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Rochet-Capellan

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

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3 **Speech breathing: variable but individual over time and according to limb**
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5 **movements**
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7 Short title: Speech breathing: variable but individual
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53 narration; limb movements
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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

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3 breathing rhythms are to some extent determined by genetic and/or physiological
4 factors. However, this initial work on the “ventilatory personality” focused on tidal
5 breathing. Does this individuality of speakers’ breathing profiles hold for other types of
6 breathing control?
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14 Breathing is the only mechanism controlled by the vegetative nervous system that can
15 also be controlled voluntarily, and that can be modified to achieve a large range of
16 skills. Voluntary breathing might be as variable, as there are skills requiring different
17 adaptations of breathing control. This leads to the question of the relationship and
18 potential interaction between the individuality of breathing profiles observed for tidal
19 breathing and behavioral breathing. The fact that breathing is highly variable between
20 activities, as well as between participants for a given activity, suggests task-specific
21 individual control of breathing. Eisele and colleagues observed no within-participant
22 stability between breathing at rest and breathing during exercise.¹² More recently,
23 Besleaga and colleagues observed “individuality” of breathing profiles during moderate
24 volitional hyperventilation, with this “individuality” being unrelated to that observed in
25 the breathing profiles at rest.¹³ Hence, breathing at rest, as well as volitional breathing
26 are variable between participants, and between tasks for a participant, but consistent
27 for the same participant in a given task. Does this also apply to breathing in spoken
28 communication, which is another highly specific facet of breathing?
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51 Speech requires radical changes in breathing that strongly vary according to linguistic,
52 cognitive, and interactive parameters.^{14,15} To some extent, speech is probably the
53 behavior involving the most dramatic reshaping of ventilation.¹⁶ Compared to non-
54 speech breathing, inhalation phases are strongly reduced while exhalation durations
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3 increase. This is particularly the case for read speech and to a lesser extent for
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5 spontaneous speech.¹⁷⁻²⁰ Speech breathing is also influenced by changes in loudness
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7 or voice quality,^{21,22} as well as interactive constraints such as turn-taking in
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9 dialogue.^{23,24,25} Different studies have investigated the link between body type and
10
11 speech breathing.^{26,27} Links between lung capacity and utterance length have been
12
13 found in developmental studies²⁸ but are so far unclear in adult populations.²⁹ Even if
14
15 speech breathing has been well described in previous works, its link to non-speech
16
17 breathing and its stability across different contexts and over time for the same speaker
18
19 remain unclear. Speech breathing is multidetermined. When speaking freely, speakers
20
21 produce quite variable breathing cycles in term of duration and volume of air inspired.
22
23 The individuality of breathing profiles previously observed in other activities across
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25 different days (i.e., the consistency in breathing parameters at different times for a
26
27 given person when compared to other persons) may thus not be observed for
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29 spontaneous speech. At the same time, speech breathing is highly dependent on
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31 cognitive and physiological resources and those are speaker specific.
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41 Speech breathing profiles may also be influenced by simultaneous physical activity,
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43 such as limb movements. Speaking while walking, for example, is a very common
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45 situation. Limb movements indeed have an effect on ventilation that may affect speech
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47 breathing. This effect is particularly well known in everyday physical activities and
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49 described in studies investigating speech production during physical effort induced by
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51 leg motion (locomotion, cycling).^{30,31,32} Numerous papers have also described the
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53 effect of arm motion, and especially hand gestures, on speech production.^{33,34}
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55 Evidence of a coupling between arm/hand motion and speech control has been
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57 provided in the course of ontogenesis.³⁵ More recently, ventilation has been introduced
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3 as a key factor in the speech-arm coupling. Pouw and colleagues suggested that the
4 biomechanical effects of upper limb movements on the breathing system may affect
5 vocal acoustics and that it may have played an important role in the phylogenesis of
6 the speech-hand link.^{36,37,38} In everyday life, limb motion is ubiquitous and introduces
7 “natural” variability in speech breathing profiles that may interact with the potential
8 individuality of speech breathing. At the same time, speech puts such huge constraints
9 on breathing that speech breathing could resist the influence of physical activity as
10 long as the latter remains fairly mild. In this framework, arm and leg motions can be
11 considered as a “bodily context” to investigate speech breathing individuality. Leg
12 motion may induce global changes in the respiratory flow while arm movements, being
13 more connected to the breathing system, should induce more local changes. Both
14 types of changes may potentially affect the speech breathing cycle and its individual
15 consistency.

