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Caterina Petrone, Susanne Fuchs, and Laura L. Koenig

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Relations among subglottal pressure, breathing, and acoustic parameters of sentence-level prominence in German

Caterina Petrone
Aix-Marseille Université, CNRS, Laboratoire Parole et Langage (LPL), Aix-en-Provence, France

Susanne Fuchs
Leibniz Centre General Linguistics (ZAS), Berlin, Germany

Laura L. Koenig[a)]
Haskins Laboratories, New Haven, Connecticut 06511, USA

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This study investigates whether acoustic correlates of prominence are related to actions of the respiratory system resulting in local changes of subglottal pressure (Psub). Simultaneous recordings were made of acoustics; intraoral pressure (Pio), as an estimate of Psub; and thoracic and abdominal volume changes. Ten German speakers read sentences containing a verb ending with /t/ followed by a noun starting with /t/. These /t#t/ sequences were typically realized as one /t:/ with a long intraoral pressure plateau. Sentence-level prominence was manipulated by shifting the position of contrastive focus within the sentences. The slope and peak values of Pio within the /t#t/ sequence were used to estimate differences in Psub across focus positions. Results show that prominence production is related to changes in the slope and maximum value of the pressure plateau. While pressure increases led to higher intensity, the increases did not relate to f0, hence, suggesting that local f0 changes primarily reflect laryngeal activity. Finally, strong individual differences were observed in the respiratory data. These findings confirm past reports of local Psub increases corresponding to sentence-level prominence. Speaker-specific activations of the respiratory system are interpreted in terms of motor equivalence, with laryngeal mechanisms also appearing to contribute to Psub changes. © *2017 Acoustical Society of America*. [http://dx.doi.org/10.1121/1.4976073]

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I. INTRODUCTION

In this paper we investigate the physiological mechanisms behind the production of prosodic prominence at the sentence level. Specifically, we test the hypothesis that acoustic correlates of prominence (as induced by focus variations) are primarily related to actions of the respiratory system leading to local changes of subglottal pressure. "Prominence" is a phonological notion, which relates to the metrical alternation of "strong" (more prominent) and "weak" (less prominent) elements within a prosodic unit. Prominence is also hierarchical: e.g., at the lexical level, word stress specifies which syllable in a word is the strongest one; at the sentence level, only stressed syllables are potential docking sites for phrase-level prosodic prominence and pitch accents. A factor affecting prosodic variation at the sentence level is focus. In German, the language under investigation here, words under focus are generally produced with a pitch accent associated with the stressed syllable, which is defined as the most prominent element in the sentence (cf. Grice *et al.*, 2005). Shifts in focus position bring about a different placement of the pitch accents within the sentence.

Phonetically, prominence in German is signaled by multiple parameters, such as fundamental frequency (f0), intensity, segmental duration, voice quality and spatiotemporal extent of articulatory movements (e.g., Féry, 1993; Niebuhr, 2008; Mooshammer, 2010; Mücke and Grice, 2014). Sentence-level prominence is primarily signaled by local and rapid f0 changes (i.e., pitch accents) on the stressed syllables. Local increases in the duration and intensity further contribute to enhancing prominence (cf. Kügler and Gollrad, 2015 and references therein). In this paper, we are particularly interested in f0 and intensity, and their relationship with breathing. Cross-linguistically, f0 and intensity have been found to co-vary in many typologically different languages such as English (e.g., Fry, 1955), French (Alain, 1993), and Swedish (Fant *et al.*, 2000). A likely explanation is that intensity and f0 have shared physiological sources (e.g., Ladefoged, 1967). As reviewed in Secs. I A and I B, it is well established that respiration contributes to intensity and in some cases to f0 variations, especially in long temporal windows (at the utterance level). The question remains, however, whether respiratory maneuvers might also play a role in generating intensity and frequency variations in short temporal windows (at the level of prominent syllables). The latter idea has a very long history, but the experimental evidence is sparse and controversial.

[a)]Also at: Adelphi University, Garden City, NY 11530, USA.

A. Relations among breathing, subglottal pressure, intensity, and f0 in long temporal windows

1. Intensity

Variations in lung volume primarily occur over long temporal intervals (Ohala, 1990). One breathing cycle in speech production is on average approximately 4 s (Rochet-Cappelan and Fuchs, 2013). In parallel, during "neutral" (in contrast to emotive) speech, subglottal pressure mainly shows long-term, gradual changes (Leanderson *et al.*, 1986) and it is highly correlated with sound pressure level, i.e., intensity. For example, Björklund and Sundberg (2016) measured subglottal pressure indirectly via intraoral pressure in 31 participants repeating the syllable [pæ] over a long time frame with increasing and decreasing loudness, but keeping f0 constant. Across speakers, the average correlation coefficient between subglottal pressure and intensity was 0.83. These results are similar to those of Lecuit and Demolin (1998), who investigated subglottal pressure directly via tracheal puncture while two speakers produced sustained vowels with different intensities. The results displayed a strong linear relationship between intensity and the logarithm of subglottal pressure, independent of variations in f0. (Studies of singing provide additional evidence for this relationship such as Herbst *et al.*, 2015; however, since speech and singing may have some differences in their underlying physiological control, our focus here will be on studies of speech.) In general, the results are coherent and reveal a tight relationship between intensity and subglottal pressure (Draper *et al.*, 1959; Ladefoged and McKinney, 1963; see also a historical review in Ohala, 1990).

Modulation of laryngeal resistance, assessed via the amount of air flow passing the vocal folds for a given subglottal pressure level, may also contribute to intensity variations (e.g., Finnegan *et al.*, 2000; Holmberg *et al.*, 1988). Variation in laryngeal resistance is usually associated in large measure with the thyroarytenoid muscle, which forms the muscular body of the vocal folds (cf. Finnegan *et al.*, 2000). The magnitude of resistance effects may vary with f0 (e.g., Hirano *et al.*, 1969; Lecuit and Demolin, 1998). In a recent paper, Zhang (2016) used a computational model of the pressure-volume-flow relationship. His results show convincingly that for durations typical of normal speech (breath groups c. 4 s long) air flow conservation is required. This can in principle be done by means of increasing glottal resistance when approaching the end of the breath group or using a larger inhalation at the beginning of the breath group.

2. f0

The relation between subglottal pressure and f0 is less clear. According to the myoelastic aerodynamic theory, an increase in subglottal pressure will give rise to some degree of f0 increase via increased vocal-fold distension and the Bernoulli effect (van den Berg, 1958). Lieberman (1967) drew on this relationship to explain the gradual decrease of f0 over the course of an utterance in a long temporal window, called f0 declination. In particular, Lieberman (1967) found a correlation between f0 declination and subglottal pressure in three English speaking subjects, and proposed that f0 declination is a passive result of the subglottal pressure decrease. In contrast, several subsequent authors argue that declination and other f0 changes in speech involve more complex mechanisms; specifically, it appears that subglottal pressure changes are not sufficient to account for the magnitude of f0 changes observed under various prosodic conditions. For example, Titze (1989) estimated this relationship (RFP, i.e., the rate of f0 change relative to the subglottal pressure change) to be on the order of 2–6 Hz/cm H_2O. Other studies have similarly concluded that f0 changes only slightly with differences in subglottal pressure (e.g., Gelfer *et al.*, 1983; Collier, 1987; cf. also Fuchs *et al.*, 2015). This implies that although subglottal pressure and f0 have a weak physiological relationship, f0 changes are primarily controlled by laryngeal muscle activity rather than via the respiratory system. For f0 increases, the cricothyroid muscle, which stretches the vocal folds and increases longitudinal tension, is usually thought to be the main contributor. Even so, Maeda (1976) noted rather wide variation in the estimated RFP across studies, and Strik and Boves (1995) pointed out that measures of f0 decrease over the course of an utterance depended strongly on the methods used to estimate those changes. Thus, the magnitude of the relationship between f0 and subglottal pressure remains a matter of some debate.

