The phonetic motivation for phonological stop assibilation

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This article examines the motivation for phonological stop assibilations, e.g. /t/ is realized as [ts], [s] or [tʃ] before /i/, from the phonetic perspective. Hall & Hamann (2006) posit the following two implications: (a) Assibilation cannot be triggered by /i/ unless it is also triggered by /j/, and (b) voiced stops cannot undergo assibilations unless voiceless ones do. In the following study we present the results of two acoustic experiments with native speakers of German and Polish which support implications (a) and (b). In our experiments we measured the friction phase after the /t d/ release before the onset of the following high front vocoid for four speakers of German and Polish. We found that the friction phase of /tj/ was significantly longer than that of /ti/, and that the friction phase of /t/ in the assibilation context is significantly longer than that of /d/. Furthermore, we unexpectedly found that the friction phase of /tj/ is significantly longer than that of /di/. An additional finding not related to the topic of the present study was that the Polish voiceless stops of the four speakers tested showed aspiration, in contrast to phonetic descriptions of these sounds as unaspirated.

1 Introduction

This article examines stop assibilations – defined here as processes which convert a (coronal) stop to a sibilant affricate or fricative before high vocoids, e.g. /t/ is realized as [ts], [s] or [tʃ] before /i/. In a typological study of phonological assibilations in more than 30 typologically diverse languages, Hall & Hamann (2006) postulate the following two implications:

(1) Implications
  a. Assibilation cannot be triggered by /i/ unless it is also triggered by /j/.
  b. Voiced stops cannot undergo assibilations unless voiceless ones do.

In the present study we present the results of two acoustic experiments with native speakers of German and Polish which support the implications in (1). It will also be shown that additional results of these two experiments point to possible universal generalizations on phonological assibilations not discussed in the literature on this process (e.g. Clements 1999, Kim 2001, Hall & Hamann 2006). The present treatment is therefore important because we

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provide additional evidence that phonological assibilations can only be adequately explained by appealing to phonetics (see the authors cited above).

The purpose of this paper is to consider implications like the ones in (1) from the phonetic perspective. In particular, since stop assibilation is a process which is phonetically motivated by the turbulent noise which occurs after the release of a stop into a following high vocoid (referred to below as the FRICTION PHASE), we postulate that implication (1a) can be supported if it can be shown that the friction phase in /tj dj/ is significantly longer than in /ti di/. The implication in (1b) would similarly derive support if the friction phase in sequences like /tj ti/ is longer than in /dj di/. We would furthermore expect that these predictions could be borne out in any one of a number of languages, since Kim's (2001) universal claims are based on a phonetic study of a single language (Korean) and Hall & Hamann's (2006) observations hold for a number of typologically diverse languages.

In the following sections we present the results of two acoustic studies of /ti tj di dj/ sequences in German and Polish. We chose these two languages because they differ in their average VOT values for /p t k/ vs. /b d g/, i.e. German is a language in which initial /p t k/ are strongly aspirated, but in Polish this is usually assumed not to be the case (Keating 1980). It needs to be stated at the outset that German is a language in which [j] is an allophone of /i/ (see below for discussion). As we noted above, the universal claims made by Kim (2001) and Hall & Hamann (2006) are intended to hold not only for languages in which /i/ and /j/ are phonemic, but also for languages like German, in which the two sounds are allophones.

This article is organized as follows. In section 2 we define in greater detail the kind of processes we understand to be assibilations and summarize briefly the typological findings in Hall & Hamann (2006) which led them to posit the implications in (1). Section 3 summarizes four predictions pertaining to the phonetic realization of sequences like /ti/, /di/, /tj/ and /dj/ which – if confirmed – would support the implications in (1). In section 4 we present the results of two acoustic studies in which the friction phase from the release of /t d/ onto a following high vocoid for several German and Polish speakers is measured. The results of these experiments are significant because they lend support to the four predictions established in section 3. In section 5 we summarize these findings and discuss three unexpected results which influence the friction phase in sequences like /ti/, namely the relevance of stress and the quality of the adjacent vowels. In section 6 we discuss the phonetic motivation of the results of the two experiments. Section 7 considers an alternative phonetic motivation for implications in (1), namely the spectral similarities in terms of center of gravity between the friction of the fricative phase of affricates and the friction before /i j/ in sequences like /ti tj di dj/. Section 8 concludes.

2 Stop assibilations

In this section we define what we mean by stop assibilation and then present several universal properties for such processes discussed by Hall & Hamann (2006), as well as by earlier authors, namely Foley (1973, 1977), Bhat (1978), Jäger (1978), Ohala (1983), Clements (1999), and Kim (2001).

Stop assibilations (or assibilations for short) are defined here as processes whereby stops become sibilant affricates or sibilant fricatives before high vocoids. Three examples of such rules have been presented in (2). These examples are synchronic ((2b, c) are purely allophonic and (2a) captures morphophonemic alternations). The generalizations we make below also hold for diachronic assibilations in as far as they emerged from synchronic assibilations.

(2) Three examples of phonological assibilation rules

a.	t → s / __ i	Finnish (Kiparsky 1973)	spirantization
b.	t d → ts dz / __ i j	Quebec French (Cedergren et al. 1991)	affrication
c.	t → tʃ / __ i	West Futuna-Aniwa (Dougherty 1983)	posteriorization

The distinction between the three outputs in (2), i.e. 'spirantizations', 'affrications' and 'posteriorizations', is not important for the present study. The three processes are referred to collectively as assibilations because they all display a similar cluster of properties (see (3) below).

Although processes like the ones in (2) can also affect a velar stop (e.g. in Late Latin /k ɡ/ surfaced as [ts dz] before /j/; Pope 1952) and in some rare languages a labial (e.g. in Lahu labial stops and nasals are affricated before /u/; Matisoff 1982: 3), we restrict our discussion to assibilations which have a coronal stop as the input segment, in particular when the input is dental or alveolar. We leave a typology of noncoronal assibilations open for further study.

Assibilations like the ones in (2) can either be lexical or postlexical rules. For example, in Finnish (see (2a) above) assibilation is lexical because it is restricted to applying within a derived environment and does not affect tautomorphemic /ti/ sequences. In Quebec French (see (2b)) the assibilation rule is postlexical because it applies across the board, both within and across words. Since the properties we discuss below hold for postlexical and lexical assibilations we do not see the need to distinguish between the two rule domains.

The term 'assibilation' is used here in a very narrow sense since we restrict our discussion below to processes like the ones in (2), which share the following three properties (based on the findings of Clements 1999 and Kim 2001):[1]

(3) Three properties of stop assibilations:
  a. The trigger is typically some subset of the high front vocoids (i.e. /i j/).
  b. The output is a sibilant (either an affricate or a fricative).
  c. The trigger is typically to the right of the target.

Several authors offer a phonetic explanation for the properties of stop assibilation in (3a–c), although they might describe it in somewhat different ways. Thus, Jäger (1978: 316) states that 'if a language has rules that either devoice, aspirate, fricate or affricate consonants before only some vowels but not others, it will be before high rather than low vowels'. Jäger attributes this implication to the fact that the narrow constriction for high vowels creates better conditions for turbulence, which can affect the preceding consonant by adding frication to it. This frication together with the preceding stop can be reinterpreted as a fricated stop, i.e. an affricate. Ohala (1983: 204) also observes that stops tend to be realized with a fricated release when they are followed by close vowels. He ascribes this tendency to the fact that the high velocity of the airflow created upon release is maintained longer when a stop is followed by a close vowel as opposed to an open vowel. Ohala furthermore concludes from phonological data that palatal glides are more liable to produce frication than close vowels without testing this difference experimentally. Clements (1999) and Kim (2001) state that the creation of sibilants from stops has its phonetic origin in the brief period of turbulence (or 'friction phase') which occurs at the release of a stop into a following high vocoid. Thus, Clements (1999) and Kim (2001) observe that the friction phase that occurs in some languages following the release of an alveolar stop into a high front vocoid is significantly longer than the friction phase of the same stop which is released into a non-high and/or non-front vocoid.

In Hall & Hamann's (2006) study, not all logical stop assibilation types are shown to be attested. In (4) the ten logical language types are presented with the variables /i/ and /j/ as triggers and /t/ and /d/ as assibilating segments. Of these ten types only the five in (4a) were shown to be occurring. The phonetic output of the assibilations in (4a) can be either fricatives like [s z] or affricates like [ts dz] or [tʃ dʒ] (recall (2)).

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[1] Properties (3a) and (3c) deserve comment. There are many languages in which processes like the ones in (2) apply in the neighborhood of high and non-high vowels, e.g. /t/ becomes [s] before [i u] AND [e o] in Woleaian (Tawerilmang & Sohn 1984: 184). It is also possible to find assibilation processes that apply AFTER the vocalic trigger, e.g. /t/ surfaces as [tʃ] after [i] in Basque (Hualde 1991: 108f.). Processes like the ones in Woleaian and Basque are excluded from the typology described below because we focus only on processes like the ones (1).

