Simultaneous measures of electropalatography and intraoral pressure in selected voiceless lingual consonants and consonant sequences of German

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This work assessed relationships among intraoral pressure (IOP), electropalatographic (EPG) measures, and consonant sequence duration, in the following obstruents, clusters, and affricates of German: /t/, /ʃ/, /ʃt/, and /t͡ʃ/. The data showed significant correlations between IOP and percentage of articulatory contact (PC) for all speakers, whereas duration and place of articulation (measured by the EPG center of gravity) contributed less to IOP changes. Speakers differed in the strength of this relationship, possibly reflecting differences in vocal tract morphology or degree of laryngeal abduction. Single-point EPG and IOP measures in fricatives showed consistent correspondences across consonantal contexts, but the relationships for the stops were more complex and reflected positional effects. Temporal compression was observed for both members of the cluster, but only the fricative portion of the affricate. Conversely, coarticulation was observed for both the stop and fricative portion of the affricate, but only for the stop portion of the cluster, possibly reflecting biomechanical constraints. No clear differences were observed in coarticulatory resistance for stops and fricatives. These data contribute to a limited literature on articulatory-aerodynamic relationships in voiceless consonants and consonant sequences, and will provide a baseline for considering longer combinations of obstruents. © *2009 Acoustical Society of America.* [DOI: 10.1121/1.3180694]

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I. INTRODUCTION

The general goal of this work is to obtain a better understanding of how intraoral pressure (IOP) varies in obstruents and obstruent sequences in relation to articulatory actions. A fuller description of IOP and articulatory variation in consonant sequences can provide insight into laryngeal and supralaryngeal control mechanisms in the rapidly-changing aerodynamic conditions of running speech, and ultimately inform aerodynamic modeling of obstruents. The specific purpose of this paper is to quantify the relationships between IOP and lingua-palatal contact, obtained via electropalatography (EPG), in a subset of voiceless stops, fricatives, affricates, and clusters of German. The results will serve as a foundation for future studies on longer obstruent sequences.

High values of IOP are a crucial feature of obstruents, particularly voiceless ones. These sounds are typically among the most affected, for example, by velopharyngeal insufficiency or by loss of laryngeal valving in laryngectomy (e.g., Edels, 1983; Rosenfield *et al.*, 1991). A variety of mechanisms can contribute to high levels of IOP: Glottal abduction, the presence of supralaryngeal closure or constriction (assuming a closed velopharyngeal port), and the duration of closures and constrictions. This work seeks to further understand these mechanisms, focusing on the relationship between IOP, supralaryngeal articulation, and duration.

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Much past research has investigated acoustic and articulatory characteristics of consonants, clusters, and affricates, but studies of IOP have mostly considered single stop consonants, with less attention to other obstruents and obstruent sequences. Further, experimental sample sizes have often been limited by rather invasive methodological (viz., transnasal) procedures. Clarifying how consonantal aerodynamics reflect oral articulation in a wider variety of phonetic contexts and across speakers is important for several reasons. First, the acoustic features of voiceless consonants require specific aerodynamic conditions to be fulfilled (Howe and McGowan, 2005; Krane, 2005; Mooshammer *et al.*, 2006; Shadle, 1990), especially in the case of fricatives. Further, pressure variations in the vocal tract affect phonatory behavior (Koenig and Lucero, 2008; Müller and Brown, 1980; Stevens, 1990; Westbury 1979, 1983), for fricatives as well as stops. Finally, evidence from both normal and clinical populations indicates that speakers actively control certain aspects of vocal tract aerodynamics, and some articulatory actions serve aerodynamic requirements (Huber *et al.*, 2004; Müller and Brown, 1980; Prosek and House, 1975; Warren *et al.*, 1992; Westbury, 1983). Yet little past work has explicitly compared IOP with simultaneously-collected supralaryngeal data. Characterizing how vocal tract aerodynamic patterns relate to articulatory activity in consonant sequences is particularly relevant for a language like German, which allows long sequences of obstruents, both within and across syllable boundaries. This work focuses specifically on articulatory contact, which affects supraglottal resistance, and, in

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turn, upper vocal tract pressure patterns. The combination of EPG and IOP used here allows an assessment of the degree to which changes in supraglottal conditions affect IOP in running speech.

The current study analyzed EPG patterns and IOP in utterance-internal, syllable-initial /t/, /ʃ/, /t͡ʃ/, and /ʃt/ for eight speakers of German to address the following questions: (1) Most simply, to what degree does IOP vary as a function of changes in articulatory contact? That is, how sensitive is the IOP signal to supraglottal articulation as measured via EPG? (2) How do affricates and fricative+stop clusters compare to singleton stops and fricatives in aerodynamic and articulatory contact patterns? (3) How do the affricate and cluster compare in their coarticulatory patterns (viz., changes in place of articulation as measured by EPG), and how much does IOP reflect such articulatory variation?

The following sections review the articulation and aerodynamics of voiceless consonants; coarticulatory patterns of obstruents, especially comparing singleton stops and fricatives with their realization in clusters and affricates; and the phonological representations of clusters and affricates.

A. Articulation and aerodynamics of voiceless consonants, affricates, and clusters

In voiceless obstruents, laryngeal actions must be coordinated with supralaryngeal constrictions. These actions and their coordination vary depending on the acoustic and aerodynamic requirements of the sound in question. Direct laryngeal data on single stops and fricatives indicate that peak glottal opening occurs near the time of oral release for aspirated stops (as occur in German), but earlier, during the turbulent noise region, for fricatives (Hoole *et al.*, 2003; Löfqvist, 1992; Ridouane *et al.*, 2006; Yoshioka *et al.*, 1981). Voiceless affricates and tautosyllabic fricative+stop clusters also tend to show peak abduction in the fricative region (Hoole *et al.*, 2003; Kagaya, 1974; Ridouane *et al.*, 2006; Yoshioka *et al.*, 1981). Finally, the degree of glottal abduction appears to be more extensive in fricatives than stops (Hirose *et al.*, 1978; Lindqvist, 1972; Lisker *et al.*, 1969; Löfqvist and Yoshioka, 1984; Ridouane *et al.*, 2006). Greater abduction extents in fricatives and abduction timed to occur within the fricative regions of obstruent sequences both suggest that speakers are implicitly sensitive to the aerodynamic requirements of fricatives, whereby sufficient airflow is needed to generate turbulent noise (e.g., Scully *et al.*, 1992). In other words, these studies provide evidence of articulatory control of aerodynamic conditions.

Much previous work on speech aerodynamics has focused on IOP in single stop consonants differing in voicing status (Lisker, 1970; Malécot, 1966; Miller and Daniloff, 1977; Müller and Brown, 1980; Svirsky *et al.*, 1997; Warren and Hall, 1973; Westbury, 1983). From studies that investigated differences among *voiceless* consonants, one comparison is particularly germane to the current work: that between stops and fricatives. The presence of a complete closure in stop consonants would lead one to expect higher IOP buildup than in fricatives, but greater vocal-fold abduction in fricatives than stops could counteract this effect. Past investigations of voiceless stops and fricatives have usually reported higher values in the stops (Arkebauer *et al.*, 1967, Koenig *et al.*, 1995; Prosek and House, 1975; Subtelny *et al.*, 1966), but there are some exceptions: Malécot (1968) found few differences, and Malécot (1969) found higher pressures in fricatives. Varying results across studies could result from a number of methodological factors, including (a) whether and how data were averaged across speakers and consonants, (b) instrumental methods, (c) speaker characteristics, and/or (d) differences in the speech materials, syllable position, elicitation conditions, speaking style, or speech rate (see Malécot, 1968, 1969). One possible effect of speech rate is that longer closure or constriction durations allow pressure to build to higher levels (at least until it reaches the maximum value of subglottal pressure; see Miller and Daniloff, 1977). The issue of duration is also relevant in considering obstruent sequences. Subtelny *et al.* (1966) found slightly higher peak pressures in affricates than in simple stops. This could be accounted for by the combination of a longer obstruent interval and extensive laryngeal abduction late in this interval, during the fricative region. In this case, it appears that the laryngeal actions affect IOP to a greater degree than the drop in oral resistance associated with the release of the stop into the fricative.