B. Relations among breathing, subglottal pressure, intensity, and f0 in short temporal windows

The idea that respiratory maneuvers might play a role in prosodic variations even within short temporal windows is very old, but solid empirical support from numerous subjects is lacking. Jespersen (1913) was one early work attributing stress variation to subglottal pressure. He defined four levels of expiratory pressure (114ff.) for syllables, with four being the heaviest syllable to one being the weakest, and zero with no expiratory pressure. In addition to respiration, Jespersen took glottal resistance into account as a further mechanism to produce accent, and suggested that accented syllables involve increased effort in all muscles. Stetson (1951) also considered respiratory contributions to short-term aspects of speech production, namely, syllables. His "chest-pulse theory" proposed that the muscles between the ribs (intercostals) produced rapid movements at the syllable level that "are like ripples on the wave of the expiratory movement of the breath group" (Stetson, 1951: p. 2).

A series of studies carried out by Ladefoged and colleagues (Ladefoged and Loeb, 2002 and references therein) failed to confirm the "chest pulses" proposed by Stetson for syllables in general. These authors did, however, propose that local intensity increases in lexically stressed syllables can be induced by short-term variation in the activity of the respiratory muscles (especially the internal intercostalis muscles.) They found peaks of subglottal pressure and local activity in the internal intercostal muscles immediately before each lexically stressed syllable for three speakers. Finnegan *et al.* (2000) confirm the general conclusion that the respiratory system is capable of generating rapid pressure changes. On the other hand, Ohala (1990), in a review of his own data, indicated that he had observed local pressure peaks only during "emphatically" stressed syllables, suggesting that the degree or level of prominence may be a relevant consideration.

In an investigation of sentence-level prominence, Gelfer *et al*. (1983) used recordings of respiratory volumes, subglottal pressure via tracheal puncture, and electromyography of the cricothyroid muscle in one speaker. Their results suggested a primary role for local increases in cricothyroid activity in prominence production. Subglottal pressure changes spanned longer temporal windows than the f0 variations (see also Collier, 1987). In contrast, in another single-speaker study, Fant *et al*. (1996) reported an increase of subglottal pressure in short temporal windows (accented syllables), measured by tracheal puncture. However, they noted that the pressure changes seemed to be more closely related in time to intensity than to f0 changes. In a similar vein, Finnegan *et al*. (2000) employed tracheal puncture and electromyographic recordings of the thyroarytenoid muscle to study mechanisms of prominence variation in six English speakers. They found that sentence-level prominence was associated both with changes in respiratory driving pressure and laryngeal airway resistance, but respiratory driving pressure played the largest role. The results of this study are stronger than the previous ones in that more speakers were involved; on the other hand the authors did not evaluate f0 or cricothyroid activity, limiting the degree to which the data speak to physiological control of prominence.

A methodological challenge in all of this work lies in separating laryngeal and respiratory effects on sentence level prominence. Short-term variations in subglottal pressure (or "ripples," following Stetson, 1951) could arise from laryngeal sources as well as respiratory ones. For example, glottal opening behind a closed vocal tract may lead to a small drop in subglottal pressure, because the oral cavity is added to the lower airways as an additional volume. Furthermore, when the glottis is open and the vocal tract released, rapid venting of air through the mouth can yield a transient drop in subglottal pressure. Thus, careful consideration of the speech material is needed to tease apart different effects and derive valid conclusions.

One way of separating laryngeal and respiratory contributions would be simultaneous recordings of subglottal pressure along with laryngeal muscle activity using electromyography (EMG). EMG studies are increasingly rare given their invasive nature. Historical methods of assessing the contributions of subglottal pressure to intensity and f0 variation were likewise invasive for both direct (tracheal puncture, e.g., Finnegan *et al*., 2000; catheter with pressure transducer, cf. Lecuit and Demolin, 1998) and indirect (oesophageal balloon, Draper *et al*., 1959; Slifka, 2000) measurements of subglottal pressure. In recent decades the most typical method has been to derive subglottal pressure from intraoral pressure during stop consonants (Löfqvist *et al*., 1982; Hertegård *et al*., 1995; Demolin *et al*., 1997; Björklund and Sundberg, 2016). Our study follows this method, using intraoral pressure as an indirect estimate of subglottal pressure (see details below), combined with non-invasively obtained data on thoracic and abdominal movements.

C. Speaker-specific behavior

Several authors have reported speaker differences in prosodic control. For example, Adams and Munro (1973) reported that one of their four speakers—who happened to be a trained singer and public speaker—used longer periods of internal intercostal activity over the course of his utterances than the others. Leanderson *et al*. (1987) reported that a few speakers maintained active diaphragmatic contraction during phonation, and among those speakers the muscle activation patterns varied as a function of pitch level. Maeda's (1976) two speakers differed in their use of laryngeal contributions to focus (specifically, activation of the adductory lateral cricoarytenoid muscle).

Ladefoged and Loeb (2002) point out in their conclusion that a variety of neuromotor combinations can be used to control subglottal pressure. The same holds true for intensity and fundamental frequency. Differing results across past studies lend support to this notion. Given the possibility of motor equivalence, i.e., varying underlying actions leading to equivalent output, we may also expect speaker-specific behavior in the underlying mechanisms that lead to differences in subglottal pressure or in the relation between respiratory maneuvers and acoustic output. Together, the possibility of speaker-specific behavior, combined with the cross-study variation evident in the results reviewed above, underscore the need for continued study of breathing control for speech, using methods that facilitate the use of multiple speakers and extensive datasets.

D. Goals and hypotheses

The goal of this paper is to use minimally invasive methods to quantify the relationships among respiratory system activity, inferred subglottal pressure, and acoustic parameters of sentence-level prominence in several speakers and in a language not yet studied via such methods (German).

Based on previous literature on German, we expect stressed syllables carrying sentence-level prominence (as a result of focus) to be acoustically marked by higher f0, higher intensity, and longer duration. If subglottal pressure (Psub) is locally controlled, sentence-level prominence will be accompanied by changes in subglottal pressure. Psub will be inferred from intraoral pressure measured during the oral closure plateau in stop consonants. We expect stops to be realized with an intraoral pressure plateau whose attributes will change depending on the position of focus relative to the surrounding vowel. If focus affects the vowel at the right side of the stop consonant, we expect subglottal pressure to rise from the consonant to the second vowel and yield a slightly rising pressure slope. If focus affects the vowel at the left side of the stop consonant, we expect a higher pressure on the first vowel and a decrease in subglottal pressure from the vowel towards the consonant, thus a negative pressure slope. Moreover, both left focus and right focus conditions should show higher maximum intraoral pressure levels as compared to no focus.

