



Speech breathing: variable but individual over time and according to limb movements

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Speech breathing: variable but individual over time and according to limb movements

Short title: Speech breathing: variable but individual

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Keywords: speech breathing; within-speaker variability, between-speaker variability, narration; limb movements

Abstract

Breathing is variable but also highly individual. Since the 1980s, evidence of a “ventilatory personality” has been observed in different physiological studies. This original term refers to within-speaker consistency in breathing characteristics across days or even years. Speech breathing is a specific way to control ventilation while supporting speech planning and phonation constrains. It is highly variable between speakers but also for the same speaker, depending on utterance properties, the involvement of the speaker in bodily actions, and the context of an interaction. Can we yet still observe consistency over time in speakers’ breathing profiles despite these variations? We addressed this question by analyzing the breathing profiles of 25 native speakers of German performing a narrative task on two days under different conditions of limb movements. The individuality of breathing profiles over conditions and days was assessed by adopting methods used in physiological studies that investigated the “ventilatory personality.” Our results suggest that speaker-specific breathing profiles are maintained over days and that they stay consistent despite light physical activity. These results are discussed with a focus on better understanding what speech breathing individuality is, how it can be assessed, and the types of research perspectives that this concept opens up.

Introduction

The primary aim of respiration is to maintain the homeostasis of the body. Respiration supports gas exchanges by means of a continuous flow of oxygen-rich air in the lungs and carbon dioxide-rich air out of the lungs. This mechanism results in fairly symmetrical inhalation and exhalation phases. The control of respiration largely depends on a central pattern generator located in the brain stem,^{1,2,3} but it is also influenced by other subcortical and cortical areas involved in the control of complex behaviors.^{2,4} Respiration is highly sensitive and adaptive: any sensorial stimulation, emotional reaction, increase in cognitive activity, or physical activity have consequences on the breathing rhythm and may even reshape the breathing cycle.^{2,5}

Despite the large flexibility of the respiratory system, within-individual consistency has also been observed. Dejour and colleagues claimed that “... even under identical conditions, the characteristics of ventilation differ from participant to participant, which leads to the concept of a ventilatory ‘personality’”⁶. While the term “ventilatory personality” is used in the literature on physiology, individual consistency in breathing profiles will be referred to as “individuality” in this paper to avoid any confusion with personality traits. Benchetrit and colleagues investigated individuality in tidal breathing by comparing within- vs. between-participant profiles at two time points separated by four to five years.⁷ The authors report a significantly lower within- than between-participant variability on different parameters used to characterize the breathing cycle. Shea and colleagues reported large between-participant differences in tidal breathing profiles but consistency for the same person recorded four times over two days⁸ and for breathing during deep sleep.⁹ Tidal breathing is also more similar in monozygotic twins than in random and dizygotic pairs.^{10,11} These findings suggest that basic

breathing rhythms are to some extent determined by genetic and/or physiological factors. However, this initial work on the “ventilatory personality” focused on tidal breathing. Does this individuality of speakers’ breathing profiles hold for other types of breathing control?

Breathing is the only mechanism controlled by the vegetative nervous system that can also be controlled voluntarily, and that can be modified to achieve a large range of skills. Voluntary breathing might be as variable, as there are skills requiring different adaptations of breathing control. This leads to the question of the relationship and potential interaction between the individuality of breathing profiles observed for tidal breathing and behavioral breathing. The fact that breathing is highly variable between activities, as well as between participants for a given activity, suggests task-specific individual control of breathing. Eisele and colleagues observed no within-participant stability between breathing at rest and breathing during exercise.¹² More recently, Besleaga and colleagues observed “individuality” of breathing profiles during moderate volitional hyperventilation, with this “individuality” being unrelated to that observed in the breathing profiles at rest.¹³ Hence, breathing at rest, as well as volitional breathing are variable between participants, and between tasks for a participant, but consistent for the same participant in a given task. Does this also apply to breathing in spoken communication, which is another highly specific facet of breathing?

Speech requires radical changes in breathing that strongly vary according to linguistic, cognitive, and interactive parameters.^{14,15} To some extent, speech is probably the behavior involving the most dramatic reshaping of ventilation.¹⁶ Compared to non-speech breathing, inhalation phases are strongly reduced while exhalation durations

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increase. This is particularly the case for read speech and to a lesser extent for spontaneous speech.¹⁷⁻²⁰ Speech breathing is also influenced by changes in loudness or voice quality,^{21,22} as well as interactive constraints such as turn-taking in dialogue.^{23,24,25} Different studies have investigated the link between body type and speech breathing.^{26,27} Links between lung capacity and utterance length have been found in developmental studies²⁸ but are so far unclear in adult populations.²⁹ Even if speech breathing has been well described in previous works, its link to non-speech breathing and its stability across different contexts and over time for the same speaker remain unclear. Speech breathing is multidetermined. When speaking freely, speakers produce quite variable breathing cycles in term of duration and volume of air inspired. The individuality of breathing profiles previously observed in other activities across different days (i.e., the consistency in breathing parameters at different times for a given person when compared to other persons) may thus not be observed for spontaneous speech. At the same time, speech breathing is highly dependent on cognitive and physiological resources and those are speaker specific.