One might also hypothesize that place of articulation would affect IOP: Specifically, a more posterior place of articulation, or smaller back cavity, could contribute to a faster rise of IOP up to the ceiling level of subglottal pressure. Past authors have considered this possibility mainly for stop consonants, again usually focusing on stop voicing (e.g., Ohala, 1983). It is not clear how much such effects may hold for voiceless consonants, however; the rapid increase in IOP associated with laryngeal abduction may simply outweigh supraglottal place effects. In fact, whereas Subtelny *et al.* (1966) observed somewhat higher pressures in /d/ than /b/, for /p/ and /t/ higher pressures were seen in the bilabials. The situation is also considerably more complicated for fricatives than for stops, since the cross-sectional area of the constriction may covary with place of articulation. For example, the larger constriction size of /ʃ/ should work against any differences that may arise as a function of placement or posterior cavity size relative to more anterior sounds. The current work assesses place of articulation [using the EPG center of gravity (COG) index; see Sec. II C 2] as a possible contributor to IOP variation, but past literature does not lead to clear predictions on this point for the sounds considered here.

B. Context effects in stops, fricatives, affricates, and clusters

Acoustic studies have frequently observed a "compression effect," whereby stops and fricatives tend to be shorter in affricates and clusters than in singleton productions (Byrd, 1993; Crystal and House, 1988; Haggard, 1973; Hawkins, 1979; Klatt, 1974, 1976). Reduced segment durations suggest that the components of a cluster or affricate overlap, i.e., coarticulate. An expansive literature exists on the factors that promote or constrain gestural overlap; this review will focus on work directly relevant to the current study, namely, comparisons between stops and fricatives and between lingual consonants varying in place of articulation.

Several authors have suggested that fricatives, particularly sibilants such as /s/ and /ʃ/, show limited context-related variability (Nguyen *et al.*, 1994; Recasens and Espinosa, 2007; Recasens *et al.*, 1997; Tabain, 2000). This could again reflect aerodynamic requirements: In a study of consonant sequences, Byrd (1996) proposed that speakers restrict coarticulatory overlap of fricatives with stops because such overlap could inhibit the airflow necessary for fricative production. Other authors have emphasized the articulators involved in forming the constriction. Recasens and colleagues (Recasens 1984, 1985; Recasens *et al.*, 1993, 1997) drew on EPG and acoustic data for alveolar, postalveolar/alveopalatal,[1] and palatal sounds in Italian and Catalan to argue that alveolar sounds permit extensive coarticulation as a function of phonetic context, whereas palatal and alveopalatal sounds restrict coarticulation because they place more constraints on tongue body position. A similar prediction for alveolar vs velar places is suggested by Butcher and Weiher's (1976) EPG study of /t/ and /k/ in German, as well as Bladon and Al-Bamerni's (1976) acoustic study of light (apical) vs dark (velar) /l/ in English. The general notion that restrictions on the tongue body may limit coarticulation dates from Öhman (1966), who proposed that the distinctively palatalized consonants of Russian led speakers of that language to constrain vowel-to-vowel coarticulation (measured by F2) as a general production strategy.

In the case of the cluster /ʃt/ and the affricate /t͡ʃ/, these considerations lead to the prediction that the stop should assimilate in place to the fricative more than the other way around. EPG studies of English speakers (Fletcher, 1989; Liker *et al.*, 2007) and a single Hindi speaker (Dixit and Hoffman, 2004) have reported a posterior placement for /t/ in /t͡ʃ/, similar to that for /ʃ/, with minimal coarticulatory influence on the fricative portion of the affricate. The study of Recasens and Espinosa (2007) on Valencian and Majorcan dialects of Catalan found that, on average, stop regions in /t͡ʃ d͡ʒ/ had less anterior contact and more palatal contact than in /t͡s d͡z/, but the differences were more extreme in Majorcan, and anteriority differences across the two places did not reach statistical significance in Valencian. This example suggests that there may be language-specific differences in the degree of coarticulation within affricates.

C. Phonological representations of clusters and affricates

A final consideration for affricates and clusters is their linguistic representation, in particular, their status as a sequence of phonemes vs a phonetic sequence associated with a single phonemic unit. Although there are some debates about whether affricates are best treated as complex stops (e.g., specified for the feature "strident") or as a phoneme-internal combination of stop and fricative features (e.g., a "contour" segment), phonologists do agree that affricates hold a single segmental position (Clements, 1999; Jakobson *et al.*, 1951; Lombardi, 1990; Rubach, 1994; Sagey, 1986). Clusters are then differentiated from affricates in that they represent two phonemes in sequence. Thus the present work will treat the distinction between affricates and fricative +stop clusters as the difference between a single phonological unit vs a sequence. For simplicity, the notations /t/ and /ʃ/ will be used hereafter to refer to the stop and fricative regions of the affricate as well as the individual stop and fricative phonemes, produced as singletons or in a cluster.

D. Predictions

In light of the aerodynamic, articulatory, and phonological considerations reviewed above, several specific predictions were identified for the current work. These are grouped into three categories to correspond to the three analysis subsets below (Secs. II D 1–II D 3).

(1) (a) Differences in oral aperture should lead to higher IOP values in stops than fricatives. A mitigating consideration is that, as noted above, laryngeal apertures may be larger for fricatives than stops. (b) Pressure should reach higher levels in longer consonantal sequences, at least so long as IOP has not reached its ceiling level of the subglottal pressure (see Miller and Daniloff, 1977; Subtelny *et al.*, 1966).

(2) (a) Stop and fricative durations should be shorter in affricates and clusters than in singleton consonants. (b) Coarticulatory effects should yield articulatory and aerodynamic differences in the stop and fricative portions of /t͡ʃ/ and /ʃt/ as compared to single stops and fricatives.

(3) In the affricate, articulatory constraints on the tongue body and aeroacoustic requirements for fricatives should yield greater accommodation of /t/ to /ʃ/ than vice versa. The same prediction should also hold true for the cluster, although one might expect less coarticulation in the cluster given its phonological representation as a sequence of two phonemes.

II. METHODS

A. Speakers and speech materials

Eight native speakers of Standard German, ranging in age from 27–42 years, were recorded. Three were females (F1–F3) and five were males (M1–M5). All of them had previously participated in EPG experiments, so they were accustomed to speaking with the artificial palates. Speakers also wore the palates for about 15 min before the recording sessions to allow for adaptation.

The full corpus was designed to include a wide variety of lingual obstruents and obstruent sequences of German. As noted above, German is useful in this regard since it allows lengthy obstruent combinations within and across syllable boundaries. Real German words were chosen that included the consonants/clusters/affricates of interest in minimal or near-minimal pairs for both syllable onset and coda positions. These words were then placed into compounds and carrier phrases where the target consonants or consonant strings were adjacent to vowels or one or more consonants so as to vary the length of the consonantal sequence. The resulting utterances were phonotactically legal in German, but

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TABLE I. List of utterances.

Word	IPA of target VCV	English gloss
Tasche	ə#tʰɑ	Pocket/bag
Schaf	ə#ʃɑ	Sheep
Stachel	ə#ʃtɑ	Spike
Tschad	ə#t͡ʃɑ	Chad

mostly semantically nonsensical. The present work addresses the small set of target words listed in Table I. Speakers read the utterances from a printed, randomized list in which each target utterance appeared ten times.

The words analyzed here were produced in the sentential frame "*Ich nasche* [ɪç nɑʃə] ___" ("I nibble ___"). The target words listed in Table I all occurred as the first member of a compound ending with *Stelle* ("place"); thus, the full utterance with the first word was "*Ich nasche Taschenstelle*." (A final -*n* is added to *Tasche* in the compound word.) The analysis focuses on the V#CV or V#CCV sequences from the final schwa of *nasche* through the first stressed syllable of the target word. The current data therefore consist of singleton /t/ and /ʃ/, the cluster /ʃt/, and the affricate /t͡ʃ/ in syllable onsets in the vocalic frame /ə#_ɑ/. As indicated by the transcriptions in Table I, the singleton /t/ in German is aspirated in this context, whereas /t/ in the fricative+stop cluster is unaspirated.

B. Instrumentation

Electropalatography (Reading system, EPG 3) was used to obtain articulatory contact information over time and in lateral as well as midsagittal planes. This method can differentiate between oral constrictions and closures and also reveals coarticulatory effects between adjacent stops and fricatives.

To record IOP, an experimental setup was designed whereby a piezoresistive pressure transducer (Endevco 8507C-2) measuring about 2.4 mm in diameter and 12 mm in length was affixed to the posterior end of the EPG palate via a flexible plastic tube (see Fig. 1). The sensor measures the difference between intraoral and atmospheric pressure (the latter obtained via a tube passed around the teeth). This arrangement offers several advantages: It permits simultaneous recording of EPG and IOP, it is not affected by saliva blocking the tube, and it is more comfortable for speakers than inserting a tube or catheter through the nose. As a result, it was possible to carry out recording sessions lasting 2 h or longer, and the recorded speech generally sounded quite natural. The speakers' past experience with EPG recordings also contributed to natural-sounding speech.

