Effects of consonant manner and vowel height on intraoral pressure and articulatory contact at voicing offset and onset for voiceless obstruents[a]

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(Received 13 September 2010; revised 3 February 2011; accepted 12 February 2011)

In obstruent consonants, a major constriction in the upper vocal tract yields an increase in intraoral pressure (P_{io}). Phonation requires that subglottal pressure (P_{sub}) exceed P_{io} by a threshold value, so as the transglottal pressure reaches the threshold, phonation will cease. This work investigates how P_{io} levels at phonation offset and onset vary before and after different German voiceless obstruents (stop, fricative, affricates, clusters), and with following high vs low vowels. Articulatory contacts, measured using electropalatography, were recorded simultaneously with P_{io} to clarify how supraglottal constrictions affect P_{io}. Effects of consonant type on phonation thresholds could be explained mainly in terms of the magnitude and timing of vocal-fold abduction. Phonation offset occurred at lower values of P_{io} before fricative-initial sequences than stop-initial sequences, and onset occurred at higher levels of P_{io} following the unaspirated stops of clusters compared to fricatives, affricates, and aspirated stops. The vowel effects were somewhat surprising: High vowels had an inhibitory effect at voicing offset (phonation ceasing at lower values of P_{io}) in short-duration consonant sequences, but a facilitating effect on phonation onset that was consistent across consonantal contexts. The vowel influences appear to reflect a combination of vocal-fold characteristics and vocal-tract impedance. © *2011 Acoustical Society of America*. [DOI: 10.1121/1.3561658]

PACS number(s): 43.70.Aj, 43.70.Gr [DAB] Pages: 3233–3244

I. INTRODUCTION

This paper investigates the effects of consonant manner and following vowel height on the aerodynamic conditions at voicing offsets and onsets around voiceless obstruents and obstruent sequences. Phonation offsets and onsets were determined for eight speakers of German, in six consonantal contexts (/t/, /ʃ/, clusters /st/, /ʃt/, and affricates /t͡ʃ/, /t͡s/) and two vowel contexts (following /ɑ/ vs /i/ or /ɪ/). At the times of voicing offset and onset, intraoral pressure (P_{io}) was measured, as was lingua–palatal contact, using electropalatography (EPG).

Although voicing has been studied extensively, gaps remain between the empirical data on obstruent voicing and theoretical formulations of the physical requirements for phonation. As detailed in subsequent sections, modeling work has generally focused on phonation thresholds in conditions with adducted vocal folds and an open vocal tract. Results from such studies cannot be straightforwardly extended to connected speech conditions that involve rapidly-varying glottal widths, upper vocal-tract postures, and intraoral pressures. Empirical work on consonant voicing, in turn, has mostly assessed the timing of phonation or the extent to which an obstruent interval contains voicing (e.g., Docherty, 1992; Lisker and Abramson, 1964; Smith, 1997; Stevens *et al.*, 1992; Weismer, 1980; Westbury, 1979). Few studies have provided direct aerodynamic and articulatory data about phonation offsets and onsets in consonantal contexts, and those that have mostly focused on voiced rather than voiceless obstruents.

Thus, the general goal of the current work is to help bridge this gap by quantifying the aerodynamic and supralaryngeal conditions at the times of voicing offsets and onsets before and after voiceless obstruent consonants produced by multiple speakers, and assessing the likely sources of variation across consonants and vowels based on past work. Along with providing a better understanding of the general relationships between speech articulation and aerodynamics, these data are intended to serve as input for aerodynamic modeling that incorporates vocal-fold abduction and variations in supraglottal conditions. This paper will focus on group patterns across consonant and vowel contexts. Future work will explore speaker differences and relate the measured data with simulations obtained via modeling of the larynx and upper vocal tract.

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[a] Portions of these data were presented at Acoustics 2008, Paris, France, and the 2010 International Conference on Advances in Laryngeal Biophysiology/International Conference on Voice Physiology and Biomechanics, Madison, WI.

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A. Modeling of the factors that influence phonation

1. Phonation threshold pressures

The physical requirements for voicing have been quantified for laryngeal models of varying complexity. Ishizaka and Matsudaira (1972) established that sustained phonation in a two-mass model of the vocal folds requires a subglottal pressure exceeding a threshold value. Titze (1988) extended this line of inquiry to the body–cover model of the vocal folds and provided the following formula for the phonation threshold pressure (P_{th}),

$$P_{\mathrm{th}} = \frac{Bcx_0k_t}{T}, \tag{1}$$

where $B =$ tissue damping, $c =$ the mucosal wave velocity (which increases with vocal-fold stiffness), $x_0 =$ the glottal half-width, $k_t =$ a transglottal pressure coefficient calculated to be about 1.1, and $T =$ vocal fold thickness. Subsequent mathematical work has explored how P_{th} varies with factors such as fundamental frequency (f0), prephonatory glottal width, glottal convergence angle, laryngeal size, and upper vocal-tract airway inertance (Chan and Titze, 2006; Lucero, 1996, 1998, 2005; Lucero and Koenig, 2005, 2007; Titze, 1992).

Many studies have also assessed P_{th} in human speakers, evaluating effects of vocal fatigue, vocal warm-up, hydration, and f0 (Chang and Karnell, 2004; Elliot *et al.*, 1995; Finkelhor *et al.*, 1987; Fisher *et al.*, 2001; Jiang *et al.*, 1999; Milbraith and Solomon, 2003; Motel *et al.*, 2003; Sivasankar *et al.*, 2008; Solomon and DiMattia, 2000; Solomon *et al.*, 2003, 2007; Verdolini *et al.*, 1994, 2002; Verdolini-Marston *et al.*, 1990). Several papers have reported extensive individual differences in P_{th} values and changes across experimental manipulations (Elliot *et al.*, 1995; Finkelhor *et al.*, 1987; Jiang *et al.*, 1999; Motel *et al.*, 2003; Solomon *et al.*, 2007; Titze, 2009). The modeling work suggests that some of this variation may reflect speaker differences in vocal-fold parameters such as glottal convergence angle, resting glottal half-width, tissue viscoelasticity, and thickness of the vocal-fold body and cover (Chan *et al.*, 1997; Chan and Titze, 2006; Lucero, 1998).

Although most modeling has adopted values appropriate for an adult male larynx, there are well-known laryngeal differences between men and women (Titze, 1989). Lucero and Koenig (2005) observed that P_{th} was higher when a two-mass model was rescaled to values appropriate for women (and children). Some work also suggests that phonatory responses to conditions such as dehydration may differ between men and women [cf. data from Solomon and DiMattia (2000) vs Solomon *et al.* (2003) for women vs men, respectively]. Thus, questions remain about how fully existing models characterize the behavior of multiple speakers, including women as well as men.

2. Offset–onset differences

The P_{th} equation defines the requirements for initiating phonation. Many studies have demonstrated that phonation offsets and onsets occur under different aerodynamic conditions. In particular, when laryngeal and supralaryngeal factors are held constant, a higher pressure is needed to initiate phonation than to maintain it, so that vocal-fold vibration shows hysteresis (Baer, 1975; Plant *et al.*, 2004). Lucero (1996, 1999, 2005) established the mathematical nature of this phenomenon as a subcritical Hopf bifurcation and showed that hysteresis results from non-linear aerodynamic damping within the vocal folds. In these models, the threshold pressure for maintaining phonation was found to be about half for that initiating it. Studies in humans, however, suggest that the extent of hysteresis may vary considerably across speakers (Plant *et al.*, 2004), presumably for the same reasons as noted above for P_{th} variation.