Speech breathing profiles may also be influenced by simultaneous physical activity, such as limb movements. Speaking while walking, for example, is a very common situation. Limb movements indeed have an effect on ventilation that may affect speech breathing. This effect is particularly well known in everyday physical activities and described in studies investigating speech production during physical effort induced by leg motion (locomotion, cycling).^{30,31,32} Numerous papers have also described the effect of arm motion, and especially hand gestures, on speech production.^{33,34} Evidence of a coupling between arm/hand motion and speech control has been provided in the course of ontogenesis.³⁵ More recently, ventilation has been introduced

as a key factor in the speech-arm coupling. Pouw and colleagues suggested that the biomechanical effects of upper limb movements on the breathing system may affect vocal acoustics and that it may have played an important role in the phylogenesis of the speech-hand link.^{36,37,38} In everyday life, limb motion is ubiquitous and introduces “natural” variability in speech breathing profiles that may interact with the potential individuality of speech breathing. At the same time, speech puts such huge constraints on breathing that speech breathing could resist the influence of physical activity as long as the latter remains fairly mild. In this framework, arm and leg motions can be considered as a “bodily context” to investigate speech breathing individuality. Leg motion may induce global changes in the respiratory flow while arm movements, being more connected to the breathing system, should induce more local changes. Both types of changes may potentially affect the speech breathing cycle and its individual consistency.

In this paper we assess the individuality of speech breathing in spontaneous speech by focusing on three general questions: (1) Is quiet breathing individuality related to potential speech breathing individuality? (2) Can speech breathing individuality be observed across multiple days, as previously observed for other non-spoken tasks? (3) Is speech breathing individuality sensitive to the global pressure induced by leg motion on the respiratory system and/or more specific changes induced by arm motion? We address these questions by applying methods previously used in physiological studies to assess the “ventilatory personality”, or “breathing individuality”, to analyze the breathing profiles of 25 native speakers of German recorded on two days while retelling short stories.

Methods

The procedure was approved by the Ethical Board of the German Linguistic Society. The data were recorded at the Leibniz-Zentrum Allgemeine Sprachwissenschaft (ZAS). The procedure was designed for the collection of speech, breathing, and limb motion data during a narrative task. The general purpose was to characterize within- and between-participant behaviors to assess the bodily anchoring of spoken language. To this end, the present paper assesses the consistency of speakers' breathing during different quiet and spoken tasks (day 1) and during spoken tasks across time (day 1 and day 2).

Participants

Twenty-five healthy participants (19 females, 6 males), aged 20 to 29 (mean = 23.3 years; standard deviation = 2.5 years), were recruited using email announcements sent via a study-participant database. All participants spoke German as their native language and reported no respiratory, motor, neurological, speech, or hearing pathologies. They signed a consent form and received €10 per hour for their participation.

Material for the narrative task

Four short stories were created. Each story was about an alien arriving on Earth and attempting to build a house. The stories' structure was based on Mandler and Johnson's work.³⁹ The number of details in the descriptions and actions was precisely controlled and all stories describe actions with similar narrative content. New stories were created instead of using existing ones in order to control the quantity and type of information speakers would be asked to recall during the narrative task and to reduce bias related to previous knowledge. The stories were presented as short animations

with the same number of pictures. The stories respectively contained 292, 264, 291, and 300 words. One story has been uploaded to the OSF repository as an example: <https://osf.io/w6nq7/>.

Experimental setup

As illustrated in Figure 1 (left), the participants were fitted with chest and waist belts to record breathing kinematics using the Inductotrace inductance plethysmography system (Ambulatory Monitoring Inc, NewYork, USA). A microphone (MKH 50 P48, Sennheiser) was used to record their speech. Motion capture (OptiTrack, NaturalPoint Inc.) and video recordings were used to get a complete picture of the participants' motion. Only the breathing data, and not the motion capture data, are analyzed in this paper. A mini-bike (SportPlus, Hamburg, Germany) was placed in front of the participant, either on a table, when biking with the hands, or at her feet, when biking with the legs.

***** INSERT FIGURE 1 HERE *****

Procedure

The data were collected using a multi-task within-participant design in a longitudinal setting on two different days. The experimental design included different tasks.

Tasks

On day 1, after reading the information sheet and signing the consent form, participants were asked to fill in questionnaires about their daily physical activities. Then participants were fitted with markers for the motion capture system and two respiratory belts, one at the ribcage and another at the abdomen, for the breathing tracking system. They sat in a chair during the entire recording.

On day 1, breathing was first recorded for 2 minutes in each of the following conditions: at rest (when doing nothing, quiet_noMot), biking with the arms (quiet_armMot) and biking with the legs (quiet_legMot) at a self-selected comfortable pace. Participants were also asked to inhale and then exhale as much air as they could in order to obtain the maximal expansion of the respiratory belts, which is an indication of vital capacity as expressed in the Inductotrace coordinate system.

On days 1 and 2, the participants' main task was to watch each story and then recall it in one of the following conditions (see Figure 1, right): (1) arms free: speaking without any constraint on limb movement (speech_armFree); (2) arms blocked: speaking with the hands holding the chair (speech_armBlock); (3) biking with the legs: speaking while comfortably biking with the legs (speech_legMot); (4) biking with the arms: speaking while comfortably biking with the arms (speech_armMot).

The order of presentation of the stories, and the presentation of a given story in a given condition were balanced: each story was presented 5 or 6 times in each condition and each condition appeared between 5 to 7 times in each position (i.e. 1st, 2nd, 3rd, 4th).

Two participants did not come back on day 2 but their data from day 1 were kept for the analyses.