Three signals were simultaneously recorded: Acoustics, recorded to DAT at a sampling rate of 48 kHz; EPG, with a sampling rate of 100 Hz; and IOP, recorded into PCQUIRER with a sampling rate of 1859 Hz.[2] The acoustic signal was used to verify that the speaker produced the target utterance accurately and to obtain durational measures. All other analyses were performed in MATLAB (Mathworks, Natick, MA) from the EPG and IOP signals.

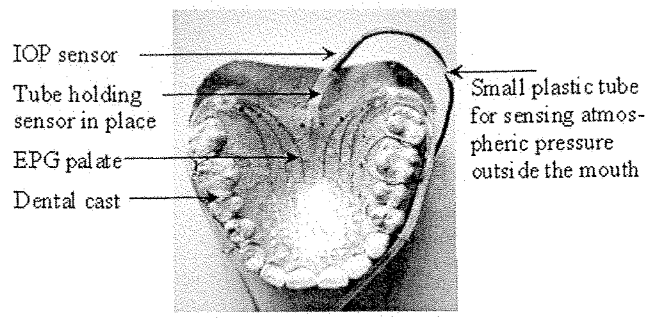

FIG. 1. Equipment setup, showing placement of IOP sensor at posterior end of the EPG palate.

C. Preliminary processing

1. Acoustics

Acoustic durations of stop, fricative, and burst or burst +aspiration regions were made for all consonants and sequences in PRAAT (version 4.4.20; see Boersma and Weenink, 2006) and used for subsequent extraction of EPG data as well as to assess the degree of durational compression in clusters and affricates. Measured examples of each sound or sequence are shown in Fig. 2. The regions were defined as follows: (a) The /t/ closure was measured from the offset of the second formant (F2) in the preceding schwa to the acoustic burst. The /t/ aspiration was measured from the burst onset to the offset of aspiration noise and beginning of voicing. (b) The /ʃ/ was measured from the onset to the offset of frication noise. (c) /ʃt/ was measured from the onset to offset of frication noise, from the offset of frication noise to the end of the stop closure, and then from the onset to the offset of the burst. (d) /t͡ʃ/ was measured from the F2 offset of the preceding vowel to the stop burst for /t/, and from the onset to the offset of frication noise for /ʃ/. As shown in Fig. 2, the burst and the frication noise were measured as a single unit since they are typically acoustically inseparable.

2. EPG

To quantify the EPG contact patterns, two parameters were extracted for each production within the acoustically-defined stop and fricative regions: The percentage of tongue-palate contacts (hereafter PC), out of a possible 62, and the COG, which represents a weighted index in the front-back dimension (Hardcastle *et al.*, 1991). Formally, the indices were defined as follows (where R corresponds to row):

$$\mathrm{PC}(\%) = \frac{\text{total number of electrodes contacted} \times 100}{62}, \quad (1)$$

$$\mathrm{COG} = \frac{(0.5 \times R8) + (1.5 \times R7) + (2.5 \times R6) + (3.5 \times R5) + (4.5 \times R4) + (5.5 \times R3) + (6.5 \times R2) + (7.5 \times R1)}{\text{total number of contacts}}. \quad (2)$$

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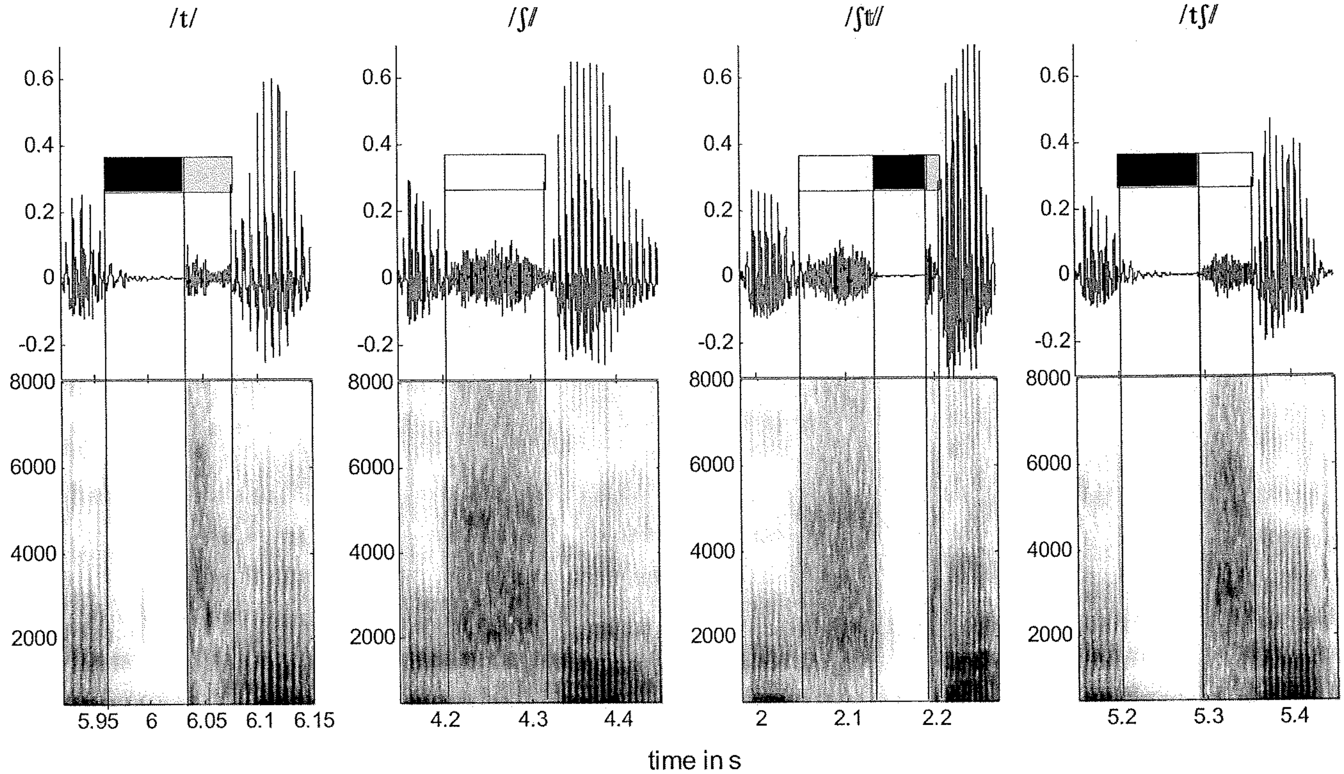

FIG. 2. Measurements of acoustic duration in /t/, /ʃ/, /ʃt/, and /t͡ʃ/ for speaker M5. Top panels: Acoustic waveforms. Bottom panels: Spectrograms. The vertical lines indicate the measured regions, following the color-coded bars shown above the waveform: Black=/t/ closure; white=/ʃ/ frication; gray=burst (in the cluster) or burst+aspiration (for single /t/ in syllable-initial position).

As indicated in Eq. (1), PC values are calculated across the entire EPG palate and are thus independent of the position of the contact (that is, place of articulation). COG, on the other hand, weights each EPG row by a coefficient that increases with anteriority and provides a measure of the place of articulation. Since the front rows are multiplied by greater weights, higher COG values correspond to a more anterior place of articulation.

To obtain a general sense of how the EPG indices varied over time, each index was ensemble averaged over all repetitions (usually 10) of each target word per speaker, and scaled to the average length of the sequence as determined from the acoustics. Specifically, the data were linearly interpolated to a common length of 100 samples; the average and standard deviation (SD) of the repetitions was obtained; and these data were expressed over time as the average duration. These average plots, ± 1 SD, were then compared to a plot of the input tokens to verify that the average accurately represented the characteristics of most individual productions. The similarity between the individual tokens and the ensemble averages, as well as the lack of evident nonlinearities in the data, indicated that more complex averaging procedures (e.g., using functional data analysis) were not required. Examples of these average EPG trajectories are included as part of Fig. 3, described in the next section.