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36 In this paper we assess the individuality of speech breathing in spontaneous speech
37 by focusing on three general questions: (1) Is quiet breathing individuality related to
38 potential speech breathing individuality? (2) Can speech breathing individuality be
39 observed across multiple days, as previously observed for other non-spoken tasks?
40 (3) Is speech breathing individuality sensitive to the global pressure induced by leg
41 motion on the respiratory system and/or more specific changes induced by arm
42 motion? We address these questions by applying methods previously used in
43 physiological studies to assess the “ventilatory personality”, or “breathing individuality”,
44 to analyze the breathing profiles of 25 native speakers of German recorded on two
45 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

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2
3 with the same number of pictures. The stories respectively contained 292, 264, 291,
4 and 300 words. One story has been uploaded to the OSF repository as an example:

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7 <https://osf.io/w6nq7/>.

8 9 10 11 12 *Experimental setup*

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14 As illustrated in Figure 1 (left), the participants were fitted with chest and waist belts to
15 record breathing kinematics using the Inductotracer inductance plethysmography
16 system (Ambulatory Monitoring Inc, New York, USA). A microphone (MKH 50 P48,
17 Sennheiser) was used to record their speech. Motion capture (OptiTrack, NaturalPoint
18 Inc.) and video recordings were used to get a complete picture of the participants'
19 motion. Only the breathing data, and not the motion capture data, are analyzed in this
20 paper. A mini-bike (SportPlus, Hamburg, Germany) was placed in front of the
21 participant, either on a table, when biking with the hands, or at her feet, when biking
22 with the legs.
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40 ***** INSERT FIGURE 1 HERE *****
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44 45 *Procedure*

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48 The data were collected using a multi-task within-participant design in a longitudinal
49 setting on two different days. The experimental design included different tasks.
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55 56 Tasks

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3 On day 1, after reading the information sheet and signing the consent form, participants
4 were asked to fill in questionnaires about their daily physical activities. Then
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6 participants were fitted with markers for the motion capture system and two respiratory
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8 belts, one at the ribcage and another at the abdomen, for the breathing tracking
9
10 system. They sat in a chair during the entire recording.
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14 On day 1, breathing was first recorded for 2 minutes in each of the following conditions:
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16 at rest (when doing nothing, quiet_noMot), biking with the arms (quiet_armMot) and
17
18 biking with the legs (quiet_legMot) at a self-selected comfortable pace. Participants
19
20 were also asked to inhale and then exhale as much air as they could in order to obtain
21
22 the maximal expansion of the respiratory belts, which is an indication of vital capacity
23
24 as expressed in the Inductotrace coordinate system.
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28 On days 1 and 2, the participants' main task was to watch each story and then recall it
29
30 in one of the following conditions (see Figure 1, right): (1) arms free: speaking without
31
32 any constraint on limb movement (speech_armFree); (2) arms blocked: speaking with
33
34 the hands holding the chair (speech_armBlock); (3) biking with the legs: speaking while
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36 comfortably biking with the legs (speech_legMot); (4) biking with the arms: speaking
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38 while comfortably biking with the arms (speech_armMot).
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42 The order of presentation of the stories, and the presentation of a given story in a given
43
44 condition were balanced: each story was presented 5 or 6 times in each condition and
45
46 each condition appeared between 5 to 7 times in each position (i.e. 1st, 2nd, 3rd, 4th) .
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49 Two participants did not come back on day 2 but their data from day 1 were kept for
50
51 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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10 11 12 Time line

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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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33 ***** INSERT FIGURE 1 HERE *****
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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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3 The respiratory signals of the thorax and abdomen were low-pass filtered at 10 Hz and
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5 down sampled from 44100 Hz to 100 Hz. To convert the changes in the thoracic and
6
7 abdominal sections recorded by the plethysmography system to overall relative
8
9 change in lung volume, a transformation is required. We used the method suggested
10
11 by Banzett, who evaluated the contribution of thoracic and abdominal circumference
12
13 changes to lung volume to be: $2 * \text{thorax displacement} + 1 * \text{abdomen displacement}$.⁴⁰
14
15 According to Mckenna and Huber, Banzett's method is more reliable than more
16
17 complex methods based on isovolume maneuvers.⁴¹
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20
21 Inhalation peaks and onsets were automatically detected and then manually corrected
22
23 after visual inspection. The analyses described below involved a total of 7,229
24
25 breathing cycles, distributed across conditions as follows: quiet_legMot: 905 cycles;
26
27 quiet_armMot: 865 cycles; quiet_noMot: 768 cycles; speech_armFree: 1,150 cycles;
28
29 speech_armBlock: 1,144 cycles; speech_legMot: 1,235 cycles; speech_armMot:
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31 1,162 cycles.
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38 *Variables, predictions and analyses*

