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Exploring the source of short-term variations in respiratory data

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Abstract: This study explores short-term respiratory volume changes in German oral and nasal stops and discusses to what extent these changes may be explained by laryngeal-oral coordination. It is expected that respiratory volumes decrease more rapidly when the glottis and the vocal tract are open after the release of voiceless aspirated stops. Two experiments were performed using Inductance Plethysmography and acoustics, varying consonantal properties, loudness, and prosodic focus. Results show consistent differences in respiratory slopes between voiceless vs voiced and nasal stops, which are more extreme in a loud or focused position. Thus, respiratory changes can even occur at a local level.

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1. Introduction

During speech production, chest wall displacements and subglottal pressures mainly show *slow, long-term variations* (e.g., Leanderson *et al.*, 1987), but *short-term changes* in respiratory signals, i.e., brief excursions from the long-term baselines, have also been observed. As elaborated in Sec. 1.1, these short-term changes have most typically been associated with word or sentence stress (Ladefoged, 1968; Ohala, 1990), but a few authors have noted the possibility of segmental effects on respiratory measures, particularly in cases where both the glottis and upper vocal tract are open, leading to rapid venting of air. Data reporting on such segmental effects have been sparse and anecdotal, however, and it is not clear whether such results can consistently be observed across multiple speakers. This paper systematically assesses respiratory displacement variation as a function of consonantal characteristics, loudness, and prosodic focus in several speakers.

1.1 Syllables, stress, and segments

Early reports of short-term excursions (or “pulses”) in respiratory system data came from Stetson (1951, originally published in 1928), who carried out a range of studies exploring respiratory control for speech. He collected various signal types, including electromyography (EMG), torso wall movements, and subglottal and esophageal pressures. Stetson proposed that individual syllables were associated with a “chest pulse” generated by the internal intercostal muscles.

Subsequent studies (e.g., Ladefoged *et al.*, 1958) challenged this chest pulse theory. To a greater extent than Stetson, Ladefoged and colleagues employed EMG methods along with measures of chest wall movements and esophageal pressures. These authors argued that the internal intercostals did not show ballistic activity for individual syllables. They did, however, report increases in subglottal pressure for stressed syllables (Ladefoged, 1968), and presented one figure quantifying the frequency of single motor unit firing in the internal intercostals to argue that such activity increased before stressed syllables (Ladefoged *et al.*, 1958).¹ Ohala (1990) subsequently summarized counterevidence to the claim that stressed syllables are associated with greater respiratory system activity, and suggested that lung volume changes correlate with syllables that have emphatic rather than lexical stress.

Ladefoged (1968) made an additional observation that has received considerably less attention, namely, subglottal pressure could show short-term decreases during

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voiceless consonants. [Ohala \(1990\)](#) also acknowledged an interaction between the respiratory and oral systems and reported having observed rapid changes in lung volume during regions of high airflow for consonants.

Despite these suggestions in the literature, there has been little subsequent consideration of the interaction between specific segmental and prosodic properties and their effect on respiratory kinematics. To the extent that previous authors have explored this possibility, the data presentation has been anecdotal and qualitative, in that the authors did not consistently quantify respiratory changes as a function of consonant type. Moreover, the number of speakers investigated in this work, although not consistently documented, was likely quite limited.

In a recent study ([Petrone *et al.*, 2017](#)) we observed a regular rapid drop in respiratory volume after oral release (burst) in voiceless alveolar stops produced by women. However, that study did not compare voiceless stops to segments with a closed glottis in similar contextual and prosodic environments. From a purely logical perspective, it would make sense for segmentally-induced loss of air to affect respiratory system volumes. On the other hand, respiratory system volumes are quite large in comparison to whatever quantity of air might be released during an individual consonant such as an aspirated stop, particularly when one considers speakers with smaller glottal apertures (*viz.*, women and children, who have smaller laryngeal structures than the men who were mainly represented in the early work). Thus, this study represents a systematic exploration of whether multiple speakers, mostly adult females, consistently show segmental effects on respiratory system displacements. In particular, we evaluate respiratory volume during consonants varying in glottal and velar opening (nasal stops, voiced oral stops, voiceless aspirated oral stops). Along with consonant type, we also consider possible interactions with prosodic changes at sentence and word levels via loudness (first experiment) and focus (second experiment) manipulations. Prosodic variation is of interest given that prosody can be manifested in articulatory changes at a segmental level. For German speakers, a larger glottal opening for voiceless stops has been observed in the production of loud in comparison to normal speech ([Fuchs *et al.*, 2004](#)) and for focused in comparison to an unfocused position ([Hoole and Bombien, 2017](#)). It is not known, however, whether such prosodic effects on consonantal characteristics are reflected in respiratory patterns.

