The Respiratory Foundations of Spoken Language

Susanne Fuchs, Amélie Rochet-Capellan

The respiratory foundations of spoken language

Susanne Fuchs,[1] and Amélie Rochet-Capellan[2]

[1]Leibniz-Zentrum Allgemeine Sprachwissenschaft (ZAS), 10117 Berlin, Germany; email: fuchs@leibniz-zas.de
[2]Univ. Grenoble Alpes, CNRS, Grenoble INP, GIPSA-lab, 38000 Grenoble, France; email: amelie.rochet-capellan@grenoble-inp.fr

Xxxx. Xxx. Xxx. Xxx. 2020. 7:1–19

https://doi.org/10.1146/((please add article doi))

Keywords

respiration, lung volume, pauses, speech planning, prosody, turn taking

Abstract

Why is breathing relevant for linguistics? In this review we approach this question from different perspectives. The most popular view is that breathing adapts to speech, because respiratory behaviour has astonishing flexibility. Among others, we review studies showing that breathing pauses occur mostly at meaningful places, breathing adapts to cognitive load during speech perception, and breathing adapts to the communicative needs in dialogue. However, speech may also adapt to breathing: e.g. the larynx can compensate for air loss, breathing can partially affect f0 declination. Enhanced breathing control may have played a role for vocalisation and language evolution. Both views are not exclusive but reveal that speech production and breathing have an interwoven relationship which depends on communicative and physical constraints. We suggest that breathing should become an important topic for different linguistic areas and that future work should investigate the interaction between breathing and speech in different situational contexts.

Contents

1. INTRODUCTION

Breathing is the source of most sounds that humans produce to communicate: learning to produce spoken language involves learning a specific control of breathing often referred to as *speech breathing*. The study of breathing with regard to speech is an old story. As an illustration, as early as 1935, Wiksell mentioned that "Respiration, which is universally accepted as a fundamental component in the physiological process of speech, has been in its many aspects the subject of much productive investigation" (Wiksell 1935, p.1). Lieberman (1966, p.52) observed that "speech is organized in terms of the expiratory air flow from the lungs". Citing Lenneberg (1967), Wilder (1974, p.19) stated that the reshaping of the respiratory flow for speech production is so important that one can find "astonishing" that humans "tolerate these modifications for an apparently unlimited period of time without experiencing respiratory distress". The production of spoken language indeed requires specific adaptations of breathing control that go beyond the aeroacoustic constrains of the articulation of speech sounds. The ubiquity of breathing adaptation in spoken language and its early observation contrasts, however, with the lack of integration of breathing into (psycho)linguistic models of spoken language. Nevertheless, in the last decades topics related to breathing sparked a renewed interest in different domains of linguistics with regards to older and newer hypotheses concerning the linguistic and communicative role of breathing.

This paper provides an overview of research showing the indisputable role of breathing at different linguistic levels of spoken language as well as the implications for spoken interactions. Breathing is primarily a physiological activity and needs to be understood and investigated as such. Basic knowledge of the breathing apparatus and its control, as well as more technical aspects concerning different recording techniques, are provided in section 2. We then discuss two views of the inter-relations between speech and breathing. The first approach, illustrated in section 3, provides evidence for the adaptation of breathing to speech production. In this framework, breathing is also studied as a behavioral window into the listener-speaker adaptations that occur during speech perception and turn-taking in communicative exchanges. This approach that we refer to as *breathing adapts to speech* is the dominant one. However, speech also adapts to breathing and breathing capacities may shape spoken language (see section 4). This second direction might be a fruitful road to a better understanding of *the body ground* of spoken language. Finally, in section 5, we highlight perspectives and challenges for future research based on the conception of a bi-directional relationship between spoken language and breathing.

Body ground of spoken language: With reference to Grounded Cognition (Barsalou 2008), we use this term to encompasses all the physiological actors that support spoken language.

2. BREATHING: SOME BASIC FACTS

Understanding the role of breathing in spoken language requires basic knowledge about breathing as a physiological function. Breathing is supported by a set of muscles and control processes that are connected to speech production mechanisms. The investigation of these connections requires recording and analyzing breathing during speech production, which involves specific material as well as the computation of a number of parameters. In this first section, we provide the reader with an overview of these aspects and with references dealing with them in more detail.

2.1. The respiratory apparatus: muscles and neural control

Breathing muscles are usually described with regards to their function for inhalatory and exhalatory motions. These two respiratory movements are illustrated in Figure 1A, with inhalation on the left and exhalation on the right. The largest muscle involved in inhalation is the diaphragm, which forms a barrier between the ribcage and the abdomen. When it contracts, it moves downwards and expands the lungs. In parallel, the contraction of the external intercostalis, small muscles running between the ribs, raises the ribcage. The expansion of the ribcage creates a negative pressure in the lungs with respect to atmospheric pressure. As a consequence, the air flows into the lungs, from high to low pressure. By contrast, expiration during speech relies on internal intercostalis and abdominal muscles (in quiet breathing it relies on the elastic recoil forces). The inner intercostalis muscles pull the ribcage down and the abdominal muscles compress the abdominal cavity and push the diaphragm upward. This reduction of lung volume yields positive pressure within the lungs, which moves the air out. The exhalation airflow in speech production is then largely modulated by the opening or closing of the glottis and actions of the upper articulators (for further details, see e.g. Gick et al. 2013; Perkins & Kent 1986; Huber & Stathopoulos 2015).

The control of breathing muscles depends on various structures of the nervous system. Recent research (Del Negro et al. 2018; Ben-Tal et al. 2019) suggests that breathing control is a complex and adaptive process, the neural substrates of which are still not fully understood. The Breathing Central Pattern Generator (CPG) is located in the brain stem, but it has numerous connections with different cortical and subcortical areas of the brain. One of these connections is with the hippocampus which is involved in memory, emotional and cognitive activities. Shea (1996) gives an overview of the different interactions of voluntary and involuntary control components of breathing and argues that it is almost impossible to separate them in the awake resting human. This has consequences for the understanding of breathing activities and implies that tidal (or restful) breathing may be influenced by other factors than ventilation need only. Breathing is involved in different processes, including cognitive and emotional ones, which are also visible at the behavioral level.

2.2. Monitoring speech breathing: a technical challenge

The investigation of speech breathing requires one to record speech and respiratory signals simultaneously without altering speech articulation, which is a challenge in itself. A variety of early techniques were developed (Golla & Antonovitch 1929) and subsequently improved over time. This section briefly illustrates the most popular apparatuses.

A first technique to measure the volume of air going inside the lungs during inhalation and outside the lungs during exhalation is the *Pneumotachograph*. It is a sealed face mask placed over the nose and mouth. The *Rothenberg mask* (Rothenberg 1977) was a further improvement. It allows recording of acoustics, airflow and air pressure during speech production, singing or in clinical settings (Koenig 2000; Dromey et al. 1995). Using a face mask, however, affects the quality of the acoustic signal, may limit the degree of jaw motion and alter breathing as it also requires some adaptation (Shea 1996; Golla & Antonovitch 1929).