39 Variables

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44 ***** INSERT FIGURE 2 HERE *****
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49 Based on previous work on speech breathing,^{7,15} each breathing cycle was
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51 characterized by three variables, which are illustrated in Figure 2:
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53 (1) The total duration of the cycle (cycleDur) measured from inhalation onset to the
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55 next inhalation onset, expressed in seconds (Figure 2.A);
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3 (2) The symmetry of the cycle (cycleSym), computed as the ratio of inhalation duration
4 (inhDur) divided by total cycle duration (cycleDur) (Figure 2.A);
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6
7 (3) A multivariate variable (cycleShape) introduced in previous work on the “ventilatory
8 personality” and representing the shape of the cycle. According to Bachy and
9 colleagues, 95% of a breathing cycle at rest can be reconstructed from the modulus
10 and the argument of the first four harmonics of the cycle (Figures 2.B and 2.C).⁴² These
11 parameters, the modulus and argument of the first four harmonics, were thus used as
12 a representation of the cycle shape. Even if less interpretable than univariate
13 measures, this variable is particularly interesting: the breathing signal, and especially
14 the speech breathing signal, may indeed be shaped by an interaction of constraints. In
15 order to calculate the cycleShape variable, each cycle was normalized in duration (a)
16 and amplitude (b) (cf. Figure 2.C):
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18

19 (a) The cycles were normalized to 64 points, corresponding to the largest and closest
20 power of 2 to the number of points included in the shortest cycle (87 points).⁴²
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23 (b) The amplitude of each cycle was normalized between 0 and 1 using the following
24 formula, where y is the cycle signal:
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$$y = \frac{y - \min(y)}{\max(y) - \min(y)}$$

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48 Each normalized cycle was then decomposed in the frequency domain using the Fast
49 Fourier Transform. The parameters of the first four harmonics (modulus and argument)
50 were extracted to characterize the cycle (Figure 2.B). They can be used to reconstruct
51 the cycle with a sum of four cosine functions, the frequency, amplitude, and phase of
52 which correspond to the frequency, modulus, and argument parameters described
53 above (Figure 2.C; note that due to temporal normalization the frequencies were the
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3 same for all the cycles). On average, the first four harmonics accounted for 95% (1st
4 quartile = 0.92; 3rd quartile = 0.99; sd = 0.059) of the signal power for the cycles at rest
5 and 90% (1st quartile = 0.88; 3rd quartile = 0.97; sd = 0.11) for the speech cycles.
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10 11 12 Analysis of the effect of motion, speech, and day on breathing

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14 We first characterized the effect of speech, motion, and day on the duration and
15 symmetry of the cycle to allow for comparison with previous work and to provide an
16 overview of the variables.
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19
20 Linear mixed models were used to assess the effects of limb motion, condition, speech,
21 and day, on both the log of breathing cycle duration and the logit of symmetry (data
22 were transformed for normality constraints). Participant was included in the model as a
23 random effect. To consider the potential autocorrelation between the consecutive
24 breathing cycles within a participant's session, the position of the cycles was included
25 in the model. Non-homogenous variance across conditions was corrected for when
26 present. A backward model selection was used to select significant factors. These
27 models were applied on the parameters of all cycles, for each participant, day, and
28 condition. We ran the analysis in the R software environment using the nlme package
29 (codes and data available at <https://osf.io/w6nq7/>).^{43,44,45}
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44 The first model was applied to the data from day 1. Its aim was to examine the effect
45 of limb motion on breathing cycle duration and symmetry in the quiet and speech
46 conditions. Note that we did not compare the quiet and speech conditions as it is
47 already evident from previous work that speech breathing cycles are longer and clearly
48 less symmetric than quiet breathing cycles. We used a two-factor model:
49 vocalCondition (speech; quiet) and limbCondition (legMot; armMot; noMot). Since
50 participants did not move the hands in either the quiet_noMot or the speech_armBlock
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3 conditions (not necessarily the case in the other conditions), speech_armBlock was
4 considered to be the equivalent speech condition of quiet_noMot.
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10 The second model was applied to the data from the speech conditions only. Its aim
11 was to examine the effect of limb motion (armFree; armBlock; legMot; armMot) and
12 day (1; 2) on speech breathing cycle duration and symmetry.
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19 Post-hoc comparisons were made using the Tukey HSD correction. The critical
20 significance threshold was fixed at 0.05. Only the significant differences are described
21 below; all the other comparisons did not show significant differences.
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28 Analysis of within-participant consistency across conditions and days