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3 The participants also performed controlled memory tests about specific information
4 included in the stories after each retelling but these are not relevant for the current
5 work.
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14 As it can be seen on Figure 1, on day 1, after the baseline conditions (quiet_noMot,
15 quiet_legMot, quiet_armMot), participants performed the main task as described
16 above. On the following day (day 2), they first recalled freely everything they could
17 remember about the stories, and then watched and retold the stories again. Note that
18 participants were invited to come back 10 days later to assess long-term memory of
19 the stories. Since the participants did not repeat all conditions again, this session is not
20 relevant for the current study.
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40 *Data processing*

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42 Due to the sensitivity of the respiratory belts to torso movements, limb movements –
43 in our case, biking motion – could affect the breathing signal. Signs of leg and arm
44 movements during cycling were indeed observed in our dataset. However, as the
45 motion was cyclical, it was easy to identify in the signal. This noise can be considered
46 acceptable because its amplitude was small and the main frequencies of the cycling
47 movements were higher than that of the breathing signal. The biking motion thus add
48 inevitable but acceptable noise to the dataset with regards to the aims of the current
49 work (especially since we do not analyze amplitude).
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The respiratory signals of the thorax and abdomen were low-pass filtered at 10 Hz and down sampled from 44100 Hz to 100 Hz. To convert the changes in the thoracic and abdominal sections recorded by the plethysmography system to overall relative change in lung volume, a transformation is required. We used the method suggested by Banzett, who evaluated the contribution of thoracic and abdominal circumference changes to lung volume to be: $2 * \text{thorax displacement} + 1 * \text{abdomen displacement}$.⁴⁰ According to Mckenna and Huber, Banzett’s method is more reliable than more complex methods based on isovolume maneuvers.⁴¹ Inhalation peaks and onsets were automatically detected and then manually corrected after visual inspection. The analyses described below involved a total of 7,229 breathing cycles, distributed across conditions as follows: quiet_legMot: 905 cycles; quiet_armMot: 865 cycles; quiet_noMot: 768 cycles; speech_armFree: 1,150 cycles; speech_armBlock: 1,144 cycles; speech_legMot: 1,235 cycles; speech_armMot: 1,162 cycles.

Variables, predictions and analyses

Variables

***** INSERT FIGURE 2 HERE *****

Based on previous work on speech breathing,^{7,15} each breathing cycle was characterized by three variables, which are illustrated in Figure 2:

(1) The total duration of the cycle (cycleDur) measured from inhalation onset to the next inhalation onset, expressed in seconds (Figure 2.A);

(2) The symmetry of the cycle (cycleSym), computed as the ratio of inhalation duration (inhDur) divided by total cycle duration (cycleDur) (Figure 2.A);

(3) A multivariate variable (cycleShape) introduced in previous work on the “ventilatory personality” and representing the shape of the cycle. According to Bachy and colleagues, 95% of a breathing cycle at rest can be reconstructed from the modulus and the argument of the first four harmonics of the cycle (Figures 2.B and 2.C).⁴² These parameters, the modulus and argument of the first four harmonics, were thus used as a representation of the cycle shape. Even if less interpretable than univariate measures, this variable is particularly interesting: the breathing signal, and especially the speech breathing signal, may indeed be shaped by an interaction of constraints. In order to calculate the cycleShape variable, each cycle was normalized in duration (a) and amplitude (b) (cf. Figure 2.C):

(a) The cycles were normalized to 64 points, corresponding to the largest and closest power of 2 to the number of points included in the shortest cycle (87 points).⁴²

(b) The amplitude of each cycle was normalized between 0 and 1 using the following formula, where y is the cycle signal:

$$y = \frac{y - \min(y)}{\max(y) - \min(y)}$$

Each normalized cycle was then decomposed in the frequency domain using the Fast Fourier Transform. The parameters of the first four harmonics (modulus and argument) were extracted to characterize the cycle (Figure 2.B). They can be used to reconstruct the cycle with a sum of four cosine functions, the frequency, amplitude, and phase of which correspond to the frequency, modulus, and argument parameters described above (Figure 2.C; note that due to temporal normalization the frequencies were the

same for all the cycles). On average, the first four harmonics accounted for 95% (1st quartile = 0.92; 3rd quartile = 0.99; sd = 0.059) of the signal power for the cycles at rest and 90% (1st quartile = 0.88; 3rd quartile = 0.97; sd = 0.11) for the speech cycles.

Analysis of the effect of motion, speech, and day on breathing

We first characterized the effect of speech, motion, and day on the duration and symmetry of the cycle to allow for comparison with previous work and to provide an overview of the variables.

Linear mixed models were used to assess the effects of limb motion, condition, speech, and day, on both the log of breathing cycle duration and the logit of symmetry (data were transformed for normality constraints). Participant was included in the model as a random effect. To consider the potential autocorrelation between the consecutive breathing cycles within a participant's session, the position of the cycles was included in the model. Non-homogenous variance across conditions was corrected for when present. A backward model selection was used to select significant factors. These models were applied on the parameters of all cycles, for each participant, day, and condition. We ran the analysis in the R software environment using the nlme package (codes and data available at <https://osf.io/w6nq7/>).^{43,44,45}

The first model was applied to the data from day 1. Its aim was to examine the effect of limb motion on breathing cycle duration and symmetry in the quiet and speech conditions. Note that we did not compare the quiet and speech conditions as it is already evident from previous work that speech breathing cycles are longer and clearly less symmetric than quiet breathing cycles. We used a two-factor model: vocalCondition (speech; quiet) and limbCondition (legMot; armMot; noMot). Since participants did not move the hands in either the quiet_noMot or the speech_armBlock

conditions (not necessarily the case in the other conditions), speech_armBlock was considered to be the equivalent speech condition of quiet_noMot.