The *Full Body Plethysmograph* requires the person to be sealed in an airtight box. Lung pressure and airflow can be measured with respect to the reference conditions in the box (DuBois et al. 1956). The technique has been used in early speech breathing research (Stetson 1951; Draper et al. 1960) but was then replaced by less bulky systems.

Inductance Plethysmography is probably the technique that is most often used nowadays. It involves two flexible belts (see Figure 2(A)) that track changes in thoracic and abdominal circumferences during inhalation and exhalation. By means of this technique the changes in lung volume during inhalation and exhalation can be estimated thanks to different calibration procedures discussed in the literature (e.g. Konno & Mead 1967; McKenna & Huber 2019). A limit of Inductance Plethysmography is its sensitivity to arm and shoulder movements that are frequent in spoken communication and can create artefacts in the breathing recording. Additional video recordings allow these events to be captured.

Vital capacity (VC): Volume of air between maximal inhalation and exhalation

Tidal breathing: Regular breathing for an awake, relaxed person at rest

Residual volume (RV): Volume of air remaining in the lungs after maximal exhalation

Total lung capacity: Overall lung volume during maximal inhalation, i.e. VC+RV

A general challenge when using the devices described above is that participants are aware that their breathing is monitored, thus their breathing profiles might be different from breathing in non-experimental conditions (Golla & Antonovitch 1929). In order to prevent this, one may design experiments with a large degree of engagement so that participants' attention is shifted towards the experimental task. Other technique may also reduce this effect such as the investigation of speech breathing based on the detection of inhalation noises in acoustic recordings (Goldman-Eisler 1955; Wang et al. 2010). This method could yet induce errors as not all inhalations are achieved with a noise.

The development of small wireless breathing sensors and wearable technologies in general may be the future of breathing recording and should limit the awareness of breathing recording (e.g. Mathew et al. 2012; Frey et al. 2018).

2.3. Characterizing speech breathing: main parameters

Once breathing and speech signals have been acquired, inhalation onset and inhalation peak can be detected reliably as the initial time point where volume starts to change rapidly and as the maximal volume respectively (see Figure 1(C) and Wlodarczak 2019). The

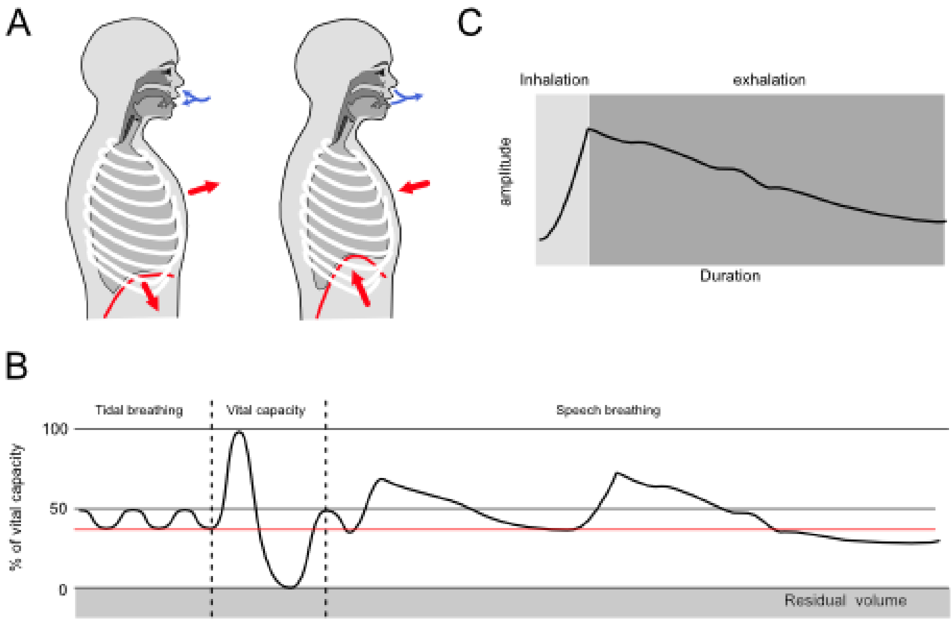

Figure 1

Basic respiratory mechanisms, data and their analysis. (A) Diaphragmatic and ribcage motions during inhalation (left) and exhalation (right). The blue arrows depict the direction of airflow while the red arrows show the direction of the main respiratory motion. (B) Respiratory kinematics for different breathing tasks starting with tidal breathing, followed by maximal inhalation and exhalation measuring vital capacity, and finally during speaking. Speech breathing involves more variable and deeper inhalations than tidal breathing (see margin notes for definitions of terms). (C) The speech breathing cycle is characterized by a strong asymmetry with a short inhalation and a long exhalation. The inhalation amplitude (or depth) is also an important parameter in speech breathing studies.

exhalation period is in general considered from an inhalation peak to the next inhalation onset. Inhalation and exhalation phases are usually described in terms of duration and volume changes. The slope of the movement could also be used. The inhalation depth is an indicator of the volume of inhaled air. It can be expressed relative to vital capacity (VC).

The breathing cycle is considered as an inhalation and the following exhalation. According to Hoit & Lohmeier (2000) the quiet breathing rate is ca. 12 breaths/min (range: 7-19 breaths/min) and the speech breathing rate ca. 20 breaths/min (range: 14-31 breaths/min). Breathing cycles are also characterized by the I-fraction (Wilder 1974, p.19), "the ratio of the length of inspiration to the total duration of the respiratory cycle". This measure varies with the task (Conrad & Schönle 1979; McFarland 2001). Quiet breathing shows the highest I-fraction (0.40 to 0.60, see Gick et al. 2013). Inhalation as a proportion of the whole breath cycle is much shorter during speech with an I-fraction of ca. 0.10 (e.g. Perkins & Kent 1986). Breathing cycles during speech production have often been described as having a sawtooth shape (see Figure 1.B and C). Conrad & Schönle (1979) introduced the idea that breathing cycles show a continuum from higher to lower I-Fraction values comparing inner speech, silent articulation and speaking aloud.

Another term that is often used in the speech breathing literature is the *breath group*. It was introduced by Lieberman (1966) as a suprasegmental and "basic feature in the hierarchy of phonological features" (p.2). "The breath-group at the articulatory level involves a coordinated pattern of muscular activity (...) during an entire expiration" (p.167). Later work considered the breath-group as the chunks of speech produced during a single exhalation (Wang et al. 2010). The breath-group can be characterized by parameters such as its duration, f0 declination and the number of syllables produced.

3. BREATHING ADAPTS TO SPEECH

The first and dominant view concerning the breathing and speech relationship is that breathing adapts to speech production. This adaptation has been investigated in different studies and reflects the flexibility of breathing to different linguistic and communicative levels. In particular, we provide evidence for breathing adaptation to: (1) location of breathing pauses at syntactic boundaries, (2) speech planning, (3) prosody, (4) speech perception, and (5) inter-personal coordination during dialogue.