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30 In agreement with the literature, the individuality of the breathing pattern was assessed
31 using the method developed by Benchetrit and colleagues.⁷ The aim was to determine
32 whether within-speaker variability is lower than between-speaker variability across
33 conditions and over time for a given parameter describing the breathing cycle. This
34 would be the case if the difference between two conditions for the same participant
35 were to be significantly smaller than the difference between two participants in the
36 same or other conditions. This difference was quantified by computing the distances
37 between a given set of values of each respiratory cycle parameter for one participant
38 and one condition and each of the 49 other sets of values of the same parameter (2
39 conditions x 25 participants = 50 sets of values). Benchetrit and colleagues used the
40 Mahalanobis distance.⁷ However, in our dataset, the distributions of the values of the
41 breathing parameters per speaker were not Gaussian and non-normality was observed
42 for all parameters. For this reason, we used the Cramér-von Mises distance.⁴⁶ Instead
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3 of using the mean and variance of the distribution of parameter values, the Cramér–
4 von Mises distance is directly based on the distribution functions.
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8 For the cycleDur, cycleSym, and cycleShape parameters, S_{ij} corresponds to the
9 distribution of the considered parameter for participant i in condition j . For each S_{ij} , the
10 distribution of the considered parameter for participant i in condition j . For each S_{ij} , the
11 49 distances to all the other distributions were computed. These distances were then
12 ranked from smallest to largest. This procedure resulted in 50 sets of 49 sorted
13 distances. The ranks of the within-participants' distances were then summed (*Twithin*
14 statistic) as well as the ranks from 25 pairs ($S_{ij}, S_{i'j'}$) taken randomly (*Tbtw* statistic).
15 To estimate the distribution of *Tbtw*, the Monte Carlo technique⁴⁷ was used: a sample
16 of 25 pairs ($S_{ij}, S_{i'j'}$) was taken randomly 1,000 times to get 1,000 values of *Tbtw*. The
17 null hypothesis (*Twithin* is not different from *Tbtw*, from condition j to condition j') is
18 rejected when the p-value resulting from the comparison between *Twithin* and the *Tbtw*
19 distribution is smaller than 0.05. Bonferroni correction was applied by multiplying the
20 p-value by the number of comparisons required for the tested hypothesis
21 (corresponding to the numbers of same-color boxes in Figure 3).
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43 The method developed by Benchetrit and colleagues⁷ was used to assess the stability
44 of speakers' breathing profiles in different conditions relative to the following aims.
45 First, in order to examine whether we could reproduce Eisele and colleagues'¹² results
46 on the inconsistency of respiratory patterns between rest and exercise, we compared
47 the three quiet conditions on day 1 (3 comparisons: in orange in Figure 3). Second, to
48 investigate the individual consistency of the breathing cycles between non-speech and
49 speech breathing, we compared the quiet and speaking conditions on day 1 (3
50 comparisons: in green in Figure 3). Because participants did not move the hands in
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3 the quiet_noMot condition, this condition was compared with speech_armBlock in the
4
5 linear mixed model analyses. Third, to investigate the stability of breathing profiles in
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7 spontaneous speech, we compared the four speaking conditions between each other,
8
9 on days 1 and 2 (12 comparisons: in blue in Figure 3). Fourth, to investigate the stability
10
11 of breathing profiles in spontaneous speech over time, we compared each speech
12
13 condition between day 1 and day 2 (4 comparisons: in yellow in Figure 3).
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19 ***** INSERT FIGURE 3 HERE *****
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25 **Results**

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27 We first provide an overview of the global effects of biking and time on the symmetry
28
29 and duration of the breathing cycle. We then present the analysis of within-participant
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31 consistency for the different parameters across conditions and days.
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33 Average changes in cycle duration and symmetry induced by limb motion

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

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43 The first analysis concerns only the data on day 1. Its purpose was to assess the effect
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45 of limb motion on the duration (cycleDur) and the symmetry (cycleSym) of quiet and
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47 speech breathing cycles. For both variables, the selected statistical models included
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49 the interaction between vocalCondition and limbCondition and the position of the cycle
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51 in the time series.
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56
57 As displayed in Figure 4, the presence of limb motion decreased the average duration
58
59 of the breathing cycle in the quiet conditions (quiet_noMot - quiet_armMot: $b=0.13$,
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3 z=3.29, p=0.009; quiet_noMot - quiet_legMot: b=0.16 z=3.96, p<0.001); while it
4
5 increased the symmetry of the cycle (quiet_noMot - quiet_armMot: b=-0.11, z=-3.98,
6
7 p<0.001; quiet_noMot - quiet_legMot: b=-0.14 z=5.1, p<0.001).

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10 By contrast, adding leg or arm motion when speaking (speech_armMot and
11
12 speech_LegMot) had no effect when compared to speaking with no motion
13
14 (speech_armBlock).