3. IOP

The IOP data were smoothed using a kaiser window, with 40 Hz passband and 100 Hz stopband edges, and a damping factor of 50 dB, using the filtfilt function in MATLAB to minimize time delays. These filtering specifications eliminated most of the oscillations associated with phonation, and yielded minimal distortion in regions of rapid pressure change (such as at stop releases). Consonantal regions from the smoothed IOP signal were then extracted to correspond with the consonantal regions as defined in the EPG signals. To correct for baseline drift in the pressure signal over the course of the recording session, a pressure minimum was obtained in the vowels preceding and following each target consonant or consonant string, and the minimum of these two values was subtracted off each extracted token. This effectively set the minimum pressure in each token to

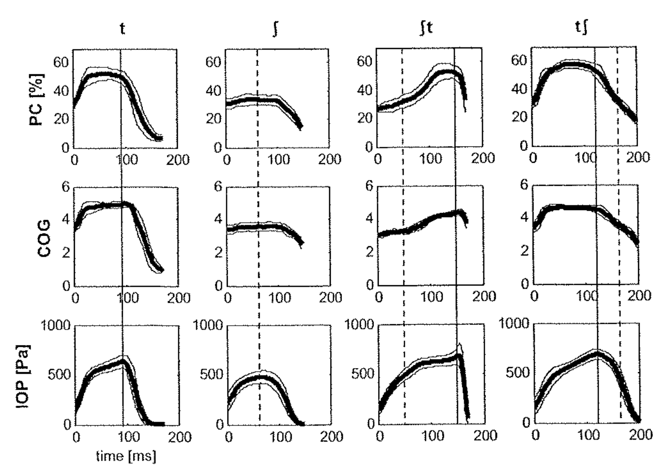

FIG. 3. Average EPG indices (COG=center of gravity, PC=percentage of contact) and IOP traces for all four utterances of one female speaker (F2). The x-axis is normalized time based on the average acoustic durations. The solid vertical lines correspond to the defined /t/ time point (either the burst or the peak IOP; see text for more details). The dotted vertical lines correspond to the fricative midpoint.

approximately zero. The IOP values presented here thus reflect the pressure change in the consonant(s) relative to this baseline. Finally, the data were ensemble averaged in a manner analogous to that used for the EPG trajectories.

Figure 3 shows an example of the average (± 1 SD) EPG and IOP data for a typical speaker (F2). The lines indicate the measurement points used for statistical analysis (explained below in Sec. II D 2). This figure demonstrates some general characteristics of the data that are relevant for subsequent aspects of the methods as well as for interpreting the results. First, the two EPG measures are highly correlated over time, and the IOP trajectory generally follows the EPG patterns for the single stop, single fricative, and the cluster. Relationships between EPG and IOP are more complex for the affricate. Second, the EPG and IOP data typically do not show distinct stop and fricative regions for either the cluster or the affricate.

D. Analyses

To address the questions identified in Sec. I, three methods of analysis were carried out. Briefly, the first assessed the degree to which IOP changes across the entire consonant or consonant sequence could be predicted from changes in EPG measures and overall duration. The second investigated EPG and IOP differences between singletons vs clusters and affricates, considering the stop and fricative regions separately and assessing the relationships between IOP and EPG changes. The third investigated temporal compression and place coarticulation in the members of the cluster and affricate as compared to singleton stops and fricatives. The following methods sections (II D 1–II D 3) correspond to the three sections in the results (III A–III C).

1. Predicting variation in IOP

To obtain a global picture of how IOP varied as a function of articulatory contact and consonant duration, differences between the maximum and minimum PC, COG, and IOP values (henceforth PCdiff, COGdiff, and IOPdiff) were obtained over the whole consonantal sequence as defined from the acoustics. Together with the acoustic durations, these data were entered into a linear stepwise regression analysis using SPSS (version 15.0) with IOPdiff as the dependent variable and PCdiff, COGdiff, and duration as the predictor variables. This procedure determines how much variance is explained by different numerical models. Data were split by speaker, but not by word, because the rather small number of repetitions (9–10 per word per speaker) would have resulted in unacceptably low statistical power.

2. IOP and EPG patterns across consonantal contexts

To permit statistical comparisons of single /t/ and /ʃ/ with the stop and fricative regions of the clusters and affricates, IOP, PC, and COG values were obtained at single time points for each individual token (shown schematically for the average signals in Fig. 3). The time points were chosen to represent reliable features of stop and fricative production, taking into account the lack of clear fricative and stop regions in the EPG and IOP noted above for /ʃt/ and /t͡ʃ/. For the fricatives, measures were taken at the temporal midpoint of the fricative noise, whether the fricative occurred alone or in a cluster or an affricate. As shown in Fig. 3, the EPG indices were fairly stable at these timepoints. For the stop regions, slightly different criteria were used in the affricate as compared to the cluster and single stop. In the affricate, the IOP value was taken at the time of the acoustic burst. For the closures in /t/ and /ʃt/, the IOP and EPG values were taken at the time of the IOP peak, which consistently occurred immediately prior to the oral release of the stop, i.e., the burst. The peak IOP values rather than the acoustic burst were used in the latter cases because there was usually an abrupt pressure drop after the burst, so that a temporal error in burst location of just a few milliseconds could have yielded greatly reduced pressure values. In the affricate, however, pressure did not peak at the end of the closure, so the burst served as the most reliable indication of the high pressure value associated with the stop.

The single-point EPG and IOP values, along with the acoustic durations (described above in Sec. II C 1) were submitted to repeated-measures analyses of variance (ANOVAs) using the *R* (version 2.7.0) function aov with error terms for speaker and repetitions,[3] following Johnson (2008), and independent variables of consonant environment: The stop region in the singleton vs cluster vs affricate, and the fricative region in the singleton vs cluster vs affricate. Since eight independent ANOVAs were being run (/t/ and /ʃ/ values for duration, IOP, PC, and COG), a rather conservative α-criterion was used for establishing statistical significance: $0.05/8=0.00625$.

3. Clusters and affricates: Compression and coarticulation

The acoustic durations were assessed to determine the degree of compression of /t/ and /ʃ/ portions of the cluster and the affricate relative to the singleton productions. To evaluate the degree of place coarticulation in the stop and the fricative regions of the affricate and cluster, the means of the COG indices for each speaker's single /t/ and /ʃ/ were taken as reference values and set to 100%. The averages for the speaker's cluster and affricate were then expressed relative to this reference value. For example, in speaker F1, the mean COG value for single /ʃ/ was 4.11, whereas her /ʃ/ in /t͡ʃ/ had a mean COG value of 4.24. This yields a ratio of $4.24/4.11=103\%$, meaning that /ʃ/ was about 3% more anterior in the affricate than the single fricative for this speaker.

III. RESULTS

A. IOP variation as a function of changes in articulatory contact and consonant sequence duration

This analysis (see Sec. II D 1) used stepwise regression analysis to assess how well the IOP change over the entire consonantal interval (IOPdiff) could be predicted from changes in the percentage of contact, center of gravity (PCdiff, COGdiff), and consonant sequence duration (Dur). The results of the regression, given in Table II, indicate that PCdiff had the strongest relationship with IOPdiff for all speakers, explaining 37%–82% of the variance. For five

TABLE II. Results of the stepwise linear regression (showing solutions significant at $p<0.001$).

Speaker	Model	R^2	F
F1	PCdiff	0.44	29.0
	PCdiff and Dur	0.51	19.0
F2	PCdiff	0.48	32.8
	PCdiff and COGdiff	0.61	27.4
F3	PCdiff	0.82	163.9
M1	PCdiff	0.58	51.4
M2	PCdiff	0.59	53.4
	PCdiff and COGdiff	0.64	32.3
	PCdiff and COGdiff and Dur	0.74	33.1
	COGdiff and Dur	0.74	50.5
M3	PCdiff	0.37	21.9
	PCdiff and Dur	0.49	17.1
M4	PCdiff	0.49	35.1
	PCdiff and Dur	0.59	26.1
M5	PCdiff	0.62	58.8
	PCdiff and Dur	0.73	48.4
	PCdiff and COGdiff and Dur	0.78	39.9

speakers (F1, M2, M3, M4, and M5), including duration in the model explained an additional 7%-12% of the variance. Changes in place of articulation, as assessed by COGdiff, yielded a slightly better fit than PCdiff alone for speakers F2, M2, and M5. Across speakers, the best-fit solutions explained, on average, 64% of the variance.

The simple linear correlations between IOPdiff and PCdiff (the strongest predictor of IOP according to the stepwise regression) are shown for all speakers in Fig. 4. The relationship was positive (and highly significant) for all speakers, but they differed in the degree of scatter around the regression line, with r-values ranging from 0.609–0.903. Speakers also showed considerable variation in their regression slopes (with values ranging from 2.9–7.0), indicating that the magnitude of IOP change could be quite different across speakers given comparable changes in articulatory contact. Similar slope variation was observed for COGdiff (values 36.9–71.9) and duration (0.8–2.5); that is, slopes could be about two to three times higher in some speakers than in others.

