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Cardiorespiratory synchronization during Zen meditation

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Abstract

The impact of meditation on cardiorespiratory synchronization with respect to breathing oscillations and the modulations of heart rate induced by respiration (respiratory sinus arrhythmia, RSA) was investigated in this study. Four different exercises (spontaneous breathing, mental task, Zen meditation and Kinhin meditation) were consecutively performed by 9 subjects mainly without any experience in meditation. An electrocardiogram and a respiratory trace were recorded simultaneously. On this basis the degree of cardiorespiratory synchronization was quantified by a technique which has been adopted from the analysis of weakly coupled chaotic oscillators. Both types of meditation showed a high degree of synchronization whereas heartbeat and respiration were hardly synchronized during spontaneous breathing. During the mental task exercise the extent of synchronization was slightly higher than during spontaneous breathing. These results were largely determined by the breathing frequency because the two types of meditation induce low breathing frequencies which led to a pronounced and in-phase RSA. During the meditation the low breathing frequencies led to a decrease in the high frequency of heart rate variability whereas the low frequency and the extent of RSA increased. The heart rate primarily reflected the degree of physical effort. The high degree of cardiorespiratory synchronization during meditation in unexperienced meditators suggests that the physiological implications of meditation does not require prior experience in meditation.

Keywords: Heart rate variability, Respiratory Sinus Arrhythmia, Respiration, Synchronization, Bivariate data analysis, Meditation

Introduction

Meditation in its various forms is a traditional exercise with a potential benefit on well-being and health. On a psychosomatic level these exercises seem to improve the salutogenetic potential in man (Antonovsky 1987). Many studies also focused on the physiological effects of different meditation techniques to gain insight into the physiological prerequisites responsible for the improvement of health (Sudsuang et al. 1991; Wenneberg et al. 1997; Lehrer et al. 1999; Peng et al. 1999; Lee et al. 2000; Barnes et al. 2001; Travis 2001; Peng et al. 2004). Especially the cardiorespiratory interaction seems to play an important role since most meditation techniques make use of special low frequency breathing patterns regardless of whether they result from a deliberate guidance of breathing or other mechanisms, e.g. the recitation of specific (religious) verse (Bernardi et al. 2001; Cysarz et al. 2004).

The modulation of the instantaneous heart rate by breathing patterns is known as respiratory sinus arrhythmia (RSA) (Angelone and Coulter 1964; Hirsch and Bishop 1981; Berntson et al. 1993). The effects of different breathing patterns on heart rate variability (HRV) and other cardiovascular parameters, e.g. baroreflex sensitivity or blood pressure, have been investigated extensively. E.g. during recitation of the rosary prayer and the ‘OM’ mantra the breathing oscillations and the endogenous blood pressure fluctuations adjust their frequencies (Bernardi et al. 2001). Furthermore, the arterial oxygen saturation SaO_2 in patients with chronic heart failure increased strongest at breathing frequency of 6 breaths per minute (Bernardi et al. 1998). These findings imply that the control of breathing patterns may be used to maintain conditions for health and seem to be advantageous for recovery processes.

Different approaches may be used to control a regular breathing behaviour, like e.g. meditation, recitation of religious verse or poetry, or biofeedback (Lehrer et al. 2000). Although the different techniques and their respective theoretical background vary remarkable they all make use of a slow paced breathing pattern or at least produce low frequency breathing oscillations. The impact of slow paced breathing patterns on cardiovascular control has been investigated extensively. E.g. the modulation of heart rate by respiration is strongest at low breathing frequencies of approximately 0.1 Hz (6 respiratory cycles / min) (Berntson et al. 1993; Bernardi et al. 2000; Stark et al. 2000). In our own investigations we were able to show that a high degree of cardiorespiratory synchronization occurs during recitation of hexameter verse (Cysarz et al. 2004). Although this type of exercise uses a breathing frequency at approximately 12 min^{-1} the therapeutically guided recitation of hexameter verse produced a low frequency oscillation in the breathing pattern (at approximately 6 min^{-1}) which led to a pronounced and in-phase RSA. This kind of cardiorespiratory synchronization may play an important physiological role with respect to a potential benefit on well-being and health.

During the different exercises of Zen meditation the depth and the duration of each respiratory cycle is determined only by the process of breathing. As a consequence, the breathing modalities are produced according to their own demands, i.e., the breathing frequency slows itself down to a range between 5-8 min^{-1} and the tidal volume is adjusted appropriately to avoid hypoventilation. This type of exercise exerts a great influence on heart rate variability and, especially, the extent of RSA. In this study, we focus on the analysis of cardiorespiratory synchronization during a succession of different exercises: two different types of Zen meditation, a mental task and quiet breathing (i.e., breathing without focussing on the breathing process). These exercises allow the classification with respect to cardiorespiratory synchronization because they all make use of different breathing frequencies and are expressed by different levels of heart rate variability.

