). Such larger glottal widths, however, increase the phonation threshold pressure (Titze 1988), i.e., make phonation less likely. In short, when faced with the competing demands of producing voicing and frication noise, speakers may effectively choose to maintain frication rather than voicing (see also Smith 1997). The other alternative, favoring voicing over frication, would involve allowing the fricative to become an approximant while maintaining the aerodynamic requirements for vocal-fold vibration. The sound changes reviewed above show that both strategies have historically been used by speakers of different languages (Kirchner 2001; Flemming 2002; Bárkányi and Kiss 2010; Ohala and Solé 2010).

The literature on the voicing contrast in obstruents includes many examples of how speakers may use supraglottal actions to maintain appropriate aerodynamics for vocal-fold vibration. Further, we have seen that speakers may use laryngeal adjustments to achieve supraglottal frication noise. There is, lastly, some evidence that supraglottal adjustments may be used to permit the combination of voicing and frication together. Returning to the fact that the supraglottal constriction must be smaller than the glottal constriction in the production of fricatives (Scully et al. 1992), in a production study on the voicing contrast in German sibilants, Fuchs et al. (2007) found a narrower medial groove for phonetically voiced than for voiceless alveolars on the basis of EPG data for several speakers. Inferring that a narrower channel could correspond to a smaller constriction area, and increased air particle velocity (provided that volume velocity remains the same), the authors suggested that speakers could be using supralaryngeal strategies to produce turbulent noise in the context of a closed glottis (see also Dixit and Hoffman 2004). For voiceless alveolar fricatives, the open glottis guarantees the high air flow necessary for the realization of turbulent noise.

3.2. *Affricates and affricate voicing*

Traditional impressionistic phonetics recognized affricates as combinations of two sound types, a stop closure and a fricative constriction. This is reflected, for example, in the IPA representation of affricates. Stevens (1993) noted that the release mechanism for an affricate differs from that of a stop consonant, and consists of two regions: an anterior area (A_1) that executes the initial rapid release from the closure and a posterior part (A_2) forming the constriction for the production of frication noise. An important difference between the two parts is that the initial release is rapid while the posterior part is held longer and released more slowly to achieve the fricative component of the affricate. Moreover, moving from a stop into a fricative requires moving from a flattened tongue blade into a grooved posture (Stone, Faber, Raphael, and Shawker 1992). Since affricates involve precise temporal control over two constriction regions, as well as changes in the coronal configuration of the tongue, one can hypothesize that they are phonetically *more complex* than singleton stops or voiced fricatives. Some authors have also observed that the stop and/or fricative portions of affricates tend to be shorter than singleton stops and fricatives (Iwata and Hirose 1967; Crystal and House 1988; Byrd 1993; Hölterhoff and Reetz 2007). Most of these production studies considered the stop regions of the affricate rather than fricative regions; however, perceptual data indicate that shorter fricative durations are also associated with perception of an affricate rather than a fricative (Mitani, Kitama, and Sato 2006). Thus, affricates seem to require not only that speakers produce a sequence of a stop and a fricative, but that they produce rather brief stop and fricative components. One can hypothesize that producing such temporally short sequences represents an additional form of motoric complexity. In sum, these factors may provide an explanation for why affricates are less common, cross-linguistically, than simple fricatives or stops.

Affricates also have unique aerodynamic conditions. As noted by Ohala and Solé (2010), the turbulence produced at plosive release, if elongated (e.g., in the context of a high vowel, where P_{io} is not rapidly discharged) may end up producing a period of frication. In this respect, stop releases may provide good conditions for frication. However, after the stop release in voiced affricates, the laryngeal and supralaryngeal conditions must allow for the competing demands of voicing as well as frication, and the P_{io} buildup from the preceding stop will tend to inhibit voicing.

A final factor to consider for affricate voicing is the overall duration. Fuchs and Koenig (2009) found that German voiceless affricates were significantly longer than single fricatives, single stops, or even consonant clusters consisting of a fricative and a stop. If the same durational pattern holds for the voiced affricates, they should be quite susceptible to devoicing, since a longer closure/constriction interval, all else being equal, allows more time for P_{io} to build up. That is, assuming that the rate (or slope) of P_{io} increase is constant, longer durations will be associated with higher peak P_{io} values. Durational features have received some attention in past considerations of consonant voicing. Ohala (1983) pointed out that there is a general cross-linguistic tendency for longer duration in voiceless obstruents compared to voiced (Lehiste 1970; see also Lisker 1957; Stevens et al. 1992). Shorter obstruent intervals leave less time for P_{io} to build up and thus facilitate voiced constriction intervals; conversely, as durations increase, it is more likely that speakers will need to use volume-increasing strategies to preserve the transglottal pressure difference (cf. Müller and Brown 1980; Westbury 1983); otherwise voicing will die out. Ohala (1983) further noted that voiced geminates are often eliminated in phonemic inventories. Some authors have proposed that durational differences between voiced and voiceless obstruents should be incorporated into phonological descriptions of voicing. For example, Jessen (1998) argued that the voicing distinction in German is best represented by the feature [tense], whose phonetic specification includes longer duration, since durational differences between voicing pairs are consistent across all contexts. Kohler (1984) similarly contended that an adequate phonological treatment of voicing (or fortis/lenis) must incorporate a temporal dimension, even beyond the temporality inherent in the measures of voice onset time typically used to characterize syllable-initial stop voicing.

To summarize, the intraoral pressure increase in voiced affricates, as with stops and fricatives, leads to a decrease in the transglottal pressure difference, which may lead to devoicing, unless certain supralaryngeal adjustments are carried out to enlarge the oral cavity. Similar to voiced fricatives, voiced affricates must fulfill the conflicting requirements for maintaining voicing and producing frication noise. In contrast to voiced stops and voiced fricatives, voiced affricates are realized with a complex release mechanism involving precise temporal control over the tongue tip and/or blade. They may also be longer in duration than singleton consonants, allowing greater time for intraoral pressure to build up and thus having a greater tendency to show devoicing. These factors provide possible explanations for why voiced affricates occur rather infrequently in the sounds of the world's languages.

4. Experimental evidence

The main goal of the experiment is to provide preliminary evidence for the idea that voiced affricates are cross-linguistically rare because of their length and articulatory and aerodynamic requirements. We will focus on measures of intraoral pressure, because P_{io} is crucial to realizing voicing and frication, and speakers make a variety of articulatory adjustments to control it. Duration is also relevant insofar as longer closure/constriction intervals should, all else being equal, be associated with a greater buildup of intraoral pressure. It is hypothesized that affricate voicing will vary with the closure/constriction duration, and with the initial rising slope of the intraoral pressure. That is, shallower pressure slopes will allow more time before the minimum transglottal pressure is achieved (see Müller and Brown 1980; Koenig and Lucero 2008). We expect that voiced affricates are shorter in duration and show a shallower rising slope than voiceless affricates.