It should be noted that equivalent articulatory and aerodynamic conditions do not hold at phonation offset and onset in many consonantal contexts (see Sec. I B). Even if the upper vocal tract is open, as for /h/ (cf. Koenig *et al.*, 2005), onset–offset differences may not reflect true hysteresis effects given variations related to syllable stress. The discussion will consider how onset–offset differences in the current data compare to those in classic hysteresis studies in the light of such considerations.

B. Assumptions required for characterizing phonation around voiceless obstruents and review of empirical studies

Several assumptions were made in obtaining the phonation threshold formula. First, the equation holds only for cases where the vocal folds do not contact, i.e., when the vocal folds are slightly abducted. The obstruent environments considered here involve a wide range of vocal-fold positions (i.e., glottal widths), from adducted to widely abducted. Changes in laryngeal height during voiceless consonants may have passive effects on vocal-fold tension (e.g., Hombert *et al.*, 1979), and speakers may also contract the cricothyroid muscle to actively increase longitudinal tension for voiceless consonants (Hoole and Honda, 2011; Löfqvist *et al.*, 1989). Extensions of Titze's model have demonstrated that higher f0, as should result from greater vocal-fold tension, increases P_{th} (Lucero and Koenig, 2007). Thus, multiple laryngeal factors may inhibit phonation around voiceless consonants.

Further, most modeling work (and, accordingly, most work on P_{th} in humans) has considered the relatively open vocal-tract postures associated with vowel production. When the vocal tract is open, P_{io} remains low (close to atmospheric pressure). The production of obstruents, in contrast, involves the formation of an oral constriction and an increase in P_{io}. This pressure change, which is particularly rapid for consonants that involve vocal-fold abduction, reduces the airflow across the glottis that fuels phonation. It may also lead to a more divergent glottal configuration and voice quality features characteristic of breathiness: Higher open quotients, more symmetrical waveshapes, and reduced vibratory amplitudes (Bickley and Stevens 1986; see also Stevens, 1991; Titze, 2009). Hence, increases in P_{io} during obstruents may also have multiple inhibiting effects on phonation.

Finally, laryngeal conditions vary as a function of consonant manner. For an aspirated stop consonant, glottal area remains fairly small as the upper vocal tract closes, whereas upon supraglottal release the vocal folds are abducted so as to yield a long voicing delay (Lisker *et al.*, 1970; Löfqvist, 1992; Löfqvist and Yoshioka, 1981; Yoshioka *et al.*, 1981). Fricatives, on the other hand, seem to be more symmetrical between offset and onset conditions, with peak glottal abduction occurring roughly in the middle of the frication noise (Hoole *et al.*, 2003; Löfqvist and Yoshioka, 1981, 1984; Ridouane *et al.*, 2006; Yoshioka *et al.*, 1981). Speakers may abduct more extensively in fricatives than in stops (Hirose *et al.*, 1978; Lindqvist, 1972; Lisker *et al.*, 1969; Löfqvist and Yoshioka, 1981; Ridouane *et al.*, 2006). Nevertheless, P_{io} rises to a higher peak value in stops than in fricatives, on average, given the presence of a complete occlusion in the former case vs a constriction (with some air escape) in the latter (Arkebauer *et al.*, 1967; Fuchs and Koenig, 2009; Koenig *et al.*, 1995).

In sum, given consonantal variations in the magnitude and timing of laryngeal abduction, the buildup of P_{io} and secondary effects on laryngeal setting related to consonant production, one may expect that the aerodynamic conditions related to voicing offsets and onsets in obstruents will differ from what has been reported in studies assuming vocalic conditions.

C. Evidence for vowel effects on phonation

Past work indicates that vowel postures may affect laryngeal behavior in a variety of ways. One widely-studied phenomenon is "intrinsic f0." The essence of this effect is that high vowels such as [i] and [u] have slightly higher f0's, on average, than low vowels such as [ɑ] (see Whalen and Levitt, 1995, for an extensive cross-language review). Although the precise origins of intrinsic f0 are not fully clear, it appears to result from elevated laryngeal height and/or increased vocal-fold tension in high vowels. Vowel quality has also been shown to influence some aspects of voice quality. The results of most relevance here are the following: Higgins *et al.* (1998) reported lower degrees of vocal-fold contact in /i/ than /ɑ/ and Chen *et al.* (2002) found lower speed quotients in /i/ compared to /ɑ, ae, and u/. Such values consistent with higher breathiness in /i/ could indicate a glottal setting less conducive to phonation in the high front vowels.

Several studies have also found that the following vowel affects voice onset times (VOTs; Lisker and Abramson, 1964). Authors have reported longer VOTs before vowels that are high (Chang, 1999; Docherty, 1992; Esposito, 2002; Higgins *et al.*, 1998; Klatt, 1975; Ohala, 1981; Port and Rotunno, 1979), long (Port and Rotunno, 1979), and/or tense (Weismer, 1979). The explanations that have been offered for these findings are diverse: Higher supraglottal impedance in high vowels, leading to slower discharge of P_{io} (Chang, 1999); elevated larynx position in high vowels (Klatt, 1975); effects of stress on tense vs lax vowels (Weismer, 1979); or perceptual enhancement (Kingston, 1993). Perceptual enhancement seems unlikely given the small magnitude of the effect (Weismer, 1980).

The preceding considerations suggest that a high vowel context could inhibit phonation, i.e., raise P_{th}. There are, however, alternative perspectives that lead to opposing predictions. Titze (1988) noted that greater inertance of the air column in the upper vocal tract facilitates phonation. Recent theoretical and modeling work (Lucero *et al.*, 2009; Ruty *et al.*, 2008) shows that increasing vocal-tract length (and thereby lowering the first formant, F1) has the effect of reducing P_{th}, via increasing vocal-tract inertance. According to these results, lower Fls (characteristic of high vowels) should have a facilitating effect on phonation. Another line of argument comes from studies that have investigated phonation for *voiced* plosives. Ohala and Riordan (1979) and Pape *et al.* (2006) observed that phonation may persist longer into voiced consonants preceding high vowels, evidently as a function of larger pharyngeal cavity volume. Similar effects could conceivably obtain for voiceless consonants as well (cf. Mohr, 1971).

D. Predictions

Based on the literature reviewed above, several predictions were made.

1. *Onset–offset differences*

Since a higher threshold pressure is required to initiate phonation than to maintain it when all other conditions are held constant, one may generally expect that phonation onsets will tend to occur at lower values of P_{io} than phonation offsets. (Note that higher P_{io} corresponds to lower transglottal pressure if P_{sub} is constant; thus, factors that make phonation more difficult to initiate or sustain should be associated with voicing at lower P_{io}s). However, in the current work, laryngeal, supralaryngeal, and aerodynamic conditions vary across phonetic contexts, so that many conditions are not held constant. Thus (as detailed in the following paragraphs), it was expected that phonation offsets and onsets would differ as a function of context.