(4) Ten logical language types

a. Occurring assibilation types

Language Type	Assibilating Segment(s)	Trigger(s)
A	/t d/	/i j/
B	/t d/	/j/
C	/t/	/i j/
D	/t/	/j/
E	none	/i j/, /i/, /j/, none

b. Nonoccurring assibilation types:

Language Type	Assibilating Segment(s)	Trigger(s)
F	/t d/	/i/
G	/t/	/i/
H	/d/	/i j/
I	/d/	/j/
J	/d/	/i/

An example of a Type A language is Quebec French, i.e. /t d/ assibilate to [ts dz] before /i j/ (see (2b)). Type B (/t/ and /d/ assibilate before /j/ but not before /i/) is attested by Sanskrit (Misra 1967: 142). Dutch (Booij 1995: 79f.) is a Type C language, i.e. /t/ (but not /d/) assibilates before /i/ and /j/. Type D (/t/ but not /d/ assibilates before /j/ but not before /i/) is attested by Latin (Pope 1952). Note that Type E describes the numerous languages that do not assibilate, i.e. sequences like /ti/ and /tj/ surface as [ti] and [tj]. Type E languages are included above for the sake of completeness.

In contrast to the occurring types in (4a) the language types F–J in (4b) are not attested. For example, a Type F language would be one in which /t/ and /d/ assibilate before /i/ but not before /j/ and in a Type G language only /t/ but not /d/ assibilates before /i/, but not before /j/.

Hall & Hamann (2006) propose that the nonoccurring language types in (4b) fall out from the two implications in (1), which we have repeated in (5) for convenience.

(5) Implications
  a. Assibilation cannot be triggered by /i/ unless it is also triggered by /j/.
  b. Voiced stops cannot undergo assibilations unless voiceless ones do.

Given the two triggers /i/ and /j/ and the two input segments /t/ and /d/, the implications in (5a–b) mean that none of the languages in (4b) is expected to occur. For example, (5a) would be violated by the hypothetical but nonoccurring languages F and G. Type H would not be in line with (5b), since only /d/ but not /t/ assibilates.

3 Predictions

Since assibilations have their phonetic origin in the friction phase which arises after the release of a coronal stop before a high vocoid, we argue that the implications in (5) and the typology in (4) can be shown to be grounded in phonetics if the four predictions in (6) are borne out:

(6) Four predictions
  a. The friction phase in /tj/ is of longer duration than in /ti/.
  b. The friction phase in /dj/ is of longer duration than in /di/.
  c. The friction phase in /tj/ is of longer duration than in /dj/.
  d. The friction phase in /ti/ /is of longer duration than in /di/.

In essence, a longer friction duration after a coronal stop is more likely to be interpreted as affricate than a shorter one. If prediction (6a–b) can be shown to be correct then this finding would lend support to implication (5a). Along the same lines, if prediction (6c–d) can be substantiated experimentally then this would support implication (5b).[2]

The typology in (4) suggests an assibilation hierarchy as in (7), in which the wedge '<' means 'is implied by'; hence, the assibilation of /ti/ implies the assibilation of /tj/, etc. Note that this typology makes no predictions concerning the relationship of /ti/ to /dj/; hence, both sequences occupy the same slot in the hierarchy in (7).

(7) An assibilation hierarchy (to be revised)

/tj/ < {/ti/, /dj/} < /di/

Should the predictions in (6a–b) be confirmed then this would lend phonetic support to the hierarchy in (7).

In addition to the voicing parameter (i.e. /t/ vs. /d/) and the parameter for the trigger (i.e. /i/ vs. /j/) there are three other factors which could potentially influence the friction phase duration. We list them in (8).

(8) a. The quality of the vowel following /tj/ and /dj/.
b. The quality of the vowel preceding /tj/, /ti/, /dj/ and /di/.
c. The position of stress with respect to /tj/, /ti/, /dj/ and /di/.

The assibilation hierarchy in (7) might also be attributable to other acoustic factors, such as the spectral similarities between the friction of the fricative phase of alveolar affricates and the friction before /i j/ in sequences like /ti tj di dj/. The assibilation hierarchy in (7) would therefore be supported if the friction in /ts dz/ were spectrally more similar to the friction in /tj/ than the one in /ti dj/, and more similar to the friction in /ti dj/ than in /di/. We discuss the three factors in (8) in greater detail in section 4.3 and section 6.3. The spectral similarities referred to above are dealt with in section 7.

4 A phonetic analysis

In this section we present phonetic evidence supporting the predictions in (6) and the hierarchy in (7). We summarize below the results of two acoustic studies of /ti tj di dj/ sequences, one with German speakers and one with Polish speakers. In our studies we measured the duration from the release of /t d/ to the onset of the following vocoid (the start of the fundamental frequency and continuous formants) as illustrated in figure 1. For purposes of our article we call this phase 'friction phase.'

For voiceless stops the friction phase includes the following phonetic components:

- burst (B) resulting from the release of the overpressure,
- local friction (F) resulting from turbulence at the supraglottal constriction,
- aspiration (A) resulting from turbulence at the glottis.

[2] Predictions (6c–d) can probably be attributed to the fact that the friction phase of /t/ is generally speaking longer than the friction phase in /d/ (regardless of the quality of the following vocalic element). See section 6.2 for discussion.

An anonymous reviewer points out that implication (5a) cannot simply be substantiated by showing that the friction phase in /tj/ is longer than in /ti/ (= prediction (6a)). In addition, it needs to be shown that the friction phase in /ti/ is longer than the friction phase in /t/ followed by other vowels, e.g. /te ta/. We do not consider the friction phase in the latter sequences because studies from other languages have demonstrated that the friction phase in /t/ followed by a high vocoid like /i j/ is significantly longer than in sequences like /te ta/. See, for example, Kim (2001) for Korean. Since Kim (2001) does not compare the friction phase in /ti/ vs. /tj/, the present study focuses on such sequences.

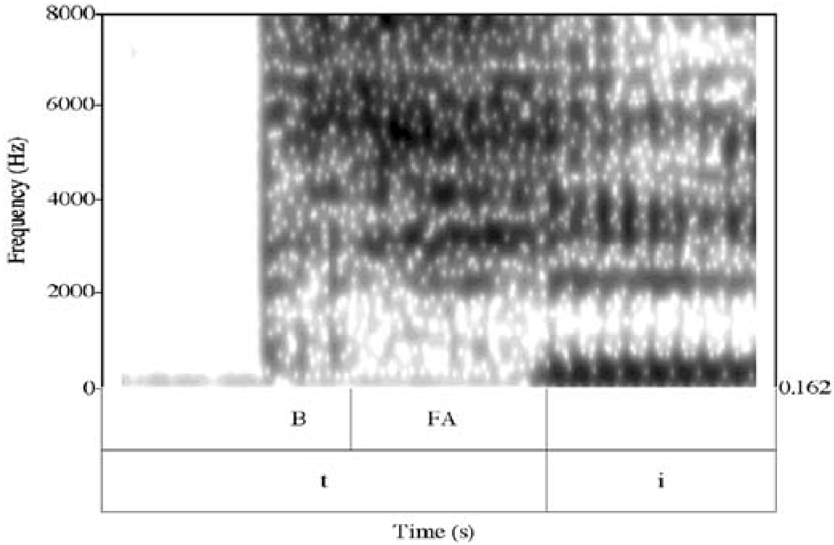

Figure 1 Spectrogram of a sample friction phase of a voiceless stop. B = burst, F = local friction, and A = aspiration.

The three components (B+F+A) which create the friction phase are shown in figure 1. 0.162 stands for the duration of the section of /ti/ in s. For voiced stops the friction phase includes only the burst (B) and the local friction (F).

While the burst immediately follows the closure phase of /t d/, local friction (for both voiceless and voiced stop) and aspiration (in the case of the voiceless stop) occur between the burst and the following vocoid, which includes all vowels and glides. The burst can be easily separated from aspiration and local friction, while it appears difficult to extract local friction from aspiration, cf. Stevens (1998). The burst shows a spectral prominence in the frequency range from 3500 to 7000 for an alveolar stop, which is due to a front cavity that is 1–2 cm long, cf. e.g. Stevens, Manuel & Matthies (1999). Local friction results from turbulence in the region of the supraglottal constriction, i.e. at dental or alveolar place of articulation in case of /t/ or /d/. If the stop is followed by a high vocoid, as in figure 1, aspiration overlaps with friction generated at the constriction of this vocoid, cf. Hanson & Stevens (2003). The friction shows a stronger concentration of energy in higher frequencies. Aspiration on the other hand is generated at the glottis and shows a stronger concentration of energy in the higher frequency region but also at formant-like peaks in lower frequency regions. Furthermore, the aspiration displays attenuation, or lack of the first formant, the so-called F1 cutback, cf. Liberman, Delattre & Cooper (1958).