Methods

Subjects and Experimental Procedure

Nine colleagues of the institution took part in the study (4 female, 3 smokers; average age: 43 ± 7 years). None of the subjects had any history of cardiovascular diseases, especially no hypo- or hypertension or antiarrhythmical therapy. One subject had a long experience in Zen meditation (a teacher of Zen-meditation) and one subject was experienced with respect to Vipassana meditation (a mindfulness-based meditation) but had no experience with Zen meditation. All other subjects did not have any experience with meditation.

The duration of the experimental procedure was approximately 50 minutes. The procedure was divided into six different exercises (see Table 1): (1) the subject sat quietly on a chair without any restrictions on breathing and without any extra-ordinary mental activity (duration: approx. 10 Minutes). There was no instruction to try to get into a relaxed state. (2) During the 'Mental task' exercise the subject still sat an a chair and had to do advanced mental arithmetic for approx. 6 minutes. (3) Subsequently, the first session of sitting meditation (Zazen) was practiced (duration: approx. 10 minutes) (Metzger 2001). This kind of meditation is characterized by breathing at a rate and depth which is only determined by the breathing process itself, i.e., any outward intention is minimized and the intention towards the breathing process is increased. The volunteers were advised to avoid any thinking, and to keep the awareness on 'just-sitting' and 'just-breathing'. To facilitate this kind of mediation the subjects sat upright on a cushion and the hands were held together in front of the navel. (4) During the next 7 minutes, a walking meditation (Kinhin) was practiced. With respect to the breathing modalities it is comparable to Zazen meditation. In contrast, this exercise is a distinct form of walking with short steps (Büssing 2001): during inspiration the foot is lifted and the whole body is slightly erected against the gravity. Then, during expiration, the foot is put down a half-step in front and gravity may slightly pull down the body again. Thus, the walking speed is unambiguously intertwined with the breathing process. The hands were held together in front of the sternum and were slightly pressed against each other and the sternum during expiration. (5) For the next 7 minutes Zazen meditation is practiced again to get back to rest in a calm fashion. (6) At the end of the procedure, the subject sat in a chair again, similar to the beginning of the experiment (duration: 10 minutes). It has to be noted that the teacher of Zen-meditation carried out this procedure alone whereas all other subjects were instructed by the teacher (sitting face to face during the Zazen meditation and walking next to him during the Kinhin meditation). This way, it was possible to give minor advices (in the sense of clarifications) to the first-time meditators.

Data acquisition

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 simultaneously recorded 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 100 Hz, respectively. This ensured an accuracy < 1 ms for the times of the identified R-peaks. The local minima and the local maxima of the nasal/oral airflow were defined as the inspiratory and expiratory onsets, respectively, since 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 data were saved to a file and were further processed using Matlab (The Mathworks, Natick, Mass, USA) and C routines. Subsequently, all automatically identified R-peaks were visually controlled i.e. the times of the R-waves were marked in the ECG. They were edited if the identified R-peaks did not match the R-peak in the ECG. The manually edited R-peaks had an accuracy of 4 ms because the recorded ECG had a sampling rate of 250 Hz.

Effects of transitions the beginning of each exercise were reduced by omitting the first two minutes of each exercise. To avoid a bias due to different durations of the recordings of each exercise the subsequent 5 minutes were used for further analysis.

Analysis of cardiorespiratory synchronization

A heart rate time series with equidistant time steps was constructed as follows: the times of successive R-peaks were first converted to a RR-tachogram, i.e., the sequence of times between successive R-peaks. 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 20^{th} sample was used. These two time series share a common time axis and served as the basis for further calculations.

Figure 1 (A) and (C) show the heart rate time series and the simultaneous nasal/oral airflow during rest on the chair and during Zazen meditation, respectively. Obviously, during resting on the chair both time series are desynchronized whereas during Zazen meditation a cardiorespiratory synchronization is present. To quantify the extent of cardiorespiratory synchronization the phases of each time series were constructed and subsequently analyzed. This procedure was adopted from the synchronisation analysis of weakly coupled chaotic oscillators (Rosenblum et al. 1996; Rosenblum et al. 1997) and yielded more consistent results than the analysis of coherence (Cysarz et al. 2004). It is based on the assumption that the coupling leading to the modulation of heart rate by respiration is essentially linear and non-linear couplings may be neglected. It is described briefly in the following (for further information, see e.g. (Cysarz et al. 2004)).