Although the data were not split by consonant for statistical purposes, Fig. 4 permits a qualitative assessment of how well the correlation coefficients reflected within- vs cross-consonant effects. On the whole, the relationships between IOPdiff and PCdiff appear to arise from differences among the four consonant types more than token-to-token variation for an individual target sequence. [Note, for example, the vertical orientation of the repetitions of /ʃ/ (circles) and /ʃt/ (triangles) for speaker F2.] Thus, the positive slopes in Fig. 4 indicate that changes in IOP and lingua-palatal contact were lowest in the single fricative, somewhat higher in the cluster, and highest in the stop and affricate. Inspection of corresponding plots for IOPdiff vs COGdiff and duration suggested that these correlations also mostly reflected cross-context differences.

B. Differences in IOP and EPG across consonantal contexts

As described in Sec. II D 2, single-point /t/ and /ʃ/ regions in the EPG and IOP data were defined in the stop, fricative, cluster, and affricate to permit statistical comparisons across the consonantal contexts. The acoustic durations were also considered in assessing which factors influence IOP. The significance results of the repeated-measures ANOVAs for the four dependent measures (IOP, PC, COG, and Duration) are given in Table III. These correspond to the data shown in Figs. 6–8 and 11.

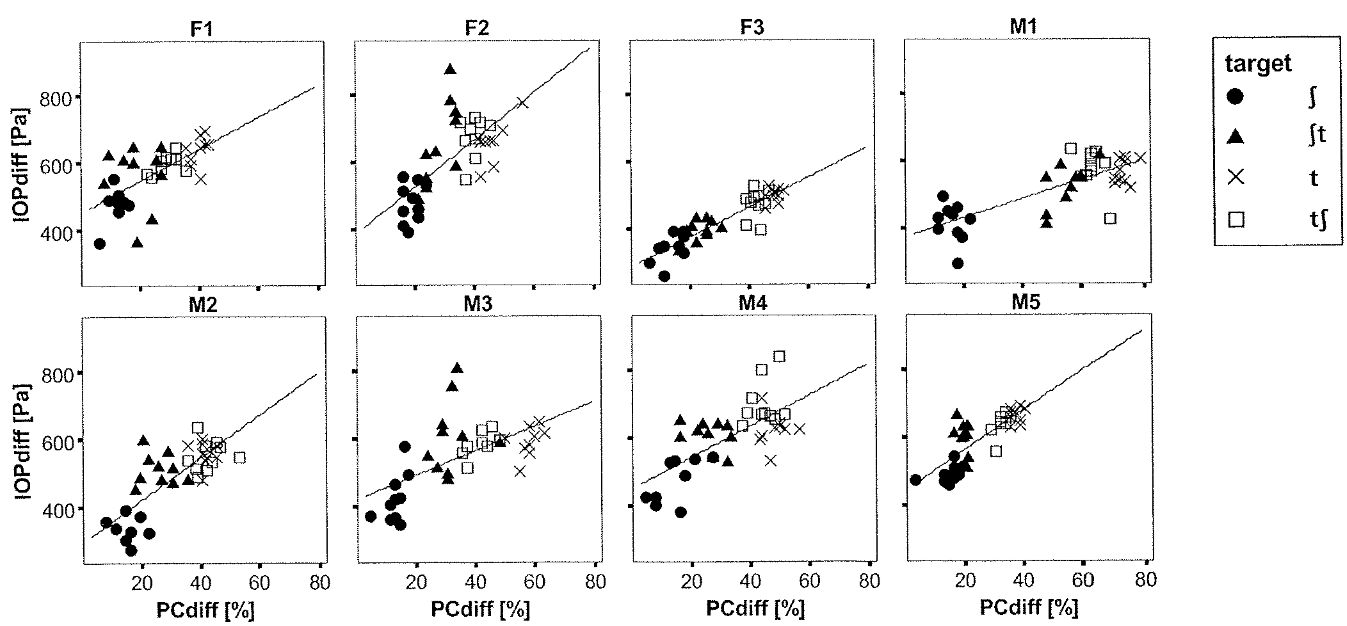

FIG. 4. Correlations for difference in percentage of articulatory contact (PCdiff) through the whole sequence interval against the change in intraoral pressure (IOPdiff) for each of the eight speakers, split by consonant type. Speakers F1–F3 are the females; M1–M5 are the males.

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TABLE III. ANOVA results (p-values) for measures of IOP, PC, COG, and Duration (Dur), for /t/ and /ʃ/, alone and in clusters and affricates. Values in bold indicate that the effect of context (singleton, cluster, affricate) was significant at $p < 0.00625$. Spkr=Speaker; Repn=Repetition; W/in=Within.

	Overall ANOVA: /t/	Pairwise comparisons /t/-/ʃt/	/t/-/t͜ʃ/	/ʃt/-/t͜ʃ/	Overall ANOVA: /ʃ/	Pairwise comparisons /ʃ/-/ʃt/	/ʃ/-/t͜ʃ/	/ʃt/-/t͜ʃ/
				IOP				
Spkr	0.210	0.825	0.275	0.114	0.072	0.084	0.031	0.237
Repn	0.598	0.936	0.045	0.420	0.707	0.715	0.484	0.902
W/in	0.007	**0.005**	0.687	0.019	**<0.001**	0.415	**0.001**	**<0.001**
				PC				
Spkr	0.154	0.733	0.148	0.051	0.027	0.293	**0.003**	0.016
Repn	0.518	0.711	0.078	0.124	0.414	0.277	0.935	0.402
W/in	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	0.042	**<0.001**	**<0.001**
				COG				
Spkr	0.398	0.82	0.176	0.303	0.615	0.879	0.273	0.334
Repn	**0.001**	0.019	0.087	**0.002**	0.979	0.841	0.990	0.108
W/in	**<0.001**	**<0.001**	**<0.001**	0.037	**<0.001**	**<0.001**	**<0.001**	**<0.001**
				Dur				
Spkr	0.634	0.855	0.376	0.450	0.419	0.614	0.209	0.752
Repn	0.010	**0.001**	0.173	**0.001**	**0.003**	0.048	**<0.001**	**0.014**
W/in	**<0.001**	**<0.001**	**0.007**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**

The acoustic durations of closure, frication, and burst or burst+aspiration for the four consonant strings are shown for the eight speakers in Fig. 5. These will be relevant in interpreting the IOP data. Of note is a general tendency for the affricate to be the longest of the four consonant sequences (the difference was statistically significant for speakers F2, F3, M2, M4; speaker M5 is the exception). The relative durations of stop and fricative regions within the affricate differ across speakers, however. For example, speaker F2 has a rather long stop portion in her affricate, whereas speaker M2 has a rather long fricative portion in his.

The average IOP data are presented in Fig. 6. The main effect of context for the fricatives was significant; for the stops the overall ANOVA did not meet significance using the conservative criterion ($\alpha = 0.00625$), but one of the *post hoc* tests did (single /t/ vs /t/ in the cluster). The general pattern is that both stops and fricatives have the highest IOP values when they appear as the last member of an obstruent sequence (i.e., when they are durationally later, giving IOP more time to build). Thus, IOP is higher during the fricative of /t͜ʃ/ than in single /ʃ/ or in /ʃt/, and higher during the stop of /ʃt/ than during single /t/. Although one might expect IOP

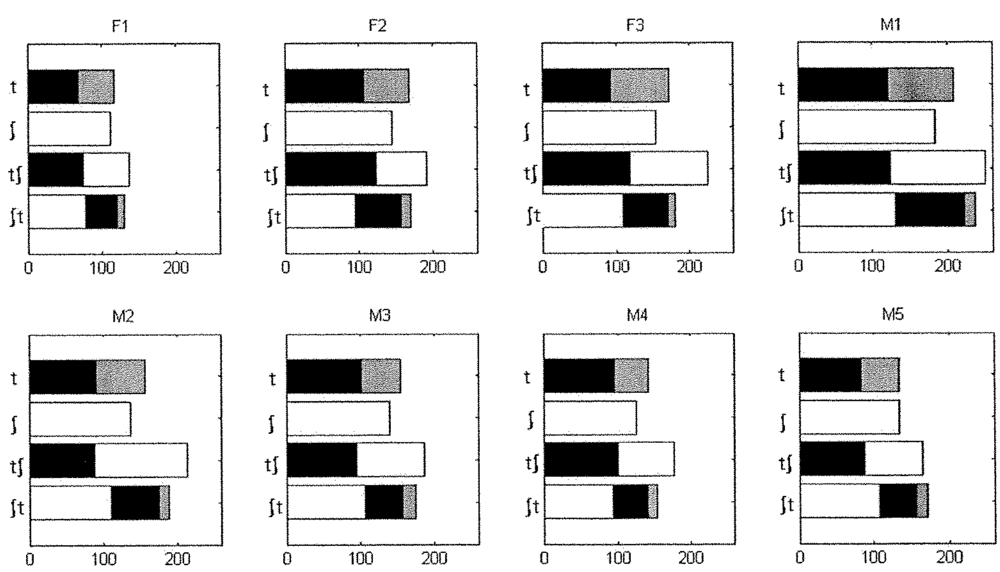

FIG. 5. Acoustic durations for individual speakers, averaged over all repetitions of a sequence. As in Fig. 2, black indicates /t/ closure; white represents /ʃ/; gray indicates burst (for /ʃt/) or burst+aspiration (for /t/). The x-axis is time in ms.