1.2 Hypotheses

We hypothesize that respiratory volume changes reflect laryngeal-oral coordination. Specifically, we expect that the slope of the respiratory volume declines more steeply at the release of voiceless aspirated stops than at the release of voiced and nasal stops. The steeper decline in voiceless stops should result from an open vocal tract after oral release which is coordinated with maximal glottal aperture. In voiced stops, phonetically realized as voiceless unaspirated or voiced word-initially in German, the glottis should be (almost) closed and less air can escape than with an open glottis, so that the slope of respiratory volume should not change to the same extent. Similarly, phonation in nasal stops should limit air loss and have only a marginal effect on respiratory volume changes.

We also expect effects to be larger in loud speech (experiment 1) and focused position (experiment 2) than in normal speech and unfocused position, because the degree of glottal opening for voiceless aspirated stops is larger in loud speech and under focus. Finally, we suppose that thoracic volume changes may be affected by loudness and focus, because the thorax is close to the larynx and the upper vocal tract and it has been discussed with respect to local respiratory changes ([Ladefoged and Loeb, 2002](#)). We do not expect consistent abdominal volume changes, since the abdomen is anatomically more distant from the larynx and upper vocal tract, and we generally associate it with slower motions ([Thomasson and Sundberg, 2001](#)).

2. Experiment 1

2.1 Methodology

Participants were 11 native speakers of German (all female) with an age between 20 and 37 yr and a body mass index between 18 and 23. All were recorded in a seated position. Thoracic and abdominal displacements (obtained using Inductive Plethysmography) were recorded simultaneously with speech acoustics (Sennheiser microphone HKH50 P48) using a multi-channel system that prevented the need for post-synchronization. The data were recorded with Edwin, software provided by the manufacturer. The data were then converted to MATLAB (version 2017b) for analysis.

The speech material consisted of bisyllabic target words containing initial /m b p/, a medial alveolar obstruent, and various vowels. Word with initial /m/ were: “Mieten”

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(rents), “Mitte” (section of Berlin), “Mate” (a tea), “Mützen” (caps), “München” 112
 (Munich). Words with /b/ were “Butter” (butter), “Büsten” (busts), “Büsum” (an island) 113
 and, with /p/, “Paddeln” (to canoe), “Pudel” (poodle), “Pita” (pita), “Pizza” (pizza), 114
 “Paten” (god-parents), “Pasta” (pasta), “Pute” (turkey), “Pudding” (pudding). Thus, pho- 115
 netically, the vowels following /m/, /b/, and /p/ were, respectively, /i i y a:/, /u y/, and /i i 116
 u u a: a:/, where /a:/ represents the tense vowel and /a/ is the lax counterpart, but both dif- 117
 fer frequently only in vowel quantity. 118

The respective target words occurred sentence-initially. A question–answer 119
 paradigm was employed. For example, the experimenter asked the question: “Magst 120
 du X?” *Do you like X?* and the participant answered: “X mag ich, aber nicht Y.” *X I 121
 like, but not Y.* The participants supplied Y. The inclusion of Y made the experiment 122
 more engaging for participants, because they could partially create their own 123
 responses. Speakers produced utterances in normal and loud conditions. Louder speech 124
 was elicited by increasing speaker-experimenter distance. 125

Segments were labeled acoustically. For /m/ the onset was defined as the 126
 beginning of vocal fold oscillation. The offset was determined as the beginning of 127
 prominent formant structure corresponding to the beginning of the following vowel. 128
 For the oral stops the onset was defined as the first visible burst and the offset as the 129
 beginning of vocal fold oscillations for the following vowel. The slopes of thoracic and 130
 abdominal volume changes were calculated from the acoustically annotated onset (x1) 131
 to the offset (x2) of the segment (see Fig. 1 lower plots). Figure 1 shows the experimen- 132
 tal setup and the annotation of the acoustic signals. 133