The second model was applied to the data from the speech conditions only. Its aim was to examine the effect of limb motion (armFree; armBlock; legMot; armMot) and day (1; 2) on speech breathing cycle duration and symmetry.

Post-hoc comparisons were made using the Tukey HSD correction. The critical significance threshold was fixed at 0.05. Only the significant differences are described below; all the other comparisons did not show significant differences.

Analysis of within-participant consistency across conditions and days

In agreement with the literature, the individuality of the breathing pattern was assessed using the method developed by Benchetrit and colleagues.⁷ The aim was to determine whether within-speaker variability is lower than between-speaker variability across conditions and over time for a given parameter describing the breathing cycle. This would be the case if the difference between two conditions for the same participant were to be significantly smaller than the difference between two participants in the same or other conditions. This difference was quantified by computing the distances between a given set of values of each respiratory cycle parameter for one participant and one condition and each of the 49 other sets of values of the same parameter (2 conditions x 25 participants = 50 sets of values). Benchetrit and colleagues used the Mahalanobis distance.⁷ However, in our dataset, the distributions of the values of the breathing parameters per speaker were not Gaussian and non-normality was observed for all parameters. For this reason, we used the Cramér-von Mises distance.⁴⁶ Instead

of using the mean and variance of the distribution of parameter values, the Cramér–von Mises distance is directly based on the distribution functions.

For the *cycleDur*, *cycleSym*, and *cycleShape* parameters, S_{ij} corresponds to the distribution of the considered parameter for participant i in condition j . For each S_{ij} , the 49 distances to all the other distributions were computed. These distances were then ranked from smallest to largest. This procedure resulted in 50 sets of 49 sorted distances. The ranks of the within-participants' distances were then summed (*Twthin* statistic) as well as the ranks from 25 pairs (S_{ij} , $S_{ij'}$) taken randomly (*Tbtw* statistic). To estimate the distribution of *Tbtw*, the Monte Carlo technique⁴⁷ was used: a sample of 25 pairs (S_{ij} , $S_{ij'}$) was taken randomly 1,000 times to get 1,000 values of *Tbtw*. The null hypothesis (*Twthin* is not different from *Tbtw*, from condition j to condition j') is rejected when the p-value resulting from the comparison between *Twthin* and the *Tbtw* distribution is smaller than 0.05. Bonferroni correction was applied by multiplying the p-value by the number of comparisons required for the tested hypothesis (corresponding to the numbers of same-color boxes in Figure 3).

The method developed by Benchetrit and colleagues⁷ was used to assess the stability of speakers' breathing profiles in different conditions relative to the following aims. First, in order to examine whether we could reproduce Eisele and colleagues'¹² results on the inconsistency of respiratory patterns between rest and exercise, we compared the three quiet conditions on day 1 (3 comparisons: in orange in Figure 3). Second, to investigate the individual consistency of the breathing cycles between non-speech and speech breathing, we compared the quiet and speaking conditions on day 1 (3 comparisons: in green in Figure 3). Because participants did not move the hands in

the quiet_noMot condition, this condition was compared with speech_armBlock in the linear mixed model analyses. Third, to investigate the stability of breathing profiles in spontaneous speech, we compared the four speaking conditions between each other, on days 1 and 2 (12 comparisons: in blue in Figure 3). Fourth, to investigate the stability of breathing profiles in spontaneous speech over time, we compared each speech condition between day 1 and day 2 (4 comparisons: in yellow in Figure 3).

***** INSERT FIGURE 3 HERE *****

Results

We first provide an overview of the global effects of biking and time on the symmetry and duration of the breathing cycle. We then present the analysis of within-participant consistency for the different parameters across conditions and days.

Average changes in cycle duration and symmetry induced by limb motion

The effect of limb motion on breathing was assessed in two analyses.

The first analysis concerns only the data on day 1. Its purpose was to assess the effect of limb motion on the duration (cycleDur) and the symmetry (cycleSym) of quiet and speech breathing cycles. For both variables, the selected statistical models included the interaction between vocalCondition and limbCondition and the position of the cycle in the time series.

As displayed in Figure 4, the presence of limb motion decreased the average duration of the breathing cycle in the quiet conditions (quiet_noMot - quiet_armMot: $b=0.13$,

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z=3.29, p=0.009; quiet_noMot - quiet_legMot: b=0.16 z=3.96, p<0.001); while it increased the symmetry of the cycle (quiet_noMot - quiet_armMot: b=-0.11, z=-3.98, p<0.001; quiet_noMot - quiet_legMot: b=-0.14 z=5.1, p<0.001).

By contrast, adding leg or arm motion when speaking (speech_armMot and speech_LegMot) had no effect when compared to speaking with no motion (speech_armBlock).

The second analysis concerns the comparison of speech breathing cycles in the different conditions of limb motion and on different days (also displayed in Figure 4). For cycleDur, the final model included limbCondition, day, and the position of the cycle in the time series. On average, the duration of the breathing cycle was smaller in speech_legMot than in speech_armfree (b = 0.06, z = 3.4, p = 0.004) and in speech_legMot than in speech_armMot (b = 0.09, z = 4.82, p < 0.001). Other comparisons were not significant. Regardless of the condition, on day 2, the cycles tended to be longer than on day 1, but the difference was not significant (b = -0.07, z = -2.61, p = 0.06).