We will investigate the voicing contrast in stops, fricatives and affricates in two languages, Polish and German, which differ in their realization of the voicing contrast (Keating 1980; Jessen 1998; Fuchs 2005). Phonologically voiced obstruents are realized as fully voiced segments in Polish (word initally and word medially), but they can be realized as voiced (e.g., word internally) or devoiced segments (e.g., word initially, word finally) in German. Phonologically voiceless obstruents are produced as voiceless in both languages, but with varying degree of aspiration for the stops. German has often been taken as an exemplar language for an aspiration contrast whereas Polish represents a language with a true voicing contrast. German is also one of the many languages where voiced affricates are missing in the native phoneme inventory. They are only found in borrowed words of foreign origin (cf. Table 1h). In contrast, Polish is a language where voiced affricates are integral to the native vocabulary.

Jessen (1998) noted that German tense (or voiceless) obstruents are often longer in aspiration and closure duration in comparison to lax obstruents. These durational aspects may play a key role in explaining positional phonetic variations in the German voicing contrast. In word-initial (strong) position, the contrast is primarily based on differences in aspiration duration whereas in word-medial (weak) position it often becomes a real voicing contrast where the duration of voicing into closure plays a major role. Thus, one may hypothesize that differences between German and Polish are less extreme in medial than initial position.

4.1. *Methods*

4.1.1. *Experimental procedures, speakers and speech materials* In the full experiment, three simultaneous recordings were carried out: first, intraoral pressure changes were recorded by means of a piezoresistive pressure transducer (Endevco 8507C-2) which was glued directly onto the subject's hard palate; second, airflow at the mouth was obtained by means of a Rothenberg mask and transducers (PTW-1); and third, the audio signal was recorded with ca. 10 cm distance from the mask to the microphone.

The analysis in the present paper considers only the intraoral pressure data. The acoustic signal was used to verify that the utterances were produced as intended.

Four native speakers of Polish (P) and four native speakers of German (G) took part in the experiment, two females (F) and two males (M) for each language (hereafter PM1, PM2, PF1, PF2 and GM1, GM2, GF1, GF2). All speakers had no known history of speech, language, or hearing impairment. The Polish speakers were between 31 and 41 years old (mean = 36) and the German speakers were between 28 and 45 (mean = 35).

The speech material consisted of words containing voiced and voiceless coronal obstruents:

(1) German: stops /d t/, fricatives /z s ʒ ʃ/, and affricates /d͡ʒ t͡ʃ/
(2) Polish: stops /d t/, fricatives /z s ʐ ʂ/, and affricates /d͡z t͡s t͡ɕ d͡ʑ/.

All target words were mono- or bisyllabic and had an initial-stressed syllable. All obstruents appeared in both word-initial and word-medial position (see Appendix A). The Polish obstruents occurred in /a/ contexts. The German obstruents mainly occurred in /a/ or /ɛ/ contexts (the statistical analysis accounts for these differences). Target words were embedded in a carrier sentence: for Polish *Powiedziała . . . do niego.* (‘She said . . . to him’) and for German *Ich habe . . . gesagt*. (‘I have said . . .’) and repeated five times in successive order.

All recordings were carried out using PCquirer (version 8.9.8.6). The audio signal was recorded with a sampling rate of 22.5 kHz, the intraoral pressure and the airflow data with 2750 Hz. All data were imported into Matlab (version 7.1). The intraoral pressure data were subsequently downsampled to 1375 Hz, and filtered in Matlab to remove the oscillations associated with voicing. A lowpass filter was used with passband edge = 40 Hz, stopband edge = 100 Hz, and stopband attenuation = 50 dB. This preserved the low-frequency (DC) variation in the signal while removing the first harmonic at F_0 values for typical men (viz., 100+ Hz) and also for women. The finite impulse response filter was designed using a Kaiser window method. Filtfilt was used so that the smoothed flow signal did not show a time delay relative to the original, unsmoothed signal. First and second derivatives were calculated from the smoothed P_{io} signal.

4.1.2. *Labeling and further procedures* The following time landmarks were labeled (see Figure 2):

– Consonant onset and offset as the acceleration peaks in the 2nd derivative of the filtered pressure signal
– The offset of voicing, from the original P_{io} signal
– The intraoral pressure peak in the filtered P_{io} signal (P_{max})
– The time point where the intraoral pressure slope starts to decelerate (turning point), as shown in the 2nd derivative of the filtered pressure

The intraoral pressure peak was obtained automatically in Matlab by searching for the maximum between consonant onset and offset in the filtered pressure data. A total of 6 landmarks were labeled for 688 target items, yielding 4128 measures.

Based on the labeled time landmarks the following durations were calculated:

– Duration of the consonant (*Dur*) as the difference between consonantal onset and offset
– Duration of voicing (*Voic*) as the difference between consonantal onset and the offset of voicing
– To account for durational differences across speakers as a function of speech rate, voicing duration was additionally normalized with respect to the duration of the consonant. In order to do so, the duration of the consonant was set to 100 percent and the corresponding relative voicing duration during this interval was calculated (*relVoic*).

For the calculation of pressure peaks (P_{max}), the absolute maximum pressure (obtained automatically, as described above) was adjusted to account for baseline shifts which can result from temperature changes (see, e.g., in Figure 2 that the pressure during the vowel is less than zero). The reference value used for this adjustment

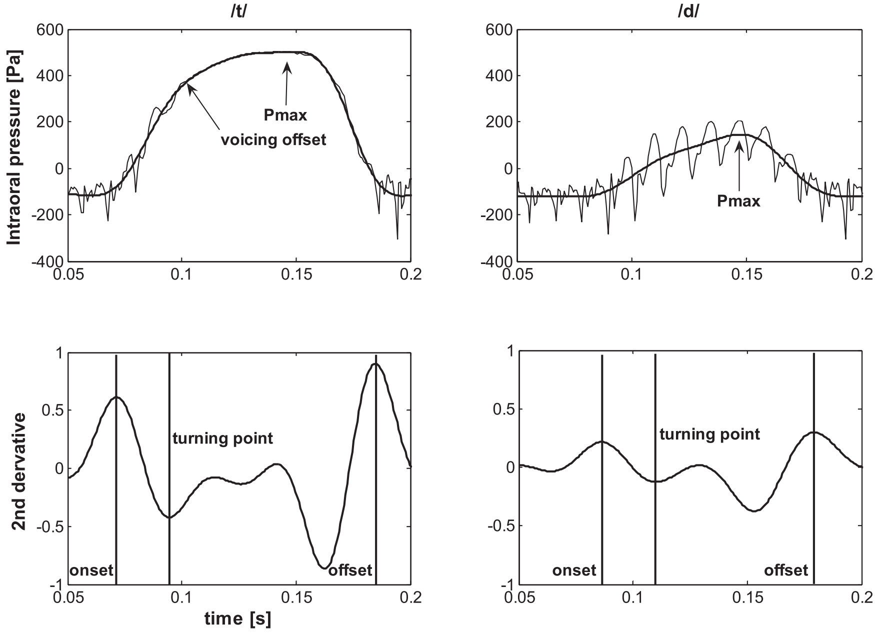

Figure 2. *Labeling of intraoral pressure (upper panels) and 2nd derivative of the filtered pressure signal in voiceless (left) and voiced (right) obstruents. The peaks in the 2nd derivative correspond to the times when the pressure begins its rapid rise, or completes its rapid fall, and provide useful aerodynamic landmarks for defining the onset and offset of the obstruent interval. The turning point was used to calculate the slope of the pressure rise, following Müller and Brown (1980) as described in the text. Intraoral pressure values are in Pascals relative to atmospheric (room) pressure. The data are taken from a Polish male speaker.*

was taken in the nearest stressed vowel (i.e., following word-initial stops, and preceding word-medial stops). In stressed open vowels, P_{io} is virtually always fully discharged and reaches a baseline level; in contrast, P_{io} may not reach a baseline in reduced vowels between obstruents (such as the schwa preceding the word-initial target in German). The stressed-vowel baseline pressure value was subtracted off the absolute maximum. All P_{max} values reported below are this adjusted value.