If the respiratory system is involved in generating local subglottal variations, the slope of the rib cage movement should be steeper under focus compared to the no focus condition as a mechanism to increase subglottal pressure during focus production. We have no particular predictions for the abdominal volume changes. On the one hand they could work independently of the rib cage, but on the other hand, coordinated activity between the two has been reported by Ladefoged and Loeb (2002) (but see Hixon and Weismer, 1995). Concerning the relationship among parameters, local increases in subglottal pressure should lead acoustically to a higher intensity. F0 and intensity might be correlated weakly via automatic laryngeal mechanisms (van den Berg, 1958) or more strongly in the sense that both are cues for focus. If local subglottal pressure changes are related to respiratory kinematics, a correlation is expected between subglottal pressure values and respiratory slopes. Finally, if thoracic and abdominal actions are interdependent, the respective slopes will correlate either positively (for coordinated activity) or negatively (for a trading-off relationship).

II. METHODOLOGY

A. Corpus and participants

The speech material consisted of five sets of German sentences containing a sequence of two target words, viz., a monosyllabic verb ending with /t/ followed by a bisyllabic noun starting with /t/ (phonetically [t^h]). The noun was lexically stressed on the initial syllable, such as "**T**anja" in the sentence "Er mal**t** **T**anja, aber nicht Sonja" (*He paints Tanja, but not Sonja*). The target word sets were "mal**t** **T**anja" (*paints Tanja*); "ha**t** **T**assen" (*has cups*); "kenn**t** **T**ine" (*knows Tine*); "nimm**t** **T**iegel" (*takes pans*); "sieh**t** **T**immy" (*sees Timmy*). The /t#t/ sequence was chosen since German speakers frequently realize it as one /t/, produced with a long closure duration (Fuchs *et al.*, 2007) which is comparable to the duration of a geminate. (In the current data, over 90% of productions showed this pattern.) Whereas a single /t/ closure may not be long enough for intraoral pressure to reach the level of subglottal pressure, especially in rapid or connected speech, the /t#t/ production typically yields a long intraoral pressure plateau that allows us to infer Psub indirectly, as well as its change over time (see Sec. II C).

An elicitation procedure was designed to obtain variation in focus position naturalistically using a question–answer paradigm. A native speaker of German (author S.F.) read a question intended to trigger a contrastive interpretation in the participant's answer. For example, if the utterance "*Er nimmt Tiegel, aber wäscht sie nicht*" (He takes cups, but he does not wash them) was prompted with the question "Wäscht er Tiegel?" (Does he wash cups?), the participant would be led to emphasize the verb "nimmt" in the response (He *takes* cups, but does not wash them). Three focus conditions were created: (1) focus on the leftmost word in the target sequence (e.g., the verb "nimmt," "left focus" condition, **lf**); (2) focus on the rightmost word in the target sequence (e.g., the noun "Tiegel," "right focus" condition, **rf**); and (3) and no focus on the first or second target word ("no focus" condition, **nf**), but on the preceding personal pronoun ("Er"). We expected a rising pitch accent to be realized on the stressed syllable of the focussed word (e.g., the first syllable of "Tiegel"), which is typical of contrastive focus in German (Mücke and Grice, 2014). The no focus condition served as a baseline, since early focus triggers post-focus deaccentuation in both target words (e.g., Baumann, 2006).

Ten speakers were recorded: seven women and three men. They were between 22 and 36 yr of age and had normal body mass index (between 19 and 25), and vital capacities within normal limits. No participants reported any history of breathing or speech difficulties, and all spoke a Northern variety of German. The speakers repeated the sentences four times in a randomized order leading to 600 sentences (5 targets $\times$ 3 focus conditions $\times$ 4 repetitions $\times$ 10 speakers). After the recording session participants were asked to do vital capacity manoeuvers (maximum inhalation followed by maximum exhalation) 3–4 times with pauses in between. The maximum of the set was taken as the participant's vital capacity.

B. Data recording and pre-processing

Speakers sat in front of a music stand and read from a printed page where the words in focus were marked in bold. They were asked to read without moving their arms and legs to avoid distortions of the breathing signal. A super cardio condenser microphone (Sennheiser HKH50 P48) was positioned about 30 cm from the mouth. The recording took approximately 15–20 min. Acoustic, aerodynamic and breathing data were simultaneously recorded to a multichannel data recording system with a sampling frequency of 11025 Hz and imported into Matlab.

Intraoral pressure (Pio) data were obtained using a pressure transducer (Endevco 8507C-2) which was glued onto the posterior end of the hard palate. This position placed the transducer posterior to the alveolar closures in the target words. The pressure signal was calibrated after each recording session using a water manometer. Pio data were smoothed using a zero-delay low-pass filter (*filtfilt* function in Matlab) with 40 Hz passband and 100 Hz stopband edges, and a 50 dB damping factor. This processing eliminated glottal pulses as well as effects of low-frequency electrical interference. From the smoothed Pio signal, the first derivative (velocity) was calculated.

Respiratory movements (measured in volts) were obtained via inductance plethysmography, using two elastic bands, one around the rib-cage and one around the abdomen, to register volume changes via changes in the electrical resistance of small wires located in the bands. Respiratory data were downsampled by a factor of 10 and filtered using a sixth-order Butterworth filter. The vital capacity (VC) manoeuvres provided a measure of each speaker's maximal compression and expansion of the rib cage as well as of the abdomen, and allowed us to measure the rib cage and abdomen slope in %VCs.

C. Labelling and measurements

Figure 1 illustrates the labelling in the acoustic, intraoral pressure and thoracic data. In the acoustic signals, we