For cycleSym, the final model included the interaction between limbCondition and day and the position of the cycle in the time series. The symmetry of the cycle was larger in speech_legMot than in speech_armFree (b = -0.07, z = -3.52, p = 0.003) and in speech_legMot than in speech_armBlock (b = -0.07, z = -3.54, p = 0.0031). Other comparisons were not significant. The cycles were also less symmetric on day 2 than on day 1 (b = 0.1, z = 3.02, p = 0.02).

***** INSERT FIGURE 4 HERE *****

Individual consistency of the breathing cycle

Consistency refers to the fact that the breathing-cycle parameter values for a given speaker in a given condition are closer to those of the same speaker in another condition (individual cross-condition consistency) or in the same condition on another day (individual cross-temporal consistency) than to those of other speakers in the same or different conditions.

Individual cross-conditions consistency in quiet and quiet vs. speech conditions on day 1

None of the comparisons between the quiet conditions for cycleDur, cycleSym and cycleShape (orange comparisons in Figure 3) were significant, except for breathing cycle duration between the quiet_legMot and quiet_armMot conditions ($P_t \leq 0.003$, Table1).

None of the comparisons between quiet and speech conditions (green comparisons in Figure 3) were significant ($P_t \geq 0.54$, Table 1). Individual cross-condition consistency was thus not observed on day 1 between quiet conditions and between quiet and speech conditions.

***** INSERT TABLE 1 HERE *****

Individual cross-condition consistency in speech conditions on day 1 and on day 2

On each day, within-speaker distances were ranked significantly lower than random association distances ($P_t \leq 0.048$) for all comparisons (blue comparisons on Figure 3),

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for cycleDur, cycleSym, and cycleShape (cf. Table 2). There was, however, a single exception: for cycleShape the difference between speech_armBlock and speech_legMot was not significant ($P_t = 0.456$).

***** INSERT TABLE 2 HERE *****

Individual cross-day consistency of speech breathing profiles

Between days, for the speech conditions (yellow comparisons in Figure 3), participants were generally closer to themselves than to other participants (cf. Table 3) in terms of cycle duration ($P_t < 0.04$), symmetry ($P_t < 0.004$) and shape ($P_t < 0.04$), except for the armFree condition, for which cycleDur is not consistent ($P_t = 0.08$).

***** INSERT TABLE 3 HERE *****

Discussion

Breathing presents individual specificities in a given task at a given time. However, individual consistency of speech breathing across tasks and over time has not yet been investigated. In the current study, we examine the individual consistency of speech breathing profiles in different conditions of limb movements and on two different days. We applied a method previously developed to assess the individuality of tidal and exercise breathing^{7,12}. We found individual consistency of breathing profiles over days even when speech is produced at the same time as light physical activity with the arms or the legs.

Our analyses also replicated the inconsistency in individual breathing profiles previously reported between breathing at rest and breathing during physical exercise¹². On day 1, biking either with the legs or the arms while remaining quiet shortened the breathing cycles and increased cycle symmetry as compared to being quiet and not moving. For the speech conditions, the effect of biking on speech breathing was observed only for leg biking: it decreased the duration and increased the symmetry of the cycles as compared with the other speech conditions. When speaking, arm motion does not have a significant effect on breathing as compared with speaking without moving. In general, changes in breathing profiles related to leg motion didn't affect the individual consistency of cycle duration, symmetry and shape between speech conditions.

This suggests that speech breathing individuality is maintained despite co-occurrent motion of the arms or the legs, at least when these are cyclic and do not strongly impact ventilation. The level of exercise to which the participants were committed was indeed light. Regarding previous work,^{30,31,32} it is well known that physical effort impacts speech breathing, what is unknown is whether this impact also affects the individuality of breathing and/or if speakers' strategies to compensate for physical effort are consistent over time. It would be interesting to examine if speech breathing patterns are maintained during intense physical activity.

Assessing the consistency of speech breathing over different bodily contexts is a way to address the specificity of speech breathing skills. In previous work, this bodily context was modulated by controlling the degree of effort. In the current work, we used leg vs. arm movements. Pouw and collaborators have recently introduced the idea that arm motion may constrain changes in speech production due to the physical impulse

they impose on the breathing system,^{36,37} which may affect vocal output. They defend the idea that this link is anchored in phylogenesis: the bipedal state freed the upper limbs and the respiratory system from being synchronized with locomotion. In return, the upper limbs may have participated in the complexification of the control of the respiratory system for speech. This is a parsimonious explanation for the mutual influences between hand movement and phonation in communication as compared with a cognitive explanation.³⁶

In the current study, we focused on the individuality of speech breathing, and did not investigate the effect of cycling on the vocal output. A next step will be to assess this question, and go further by comparing the effect of lower vs upper limb. Local effects of manual cycling on vocal acoustics, thereby on speech breathing, may appear.

We found individual consistency of the breathing profiles from one day to another, for all comparisons, and changes in cycle duration and symmetry between day 1 and day 2 did not affect this consistency – except for the cycle duration in speech_armFree. These results are in line with the individual consistency of the tidal breathing profiles from one day to another.⁸ It would be interesting to see if, as for tidal breathing, we find this consistency across years.⁷

Beyond these specific points, the study raised the question of why should speech breathing be consistent or not be for a same speaker over bodily contexts and days? Different constraints related to speech production might shape the breathing cycle.