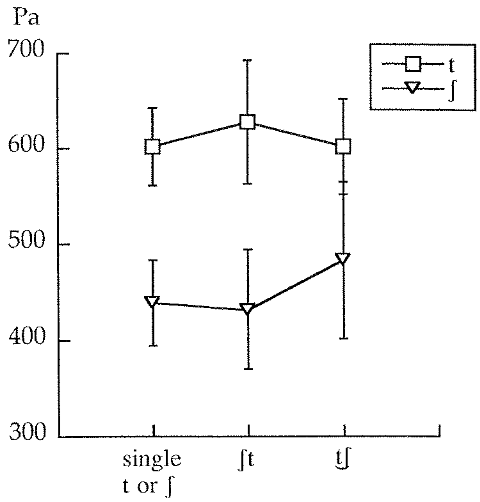

FIG. 6. Average IOP data for single /t/ and /ʃ/ compared with the stop and fricative regions of the cluster and affricate.

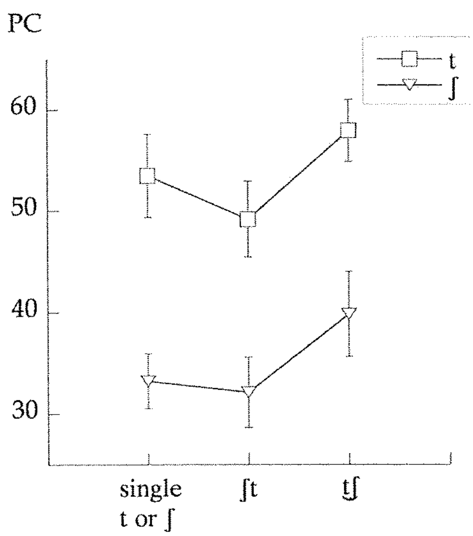

FIG. 7. Average PC data for single /t/ and /ʃ/ compared with the stop and fricative regions of the cluster and affricate.

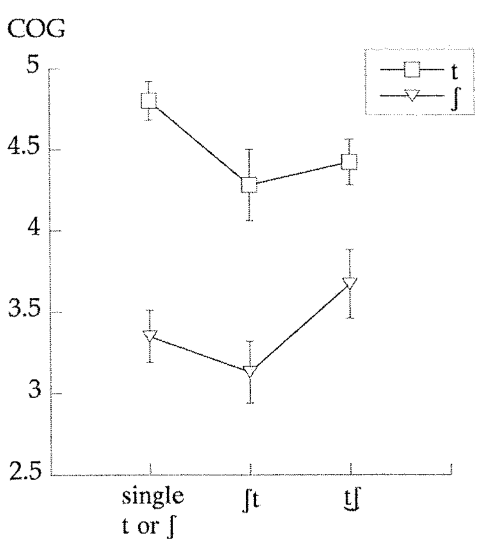

FIG. 8. Average COG data for single /t/ and /ʃ/ compared with the stop and fricative regions of the cluster and affricate.

to reach a ceiling value early in a voiceless stop, the current data show that IOP continues to rise slowly after its rapid initial increase, reaching slightly higher values in /t͡ʃ/ than /t/ (about 7% on average), as seen in Fig. 3 above.

Figures 7 and 8 present the results for the average EPG indices. To assist in interpreting these indices, Fig. 9 shows EPG contact frequencies across all productions of the four targets/target sequences in all speakers. The single time frame shown for each production is the same as that used to obtain the PC and COG indices.

As noted above (see Fig. 3), the percentage of contact and COG measures tend to show similar patterns. The higher PC and COG values for /t/ than /ʃ/ simply indicate that /t/ is articulated with complete closure at a more anterior place of articulation (refer to the EPG contact patterns in Fig. 9). Of more interest is how the stop and fricative regions in the clusters and affricates compare to the single stops and fricatives, and how the contact patterns relate to IOP.

The data for PC (Fig. 7) show that /t/ was articulated with the least contact in the cluster and the most in the affricate. The fricative also had the most contact in the affricate, but there was no significant difference between the fricative portions of the singleton and cluster. The EPG frequency plot (Fig. 9) indicates that the higher value of PC in the affricate mostly reflected greater lateral contact and/or a more anterior place of articulation. For COG (Fig. 8), the ANOVA showed lower values (a retracted place of articulation) for /t/ in the affricate and cluster as compared to single /t/, indicating coarticulation with /ʃ/. Conversely, /ʃ/ in the affricate had higher COG values than single /ʃ/, suggesting coarticulatory influence from /t/. Unexpectedly, /ʃ/ in the cluster was produced most posteriorly; i.e., it did not show more anterior placement under the influence of the upcoming /t/. The EPG frequency plot shows that this effect, although statistically significant, was rather small in magnitude. A more posterior placement in the cluster may reflect biomechanical constraints. Specifically, a more posterior fricative articulation could allow for greater tongue-tip flexibility for producing the apical stop.

A comparison of the EPG and IOP data in Figs. 6–8 reveals some general correspondences among the three measures for the fricatives. The posterior place of articulation (low COG values) for /ʃ/ in the cluster co-occurs with a reduced percentage of contact. As the tongue moves off the back end of the EPG palate, PC typically decreases. Less articulatory contact, in turn, corresponds to lower IOP values. The results for /t/ are more complex. In the cluster, the preceding fricative retracts the /t/ occlusion (lower COG), with corresponding reduction in PC as seen for the fricative. The high IOP value in this context can be attributed to the positional effect noted above (higher pressure in the second member of a sequence). In the affricate, the retracted place of articulation can again be explained as place assimilation to /ʃ/. The high PC value appears to reflect lateral tongue contact in preparation for /ʃ/. Although speakers varied somewhat in their IOP patterns for affricates, the peak IOPs in the affricate were generally as high as, or higher than, those in

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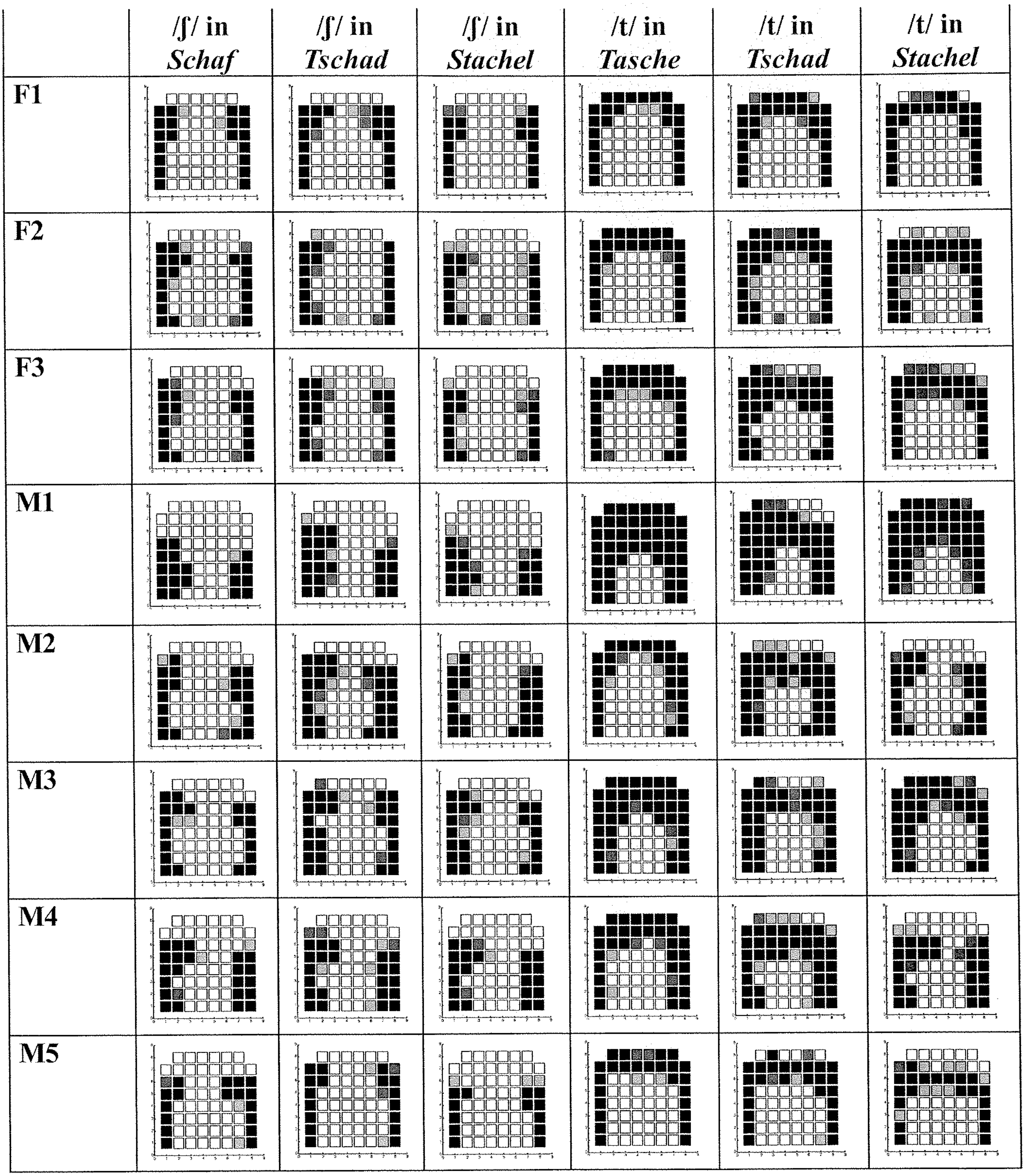