Two experiments were conducted in order to test the predictions in (6), one with German native speakers and one with Polish native speakers. Polish differs from German in terms of voicing: German contrasts voiced with voiceless stops, i.e. /b d g/ vs. /p t k/, where the voiceless series is aspirated in stressed position, i.e. [p^h t^h k^h], and the voiced series is often devoiced, i.e. [p t k] (see e.g. Jessen & Ringen 2002). Polish has phonologically the same contrast between voiced and voiceless stops /b d g/ vs. /p t k/, but the voiced series is always fully voiced [b d g], and the voiceless one is described as being unaspirated [p t k] (Keating 1980). This language-specific difference in the realization of the voicing contrast leads us to expect a difference in overall friction length: since the duration from the burst until the onset of a vowel is shorter for truly voiced stops than for voiceless ones and aspiration adds to this length of friction, we expect Polish to show generally shorter friction duration than German. It will be shown below that the results of both experiments support not only

Table 1 Twenty eight sequences involving /t d/ with /i j/ used in Experiment 1 and 2.

Atik	aTIK	Adik	aDIK
Itik	iTIK	Idik	iDIK
Utik	uTIK	Udik	uDIK
Atjak	aTJAK	Adjak	aDJAK
Itjak	iTJAK	Idjak	iDJAK
Utjak	uTJAK	Udjak	uDJAK
Atjuk	aTJUK	Adjuk	aDJUK

(6a–d) but also the difference in friction duration between Polish and German referred to above.

4.1 German

Four native speakers of German (two male, CG and JD, and two female, SF and SH) were asked to read the twenty-eight nonce words given in table 1 in a randomized order. All are phonotactically well-formed in German.[3,4] Capitals indicate stress.

The nonce words were embedded in the frame sentence *Ich habe __ gesagt* 'I said __'. The subjects repeated the test words with the frame sentence ten times at normal speed. The recordings were made at a sampling rate of 44100 Hz and resampled to 22050 Hz. The items were further analyzed with PRAAT (version 4.3). For statistical calculations SPSS (version 11.0) was used.

Figure 2 shows broad band spectrograms (with a window length of 5 ms and a dynamic range of 50 dB) for the examples /aTIK/ and /aTJAK/ for speaker JD. The duration of the friction phase is indicated in the examples in the first line below each spectrogram (the /a/ at the beginning and at the end of each word are not given in their whole duration). The duration of the entire sequence is given at the right edge of the spectrogram, i.e. 0.338 s and 0.330 s.

A comparison of the two spectrograms in figure 2 shows that the example with a following /i/ in (a) has a shorter friction phase than the one with a following glide /j/ in (b).

For all four speakers together, the friction duration after /d/ is shorter than it is after /t/, as illustrated in figure 3. The vertical axis indicates duration of the friction phase in seconds. The different shadings of the bars correspond to /i/ or /j/, as indicated in the legend to the right.

A two-factorial ANOVA with /d t/ and /i j/ as independent variables and friction duration as the dependent variable reveals that all differences presented in figure 3 are highly significant. These results support predictions (6a–d). (6a) is supported because the friction duration for /tj/ is significantly longer than /ti/ ($F(1,555) = 143.567$, $p < .001$), as is (6b) because the friction duration for /dj/ is significantly longer than /di/ ($F(1,563) = 248.975$, $p < .001$). (6c–d) also derive support because the friction phase for /tj/ is significantly longer than for /dj/, ($F(1,636) = 1272.829$, $p < .001$). For /ti/ vs. /di/ the results are also significant ($F(1,482) = 887.476$, $p < .001$). One unexpected finding in Experiment 1 is that

[3] The sequences [di] and [ti] are common in German, e.g. *Dieb* [diːp] 'thief', *tief* [tiːf] 'deep'. Examples containing [dj] occur in many (frequent) non-native words, e.g. *Studium* [ˈʃtuːdjʊm] 'studies' (sg). Examples of [tj] sequences are attested in words with orthographic <dj>, e.g. *Adjektiv* [ˈatjɛktiːf] 'adjective'. See Hall (2004) for discussion of the distribution of [tj] and [tsj] sequences in Modern German.

[4] We chose nonce words to be able to control for stress and vowel context, because minimal pairs with real words alternating only in these parameters do not occur in German.

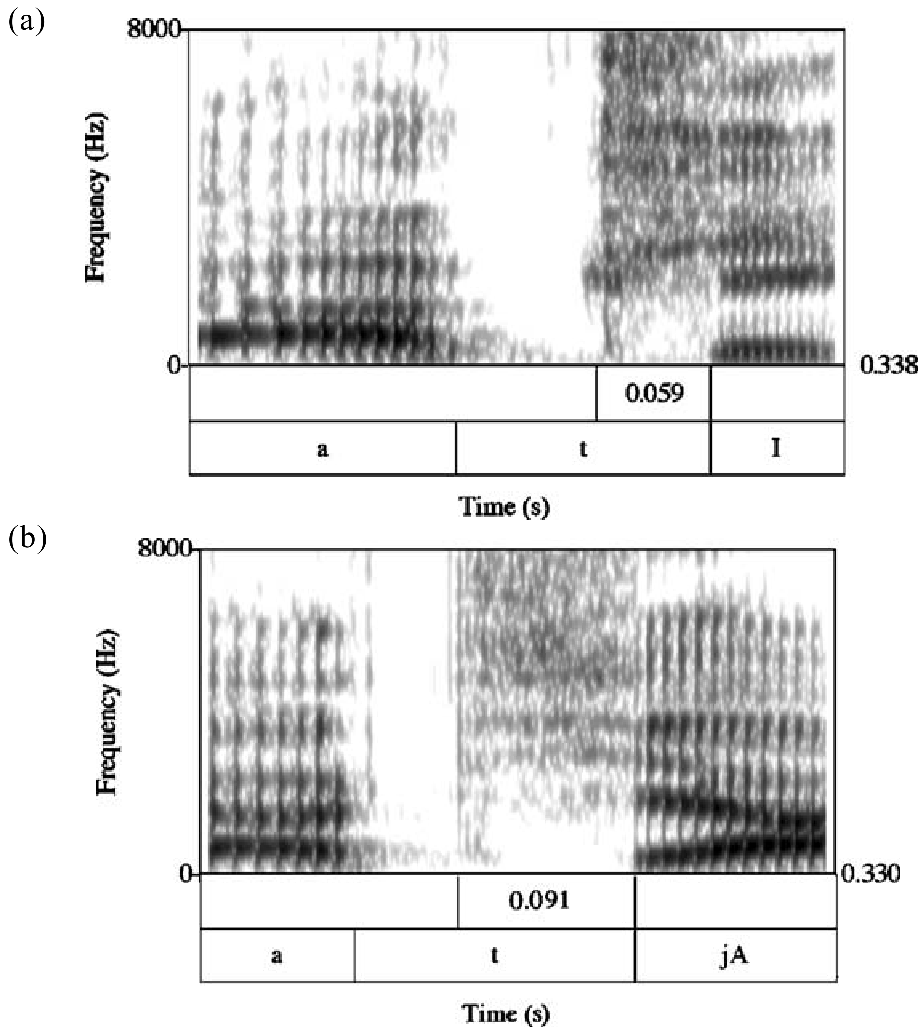

Figure 2 Spectrograms of (a) aTIK and (b) aTJAK (German speaker JD).

the friction phase duration of /ti/ is significantly longer than that of /dj/ ($F(3,119) = 844.722$, $p < .001$); the latter results follow from a post-hoc Scheffé test. In section 6 we return to this point.

Figure 4 presents results in the form of box plots, as obtained for individual speakers. The results are averaged over vowels and stress condition. The order of the single box plots within each window corresponds to the order of bars in figure 3. Each boxplot shows the median, quartiles, and extreme values within a category. The median value is shown by a horizontal line displayed in each of the boxplots. The box length is the interquartile range and covers 50% of the data. It is limited by the first (25%) and third quartile (75%). Figure 4 also presents outliers marked by small circles above and below the boxes which represent cases with values between 1.5 and 3 box lengths from the upper or lower edge of the box.

Figure 4 illustrates that all four speakers of German individually support predictions (6c–d): statistically, the friction phase is significantly longer in /tj/ than in /dj/ and in /ti/ than

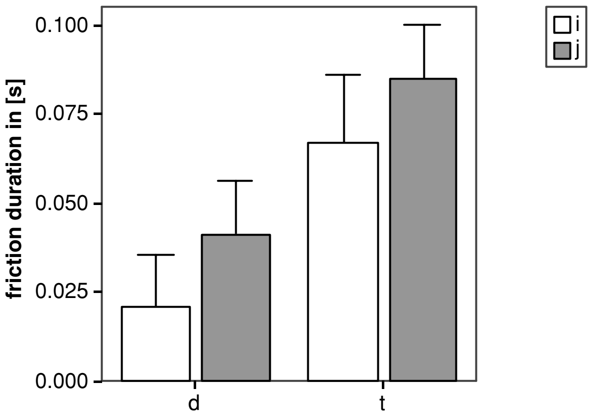

Figure 3 The average duration of friction in seconds after /d/ and /t/ for all German speakers.