2. *Consonant differences*

Phonation offsets were predicted to occur at higher levels of P_{io} for stops than fricatives. Closely-approximated vocal folds entering stops should facilitate phonation and allow it to persist to a higher level of P_{io}, whereas earlier abduction for fricatives would inhibit phonation. One would further expect that the first member in a consonantal sequence should have the greatest influence on voicing offset, so that phonation offsets should be similar for /ʃ/, /ʃt/, and /st/ on one hand and /t/, /t͡s/, and /t͡ʃ/ on the other.

For voicing onsets, a large glottal width at the release of aspirated stops should inhibit phonation, so that voicing would resume at a low value of P_{io}. An important difference between the single /t/ and that in clusters is that the latter is unaspirated in German. As such, phonation should resume at higher levels of P_{io} after /st/ and /ʃt/ compared to /t/. The earlier timing of abduction in fricatives compared to aspirated stops should also lead to phonation onset at higher levels of P_{io} for /ʃ/, /t͜ʃ/, and /t͜s/ as compared to the aspirated stop.

Finally, place of articulation in /t͜s/ vs /t͜ʃ/ and /st/ vs /ʃt/) was not expected to yield large effects for offsets or onsets, but small effects might be observed owing to differences in fricative channel width and tongue grooving reported in past work (Dixit and Hoffman, 2007; Fletcher and Newman, 1991; Recasens and Espinosa, 2007; Stone *et al.*, 1992).

3. *Vowel effects*

Several lines of evidence suggest that high vowels may have an inhibitory effect on phonation, possibly because of higher intrinsic f0 (which could relate to higher vocal-fold stiffness), voice quality features associated with a breathy voicing posture, and/or higher impedance in a more constricted supraglottal tract. This would lead to phonation occurring at lower values of P_{io} preceding high vowels compared to low ones. On the other hand, the source–filter interactions discussed in recent modeling work and effects of pharyngeal constrictions on pressure conditions near the glottis could lead to precisely the opposite result. In either case, vowel effects in the present data would presumably be stronger at voicing onset, adjacent to the target vowel, than at voicing offset.

II. METHODS

The speakers and instrumentation used here were identical to those described in Fuchs and Koenig (2009). The current study analyzed a larger set of utterances using different analysis methods (particularly for the P_{io} signal).

A. Speakers and stimuli

Eight adult speakers of Standard German were recorded: Three females (F1–F3) and five males (M1–M5). The consonant and vowel contexts chosen for analysis are shown in Table I. As indicated in the table, the target consonant sequences were single /t/ and /ʃ/, the affricates /t͜ʃ/ and /t͜s/, and the clusters /ʃt/ and /st/. The following vowel was either low (/ɑ/) or high (/i/ or /ɪ/).[1] The single fricative was limited to /ʃ/ because /s/ does not occur word-initially in German. It should be also noted that the cluster /st/ is rare in German, occurring only as a variant in some borrowed words. Speakers were instructed for the two words containing this cluster (*Stalin* and *Stil*) to use the pronunciation /st/ rather than /ʃt/. Finally, single /t/ is aspirated in German, whereas /t/ in the clusters is unaspirated.

The words were produced in the sentential frame *Ich nasche* ____ ("I nibble ____"), as the first member of a compound with the word *Stelle* ("place"). Thus, the full utterance for the first word was *Ich nasche Taschenstelle*. Initial position in the compound put the target word in a prosodically-focused position. Although the utterances used all real words of German, the sentences were mostly semantically nonsensical. Speakers produced each utterance ten times in a list with all utterances fully randomized. A total of 960 productions was collected (8 speakers × 12 utterances × 10 repetitions). The final data set (after removing productions with unanalyzable signals, disfluencies, or pauses) consisted of 921 tokens.

TABLE I. Speech stimuli. Note that transcriptions in the table are phonetic, whereas the text uses the phonemic representations.

Consonant	Following vowel	Full word	Gloss
[tʰ]	[ɑ]	Tasche	Bag
[ʃ]	[ɑ]	Schaf	Sheep
[t͜ʃ]	[ɑ]	Tschad	Chad (the country)
[t͜s]	[ɑ]	Zander	Kind of fish
[ʃt]	[ɑ]	Stachel	Spike
[st]	[ɑ]	Stalin	Stalin
[tʰ]	[ɪ]	Tisch	Table
[ʃ]	[ɪ]	Schiff	Ship
[t͜ʃ]	[i]	Tschibo	Brand of coffee
[t͜s]	[ɪ]	Zitze	Teat
[ʃt]	[ɪ]	Stich	Prick
[st]	[i]	Stil	Style

B. Instrumentation and preliminary processing

The Reading EPG System 3 was used to record lingua–palatal contacts, using a sampling rate of 100 Hz. A pressure transducer (Endevco 8507C-2, San Juan Capistrano, CA) was affixed to the back end of the EPG palate via a small plastic tube and a separate tube was passed around the teeth to obtain a stable recording of atmospheric pressure. This recording method permits an assessment of P_{io} variation for sounds produced anterior to the palatal place of articulation and is less invasive than recording pharyngeal pressure via a catheter fed through the nose. The pressure signal was recorded to PCQuirer using a sampling rate of 1859 Hz. An acoustic signal was recorded to DAT at a sampling rate of 48 kHz.

In MATLAB, the P_{io} signals were smoothed using the filtfilt function and a kaiser window with 40 Hz passband and 100 Hz stopband edges, and a 50 dB damping factor. This processing eliminated the high-frequency oscillation associated with phonation and yielded minimal distortion around the regions of rapid pressure changes associated with obstruent closure and release. The first derivative (velocity) of the P_{io} signal was calculated from the smoothed signal. Voicing offsets and onsets were obtained interactively (i.e., visually) from the original (unsmoothed) P_{io} signal. Other measures described below were obtained automatically in MATLAB based on the times of voicing offsets and onsets. EPG frames were also extracted at the times of voicing offsets and onsets, using the acoustic signal as a reference for alignment with the P_{io}.

To correct for drift in the P_{io} signal over the course of the recording session, a pressure minimum was obtained in vowels on either side of the target consonant or consonantal sequence. Initially, these minima were taken in the vowels immediately before and after the target. In the course of obtaining these values, it was observed that the pressure often did not return to baseline when the target consonant preceded a high vowel (/i/ or /ɪ/), not only in the high vowel itself, but also in the preceding schwa. Since one purpose of this work was to quantify voicing thresholds in absolute