Thoracic and abdominal slopes were calculated using formula (1) where x 134
 denotes the on- and offset of the segment (see Fig. 1) and y1 and y2 are the respiratory 135
 signals obtained at times x1 and x2 from either the rib cage or the abdomen. 136

$$\text{Slope} = (y2 - y1)/(x2 - x1). \tag{1}$$

The units for the respiratory data are arbitrary, but are consistent within each 137
 speaker.² 138

2.2 Results 139

Linear mixed effect models [version R 3.4.3, R Core Team, 2018], *lme4* (Bates et al., 140
 2015), *lmerTest* (Kuznetsova et al., 2017) were run with thoracic slope or abdominal 141
 slope as the dependent variable, loudness, phoneme, and their interaction as independ- 142
 ent factors and speaker-specific slopes for loudness and phoneme. The reference level 143
 was set to /p/ and normal speech. For pairwise comparisons involving other levels than 144
 /p/ (/b/ vs /m/), the reference level was changed and only *p*-values smaller than 0.025 145
 [*p*=0.05 divided by the number of models (2) run] were treated as significant. 146
 Thoracic slope for /p/ was significantly steeper than in /m/ [$\beta = -0.316$, standard error 147

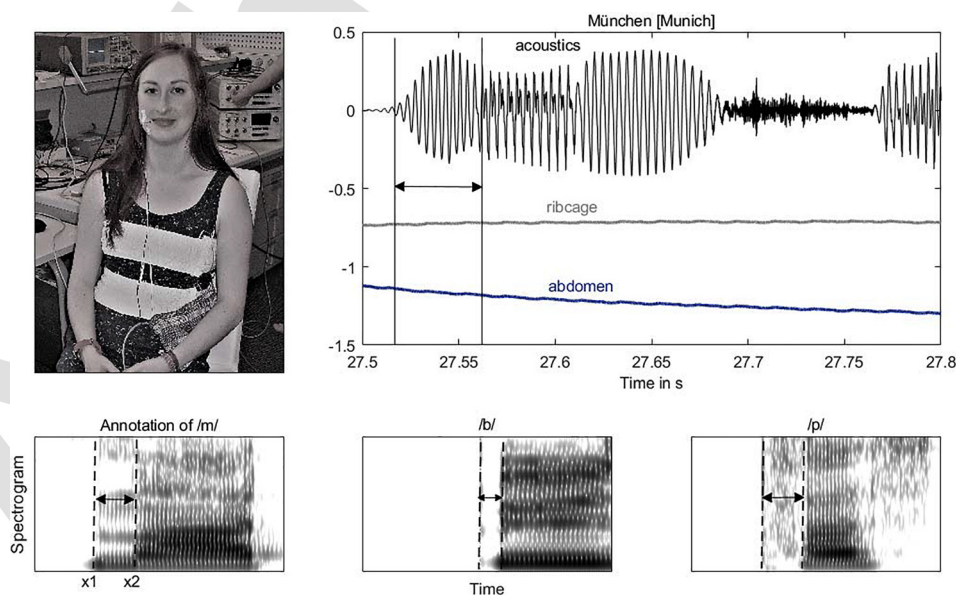


Fig. 1. (Color online) The upper plots show the experimental setup (participant sitting on a chair wearing the two respiratory belts) and the corresponding signals [acoustics (black line), thoracic volume changes (gray line), and abdominal volume changes (dark gray line below the ribcage signal) in arbitrary units]. The graphs below show the acoustic annotation which served as the input for obtaining the respiratory data during these regions.