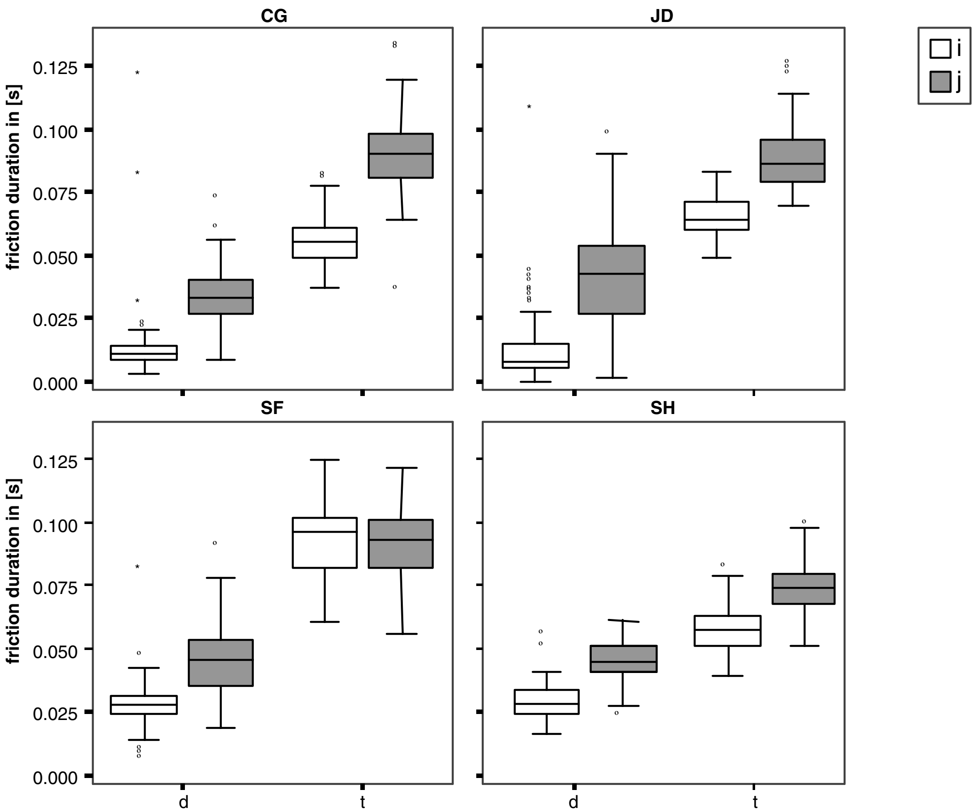

Figure 4 The average duration of friction in seconds after /d/ and /t/ split according to German speakers.

in /di/, (for (6c) speaker CG $F(1,158) = 660.724$, $p < .001$; speaker JD $F(1,158) = 245.311$, $p < .001$; speaker SF $F(1,158) = 420.671$, $p < .001$; speaker SH $F(1,159) = 433.072$, $p < .001$; for (6d) speaker CG $F(1,120) = 244.719$, $p < .001$; speaker JD $F(1,120) = 497.459$, $p < .001$; speaker SF $F(1,119) = 838.043$, $p < .001$; speaker SH $F(1,120) = 278.373$, $p < .001$).

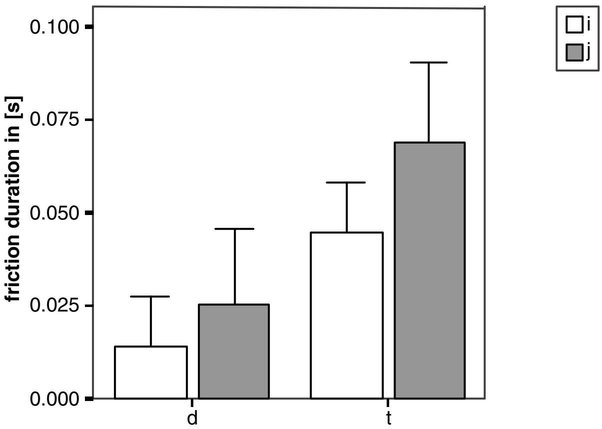

Figure 5 The average duration of friction in seconds after /d/ and /t/ for all Polish speakers.

Prediction (6b) (i.e. the friction phase in /dj/ is of longer duration than in /di/) is also significantly supported by all four speakers (for each speaker $p < .001$). Prediction (6a) (i.e. the friction phase in /tj/ is of longer duration than in /ti/) is supported by speakers CG, JD, and SH but not by speaker SF, who has almost equal values for /tj/ and /ti/; the difference is not significant ($F(1,137) = .838$, $p = .361$).

4.2 Polish

Four native speakers of Polish (two female DZ, MR and two male SL, KZ) were asked to read the nonce words presented in table 1 in the carrier sentence *Powiedziałem __ do ciebie* 'I said __ to you' ten times in randomized order at normal speed.[5,6]

The average duration of the friction phase duration as obtained by all four speakers together is presented in figure 5.

The results presented in figure 5 support the predictions in (6a–d). Again, a two-factorial ANOVA with /d t/ and /i j/ as independent variables and friction duration as the dependent variable reveals that all differences presented in figure 5 are highly significant: /tj/ vs. /ti/ ($F(1,544) = 225.219$, $p < .001$), /dj/ vs. /di/ ($F(1,563) = 50.959$, $p < .001$), /tj/ vs. /dj/ ($F(1, 629) = 680.829$, $p < .001$), and /ti/ vs. /di/ ($F(1,478) = 664.349$, $p < .001$). As in German, the friction duration for /ti/ in Polish is significantly longer than for /dj/ ($p < .001$). See section 6 below for discussion.

An additional finding is that the Polish voiceless stops are all aspirated for our subjects. This suggests that – at least for certain speakers – Polish is developing aspiration for voiceless stops (in accordance with I. Sawicka, p.c.).

Figure 6 presents the results split between the individual speakers in the form of box plots. Again, the results are averaged over vowels and stress condition.

The results in figure 6 show that predictions (6a, c–d) are supported by the results from all four speakers for all three predictions (for (6a) speaker DZ $F(1,137) = 54.268$,

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5 The sequences [tj dj] plus vowel and [ti di] are well-formed in Polish, occurring in words of foreign origin, e.g. [dj]*alekt* 'dialect' [tj]*ara* 'tiara', [di]*wa* 'diva', [ti]*k* 'tick.' We consider Polish words like these to be well integrated into the language because they undergo native morphophonological rules, e.g. palatalization in some declension cases, e.g. *tiara* 'tiara' (nom) vs. *tia*[ʑ]*e* (gen). In contrast to this example, there are foreign words which do not undergo such morphophonological rules and are therefore unintegrated loan words.

6 The motivation for using nonce words is identical to that for German, cf. footnote 4.

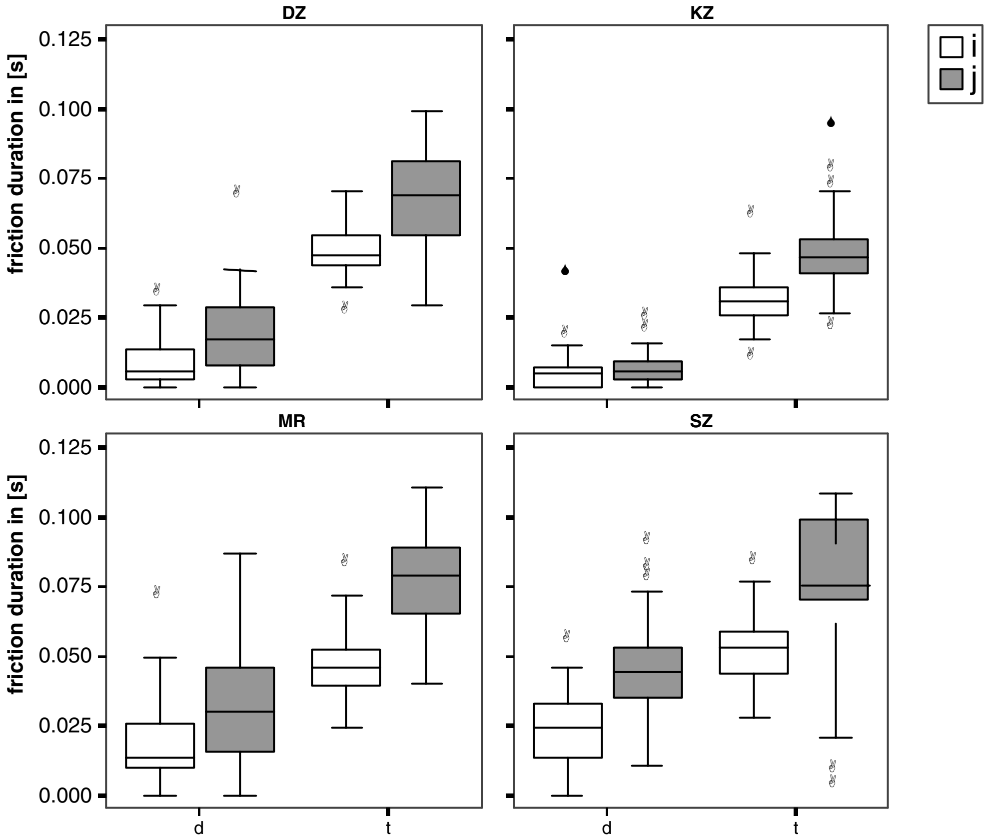

Figure 6 The average duration of friction in seconds after /d/ and /t/ split according to Polish speakers.