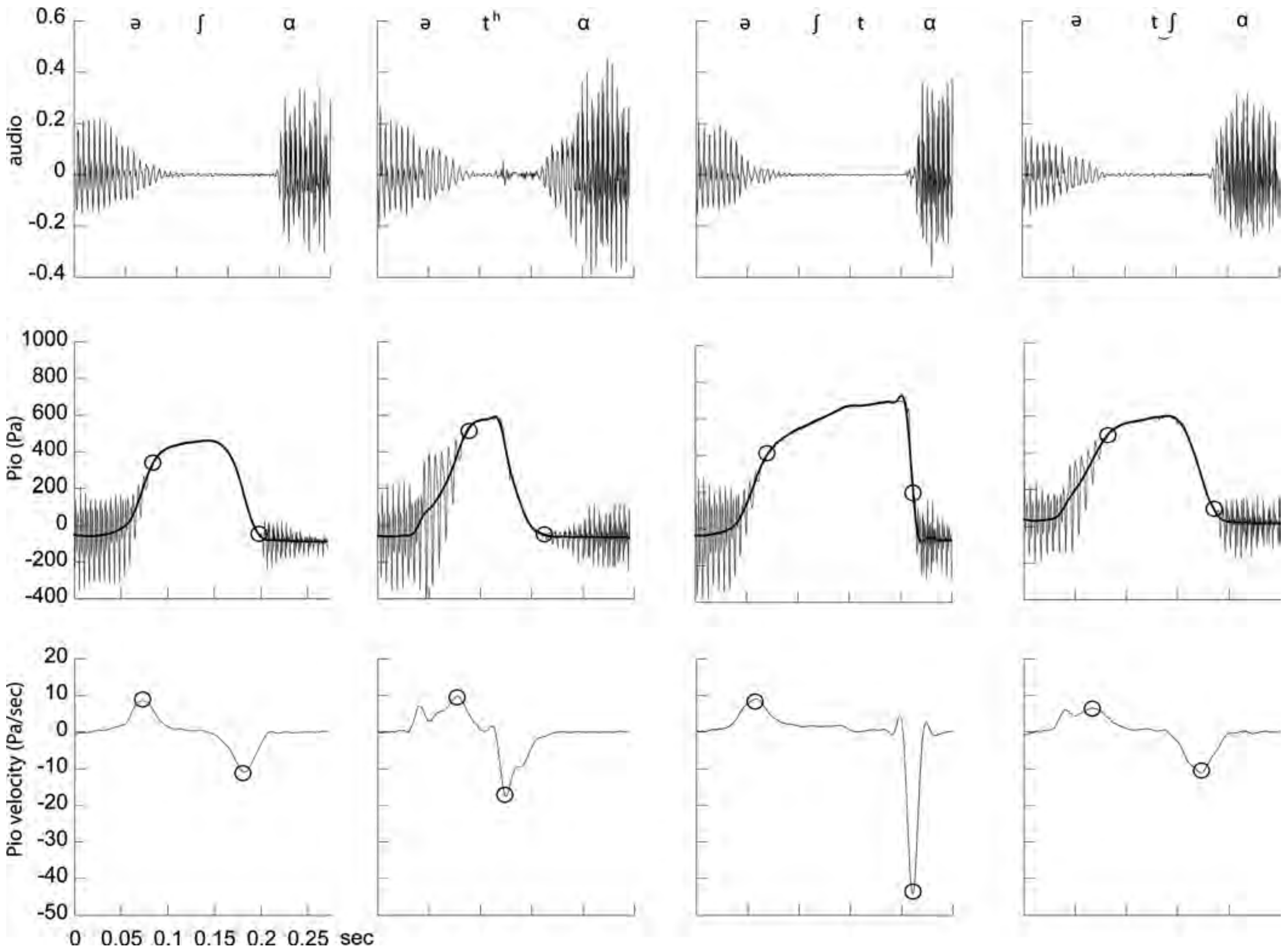

FIG. 1. Examples of selected fricative, stop, cluster, and affricate productions as produced by speaker M4. From left to right: /əʃɑ/, /ətɑ/, /əʃtɑ/, /ət͜ʃɑ/. From top to bottom: Audio signal; original and smoothed P_{io} signals (where the smoothed is the heavy line); velocity of smoothed P_{io}. The circles in the P_{io} signals show locations of voicing offsets and onsets. The circles in the velocity signal show maximum positive and negative values. As described in the text, there were a few differences between the two clusters (/st/ and /ʃt/) and the two affricates /t͜s/ and /t͜ʃ/ in the P_{io} values at phonation onset and offset, but the overall P_{io} profiles were qualitatively similar.

terms, for these high-vowel utterances, a baseline measure was also obtained in the nearest low vowel, namely the /ɑ/ in *nasche*. This provided a value near the speaker's baseline pressure (as evident between utterances) and was thus more valid for present purposes. Finally, for all utterances, the minimum pressure value in the neighboring vowels was determined (based on two vowels for utterances with /ɑ/ words and three vowels for utterances with /i/ or /ɪ/ words) and subtracted off the pressure values at voicing offset and onset obtained from the smoothed P_{io} signal.

C. Measures

After voicing offset and onset times had been determined, the following measures were obtained automatically in MATLAB for each token: (a) The pressure values in the smoothed P_{io} signal at voicing offset and offset, corrected for baseline drift as described above. (b) The peak positive pressure velocity associated with the P_{io} rise into the consonant and the minimum negative pressure velocity associated with the P_{io} fall coming out of the consonant. This measure was included following Lucero (2005), who found that a rapid increase in driving pressure could push the vocal folds into a stable vibratory pattern that would not be achieved with a more gradual pressure change. The signals and measurement points are shown for one production of a fricative, stop, cluster, and affricate for one male speaker (M4) in Fig. 1.[2]

To quantify tongue–palate contact patterns, two measures were obtained for each EPG frame extracted at voicing offset and onset: The overall percentage of contact (PC) and the center of gravity (COG). The PC measure is simply the total percentage of contacts on the EPG palate out of a possible 62 (six electrodes in the most anterior row and eight electrodes in the remaining seven rows). The COG measure weights contact in each row (Rl-8, numbered anterior to posterior) by a coefficient that increases by 1, from 0.5 to 7.5, with anteriority. The sum of the weighted contacts is then divided by the total number of contacts. Higher COG values correspond to more anterior places of articulation.

D. Statistical methods

All statistics were computed in R (R Development Core Team, 2008). To evaluate global differences between

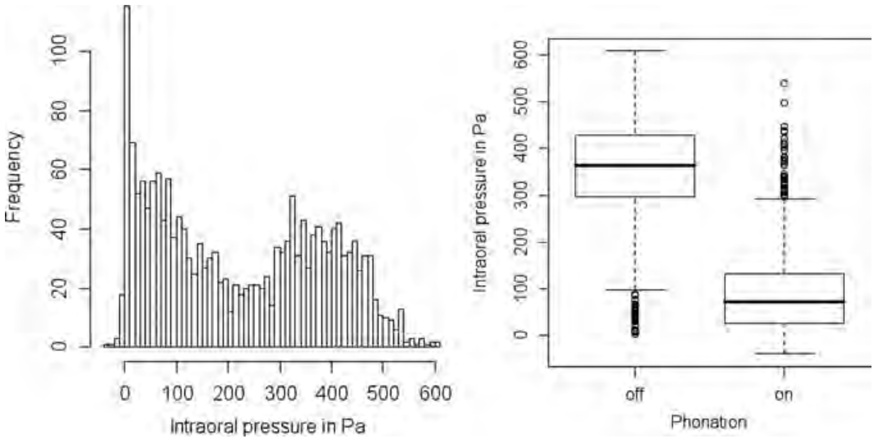

FIG. 2. Histogram of all pressure data (left) and box-plots of values for voicing onset and offset (right). In the box-plots, the thick lines in the box indicate the mean; the size of the boxes shows the 25–75th quartiles; and the dotted lines indicate the 10–90th percentiles. Isolated circles represent outliers.

phonation offsets and onsets, a paired *t*-test was calculated. The vowel and consonant effects on P_{io} at voicing offsets and onsets were assessed by repeated-measures ANOVAs with vowel and consonant as independent factors and speaker and repetition as error terms. Pair-wise post-hoc tests were carried out to evaluate specific consonant effects. For vowel effects, one-way ANOVAs were conducted for each consonantal context separately, with vowel height as the independent factor and speaker and repetition as error terms. While it was of interest to assess whether there was an interaction between consonant and vowel effects in general, a full set of pair-wise post-hoc analyses was not performed for all consonant–vowel combinations because not all of these were deemed meaningful. For example, possible differences in vowel effects for /tɑ/-/tɪ/ vs /ʃtɑ/-/ʃtɪ/ were of interest, whereas differences between /tɑ/ and /ʃtɪ/ were not. The EPG and pressure velocity data were reviewed in selected cases to help interpret patterns in the pressure data.