FIG. 9. EPG contact frequency in all repetitions of each sound for all speakers. White squares: Contact occurred in 0%–25% of productions. Light gray squares: Contact occurred in 26%–50% of productions. Dark gray squares: Contact occurred in 51%–75% of productions. Black squares: Contact occurred in 76%–100% of productions.

the single stop, possibly resulting from small supraglottal apertures throughout the course of the affricate combined with a longer duration of IOP buildup.

Some speaker differences were also evident in the relationships among EPG and IOP for these single-point measures. Examples of IOP and PC data from two speakers are shown in Fig. 10. For speaker F2 (left plot), PC was only slightly higher in the stop portion of the affricate than the cluster, whereas speaker M2 (right plot) had a much larger difference. Despite this difference in articulatory contact, both speakers had a similar, slight drop in IOP in the /t/ portion of the affricate compared to the cluster. Further, F2

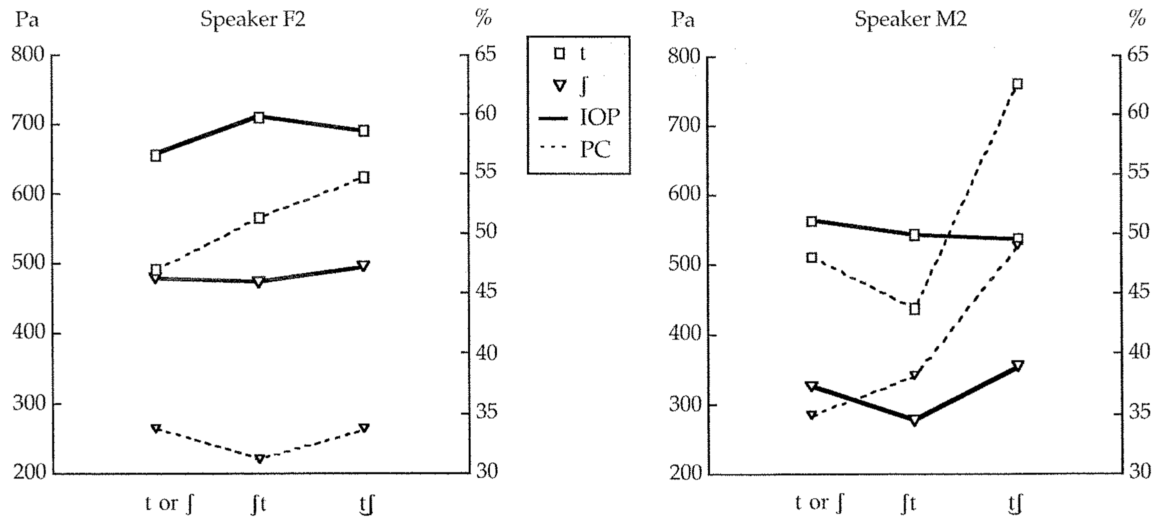

FIG. 10. IOP and PC data for single /t/ and /ʃ/ compared with the stop and fricative regions of the cluster and affricate, showing differences between two speakers.

had a slight drop in PC for the fricative portion of the cluster compared to single /ʃ/, with approximately equal IOP in the two contexts; in contrast, M2 had increased PC in the cluster but lower IOP values.

C. Differences between clusters and affricates in compression and coarticulation

Figure 11 shows the average durational data, dividing out the stop and fricative portions of the cluster and affricate for comparison with the single stop and fricative. Of interest here is how the occlusion and frication phases of the affricate and cluster compare with the single consonants, i.e., the extent to which there is a compression effect in the two types of consonantal sequences.

The ANOVA revealed all consonant effects to be significant. In the cluster, both the stop and the fricative regions were shorter than in the single consonants. In the affricate, the closure duration was about the same as for the single stop, whereas the fricative region was shorter than in the singleton. Thus, compression was observed for both segments in the cluster, but only for the fricative portion of the affricate.

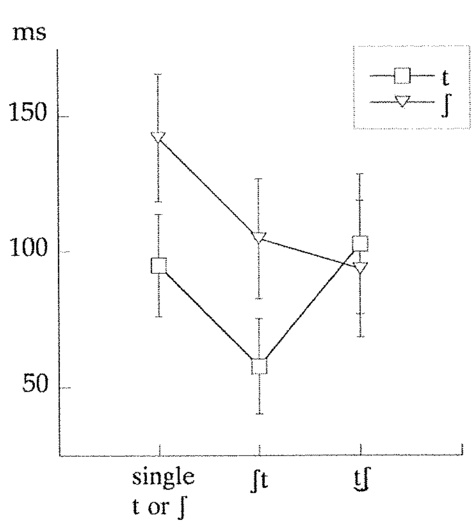

FIG. 11. Average acoustic durations for single /t/ and /ʃ/ compared with the stop and fricative regions of the cluster and affricate.

To assess the degree to which stop and fricative placement changed in the cluster and affricate compared to their single productions for each speaker, proportional changes in COG were obtained as described in Sec. II D 3. Positive values indicate COG proportions greater than 100%, or more anterior placement in the cluster/affricate than the singleton. Negative values indicate lower COG and more posterior placement. These individual speaker values supplement the average data shown above in Fig. 8, and speak to the question of whether the fricative and stop show similar degrees of coarticulatory influence (or resistance) in these consonant sequences.

The results, presented in Table IV, indicate that /t/ was 8%–11% more posterior when produced in combination with /ʃ/ than when produced alone. This retraction was a bit more extensive in the cluster than the affricate on average, but three of the eight speakers showed the reverse pattern (F3, M1, and M3). Compared to the single fricative, /ʃ/ in the affricate was on average 6% more anterior, but 11% more

TABLE IV. Relative amount of coarticulation in articulatory place, measured as a percentage of COG. Negative values indicate more posterior places of articulation in the cluster or affricate as compared to the single stop or fricative.

Speaker	/ʃ/-/ʃt/ diff.	/ʃ/-/t͡ʃ/ diff.	/t/-/ʃt/ diff.	/t/-/t͡ʃ/ diff.
F1	−4	3	−4	0
F2	−9	3	−14	−8
F3	−10	6	−3	−8
M1	0	32	3	−9
M2	−6	9	−24	−15
M3	−5	8	−1	−7
M4	−1	9	−28	−10
M5	−15	15	−15	−6
Mean	−6	11	−11	−8

posterior in the cluster. Although /ʃ/ demonstrated less coarticulatory change on average than /t/, the difference was very small, and not all speakers showed this pattern. For example, speaker M1 had much larger coarticulatory changes for the fricative than for the stop portion of /t͡ʃ/. Speaker-specific differences in placement of the single consonants may have contributed to some of this variability. For example, the three speakers who had the most posterior movement of /ʃ/ in the cluster (F2, F3, and M5) were among those who had the most anterior articulation of the single fricative (COG values 3.5–3.6, within the range of 2.19–4.11 for all eight speakers). Thus, these speakers may have retracted their /ʃ/ articulation so as to allow more tongue-tip movement toward the /t/.