$p < .001$; speaker KZ $F(1,138) = 82.767$, $p < .001$; speaker MR $F(1,128) = 170.477$, $p < .001$; speaker SZ $F(1,138) = 95.551$, $p < .001$; for (6c) speaker DZ $F(1,159) = 418.822$, $p < .001$; speaker KZ $F(1,159) = 858.693$, $p < .001$; speaker MR $F(1,149) = 250.221$, $p < .001$; speaker SZ $F(1,159) = 157.\ 321$, $p < .001$; and for (6d) speaker DZ $F(1,118) = 599.272$, $p < .001$; speaker KZ $F(1,119) = 389.158$, $p < .001$; speaker MR $F(1,119) = 176.979$, $p < .001$; speaker SZ $F(1,119) = 134.688$, $p < .001$). (6b) is supported by three speakers (speaker MR $F(1,140) = 19.264$, $p < .001$; speaker SZ $F(1,140) = 59.190$, $p < .001$; speaker DZ $F(1,140) = 20.867$, $p < .001$). By contrast, speaker KZ did not have a significant difference between the friction phase duration of /di/ vs. /dj/ ($F(1,140) = 1.696$, $p = .195$).

In addition, the results show that the friction phase is on average shorter in Polish than in German which is in accordance with our expectations (for Polish /di/ (0.014 s) vs. German /di/ (0.021 s) $p < .001$, for Polish /dj/ (0.025 s) vs. German /dj/ (0.041 s) $p < .001$, for Polish /ti/ (0.045 s) vs. German /ti/ (0.067 s) $p < .001$, for Polish /tj/ (0.069 s) vs. German /tj/ (0.085 s) $p < .01$; see figures 3 and 5).

4.3 Further parameters

In this section we report on the results of the two experiments with respect to the three factors mentioned above in (8), namely the influence of the following vowel quality (8a), of the preceding vowel quality (8b), and of stress (8c).

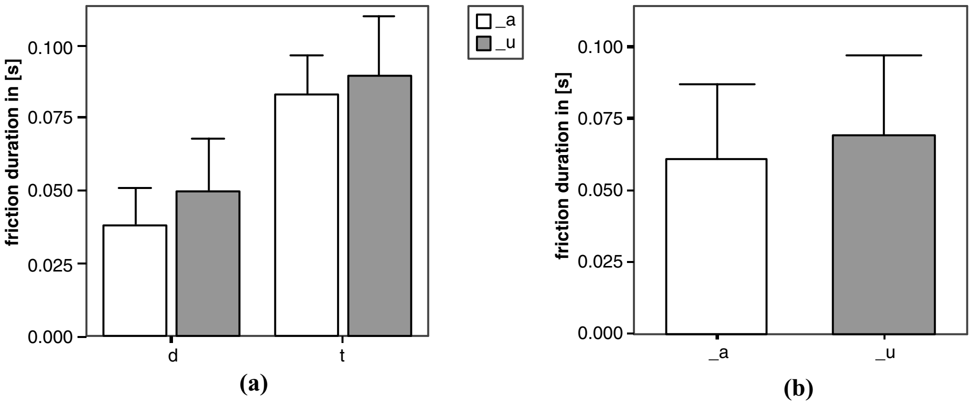

Figure 7 The average duration of friction in seconds dependent on the following vowel for /dj/ and /tj/ separately (a) and for /tj/ and /dj/ together (b). German speakers.

As far as the quality of the following vowel is concerned, the analysis is restricted to /t d/ plus /j/ sequences. We did not consider a vowel following /ti/ and /di/ sequences, as e.g. /atia/ or /atiu/ because sequences like these are typically realized with a glide in German and Polish, i.e. [atja], [atju]. (In German the glide [j] is an allophone of the vowel /i/; hence an /i/ in prevocalic position will surface as [j]). Figure 7 shows average friction durations for German dependent on the vowel following /tj/ and /dj/.[7]

The results provide evidence that the friction duration in German /tj/ and /dj/ sequences is influenced by the following vowel. In particular, longer friction occurs if the sequences are followed by _u than by _a. The results are significant (for /dj/ sequences $p < .01$, $F(1,319) = 37.713$ and for /tj/ sequences $p < .001$, $F(1,315) = 10.014$). Taken together, the average friction duration for /tj/ and /dj/ leads to statistically significant differences: a following _u results in a longer duration than a following _a ($p < .01$, $F(1,635) = 11.898$); cf. figure 7(b).

The influence of the vowel after /tj/ and /dj/ in the Polish items is given in figure 8.

As in German, the _u context in Polish triggers longer duration in /tj/ and /dj/ sequences than the _a context. The differences are again significant (for /dj/ sequences $p < .01$, $F(1,319) = 6.813$ and for /tj/ sequences $p < .05$, $F(1,305) = 4.523$). Taking the results for /dj/ and /tj/ together, figure 8(b) shows a similar difference in friction duration: the sequences in the _u context have a longer friction than the sequences in the _a context. The difference is statistically significant ($p < .05$, $F(1,625) = 5.097$). The influence of vowel quality on a preceding glide and its consequence on friction duration is discussed in section 6.3 below.

Another factor we varied in this experiment was the preceding vowel, cf. (8b). Here all items of table 1 were included in the calculations. Figure 9 shows how the preceding vowels a_, i_ and u_ influence the friction length of the stop-vocoid sequences in German.

Results obtained for German show that if /dj di/ are preceded by a_ the friction is longest (for a_ vs. i_ $p < .001$, a_ vs. u_ $p < .01$, $F(2,563) = 12.563$). Other contexts do not show any clear tendencies, cf. figure 9(a). The i_ vs. u_ context is significant neither in /t/ nor in /d/ sequences. The preceding vowel does not influence the friction length if all items are calculated together, cf. figure 9(b). Here, the contexts a_ vs. u_, a_ vs. i_ and u_ vs. i_ are not significant.

[7] We did not consider [tj dj] when followed by [i] because these sequences are systematic gaps in both German and Polish.

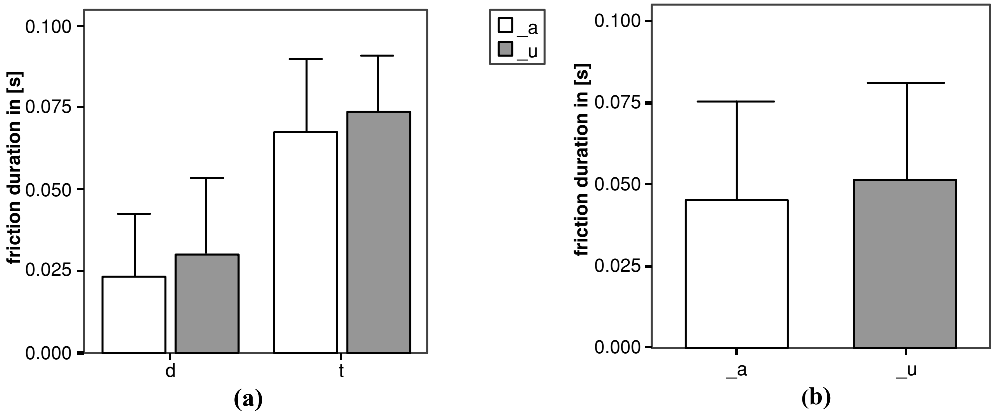

Figure 8 The average duration of friction in seconds dependent on the following vowel for /dj/ and /tj/ separately (a) and for /tj/ and /dj/ together (b). Polish speakers.

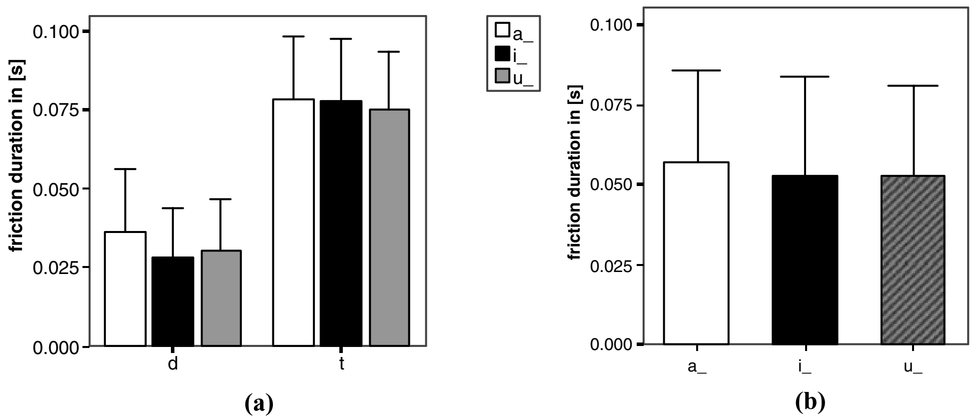

Figure 9 The average duration of friction in seconds dependent on the preceding vowel for /d/ and /t/ sequences separately (a) and for all sequences together (b). German speakers.

Figure 10 presents the results of the influence of the preceding vowel obtained for Polish speakers.