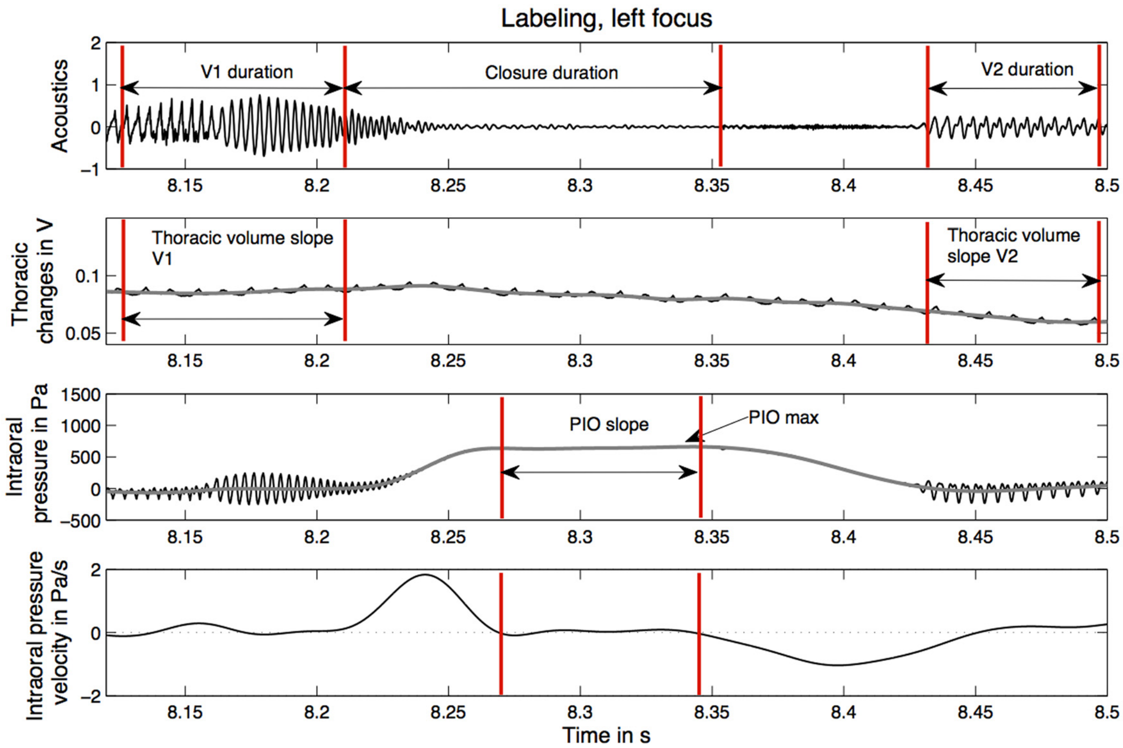

FIG. 1. (Color online) Example for labeling acoustic, respiratory, and intraoral parameters for the target phrase "*Er nimmt Tiegel*" from the sentence "*Er nimmt Tiegel, aber wäscht sie nicht*" ("He takes cups, but does not wash them"). The phrase is produced with a left focus on the verb "*nimmt*" ("takes"). First track acoustic signal, second track thoracic volume changes, third and fourth tracks intraoral pressure, and intraoral pressure velocity. Black lines are raw data, while grey lines superimposed on thoracic and intraoral pressure data represent filtered data. Vertical lines (red) and horizontal arrows are interval boundaries. Pressure maximum (Pio_max) is indicated by an arrow.

labelled the onsets and offsets of the vowels preceding (V1) and following (V2) the /t#t/. In three cases (*malt*, *kennt*, *nimmt*), the vowel V1 was not immediately adjacent to the /t/ because of the presence of an intervening sonorant consonant, which was included in the measurement of the vowel portion. V2 always followed the /t/. Intensity effects were measured as the difference in mean intensity between the vowel following and preceding the /t#t/ (**Int_diff**). This relative intensity measurement minimized effects of slow changes in mouth-to-microphone distance over the course of the recording session. (As indicated above, speakers were sitting and explicitly asked to avoid major bodily movements during the recording to limit noise in the respitrace signal.) Analogously, relative measurements were taken for f0 and duration. For f0, we calculated the mean difference between V2 and V1 (**f0_diff**); the presence of a pitch accent in the focused word should be reflected in a higher f0 in the vowel compared to the unfocused one. For duration, we extracted the mean difference between V2 and V1 (**Dur_diff**), as we expected the vowel in the focused word to undergo lengthening compared to that of the unfocused word. Finally, the closure duration (**Clos_dur**) was calculated as the difference between the onset of the consonantal burst and the end of the preceding vowel.

In the Pio data, we searched automatically for the pressure maximum (**Pio_max**) in the acoustically defined consonant closure. We also labelled the onset and offset of the pressure plateau in the /t#t/ using zero crossings in the velocity signal, and measured the intraoral pressure slope (**Pio_slope**) between these time points (calculated as the difference in Pascals between the onset and offset divided by the duration of the plateau). The Pio slope measure used here follows past work comparing intraoral and subglottal pressure and is based on the assumption that Pio quickly rises to the level of Psub when the vocal tract is completely closed and the glottis is open as in voiceless aspirated stops. Data comparing Pio with directly obtained subglottal or tracheal pressure shows a strong correlation between the two values, at least for driving pressures typical of speech (see Löfqvist *et al.*, 1982; Kitajima and Fujita, 1990; Hertegård *et al.*, 1995). In sequences of repeated equally stressed syllables, Pio contours show a rather flat plateau, and authors use this value to infer the (stable) Psub. However, Pio may also change during a voiceless stop closure interval if Psub is changing (Löfqvist *et al.*, 1982; Hertegård *et al.*, 1995). In this study we drew on that observation to use the slope of Pio as an indication of changing Psub depending on the focus position. Some examples from the data are shown in Fig. 2. Data were excluded (7.7% of the database) when no clear plateau phase could be defined since speakers either realized two /t/s or they spirantized the stop.

Concerning the respiratory contributions to focus, after visual inspections of the data (Fig. 3), we decided to focus only on the first and second vowel and exclude the consonant portion. This is because we found a small, but very consistent drop in the thoracic movements occurring at the release burst. We interpreted the drop at the release burst as an automatic consequence of the increased airflow which coincides with maximal glottal aperture at the oral release (cf. Ohala, 1990 for similar observations) and wanted to eliminate the

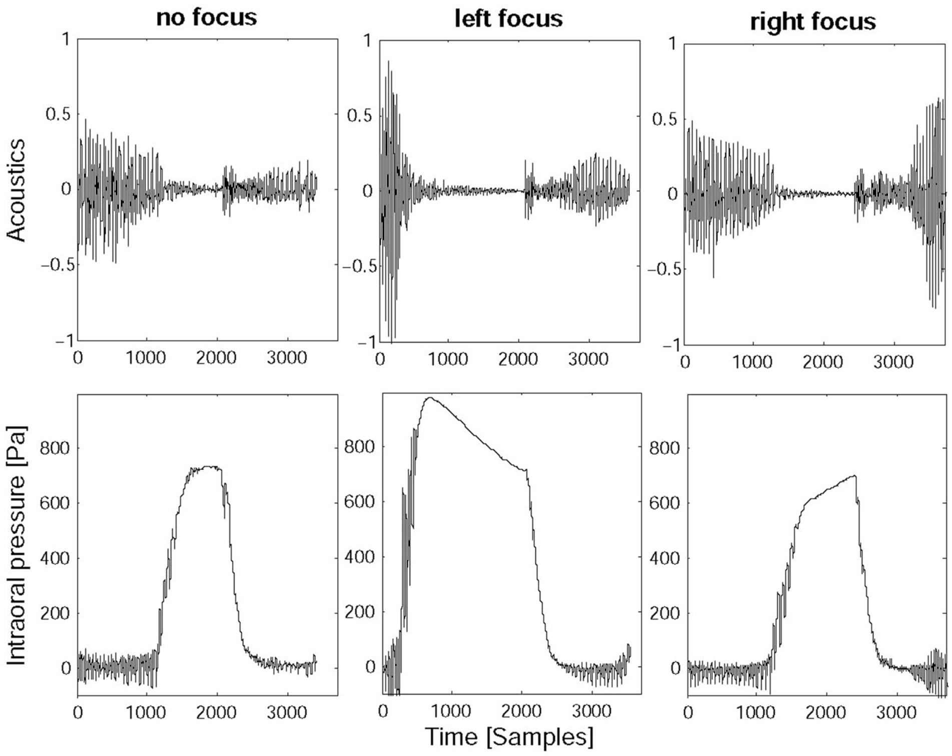

FIG. 2. Examples of tokens for the no focus, left focus and right focus conditions. Top panels: Acoustics. Bottom panels: Intraoral pressure. In these examples the slope of the pressure plateau during the oral stop appears different across the focus conditions (flat in nf, falling in lf and rising in rf).

impact of glottal opening on the respiratory signals. That is, in the vowels it is reasonable to assume a closed glottis, whereas during the consonantal region we expect an abduction whose precise timing may vary across tokens and which may additionally perturb Pio data for reasons unrelated to respiratory actions.