3.1. Inhalation at syntactic boundaries

One of the most convincing argument for the adaptation of breathing to speech is that inhalation does not occur randomly in the speech stream, but very often coincides with constituent boundaries. Inhalation at a certain place may not only be required for the purpose of oxygen supply (Conrad et al. 1983), but is intimately linked to linguistic structure, especially in reading. For read speech, Conrad et al. (1983) reported that inhalation occurs exclusively at syntactic boundaries. Similarly, Winkworth et al. (1994) found that 88% of inhalations occurred at constituent boundaries in reading (see also, Grosjean & Collins 1979; Wang et al. 2010; Henderson et al. 1965). However, the studies have differed in how they define syntactic constituents and how many constituents were investigated. Some authors have also extended the results to spontaneous speech, where speakers also have to plan the content of their speech. Henderson et al. (1965) found that during spontaneous speech the majority of inhalations were placed at syntactic boundaries, but approximately 30% could not be explained by syntactic constituents. Comparable percentages were reported in Winkworth et al. (1995). Inhalation are also deeper when occurring at higher syntactic constituents, i.e. between sentences, than when occurring at lower constituents, i.e. between clauses. This was observed in read and spontaneous speech (e.g. Conrad et al. 1983; Rochet-Capellan & Fuchs 2013) and may reflect speech planning.

3.2. Anticipating the length of the upcoming sentence

Breathing is adaptive with respect to the length of the upcoming sentence. Hird & Kirsner (2002) proposed "that processes integral to neural planning of the respiratory system anticipate the demands associated with future utterances, and that they do not simply supply the power for phonation and articulation subsequent to higher order planning" (p.538). Speakers may roughly anticipate the length of the upcoming sentence when inhaling and may plan the required air volume before starting to talk. This anticipation goes hand in hand with a deeper inhalation for longer than for shorter sentences. Different studies have shown such an effect in read and spontaneous speech (e.g. Sperry & Klich 1992; McFarland & Smith 1992; Winkworth et al. 1994, 1995; Whalen & Kinsella-Shaw 1997; Fuchs et al.

2013; Rochet-Capellan & Fuchs 2013). However, one may not find differences in inhalation depth when sentences differ in a few syllables only (e.g. 3 syllables) or when they are rather short. For multi-party conversations, Wlodarczak (2017) pointed out that units of speech shorter than 1 second do not require the same tight coordination between respiration and speech as it is known for longer utterances (Rasskazova et al. 2019). This is observable on the example displayed in Figure 2(B), bottom signal: short feedback utterances (backchannels) are produced during listening breathing cycles, in the middle of the exhalation phase. Speakers can produce this short utterance without taking a new inhalation, the utterance can occur anywhere during an exhalation phase, as there is always enough air in the lungs to produce it. Hence, breathing has to be involved in speech planning, at least when speakers plan long utterances.

Taking a break to take a breath also has effect on prosody, specifically the temporal organization of speech, but local adaptations of breathing to prominent syllables can occur as well.

3.3. Breathing and prosody

The assumption of breathing adaptation with respect to prosody, and specifically prominence, goes at least back to Jesperson (1913). The first empirical evidence we are aware of comes from Stetson (1951). In his famous *chest-pulse theory* he proposed that the internal intercostalis muscles of the ribcage would be activated for every syllable, leading to pulses or ripples visible on the respiratory signals. Later research has questioned Stetson's idea that such pulses would be purely the result of respiratory activity (Fuchs et al. 2019) and would occur on every single syllable. Instead, the internal intercostalis muscles might be active for stressed in comparison to unstressed syllables. Ladefoged & Loeb (2002) provided evidence for this claim on the basis of electromyographic recordings of a few speakers, taking into account some of the critics (Hixon & Weismer 1995) of his earlier work (Ladefoged 1963). Ohala (1990) mentioned that even if the activity of these muscles might have been found in some studies, it is still unclear whether one should interpret it as evidence for the involvement of respiration in stress or as a compensatory reaction to glottal resistance. Recent work (Petrone et al. 2017) investigated the relation between acoustic and respiratory parameters in the production of sentence level prominence, i.e. words in a sentence that were produced with or without focus. The authors observed an increase in subglottal pressure associated with the word under focus, which correlated positively with speech intensity, but not with fundamental frequency. Thoracic volume also changed with focus, but not in a consistent manner across speakers. The speaker-specific analysis suggested that individuals may use various mechanisms to produce prosodic variations.

Prosody: refers to the suprasegmental structure of the utterance, encoding prominence and phrasal organization" (Krivokapić 2014, p.1)

3.4. Breathing when processing speech

Early on, breathing during speech perception was investigated as a potential indicator for listener empathy. For instance, Ainsworth (1939) found that listening to a speaker who stutters in face-to-face settings increases the variability of the listener breathing. The discovery of a potential role of the motor system during action perception (Rizzolatti & Arbib 1998; Arbib 2010; Schwartz et al. 2012) led to new assumptions concerning the role of breathing in speech perception. If the motor system contributes to speech perception, breathing during perception should mirror some properties of breathing during production. This assumption was previously made for the perception of non-speech actions suggesting that breathing "could represent a basis for understanding and imitating actions performed by other people" (Paccalin & Jeannerod 2000, p.194). Rochet-Capellan & Fuchs (2013) evaluated this hypothesis for speech perception by investigating changes in listeners' breathing while listening to pre-recorded read speech, produced in different ways. They found that listeners breathed faster when listening to loud speech as compared with normal-level speech, and slower when listening to slow speech as compared to normal-rate speech. However, these changes were not directly related to changes in readers' breathing. Moreover, in these playback conditions, no synchronization between listener and speaker breathing was found. These results suggest that in this particular situation, the adaptations of breathing were more related to cognitive or emotional processes than to the imitation of speakers' breathing. Results could also be related to the fact that listeners-speakers were not in face-to-face setting nor involved in an interactive task.

3.5. Breathing while speaking together

Inter-personal coordination of breathing has been investigated in singing or reading together, either in synchrony or in alternation. In these situations, inter-personal coordination is imposed by the task. When singing in unison, trained choral singers breath together (Müller & Lindenberger 2011). Bailly et al. (2013) suggested that when speakers are asked to read together or in alternation they tend to display in-phase vs. anti-phase coordination of breathing respectively. The synchronization was stronger when reading simultaneously. To some extent this is not surprising, because the task is to synchronize speech. Thus, joint speech includes synchronized breathing as speaking together involves making pauses together and thus inhaling together. The way speakers manage to achieve this adaptation of breathing and the limits of these adaptations still require some more investigations.

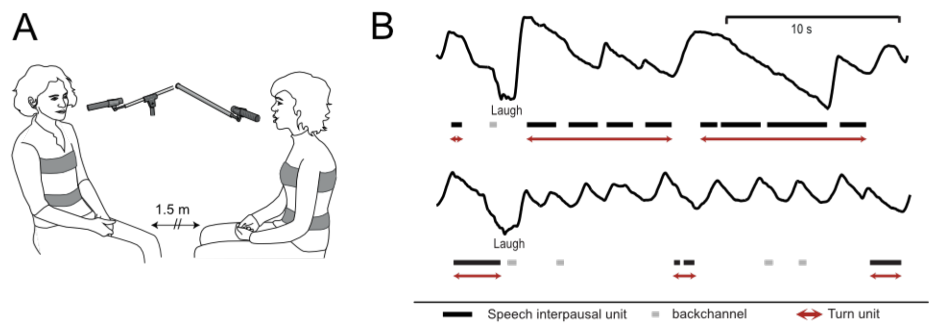

Figure 2

Breathing during dialogue: (A) Experimental setup with two interlocutors wearing breathing belts. (B) Sample of recorded respiratory motions for two interlocutors. Stretches of speech are indicated with black bars and a whole turn of a speaker with red arrows. Gray bars are feedback or back-channels which are mainly produced during listening phases.