As figure 10(a) shows, the longest friction in Polish is attested when /t/ is preceded by a_ and i_ (the difference between a_ and i_ context is not significant, whereas for a_ vs. u_ context $p < .01$ and for i_ vs. u_ $p < .001$, $F(2,544) = 8.767$). In /d/ sequences neither of the given contexts causes significant differences in friction duration. Taking /t/ and /d/ sequences together, cf. figure 10(b), the frication is longer in the a_ and i_ context than in the u_ context (a_ vs. u_ $p < .05$, i_ vs. u_ $p < .05$, a_ vs. i_ is not significant $F(2,1108) = 4.289$).

Finally, the influence of stress on the friction duration was investigated. The results indicate that stress does not have an influence on the friction duration in German. For Polish speakers, the differences in friction duration for /d/ and /t/ are statistically highly significant (for /d/ $F(1,543) = 19.823$, $p < .001$ and for /t/ $F(1,544) = 16.562$, $p < .001$), showing that in Polish the friction duration is longer before the stressed vowel than after it. We have no explanation for why stress should influence the friction duration in Polish but not in German and therefore leave this question open for further research.

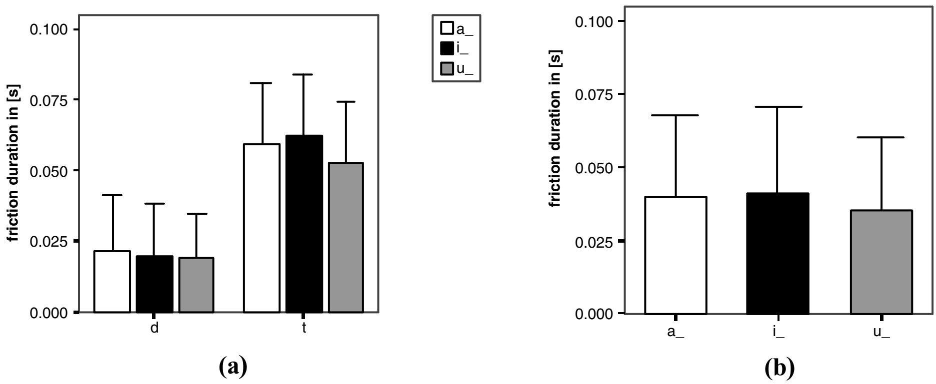

Figure 10 The average duration of friction in seconds dependent on the preceding vowel for /d/ and /t/ sequences separately (a) and for all sequences together (b). Polish speakers.

5 Summary

In addition to supporting the four predictions in (6) and the assibilation hierarchy in (7), the two experiments described in the previous section led to several findings not discussed in the literature on assibilations. In this section we summarize these findings.

One finding supported by our experiments which was not made by Hall & Hamann (2006) or in any earlier study to our knowledge is stated in (9).

(9) The friction phase in /dj/ is shorter than in /ti/.

The finding in (9) suggests that the assibilation hierarchy presented above in (7) should be modified as in (10):

(10) An assibilation hierarchy
/tj/ < /ti/ < /dj/ < /di/

If the hierarchy in (10) is truly universal then one would expect it to be reflected in a typology like the one summarized above in (4). For example, one should be able to find evidence for an implication of the form 'if /d/ assibilates before /j/ then /t/ assibilates before /i/ '. This is clearly a question we leave open for further research.

Three additional results of the three experiments conducted are summarized in (11).

(11) Three additional results
a. The vowel following /tj/ and /dj/ influences the friction phase in the sense that a following _u results in a longer duration than a following _a.
b. In German, the preceding /a/ causes longer friction than /u/ and /i/ in /d/ sequences; in Polish, the preceding /a/ and /u/ trigger longer friction than /i/ in /t/ sequences. If the /t d/ sequences are taken together, no significant differences occur in German. In Polish the frication is longer in sequences with preceding /a/ and /i/ than with the preceding /u/.
c. Stress of the vowels adjacent to /tj/, etc. does not influence the duration of the friction phase in German but it does in Polish in the sense that there is a longer friction phase if the /t d/ sequences are in a stressed position.

Again, results like the ones in (11) can be (dis)confirmed by considering phonological assibilation rules from the typological perspective.

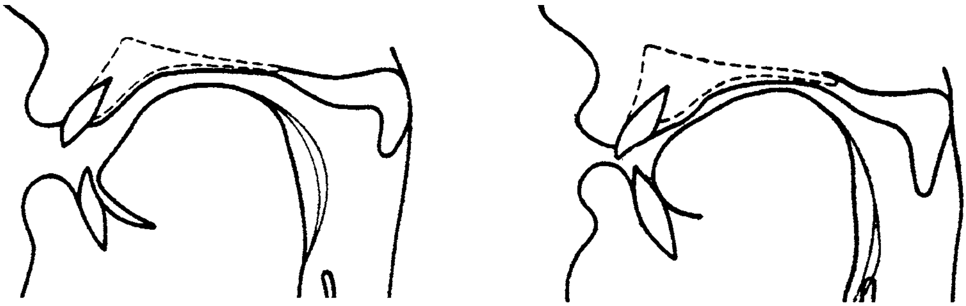

Figure 11 X-ray tracings for (a) /i/ and (b) /j/ in Polish. The thin lines at the back of the tongue indicate the lateral tongue positions.

6 Discussion

In this section, possible explanations for the attested differences in friction length are discussed. Section 6.1 focuses on the difference in outcome for /i/ versus /j/, section 6.2 on the difference for /d/ versus /t/, and section 6.3 on the influence of the quality of the vowel following /tj dj/ sequences.

6.1 The distinction between /i/ and /j/

Both acoustic experiments show that a coronal stop (be it voiceless or voiced) followed by a palatal glide /j/ has a longer total friction phase than a coronal stop followed by the vowel /i/. Three different factors can contribute to this difference.

The first factor is the articulatory difference between the vowel /i/ and the glide /j/: the palatal glide might be articulated with a narrower constriction. Consequently, the glide offers a greater impediment to the air escaping from the mouth. This causes a delay in the transglottal pressure differential, which is required for voicing and results in a longer friction phase, cf. Klatt (1975), Ohala (1983), and Chang (1999). However, data on the articulatory difference between the palatal glide and a high front vowel which could potentially support this point are scarce. In figure 11 we have provided an x-ray tracing for /i/ and /j/ in Polish from Wierzchowska (1971).[8]

A comparison of the tongue body in /i/ vs. /j/ reveals an obvious difference between the two: For /j/ the constriction is longer and narrower than for /i/.

The difference in degree and length of constriction between /i/ and /j/ for the Polish speaker in figure 11 is also assumed for the languages investigated by Maddieson & Emmorey (1985). They compared the formant frequencies of the palatal glide and the high front vowel in Amharic, Yoruba, and Zuni and found that in all three languages the glide has a lower first formant frequency than the vowel. Their conclusion is that the glide /j/ is produced with a narrower constriction than the vowel /i/. The recordings leading to this result only include tokens of /i/ in palatal glide context (in the nonsense word *iji*). The glide in this sequence might be articulated with a closer constriction than in other vocalic contexts in order to maintain a perceptual difference between glide and vowel.

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[8] The two x-ray tracings of Polish in figure 11 appear to stem from different speakers, and Wierzchowska does not comment on this point. For lack of more comparable data, we have to be content with these. The same point holds for the two x-ray tracings of German in figure 12 (see below).

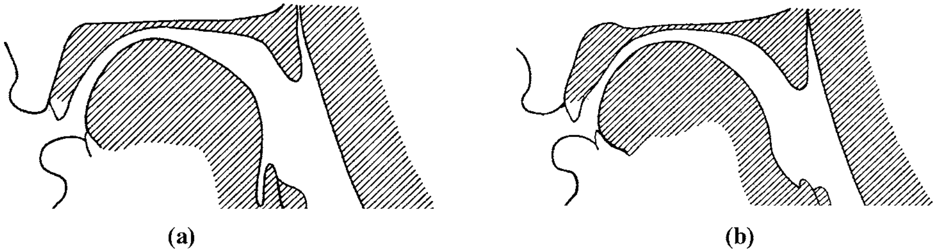

Figure 12 X-ray tracings for (a) /iː/ and (b) /j/ in German.

In other languages the difference in length and degree of constriction is not as obvious as in Polish. For example, Wängler's (1958) x-ray tracings of German /iː/ and /j/, given in figure 12, show that the two segments are articulated almost identically.

A comparison of figures 12(a) and (b) reveals that the palatal glide /j/ has a minimally longer constriction, i.e. the tongue front is raised a bit further than for the /i/. At this point one can only speculate that this minor difference in length of constriction between /i/ and /j/ might be responsible for the longer duration of the friction phase in /tj dj/ vs. /ti di/ in German.

Like German, Romanian does not seem to support an articulatory difference between glide and vowel, either. Chitoran (2002, 2003) investigated the acoustic difference between the high front vowel /i/ and the glide /j/ in Romanian, and measured their friction duration after the stop /p/,[9] and the formant values at the starting point of both segments. The duration of the friction phase was expected to be longer for the glide, indicating a narrower constriction. However, no significant differences could be found. Furthermore, Chitoran expected significant differences in the formant values at the beginning of the two segments. She found – contrary to what one would expect if /j/ has a narrower constriction than /i/ – that the second formant was higher in the vowel for two of her three speakers. Chitoran (2003: 3016) interprets the lower F2 values for the glides as a 'target undershoot', which means that the glide is articulated with even less constriction than the vowel in the same context.