Thus, to factor out such potential laryngeal effects, we measured thoracic and abdominal slope values between the on- and offset of V1 and V2 (in %VC) divided by V1 or V2 duration (in s), respectively. Analogously to the other measures we calculated the differences in slope of the respiratory signals between the first and the second vowel (**Thor_diff, Abd_diff**). For example, for focus on the left, we would expect a steeper slope for V1 (greater degree of thoracic compression) than V2 and consequently a negative value (V2 thoracic slope–V1 thoracic slope) of Thor_diff. For focus on the right vowel, we would expect a steeper slope for V2 and henceforth a positive Thor_diff.

D. Statistics

Linear mixed models were run with the statistical software R (R Development Core Team, 2016, version 3.3.0). For each model, the dependent variables were (a) acoustics: Dur_diff, Clos_dur, Int_diff and f0_diff; (b) intraoral pressure: Pio_slope, Pio_max; (c) breathing: Thor_diff, Abd_diff. The pressure maximum was logarithmically transformed to achieve a normal distribution. The factor Focus (nf/lf/rf) was included as a fixed effect, with the condition "no focus" as the reference level. For f0_diff, sex was additionally included as a fixed factor to account for f0 differences across male and female speakers.

To study the relationships among acoustics (f0_diff, Int_diff) and aerodynamics (Pio_slope, Pio_max), four covariance models were run with f0 differences (f0_diff) depending on intensity differences (Int_diff), focus and sex; f0_diff depending on Pio_slope, focus and sex; intensity differences depending on Pio_slope and focus; and intensity differences depending on Pio_max and focus. Pio_slope was separately correlated to thoracic and abdomen slopes. Finally, a covariance model was run to evaluate the relationship between thoracic and abdominal volume changes. We started the statistical analysis by fitting each model with all possible random effect components included (Barr *et al.*, 2013). Since the full models showed some over-parameterization (e.g., when the variance explained by a specific factor is close to zero), backward elimination based on likelihood-ratio tests was used to decide which components should be retained in the models (Pinheiro and Bates, 2000). Likelihood-ratio tests were run comparing full models (e.g., which contained a random component) with simpler ones (e.g., without that component). As for *p*-values, the standard functions in R to calculate linear mixed models do not provide them when the dependent variables are continuous (e.g., duration differences between the target vowels). Hence, we employed bootstrapping methods with replacement from the original sample (number of samples = 500) to estimate *p*-values and 95% confidence intervals (CI) for each mixed model (package R *lme4*, function confint.merMod, Wald method). The cut-off point for significance was set at $p < 0.05$. Given that multiple parameters were collected from the same dataset and they might not be independent, p-values were adjusted through the "false discovery rate" correction (Benjamini and Yekutieli, 2001).

III. RESULTS

A. Acoustics

Speakers realized contrastive focus successfully. When focus was present, f0 differences became larger than in the

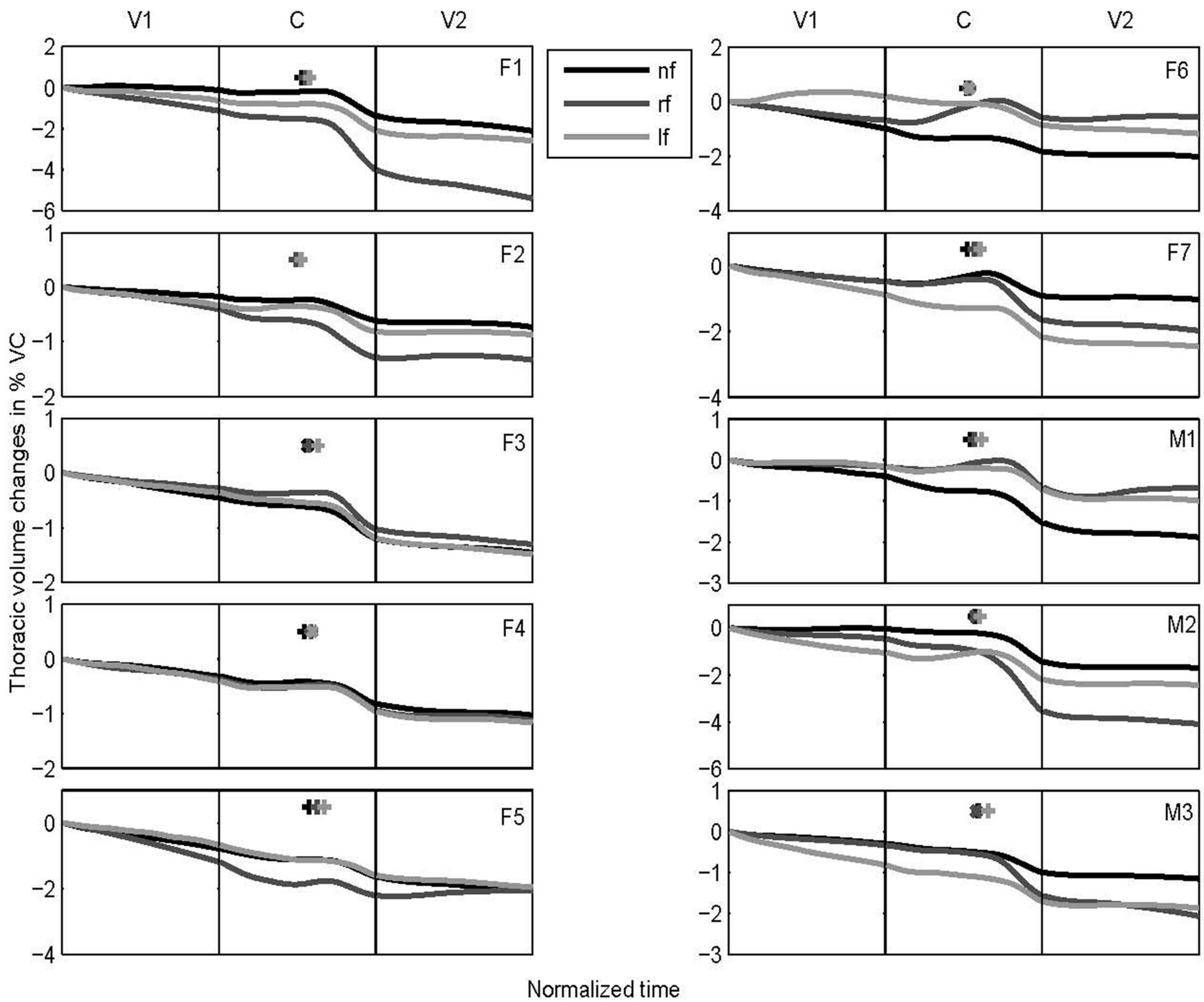

FIG. 3. Time normalized averaged thoracic volume changes for each speaker (F = female, M = male), vowel1-consonant-vowel2 sequence (V1-Cons-V2) and focus condition (in gray scale) in percent vital capacity. The consonant is always a /t/. "+" signs indicate the average burst location in each focus condition based on the acoustic measures. Time normalization was accomplished by obtaining 100 temporally equidistant data points for each target segment (V1, Cons, V2). All data were vertically aligned by subtracting out the first thoracic value in V1 so that all contours start with 0.