First, the cycle shape, as defined in the current work, may be heavily affected by segmental and prosodic aspects of the produced speech material. For instance, voiceless sounds, produced with an open glottal configuration, can lead to a steeper

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3 respiratory slope than voiced sounds.^{48,49} The measured kinematic output in speech
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5 production is therefore heavily modulated by the opening or closing of the laryngeal
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7 valve which can also compensate for the loss of air.^{50,51}
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11 Second, speech breathing rhythm is in general irregular: cycle durations, and
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13 especially exhalation durations, are related to the length of the utterance produced.
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15 The current study focused on the analysis of the breathing cycles only. It is however
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17 possible that consistency in breathing profiles – and in particular for the duration
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19 parameter – could be explained by the fact that people are consistent in the duration
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21 of their utterances. Further analyses of our dataset suggest that utterance duration is
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23 indeed correlated to cycle duration (Pearson's correlation: $r=0.9$, $t = 138.83$, $df = 4689$,
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25 $p\text{-value} < 2.2e-16$) and to a lesser extent to cycle symmetry ($r=-0.65$, $t = 57.9$, $df =$
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27 4689 , $p < 2.2e-16$). Utterance duration is also consistent between day 1 and day 2 and
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29 across conditions.
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38 But the question rises of how to rule out whether utterance length is determined by
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40 breathing cycle duration or by the volume of air available in the lungs? The fact that
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42 breathing profiles during spontaneous speech are clearly different than during reading
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44 and in particular the fact that the link between inhalation profile and utterance
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46 properties is weaker in the former than in the latter^{52,53,54} suggests that two levels of
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48 control are involved: (1) a global planification; (2) an online adaptation. The contribution
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50 of these two types of controls (that echo forward vs. feed-forward model of motor
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52 control)^{55,56} might be specific to the speaker and may depend at least on three types
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54 of elements: (1) bodily-related constraints; (2) cognitive and linguistic constraints; and
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56 (3) interactive constraints.
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3 First, speech breathing might be individually consistent due to body properties. A first
4 factor considered in the literature to affect breathing is lung volume capacity that is
5 variable among speakers and depends on the size of the body.^{26,27,29} In the course of
6 child development, evolution of utterance length was observed in relation to increase
7 in lung volume.²⁸ One can expect speakers with larger lung volume, taller people for
8 example, to produce longer utterances. This wasn't observed so far: positive
9 correlation between vital capacity (the maximal amount of air one can inhale) and
10 utterance duration has not been confirmed for adults in the literature.²⁹ Besides, in their
11 investigation of the implication of the forebrain in breathing individuality, Shea and
12 collaborators⁹ reported different cycle shapes for same body types, and variable body
13 types for similar cycle shapes.

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33 Second, cognitive functioning and abilities such as working memory, attentional
34 capacity, but also specific linguistic experience might also affect speech breathing. The
35 hypothesis of a link between cognitive processing and breathing profiles was indeed
36 introduced early. In 1929, Golla and Antonovitch, suggested that people who rely more
37 on visual mental imagery display more regular breathing profiles at rest than people
38 who rely more on auditory imagery.⁵⁷ Grassman and colleagues, show that "mentally
39 demanding episodes are clearly marked by faster breathing and higher minute
40 ventilation" (p.1).⁵⁸ More recently, in a comprehensive study, Park and colleagues
41 investigate the "readiness potential", an ERP component consistently found before
42 initiating voluntary actions.⁵⁹ Their findings show that voluntary actions occur
43 frequently during exhalation, and that the amplitude of readiness potential depends on
44 the respiratory phase, i.e., actions are phase coupled to breathing. While they do not

report individual differences, they refer to the literature on different participant groups, showing, for example, differences among athletes and non-athletes.

Finally, the study was run in a monologue situation while speech is most often produced in a dialogue situation. Previous work shows that breathing adapts to dialogue constraints and in particular to the turn-taking process^{23,24,25} but didn't find overall coordination of breathing^{23,24} expect in synchronous reading.⁶⁰ In conversational settings, speakers have to adapt to their interlocutor. The breathing individuality would be particularly interesting to assess during dialogue as a way to investigate (1) if speakers develop a specific way to control breathing in dialogue consistent across interlocutors or (2) if they rather lose their individuality to adapt to their interlocutor.

The results of these different investigations do not tell anything on the causal link between speech and breathing and their potential individuality. Speech breathing is complex and determined by many variables in interaction with one another in such a way that disentangling speech from breathing mechanisms would require multifactorial analyses with cognitive and physiological parameters. The aim of this paper was not to understand these underlying mechanisms, but to first ascertain the individual specificity of the patterns characterizing the breathing cycle.

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Author contributions

Hélène Serré contributed to the conception of the study, the data collection, the data analysis. She wrote an initial draft of the paper.

Susanne Fuchs, Marion Dohen and Amélie Rochet-Capellan contributed to the conception of the study, the data collection and the writing.

Silvain Gerber contributed to the statistical analysis.

Hélène Serré accepts to be responsible for the integrity of the data analyzed.

Competing interests

All authors declare no competing interests.

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Figure and table captions

Figure 1: Left: illustration of the experimental setup for the biking with the arms condition (speech_armMot). Right: Participants’ task according to day. From left to right: quiet doing nothing (quiet_noMot), quiet with legs biking (quiet_legMot), quiet with arms biking (quiet_armMot), speech with arms free (speech_armFree), speech with arms blocked (speech_armBlock), speech with legs biking (speech_legMot), speech with arms biking (speech_armMot).