Despite being the most natural setting of speech production, conversation is often not a favored task in experimental studies, since it is highly unpredictable and variable. However, some researchers have ventured to investigate breathing during spontaneous conversation (see Figure 2) with different assumptions. Warner et al. (1983) assumed a mutual entrainment of interlocutors during spontaneous conversation with respect to amount of talk and breathing. Testing this idea empirically, they found evidence for entrainment in the amount of talk, but not in breathing activities. Recently, McFarland et al. (2020) suggest that "biological synchrony provides a developmental platform that promotes behavioral interactive abilities" (p.2). They assessed respiratory synchrony in 10 mothers and their infants aged 7 to 8.5 months, while interacting spontaneously in face-to-face settings. The overall time of synchrony was low and variable across dyads, ranging from 7% to 24% of the time. McFarland (2001) and then Rochet-Capellan & Fuchs (2014) analyzed inter-personal synchronization of breathing in native English speakers and native German speaker dyads respectively. Coordination between the interlocutors breathing was not observed when taking all the dialogue phases together. However, local coordination occurred at turn-taking events. Rochet-Capellan & Fuchs (2014) observed that when speakers want to take the turn, they often take a breath at the end of the other speakers exhalation leading to an anti-phase coordination. When a speaker wants to keep the turn but needs a pause to inhale, she inhales fast and quickly, which could indicate to the listener that she has not finished yet. Torreira et al. (2015) confirmed the tendency to take a breath at the end of the speaker's turn when answering to a question, which suggests that the speaker anticipates the end of the turn of the other speaker. The coordination of breathing during conversation thus appears to be specific to turn-taking, and a potential marker of dialogue events and inter-speaker synchrony (McFarland 2001). Inhalation noises also play a role in spoken communication and could be seen as part of non-verbal communication (Trouvain 2014).

Turn-taking: In dialogue it refers to the apportioning of who is to speak next and when (Stivers et al. (2009) p.10587).

In-phase coordination for breathing: Speakers start to inhale and exhale at the same time.

Anti-phase coordination for breathing: One speakers starts to inhale when the other has just finished.

These observations have some parallel in speech technology domains where breathing is considered to improve dialogue systems. In particular, inhalation noise makes the perception of robots more social (Terzioğlu et al. 2020) and analyses of breathing kinematic allows anticipating turn-taking. For instance, Bari et al. (2018) introduced a system that is able to identify speech vs. non-speech phases of conversation based on breathing profiles. Ishii et al. (2014) proposed a model of turn prediction in multi-party meetings based on the analysis of inhalation profiles.

4. SPEECH ADAPTS TO BREATHING

The flexibility of breathing control described in previous sections shows how breathing adapts to speech production. We considered this approach as a first point of view concerning the relationship between spoken communication and breathing. But the relationship could also be seen from the reverse point of view: With breathing being so important to spoken communication, yet at the same time a vital function, spoken language had no choice but to adapt to the limits of breathing flexibility. Different types of arguments are provided here: (1) the larynx can compensate for air loss, (2) intonation is partially affected by breathing, (3) body properties correlate with lung volume play a role in language acquisition, and (4) aspects of linguistic evolution may have corresponded with changes in respiratory system control.

4.1. Laryngeal compensation for air loss

In the section above, we have discussed that inhalation pauses mostly occur at meaningful places within the speech stream. This view may be a bit too simplistic, because the larynx and the upper articulators may adjust to breathing and compensate for the loss of air, especially in long utterances. Potential compensation strategies may be to reduce speech intensity or to increase glottal resistance. Zhang (2016) modelled the relation between respiration and glottal resistance using a pressure-volume-flow model. Results of his model show that increasing glottal resistance is a way to reduce airflow and a mechanism to conserve air. If breath groups are relatively long, such as in normal conversations (on average ca. 4 seconds), either a deep inhalation or an increased glottal resistance may be required, otherwise the speaker might run out of air.

Increased glottal resistance has also been found in experimental data of natural multi-party conversations (Aare et al. 2018). The authors show that creaky voice is more frequent in longer than in shorter exhalation periods, as predicted in the model of Zhang (2016). Moreover, speech including creaky voice lasted longer than when the exhalation phase did not contain creaky voice. The traditional explanation for utterance-final creak was an extension of the logic that subglottal pressure declines towards the end of the sentence (Lieberman 1966) which results in f0 declination. However, as it is discussed in the next section, f0 declination is not purely a byproduct of changes in subglottal pressure, but also due to active changes in laryngeal settings. So vocal folds change their resistance to prevent air loss.

Furthermore, if we consider the interaction between respiration and vocalisation from a motor control perspective, we may keep in mind that the primary respiratory system (i.e. motion of the diaphragm) is rather slow, while actions of the larynx are very quick, because their primary function is to protect the lungs from the penetration of external bodies, for example when eating. Within this view, the larynx can adjust more quickly than the respiratory system and this may be more economic, even if adjustments by both systems may in principle be possible.

4.2. Breathing and f0 declination

Another argument that breathing affects speech comes from the literature on intonation, specifically on f0 declination. Broadly speaking, f0 declination can be described as a gradual decrease of fundamental frequency (f0) over the course of an utterance. It has been reported for a variety of languages, particularly in reading studies and in vocalizations of certain other species (cf. review in Fuchs et al. 2015). Some authors have claimed it to be universal (Hombert 1974). Lieberman (1966) suggested that f0 declination might a direct consequence of a decrease in subglottal pressure over the course of an utterance. Under the assumption of a constant laryngeal setting, his results on subglottal pressure and f0 supported his claim. Other authors, however, questioned the assumption that laryngeal tension stays constant and that f0 declination is a pure byproduct of subglottal pressure variation (e.g. Strik & Boves 1995). Subglottal pressure decrease may play a role in f0 declination, but it does not appear to be sufficient to explain the magnitude of f0 changes that have been observed (Titze 1989).

Watson et al. (2003) looked at the effect of breathing on general acoustic properties by means of initiating speech from different lung volume levels (high, typical, low). Starting with a higher lung volume raised the average sound pressure level, average f0 and let to a steeper f0 declination in contrast to starting with a lower lung volume.

Beyond these observable effects of breathing states on speech parameters, more general claims have been made with regards to the implication of breathing in the evolution and development of spoken language.