The turning point was used to calculate the P_{io} slope (*Slope;* pressure difference divided by time difference) between consonant onset and the turning point. Müller and Brown (1980) demonstrated that a slow-rising initial P_{io} trajectory was characteristic of phonetically voiced stops. Koenig and Lucero (2008) subsequently found that, in adult speakers (but not children), the amount of stop voicing was correlated with Müller and Brown's measure of P_{io} slope changes in the early phases of the stop closure, with *r*-values ranging from c.0.5–0.8 across speakers. The relationship between voicing and the slope of the initial P_{io} increase in the current data is evident in Figure 3. Specifically, the voiced productions show a shallower P_{io} slope than the devoiced and phonologically voiceless tokens.

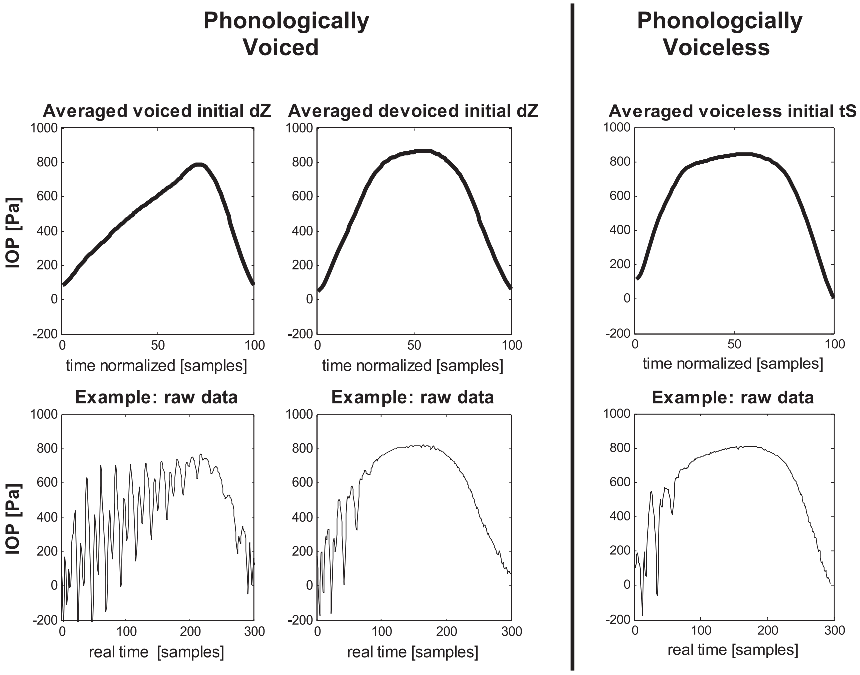

Figure 3. *Examples of initial /d͡ʒ/ (realized with voicing [left], and with some devoicing [middle]) in comparison to initial /t͡ʃ/ (right) for a German male speaker. The top row shows time normalized, averaged P_{io} trajectories over 5 repetitions; the bottom row shows one representative example of the unfiltered P_{io} signal.*

It was expected that voiced phonemes would have longer relative voicing durations, possibly shorter overall consonant durations, lower intraoral pressure peaks, and shallower slope values in comparison to voiceless. The slope value may differentiate between phonetically voiced and voiceless items, since it reflects in an indirect way how quickly the transglottal pressure decreases.

4.1.3. *Statistical design* In order to achieve interpretable statistics of the complex dataset, data were split according to the position of the phoneme under consideration (word-initial position with $n = 348$ and word-medial position with $n = 340$). All statistical analyses were carried out using the open source software R (version 2.8.0, R Development Core Team 2008), including the two packages *languageR* and *lme4*. Since our database was unbalanced, and involved different phonemes and words in Polish and in German, we decided to run linear mixed models instead of the classical repeated measures ANOVA. Thus, we were able to include all the data in the calculations. As fixed factors, LANGUAGE (German or Polish), VOICE (phonologically voiced versus voiceless) and ARTICULATION (stops, fricatives, or affricates) were chosen. As random factors, SPEAKER and WORD were selected. The linear mixed models were run separately for each dependent variable (consonant duration, relative voicing, intraoral pressure peak, slope of pressure rise). The output consists of a *t*-value[10] for the fixed effects and an associated *pMCMC* value. In linear mixed models, a valid alternative to standard *p*-values is to calculate the *p*-value from a MONTE CARLO sampling by Markov chain (*pMCMC* = Monte Carlo Markov Chain; see Baayen 2008). Interactions between the fixed factors were also tested. In cases where interactions were not significant, the data were grouped and simpler, additive models were fitted to the data to check the significance of main effects. Significant effects between voiceless obstruents or interactions between factors which are out of the scope of this study (e.g., comparisons between voiceless stops and voiced fricatives) are not discussed.

4.2. *Results*

In the following sections, word-initial position is discussed first and the word-medial position second. Each section provides an answer to the following three questions:

(1) Is the respective parameter relevant in the production of the voicing contrast?
(2) What do voiced affricates have in common with voiced stops and voiced fricatives?
(3) How do voiced affricates differ from voiced stops and fricatives?

4.2.1. *Temporal results: word-initial position* Figure 4 displays consonant duration for phonologically voiced obstruents (in grey) and their voiceless counterparts (in white). The boxes in the boxplots correspond to the 25th to 75th percentiles of

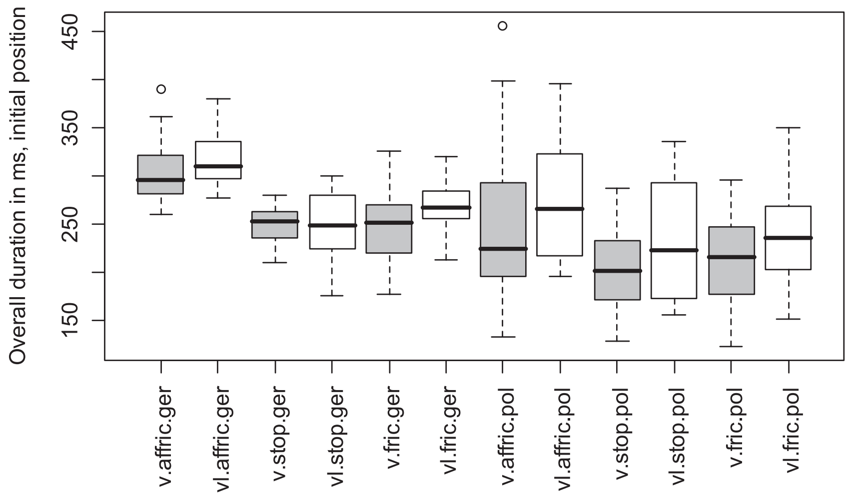

Figure 4. *Box plots with standard deviations for voiced (grey boxplots) and voiceless (white boxplots) phonemes in word-initial position. Data are split with respect to voicing (v = phonologically voiced, vl = phonologically voiceless), language (ger = German, pol = Polish) and articulation (affric = affricates, fric = fricatives, stop = stops).*

the respective data. The median is marked by a black horizontal line. Whiskers extend to the data point furthest from the median within 1.5 times the box length. These specifications will be used for all subsequent plots. Statistical results are provided in Appendix B, Table B1 (left data columns).