Figure 2: Characterization of the speech breathing cycle. Column A illustrates the measurement of the cycle duration (cycleDur). Symmetry (cycleSym) was obtained by dividing the duration of inhalation (InhDur) by cycleDur. Column B displays the vectorial

representation (phase angles) and the magnitude of the first four harmonics of the Fourier transform applied on the cycle. The vectorial representation does not have axes per se: the length of the vector represents the amplitude of the given harmonic, and its orientation with respect to the horizontal axis corresponds to the phase angle. Column C displays an example of a normalized cycle (solid line) and the corresponding reconstructed airflow profile from the first four harmonics (dashed line). The axes are unitless because of the normalization

Figure 3: Summary of the 22 comparisons achieved to assess breathing individuality. Orange (o): changes due to moderate exercise while remaining quiet; Blue (b): stability in breathing profiles in spontaneous speech; Green (g): relation between non-speech and speech breathing; Yellow (y): stability of breathing profiles in spontaneous speech over time; White: comparisons we did not investigate.

Figure 4: violin plots of cycleDur (left) and cycleSym (right) in the different conditions of limb movements and over days. The values are z-scaled per participants.

Table 1: probability of T_{within} to be from the distribution of T_{btw} for each comparison between two quiet conditions, and between one quiet and one speech condition, within day 1 (p-values are considered significant when smaller than 0.05). T_{alpha} is the threshold value of rejection: under the null hypothesis (T_{within} comes from the distribution of T_{btw}), the probability of T_{alpha} is 0.05. Tw: T_{within} . Ta: T_{alpha} .

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Table 2: probability of Tw_{within} to be from the distribution of T_{btw} for each comparison between two speech conditions, respectively within day 1 and day 2. The significance threshold is 0.05 (as in Table 1). Tw: *Tw_{within}*. Ta: Talpha.

Table 3: probability of Tw_{within} to be from the distribution of T_{btw}, for each comparison from day 1 and day 2, respectively within each speech condition. The significance threshold is 0.05 (as in Table 1). Tw: *Tw_{within}*. Ta: Talpha.

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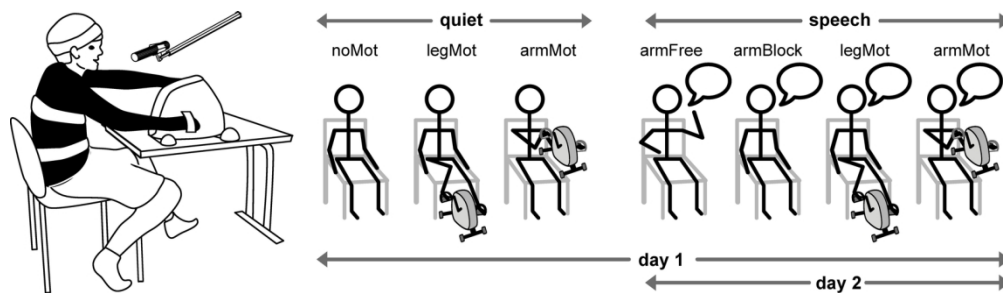


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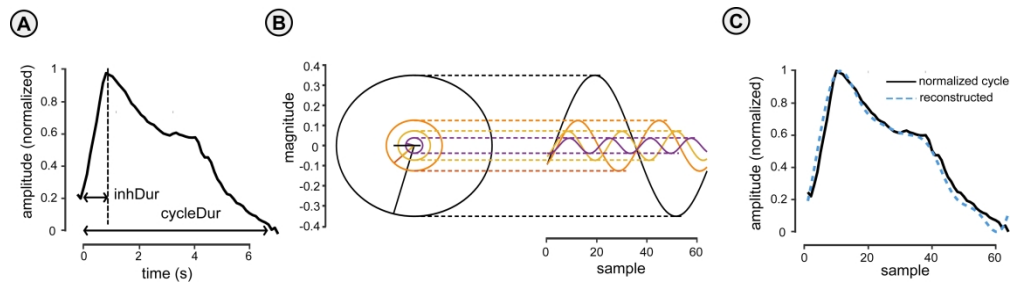


