American Journal of Physiology – Heart and Circulatory Physiology
287(2): H579 - H587 (2004)

Oscillations of heart rate and respiration synchronize during poetry recitation

Dirk Cysarz[1,2], Dietrich von Bonin[3], Helmut Lackner[4], Peter Heusser[3], Maximilian Moser[4,5], Henrik Bettermann[1]

[1] *Department of Clinical Research, Gemeinschaftskrankenhaus Herdecke, 58313 Herdecke, Germany*

[2] *Institute of Mathematics, University of Witten/Herdecke, 58448 Witten, Germany*

[3] *Institute for Complementary Medicine KIKOM, University of Berne, 3010 Bern, Switzerland*

[4] *Institute for Noninvasive Diagnostics, Joanneum Research, 8160 Weiz, Austria*

[5] *Physiological Institute, University of Graz, 8010 Graz, Austria*

Running head: Cardioresp. synchronization during hexameter recitation

Address for correspondence:
Dirk Cysarz, PhD
Department of Clinical Research
Gemeinschaftskrankenhaus Herdecke
Gerhard-Kienle-Weg 4
58313 Herdecke, Germany
Tel.: +49 2330 62-3637
Fax: +49 2330 62-4062
Email: d.cysarz@rhythmen.de

Abstract

Objective of this study was to investigate the synchronization between low frequency breathing patterns and respiratory sinus arrhythmia (RSA) of heart rate during guided recitation of poetry, i.e. recitation of hexameter verse from ancient Greek literature performed in a therapeutic setting. 20 healthy volunteers performed three different types of exercises with respect to a cross-sectional comparison: recitation of hexameter verse, controlled breathing and spontaneous breathing. Each exercise was divided into three successive measurements: a 15-minute baseline measurement (S1), 20 minutes of exercise and a 15-minute effect measurement (S2). Breathing patterns and RSA were derived from respiratory traces and electrocardiograms, respectively, which were recorded simultaneously using an ambulatory device. The synchronization was then quantified by the index g which has been adopted from the analysis of weakly coupled chaotic oscillators. During recitation of hexameter verse g was high, indicating prominent cardiorespiratory synchronization. The controlled breathing exercise showed cardiorespiratory synchronization to a lesser extent and all resting periods (S1 and S2) had even fewer cardiorespiratory synchronization. During spontaneous breathing cardiorespiratory synchronization was minimal and hardly observable. The results were largely determined by the extent of a low frequency component in the breathing oscillations that emerged from the design of hexameter recitation. In conclusion, recitation of hexameter verse exerts a strong influence on RSA by a prominent low frequency component in the breathing pattern, generating a strong cardiorespiratory synchronization.

Keywords: Heart rate, Respiration, Creative arts therapy, Cross sectional study design, Bivariate data analysis

Introduction

The effects of different breathing frequencies and patterns on cardiovascular regulation have been investigated extensively in recent years. In this context various effects of poetry recitation on cardiovascular parameters, especially on heart rate oscillations, have been demonstrated (4;9;50). Bernardi et al. found a frequency adjustment of breathing oscillations with endogenous blood pressure fluctuations (Mayer waves) and even cerebral blood flow oscillations during the recitation of the rosary and the ‘OM’ mantra (4). This effect was attributed to the breathing frequency of approximately 6 breaths per minute induced by the metric of both religious verse. Furthermore, they noticed an increased arterial baroreflex sensitivity which is a favourable long term prognostic factor in cardiac patients (3). In another study Bernardi et al. observed a significant increase in arterial oxygen saturation SaO_2 during controlled breathing at frequencies of 15/6/3 breaths per minute in patients with chronic heart failure and healthy controls (5). The strongest increase was found at a breathing frequency of 6 breaths per minute. Thus, recitation of specific poetry as a means to control breathing patterns was proposed and the rosary prayer to be ‘viewed as a health practice as well as a religious practice’ (4).

In our own investigations on cardiovascular and cardiorespiratory regulation during and after recitation of poetry we were led by the observation of therapists that creative arts greatly influence well-being in man by various means. On a psychosomatic level these therapies increase the salutogenetic potential in man (2;17). Furthermore, the autonomic regulation is affected in order to enhance the flexibility of regulatory processes to maintain stability and coherence between different functions. As a result a temporal order of physiological functions appears (20). This seems to apply especially when therapeutic speech as rhythmic poetry is recited using different breathing modalities. These breathing modalities are used to activate or calm down the patient. For example, some exercises of Anthroposophic Therapeutic Speech (ATS) (14), which is originally based on the philosophy of R. Steiner, use the recitation of poetry to treat stress-related symptoms in the cardiorespiratory system (50).

The physiological influences of various breathing patterns on heart rate fluctuations are well known (1;6;15;21). Thus, in a first study, we examined heart rate variability (HRV) in healthy subjects during and after recitation of poetry (50). Two different examples of old poetry, hexameter and alliterative verse, were used. Although no pacemakers had been used, recitation of hexameter verse always modulated heart rate at a frequency of 12 per minute and 6 per minute (i.e., 2:1 frequency ratio). Furthermore, during 15 minutes of rest after the exercise, an increased high frequency component of HRV (50) and a predominance of typical short ‘heart rate patterns’ resulting from intermittent cardiorespiratory synchronization were observed (9). In contrast, these observations were not found during/after normal conversation which was used as a control exercise. Thus, recitation of poetry changed cardiorespiratory interaction whereas normal conversation did not.

Many features of the cardiorespiratory control during recitation of poetry are still unknown. Recently, on the basis of simultaneous recordings of an electrocardiogram and a respiratory trace, new techniques for the analysis of cardiorespiratory interaction have been developed (41;42). They unambiguously revealed that heart rate and respiration may intermittently synchronize. The application of these techniques promises new information about the cardiorespiratory interaction, e.g. after myocardial infarction (22;25).

In this study we investigated on the cardiorespiratory synchronization in healthy subjects during recitation of hexameter verse since our first results were most obvious with this exercise. Cardiorespiratory synchronization was analyzed with respect to a respiratory trace and the oscillations in heart rate induced by respiration, i.e. respiratory sinus arrhythmia (RSA). For this purpose, we adapted recently developed techniques since they offer to define a continuous phase which may easily be analyzed (23;43). We show that this technique is able to capture important information. Three different exercises were compared using a cross sectional study design: recitation of hexameter verse, controlled breathing and spontaneous breathing. The results of this study may improve our understanding of regulatory processes that maintain stability and coherence between different physiological functions since cardiorespiratory interaction seems to play a crucial role in this context.

Materials and Methods

Subjects

23 healthy subjects without experience in ATS and without prior knowledge of the hexameter text used for the recitation were enrolled in the study. After an initial check 3 subjects had to be excluded due to frequent ectopic heartbeats. The remaining 20 subjects (10 female; age: 43 ± 6.6, average ± SD; 3 smokers) were included and had no history of cardiovascular diseases, especially no hypo- or hypertension or antiarrhythmical therapy. All subjects gave their informed written consent to take part in the study. The study protocol was approved by the Ethics Commitee of the University of Berne, Switzerland.

Experimental procedure

All subjects were invited individually three times to the therapy centre at the same time of day. In each of the three sessions the subjects performed a different exercise (in random order): Hexameter recitation (H), controlled breathing (C) and spontaneous breathing (S), see Table 1. During each session an electrocardiogram and the nasal/oral airflow were recorded simultaneously (see Data acquisition). The overall duration of each session was 50-60 minutes, divided into three successive measurements: 15 minutes quiet rest in a resting chair (baseline measurement S1; see Table1), 20 minutes exercise measurement (H, C, S) and 15 minutes quiet rest in a resting chair (effect measurement S2). During S1 and S2 the subjects were allowed to breath spontaneously. This procedure resulted in 9 different measurements of each subject. To ensure comparable levels of physical activity during the three types of exercises, the subjects walked through the room at a pace of 50 steps per minute (given by an electric metronome). The three experiments had to be at least 24 hours apart but within 14 days.