The overall duration of the consonant in word-initial position does reflect differences in the voicing contrast in both languages ($t = 2.256$, *pMCMC* = 0.0106; a simple additive model was used, since no interactions between the factors were found). Voiced obstruents are generally shorter than voiceless. Among all the voiced obstruents studied, the voiced affricate had the longest duration in both languages (all comparisons are highly significant), and voiced stops do not differ from voiced fricatives. Overall, Polish and German results show a tendency towards a difference in duration, but this is not significant.

Another consistent temporal parameter for the voicing contrast in word-initial position is the *relative voicing duration*. Relative voicing turned out to be highly significant with respect to the voicing contrast for both languages and all articulations (see Table B2 for details). Voiced affricates, however, show a shorter relative voicing than the voiced fricatives in German ($t = 2.925$, *pMCMC* = 0.0054). In addition, all the investigated German voiced obstruents are produced with significantly shorter relative voicing than the comparable Polish voiced obstruents (affricates: $t = 4.809$, *pMCMC* = 0.0001; stops: $t = 4.033$, *pMCMC* = 0.0014; fricatives: $t = 3.588$, *pMCMC* = 0.0022). These results are in agreement with the fact that Polish is characterized as a language with a real voicing contrast in initial position, whereas Standard German is known for its aspiration contrast (Keating 1980; Jessen 1998). Such differences between the languages should be particularly evident in word-initial position. In word-medial position, we expect a weakening of the language differences, since consonants in this position are often shorter in overall duration (Krakow 1999). Moreover, in medial position phonologically voiced stops in German are realized as phonetically voiced.

4.2.2. *Temporal results: word-medial position* Temporal differences between voiced and voiceless obstruents and among the voiced obstruents are evident in the word-medial position (see Figure 5 and a summary in Table B1, right columns). As in word-initial position, word-medial voiced affricates are shorter than voiceless in Polish and German (Polish: $t = 4.713$, $pMCMC = 0.0002$; German: $t = 5.357$, $pMCMC = 0.0001$). The same holds true for stops (Polish: $t = 2.83$, $pMCMC = 0.0046$; German: $t = 4.07$, $pMCMC = 0.0006$) and for fricatives in German ($t = 2.201$, $pMCMC = 0.0226$).

Considering the voiced articulations only, voiced affricates are longer than voiced stops and fricatives in German (affricates vs. stops: $t = 10.258$, $pMCMC = 0.0001$; affricates vs. fricatives $t = 6.201$, $pMCMC = 0.0001$). Hence, the long duration of the voiced affricate in comparison to the other voiced obstruents is consistent for both word positions. In the Polish data, the voiced affricate patterns together with the voiced stop in having a shorter overall duration than the

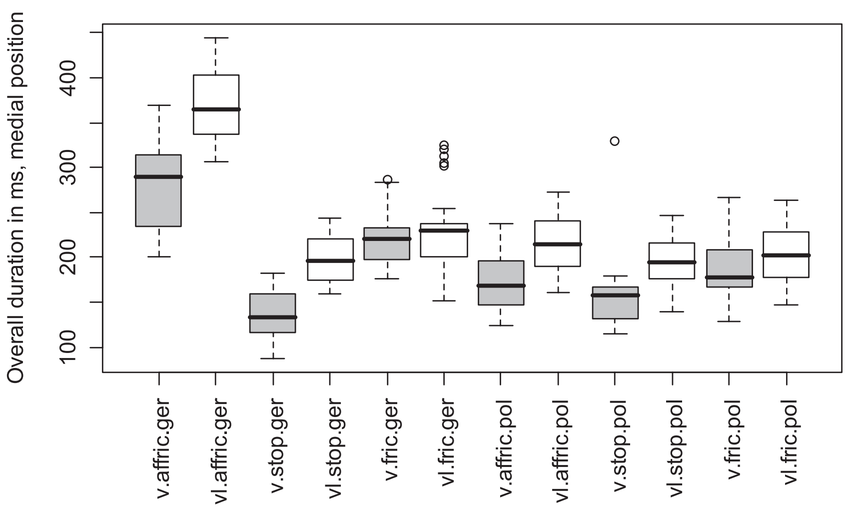

Figure 5. *Box plots with standard deviations for voiced (grey boxplots) and voiceless (white boxplots) phonemes in word-medial position. Data are split with respect to voicing (v = phonologically voiced, vl = phonologically voiceless), language (ger = German, pol = Polish), and articulation (affric = affricates, fric = fricatives, stop = stops).*

fricative (affricates vs. fricatives: $t = 2.477$, $pMCMC = 0.0158$; stops vs. fricatives: $t = 2.577$, $pMCMC = 0.0076$). Finally, Polish and German show significant differences in their voiced affricates only ($t = 6.203$, $pMCMC = 0.0001$), with longer durations for the German than for the Polish speakers.

The second temporal parameter, relative voicing, is again a reliable temporal parameter where all voiced-voiceless pairs in German and Polish (except the Polish fricative pair) can be distinguished, with longer relative voicing durations in voiced obstruents in comparison to voiceless ones (all highly significant for German and for affricates in Polish and moderately significant for voiced vs. voiceless stops in Polish [$t = 3.009$, $pMCMC = 0.0066$]. In addition, voiced affricates in German show shorter relative voicing portions than voiced fricatives ($t = 4.775$, $pMCMC = 0.0001$) and voiced stops ($t = 5.526$, $pMCMC = 0.0001$). For Polish, voiced affricates differ from voiced stops ($t = 2.176$, $pMCMC = 0.021$), but not fricatives. Relative voicing is shorter in affricates than in stops.

The differences between German and Polish voiced obstruents in word-medial position show that only voiced affricates are realized with significant differences in relative voicing between the two languages ($t = 4.661$, $pMCMC = 0.0001$). The Polish data show a longer relative voicing than the German data in both word positions.

4.2.3. *Results for intraoral pressure: word-initial position* The two intraoral pressure parameters, pressure peak (P_{max}) and pressure slope (Slope), will be discussed in this section (for a summary see also Appendices B.3–B.4).