no focus condition (see Fig. 4). When focus was placed on the left, f0_diff was larger with respect to the reference level [$\beta = -40.58$, SE = 11.99, t = −3.38, p = 0.003, CI = −62.62; −15.36], with f0 values being higher in V1 (217.5 Hz) than in V2 (162.2 Hz). f0_diff was significantly larger in the right focus than in no focus condition [$\beta = 51.21$, SE = 12.08, t = 4.23, p = 0.003, CI = 26.17; 76.20], with f0 values being higher in V2 (225.9 Hz) than in V1 (164.9 Hz). Sex did not affect the f0 differences significantly and showed no interaction with focus. Figure 4 shows that the f0_diff patterns were consistent in nine out of 10 speakers. At first glance, speaker F1 does not seem to show the expected f0 patterns for focus. That is, for this speaker, Fig. 4 shows no difference between the target vowels in the

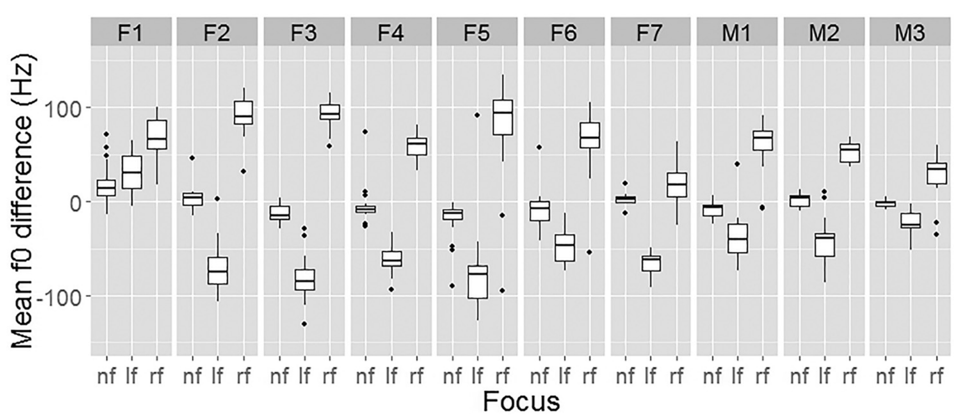

FIG. 4. Boxplots for mean f0 differences between V2 and V1 (y-axis) against the three focus conditions (x axis) and split by speakers (F = female, M = male). Values at zero indicate no difference between the two vowels. Positive values indicate that f0 is higher in V2 than in V1, negative values that it is higher in V1. Here and in all subsequent boxplots the median value is indicated as a horizontal bar, the boxes correspond to the 25th–75th percentile range, and the whiskers correspond to the ±1.5 interquartile range.

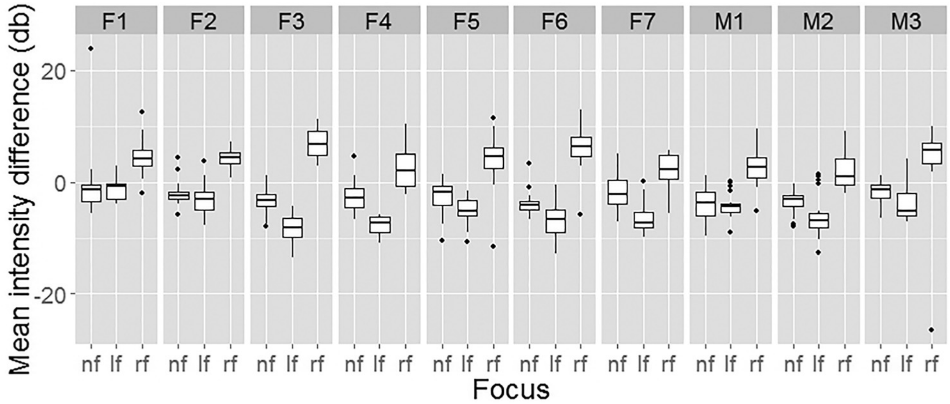

FIG. 5. Boxplots for mean intensity differences between V2 and V1 (y-axis) against the three focus conditions (x axis) and split by speakers (F = female, M = male). Values at zero indicate no difference between the two vowels. Positive values indicate that intensity is higher in V2 than in V1, negative values that it is higher in V1.

lf condition. However, a closer inspection of the acoustic data revealed that F1 realized focus by means of f0, but with a different f0 contour than the other speakers. This is because the left focus was characterized by high f0 plateau spanning the first to the second target word (corresponding to a continuation contour), which resulted in the lack of f0 differences between V2 and V1 in this focus condition.

Intensity differences between V2 and V1 behaved similarly to f0. When focus was present, intensity differences became larger relative to the no focus condition (see Fig. 5). The direction of the effect depended on the focus position. In left focus, the first vowel had higher intensity (82.3 dB) than the second one (76.7 dB). Hence, the intensity difference between V2 and V1 was negative and the effect was significant compared to the no focus condition [$\beta = -2.22$, SE = 0.82, t = −2.69, p = 0.011, CI = −3.91; −0.70]. In right focus, Int_diff was positive, with higher values in the second vowel (81.6 dB) than in the first one (77.7 dB). The comparison between right focus and no focus was also significant [$\beta = 5.80$, SE = 0.81, t = 7.09, p = 0.003, CI = 4.01; 7.44]. Figure 5 shows that the effect of intensity is rather consistent across speakers. F1 and M1 do not use intensity to distinguish no focus and left focus. Given a possible co-variance between f0 and intensity, the different intensity pattern for F1 could be related to the different f0 pattern employed by this speaker.

As for vowel duration, we found a significant difference between V2 and V1 in left focus (V1 = 139 ms; V2 = 81.6 ms) compared to the no focus condition (V1 = 102.5 ms; V2 = 80.09 ms) [$\beta = -32.19$, SE = 14.49, t = −2.2, p = 0.05, CI = −59.27; −2.94]. This difference was consistent across speakers. The contrast between right focus and no focus condition was not significant, but graphical exploration reveals some speaker-specific variation for this contrast. Furthermore, closure duration was consistently longer under focus (nf = 86 ms; lf = 111 ms; rf = 99 ms) [for left focus: $\beta = 0.28$, SE = 0.02, t = 10.1, p = 0.003, CI = 0.22; 0.34; for right focus: $\beta = 0.15$, SE = 0.02, t = 5.57, p = 0.003, CI = 0.10; 0.20].