[insert Table 1 here]

Hexameter recitation:
Hexameter is the oldest rhythmic verse in Ancient Greece, where it is found in the two of the largest pieces of epic poetry yet known, the Iliad and Odyssey. A line of hexameter verse contains six feet (a foot is the basic rhythmic unit), usually dactyls (a single dactyl comprises one long and two short parts). The line is mostly split in two parts by a break (caesura), which in the most archetypal form (Iliad) mainly takes place after the long part of the third dactyl. This results in a convenient and regular breathing pattern for the speaker (24). We used a piece from Homers Odyssey in a German translation which did not alter the rhythmic scheme of the verse. [*Footnote 1*].

Hexameter recitation was carried out with the mentioned breathing pattern. The therapist walked at the same pace as the subject, speaking the first part of the hexameter line. The sequence of steps was divided as follows: inspiration always took one step, speaking three steps. In order to support a full inspiration, recitation was accompanied by lifting the stretched arms to the level of the shoulders during inspiration and lowering the arms during recitation. The subject listened to the text recited by the therapist without lifting the arms (but continued walking) and subsequently repeated it in the therapist's fashion. This alternating procedure was repeated for 20 min. The walking pace, the movement of the arms and the alternating fashion of listening and reciting ensured a high temporal coordination between these tasks and made the recitation more comfortable.

Controlled breathing:
Controlled breathing consisted of breathing in the 'hexameter-pattern', i.e., inspiration during one step, expiration during three steps. The duration of expiration (3 steps) was maintained by control of breath with the lips. Similar to hexameter recitation, the therapist first demonstrated the specific type of breathing. Again, the breathing was accompanied by lifting the stretched arms to the level of the shoulders during inspiration and lowering the arms during expiration. The subject 'listened' to the breathing by the therapist without lifting the arms and subsequently imitated it. This alternating procedure ensured a comparable breathing pattern with respect to hexameter recitation.

Spontaneous breathing:
During 'Spontaneous breathing' the subjects walked at the same pace as in the two other exercises, but were instructed to breath spontaneously. Furthermore, there were no restrictions with respect to the movement of the arms.

Data acquisition and pre-processing

The electrocardiogram (ECG, standard lead) and the uncalibrated nasal/oral airflow (derived by three thermistors that were placed next to the nostrils and in front of the mouth) were recorded simultaneously in all subjects using solid state recorders (Medikorder MK2, Tom-Signal, Graz, Austria). The sampling rates of the ECG and the nasal/oral airflow were 3000 Hz and 50 Hz, respectively. This ensured an accuracy < 1 ms for the times of the identified R-peaks. The inspiratory and expiratory onsets were defined as the local minima and the local maxima, respectively, of the nasal/oral airflow because they were due to the change from exhaling warm air (warmed by the respiratory tract) to inhaling air at the temperature of the environment (and vice versa). For further analysis the acquired data were saved to a file and were further processed using Matlab (The Mathworks, Natick, Mass, USA) and C routines. All automatically identified R-peaks were visually controlled and edited where necessary. The manually edited R-peaks (approximately 0.1 % of all R-peaks) had an accuracy of 5 ms because the ECG was recorded with a sampling rate of 200 Hz.

To obtain a heart rate time series with equidistant time steps, the times of successive R-peaks were first converted to a RR-tachogram, i.e., the sequence of times between successive R-peaks. Next, the resulting RR-tachogram was re-sampled at a rate of 5 Hz using linearly interpolated values. To get a time series for the nasal/oral airflow at corresponding sampling times, each 10^{th} sample was used. These two time series share a common time axis and served as the basis for further calculations.

Figure 1 (a) shows a short trace of the electrocardiogram and the simultaneous nasal/oral airflow during recitation of hexameter verse. The breathing oscillations show two different frequencies. A high frequency component at approximately 12 breaths per minute resulted from the design of the hexameter exercise (duration of a full respiratory cycle: approx. 4.8 seconds, cf. 'Experimental procedure'). Furthermore, a low frequency component appears at approximately 6 cycles per minute. This low frequency oscillation reflects the alternation of a shallow breathing cycle during listening and a deeper breathing cycle during recitation. The heart rate time series shows an oscillation that is obviously synchronized to the low frequency oscillations of the breathing pattern. Thus, to obtain a nasal/oral time series that contains merely the low frequency component of the breathing pattern, the time series was band-pass filtered. Since the filtering must leave the phase of the time series unaltered (for definition of the phase, see below), the technique used in this study consisted of two consecutive steps. First, a moving average with two windows of different lengths (20 and 60 samples, i.e. 4 s and 12 s) was calculated. Next, the filtered time series was obtained by subtraction of the moving average time series with the longer window length from the moving average time series with the shorter window length, see Figure 1 (b). The changes in the amplitude of the oscillations caused by this filtering technique is not disadvantageous in the context of this study because the amplitudes are irrelevant for the analysis of synchronization. If higher moments of the time series have to be preserved, more sophisticated filtering techniques should be used, e.g. the Savitzky- Golay filter (34).

[insert Figure 1 here]

Analysis of cardiorespiratory phase synchronization

The median heart rate and the median breathing frequency of each measurement served as the basic parameters. Since the breathing patterns of the three exercises modulate the heart rate differently the extent of RSA of each measurement is expressed as the median of the longest RR-interval minus the shortest RR-interval of each respiratory cycle. In the following, two different techniques are used to quantify cardiorespiratory synchronization. The first one is based on the Fourier transformation of both filtered time series x_{heart}, x_{resp} and their corresponding cross spectrum $C_{hr}(f) = (\mathrm{F}\, x_{heart})(f)(\mathrm{F}\, x_{resp})^*(f)$ (F denotes the Fourier transformation and * denotes complex conjugate). The normalized amplitude of $C_{hr}(f)$ is called the coherence function and may be used as a simple measure of synchronization (35):

$$\Gamma_{hr}(f) = \frac{\left|\langle C_{hr}(f)\rangle\right|}{\sqrt{\langle C_{hh}(f)\rangle}\sqrt{\langle C_{rr}(f)\rangle}}.$$

The brackets $\langle ... \rangle$ denote an average using epochs containing 300 samples, i.e. 1 minute, and an overlap of 150 samples between successive epochs. In this study, $x = \Gamma_{hr}(f_{resp})$ at the centre frequency f_{resp} of the nasal/oral airflow serves as a simple means to quantify cardiorespiratory synchronization.

The second technique has its origin in the analysis of two weakly coupled chaotic systems (38;39). First of all, because each oscillator is completely described by its amplitude and its phase as a function of time, a suitable phase has to be defined for a time series that merely contains oscillations in a relatively narrow frequency band. For the purposes of this study, the amplitude is not required and, hence, not calculated. In recent studies, the phase of such a time series was defined using the concept of analytic signals (37;40;43). They made use of the Hilbert-transform $\tilde{x}(t_i)$ of the band-pass filtered time series $x(t_i)$. The Hilbert-Transform is defined as the convolution of $x(t_i)$ and the function $1/(p\, t_i)$ (11):

$$\tilde{x}(t_i) = x(t_i) * 1/p\, t_i.$$

Notice that '$*$' denotes a convolution. Practically, the convolution may be calculated more easily in the frequency domain using the Fourier-Transform of this equation because the convolution is then turned into a simple multiplication. With the definition of the Hilbert-transform, the phase $f(t_i)$ of a time series is obtained by calculation of

$$f(t_i) = \arctan \tilde{x}(t_i)/x(t_i) .$$

Using this definition the phase is calculated for the interpolated heart rate times series and the filtered nasal/oral airflow, yielding a phase $f_{heart}(t_i)$ and a phase $f_{resp}(t_i)$. Next, the difference $j(t_i)$ between these two both phases is

$$j(t_i) = f_{resp}(t_i) - f_{heart}(t_i) .$$

The heart rate time series and the nasal/oral time series, i.e. RSA and breathing pattern, are *synchronized* if this phase difference is constant, i.e.,

$$\left| j(t_i) - d \right| < const ,$$

with d being a constant offset (the phase difference $j(t_i)$ needs not necessarily to be around zero). In the case of synchronization the constant phase difference $j(t_i)$ is proportional to the time delay between both time series since neither the definition of the phases $f_{heart}(t_i)$ and $f_{resp}(t_i)$ nor the preceding filtering procedure introduced any additional constant or time-dependent phase-shift.