On the basis of the intraoral pressure peak (see Figure 6), voiced and voiceless obstruents in word-initial position can be distinguished consistently for the Polish speakers (affricates: $t = 2.552$, $pMCMC = 0.0066$; stops: $t = 1.922$, $pMCMC = 0.031$; fricatives: $t = 3.304$, $pMCMC = 0.0006$) with lower maximum pressure for voiced in comparison to voiceless obstruents. In contrast, German speakers do not realize a difference at all.

Polish and German speakers produce voiced affricates with higher pressure peaks than voiced fricatives (Polish: $t = 2.422$, $pMCMC = 0.0072$, German: $t = 2.486$, $pMCMC = 0.0054$). These differences are interpreted with respect to the production of an air-tight seal during the stop phase of the affricate, leading to a greater pressure build up. In fricatives, the lack of a stop phase allows air to escape continually so that the overall pressure buildup tends to be lower. In both languages voiced affricates reach pressure peak values similar to the voiced stops. There is an insignificant trend for voiced affricates to have higher pressure peaks in German than Polish ($t = 1.431$, $pMCMC = 0.0596$).

Based on Müller and Brown (1980) the slope of the pressure increase up to the turning point could be another reliable parameter distinguishing voiced and voiceless productions. This measure reflects the speed of P_{io} rise and is interpreted as a consequence of laryngeal-oral coordination. Figure 7 displays the results for the two languages.

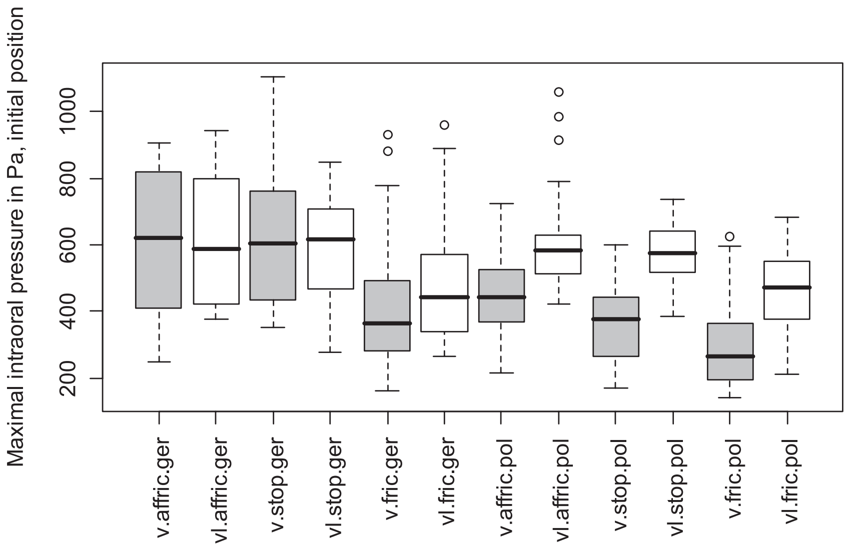

Figure 6. *Box plots for intraoral pressure peaks in voiced (grey) and voiceless (white) phonemes. Data are split with respect to voicing (v = phonologically voiced, vl = phonologically voiceless), language (ger = German, pol = Polish), and articulation (affric = affricates, fric = fricatives, stop = stops).*

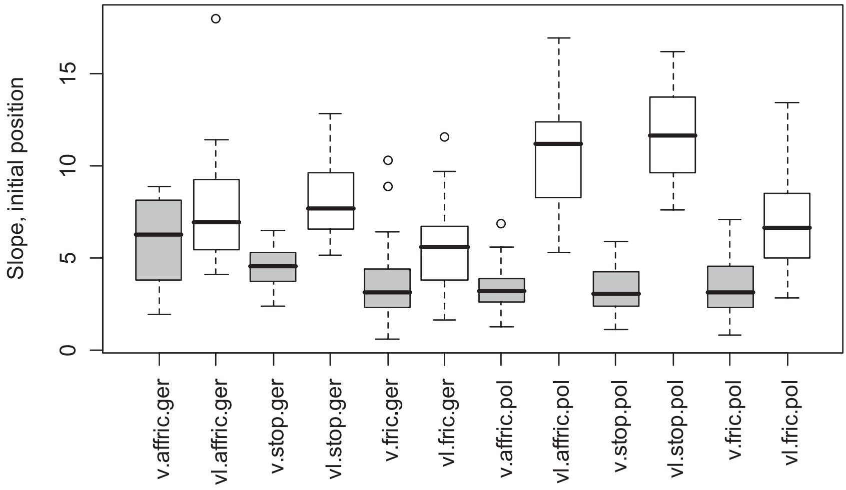

Figure 7. *Box plots for slope values (measured in Pa/sec) from the stop closure to the turning point (as shown in Figure 2) in voiced (grey) and voiceless (white) phonemes. Data are split with respect to voicing (v = phonologically voiced, vl = phonologically voiceless), language (ger = German, pol = Polish), and articulation (affric = affricates, fric = fricatives, stop = stops).*

The differences in slope values between voiced and voiceless obstruents (with steeper slope for voiceless and shallower slope for voiced) are all highly significant (*pMCMC* always 0.0001) for Polish speakers. For German speakers, slope values differ for voiced vs. voiceless affricates and stops (affricates: $t = 2.605$, *pMCMC* = 0.0032; stops: $t = 3.343$, *pMCMC* = 0.0001), but not for fricatives. The latter is consistent with the fact that in word-initial position, there are only a few minimal pairs for /s/ and /z/ and in most cases the alveolar fricative is phonologically voiced (with a few exceptions borrowed from English). Thus, German speakers are free to realize a wide range of variation between phonetically voiced and voiceless /z/.

Slope values for voiced obstruents do not differ among the various articulations and they also do not differ among the languages. We conclude that the slope of the initial pressure rise is a specific parameter differentiating between voiced and voiceless obstruents.

4.2.4. *Results for intraoral pressure: word-medial position* As in word-initial position, the intraoral pressure peak in word-medial position is a good predictor to distinguish between the voiced and voiceless items in Polish, with voiced obstruents having lower pressure peaks (affricates: $t = 2.478$, *pMCMC* = 0.0124; stops: $t = 3.94$, *pMCMC* = 0.0004; fricatives: $t = 2.309$, *pMCMC* = 0.0188). This is consistent with the word-initial position. In contrast, German speakers only realize a difference for stops ($t = 3.458$, *pMCMC* = 0.001).

For German speakers, a higher intraoral pressure peak consistently distinguishes the voiced affricate from the voiced fricative ($t = 3.744$, *pMCMC* = 0.0006), and voiced stop ($t = 3.717$, *pMCMC* = 0.0012). Similar results were found for the Polish affricate-fricative distinction ($t = 2.398$, *pMCMC* = 0.014).

The languages differ with respect to the voiced affricate where German speakers realize a higher pressure peak than Polish speakers ($t = 1.887$, *pMCMC* = 0.0288). This result can be attributed to the longer overall duration of voiced affricates in German and not to the differences in pressure rise (slope).