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19 The second analysis concerns the comparison of speech breathing cycles in the
20
21 different conditions of limb motion and on different days (also displayed in Figure 4).

22
23 For cycleDur, the final model included limbCondition, day, and the position of the cycle
24
25 in the time series. On average, the duration of the breathing cycle was smaller in
26
27 speech_legMot than in speech_armfree (b = 0.06, z = 3.4, p = 0.004) and in
28
29 speech_legMot than in speech_armMot (b = 0.09, z = 4.82, p < 0.001). Other
30
31 comparisons were not significant. Regardless of the condition, on day 2, the cycles
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33 tended to be longer than on day 1, but the difference was not significant (b = -0.07, z
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35 = -2.61, p = 0.06).

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42 For cycleSym, the final model included the interaction between limbCondition and day
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44 and the position of the cycle in the time series. The symmetry of the cycle was larger
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46 in speech_legMot than in speech_armFree (b = -0.07, z = -3.52, p = 0.003) and in
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48 speech_legMot than in speech_armBlock (b = -0.07, z = -3.54, p = 0.0031). Other
49
50 comparisons were not significant. The cycles were also less symmetric on day 2 than
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52 on day 1 (b = 0.1, z = 3.02, p = 0.02).

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58 ***** INSERT FIGURE 4 HERE *****
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8 Individual consistency of the breathing cycle
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12 Consistency refers to the fact that the breathing-cycle parameter values for a given
13 speaker in a given condition are closer to those of the same speaker in another
14 condition (individual cross-condition consistency) or in the same condition on another
15 day (individual cross-temporal consistency) than to those of other speakers in the
16 same or different conditions.
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24 Individual cross-conditions consistency in quiet and quiet vs. speech conditions on
25 day 1
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27
28 None of the comparisons between the quiet conditions for cycleDur, cycleSym and
29 cycleShape (orange comparisons in Figure 3) were significant, except for breathing
30 cycle duration between the quiet_legMot and quiet_armMot conditions ($P_t \leq 0.003$,
31 Table1).
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38 None of the comparisons between quiet and speech conditions (green comparisons in
39 Figure 3) were significant ($P_t \geq 0.54$, Table 1). Individual cross-condition consistency
40 was thus not observed on day 1 between quiet conditions and between quiet and
41 speech conditions.
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49 ***** INSERT TABLE 1 HERE *****
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54 Individual cross-condition consistency in speech conditions on day 1 and on day 2
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56 On each day, within-speaker distances were ranked significantly lower than random
57 association distances ($P_t \leq 0.048$) for all comparisons (blue comparisons on Figure 3),
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1
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3 for cycleDur, cycleSym, and cycleShape (cf. Table 2). There was, however, a single
4
5 exception: for cycleShape the difference between speech_armBlock and
6
7 speech_legMot was not significant (Pt = 0.456).
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12 ***** INSERT TABLE 2 HERE *****
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16 17 Individual cross-day consistency of speech breathing profiles

18
19 Between days, for the speech conditions (yellow comparisons in Figure 3), participants
20
21 were generally closer to themselves than to other participants (cf. Table 3) in terms of
22
23 cycle duration (Pt < 0.04), symmetry (Pt < 0.004) and shape (Pt < 0.04), except for the
24
25 armFree condition, for which cycleDur is not consistent (Pt = 0.08).
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31 ***** INSERT TABLE 3 HERE *****
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36 37 **Discussion**