B. Subglottal pressure

Results for intraoral pressure slope (Pio_slope) within the closure portion of the /t#t/ provide consistent evidence of subglottal pressure changes in the different focus conditions. As shown in Fig. 6, both the no focus (mean slope = 0.07) and the right focus (mean slope = 0.14) conditions were characterized by a positive slope value. Hence, in those conditions, the intraoral pressure plateau was rising from the beginning to the end of the closure, with a larger change in the focused condition. The slope value in left focus was around zero or negative, indicating a flat or slightly falling plateau (mean slope = 0.004). Patterns of Pio_slope were consistent across speakers. The statistical analysis confirmed that the slope value in the no focus condition (the reference level in our model) was significantly different from zero [$\beta = 0.073$, SE = 0.018, t = 4.03, p = 0.003, CI = 0.037; 0.108]. The slope was significantly steeper in right than in no focus [$\beta = 0.068$, SE = 0.015, t = 4.49, p = 0.003, CI = 0.038; 0.094]. The slope in the left focus condition was significantly flatter compared

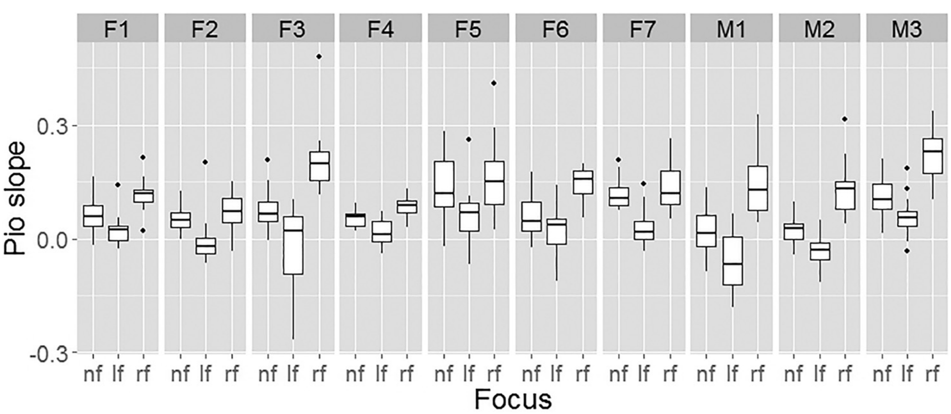

FIG. 6. Boxplots for the slope of the intraoral pressure plateau (y-axis) against the three focus conditions (x axis), split by speakers (F = female, M = male). Values at zero indicate that the plateau is flat. Positive values indicate that the Pio signal is rising, negative values that it is falling.

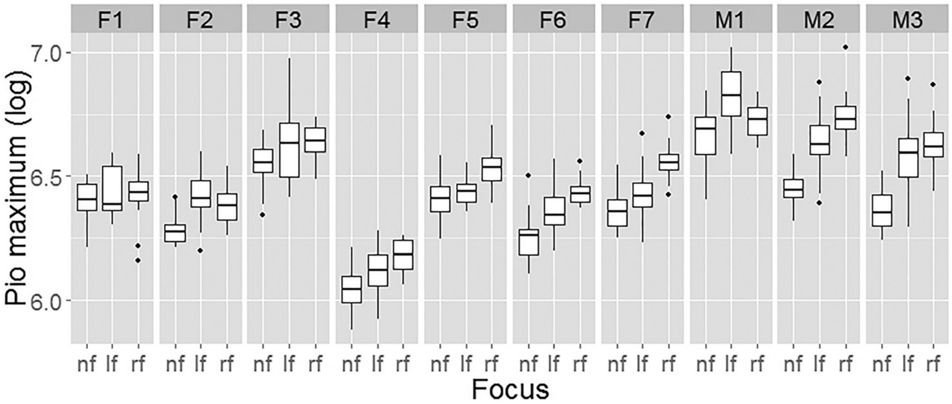

FIG. 7. Boxplots for the pressure maximum (log) of the intraoral pressure plateau (*y*-axis) against the three focus conditions (*x* axis), split by speakers (F = female, M = male).

to the no focus condition [$\beta = -0.067$, SE = 0.015, t = −4.4, p = 0.003, CI = −0.09; −0.03].

The involvement of Psub in focus production is also substantiated by the results from the pressure maximum (Pio_max) within the closure portion of the /t#t/ (Fig. 7). The Pio_max value was higher under focus than with no focus (nf = 595 Pa; lf = 681 Pa; rf = 694 Pa). Compared to the no focus condition, the (logarithmically transformed) pressure maximum was significantly higher both in the left focus [$\beta = 0.12$, SE = 0.02, t = 4.27, p = 0.003, CI = 0.07; 0.18] and in the right focus conditions [$\beta = 0.15$, SE = 0.02, t = 5.19, p = 0.003, CI = 0.09; 0.21]. Whereas the Pio_slope results were quite consistent across speakers, Fig. 7 shows some differences in Pio_max across speakers. In nine out of 10 speakers, Pio_max is higher under focus than in no focus. Five speakers (F4, F5, F6, F7, M2) have higher pressure maximum values in the right than in the left focus; F2 and M1 have the reverse pattern, with higher values in the left focus; and F3 and M3 have similar values for left and right focus. F1 is the only speaker who shows no differences at all across the three focus conditions.

C. Respiratory kinematics

The results for the respiratory kinematics are less clear than the results reported thus far. We found no effect of focus on the slope differences between V2 and V1, either for thoracic and abdominal volume changes. However, the kinematic data showed considerable speaker specific differences in volume changes. For instance, for the thorax (Fig. 8), three speakers showed an increase of thorax slope when focus was on the right (F4, F6, M2); four speakers displayed a decrease in thorax slope (F2, F3, F5, F7), and three speakers had no effect of focus at all (F1, M1, M3). Results for abdominal changes were comparable.

D. Relations among parameters

The V2–V1 differences in f0 and intensity were positively correlated with one another [$\beta = 1.3$, SE = 0.45, t = 2.93, p = 0.008, CI = 0.42; 2.19]. There was no interaction between intensity and focus. Intensity differences were also significantly correlated with Pio slope (Fig. 9, left) [$\beta = 9.52$, SE = 2.28, t = 4.17, p = 0.003, CI = 5.24; 13.98], whereas we found no correlation with Pio maximum. We did not find any significant relation between f0 differences and the Pio slope (Fig. 9, right). Pio slope was also independent of thoracic and abdominal volume changes. Finally, thoracic and abdominal slope differences were positively correlated across all focus conditions [$\beta = 1.31$, SE = 0.06, t = 20.00, p = 0.003, CI = 1.19; 1.44]. This is illustrated in Fig. 10.

IV. DISCUSSION AND CONCLUSION

The acoustic measurements confirmed the correct elicitation of contrastive focus, by which stressed syllables in the target words bear sentence-level prominence reflected in f0, intensity, and durational differences. In line with the literature (e.g., Kügler and Gollrad, 2015), f0 is the most robust acoustic cue of sentence-level prominence in German, in that changes due to focus were essentially consistent across speakers. At the aerodynamic level, focus production was related to different intraoral pressure slopes in the voiceless

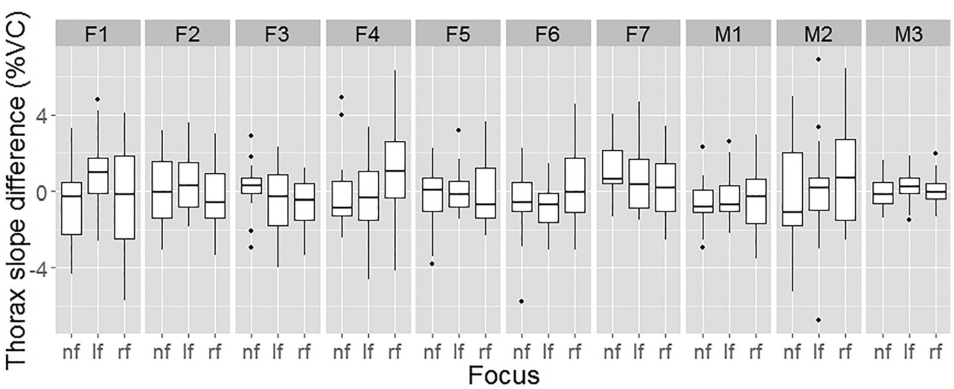

FIG. 8. Boxplots for the slope difference of rib cage movement in V2 and V1 (*y*-axis) against the three focus conditions (*x* axis), split by speakers (F = female, M = male). Values at zero indicate that there is no difference in slope between V2 and V1. Positive values indicate that the slope in V2 is steeper than in V1 and negative values that the slope in V1 is steeper than in V2.