Significant differences are found for the slope parameter between all voiced-voiceless pairs. As in word-initial position, this parameter is very robust in distinguishing the voiced from the voiceless obstruents and does not differ among the two languages. Finally, considering voiced obstruents only, voiced affricates have greater slope values than fricatives ($t = 2.087$, *pMCMC* = 0.0188 for both languages, since there is no interaction between language and articulation).

4.2.5. *Brief summary of the results* We will now briefly summarize the results (see also Table 2) with respect to the research questions.

Which parameters are relevant in the production of the voicing contrast in German and Polish? The most consistent parameters to describe the voicing contrast in both word positions and both languages are the consonant duration, the relative voicing duration during closure, and the intraoral pressure slope. These last two may even go hand in hand in the sense that a shallow intraoral pressure slope

Table 2. *Summary of significant results for the parameters consonant duration (Cdur), relative voicing RelV), maximum pressure (Pmax), and pressure slope (Slope).*

		Word-initial				Word-medial			
		Cdur	RelV	P_{max}	Slope	Cdur	RelV	P_{max}	Slope
Voicing	Polish								
	voiced vs. voiceless affricates	<	>	<	<	<	>	<	<
	voiced vs. voiceless stops	<	>	<	<	<	>	<	<
	voiced vs. voiceless fricatives	<	>	<	<			<	<
	German								
	voiced vs. voiceless affricates	<	>		<	<	>		<
	voiced vs. voiceless stops	<	>		<	<	>	<	<
	voiced vs. voiceless fricatives	<	>			<	>		<
Articulation	Polish voiced								
	affricates vs. stops	>					<		
	affricates vs. fricatives	>		>		<		>	>
	voiced stop vs. fricatives					<	<		>
	German voiced								
	affricates vs. stops	>				>	<	>	
	affricates vs. fricatives	>	<	>		>	<	>	>
	voiced stop vs. fricatives			>		<			>
Language	German vs. Polish voiced								
	affricates		<			>	<	>	
	stops		<	>					
	fricatives		<						

facilitates the continuation of voicing. In contrast, voiceless obstruents are consistently produced with a quick intraoral pressure rise (due to glottal opening and oral closure) leading to a fast cessation of voicing and consequently a short relative closure voicing duration. Furthermore, the three parameters are the ones where voiced affricates behave like the other voiced obstruents in the present study. For Polish speakers voiced and voiceless obstruents can also be distinguished by the intraoral pressure peak, which is higher for voiceless phonemes than for voiced ones.

However, in what respect do voiced affricates differ from voiced stops and fricatives? In German and Polish, word-initial voiced affricates are significantly longer than voiced stops and fricatives in their absolute duration. Similar findings can also be found for German in word-medial position, but not for Polish. Interestingly, in Polish, voiced affricates and stops are shorter than voiced fricatives in this position. All other parameters do not distinguish voiced affricates consistently from the other articulations. Voiced affricates, however, have larger pressure peak values than voiced fricatives in both languages.

In word-medial position the results show a language specific effect. German speakers realize voiced affricates differently from other obstruents in all analyzed parameters with the exception of slope for affricates vs. stops. They have a longer consonant duration, a shorter relative voicing duration, a higher intraoral pressure peak than voiced stops and fricatives, and a higher slope than voiced fricatives. For Polish speakers, voiced affricates differ from voiced fricatives in having shorter durations, higher pressures, and higher slopes, whereas they differ from voiced stops in having shorter relative voicing duration. In other words, none of the described parameters consistently differentiates voiced affricates from other voiced obstruents in Polish.

Finally, how do voiced affricates in German and Polish differ? The only consistent parameter for both word positions is the relative voicing duration. In word-medial position they also differ in consonant duration (longer for German than Polish speakers) and intraoral pressure maximum (higher for German than Polish speakers).

5. Discussion and conclusion

If voiced affricates are less frequent than their voiceless counterparts in phoneme inventories of the world's languages, how do they differ from voiced stops and fricatives? A review of phonetic considerations suggested possible explanations in the form of durational, aerodynamic, and lingual release characteristics. In order to gain more insight into the durational and aerodynamic characteristics of voiced affricates, we compared the findings of two languages: German, a language lacking voiced affricates (they are only present in non-native vocabulary), and Polish, one of the less common languages realizing voiced affricates. Differences between the two languages may provide some evidence for the parameters that speakers must control in order to produce voiced affricates. The data show that German voiced affricates are longer in duration than all other voiced obstruents, and in word-medial position they are longer than the Polish voiced affricates. This could mean that the Polish speakers control medial affricate duration in order to achieve voicing during closure.

The question arises whether the long duration of German voiced affricates could be a consequence of the non-native vocabulary which we included in our corpus. The data suggest that it is not. The current German speakers show this pattern not only for the non-native voiced affricates, but for the native voiceless ones too. This is consistent with the finding of Fuchs and Koenig (2009) for voiceless consonants, where all speakers had longer durations for affricates than for single stops and fricatives, and 4 of 8 had longer durations for affricates than for clusters. Studies of other languages support the claim that affricates are usually longer than comparable obstruents. For example, Byrd (1993) shows that in American English affricates [t͡ʃ] and [d͡ʒ] are longer than /t/ and /d/. Kochetov and Lobanova (2007) show that among Komi-Permyak voiceless coronal stops, fricatives, and affricates, the latter are the longest segments: [t͡ʂ] 140 ms > [t͡ɕ] 116 ms > [ʂ] 110 ms > [c] 104 ms > [s] 102 ms > [ɕ] 97 ms > [t] 88 ms (values obtained for one selected speaker). The current Polish data, however, appear to represent an exception to this general tendency, since in medial position the affricates are actually shorter than the fricatives.

In the present study voiced and voiceless obstruents can be reliably distinguished on the basis of the maximum intraoral pressure for Polish speakers. Voiced obstruents in Polish have a lower P_{max} than their voiceless counterparts. However, similar results were not found for German speakers with the exception of stops in word-medial position. Moreover, the P_{max} in voiced affricates is in all cases higher than in voiced fricatives. This can be attributed to the airtight seal in the stop portion of the affricate. In German, affricates also have higher P_{max} than stops in word-medial position, and shorter relative voicing duration. This is consistent with the long duration of voiced affricates in German in the sense that a longer duration of the closed phase can lead to a higher pressure. German and Polish speakers do not differ significantly with respect to the intraoral pressure maximum in word-initial voiced affricates and fricatives, but they differ regarding voiced stops. Hence, on the basis of the pressure peak alone, it would be hard to make any further conclusions about their phonological voicing status. For the voicing contrast cross-linguistically, it appears to be more important to analyze the pressure shape, and in particular the initial pressure rise parameter (Slope). Slope differentiated voiced and voiceless obstruents in all cases in both languages, with the exception of word-initial fricatives in German (where, as noted above, native vocabulary does not show a voicing contrast).

In summary, this paper shows that several typologically unrelated languages share the tendency to lack voiced sibilant affricates. In the phonemic inventories of Bantu, Niger-Congo, Mongolic, Sino-Tibetan, Indo-European, and other languages, a phonemic gap is attested: Voiced coronal affricates do not occur, though their voiceless counterparts are present. In several of these inventories, stops and fricatives do, however, create a contrast with respect to voicing. The rarity of voiced affricates is supported by several phonological processes showing that, on the one hand, voiced stops are less likely to undergo affrication than their voiceless counterparts, and, on the other hand, voiced affricates are more likely to undergo deaffrication processes than their voiceless cognates.