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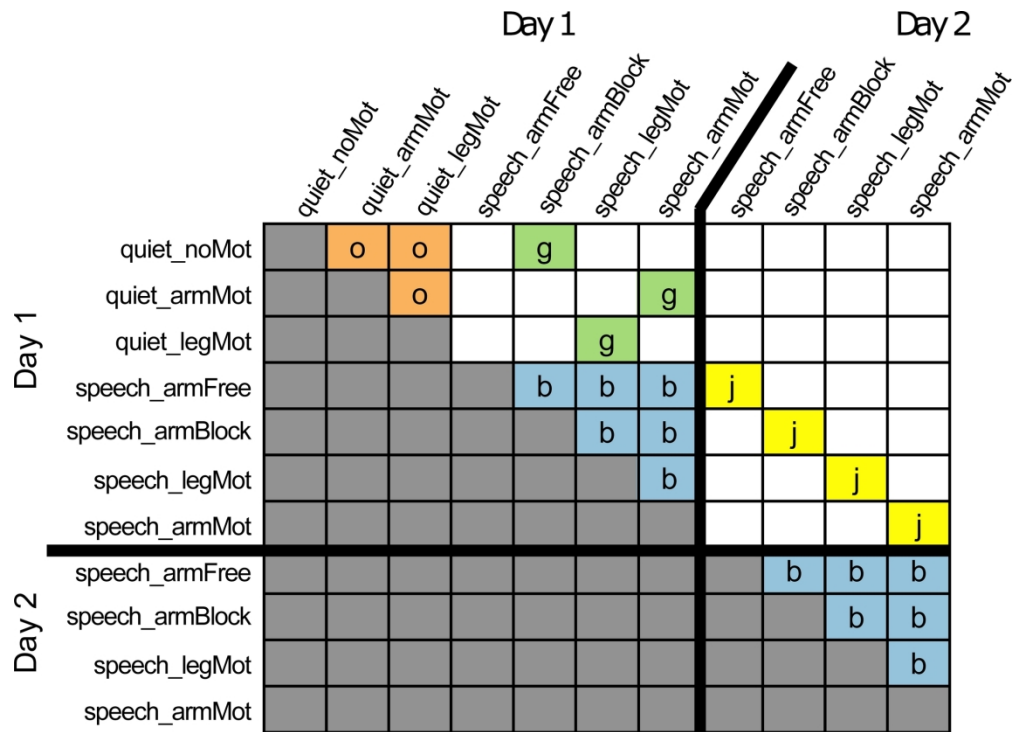


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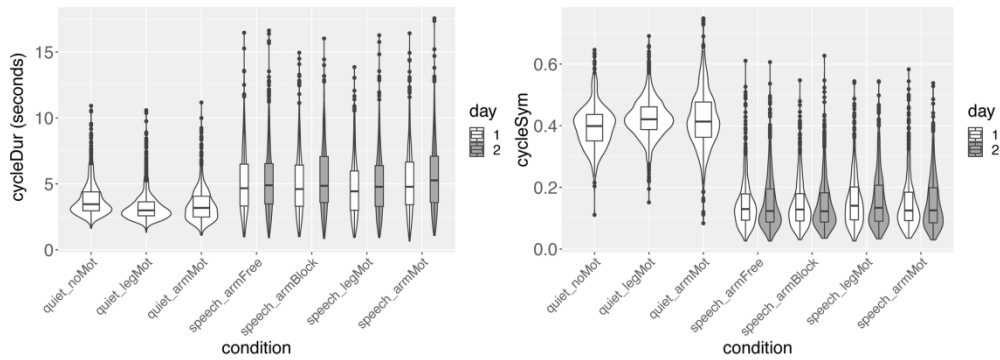


Figure 4: violin plots of cycleDur (left) and cycleSym (right) in the different conditions of limb movements and over days.

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		cycleDur			cycleSym			cycleShape		
Conditions compared		Ta	Tw	Pt	Ta	Tw	Pt	Ta	Tw	Pt
Day 1 quiet	quiet_legMot quiet_armMot	921	745	<0.003	937	998	0.021	939	1263	1
	quiet_noMot quiet_legMot	893	1285	1	947	1127	0.26	935	1234	1
	quiet_noMot quiet_armMot	995	1177	0.48	925	1168	0.39	880	1457	1
Day 1 quiet Vs speech	quiet_noMot speech_armBlock	932	1406	1	982	1838	1	906	1356	1
	quiet_legMot speech_legMot	918	1357	1	917	1867	1	857	1221	1
	quiet_armMot speech_armMot	932	1171	0.54	908	1862	1	931	1402	1

		cycleDur			cycleSym			cycleShape		
Conditions compared		Ta	Tw	Pt	Ta	Tw	Pt	Ta	Tw	Pt
Day 1 Speech	speech_armFree speech_armBlock	918	780	<0.012	971	515	<0.012	950	660	<0.012
	speech_armFree speech_legMot	955	815	<0.012	890	638	<0.012	924	923	0.012
	speech_armFree speech_armMot	881	837	<0.012	920	580	<0.012	917	873	<0.012
	speech_armBlock speech_legMot	911	796	<0.012	979	613	<0.012	920	1085	0.456
	speech_armBlock speech_armMot	970	888	<0.012	947	647	<0.012	923	900	<0.012
	speech_armMot speech_legMot	934	779	<0.012	920	636	<0.012	962	845	<0.012
Day 2 Speech	speech_armFree speech_armBlock	769	623	<0.012	812	390	<0.012	774	653	<0.012
	speech_armFree speech_legMot	745	735	0.012	778	479	<0.012	769	626	<0.012
	speech_armFree speech_armMot	744	725	0.012	799	570	<0.012	726	745	0.036
	speech_armBlock speech_legMot	722	745	0.036	751	420	<0.012	785	722	<0.012
	speech_armBlock speech_armMot	736	756	0.048	764	445	<0.012	749	735	<0.012
	speech_armMot speech_legMot	762	656	<0.012	761	322	<0.012	742	528	<0.012

		cycleDur			cycleSym			cycleShape		
Conditions compared from day 1 to day 2		Ta	Tw	Pt	Ta	Tw	Pt	Ta	Tw	Pt
Speech	speech_armFree	725	893	0.08	762	621	<0.004	749	818	0.04
	speech_armBlock	778	581	<0.004	771	554	<0.004	796	733	<0.004
	speech_legMot	756	838	0.04	786	460	<0.004	742	761	0.012
	speech_armMot	775	751	0.004	723	545	<0.004	797	742	0.004