Unfortunately, noise and other sources of interference in both time series lead to random-like 'phase jumps' of $\pm 2p$ in the sequence of $f_{heart}(t_i)$ and $f_{resp}(t_i)$. Thus, even in a synchronized state, the phase difference $j(t_i)$ is *not* constant anymore. Hence, the above mentioned condition for a synchronized state is not suitable anymore. Instead, the synchronized state is characterized by a statistical preference of some values of

$$\Psi(t_i) = j(t_i) \bmod 2p ,$$

i.e., a preference of some values of $j(t_i) \pm 2np$ (with *n* being an integer). Thus, in the case of synchronization of two systems that are disturbed by noise the distribution of $\Psi(t_i)$ shows one unambiguous maximum. In this study, the distribution of $\Psi(t_i)$ is quantified by

$$g = \langle \cos \Psi(t_i) \rangle^2 + \langle \sin \Psi(t_i) \rangle^2 , \qquad 0 \le g \le 1,$$

where $\langle \; \rangle$-brackets denote an average (27;46). Theoretically, if $g = 1$, $\Psi(t_i)$ is constant because both time series are completely synchronized in a statistical sense. In this case, the location of the maximum of $\Psi(t_i)$ is the preferred phase difference between both time series. If $g = 0$, both time series are completely desynchronized because the values of $\Psi(t_i)$ are equally distributed in the range $[-p, p]$, i.e. no preference of any phase at all. For further details, see the literature.

For real world data the lower bounds of g and x have to be estimated since even in the absence of any coupling synchronized patterns may appear by chance. To accomplish this task, the concept of surrogate data for bivariate data is used (28). The bivariate surrogate data were created as follows. The nasal/oral airflow was left unchanged whereas the sequence of the original RR-tachogram was randomized. Subsequently, the heart rate time series was constructed as described above. This procedure maintains the distribution of the RR-tachogram, i.e. the mean and standard deviation of the RR-distances are the same as in the original RR-tachogram, whereas the temporal structure is completely destroyed. Hence, any cardiorespiratory synchronization due to coupling is also destroyed. In the surrogate data spurious synchronization may occur due to fluctuations of the RR-distances and the subsequent filtering procedure used for the synchronization analysis. Without going into detail, the 95%-percentile of the surrogate data of all 180 measurements (one realization per measurement) yields $g = 0.14$ (analysis of phase difference) and $x = 0.23$ (coherence analysis). These estimations serve as a lower bounds of g and x. It shows that even in the absence of synchronization the fluctuations in the randomized RR-tachogram result in low frequency oscillations which may be spuriously synchronized to the nasal/oral airflow. In the following, g and x serve as two different indices of cardiorespiratory synchronization.

An example of cardiorespiratory phase synchronization analysis is illustrated in Figure 2. The phases $f_{heart}(t_i)$ and $f_{resp}(t_i)$ have been calculated as described above. First, during the baseline measurement, cardiorespiratory interaction is not synchronized. As a result, the phase difference $j(t_i)$ increases with time, see Figure 2 (a). Thus, the values of $\Psi(t_i)$ are almost equally distributed resulting in a low g-value ($g = 0.14$) which is equal to the estimated lower bound. Hence, this example contains hardly any cardiorespiratory synchronization. Recitation of hexameter verse synchronizes both systems which is reflected in both time series, see for example Figure 1 (b). Thus, the phase difference $j(t_i)$ is approximately constant for some period of time and in the phase difference certain plateaus appear, see Figure 2 (b). Furthermore, the distribution of $\Psi(t_i)$ shows one distinct peak that leads to a much higher g-value ($g = 0.78$). In this example, the peak of $\Psi(t_i)$ is located at $\Psi(t_i) = 1.58$ which is approximately $p/2$. Hence, the phase of the respiratory time series advances the phase of the heart rate time series by approximately a quarter of an oscillation. Notice that the analysis of the coherence as a measure of cardiorespiratory synchronization yields $x = 0.59$ and $x = 0.68$, respectively, for the examples in Figure 2 (a) and (b).

[insert Figure 2 here]

Statistics

The objective of this study was to assess the effects of hexameter recitation on cardiorespiratory synchronization in contrast to controlled breathing and spontaneous breathing. To this end descriptive methods are used. Since the number of subjects is small (N=20) and the distribution of the g-values is not known the median instead of the mean is used to quantify the distributions. Median heart rate, median frequency of the low frequency breathing oscillations, extent of RSA, the g-value and the x-value were calculated for each measurement of each subject. Effects of transitions at the beginning of each measurement were reduced by omitting the first two minutes of the recording. To avoid a bias due to slightly different durations of each measurement, the subsequent 13 minutes were analyzed. 7 out of 180 measurements (20 subjects $\times$ three exercises $\times$ three measurements per exercise) were slightly shorter than 13 minutes. Subsequently, the three measurements of each exercise (S1, exercise, S2) were characterized by the median, lower and upper quartile of the subjects' median heart rate, median frequency of low frequency breathing oscillations and extent of RSA.. Box and whisker plots were used for visualization of the distribution of the g- and the x-values.

The non-parametric Friedman-test was used to calculate the probability of equality between the three measurements of each session (S1, exercise and S2) and between the three exercise measurements (Hexameter, Controlled breathing, Spontaneous breathing). Subsequently, an appropriate post-hoc test for multiple comparisons was used to calculate the probability of equality between two different measurements (10). A $p_{Friedman}$-value near zero indicates a high probability of differences between the three measurements with respect to the analyzed parameter.

For low values of $p_{Friedman}$ low p-values of the post-hoc test indicate the pair of measurements with likely differences.

Results

In total 180 measurements were analyzed with respect to cardiorespiratory synchronization. All exercises were associated with an increase of heart rate compared to baseline (S1) and effect measurement (S2), cf. Table 2. The hexameter exercise showed the highest heart rate (82.9 beats/min). Furthermore, in all three exercises the heart rate of S2 was decreased compared to S1. The frequency of the low frequency breathing oscillations decreased during hexameter exercise and controlled breathing exercise compared to S1 and S2, cf. Table 3. During the spontaneous breathing exercise this frequency increased compared to S1 and S2. The frequency of the low frequency breathing oscillations was lowest for the hexameter exercise (6.4 breaths/min) and highest for the spontaneous breathing exercise (12.5 breaths/min). The measurements S1 and S2 showed an intermediate frequency of the low frequency component at approximately 8.5 breaths/min. Although the frequency of the low frequency breathing oscillations decreased during the hexameter exercise and during controlled breathing the RSA did not change noticeably compared to S1 and S2, cf. Table 4. On the contrary, the increase of this frequency during spontaneous breathing decreased the extent of RSA compared to S1 and S2.

[insert Table 2, 3 and 4 here]

The results of the g -values as a quantitative index of cardiorespiratory phase synchronization are shown in Figure 3 (a)-(c). Clearly, the recitation of hexameter and controlled breathing led to an increase of the g -values compared to S1 and S2. The increase was largest for the recitation of hexameter verse (hexameter exercise: median $g = 0.70$, controlled breathing exercise: median $g = 0.57$). For both exercises the comparisons S1 vs. exercise and exercise vs. S2 yielded low p-values. Thus, during these two exercises the cardiorespiratory interaction was more synchronized compared to S1 and S2. In contrast to these findings, spontaneous breathing led to a decrease of the g -values compared to S1 and S2 (median $g = 0.15$). This is very close to the lower bound of the g -values and indicates a high degree of desynchronization. Again, the comparison S1 vs. exercise and exercise vs. S2 yielded low p-values. Hence, during the spontaneous breathing exercise the cardiorespiratory interaction was less synchronized compared to S1 and S2. Comparing S1 and S2 of all exercises, the g -values always were $g \approx 0.3$.