III. RESULTS

A. Global P_{io} values at phonation offset and onset

Figure 2 (left) shows a histogram of all the P_{io} data pooled across speakers, consonants, and vowels. Figure 2 (right) splits the data by phonation offset vs onset. It is evident that the pressure data were roughly bimodal distributed [Fig. 2 (left)] and that despite differences in laryngeal and aerodynamic conditions across contexts, voicing offsets tended to occur at higher values of P_{io} [Fig. 2 (right)]. The group mean values were 350 Pa for voicing offsets vs 94 Pa for voicing onsets. A two-sample *t*-test showed this difference to be highly significant ($t = 54.35$, $p < 0.001$, $\mathrm{df} = 920$).

At the same time, there is clearly a wide range of values for both voicing offsets and onsets, as well as considerable overlap between offset and onset values. The following sections explore how this variation, including high and low outlying values, reflects consonant and vowel context. The main effects from the repeated-measures ANOVA for vowel and consonant factors are given in Table II. Consonant and vowel height effects were significant for both phonation offset and onset, as were the consonant-by-vowel interactions. Results of post-hoc tests are provided below.

TABLE II. Main effects and interactions of the ANOVAs on P_{io} at voicing offset and onset. Consonant (C) and vowel height (V height) were independent factors; speaker and repetition were error terms. Values in boldface are significant at the 0.05 level. Post-hoc results are given in Table III for the consonants and summarized in the text for the vowels.

Phonation offsets				Phonation onsets			
Factor	DFs	*F*-value	*p*-value	Factor	DFs	*F*-value	*p*-value
C	5	98.120	**<0.001**	C	5	136.848	**<0.001**
V height	1	8.392	**0.004**	V height	1	408.066	**<0.001**
C × V height	5	2.283	**0.045**	C × V height	5	12.641	**<0.001**
Residuals	894			Residuals	894		

B. Differences across consonantal contexts

1. Phonation offset

It was predicted that phonation offsets would occur at lower values of P_{io} for /ʃ ʃt st/ as compared to /t t͜ʃ t͜s/. Table II (left) shows that the main effect of consonant on voicing offsets was significant; the post-hoc pair-wise tests are given in Table III (left) and the data are plotted in Fig. 3. The results were as expected: All comparisons between /ʃ ʃt st/ vs /t t͜ʃ t͜s/ were significant and phonation ceased at lower values of P_{io} before fricatives than stops. Two of the fricative-initial sequences, namely /ʃ/ and /ʃt/, account for most of the very low offset values seen in Fig. 2 (right). Differences among the stop and the affricates were not significant, nor were differences among the single fricative and the clusters.

2. Phonation onset

The main effect of consonant was also significant for voicing onsets (Table II, right). Post-hoc results are given in Table III (right) and the data are graphed in Fig. 4. The primary expectation was that aspirated vs unaspirated stops would differ. The data were consistent with this prediction: Phonation began at higher values of P_{io} after unaspirated stops (i.e., those in the clusters) than the aspirated ones. The clusters account for most of the high-end outliers seen for

TABLE III. Post-hoc results (p-values) for P_{io} at phonation offset and onset as a function of consonant. For 15 pair-wise comparisons at each location, the adjusted α is 0.00333. Significant comparisons are indicated in boldface.

	Phonation offsets							Phonation onsets					
	ʃ	ʃt	st	t	t͜s	t͜ʃ		ʃ	ʃt	st	t	t͜s	t͜ʃ
ʃ	–	0.195	0.092	**<0.001**	**<0.001**	**<0.001**	ʃ	–	**<0.001**	**<0.001**	0.020	<0.001	0.009
ʃt		–	0.016	**<0.001**	**<0.001**	**<0.001**	ʃt		–	0.033	<0.001	<0.001	**<0.001**
st			–	**<0.001**	**<0.001**	**<0.001**	st			–	<0.001	<0.001	**<0.001**
t				–	0.157	0.347	t				–	<0.001	**<0.001**
t͜s					–	0.467	t͜s					–	**<0.001**

onsets in Fig. 2 (right). P_{io} at phonation onset for the unaspirated stops was also significantly higher than for the fricative and affricates. Qualitatively, the aspirated stop showed the lowest P_{io} at phonation onset of all the contexts; the difference was not significant for the single fricative, but it was for the affricates.

A difference was also observed between the two affricates: Phonation began at slightly higher values of P_{io} following /t͜s/ than /t͜ʃ/. This might be a result of more articulatory contact for /t͜ʃ/ (i.e., greater supraglottal constriction). The EPG data showed that, for most speakers, average PC values at voicing onset were higher following the postalveolar than the alveolar. The overall difference was very small, however (about 3%), and reflected a pattern observed in the high vowel context. Specifically, seven out of the eight speakers had higher average PC values for /t͜ʃi/ than /t͜sɪ/ (group average of 10%). Conversely, seven out of eight had the reverse EPG pattern in the low vowel context (more contact for /t͜sɑ/ than /t͜ʃɑ/), but in this case the average difference was only 3%. To help clarify these PC values, EPG plots, showing contact frequency over all repetitions, are shown for a representative speaker (M5) in Fig. 5. This particular speaker had PC values of 33.4% for /t͜ʃi/ vs 24.8% for /t͜sɪ/ (8.5% difference), compared to 18.3% for /t͜ʃɑ/ and 19.4% for /t͜sɑ/ (1.1% difference).

C. Differences across vowel contexts

The main effect of vowel was significant for both voicing offsets and onsets, as was the consonant-by-vowel interaction (Table II). Thus, the plots in this section show the data split by both consonant and vowel. However, as explained in Sec. II D, the statistics only assessed vowel effects within each consonantal context.

1. Phonation offset

Data for voicing offsets as a function of vowel are given in Fig. 6. The post-hoc tests showed that, of the six consonantal contexts, vowel effects were significant ($p < 0.001$, using an adjusted α of $0.05/6 = 0.00833$) for the single stop, the single fricative, and the cluster /ʃt/, with phonation persisting to higher levels of P_{io} before low vowels. This implies that a higher transglottal pressure was needed to maintain phonation before a high vowel.