The impact of lung volume on marmosets' vocalization

Zhang & Ghanzafar (2018) investigated the impact of lung volume on vocalization in calls of marmoset monkeys. In the first few months, marmoset calls develop from short, undifferentiated calls to long contact calls. This development goes hand in hand with a growth in lung volume. The authors designed an experiment where young marmosets who already produced long contact calls and had a large lung volume, were placed in a helium-oxygen environment with lighter gas. The lighter gas allowed much shorter respiratory cycles using the same muscular effort and caused a reversal in development from longer contact calls to undifferentiated short calls. The authors suggest that lung volume alone may have had an effect on the development of vocalization in monkeys.

4.3. Breathing and language acquisition

Breathing cycles provide a temporal upper limit for the length of an utterance. In this sense, taller speakers, who have on average a larger lung volume, may be less constrained in producing relatively long utterances than speakers with lower lung volumes. Speakers with lower lung volumes may be able to compensate with various mechanisms. They can for instance increase the laryngeal resistance to prevent the loss of air or increase their speech rate to realize the intended utterance in a given time window. The empirical evidence for a relation between lung volume and utterance length is rather sparse.

One relevant study is by Boucher & Lalonde (2015) who investigated the relation between mean utterance length and the development of breathing capacities during language acquisition. For this purpose, vital capacity was recorded in 50 children and adolescents between the age of 5 and 27 years. They found a strong positive correlation between vital capacity and utterance length, with older children having a larger vital capacity and producing longer utterances than younger children. These findings are however not unambiguous, because children and adolescents additionally mature in their cognitive abilities and may therefore produce longer and more complex utterances.

Sperry & Klich (1992) compared older (ca. 66 years) and younger (ca. 23 years) female adults who differed in vital capacity with lower VC for the older females. While reading sentences of different lengths, older females inhaled deeper and used a higher percentage of their vital capacity compared to younger females, specifically in longer sentences. Here again one needs to distinguish between cognitive and respiratory factors.

4.4. Breathing and the evolution of language

MacLarnon & Hewitt (1999) pointed to the fact that among the range of cognitive and physiological factors that have changed to support the evolution of spoken language, the fine control of breathing "has more or less been ignored in the language debate". Evidence for a change in breathing control comes from anatomical data. MacLarnon & Hewitt (1999) reported an expanded thoracic vertebral canal in modern humans and Neanderthals compared with earlier hominids and nonhuman primates. They provided different explanations for the expanded vertebral canal, and argued that the control of breathing for speech production could account for it. In other words, increased innervation to thoracic muscles which support respiration may have supported the evolution of spoken language.

Similarly, Provine (2004) suggested that enhanced breathing control is a foundation of speech. It allows humans to vocalize over a relatively long temporal window on the exhalatory air stream. He compared the vocalization behavior of laughter between chimpanzees and humans. Humans are able to realize several laughter bouts on exhalation, while chimpanzees produce one laugh on one breathing cycle, including inhalation and exhalation phases. Provine suggested that bipedalism may have played a major role in enhanced respiratory control. While quadrupeds have a tight respiratory-locomotor coupling (Bramble & Carrier 1983), with a frequency of one breath to one step, bipeds are less constrained. The authors proposed that "The evolution of bipedalism permitted flexibility in the coordination of breathing, running, and vocalizing." (p.217).

Breathing in fMRI: Functional Magnetic Resonance Imaging measures the BOLD response, i.e. the Blood-Oxygen-Level Dependent signal as an indication of brain activity (Ogawa et al. 1990).

Perl et al. (2019) put forward the idea that cognitive processes, among them language processing, are tightly coupled to respiration. This coupling is rooted in an ancient sensory system where information of olfactory stimuli was processed with the support of respiration. The authors claim that information processing rooted in olfaction even persists for other non-olfactory stimuli. They supported their claim by testing lexical and visuospatial stimuli in humans, finding an increased task-related brain activity and behavioural performance when the task was phase-locked with inhalation. On the other hand, it may not be so surprising that cognitive activities are phase-locked with inhalation, i.e. an oxygen rich blood supply, because the brain is one of the largest oxygen consumers, which is commonly investigated in fMRI studies.

5. SUMMARY AND OUTLOOK: BREATHING AND SPEECH AS INTERWOVEN PROCESSES

Beyond "provide the driving forces necessary for the generation of sounds" (Hixon, 1973 cited by Conrad & Schönle 1979, p.253), we showed that breathing adaptation occurs across different linguistic levels. Breathing is specifically modified during speech planning, perception and inter-personal interaction. However, the assumption that breathing also shapes spoken language should not be neglected. It is obvious that taking a breath is a vital function to take a break, even at the risk of a speaker losing the turn and/or altering the prosody, and sometimes the syntactic structure of her message. In general, speakers avoid such risks: inhalation pauses are not just ventilation-related events occurring anywhere in the speech flow. As we showed in section 4, inhalation pauses are rather closely coordinated with syntax, with planning of the upcoming utterance, and with turn-taking processes. This suggests that spoken language is closely connected to the breathing system and that the efficiency of spoken communication also depends on this connection. However, disentangling whether changes in breathing over the course of child development or human evolution affect the development of spoken language or if the development of spoken language induced changes in breathing control is a chicken and egg issue. Breathing and spoken language should rather be seen as interwoven processes. We will now provide some directions for future research in line with this idea.

5.1. Constrain the breathing system to understand its limits and its role in speech production

Recently, Wlodarczak (2017, p.3) "propose[d] to abandon the view of the relationship of speech and respiration as a one-way execution pathway. Instead, we are interested in whether and how the respiratory state itself shapes speech production." In particular, the authors provided evidence that breathing is not always set-up for speech. Sometimes, speech has to adapt to the current state of the breathing system. For example, when we need to speak really quickly, we may not take the time to inhale (Grosjean & Collins 1979). Starting to speak at a low lung volume level while having a lot to say will certainly lead to some adaptation of speech articulation (Watson et al. 2003), but probably also to adjustments in the use of vocabulary and syntactic structure. This might be particularly noticeable when breathing is constrained by physical activity. Driving the motor system to its limit to better understand its functioning is a classic paradigm in speech research (e.g. Rochet-Capellan & Schwartz 2007). When the motor system is responding to multiple demands, it may reveal economical strategies that could also explain common behavior in less constrained situations. For example, when the breathing system is constrained by increased oxygen consumption due to body motion, such as walking or biking, speech production may be reorganized. This reorganisation may provide insight into the adaptation of spoken language to breathing. We are currently following such an approach in the SALAMMBO project, investigating the relation between body motion-breathing and speech (for some preliminary work, see Fuchs et al. 2015).

SALAMMBO: is an ANR-DFG project for Spoken lAnguage in motions: Learning and Adaptation of speech coMMunication in the context of BOdy motions)
.