In Figure 3 (d) the comparison of the g -values during the three different exercises is shown. This diagram shows that the difference of the g -values between the hexameter exercise and the controlled breathing exercise was large enough to yield a low p-value. Thus, reciting hexameter verse results more often in an synchronized cardiorespiratory interaction than does controlled breathing. Almost trivially, the low g -values of the spontaneous breathing exercise produce low p-values between the other two exercises. As these g -values are also lower than before or after the exercise, the spontaneous breathing exercise desynchronizes the oscillations of heart rate and respiration.

[insert Figure 3 here]

The results of the distributions of x -values derived from the coherence analysis are shown in Figure 4 (a)-(c). Although the hexameter recitation leads to an increase of the x -values compared to S1 and S2, only the difference between hexameter and S2 is likely as indicated by the low p-value. In contrast to the analysis of phase differences, the controlled breathing exercise does not show any difference between exercise, S1 and S2. And during the spontaneous breathing exercise the x -values are slightly lower compared to S1, but compared to S2 no difference is observable. The comparison of the three exercises in Figure 4 (d) shows a similar result compared to the g -values. Notice that all $p_{Friedman}$-values are increased compared to the analysis of phase synchronization indicating that the differences between the measurements and exercises are smaller.

[insert Figure 4 here]

The synchronization of oscillations in heart rate and respiration during hexameter recitation and for controlled breathing allowed the calculation of the maximum of the distribution of $\Psi(t_i)$ as the preferred phase difference between both time series. The preferred phase difference differed largely in each exercise and thus could not easily be condensed in one number (see Table 5). Furthermore, most subjects showed a different preferred phase difference for recitation of hexameter verse than for controlled breathing. Remarkably, during both exercises many subjects showed a preferred phase difference of approximately $3/4p \approx 2.4$. In this case, the low frequency breathing oscillations preceded the heart rate oscillations by this phase difference, i.e. less than half an oscillation.

[insert Table 5 here]

Discussion

In this study cardiorespiratory interaction during recitation of hexameter verse has been investigated. In ATS this exercise is often used to ‘harmonize’ and ‘strengthen’ rhythmic processes in man. This is thought to be achieved by the recitation of speech which is supported by the therapeutic method the recitation is carried out: the breathing pattern is coordinated to the walking pattern and to the rhythm of the poetry. With respect to cardiorespiratory interaction the results of the analysis of the phase difference and the coherence analysis revealed the following classification. (A) During recitation of hexameter verse the low frequency oscillations of the breathing pattern were synchronized to a large extent with the heart rate oscillations. (B) The cardiorespiratory interaction was also synchronized during the controlled breathing exercise, but to a slightly lesser extent. (C) The resting periods before and after the exercises showed a further reduction of cardiorespiratory synchronisation. (D) During the spontaneous breathing exercise the cardiorespiratory interaction was almost completely desynchronized. Rhythmic speech thus has the strongest impact on synchronization of low frequency breathing oscillations and heart rate fluctuations whereas cardiorespiratory interaction during everyday activities is rarely synchronized.

This kind of cardiorespiratory interaction has its origin in the modulation of heart rate by respiration, i.e. respiratory sinus arrhythmia (RSA) (1). For breathing frequencies above 0.15 Hz the magnitude of RSA serves as an index of parasympathetic activity of the autonomic nervous system (15) because the latencies of heart rate responses and the corresponding decay constants of the vagal cardiac effectors are far shorter compared to the sympathetic branch (7). However, this notion has been challenged recently by the finding that sympathetic activity also influences RSA in the frequency range of breathing oscillations (47). RSA is a frequency- and amplitude-dependent phenomenon. If the breathing frequency is constant the magnitude of RSA increases as the tidal volume increases (21). For a given tidal volume, many studies consistently showed that breathing oscillations modulate heart rate strongest for frequencies below 0.15 Hz (6;12;18;21;32;44). Mental stress decreases RSA whereas reading aloud shifts RSA fluctuations into the low frequency range of the breathing frequency and thus increases RSA (6). Furthermore, the magnitude of RSA is larger if a short, rapid inspiration is followed by a long expiration than vice versa (45). Remarkably, during speech production the physiologic demands regarding pulmonary gas exchange may be overridden within wide limits (13;30). This effect is at least partly counterbalanced by an improved pulmonary gas exchange resulting from RSA (16;19). This short and by no means complete description may give an impression of the complexity of interactions that affect the magnitude of RSA. Although the phase relation between respiratory oscillations and modulations of heart rate have been investigated in experimental situations (1;15), to the best of our knowledge cardiorespiratory synchronization between breathing oscillations and RSA during speech production has not been systematically investigated.

During hexameter recitation most of the mentioned influences have to be taken into account. A slight mental activity was required in order to recite the text properly. The adjusted walking scheme during the exercise needed mild physical effort. Both, mental and physical activity increased the heart rate. On the other hand, the recitation produced a low frequency component in the breathing oscillations at approximately 6 cycles per minute, i.e. half of the actual breathing frequency. This oscillation appeared due to a longer duration and a larger amplitude of the breathing cycle during recitation compared to listening (cf. Figure 1). In contrast to the mental and physical activities, these properties lead to an increase of the magnitude of RSA. In summary, the reduction of the RSA due to an increase of the heart rate during recitation and controlled breathing was compensated by the increase of RSA due to the alternation of recitation and listening. Furthermore, the results of the analysis of cardiorespiratory synchronization revealed that during hexameter recitation RSA is synchronized with the low frequency component of the respiratory oscillations. The phase difference between the phase of the low frequency oscillations of the respiratory signal and the phase of the heart rate time series is $3/4p \approx 2.4$ for many subjects which is in agreement with the results of an experimental study at low breathing frequencies (15).

The emergence of cardiorespiratory synchronization during a regular breathing pattern at a low (and almost constant) frequency may be explained by the regular excitatory and inhibitory effects of the central respiratory generators on vagal and sympathetic outflow. Surprisingly, the high frequency breathing oscillations during hexameter recitation (cf. Figure 1 (A), unfiltered heart rate time series) modulated the heart rate only to a minor extent. Thus, the low frequency modulations of vagal and sympathetic cardiac effectors seem to override the modulations at higher frequencies. This effect may be due to the local maximum of the cardiorespiratory transfer function at low frequencies (approx. 0.1 Hz) (7). However, the complete physiological origin of the phase synchronization is difficult to explain, since the contributions of the central and the peripheral mechanisms to the generation of RSA are not yet fully understood (7;31). Other mechanisms, like the optimization of pulmonary gas exchange and the increase in arterial oxygen saturation (5;19), may also be of importance for the emergence of cardiorespiratory synchronization.

In principle, the same holds for the controlled breathing exercise except that this exercise showed synchronization to a lesser degree. A reason could be a slightly lower extent of RSA compared to the hexameter recitation. Although we did not control for it, the differences in the extent of synchronization and RSA might be due to a slightly larger tidal volume during recitation compared to controlled breathing. During spontaneous breathing the breathing oscillations did not contain a low frequency component. Hence, during this exercise the reduction of the magnitude of RSA by the physical activity was not compensated and, as a consequence, cardiorespiratory synchronization hardly ever occurred. Although there were no restrictions on breathing behaviour during the resting periods, cardiorespiratory synchronization then occurred more often than during spontaneous breathing but less often than during the other two exercises. This result may be explained by the reduced physical activity which decreased the heart rate and, in turn, increased the magnitude of RSA compared to the spontaneous breathing exercise. In principle, these results are accordance with the recent observation that the extent of cardiorespiratory synchronization increases if the breathing frequency decreases (33). However, in the present study the degree of synchronization depended on different breathing patterns and on physical activity whereas in the cited study only the breathing frequency varied. A study where both, breathing frequency and physical activity, were varied with respect to cardiorespiratory synchronization has not been carried out yet.