Phonetic considerations suggest possible explanations for this relative rarity of voiced affricates. Affricates in general may require complex control over supralaryngeal apertures, and they appear to have long durations in many languages. Long duration and complete oral closure at the beginning of affricates contribute to a buildup of intraoral pressure which impedes phonation. We suggest that languages having voiced affricates in their phoneme inventory may tend to control the duration of these sounds, otherwise vocal fold vibration will be lost quickly. To realize complex supralaryngeal apertures in a short duration may, however, be articulatorily demanding.

The current study did not provide direct measures of supralaryngeal articulation. Combining aerodynamic methods with articulatory data such as electropalatography could yield greater understanding of the supralaryngeal characteristics of voiced affricates. Future work might also evaluate the timing of voicing offset with regard to the stop and fricative regions, and consider other acoustic characteristics such as amplitude envelope or spectral properties of the frication part for the description of the voicing contrast. Finally, it is possible that perceptual considerations may also provide some explanations for the tendency for affricates to be voiceless rather than voiced (see, e.g., Ohala and Solé 2010).

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Appendix A

Speech material

Table A1. *Polish phonemes, their corresponding words for the two positions, and English translations. In all Polish words, stress falls on the first syllable.*

Phoneme	Initial position		Medial position	
/d/	ˈ/d/ata	‘date’	ˈra/d/a	‘advice’
/t/	ˈ/t/aca	‘tray’	ˈra/t/a	‘installment’
/z/	ˈ/z/araz	‘in a moment’	ˈga/z/a	‘gauze’
/s/	ˈ/s/arna	‘roe deer’	ˈka/s/a	‘cash’
/ʂ/	ˈ/ʂ/ara	‘gray’ sg. fem.	ˈka/ʂ/a	‘groats’
/ʐ/	ˈ/ʐ/aba	‘frog’	ˈga/ʐ/a	‘salary’
/d͡z/	ˈ/d͡z/aga	proper name, gen.	ˈsa/d͡z/a	‘soot’
/t͡s/	ˈ/t͡s/ara	‘tsar’ gen.	ˈba/t͡s/a	‘sheepherder’
/d͡ʑ/	ˈ/d͡ʑ/ało	‘cannon’	ˈna/d͡ʑ/ać	‘to stuff’
/t͡ɕ/	ˈ/t͡ɕ/ało	‘body’	ˈbra/t͡ɕ/a	‘brother’ pl.

Table A2. *German phonemes, their corresponding words for the two positions, and English translations. In all German words, stress falls on the first syllable.*

Phoneme	Initial position		Medial position	
/d/	ˈ/d/ecke	‘blanket’	ˈScha/d/en	‘damage’ pl.
/t/	ˈ/t/echnik	‘technics’	ˈTa/t/en	‘act’ pl.
/z/	ˈ/z/ekt	‘sparkling wine’	ˈBa/z/e	‘cousin’
/s/	ˈ/s/ent	‘cent’	ˈKa/s/e	‘cash’
/ʒ/	ˈ/ʒ/enie	‘genius’	ˈRa/ʒ/e	‘rage’
/ʃ/	ˈ/ʃ/eck	‘check’	ˈwa/ʃ/en	‘wash’
/d͡ʒ/	ˈ/d͡ʒ/ungel	‘jungle’	ˈMana/d͡ʒ/er	‘manager’
/t͡ʃ/	ˈ/t͡ʃ/eche	‘Czech’	ˈLa/t͡ʃ/en	‘traipse’

Appendix B

Statistical results for temporal (Tables B1, B2) and aerodynamic (Tables B3, B4) parameters in initial and medial positions using linear mixed models (*lmer* in R). Pair-wise comparisons in 1st column, followed by direction of significance (if applicable), *t*-value, and *pMCMC* values for initial and medial positions, respectively.

Table B1. *Consonant duration.*

Fixed factor	Pair-wise comparisons		Initial position*			Medial position	
			t-value	*pMCMC* value		*t*-value	*pMCMC* value
Voicing	Polish						
	voiced vs. voiceless affricates	<	all	**all**	<	4.713	**0.0002**
	voiced vs. voiceless stops	<	2.256	**0.0106**	<	2.830	**0.0046**
	voiced vs. voiceless fricatives	<			=	0.494	0.5694
	German						
	voiced vs. voiceless affricates	<	all	**all**	<	5.357	**0.0001**
	voiced vs. voiceless stops	<	2.256	**0.0106**	<	4.070	**0.0006**
	voiced vs. voiceless fricatives	<			<	2.201	**0.0226**
Articulation	Polish						
	voiced affricates vs. stops	>	4.337	**0.0001**	=	0.461	0.5878
	voiced affricates vs. fricatives	>	3.797	**0.0001**	<	2.477	**0.0158**
	voiced stop vs. fricatives	=	1.179	0.1930	<	2.577	**0.0076**
	German						
	voiced affricates vs. stops	>	4.337	**0.0001**	>	10.258	**0.0001**
	voiced affricates vs. fricatives	>	3.797	**0.0001**	>	6.201	**0.0001**
	voiced stop vs. fricatives	=	1.179	0.1930	<	5.588	**0.0001**

Table B1. *(Continued)*

Fixed factor	Pair-wise comparisons		Initial position*			Medial position	
			t-value	*pMCMC* value		*t*-value	*pMCMC* value
Language	German vs. Polish voiced affricates	=	all	all	>	6.203	**0.0001**
	German vs. Polish voiced stops	=	1.298	0.0774	=	0.881	0.3078
	German vs. Polish voiced fricatives	=			=	1.054	0.2254

* No interactions were found between the factors VOICING and ARTICULATION, VOICING and LANGUAGE, or LANGUAGE and ARTICULATION, so data were grouped and only main effects are reported for word-initial position.

Table B2. *Relative voicing during the overall consonant duration.*

Fixed factor	Pair-wise comparisons		Initial position			Medial position	
			t-value	*pMCMC* value		*t*-value	*pMCMC* value
Voicing	Polish						
	voiced vs. voiceless affricates	>	11.964	**0.0001**	>	7.339	**0.0001**
	voiced vs. voiceless stops	>	9.982	**0.0001**	>	3.009	**0.0066**
	voiced vs. voiceless fricatives	>	15.176	**0.0001**	=	0.397	0.5922
	German						
	voiced vs. voiceless affricates	>	4.619	**0.0002**	>	4.222	**0.0001**
	voiced vs. voiceless stops	>	4.863	**0.0002**	>	6.860	**0.0001**
	voiced vs. voiceless fricatives	>	8.162	**0.0001**	>	8.780	**0.0001**
Articulation	Polish						
	voiced affricates vs. stops	=	0.353	0.6854	<	2.176	**0.0210**
	voiced affricates vs. fricatives	=	1.228	0.1866	=	1.454	0.1156
	voiced stop vs. fricative	=	0.665	0.4530	<	2.736	**0.0098**
	German						
	voiced affricates vs. stops	=	0.840	0.3602	<	5.526	**0.0001**
	voiced affricates vs. fricatives	<	2.925	**0.0054**	<	4.775	**0.0001**
	voiced stop vs. fricative	=	1.903	0.0516	=	1.627	0.0826
Language	German vs. Polish voiced affricates	<	4.809	**0.0001**	<	4.661	**0.0001**
	German vs. Polish voiced stops	<	4.033	**0.0014**	=	0.629	0.4866
	German vs. Polish voiced fricatives	<	3.588	**0.0022**	=	1.490	0.1240

Table B3. P_{max}.