5.2. Putting breathing back into spoken interaction

While strong assumptions have been made regarding the role of breathing in inter-personal adaptions and conversational dialogue (see section 3), the number of studies focusing on the topic is rather small. So far, there is no evidence of a global synchronisation of partners' breathing during dialogue. However, it is possible that inter-speaker adaptation of breathing appears at longer time scales. It would be interesting to investigate inter-personal adaptation in speech breathing in longitudinal approaches and longer recordings. One could also ask whether members of the same family might show similar profiles of speech breathing and distinguish between genetic vs. learnt aspects. The most robust result concerning breathing and inter-personal interaction is the involvement of breathing in turn-taking processes, both as a marker of these events and as a non-verbal indicator of the intention to take or hold the turn. As mentioned in section 3, speech technologies suggest it could be possible to improve dialogue system thanks to breathing analyses, for example, by predicting who wants to take the turn based on inhalation profiles. But since breathing is also an indicator of emotional states(Boiten 1998), monitoring it will raise ethical question that will have to be treated in future research. Breathing was also not considered in interactive models of speech production. As described in the *Interactive alignment model* for dialogue, speakers adapt to each other and tend to align their utterance at different linguistic levels (Pickering & Garrod 2004). However, inter-speaker alignment is also visible at the motor level (Shockley et al. 2009). While breathing is involved in speech and joint motor action, neither the linguistic approach of speakers alignment, nor the motoric one has considered the potential role of breathing. This is an important challenge for future work.

5.3. Tackle the speech breathing personality

The idea of a *ventilatory personality* was explored in Shea & Guz (1992). This idea comes from the observation of "very high significance levels relating to differences in breathing patterns between individuals even when under identical standardised conditions" (p.275). It was explored in earlier work such as Golla & Antonovitch (1929) who addressed the relationship between breathing profiles at rest and a range of cognitive abilities. Shea et al. (1987) observed large inter-individual differences in tidal breathing profiles, but consistent profiles for the same person recorded several times. Shea & Guz (1992) argued that the ventilatory personality might be determined by multiple factors and not only lung volume capacity, especially because two persons with similar lung volume can show different breathing profiles and vice versa. So far we don't know to what extent the breathing personality transfers to speech breathing. Breathing may also determine some speaking strategies with social implications. As an illustration, recent sociolinguistic findings (Yuasa 2010) suggest that female American speakers frequently use creaky voice at the end of a sentence. Creaky voice is one way which allows the speaker to talk for a long time without inhaling. So far the phenomenon has been associated with a certain social behaviour, but an interaction with breathing and lung volume may be possible and should be considered in future work.

5.4. Cross-linguistic evidence for the breath group

The breath group was first introduced as a intonation unit (Lieberman 1966) that could explain some universals in spoken language. In this paper we showed that with regards to current knowledge on speech breathing, we can draw some inter-relations between breathing and spoken language, and assume some relevance of this inter-relations in the course of human evolution and child development. But many aspects of the role of breathing in human spoken language are still not understood. An important way to address universals in language is to develop cross-linguistic studies. This has been done for many aspects of spoken language such as turn-taking (Stivers et al. 2009), speech planning (Seifart et al. 2018), phonological structure (Schwartz et al. 1997; Ohala & Solé 2010), phonetic properties (Cho & Ladefoged 1999; Whalen & Levitt 1995): if a phenomenon is consistently observed across diverse languages, one may suppose underlying physiological mechanisms. For speech breathing, the first missing information is a description of the linguistic structure within breath groups across different speakers and languages. We have some information such as number of syllables, the duration, the number of clauses, f0 declination, but only for a limited set of languages and using different methodologies (e.g. Lieberman 1966; Wang et al. 2010; Rochet-Capellan & Fuchs 2013). It is now crucial to collect breathing profiles in spontaneous speech and dialogue over many of languages, linking speaker-specific parameters (e.g. lung volume, body height, physical training) to breathing profiles and speech parameters. This would allow us to discuss the potential universality of the breath group as one major foundation of spoken language production.

SUMMARY POINTS

1. Spoken language involves a specific control of breathing which is still not fully understood.
2. The literature provides evidence of breathing adaptation to spoken language at different linguistic levels.
3. The adaptation of breathing to spoken language is not only related to the production of speech sounds, breathing is also involved in speech perception and turn-taking behaviors.
4. Breathing influences spoken language as well as the reverse.
5. Spoken language and breathing are interwoven in human evolution and child devel-

opment.

FUTURE ISSUES

1. Future issue 1. To what extent do breathing abilities and states determine spoken language at different linguistic levels?
2. Future issue 2. Is there a speech breathing personality? Future work should investigate characteristics of vegetative breathing correlate to those of speech breathing.
3. Future issue 3. Is the breath group a universal unit that shares properties across different languages or is it rather language-specific?
4. Future issue 4. How can we integrate the ubiquitous need to breathe for speech into models of spoken communication?

DISCLOSURE STATEMENT

The authors are not aware of any affiliations, memberships, funding, or financial holdings that might be perceived as affecting the objectivity of this review.

ACKNOWLEDGMENTS

This work has been supported by the Leibniz Association and support from a bilateral French-German ANR-DFG grant to the SALAMMBO project (FU791/8-1). We like to thank Laura L. Koenig, Jelena Krivokapić and Caterina Petrone for fruitful discussions on parts of the paper.

LITERATURE CITED

Aare, K, Lippus, P, Wodarczak, M, Heldner, M. 2018. Creak in the respiratory cycle. In *Proceedings of Interspeech*, Hyderabad (India): 1408–1412

Ainsworth, S. 1939. Studies in the psychology of stuttering: XII: Emphatic breathing of auditors while listening to stuttering speech. *Journal of Speech Disorders*4.2: 149–156

Arbib, MA. 2010. Mirror system activity for action and language is embedded in the integration of dorsal and ventral pathways. *Brain and Language* 112.1:12–24

Bailly, G. Rochet-Capellan, A, Vilain, C. 2013. Adaptation of respiratory patterns in collaborative reading. In *Proceedings of Interspeech* Lyon (France) 1653–1657

Bari, R, Adams, RJ, Rahman, MM, Parsons, MB, Buder, EH, Kumar, S. 2018. rconverse: Moment by moment conversation detection using a mobile respiration sensor. In *Proceedings of the ACM on interactive, mobile, wearable and ubiquitous technologies* 2.1. 1–27

Barsalou, LW. 2008. Grounded cognition. *Annu. Rev. Psychol.*59: 617–645

Ben-Tal, A, Wang, Y, Leite, MCA. 2019. The logic behind neural control of breathing pattern. *Scientific Reports* 9:9078

Boiten, FA. 1998. The effects of emotional behaviour on components of the respiratory cycle. *Biological Psychology*49.1-2:29–51

Boucher, VJ, Lalonde, B. 2015. Effects of the growth of breath capacities on mean length of utterances: How maturing production processes influence indices of language development. *Journal of Phonetics* 52:58–69

Bramble, DM, Carrier, DR. 1983. Running and breathing in mammals. *Science* 219.4582:251–256

Cho, T, Ladefoged, P. 1999. Variation and universals in VOT: Evidence from 18 languages. *Journal of Phonetics* 27.2:207–229

Conrad, B, Schönle, P. 1979. Speech and respiration. *Archiv fr Psychiatrie und Nervenkrankheiten* 226: 251–268

Conrad, B, Thalacker, S, Schönle, P. 1983. Speech respiration as an indicator of integrative contextual processing. *Folia Phoniatrica.* 32: : 220–225

Del Negro, CA, Funk, GD, Feldman, JL. 2018. Breathing matters. *Nature Reviews Neuroscience* 19(6):351–367