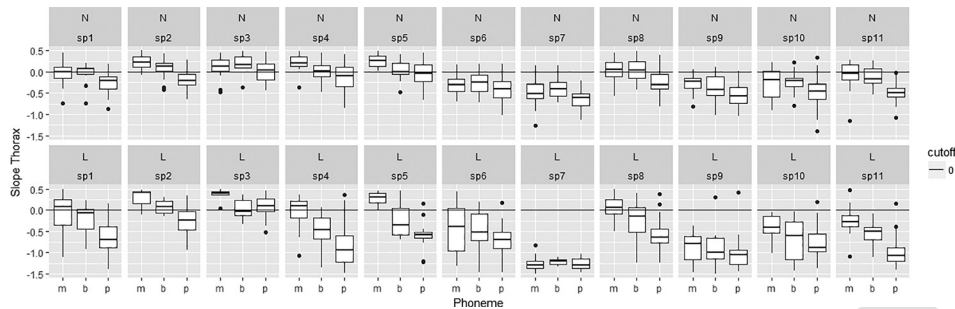


Fig. 2. Slope of the thoracic volume between the acoustically annotated on- and offsets (y -axis) split by phoneme (x axis) and loudness (upper panels: normal, lower panels: loud). Individual speakers' results (sp1–sp11) are displayed in the subplots. The horizontal line depicts a threshold. All values below this line refer to a decrease in thoracic volume (negative slope) while values above correspond to an increase in thoracic volume (positive slope).³ The number of all samples (n) is 1705.

AQ5 (SE)=0.051, $t=-6.16$, $p<0.001$] and also steeper in /p/ than /b/ ($\beta=-0.24$, SE=0.055, $t=-4.4$, $p<0.001$) (see Fig. 2). No significant differences were found between /b/ and /m/.

Loudness also revealed an effect with steeper slopes for loud speech than normal in /p/ ($\beta=-0.49$, SE=0.195, $t=-2.49$, $p=0.021$), but no significant differences in loudness were found for /b/ and /m/.

The abdominal slope revealed a difference between /p/ and /b/ with a shallower (less negative) slope for /b/ ($\beta=0.359$, SE=0.122, $t=2.95$, $p=0.005$), and a shallower slope in /b/ than /m/ ($\beta=0.391$, SE=0.128, $t=3.05$, $p=0.003$). No differences between /p/ and /m/ were found and there was no effect of loudness.

3. Experiment 2

3.1 Methodology

Seven women and three men, all native speakers of German, were recorded. Respiratory equipment and data annotation were the same as in experiment 1. Speakers had an age between 22 and 36 yr and body mass index between 19 and 25 (see Petrone *et al.*, 2017). The speech material consisted of sentences with contrastive focus, i.e., a word in a target utterance was contrasted with another word in the preceding context. The target sentences were elicited using a question–answer paradigm. The experimenter asked a question and the participant read the answer from a sheet of paper. Focused words were written in capital letters. For example, the question “Wäscht er Tiegel?” (Does he wash cups?) was used to prompt contrastive focus in the target utterance “*Er NIMMT Tiegel, aber wäscht sie nicht*” (He TAKES cups, but does not wash them). Prompts that put the final noun (e.g., “Tiegel”) in focus yielded the no-focus condition for the verbs. For analysis, we selected three verbs starting with a nasal or oral stop, i.e. /n/ in “nimmt” (takes), /m/ in “malt” (paints), and /k/ in “kennt” (knows); the vowels in the three words were /ɪ a: ɛ/, respectively. Note that the current analysis differs from the original study because here we assess the initial consonant of the verb whereas Petrone *et al.* (2017) investigated the /t/ at the end of the verb.

3.2 Results

Two linear mixed-effects models (using the packages *lme4*, *lmerTest*) were run with thoracic slope or abdominal slope as the dependent variable and focus, phoneme, and their interaction as independent factors. The random structure included speaker specific slopes for focus and phoneme. The voiceless stop /k/ in the focus condition served as the reference level and it was changed when comparing other phoneme pairs.

Statistical results showed that the thoracic slope was significantly shallower in /n/ than /k/ ($\beta=0.36$, SE=0.043, $t=8.35$, $p<0.001$), shallower for /m/ than /k/ ($\beta=0.34$, SE=0.043, $t=8.02$, $p<0.001$), and did not differ between /n/ and /m/ (see Fig. 3). Thoracic slope was affected by focus in /k/, with a shallower slope for the no focus than for the focus condition ($\beta=0.14$, SE=0.041, $t=3.36$, $p=0.0016$). Focus did not affect thoracic slope in /m/ and /n/, and individual variation is evident (Fig. 3).

Results revealed no effect of focus on abdominal slope, but an effect of phoneme with a shallower slope for /n/ than /k/ ($\beta=0.176$, SE=0.062, $t=2.85$, $p=0.0078$), but not for /k/ versus /m/. There were no differences between /n/ and /m/.