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39 Breathing presents individual specificities in a given task at a given time. However,
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41 individual consistency of speech breathing across tasks and over time has not yet been
42
43 investigated. In the current study, we examine the individual consistency of speech
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45 breathing profiles in different conditions of limb movements and on two different days.
46
47 We applied a method previously developed to assess the individuality of tidal and
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49 exercise breathing^{7,12}. We found individual consistency of breathing profiles over days
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51 even when speech is produced at the same time as light physical activity with the arms
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53 or the legs.
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3 Our analyses also replicated the inconsistency in individual breathing profiles
4 previously reported between breathing at rest and breathing during physical exercise¹².
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6
7 On day 1, biking either with the legs or the arms while remaining quiet shortened the
8 breathing cycles and increased cycle symmetry as compared to being quiet and not
9 moving. For the speech conditions, the effect of biking on speech breathing was
10 observed only for leg biking: it decreased the duration and increased the symmetry of
11 the cycles as compared with the other speech conditions. When speaking, arm motion
12 does not have a significant effect on breathing as compared with speaking without
13 moving. In general, changes in breathing profiles related to leg motion didn't affect the
14 individual consistency of cycle duration, symmetry and shape between speech
15 conditions.
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30 This suggests that speech breathing individuality is maintained despite co-occurrent
31 motion of the arms or the legs, at least when these are cyclic and do not strongly impact
32 ventilation. The level of exercise to which the participants were committed was indeed
33 light. Regarding previous work,^{30,31,32} it is well known that physical effort impacts
34 speech breathing, what is unknown is whether this impact also affects the individuality
35 of breathing and/or if speakers' strategies to compensate for physical effort are
36 consistent over time. It would be interesting to examine if speech breathing patterns
37 are maintained during intense physical activity.
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49 Assessing the consistency of speech breathing over different bodily contexts is a way
50 to address the specificity of speech breathing skills. In previous work, this bodily
51 context was modulated by controlling the degree of effort. In the current work, we used
52 leg vs. arm movements. Pouw and collaborators have recently introduced the idea that
53 arm motion may constrain changes in speech production due to the physical impulse
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3 they impose on the breathing system,^{36,37} which may affect vocal output. They defend
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5 the idea that this link is anchored in phylogenesis: the bipedal state freed the upper
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7 limbs and the respiratory system from being synchronized with locomotion. In return,
8
9 the upper limbs may have participated in the complexification of the control of the
10
11 respiratory system for speech. This is a parsimonious explanation for the mutual
12
13 influences between hand movement and phonation in communication as compared
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15 with a cognitive explanation.³⁶
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19 In the current study, we focused on the individuality of speech breathing, and did not
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21 investigate the effect of cycling on the vocal output. A next step will be to assess this
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23 question, and go further by comparing the effect of lower vs upper limb. Local effects
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25 of manual cycling on vocal acoustics, thereby on speech breathing, may appear.
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30 We found individual consistency of the breathing profiles from one day to another, for
31
32 all comparisons, and changes in cycle duration and symmetry between day 1 and
33
34 day 2 did not affect this consistency – except for the cycle duration in
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36 speech_armFree. These results are in line with the individual consistency of the tidal
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38 breathing profiles from one day to another.⁸ It would be interesting to see if, as for
39
40 tidal breathing, we find this consistency across years.⁷
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46 Beyond these specific points, the study raised the question of why should speech
47
48 breathing be consistent or not be for a same speaker over bodily contexts and days?
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50 Different constraints related to speech production might shape the breathing cycle.
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54 First, the cycle shape, as defined in the current work, may be heavily affected by
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56 segmental and prosodic aspects of the produced speech material. For instance,
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58 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
12
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
16
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
22
23 indeed correlated to cycle duration (Pearson's correlation: $r=0.9$, $t = 138.83$, $df = 4689$,
24
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
47
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
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3 report individual differences, they refer to the literature on different participant groups,
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5 showing, for example, differences among athletes and non-athletes.
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9 Finally, the study was run in a monologue situation while speech is most often
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11 produced in a dialogue situation. Previous work shows that breathing adapts to
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13 dialogue constraints and in particular to the turn-taking process^{23,24,25} but didn't find
14
15 overall coordination of breathing^{23,24} expect in synchronous reading.⁶⁰ In
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17 conversational settings, speakers have to adapt to their interlocutor. The breathing
18
19 individuality would be particularly interesting to assess during dialogue as a way to
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21 investigate (1) if speakers develop a specific way to control breathing in dialogue
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23 consistent across interlocutors or (2) if they rather lose their individuality to adapt to
24
25 their interlocutor.
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30 The results of these different investigations do not tell anything on the causal link
31
32 between speech and breathing and their potential individuality. Speech breathing is
33
34 complex and determined by many variables in interaction with one another in such a
35
36 way that disentangling speech from breathing mechanisms would require multifactorial
37
38 analyses with cognitive and physiological parameters. The aim of this paper was not
39
40 to understand these underlying mechanisms, but to first ascertain the individual
41
42 specificity of the patterns characterizing the breathing cycle.
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51
52
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54
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58
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8
9 Motions: Learning and Adaptation of Speech Communication in the context of Body
10
11 Motions).

16 17 **Author contributions**

18
19 Hélène Serré contributed to the conception of the study, the data collection, the data
20
21 analysis. She wrote an initial draft of the paper.

22
23 Susanne Fuchs, Marion Dohen and Amélie Rochet-Capellan contributed to the
24
25 conception of the study, the data collection and the writing.

26
27
28 Silvain Gerber contributed to the statistical analysis.

29
30 Hélène Serré accepts to be responsible for the integrity of the data analyzed.

34 35 **Competing interests**

36
37 All authors declare no competing interests.