Draper, MH, Ladefoged, P, Whitteridge, D. 1960. Expiratory pressures and air flow during speech. *British Medical Journal* 1(5189):1837–1843

Dromey, C, Ramig, LO, Johnson, AB. 1995. Phonatory and articulatory changes associated with increased vocal intensity in Parkinson disease: A case study. *Journal of Speech, Language and Hearing Research* 38.4:751–764

DuBois, AB, Botelho, SY, Comroe, JH. 1956. A new method for measuring airway resistance in man using a body plethysmograph: values in normal subjects and in patients with respiratory disease. *The Journal of Clinical Investigation* 35.3:327–335

Frey, J, Grabli, M, Slyper, R, Cauchard, JR. 2018. Breeze: sharing biofeedback through wearable technologies. *In Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems* 1–12

Fuchs, S, Koenig, LL, Petrone, C. 2019. Exploring the source of short-term variations in respiratory data. *The Journal of the Acoustical Society of America* 145(1): EL66–EL71

Fuchs, S, Petrone, C, Krivokapić, J, Hoole, P. 2013. Acoustic and respiratory evidence for utterance planning in German. *Journal of Phonetics* 41:29–47

Fuchs, S, Petrone, C, Rochet-Capellan, A, Reichel, UD, Koenig, LL. 2015. Assessing respiratory contributions to f0 declination in German across varying speech tasks and respiratory demands. *Journal of Phonetics* 52: 35–45

Fuchs, S, Reichel, UD, Rochet-Capellan, A. 2015. Changes in speech and breathing rate while speaking and biking. In *Proceedings of the ICPhS* Glasgow (UK), paper 1005

Gick, B, Wilson, I, Derrick, D. 2013. *Articulatory Phonetics* John Wiley & Sons

Grosjean, F, & Collins, M. 1979. Breathing, pausing and reading. *Phonetica* 36: 98–114

Goldman-Eisler, F. 1955. Speech-breathing activity-a measure of tension and affect during interviews. *British Journal of Psychology* 46.1: 53–63

Golla, FL, & Antonovitch, S. 1929. The respiratory rhythm in its relation to the mechanism of thought. *Brain* 52.4: 491–509

Henderson, A, Goldman-Eisler, F, Skarbek, A. 1965. Temporal patterns of cognitive activity and breath control in speech. *Language and Speech* 8(4): 236–242

Hird, K, Kirsner, K. 2002. The relationship between prosody and breathing in spontaneous discourse. *Brain and Language* 80(3):536–555

Hixon, TJ. 1973. Respiratory function in speech. *Normal aspects of speech, hearing, and language* 80.3: 73–125

Hixon, TJ, Weismer, G. 1995. Perspectives on the Edinburgh study of speech breathing. *Journal of Speech, Language, and Hearing Research* 38.1:42–60

Hoit, JD, Lohmeier, HL. 2000. Influence of continuous speaking on ventilation. *Journal of Speech, Language and Hearing Research*43:1240–1251

Hombert, JM. 1974. Universals of downdrift: Their phonetic basis and significance for a theory of tone. In *Papers from the fifth conference on African linguistics* ed. WR Leben, Supplement 5, pp. 169-183

Huber, JE, Stathopoulos, ET. 2015. Speech breathing across the life span and in disease. *Handbook of Speech Production*13–33

Ishii, R, Otsuka, K, Kumano, S, Yamato, J. 2014. Analysis of respiration for prediction of "Who will be next speaker and when?" in multi-party meetings. In *Proceedings of the 16th International Conference on Multimodal Interaction*: 18–25

Jesperon, O. 1913. *Lehrbuch der Phonetik*. 2nd ed. Leipzig: Teubner

Koenig, LL. 2000. Laryngeal factors in voiceless consonant production in men, women, and 5-year-olds. *Journal of Speech, Language and Hearing Research* 43.5:1211–1228

Konno, K, Mead, J. 1967. Measurement of the separate volume changes of rib cage and abdomen during breathing *Journal of Applied Physiology* 22.3:407-422

Krivokapić J. 2014. Gestural coordination at prosodic boundaries and its role for prosodic structure and speech planning processes. *Philosophical Transactions of the Royal Society B: Biological Sciences*369:20130397

Ladefoged, P. 1963. Some physiological parameters in speech. *Language and Speech* 6(3):109–119.

Ladefoged, P, Loeb, G. 2002. Preliminary studies on respiratory activity in speech. *UCLA Work. Pap. Phon.* 101: 50-60

Lenneberg, EH. 1967. The biological foundation of language. *Hospital Practice* 2.12:59–67

Lieberman, P. 1966. *Intonation, perception, and language.* Doctoral dissertation, MIT

MacLarnon, A, Hewitt, G. 1999. The evolution of human speech: The role of enhanced breathing control. *American Journal of Physical Anthropology: The Official Publication of the American Association of Physical Anthropologists* 109.3:341-363

Mathew, J, Semenova, Y, Farrell, G. 2012. A miniature optical breathing sensor. *Biomedical Optics Express* 3.12: 3325–3331

McFarland, DH, Fortin, AJ, Polka, L. 2020. Physiological measures of motherinfant interactional synchrony. *Developmental Psychobiology* 62.1:50–61

McFarland, DH, Smith, A. 1992. Effects of vocal task and respiratory phase on prephonatory chest wall movements. *Journal of Speech, Language, and Hearing Research* 35: 971-982

McFarland, DH. 2001. Respiratory markers of conversational interaction. *Journal of Speech, Language, and Hearing Research.* 44.1:128–143

McKenna, VS, Huber, JE. 2019. The accuracy of respiratory calibration methods for estimating lung volume during speech breathing: A comparison of four methods across three adult cohorts. *Journal of Speech, Language and Hearing Research* 62.8: 2632–2644

Müller, V, Lindenberger, U. 2011. Cardiac and respiratory patterns synchronize between persons during choir singing. *PLoS one*6.9

Ogawa, S., Lee, TM, Kay, AR, Tank, DW. 1990. Brain magnetic resonance imaging with contrast dependent on blood oxygenation. *Proceedings of the National Academy of Sciences* 87(24):9868–9872

Ohala, JJ. 1990. Respiratory activity in speech. In *Speech production and speech modelling*, ed. WJ Hardcastle, A Marchal, pp. 23–53. Springer

Ohala, JJ, Solé, MJ. 2010. Turbulence and phonology. In *Turbulent sounds. An interdisciplinary guide*, ed. S Fuchs, M Toda, M Zygis, pp. 37–97. deGryuter: Berlin

Paccalin, C, Jeannerod, M. 2000. Changes in breathing during observation of effortful actions. *Brain Research* 862:194–200

Perkins, WH, Kent, RD. 1986. *Functional Anatomy of Speech, Language, and Hearing. A Primer.* 505 pp. Little Brown/CollegeHill Press, San Diego, California

Perl, O, Ravia, A, Rubinson, M, Eisen, A, Soroka, T, Mor, N, Secundo, L, Sobel, N. 2019. Human non-olfactory cognition phase-locked with inhalation. *Nature Human Behaviour* 3(5):501–512