Unlike the analysis of special heart rate patterns during hexameter recitation in our previous investigation that incorporated a combination of a cross-sectional and a longitudinal study design with a low number of subjects (9), we did not find any immediate effect after the exercises. In other words, hexameter recitation did not affect cardiorespiratory synchronization straight after the exercise. However, the analysis of the previous data only showed immediate effects after the subjects were familiar with the exercise, i.e. after 2-3 weeks of exercise. Additionally, our previous investigation dealt with an analysis of specific ‘heart rate patterns’ (8) that is based on cardiorespiratory interaction at breathing frequencies well above 0.1 Hz. In contrast, the present study is based on a cross-sectional study design analysing cardiorespiratory interaction at breathing patterns of approximately 0.1 Hz. Thus, persistent effects of hexameter recitation on heart rate variability and presumably also on cardiorespiratory interaction need a certain familiarisation with the exercise.

Compared to established techniques to analyze bivariate data, like e.g. the calculation of the coherence, the analysis of phase differences yields more consistent results with respect to cardiorespiratory interaction, i.e. to the interplay of respiratory oscillations with heart rate fluctuations. The calculation of the coherence separated the different exercises to a lesser degree, particularly the differences between S1, exercise and S2 were less obvious. Thus, especially during uncontrolled breathing the coherence analysis seems to be less powerful. A reason is that the coherence mainly puts emphasize on the appearance of certain frequencies in both time series regardless of the phase difference between the oscillations. On the contrary, the analysis of phase differences is explicitly based on the interaction between both oscillations. A more detailed comparison and an analysis of the features and restrictions of each method is beyond the scope of this study and will be deferred to another study. Using the method presented here, we also expect cardiorespiratory synchronization for other techniques of artistic or religious speech creation, e.g. the ‘OM’-meditation, since they also use breathing patterns at low frequencies (26;29;48;49). Furthermore, data from many other studies investigating influences of low frequency breathing patterns on heart rate variability likely contain cardiorespiratory synchronization. More generally, since speech production is accompanied by an increase of the magnitude of RSA (36), we do not preclude the possibility that cardiorespiratory synchronization may also emerge to a certain extent during normal speech production.

In conclusion, the special breathing pattern used for the recitation of hexameter verse produced a strong cardiorespiratory synchronization with respect to low frequency breathing oscillations and heart rate variations. Controlled breathing showed cardiorespiratory synchronization to a lesser extent. The physiological origin of this kind of cardiorespiratory interaction still needs to be explored in more detail. Furthermore, it remains to be shown if and how cardiorespiratory synchronization affects arterial oxygen saturation at low breathing frequencies (5). A possible explanation would be that cardiorespiratory synchronization is more advantageous with respect to oxygen uptake since it takes advantage of synergistic effects.

Footnotes

[Footnote 1]
The enormous length of this narrative poetry (the Iliad consists of 15693 lines of hexameter), which has been recited by special 'singers' (aoides) in full length (24), seems to suggest at least a harmonious, beneficial, health maintaining influence not only on the speaker but also on the audience. However, there is a certain disagreement regarding the purpose of the caesura. Is it mainly introduced to take breath, or, to put emphasis on certain words or parts of a phrase? We tend to prefer the former, although both interpretations might apply. In ATS, the rhythmic function of the caesura is of importance. The caesura is regarded to take the duration of another dactyl. Thus, taking into account that only half a line is recited each time, each breath cycle in rhythmic hexameter recitation covers the length of 4 feet (recitation: 3 feet, caesura or breath taking: 1 foot). This pattern is experienced as especially harmonious.

Acknowledgements

This work was financially supported by the Weleda AG, Germany (DB, DC and HB) and the Wala AG, Germany (DB). David Auerbach helped in the preparation of the final version of the manuscript.

References

1. Angelone, A. and N. A. Coulter. Respiratory sinus arrhythmia: a frequency dependent phenomenon. *J.Appl.Physiol.* 19: 479-482, 1964.
2. Antonovsky, A. Unraveling the mystery of health. How people manage stress and stay well. San Francisco, Jossey-Bass. 1987.
3. Bernardi, L., A. Gabutti, C. Porta, and L. Spicuzza. Slow breathing reduces chemoreflex response to hypoxia and hypercapnia, and increases baroreflex sensitivity. *J.Hypertens.* 19: 2221-2229, 2001.
4. Bernardi, L., P. Sleight, G. Bandinelli, S. Cencetti, L. Fattorini, J. Wdowczyc-Szulc, and A. Lagi. Effect of rosary prayer and yoga mantras on autonomic cardiovascular rhythms: comparative study. *BMJ* 323: 1446-1449, 2001.
5. Bernardi, L., G. Spadacini, J. Bellwon, R. Hajric, H. Roskamm, and A. W. Frey. Effect of breathing rate on oxygen saturation and exercise performance in chronic heart failure. *Lancet* 351: 1308-1311, 1998.
6. Bernardi, L., J. Wdowczyk-Szulc, C. Valenti, S. Castoldi, C. Passino, G. Spadacini, and P. Sleight. Effects of controlled breathing, mental activity and mental stress with or without verbalization on heart rate variability. *J.Am.Coll.Cardiol.* 35: 1462-1469, 2000.
7. Berntson, G. G., J. T. Cacioppo, and K. S. Quigley. Respiratory sinus arrhythmia: autonomic origins, physiological mechanisms, and psychophysiological implications. *Psychophysiology* 30: 183-196, 1993.

8. Bettermann, H., D. Cysarz, and P. Van Leeuwen. Comparison of two different approaches in the detection of intermittent cardiorespiratory coordination during night sleep. *BMC Physiol.* 2: 18, 2002.
9. Bettermann, H., D. von Bonin, M. Frühwirth, D. Cysarz, and M. Moser. Effects of speech therapy with poetry on heart rate rhythmicity and cardiorespiratory coordination. *Int.J.Cardiol.* 84: 77-88, 2002.
10. Bortz, J., G. A. Lienert, and K. Boehnke. Verteilungsfreie Methoden in der Biostatistik. Berlin, Springer. 2000.
11. Bracewell, R. The Fourier transform and its applications. New York, McGraw-Hill. 1965.
12. Brown, T. E., L. A. Beightol, J. Koh, and D. L. Eckberg. Important influence of respiration on human R-R interval power spectra is largely ignored. *J.Appl.Physiol.* 75: 2310-2317, 1993.
13. Bunn, J. C. and J. Mead. Control of ventilation during speech. *J.Appl.Physiol.* 31: 870-872, 1971.
14. Denjean, B. and D. von Bonin. Therapeutische Sprachgestaltung. Stuttgart, Urachhaus. 2000.
15. Eckberg, D. L. Human sinus arrhythmia as an index of vagal cardiac outflow. *J.Appl.Physiol.* 54: 961-966, 1983.
16. Giardino, N. D., R. W. Glenny, S. Borson, and L. Chan. Respiratory sinus arrhythmia is associated with efficiency of pulmonary gas exchange in healthy humans. *Am.J.Physiol.Heart Circ.Physiol.* 284: H1585-H1591, 2003.
17. Grossarth-Maticek, R., H. J. Eysenck, G. Uhlenbruck, H. Rieder, H. Vetter, C. Freesemann, L. Rakic, G. Gallasch, D. T. Kanazir, and H. Liesen. Sport activity and personality as elements in preventing cancer and coronary heart disease. *Percept.Mot.Skills* 71: 199-209, 1990.
18. Hayano, J., S. Mukai, M. Sakakibara, A. Okada, K. Takata, and T. Fujinami. Effects of respiratory interval on vagal modulation of heart rate. *Am.J.Physiol.* 267: H33-H40, 1994.
19. Hayano, J., F. Yasuma, A. Okada, S. Mukai, and T. Fujinami. Respiratory sinus arrhythmia: A phenomenon improving pulmonary gas exchange and circulatory efficiency. *Circulation* 94: 842-847, 1996.
20. Hildebrandt, G. Reactive modifications of the autonomous time structure in the human organism. *J.Physiol.Pharmacol.* 42: 5-27, 1991.
21. Hirsch, J. A. and B. Bishop. Respiratory sinus arrhythmia in humans: how breathing patterns modulates heart rate. *Am.J.Physiol.* 241: H620-H629, 1981.
22. Hoyer, D., U. Leder, H. Hoyer, B. Pompe, M. Sommer, and U. Zwiener. Mutual information and phase dependencies: measures of reduced nonlinear cardiorespiratory interactions after myocardial infarction. *Med.Eng.Phys.* 24: 33-43, 2002.
23. Kotani, K., I. Hidaka, Y. Yamamoto, and S. Ozono. Analysis of respiratory sinus arrhythmia with respect to respiratory phase. *Methods Inf.Med.* 39: 153-156, 2000.
24. Latacz, J. Troja und Homer. Berlin, Koehler und Amelang. 2001.
25. Leder, U., D. Hoyer, M. Sommer, V. Baier, J. Haueisen, U. Zwiener, and H. R. Figulla. Cardiorespiratory desynchronisation after acute myocardial infarction. *Z.Kardiol.* 89: 630-637, 2000.