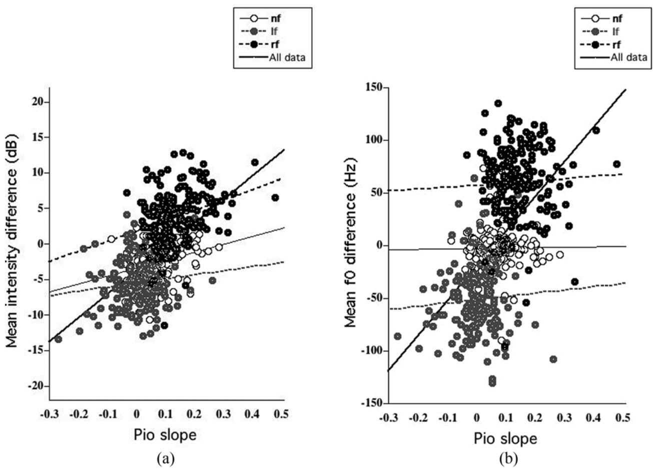

FIG. 9. Scatterplots with the mean differences (dots) in intensity (*y*-axis) and intraoral pressure slope (*x* axis) between the V2 and V1 (left); and with mean differences (dots) in f0 (*y*-axis) and intraoral pressure slope (*x* axis) between the V2 and V1 (right). Trendlines are superimposed. Different shades of gray and line types indicate different focus conditions. A trendline for all data (collapsing across focus conditions) was added.

alveolar stop. Furthermore, the maximum pressure value was higher in the focus conditions than in the no focus one. These indirect estimates of Psub confirm the relationship between sentence-level prominence and subglottal pressure suggested in the previous literature (e.g., Fant *et al.*, 1996; Finnegan *et al.*, 2000) and allow generalization across a higher number of speakers. While the peak of the intraoral pressure is correlated with the presence/absence of prominence, the pressure slope measurements suggest that the Psub reaches a maximum within the focused word and decays afterwards. Moreover, we found that different intraoral pressure slopes accompany differences in V2 and V1 intensity. This provides evidence that prominent syllables are produced with local increases of Psub and that the slope of the intraoral pressure contour is related to intensity differences between the two vowels surrounding the consonant.

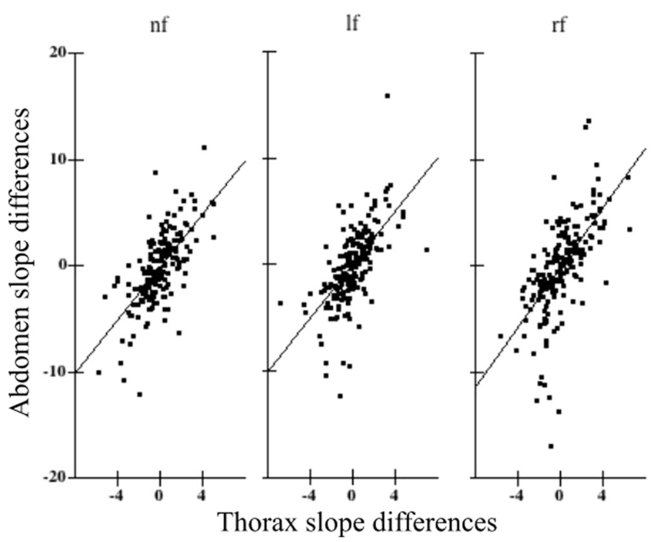

FIG. 10. Scatterplots with the mean differences (dots) in abdomen (*y*-axis) and thorax (*x* axis) slopes between V2 and V1 for the three focus conditions. Trendlines are superimposed.

Also, we found a positive correlation between intensity and f0 differences between V2 and V1. Given that prominent syllables carried a rising pitch accent, it is not surprising that higher f0 values are related to higher intensity. However, this finding cannot be generalized to other intonation contours, in which prominent syllables carry different pitch accents (e.g., low or falling accents). On the other hand, the lack of relationship between f0 and intraoral pressure speaks to their relative independence in the production of prominence and supports the view that local f0 changes are related to laryngeal mechanisms, such as changes in the activity of intrinsic laryngeal muscles (e.g., Hirano *et al.*, 1969; Ohala, 1990).

Concerning the respiratory data, we evaluated separately the respiratory signal from the thorax and the abdomen. The literature has suggested that muscles of the rib cage (internal intercostals) play a major role in prominence production (Ladefoged and Loeb, 2002), and we hypothesized that the thoracic signal might show reliable relationships with subglottal pressure and acoustic measures. By recording both thoracic and abdominal volume changes, but analyzing them separately, we were able to test both whether the thorax movements relate to local changes brought about by focus and whether speakers use the thorax and abdomen in a trading relation. While we found a positive relation between thorax and abdomen slopes (which speaks for a coordinated activity), there were no consistent effects of prominence for either of the two respiratory signals. Graphical inspections suggested, rather, a more complex scenario (Fig. 3), where speakers adopted different strategies across the three focus conditions. Thus, involvement of the respiratory muscles, and the division of labor among thoracic and abdominal mechanisms, appears to be speaker-specific and not mandatory in generating the local acoustic changes associated with focus. That is, some speakers may realize sentence-level prominence via respiratory means and other speakers via other mechanisms. For example, laryngeal lowering may lead to a slight increase in subglottal pressure, since lung volume is decreased to a small extent. Differences in glottal resistance may also explain speaker-specific patterns. This is in line with the idea that speakers can achieve the same acoustic result with different articulatory strategies ("motor equivalence").

One might ask whether the lack of consistent correspondences between the respiratory data and the intraoral pressure and acoustic data relate to the adequacy of Inductance Plethysmography. However, we could observe (Fig. 3) a dip in the respiratory signals after the stop burst that was consistent across speakers and focus conditions but small (at 1%–2% thoracic VC level). This observation implies that Inductance Plethysmography is sensitive to small changes in lung volume.

In sum, our findings provide evidence that sentence-level prominence is accompanied quite consistently by local increases of subglottal pressure, especially as measured via Pio_slope, and these correlate well with intensity but not with f0. They do not indicate a prominent and general role for thoracic volume changes in generating local subglottal pressure changes or changes in f0, one of the main acoustic correlates of focus. It may be that emphatic stress would show clearer involvement of respiratory mechanisms (cf.

Ohala, 1990), but for sentential focus we conclude that thoracic mechanisms do not play a decisive role for most speakers.

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