IV. DISCUSSION

A. Influences on IOP changes

The first question in this study was the extent to which IOP variation could be predicted from articulatory contact patterns (PC, COG) and constriction duration. Results from the stepwise regression indicated that the EPG indices and overall consonant durations explained, on average, about 64% of the variance. These rather strong relationships were obtained despite the fact that the EPG indices used here provide fairly global information on articulation. For all speakers, changes in PC (i.e., PCdiff) accounted for most of the IOP variation in consonant sequences. Differences in place of articulation, as reflected by the COGdiff values, contributed little to IOP variation. The general pattern for PC and IOP was /ʃ/ < /ʃt/ < /t/, /t͡ʃ/. The differences between the single stop and fricative were in accord with the expectations laid out in the Introduction.

Considerable interspeaker variation was observed in the strength of these relationships, however. One way to quantify this variation is to consider the slopes for the simple correlations. As indicated in Sec. III A, slope values for PC ranged from 2.9 (speaker M1) to 7.0 (speaker F2). Given these slopes and the associated intercept values, a pressure change of 100 Pa corresponded to a PC difference of 35% for M1 vs 14% for F2. In terms of electrode activation, this reflects about 21 electrodes contacted for M1 vs about 9 for F2. There are at least two likely sources for this variation. One is the magnitude and, possibly, timing of glottal area changes for the voiceless consonant targets. More extreme changes in glottal opening could offset less extreme changes in oral constriction areas to yield a similar IOP increase across speakers. Another is individual variation in oral anatomy. Recent EPG studies have obtained high correlations between measures of palatal doming and percentage of articulatory contact (Brunner *et al.*, 2009; Fuchs and Toda, 2008). The combination of EPG and IOP data may ultimately help clarify how individual speakers achieve aerodynamic conditions in obstruents despite morphological variation.

B. Aerodynamics and articulatory contact in stops, fricatives, clusters, and affricates, with particular focus on affricates

The average IOP data showed that both stops and fricatives had the highest values when they were the last member of a consonant sequence, suggesting that duration contributes to the IOP value obtained in a cluster or affricate. Miller and Daniloff (1977), observing poorer correlations between duration and IOP in voiceless stops than in voiced ones, proposed that IOP rapidly reaches a ceiling level in the voiceless stops, reducing such correlations. In the current data, pressure typically rose quickly early in the stop, but it did not always quickly reach a plateau. Further, IOP could increase throughout most of the duration of an affricate for some speakers, and indeed reached a slightly higher peak, on average, in the affricate than in the plain stop. Subtelny *et al.* (1966) also found higher pressures in /t͡ʃ/ than in /t/ for English: 7.1 vs 6.8 cm H_2O, respectively. This corresponds to a difference of about 300 Pa, or 4% over the value for single /t/. This appears to be consistent with the 7% difference found here between /t͡ʃ/ and /t/. An extended plateau of IOP was observed during the affricate for some speakers; other speakers had a steadily rising pattern. Both of these indicate that pressure is not vented rapidly after the release of the occlusion phase. In a modeling study of affricates, Stevens (1993) obtained good fits with acoustic data using a relatively constant constriction area for about 50 ms following stop burst, combined with large glottal areas. Oral airflow data in that study also showed a rather gradual increase following affricate release. Again, the current data appear to be consistent with this past work. Stevens (1993) also noted that rates of constriction release may vary considerably across speakers, which would account for the varying IOP profiles seen across the eight speakers recorded here.

C. Compression and coarticulation: Clusters vs affricates

Several past studies have reported durational data for clusters and affricates. Since the degree of temporal compression in such sequences may vary as a function of the articulatory place of the consonants involved (Borden and Gay, 1979; Haggard, 1973; O'Shaughnessy, 1981), comparisons with the present results will be limited to alveolar stops combined with alveolar or postalveolar (sibilant) fricatives. The shortening of stops and fricatives seen here in clusters is consistent with most past work (Haggard, 1973; Hawkins, 1979; Klatt, 1974, 1976), although Crystal and House (1988) found compression of fricatives but not stops in clusters. Data on compression in the affricate has mostly been limited to measures of the stop portion, and findings here are conflicting. Some authors have observed compression of the occlusion phase (Byrd, 1993; Hoelterhoff and Reetz, 2007), but Liker *et al.* (2007) found, as in the current data, that stop regions did not shorten in affricates.

An assessment of the degree of coarticulatory place change as a proportion of the COG value for the singleton did not reveal clear differences between /t/ and /ʃ/ in the context of an affricate or cluster. Values for the fricative varied less on average than those of the stop, but the difference was very small and inconsistent across speakers. In the affricate, both the stop and the fricative portions showed coarticulatory effects. This contrasts with previous work that has observed retracted placement of /t/ in the affricate, but a fricative similar in place to single /ʃ/ (Dixit and Hoffman, 2004; Fletcher, 1989; Liker *et al.*, 2007). The data therefore did not support predictions of greater coarticulatory resistance (more stable placement) for /ʃ/ given its postalveolar place of articulation and the necessity of a precisely shaped constriction for the fricative (Recasens, 1984, 1985; Recasens *et al.*, 1993, 1997). Such differences across studies may arise from variation in measurement methods or possibly from cross-linguistic differences in coarticulatory behavior (Recasens and Espinosa, 2007). Another possibility is that some speakers may increase lip rounding to achieve frequencies appropriate for /ʃ/ in the context of a somewhat fronted articulation. That is, speakers may accomplish some aspects of the acoustic characteristics of /ʃ/ using articulators other than the tongue. Finally, recent work suggests that /t/ is subject to some restrictions on coarticulation as well; Mooshammer *et al.* (2006) argued that apical stops had to maintain an anterior place of articulation in order to ensure appropriately high frequencies in the release burst. Thus, a variety of factors may come into play in determining coarticulatory behavior in addition to coarticulatory resistance: speaker-specific differences in anatomy and speech sound production, language-specific characteristics, the extent to which motor equivalence yields multiple possibilities for achieving a sound's characteristic acoustics, and biomechanical constraints on articulatory activities for sequential sound production.

The phonological distinction between affricates and clusters, namely, a difference between one segment and two, could suggest that compression and/or coarticulation should be more extreme in the affricate than the cluster. The current data do not show either of these effects. The affricate was usually durationally longer than the cluster, so temporal compression was not more extensive. It was the case that the affricate showed coarticulatory effects for both the stop and the fricative regions, whereas only the stop portion of the cluster showed a place change relative to the singleton. One might argue that finding coarticulatory processes for both stop and fricative portions of the affricate provides some support for greater phonological unity in the affricate. More likely, however, is that the lack of coarticulation seen for the /ʃ/ portion of the cluster simply reflects biomechanical constraints on articulating an apical stop when the body of the tongue is elevated for a postalveolar fricative.

D. Conclusions

There have essentially been no previous studies comparing IOP and EPG in obstruents; thus this work was somewhat exploratory. The results indicate that much of the variance in overall IOP change in an obstruent sequence can be predicted simply from consideration of changes in articulatory contact, with little influence of articulatory place, at least for the small consonant set investigated here. Both EPG and IOP data showed that stop and fricative regions in clusters and affricates differed from singleton productions in ways that reflected coarticulatory behavior as well as durational effects and biomechanical effects. The data did not support expectations of greater coarticulatory resistance in /ʃ/ vs /t/, or greater cohesion within an affricate than a cluster. These data will provide baseline information for considering more complex consonantal strings in the full corpus, and provide input to future modeling of low-frequency consonantal aerodynamics in running speech.

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[1]For Italian and Catalan, Recasens and colleagues use the term alveopalatal to characterize /ɲ/ and /ʎ/ as well as /ʃ/. The fricative /ʃ/ and affricate /t͡ʃ/ in German are traditionally characterized as postalveolar (Pompino-Marschall, 2003). The main point in the present context is that /ʃ/, having more posterior articulation, involves the tongue body to a greater extent than /t/.

[2]The PCQUIRER program automatically adjusts sampling rates depending on the frequency range chosen for analysis. What is important for present purposes is that the pressure data were sampled at a rate much higher than the low-frequency variations of interest.

[3]In the aov function, data from all repetitions are included, rather than entering means for each subject. The repetition error term accounts for the repeated measures within speaker. This option is not available in some other statistical packages such as SPSS.

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