The significant vowel effects for the singleton consonants can be explained by their shorter duration as compared to the clusters and affricates (cf. the durational data for a subset of German stops, fricatives, affricates, and clusters in Fuchs and Koenig, 2009). That is, a shorter transvocalic consonant interval permits more influence of the following vowel. Durational effects also appear to explain the significant vowel effect for /ʃt/ but not /st/: The cross-speaker average duration of /ʃt/, across the two vowel contexts, was 201 ms (SD = 49 ms), whereas for /st/ it was 237 ms (SD = 59 ms). This pattern was quite consistent across speakers and may reflect the fact that /st/ is rare in German (i.e., speakers may have tended to produce this cluster more slowly and carefully). The vowel effect for /ʃt/ but not /st/ does *not* appear to reflect differences in the degree or placement of articulatory contact. Vowel-related differences in average PC and COG values at voicing offset were very small and virtually identical for the two clusters: For PC, a vowel difference of 0.71% for /ʃt/ vs 1.18% for /st/; and for COG, 0.04 for /ʃt/ vs 0.25 for /st/.

2. Phonation onset

The pattern for phonation onsets was more consistent: For all consonantal contexts, voicing onsets occurred at

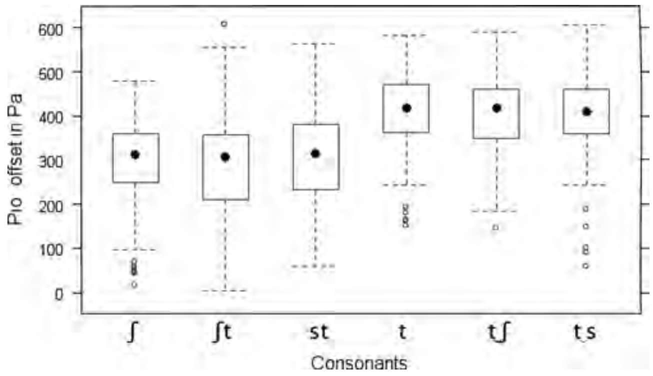

FIG. 3. P_{io} at phonation offsets as a function of consonant.

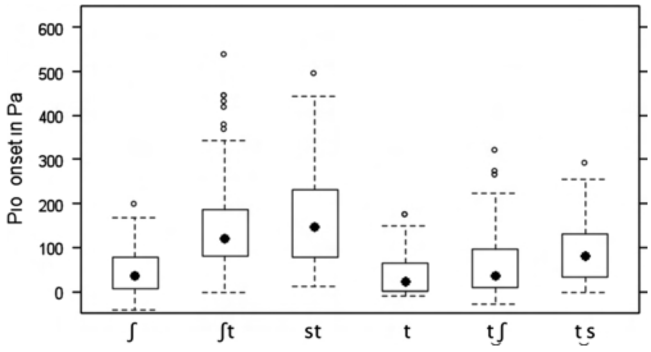

FIG. 4. P_{io} at phonation onsets as a function of consonant.

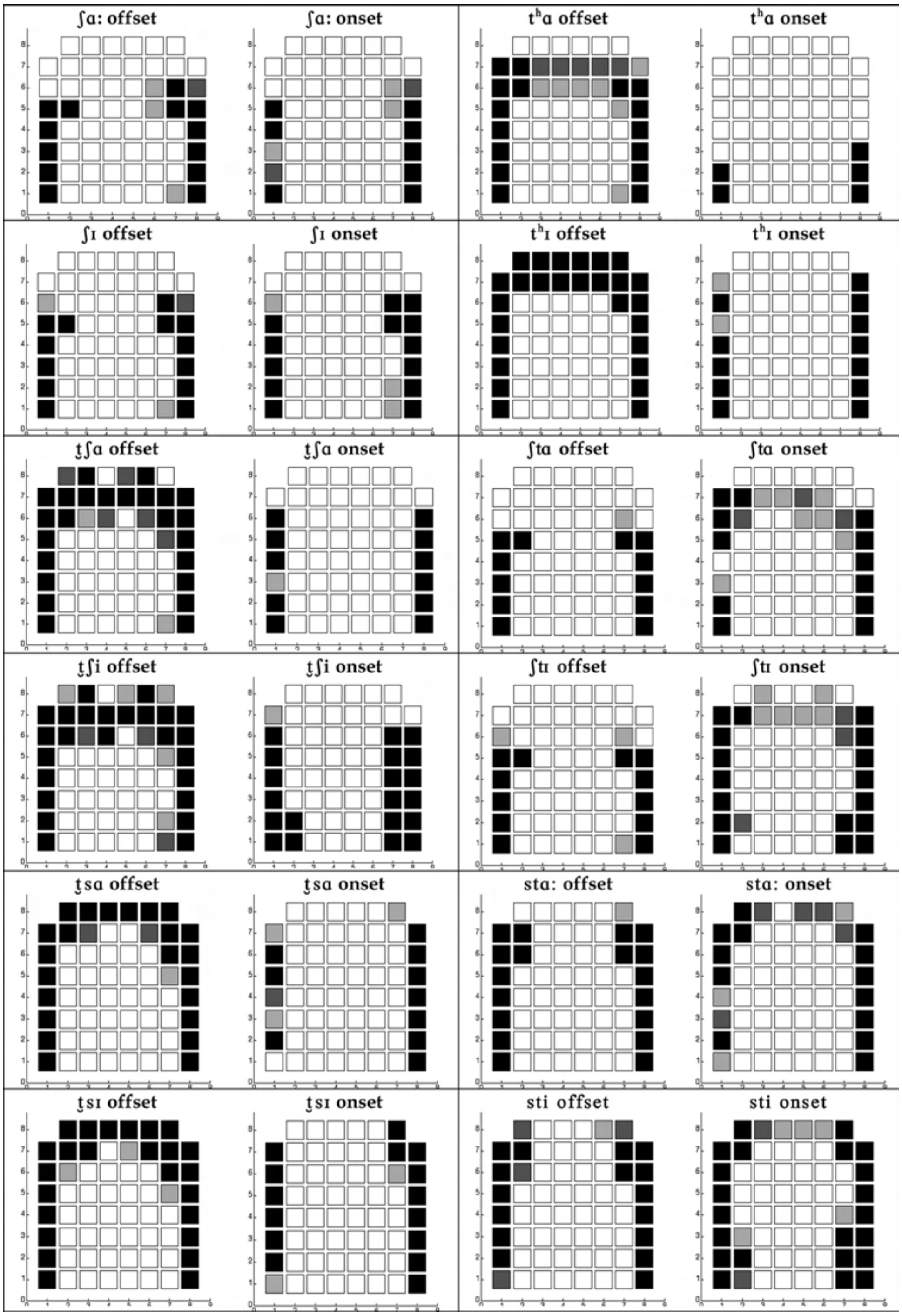

FIG. 5. EPG frequency plots for all utterances of one speaker. Each plot shows electrode rows 1–8, from top to bottom; row 1, at the top, is the most anterior. Within the frequency plot for each utterance, black cells indicate contact in 76%–100% of productions; dark gray in 51%–75% of productions; light gray in 26%–50% of productions; unfilled in 0%–25% of productions.

significantly higher levels of P_{io} before high vowels ($p < 0.001$, with $\alpha = 0.00833$). The effect was also consistent across speakers. The group data are given in Fig. 7, and Fig. 8 shows one representative pair in the /t/ context for speaker Fl.