26. Lehrer, P., Y. Sasaki, and Y. Saito. Zazen and cardiac variability. *Psychosom.Med.* 61: 812-821, 1999.

27. Mrowka, R., A. Patzak, and M. Rosenblum. Quantitative analysis of cardiorespiratory synchronization in infants. *Int.J.Bifurcat.Chaos* 10: 2479-2488, 2000.

28. Palus, M. Detecting phase synchronization in noisy systems. *Phys.Lett.A* 235: 341-351, 1997.

29. Peng, C. K., J. E. Mietus, Y. Liu, G. Khalsa, P. S. Douglas, H. Benson, and A. L. Goldberger. Exaggerated heart rate oscillations during two meditation techniques. *Int.J.Cardiol.* 70: 101-107, 1999.

30. Phillipson, E. A., P. A. McClean, C. E. Sullivan, and N. Zamel. Interaction of metabolic and behavioral respiratory control during hypercapnia and speech. *Am.Rev.Respir.Dis.* 117: 903-909, 1978.

31. Piepoli, M., P. Sleight, S. Leuzzi, F. Valle, G. Spadacini, C. Passino, J. Johnston, and L. Bernardi. Origin of respiratory sinus arrhythmia in conscious humans: An important role for arterial carotid baroreceptors. *Circulation* 95: 1813-1821, 1997.

32. Pitzalis, M. V., F. Mastropasqua, F. Massari, A. Passantino, R. Colombo, A. Mannarini, C. Forleo, and P. Rizzon. Effect of respiratory rate on the relationships between RR interval and systolic blood pressure fluctuations: a frequency-dependent phenomenon. *Cardiovasc.Res.* 38: 332-339, 1998.

33. Porta, A., S. Guzzetti, N. Montano, M. Pagani, V. Somers, A. Malliani, G. Baselli, and S. Cerutti. Information domain analysis of cardiovascular variability signals: evaluation of regularity, synchronisation and co-ordination. *Med.Biol.Eng.Comput.* 38: 180-188, 2000.

34. Press, W. H., S. A. Teukolsky, W. T. Vetterling, and B. P. Flannery. Numerical recipes in C. Second Edition. Cambridge, Cambridge University Press. 1992.

35. Quian Quiroga, R., A. Kraskov, T. Kreuz, and P. Grassberger. On the performance of different synchronization measures in real data: a case study on EEG signals. *Phys.Rev.E* 65: 041903, 2002.

36. Reilly, K. J. and C. A. Moore. Respiratory sinus arrhythmia during speech production. *J.Speech Lang.Hear.Res.* 46: 164-177, 2003.

37. Rosenblum, M. G. and J. Kurths. Analysing synchronization phenomena from bivariate data by means of the Hilbert transform. In Kantz, H., J. Kurths, and G. Mayer-Kress, eds. Nonlinear analysis of physiological data. Berlin, Springer. 1998, 91-99.

38. Rosenblum, M. G., A. S. Pikovsky, and J. Kurths. Phase synchronization of chaotic oscillators. *Phys.Rev.Lett.* 76: 1804-1807, 1996.

39. Rosenblum, M. G., A. S. Pikovsky, and J. Kurths. From phase to lag synchronization in coupled chaotic oscillators. *Phys.Rev.Lett.* 78: 4193-4196, 1997.

40. Rosenblum, M. G., A. S. Pikovsky, C. Schäfer, P. Tass, and J. Kurths. Phase synchronization: from theory to data analysis. In Moss, F. and S. Gielen, eds. Neuro-Informatics and Neural Modeling. Amsterdam, Elsevier Science. 2001, 279-321.

41. Schäfer, C., M. G. Rosenblum, H. H. Abel, and J. Kurths. Synchronization in the human cardiorespiratory system. *Phys.Rev.E* 60: 857-870, 1999.

42. Schäfer, C., M. G. Rosenblum, J. Kurths, and H. H. Abel. Heartbeat synchronized with ventilation. *Nature* 392: 239-240, 1998.

43. Schiek, M., F. R. Drepper, R. Engbert, H. H. Abel, and K. Suder. Cardiorespiratory synchronization. In Kantz, H., J. Kurths, and G. Mayer-Kress, eds. Nonlinear analysis of physiological data. Berlin, Springer. 1998, 191-209.

44. Stark, R., A. Schienle, B. Walter, and D. Vaitl. Effects of paced respiration on heart period and heart period variability. *Psychophysiology* 37: 302-309, 2000.

45. Strauss-Blasche, G., M. Moser, M. Voica, D. R. McLeod, N. Klammer, and W. Marktl. Relative timing of inspiration and expiration affects respiratory sinus arrhythmia. *Clin.Exp.Pharmacol.Physiol.* 27: 601-606, 2000.

46. Tass, P., M. G. Rosenblum, J. Weule, J. Kurths, A. S. Pikovsky, J. Volkmann, A. Schnitzler, and H. J. Freund. Detection of n:m phase locking from noisy data: application to magnetoencephalography. *Phys.Rev.Lett.* 81: 3291-3294, 1998.

47. Taylor, J. A., C. W. Myers, J. R. Halliwill, H. Seidel, and D. L. Eckberg. Sympathetic restraint of respiratory sinus arrhythmia: implications for vagal-cardiac tone assessment in humans. *Am.J.Physiol.Heart Circ.Physiol.* 280: H2804-H2814, 2001.

48. Telles, S. and T. Desiraju. Autonomic changes in Brahmakumaris Raja yoga meditation. *Int.J.Psychophysiol.* 15: 147-152, 1993.

49. Telles, S., R. Nagarathna, and H. R. Nagendra. Autonomic changes during "OM" meditation. *Indian J.Physiol.Pharmacol.* 39: 418-420, 1995.

50. von Bonin, D., M. Frühwirth, P. Heusser, and M. Moser. Effects of speech therapy with poetry on heart rate variability and well-being. *Forsch.Komplementarmed.Klass.Naturheilkd.* 8: 144-160, 2001.