The results of these cross-linguistic studies might indicate a language-specific difference between the glide /j/ and the vowel /i/: in German, the two seem to be articulated similarly, in Romanian the glide /j/ seems to be articulated with a less narrow constriction than the vowel /i/, and in Amharic, Yoruba, Zuni, and Polish the glide seems to have a more narrow constriction. However, it has to be kept in mind that the differences in the realization of /j/ might be due to a different vocalic context. Furthermore, these are mostly the interpretations of acoustic studies and neither Chitoran, nor Maddieson & Emmorey, nor the present authors conducted articulatory studies on the difference between /i/ vs. /j/ to test these interpretations.[10]

A second factor influencing the difference in friction length between glide and vowel could be the coarticulatory effect of the glide on the preceding stop. As B. Hurch (p.c.) pointed out to us, the glide can cause an inherent palatalization of the preceding stop: the stop before the glide is articulated with a raised tongue middle, which can, due to a longer constriction, result in more friction than the non-palatalized stop before the high front vowel. The stop before the

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[9] Chitoran's definition of friction duration differs from the one applied in the present article: it is the duration measured from the end of the [p] release burst to the onset of F1 (Chitoran 2003: 3014).

[10] The cross-linguistic difference between high front vowel and the corresponding glide might be based on the fact that languages differ in their realization of the vowel [i], as P. Boersma (p.c.) pointed out to us. Thus, a very high [i] as it is the case in German might result in little articulatory difference between vowel and glide, whereas a lower [i] as we assume to be the case in Polish might result in a bigger articulatory difference between vowel and glide. We have at present no comparative data from German, Polish or any other language which might support this hypothesis.

high front vowel, on the other hand, does not show this inherent palatalization. Like the first factor, this one still has to be empirically tested.

A third factor might be aerodynamic differences (see also the authors discussed in section 2). It could be argued that the glide is produced with stronger airflow than the vowel, and that the higher airflow results in longer friction noise following the release of the stop, but this hypothesis still has to be tested.

6.2 The distinction between /t/ and /d/

The voiced stops /di dj/ generally show a shorter friction duration than the corresponding voiceless stops /ti tj/. One reason for this observation is that whereas the open vocal folds for a voiceless stop allow air to pass unimpeded, the vibrating vocal cords of the voiced stop restrict the air flow volume. This results in less air pressure behind the alveolar constriction for voiced stops and thus less friction noise at the release of the voiced stop. Furthermore, the voicing of stops requires a difference between subglottal and supraglottal pressure (in order to let the vocal folds vibrate), which is usually maintained by pharyngeal expansion and larynx lowering (Kent & Moll 1969, Perkell 1969, Bell-Berti 1975). Pharyngeal expansion also results in less air pressure at the constriction and less friction at the stop release (Ohala & Riordan 1979). The higher subglottal pressure and lower intraoral air pressure for voiced stops compared to voiceless stops has been attested by Netsell (1969) for American English.

Another factor to consider is a possible difference in articulation between the voiced and the voiceless stop. The voiced stop can differ from the voiceless one in place of articulation, in active articulator, and in overall palatal contact. If /t/ is a laminal sound and /d/ an apical (as in some West-African languages, see Ladefoged 1964),[11] then one might expect the former to assibilate, as apicals should be less prone to assibilation than laminals due to their smaller oral closure. The same holds if /d/ is articulated further back and/or with less palatal contact. Since the two experiments described in section 4 were acoustic and not articulatory, we do not know if the subjects had any articulatory distinction between /t/ and /d/. However, such differences are testable in an articulatory experiment. Articulatory investigations of German /t/ and /d/ show that in post-stressed, intervocalic position /d/ has less palatal contact than /t/ and often has a place of articulation that is slightly further back than /t/ (Fuchs & Perrier 2003).

6.3 The quality of the following vowel

The influence of the vowel following stop plus /j/ sequences was another factor shown in our experiments to influence the friction phase. In section 4.3 we saw that the friction duration of a stop is longer if an /u/ follows compared to a following /a/ (see figures 7 and 8 above). The vowel /u/ is articulated with a high tongue body, which could have an influence on the articulation of the adjacent glide, requiring that this glide is articulated with a higher tongue body position. This could lead to more airflow, see the explanation in section 6.1 above. The hypothesis on the influence of the following vowel on stop-glide sequences could in principle be tested articulatorily.

7 Alternative explanation: center of gravity

In this section we report on the results of acoustic measurements that investigated the spectral similarities between the friction of the alveolar fricative part of affricates like /ts dz/ and

[11] The difference between tongue tip and tongue blade reported by Ladefoged (1964) goes together with a difference in place of articulation, with apicals being articulated in the (post)alveolar area, and laminals in the dental area.

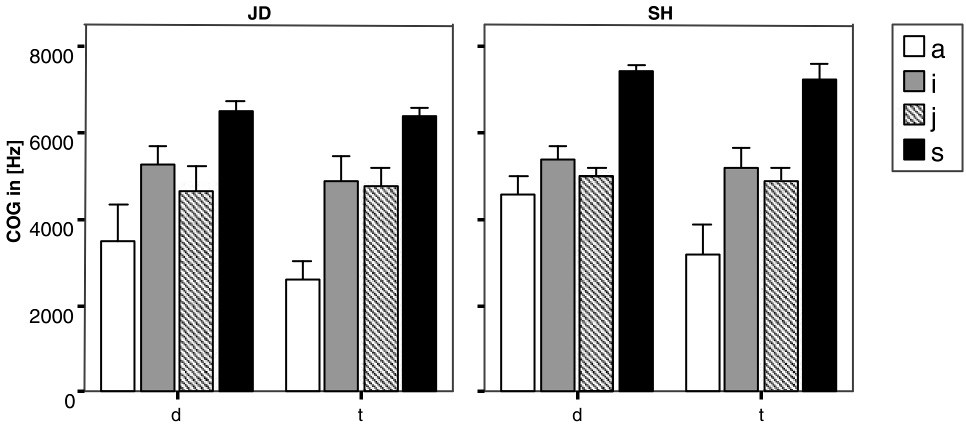

Figure 13 The average COG in Hz for the two German speakers. The 's' context includes the fricative part of the alveolar affricates in *tsik* and *dzik*.

the friction before /i j/ in sequences like /ti tj di dj/. We expected the results to support the assibilation hierarchy in (7) in that the friction part in the affricates /ts dz/ should be spectrally more similar to the friction in /tj/ than the one in /ti di dj/, and more similar to the friction in /tj ti dj/ than in /di/.

In order to test this expectation we conducted an additional pilot study in which we measured the center of gravity (henceforth COG) (cf. Jassem 1979, Forrest et al. 1988, Nittrouer, Studdert-Kennedy & McGowan 1989, Jongman, Wayland & Wong 2000, Gordon, Barthmaier & Sands 2002). COG is the average of frequencies over the entire frequency domain weighted by the amplitude. In our measurements, the weighting was done by using the power spectrum ($p = 2$) in PRAAT without pre-emhpasis of the signal. For the COG calculations we excluded the burst (ca. 10 ms) and measured the friction up to the beginning of continuous formants. To exclude the influence of the fundamental frequency in the voiced items, we band pass filtered all signals with a pass Hann band of 500–12000 Hz (and a smoothing of 100 Hz).

COG values were measured for the items /tak tjak tik tsik dak djak dik dzik/ spoken by two German speakers (female SH and male JD) and two Polish speakers (female MZ and male SL). The items were repeated five times in the same carrier sentences as used in experiments 1 and 2, sections 4.1 and 4.2 above.

The results for the German speakers are presented in figure 13.

Both German speakers show an ordering of the COG values for items like the ones in (12), where the wedge '<' means 'has a lower COG value than'; hence, /tak/ has a lower COG value than /tjak/, etc.

(12) tak < (tjak, tik) < tsik
     dak < (djak, dik) < dzik

The wedges between *tjak* and *tik* and between *djak* and *dik* are in brackets, because a post-hoc Scheffé test shows that for both speakers the difference between /i/ and /j/ for both /t/ and /d/ is not significant. For speaker SH the difference between /da/ and /dj/ is also not significant. All other differences are significant. (For JD /da/ vs. /di/ $p < .01$, /da/ vs. /dj/ $p < .05$, /da/ vs. /dz/ $p < .001$, /di/ vs. /dz/ $p < .05$, /dj/ vs. /dz/ $p < .01$. For SH /da/ vs. /di/ $p < .01$, /da/ vs. /dz/ $p < .001$, /di/ vs. /dz/ $p < .001$, /dj/ vs. /dz/ $p < .001$. All remaining differences for /t/ for both speakers are highly significant $p < .001$.)