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33 **Figure and table captions**

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37 Figure 1: Left: illustration of the experimental setup for the biking with the arms
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39 condition (speech_armMot). Right: Participants' task according to day. From left to
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41 right: quiet doing nothing (quiet_noMot), quiet with legs biking (quiet_legMot), quiet
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43 with arms biking (quiet_armMot), speech with arms free (speech_armFree), speech
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45 with arms blocked (speech_armBlock), speech with legs biking (speech_legMot),
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47 speech with arms biking (speech_armMot).
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53 Figure 2: Characterization of the speech breathing cycle. Column A illustrates the
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55 measurement of the cycle duration (cycleDur). Symmetry (cycleSym) was obtained by
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57 dividing the duration of inhalation (InhDur) by cycleDur. Column B displays the vectorial
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3 representation (phase angles) and the magnitude of the first four harmonics of the
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5 Fourier transform applied on the cycle. The vectorial representation does not have
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7 axes per se: the length of the vector represents the amplitude of the given harmonic,
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9 and its orientation with respect to the horizontal axis corresponds to the phase angle.
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11 Column C displays an example of a normalized cycle (solid line) and the corresponding
12
13 reconstructed airflow profile from the first four harmonics (dashed line). The axes are
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15 unitless because of the normalization
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21 Figure 3: Summary of the 22 comparisons achieved to assess breathing individuality.
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23 Orange (o): changes due to moderate exercise while remaining quiet; Blue (b): stability
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25 in breathing profiles in spontaneous speech; Green (g): relation between non-speech
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27 and speech breathing; Yellow (y): stability of breathing profiles in spontaneous speech
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29 over time; White: comparisons we did not investigate.
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35 Figure 4: violin plots of cycleDur (left) and cycleSym (right) in the different conditions
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37 of limb movements and over days. The values are z-scaled per participants.
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42 Table 1: probability of T_{within} to be from the distribution of T_{btw} for each comparison
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44 between two quiet conditions, and between one quiet and one speech condition, within
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46 day 1 (p-values are considered significant when smaller than 0.05). T_{alpha} is the
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48 threshold value of rejection: under the null hypothesis (T_{within} comes from the
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50 distribution of T_{btw}), the probability of T_{alpha} is 0.05. T_w : T_{within} . T_a : T_{alpha} .
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3 Table 2: probability of T_{within} to be from the distribution of T_{btw} for each comparison
4 between two speech conditions, respectively within day 1 and day 2. The significance
5 threshold is 0.05 (as in Table 1). T_w : *Twithin*. T_a : Talpha.
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12 Table 3: probability of T_{within} to be from the distribution of T_{btw} , for each comparison
13 from day 1 and day 2, respectively within each speech condition. The significance
14 threshold is 0.05 (as in Table 1). T_w : *Twithin*. T_a : Talpha.
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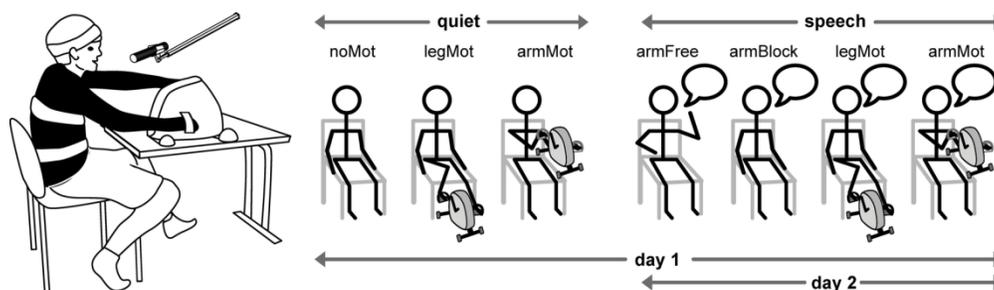


Figure 1: Left: illustration of the experimental setup for the biking with the arms condition (speech_armMot). Right: Participants' task according to day. From left to right: quiet doing nothing (quiet_noMot), quiet with legs biking (quiet_legMot), quiet with arms biking (quiet_armMot), speech with arms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

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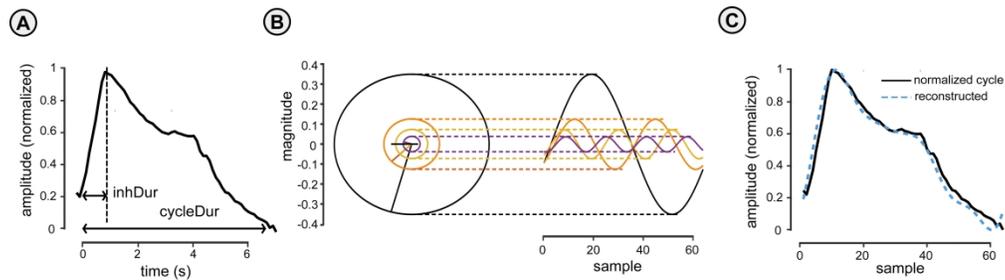