One reason vowel effects were of interest here was because of past studies reporting longer VOTs before high vowels. The current data did not show such an effect. An ANOVA on VOT measures for /t/ (vowel height as the independent variable, speaker and repetition as error terms) yielded a p-value of 0.029, with VOTs being slightly longer before the *low* vowel (about 3 ms on average). A review of individual speakers indicated that this average effect could be attributed to three of the eight speakers, who showed longer VOTs before /ɑ/ on the order of 10 ms. The other five speakers either had equivalent VOTs for the two vowel contexts, or very slightly longer VOTs in the high vowel context (<10 ms). Because of these speaker differences, the ANOVA was also run without speakers as an error term. In this case, the p-value was 0.258. We conclude that vowel context did not consistently affect VOT in these data.

Despite the lack of a clear vowel effect on VOT in the expected direction, other vowel-related effects postulated by past authors could still hold, not only stops but also across consonantal contexts. As outlined in Sec. I C, the most common considerations have included effects of (a) vowel

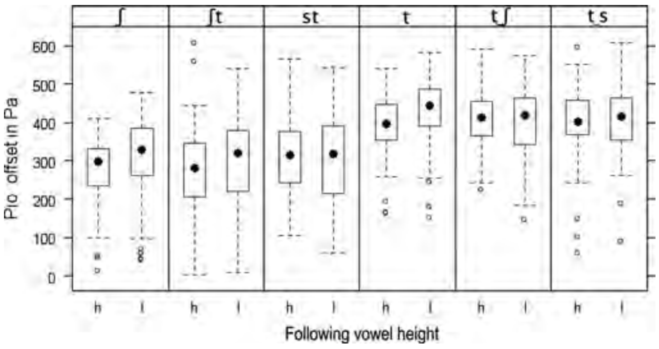

FIG. 6. P_{io} at phonation offsets as a function of vowel (h = high, l = low) in different consonantal contexts.

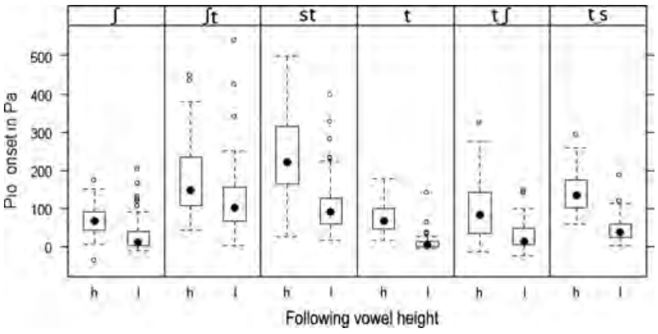

FIG. 7. P_{io} at phonation onsets as a function of vowel (h = high, l = low) in different consonantal contexts.

articulation on vocal-fold characteristics, especially tension (leading to the intrinsic f0 effect), and (b) supralaryngeal constriction degree on the rate of P_{io} discharge. To evaluate whether these hypothesized conditions held here, follow-up analyses were carried out on the EPG and pressure velocity data, as well as f0 (measured from the acoustic signal over the first three pulses of the post-consonantal vowel). The intrinsic f0 effect was evident in the data: In the high vowel context, the average f0 across speakers was 177.8 Hz (SD = 54.7 Hz), compared to 152.1 Hz (SD = 45.95 Hz) in the low vowel context, with males and females showing a comparable frequency ratio. The average PC values from the EPG data also showed the predicted greater contact in the high vowel context (across speakers and consonantal contexts, a difference of about 12%). PC data for all consonants, split by vowel, are shown in Fig. 9. This difference was, moreover, reflected in the rate of the pressure change at release (as seen in the example in Fig. 8). The velocity minimum reflecting the P_{io} discharge averaged -9.89 Pa/s for the high vowel context (SD = 5.70), compared to -14.71 Pa/s for the low vowels (SD = 8.53). The direction was consistent across consonantal contexts, but the magnitude was most extreme in the clusters (where the unaspirated stops were associated with a very rapid P_{io} decrease; cf. Fig. 1). In short, predictions of past work based on intrinsic f0 and rate of pressure discharge in high vowel contexts were met, yet still the high vowel context had a facilitating effect on phonation onsets.

IV. DISCUSSION

As expected, on average phonation onsets occurred at lower values of P_{io} than phonation offsets. As reviewed in Sec. I A 2, past studies have established that, under identical conditions, initiating vocal-fold vibration requires a higher level of transglottal pressure than sustaining it (i.e., there is hysteresis). In this study, onset–offset differences are not appropriately referred to as hysteresis, however, since the conditions at offset and onset are not symmetrical. Differences arise as a function of supraglottal conditions, laryngeal–supralaryngeal timing, and vocal-fold characteristics related to stress and accent. Since the target consonant here initiated a stressed syllable and the word was in a prosodically-focused position, f0 was generally higher on the second vowel of the sequence. Some component of the offset–onset differences observed here must be ascribed to these f0 differences (Lucero, 2005; Lucero and Koenig, 2007; Lucero *et al.*, 2011; Solomon *et al.*, 2007; Verdolini-Marston *et al.*, 1990), as well as the consonant and vowel effects discussed below. These contextual factors provide an explanation for why the offset–onset differences found here are larger than those observed in past studies. In these data (see Fig. 2 and associated discussion), phonation onset occurred, on average, at 94 Pa vs 350 Pa for offsets, a difference of 256 Pa and a ratio of 3.73. For comparison, Lucero (2005) obtained a difference of about 120 Pa for a two-mass model of the vocal folds and Lucero (1995) reported a ratio of about 2 for the body–cover model of the vocal folds [cf. also comparable data from Baer (1975) on canine larynges and Titze *et al.* (1995) on a physical model]. Thus, the direction of the current onset–offset differences is consistent with past modeling work, but the magnitude of the effect is considerably larger and could not have been easily predicted.

It should also be noted that the current study used P_{io} data to infer transglottal pressure, assuming that P_{sub} was constant. Several considerations limit the accuracy of this assumption. First, P_{sub} may decrease a bit when the vocal

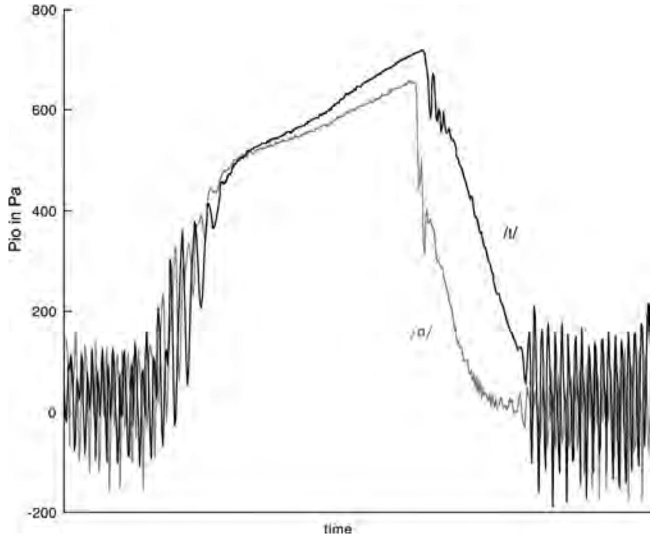

FIG. 8. Unsmoothed P_{io} data for two individual productions of /tɑ/ (gray) and /tɪ/ (black) from speaker FI. These examples show the typical pattern of phonation onset occurring at a higher value of P_{io} for the high vowel context.