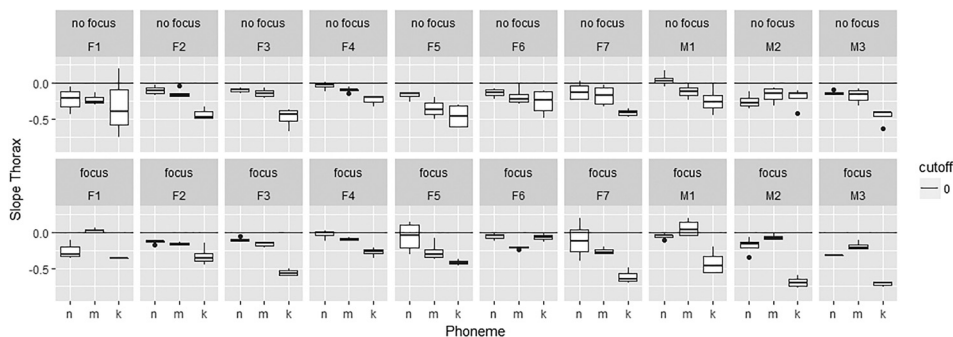


Fig. 3. Slope of the thoracic volume between the acoustically annotated on- and offsets (y -axis) split by consonant (x axis) and focus (upper track: no focus, lower track: focus). Individual speakers' results are displayed in the subplots (seven females, three males). All values below the black horizontal line at zero indicate a decrease in thoracic volume (negative slope) while values above correspond to an increase in thoracic volume (positive slope). The number of all samples (n) is 221.

4. Discussion and conclusion

Results for two experiments with different participants revealed consistent local effects on thoracic volume in voiceless aspirated consonants, which differ from voiced stops and nasals in their laryngeal-oral coordination. Specifically, a larger amount of air can escape when the vocal tract and the glottis are open in comparison to configurations where the glottis is closed or the vocal folds vibrate. Patterns for voiceless stops were rather consistent across speakers, with only a few speakers differing from the overall pattern (Fig. 2: sp7, loud condition; Fig. 3, M2 and F6). A review of the acoustic data for these few unusual speakers did not immediately show a reason for their atypical behaviour.

We also obtained evidence for prosodic effects (loudness, focus) in the slope of the thorax, but not the abdomen, in the vicinity of voiceless aspirated stops. The thorax is closer to the larynx and thoracic muscles may also be more flexible and adaptable to short temporal changes in comparison to the global abdominal motions (e.g., Ladefoged *et al.*, 1958). It may also be that abdominal movements reflect greater inertia than those of the thorax (cf. Thomasson and Sundberg, 2001). However, we note that kinematic data do not necessarily allow firm conclusions about underlying physiological processes. In our study the results could reflect an active involvement of the thorax muscles, mechanical properties of the thorax and abdomen, or simply a larger glottal aperture. A study adding measures of vocal-fold abduction or subglottal pressure could help disentangle the possibilities here.

Our results also demonstrate that prosody affects the degree to which differences in consonantal aerodynamics are reflected in respiratory data. The effects are not restricted to specific conditions, but are more extreme in loud speech and in words under focus. This is in line with literature on prosodic strengthening and in particular on laryngeal kinematics, where a larger glottal opening has been reported for strong prosodic conditions than in weak ones (Fuchs *et al.*, 2004; Hoole and Bombien, 2017).

Finally, we suggest that the short term negative excursions seen here may provide an alternative explanation for Stetson's chest pulses. That is, when one observes an undulating signal, one might focus on the local increases (pulses) rather than the local decreases ("valleys") as a phenomenon calling for explanation. Stetson's speech material consisted to a large extent of CV syllables with C being voiceless stops; hence it may not be surprising to find excursions on every syllable. Further, Stetson's experimental design may have led to rather careful or staccato speech, i.e., the syllables could also have received accentuation.

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- ¹As pointed out by Ladefoged and Loeb (2002), the technology available at the time did not allow calculating averaged EMG data; the only cases where EMG data could be quantified was when a single motor unit was recorded.

- ²Since we did not merge thorax and abdomen kinematics to obtain overall lung volume, we cannot provide the slope values in percent vital capacity. 236
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- ³It is possible that some cases of positive slopes reflect preparatory chest wall positioning (cf. Hixon *et al.*, 1988). However, we also obtained a few cases of positive slopes in experiment 2, where the analyzed words were not in utterance-initial position. 238
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