Figure 2: Characterization of the speech breathing cycle. Column A illustrates the measurement of the cycle duration (cycleDur). Symmetry (cycleSym) was obtained by dividing the duration of inhalation (InhDur) by cycleDur. Column B displays the vectorial representation (phase angles) and the magnitude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

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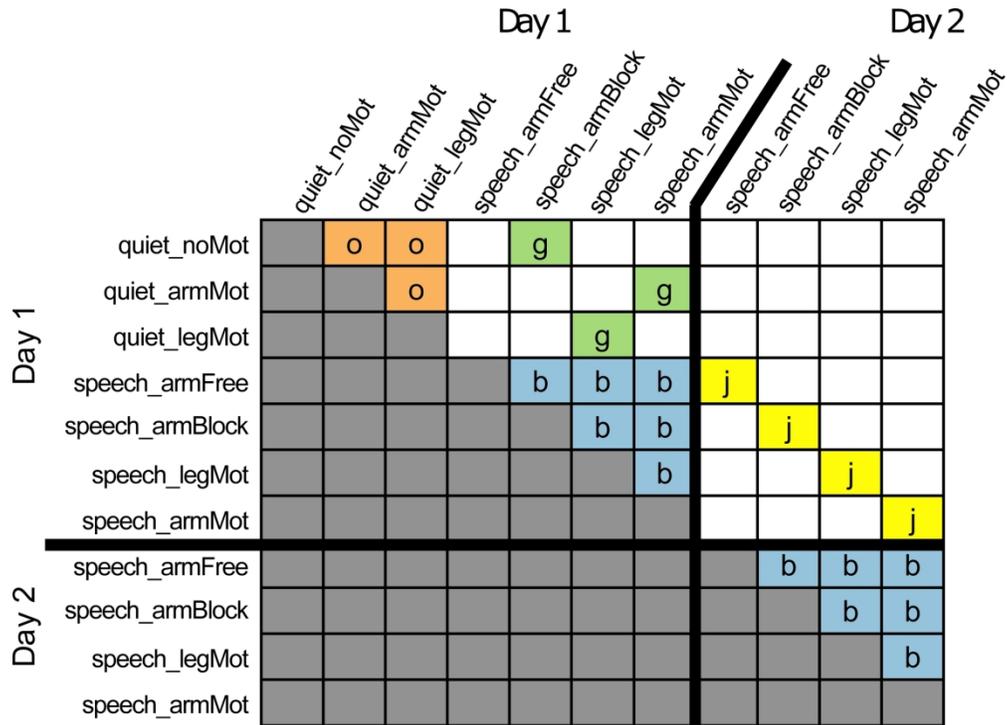


Figure 3: Summary of the 22 comparisons achieved to assess breathing individuality. Orange (o): changes due to moderate exercise while remaining quiet; Blue (b): stability in breathing profiles in spontaneous speech; Green (g): relation between non-speech and speech breathing; Yellow (y): stability of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

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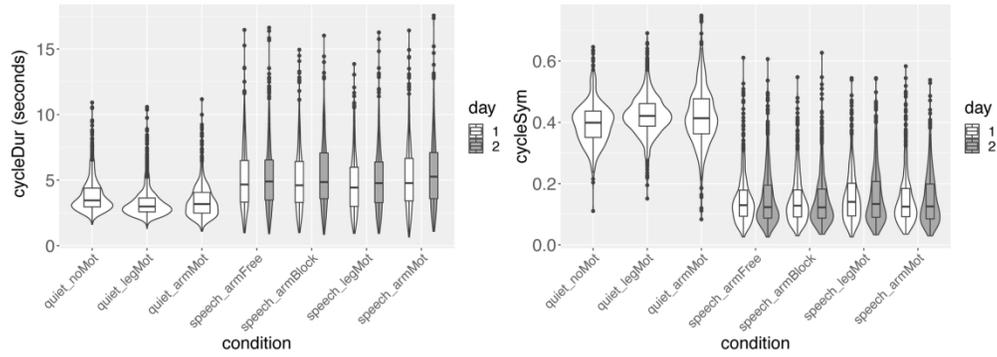


Figure 4: violin plots of cycleDur (left) and cycleSym (right) in the different conditions of limb movements and over days.

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Conditions compared		cycleDur			cycleSym			cycleShape		
		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

Conditions compared		cycleDur			cycleSym			cycleShape		
		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

Conditions compared from day 1 to day 2		cycleDur			cycleSym			cycleShape		
		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