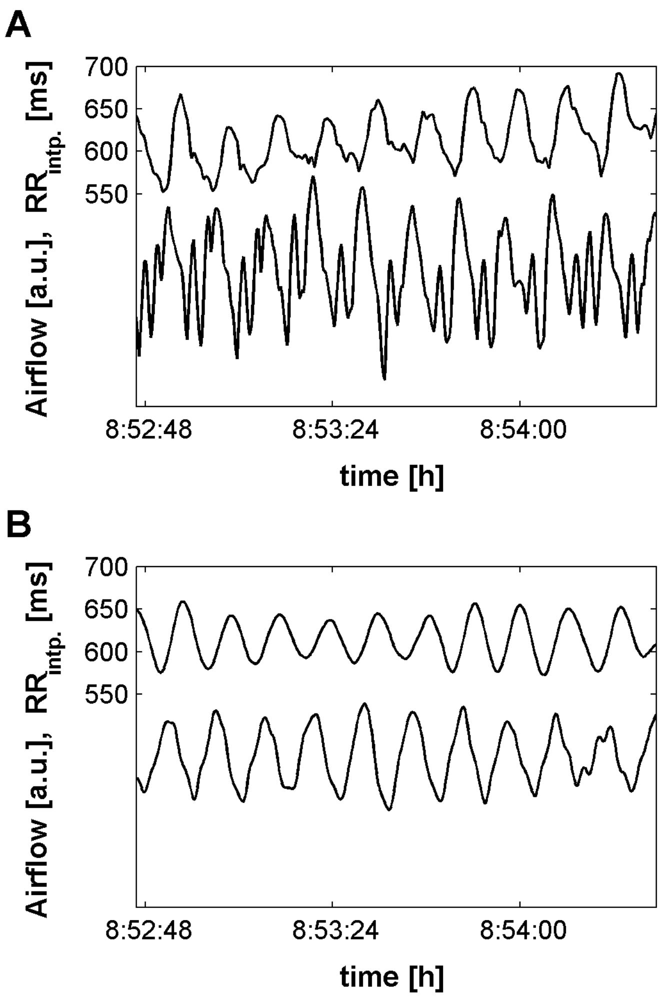

Figure 1: (A) Heart rate time series derived from the interpolated RR-tachogram (upper trace) and nasal/oral airflow (in arbitrary units, lower trace) during recitation of hexameter before filtering. Obviously, the heart rate time series mainly shows a low frequency oscillation whereas the nasal/oral airflow contains a low and a high frequency oscillation.

(B) Heart rate time series and nasal/oral airflow after the filtering procedure. In the nasal/oral airflow only the low frequency oscillation remain. The synchronization is obvious.

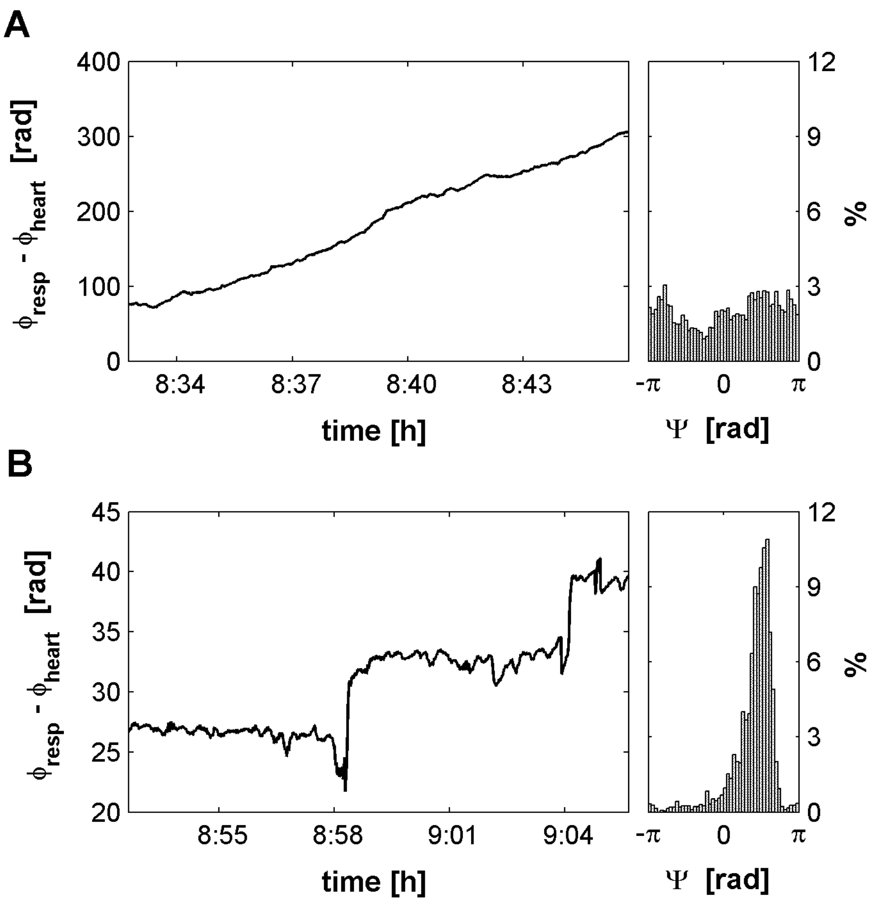

Figure 2: (A) The increase of the phase difference $f_{resp}(t_i) - f_{heart}(t_i)$ during baseline measurement S1 denotes a desynchronized state between the heart rate time series and the low frequency component of the nasal/oral time series ($g = 0.14$).

(B) Cardiorespiratory synchronization during hexameter recitation: the phase difference shows plateaus at different levels and an obvious maximum in the distribution of $\Psi(t_i)$ which is also reflected by $g = 0.78$.

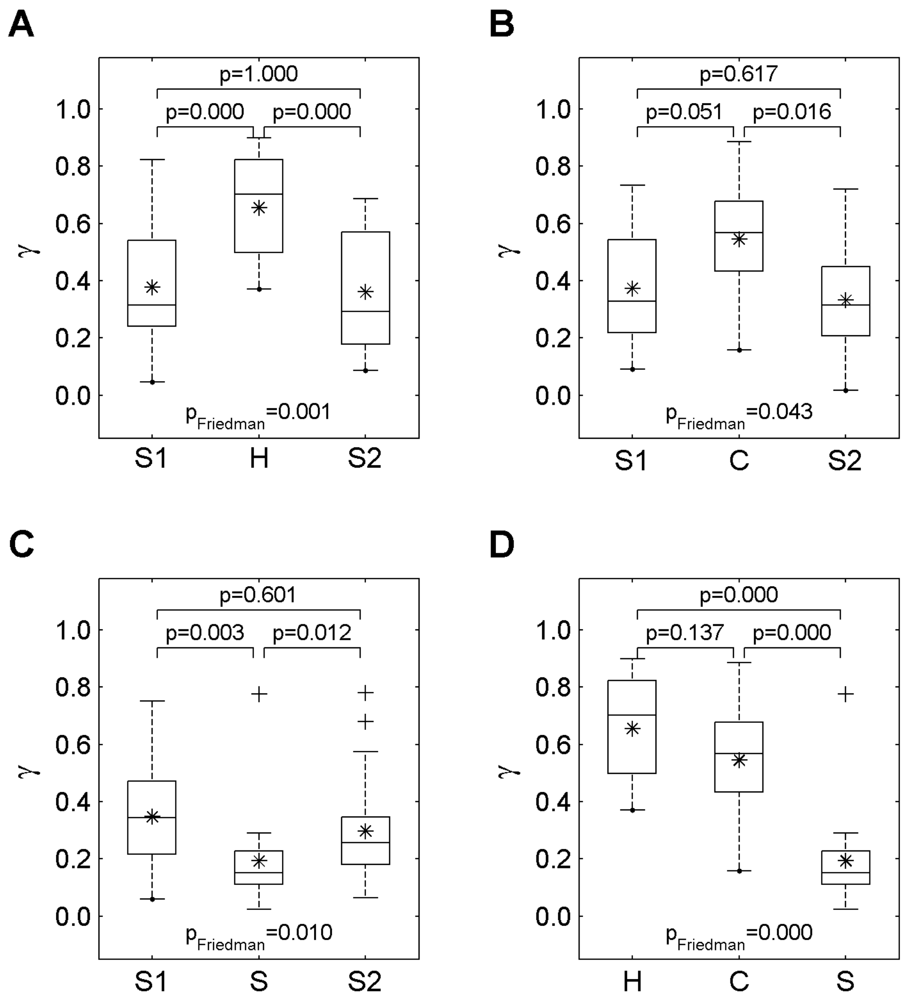

Figure 3: Box and whisker plots of the g -values quantifying cardiorespiratory phase synchronization. (A)-(C) Comparison of the three measurements of each exercise. (D) Comparison of the three exercise measurements (hexameter, controlled breathing, spontaneous breathing). In all diagrams a low value of $p_{Friedman}$ indicates likely differences between the g -values of the three measurements. The probability of similar g -values between two measurements is indicated by the p-values above the box and whisker plot. The box plots show median and quartiles (horizontal lines), mean value (star), and maximum and minimum values (whiskers). For abbreviations of the measurements see Table 1.