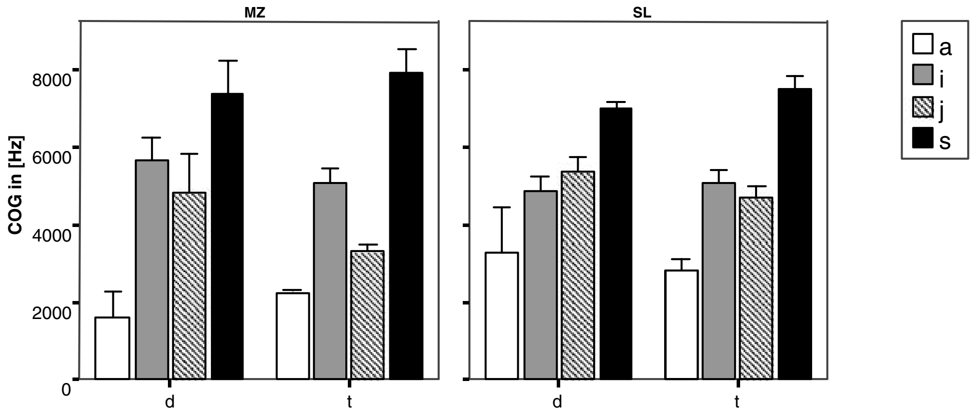

Figure 14 The average COG in Hz for the two Polish speakers. The context 's' includes the fricative part of the alveolar affricates in *tsik* and *dzik*.

The results for the Polish speakers are given in figure 14. The ordering of the items for the Polish speakers according to their COG values is similar to the German speakers in figures 13, with the only exception being that speaker SL has a reverse ordering for /di/ and /dj/. The difference between /di/ and /dj/ is not significant for any of the speakers. For speaker SL the difference between /ti/ and /tj/ is also not significant, whereas for speaker MZ this difference is highly significant. All other differences are significant. (For MZ /di/ vs. /dz/ $p < .05$, /dj/ vs. /dz/ $p < .01$, all other differences with /d/ are $p < .001$, /ta/ vs. /tj/ is significant $p < .01$, all other differences with /t/ are highly significant. For SL /da/ vs. /di/ $p < .005$, /da/ vs. /dj/ $p < .01$, /di/ vs. /dz/ $p < .01$, /dj/ vs. /dz/ $p < .01$, /da/ vs. /dz/ highly significant; for /t/ all differences apart from /ti/ vs. /tj/ are highly significant.)

The COG values for all four speakers thus show that sequences of coronal stop plus /i j/ are more similar in their friction domain and amplitude to the respective coronal fricative phase in the affricates /ts dz/ than sequences of coronal stop plus /a/. This finding points to a reason that assibilation is triggered by high front vowels but not by low vowels. However, an explanation for implication (1a) could not be found in the COG values. The reason is that none of the speakers has a significant difference in COG values between /i/ and /j/ items (apart from speaker MZ whose /ti/ items have significantly higher COG values than the /tj/ items) and the ordering between /i/ and /j/ is actually reverse from the expected.

Were the results of these COG measurements to support implication (1b), we would expect to find a greater difference in COG values between /di dj/ and /dz/ than between /ti tj/ and /ts/. For these calculations we measured the COG values of the fricatives including the fundamental frequency (i.e., no band pass filtering as in the COG measurements above was conducted). The results for the German speakers are given in figure 15. COG mean values of /di/ were subtracted from COG mean values of /dz/, which is shown in the first column on the left; the second column shows the difference in the COG mean values of /dz/ and /dj/. In a parallel manner the differences for voiceless stops are shown by the columns on the right.

For speaker JD, the value /dz/ – /di/ (first column) is smaller than that for /ts/ – /ti/ (third column), and /dz/ – /dj/ (second column) is smaller than /ts/ – /tj/ (fourth column). This finding is important because it does not support the expected result that differences for the voiced stop are larger than the voiceless stops. A different picture arises for speaker SH, for whom /dz/ – /di/ is almost identical to /ts/ – /ti/, and /dz/ – /dj/ is greater than /ts/ – /tj/.

The differences in COG values between the affricate and the sequence stop plus /i j/ for the Polish speakers are given in figure 16, again for the voiced stops on the left and the voiceless stops on the right.

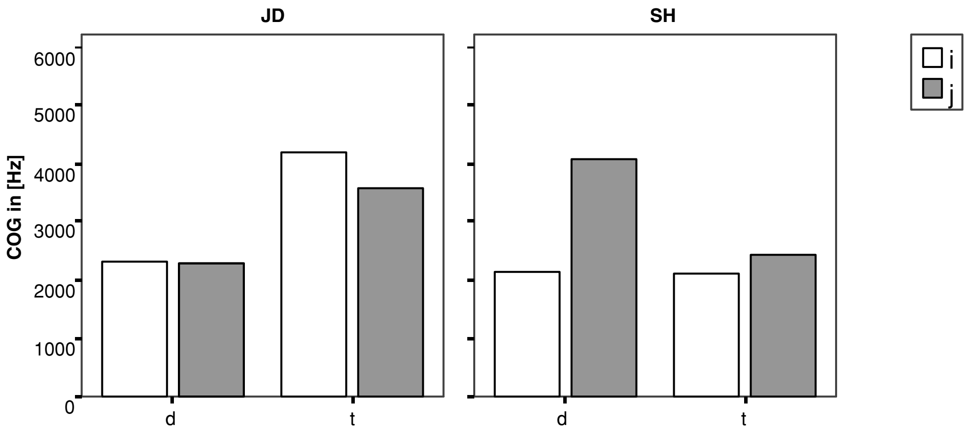

Figure 15 The average difference in COG in Hz between the affricates and the corresponding stop + i/j sequences for the two German speakers.

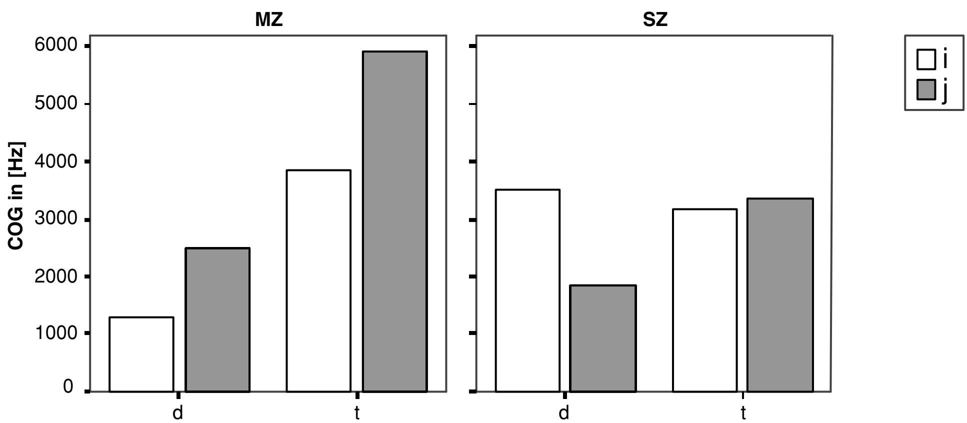

Figure 16 The average difference in COG in Hz between the affricates and the corresponding stop + i/j sequences for the two Polish speakers.

Speaker MZ shows a larger value for both voiceless alveolar stops than for the voiced alveolar stops, and speaker SZ has a larger value for /dz/ – /di/ than for /ts/ – /ti/, but a smaller value for /dz/ – /dj/ than for /ts/ – /tj/. The results of both German and Polish speakers are so diverse that a statistical analysis is unnecessary. In sum, there is no general tendency that the difference in COG values for voiced stops is greater than the difference between voiceless stops, and therefore no evidence for implication (5b).

Summing up this section, the results of the COG measurements can account for the fact that assibilation takes place before high front vocoids and not before low vowels, but they do not provide evidence for the assibilation hierarchy in (10) or for the implications in (5).[12]

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[12] In addition to COG measurements, we conducted an acoustic study in which the highest spectral peak of the frication was measured. The items investigated were the same as in the COG study. Like the COG values, the highest peaks were obtained for /dz/ and /ts/ followed by items containing /j/ and /i/. The

8 Conclusion

In this article we reported on the results of two acoustical experiments in which the duration of the friction phase of /ti di tj dj/ were measured in German and Polish and showed the relevance of these experiments to language typology. The results indicate that the friction phase for these four sequences can be arranged in the order /tj/ < /ti/ < /dj/ < /di/, meaning that the friction phase in /tj/ is longer than in /ti/ and /dj/, etc. The results of these experiments are important because they lend phonetic support to two proposed implications with respect to phonological stop assibilation which were made in an earlier study (Hall & Hamann 2006), namely (a) assibilation cannot be triggered by /i/ unless it is also triggered by /j/, and (b) voiced stops cannot undergo assibilations unless voiceless ones do.

The additional COG measurements showed that this parameter does not provide evidence for the assibilation hierarchy /tj/ < /ti/ < /dj/ < /di/. However, further investigations into the spectral shape of the friction phase in the sequences /tj ti dj di/ and the fricative component of /dz ts/ could account for the observed ordering among alveolar stop plus high vocoid sequences. Furthermore, articulatory investigations, such as EPG and EMMA, and an airflow study of /j i/ in the two stop contexts could shed light on the difference in articulation and amount of airflow between the four sequences.

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lowest peaks were observed for /da/, /ta/. The investigation did not provide supporting evidence for the assibilation hierarchy /tj/ < /ti/ < /dj/ < /di/.

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