Fixed factor	Pair-wise comparisons		Initial position			Medial position	
			t-value	*pMCMC* value		*t*-value	*pMCMC* value
Voicing	Polish						
	voiced vs. voiceless affricates	<	2.552	**0.0066**	<	2.478	**0.0124**
	voiced vs. voiceless stops	<	1.922	**0.0310**	<	3.940	**0.0004**
	voiced vs. voiceless fricatives	<	3.304	**0.0006**	<	2.309	**0.0188**
	German						
	voiced vs. voiceless affricates	=	0.135	0.8722	=	1.607	0.0784
	voiced vs. voiceless stops	=	0.026	0.9964	<	3.458	**0.0010**
	voiced vs. voiceless fricatives	=	0.709	0.3756	=	1.780	0.0542
Articulation	Polish						
	voiced affricates vs. stops	=	0.627	0.4370	=	1.620	0.0838
	voiced affricates vs. fricatives	>	2.422	**0.0072**	>	2.398	**0.0140**
	voiced stop vs. fricatives	=	1.365	0.1036	=	0.379	0.6386
	German						
	voiced affricates vs. stops	=	0.357	0.6682	>	3.717	**0.0012**
	voiced affricates vs. fricatives	>	2.486	**0.0054**	>	3.744	**0.0006**
	voiced stop vs. fricatives	>	2.024	**0.0206**	=	0.578	0.4848
Language	German vs. Polish voiced affricates	=	1.431	0.0596	>	1.887	**0.0288**
	German vs. Polish voiced stops	>	1.533	**0.0446**	=	0.427	0.6022
	German vs. Polish voiced fricatives	=	1.208	0.1060	=	1.029	0.1818

Table B4. *Slope.*

Fixed factor	Pair-wise comparisons		Initial position			Medial position[1]	
			t-value	*pMCMC* value		*t*-value	*pMCMC* value
Voicing	Polish						
	voiced vs. voiceless affricates	<	6.522	**0.0001**	<	all	**all**
	voiced vs. voiceless stops	<	6.010	**0.0001**	<	5.000	**0.0001**
	voiced vs. voiceless fricatives	<	4.630	**0.0001**	<		
	German						
	voiced vs. voiceless affricates	<	2.605	**0.0032**	<		**all**
	voiced vs. voiceless stops	<	3.343	**0.0001**	<	5.000	**0.0001**
	voiced vs. voiceless fricatives	=	0.877	0.2684	<		

Table B4. *(Continued)*

Fixed factor	Pair-wise comparisons		Initial position			Medial position[1]	
			t-value	*pMCMC* value		*t*-value	*pMCMC* value
Articulation	Polish						
	voiced affricates vs. stops	=	0.139	0.8608	=	0.406	0.6136
	voiced affricates vs. fricatives	=	0.400	0.6012	>	2.087	**0.0188**
	voiced stop vs. fricative	=	0.482	0.5528	>	2.307	**0.0086**
	German						
	voiced affricates vs. stops	=	0.876	0.2768	=	0.406	0.6136
	voiced affricates vs. fricatives	=	0.872	0.2816	>	2.087	**0.0188**
	voiced stop vs. fricative	=	0.138	0.8768	>	2.307	**0.0086**
Language	German vs. Polish voiced affricates	=	1.161	0.1750	=	all	all
	German vs. Polish voiced stops	=	0.167	0.8216	=	0.504	0.5328
	German vs. Polish voiced fricatives	=	0.794	0.3506	=		

[1] No interactions were found between the factors VOICING and ARTICULATION, VOICING and LANGUAGE, or LANGUAGE and ARTICULATION, so data were grouped and only main effects are reported for word-medial position.

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Notes

1. Calculations that include language varieties and secondary articulations show qualitatively the same patterns as those illustrated in Figure 1. The UCLA Phonological Segment Inventory Database (Maddieson and Precoda 1992), which includes phonemic inventories of 451 languages, also shows similar voiced:voiceless patterning: 343:509 for stops, 203:606 for fricatives, and 175:338 for affricates.
2. Chomsky and Halle (1968) used stridency as a feature for differentiating bilabials from labiodentals: /θ ð/ were represented as being [−strident] and /f v/ were [+strident]. Since the introduction of feature geometric theories (McCarthy 1988), [strident] is represented as being dependent on the coronal node. In this work, we follow the more current usage for this feature.
3. Different criteria are applied for defining markedness by different authors. Generally, marked sounds are considered as being not only less frequent but also articulatorily more complex and acquired later in a language acquisition processes than their unmarked counterparts. Marked sounds also show a certain amount of 'instability' in phonological patterns and processes from a diachronic point of view.
4. It is noteworthy for the Slavic languages that the asymmetry in the affricate inventory was not a feature of Proto Slavic, but arose independently in the languages via different processes such as, e.g., palatalizations and Jotation (see Carlton 1991 for an overview). For example, /tj/ changed to [t͡ʃ] in East Slavic languages while /dj/ became [z] in Russian and [d͡ʒ] or [ʒ:] in Belorussian and Ukrainian (Carlton 1991: 114).
5. Wali and Koul (1997: 294) use the symbols /t d th ts tsh s z/ and /ṭ ḍ/ and describe them as alveolar-dental and retroflex sounds, respectively.

6. Stop assibilations are defined here as processes whereby coronal stops become sibilant affricates or fricatives before high vocoids (Hall and Hamann 2006: 1195).
7. Supportive phonetic evidence in favor of the implicational rules is provided by Hall, Hamann, and Żygis (2006), who show that the inputs to assibilations can be arranged in the order /tj/ < /ti/ < /dj/ < /di/ on the basis of frication duration meaning that the frication phase in /tj/ is longer than in /ti/ and /dj/, etc. The results suggest that the frication length could contribute to the explanation of assibilation patterns found cross-linguistically. Cf. also, e.g., Jäger (1978) and Kim (2001).
8. Telfer used the term coronalization, rather than affrication. Coronalization was defined as a process where 'typically a velar stop, such as /k/, becomes a coronal affricate [t͡s] or [t͡ʃ] when followed by a high front vowel /i/' (Telfer 2006: 1). (The notation marks / / and [ ] have been added by us).
9. Telfer (2006) refers to an earlier version of Hall and Hamann's study (2006), namely, Hall and Hamann (2003). In the earlier version ca. 45 languages were investigated.
10. All *t*-values reported in this paper are absolute values.

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