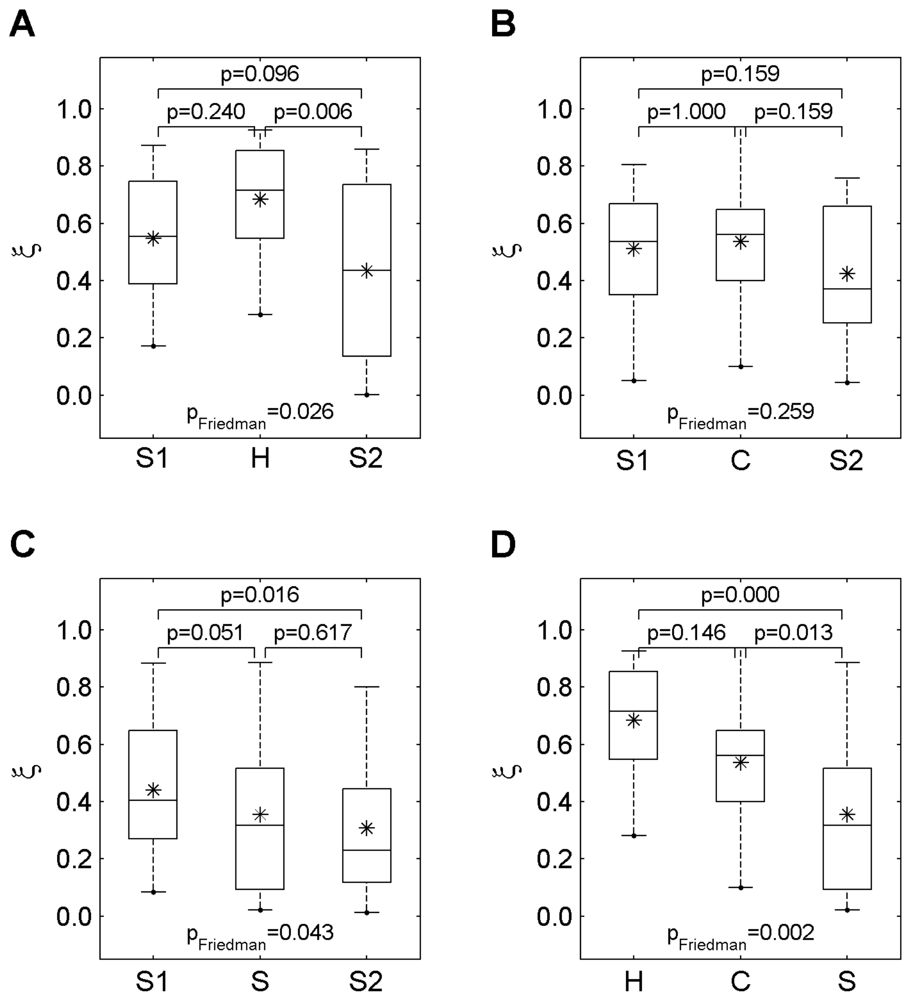

Figure 4: Box and whisker plots of the x -values quantifying cardiorespiratory coherence as a simple measure of cardiorespiratory synchronization (further details: see Figure 3).

	15 minutes sitting →	20 minutes walking + exercise →	15 minutes sitting
Session 1	baseline measurement (S1)	**hexameter exercise (H)**	effect measurement (S2)
Session 2	baseline measurement (S1)	**controlled breathing (C)**	effect measurement (S2)
Session 3	baseline measurement (S1)	**spontaneous breathing (S)**	effect measurement (S2)

Table 1: Experimental protocol: Each subject had to perform three different exercises, one exercise per session. The sessions were divided into three successive measurements: quiet rest without any restrictions on breathing during the baseline measurement (S1), exercise (H, C or S), and quiet rest without any restrictions on breathing during the effect measurement (S2, further details: see text).

	Heart rate (1/min)								
	S1			Exercise			S2		
	lq	median	uq	lq	median	uq	lq	median	uq
Exercise **H** $p_{Friedman}$=0.000	62.7	**71.1**	83.1	74.4	**82.9**$^{*,\#}$	92.9	59.2	**67.5****	75.2
Exercise **C** $p_{Friedman}$=0.000	60.0	**66.1**	81.0	75.2	**81.0***	91.1	57.6	**62.7****	74.2
Exercise **S** $p_{Friedman}$=0.000	62.8	**72.3**	78.3	74.7	**78.8***	84.7	58.9	**66.8****	73.6
					$p_{Friedman}$=0.086				

* p<0.001 vs. S1 and S2 ** p<0.001 vs. S1 $^{\#}$ p<0.05 vs. exercise S

Table 2: Median (bold), lower (lq) and upper quartile (uq) of the subjects' median heart rate (in 1/min) of each measurement. A low value of $p_{Friedman}$ indicates likely differences between the three measurements. For abbreviations see Table 1.

	frequency of the low frequency breathing oscillations (1/min)								
	S1			Exercise			S2		
	lq	median	uq	lq	median	uq	lq	median	uq
Exercise **H** $p_{Friedman}=0.000$	7.7	**8.3**	9.5	6.2	**6.4**$^{*,\#,\#\#}$	6.5	7.5	**8.5**	9.9
Exercise **C** $p_{Friedman}=0.000$	7.2	**8.5**	8.8	6.4	**6.5**$^{*,\#}$	6.6	7.5	**7.8**	8.7
Exercise **S** $p_{Friedman}=0.002$	7.5	**8.6**	9.9	8.3	**12.5****	20.0	7.5	**8.3**	10.7
					$p_{Friedman}=0.000$				

* $p<0.001$ vs. S1 and S2 ** $p<0.01$ vs. S1 and S2 $^{\#}$ $p<0.001$ vs. exercise C
$^{\#\#}$ $p<0.001$ vs. exercise S

Table 3: Median (bold), lower (lq) and upper quartile (uq) of the subjects' median frequency of the low frequency breathing oscillations (in 1/min) of each measurement. A low value of $p_{Friedman}$ indicates likely differences between the three measurements. For abbreviations see Table 1.

	Extent of RSA (ms)								
	S1			Exercise			S2		
	lq	median	Uq	lq	median	uq	lq	median	Uq
Exercise **H** $p_{Friedman}=0.287$	40.8	**50.9**	75.6	45.2	**62.9**	78.3	44.1	**51.5**	98.5
Exercise **C** $p_{Friedman}=0.387$	46.0	**60.5**	82.2	43.2	**57.6**#	100.9	46.7	**66.4**	102.5
Exercise **S** $p_{Friedman}=0.000$	42.1	**46.9**	63.7	30.8	**40.8***	48.3	43.7	**55.4**	86.3
					$p_{Friedman}=0.035$				

* $p<0.001$ vs. S1 and S2 # $p<0.05$ vs. exercise S

Table 4: Total median (bold), lower (lq) and upper quartile (uq) of the subjects' extent of RSA (in ms) of each measurement. A low value of $p_{Friedman}$ indicates likely differences between the three measurements. For abbreviations see Table 1.

	Preferred Ψ (rad)	
Subject	Hexameter	Controlled Breathing
1	0.73	0.92
2	-3.13	0.80
3	2.11	3.02
4	0.72	2.76
5	2.42	1.89
6	2.33	2.06
7	2.76	3.10
8	2.34	2.34
9	2.50	2.75
10	2.45	1.25
11	1.12	2.92
12	2.66	2.27
13	1.31	2.87
14	-0.07	1.29
15	0.80	0.48
16	1.13	1.99
17	2.21	2.41
18	-2.02	-0.68
19	1.58	2.29
20	0.13	2.57

Table 5: Preferred phase difference $\Psi(t_i)$ (in rad) between heart rate and breathing oscillations during hexameter and controlled breathing exercise of each subject.