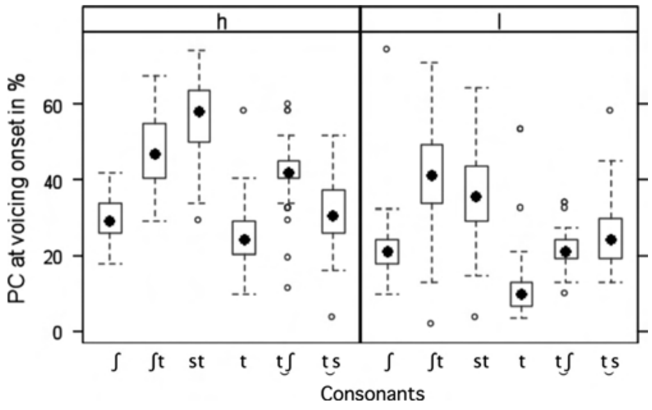

FIG. 9. EPG percent contact (PC) at phonation onset as a function of consonant and vowel (h = high, l = low).

folds are widely abducted (Hirose and Niimi, 1987; Lucero and Koenig, 2005). Our speakers also used self-selected loudness and pitch, and variations in these factors will contribute some noise to the data. For the most part, any such variations (as well as any vocal fatigue effects over the course of the recording session) should be randomly distributed across utterances, although the words containing the rare cluster /st/ may have been produced with systematically greater loudness and pitch as well as the observed greater duration. A post-hoc analysis indicated that the /st/ clusters had slightly higher average peak pressures within the consonantal interval on the order of 40 Pa. Data from other languages will be needed to clarify the extent to which the small voicing differences observed between /st/ and /ʃt/ here reflect the effects of rarity vs intrinsic differences in supraglottal articulation and aerodynamics between the two sequences. Modeling can also help disentangle the influences of all of these factors.

A. Consonant effects

Reports of earlier glottal abduction for fricatives compared to stops led to the prediction that voicing would cease at lower values of P_{io} before fricatives and fricative-initial sequences (i.e., clusters) as compared to stops and stop-initial sequences (i.e., affricates). The data bore out this expectation. For phonation onsets, the main pattern was that phonation began at higher levels of P_{io} for the unaspirated stops of the clusters compared to the other contexts. It was somewhat surprising that phonation onset was not different for the aspirated stop vs the single fricative, since the maximum abduction in the aspirated stop occurs very late relative to supraglottal closure compared to the fricative (Hoole *et al.*, 2003; Lofqvist and Yoshioka, 1981, 1984; Ridouane *et al.*, 2006; Yoshioka *et al.*, 1981). One possibility is that a faster pressure drop at plosive release compared to fricative release (cf. examples in Fig. 1) helps counteract the wide glottal aperture at aspirated stop release. Lucero (2005) observed that a rapid pressure change could be more effective at initiating phonation than a gradual change. Phonation at high levels of P_{io} after the unaspirated stops could then reflect the combination of the adducted glottal posture and the rapid pressure change. Both of these factors contribute to early phonation onsets.

B. Vowel effects

The vowel effects on phonation offset and onset present a paradox. At least for the shorter consonantal sequences, following high vowels had a slight inhibitory effect on phonation, with voicing offsets occurring at lower values of P_{io}. At voicing onset, a very consistent effect in the opposite direction was observed: Phonation began at higher levels of P_{io} entering high vowels. It was predicted that the following vowel context would have a greater influence on phonation onsets than on phonation offsets, and comparison of Fig. 6 and 7 shows that vowel effects were much larger in the case of phonation onset.

The most sensible explanation for the inhibitory effect of high vowels on phonation offsets would appear to be an anticipatory laryngeal raising for a following high vowel, leading to slight increases in vocal-fold tension. In contrast, the effects for voicing onsets go against expectations based on intrinsic f0 (whereby more vocal-fold tension in the high vowel context should inhibit phonation), as well as those based on supraglottal areas (whereby slower P_{io} discharge during the release phase of obstruents before high vowels should inhibit phonation). The explanation that does seem to account for these data is one based on vocal-tract inertance (Lucero *et al.*, 2009; Ruty *et al.*, 2008). As indicated in Sec. I C, these studies have demonstrated reduced P_{th} values with lower values of F1.

V. CONCLUSIONS

The consonant and vowel patterns in the current data reflect the multitude of factors that affect phonation thresholds and contribute to an understanding of the nature and magnitude of supraglottal influences on vocal fold behavior. Although voicing offsets, on average, occurred at higher values of P_{io} than voicing onsets, there was considerable overlap between onset and offset values and contextual effects on onset–offset patterns were substantial. The P_{io} levels at phonation onset and offset across consonantal contexts could generally be explained in terms of differing supraglottal conditions, as evident in the EPG data, and laryngeal-oral timing. The P_{io} patterns for the vowels were more complex than those for the consonants. For the current data, explanations for the opposing onset vs offset patterns could be found in past studies of vowel effects on laryngeal states and recent work on the influence of vocal-tract inertance on P_{th}, but given the limited set of vowel contrasts used here, more work is needed to clarify how adjacent vowels affect phonation onsets and offsets around consonants.

The methodology used here was designed specifically to permit non-invasive recording of naturalistic speech from multiple speakers. Assessing the adequacy of laryngeal and supralaryngeal modeling to describe typical speech patterns requires such data. At the same time, the present method left some factors uncontrolled (e.g., loudness, intonation contours, and the tense–lax feature of vowels). Clarifying the effects of these parameters will require focused empirical studies that exercise control over specific variables of interest, as well as modeling work that permits changing single parameters independently.

ACKNOWLEDGMENTS

We express our appreciation to our speakers; to Jörg Dreyer for designing the experimental setup; and to Anders Löfqvist, Doug Whalen, and two anonymous reviewers for comments on earlier versions of this manuscript. This study was funded by a grant to the PILIOS project from the DFH Saarbrücken, a grant from the Federal Ministry of Education and Research (BMBF) to PB1 at ZAS, and grants from MCT/CNPq (Ministério da Ciência e Tecnologia/Conselho Nacional de Desenvolvimento Científico e Tecnológico) and CAPES (Coordenação de Aperfeiçoamento de Pessoal de Nível Superior), Brazil.

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[1] It is acknowledged that the vowel set does not control for tense vs lax quality. This is true for /i/ vs /ɪ/ as well as for /ɑ/ in different syllabic contexts: The words *Schaf* and *Stachel* contain the lax variant of the vowel. As such, the vowel context was coded as one of height only. It was not possible to fully control for tense–lax and still use real words of German. One goal of the work was to analyze fairly naturalistic speech, so we opted for real words recognizing that this would entail some loss of control over all phonetic features for the vowels.

[2] As evident in Fig. 1, the pressure velocity signals sometimes had multiple positive or negative excursions entering or exiting the consonant. For present purposes, a single positive/negative pressure velocity value was obtained. However, in future work it may be of interest to characterize such tokens in order to more fully understand the P_{io} changes associated with obstruent production.

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