Petrone, C, Fuchs, S, Koenig, LL. 2017. Relations among subglottal pressure, breathing, and acoustic parameters of sentence-level prominence in German. The Journal of the Acoustical Society of America 141(3): 1715–1725

Pickering, MJ, Garrod, S. 2004. Toward a mechanistic psychology of dialogue. Behavioral and Brain Sciences 27.2, 169–190

Provine, RR. 2004. Laughing, tickling, and the evolution of speech and self. Current Directions in Psychological Science 13.6: 215–218

Rasskazova, O, Mooshammer, C, Fuchs, S. 2019. Temporal coordination of articulatory and respiratory events prior to speech initiation. *Proc. Interspeech*, Graz (Austria): 884–888

Rizzolatti, G, Arbib, MA. 1998. Language within our grasp. *Trends in Neurosciences* 21.5: 188–194

Rochet-Capellan, A, Fuchs, S. 2013. Changes in breathing while listening to read speech: the effect of reader and speech mode. *Frontiers in Psychology* 4: article 906

Rochet-Capellan, A, Fuchs, S. 2013. The interplay of linguistic structure and breathing in German spontaneous speech. In *Proceedings of Interspeech*, Lyon (France): 2014–2018

Rochet-Capellan, A, Fuchs, S. 2014. Take a breath and take the turn: how breathing meets turns in spontaneous dialogue. *Philosophical Transactions of the Royal Society B: Biological Sciences*369: 20130399

Rochet-Capellan, A, Schwartz, JL. 2007. An articulatory basis for the labial-to-coronal effect:/pata/ seems a more stable articulatory pattern than /tapa/. *The Journal of the Acoustical Society of America* 121.6: 3740–3754

Rothenberg M. 1977. Measurement of airflow in speech. *Journal of Speech, Language and Hearing* 20.1: 155–176.

Schwartz, JL, Basirat, A, Ménard, L, Sato, M. 2012. The Perception-for-Action-Control Theory (PACT): A perceptuo-motor theory of speech perception. *Journal of Neurolinguistics* 25.5:336–354

Schwartz, JL, Boë, LJ, Vallée, N, Abry, C. 1997. The dispersion-focalization theory of vowel systems. *Journal of Phonetics* 25.3:255–286

Seifart, F, Strunk, J, Danielsen, S, Hartmann, I, Pakendorf, B, Wichmann, S, Witzlack-Makarevich, A, de Jong, NH, Bickel, B. (2018). Nouns slow down speech across structurally and culturally diverse languages *Proceedings of the National Academy of Sciences* 115.22:5720–5725

Shea, SA. 1996. Behavioural and arousalrelated influences on breathing in humans. *Experimental Physiology: Translation and Integration* 81.1:1–26

Shea, SA, Guz, A. 1992. Personnalité ventilatoirean overview. *Respiration Physiology* 87.3: 275–291

Shea, SA, Walter, J, Pelley, C, Murphy, K, Guz, A. 1987. The effect of visual and auditory stimuli upon resting ventilation in man. *Respiration Physiology* 68:45–57

Shockley, K, Richardson, DC, Dale, R. 2009. Conversation and coordinative structures. Topics in Cognitive Science 1.2: 305–319

Sperry, EE, Klich, RJ. 1992. Speech breathing in senescent and younger woman in oral reading. *Journal of Speech and Hearing Research* 35: 1246–1255

Stetson, RH. 1951. *Motor phonetics: A study of speech movements in action.* Amsterdam: North-Holland

Stivers, T, Enfield, NJ, Brown, P, Englert, C, Hayashi, M, Heinemann, T, Hoymann, G, Rossano, F, de Ruiter, JP, Yoo, KE, Levinson, SC. 2009. Universals and cultural variation in turn-taking in conversation. *Proceedings of the National Academy of Sciencesn* 106.26:10587–10592

Strik, H, Boves, L. 1995.Downtrendin f0 and Psub. *Journal of Phonetics* 23:203–220

Terzioğlu, Y, Mutlu, B, ahin, E. 2020. Designing social cues for collaborative robots: The role of gaze and breathing in Human-Robot Collaboration. In *Proceedings of the 2020 ACM/IEEE International Conference on Human-Robot Interaction* pp.343–357

Titze, I. 1989. On the relation between subglottal pressure and fundamental frequency in phonation. *The Journal of the Acoustical Society of America* 85:901-906

Torreira, FJ, Bögels, S, Levinson, SC. 2015. Breathing for answering. The time course of response planning in conversation. *Frontiers in Psychology*6:284

Trouvain, J. 2014. Laughing, breathing, clicking. The prosody of nonverbal vocalisations. In *Proceedings of Speech Prosody* 7:598–602

Wang, YT, Green, JR, Nip, IS, Kent, RD, Kent, JF. 2010. Breath group analysis for reading and spontaneous speech in healthy adults. *Folia Phoniatrica et Logopaedica* 62.6: 297–302

Warner, RM, Waggener, TB, Kronauer, RE. 1983. Synchronized cycles in ventilation and vocal activity during spontaneous conversational speech *Journal of Applied Physiology* 54.5:1324–1334

Watson, PJ, Ciccia, AH, Weismer, G. 2003. The relation of lung volume initiation to selected acoustic properties of speech. *The Journal of the Acoustical Society of America* 113.5:2812–2819

Whalen, DH, Kinsella-Shaw, JM. 1997. Exploring the relationship of inspiration duration to utterance duration. *Phonetica* 54: 138–152

Whalen, DH, Levitt, AG. 1995. The universality of intrinsic F 0 of vowels textitJournal of Phonetics 23.3:349–366

Wiksell, WA. 1935. *An Experimental Study of Controlled and Uncontrolled Types of Breathing.* (Unpublished doctoral dissertation). Louisiana State University, Historical Dissertations and Theses. 7778

Wilder, CN. 1974. Respiratory patterns in infant cry. *Developmental Psychology* 6:293–301

Winkworth, AL, Davis, P, Ellis, E, Adams, RD. 1994. Variabilitz and consistencz in speech breathing during reading¿ Lung volumens, speech intensity and linguistic factors. *Journal of Speech, Language and Hearing Research* 37:535-565

Winkworth, AL, Davis, P, Adams, RD, Ellis, E. 1995. Breathing patterns during spontaneous speech. *Journal of Speech, Language and Hearing Research* 38: 124-144

Wlodarczak, M. 2019. RespInPeace: toolkit for processing respiratory belt data. In *Proceedings of Fonetik*, Stockholm (Sweden): 115-118

Wlodarczak, M, Heldner, M. 2017. Respiratory constraints in verbal and non-verbal communication. *Frontiers in Psychology*8: 708

Yuasa, IP. 2010. Creaky voice: A new feminine voice quality for young urban-oriented upwardly mobile American women? *American Speech* 85.3: 315-337

Zhang, Z. 2016. Respiratory-laryngeal coordination in airflow conservation and reduction of respiratory effort of phonation. *Journal of Voice* 30.6: 760.e7-760.e13

Zhang, YS, Ghazanfar, AA. 2018. Vocal development through morphological computation. *PLOS Biology* 16(2): e2003933