First, both time series are low-pass filtered with a cut-off frequency of 0.25 Hz. Next, the so-called phase of each time series, i.e., $f_{heart}(t_i)$ and $f_{resp}(t_i)$, is constructed with the help of the Hilbert-transformation (Rosenblum and Kurths 1998). Both times series are synchronized if the phase difference $j(t_i) = f_{resp}(t_i) - f_{heart}(t_i)$ is constant, i.e., $\left| j(t_i) - d \right| < const$ (d is an offset since the phase difference needs not to be around zero). The phase difference is quantified by $g = \langle \cos(j(t_i) \bmod 2p) \rangle^2 + \langle \sin(j(t_i) \bmod 2p) \rangle^2$ where brackets denote an average. Theoretically, $0 \le g \le 1$ and $g = 1$ if the two time series are completely synchronized, i.e. a constant phase difference, and $g = 0$ if they are desynchronized. However, for real world data, the data may always contain some spuriously synchronized patterns although the systems are completely desynchronized. Thus, the lower bound of g was estimated with the help of so-called surrogate data, i.e. artificial data without any coupling which were constructed on the basis of the original data. This estimation yielded $g = 0.14$ as an estimation of the lower bound of g, i.e. any value $g \le 0.14$ may be considered as completely desynchronized.

The temporal course of the phase difference $j(t_i)$ (in radians) and the distribution of $j(t_i) \bmod 2p$ is shown in Figure 1 (B) and (D). In the desynchronized state the temporal course of the phase difference seems to be erratic and the values of $j(t_i) \bmod 2p$ are almost equally distributed. This is also reflected in the low g-value ($g = 0.14$) which denotes a desynchronized state. On the contrary, the synchronized state the temporal course of the phase difference is almost constant which is also reflected by the clear maximum in the distribution of $\varphi(t_i) \bmod 2\pi$. Now, the synchronization gives rise to a γ-value near 1 ($\gamma = 0.92$).

Heart rate variability (HRV)

In addition to the quantification of cardiorespiratory synchronization the heart rate variability was calculated according to the guidelines (Task Force of the European Society of Cardiology and the North American Society of Pacing and Electrophysiology 1996). A power spectrum based on the fast Fourier transformation (FFT) was calculated for the resampled RR-tachogram derived from the 5-minute-recording of each exercise. Next, the resulting power spectral density distribution was integrated in the low frequency band (0.04-0.15 Hz, LF) and the high frequency band (0.15-0.4 Hz, HF). The guidelines suggest to calculate the power in these frequency bands in milliseconds^2 (corresponding to the variance of the RR-intervals in the particular frequency bands). In difference to the guidelines, we use the square root of LF and HF power to obtain values in milliseconds that correspond to the standard deviation of the particular band-pass filtered RR-tachogram because these values allow to estimate the amplitude of the oscillations in each frequency band. Furthermore, the balance bal=LF/HF was also calculated as a rough quantitative estimate of the balance between the sympathetic and parasympathetic activity of the autonomous nervous system. In addition, the extent of RSA is expressed as the median of the longest RR-interval minus the shortest RR-interval of each respiratory cycle.

Statistics

Descriptive methods are used to assess the effects of Zen meditation on cardiorespiratory synchronization. Since the number of subject is small (N=9) the distributions of the different parameters are not known. Thus, the median is used to quantify the distributions of the parameters. The two sitting periods and the two Zazen meditations, respectively, were condensed in one quantity by taking the average. In total, four different exercises were compared: sitting (S), mental task (T), Zazen meditation (MT) and Kinhin meditation (MK). The γ-value, mean heart rate, mean respiratory frequency, extent of RSA, HF, LF and balance and were calculated for each exercise of each subject. Box and whisker plots were used for visualization of the distribution of heart rate, respiratory frequency, γ-value, extent of RSA, LF, HF and balance.

The probability of equality between the four different exercises was quantified by the non-parametric Friedman-test, a non-parametric one-way ANOVA. A $p_{Friedman}$-value near zero indicates a high probability of differences between the different exercises with respect to the analyzed parameter. An appropriate post hoc test for multiple comparisons was used to calculate the probability of equality between two exercises (Bortz et al. 2000). If the $p_{Friedman}$-value of a parameter is low, low p-values of the post hoc test indicate which exercises differ considerably.

Results

In all subjects cardiorespiratory interaction was most de-synchronized during sitting (S) at the beginning of the procedure ($\gamma = 0.23$), c.f Figure 2C. During the mental task exercise (T) the degree of synchronization increased in all subjects to an intermediate level ($\gamma = 0.40$). Practicing Zazen meditation (MZ) or Kinhin meditation (MK) increased the extent of synchronization to a high level (MZ: $\gamma = 0.77$, MK: $\gamma = 0.80$).

The heart rate was lowest during the Zazen meditation (68.2 beats/min) and highest for Kinhin meditation (77.5 beats/min), cf. Figure 2A. Sitting and the mental task showed intermediate heart rates (S: 72.8 beats/min, T: 75.9 beats/min). During sitting and mental task the respiratory frequency was at a normal level (S: 16.2 breaths/min, T: 16.6 breaths/min) whereas the two meditations decreased the respiratory frequency enormously (MZ: 8.4 breaths/min, MK: 6.1 breaths/min), cf. Figure 2B.

The high frequency variations of heart rate variability were approximately the same during sitting, mental task and Zazen meditation (S: 18.9 ms, T: 19.2 ms, MZ: 19.0 ms), cf. Figure 3A. During Kinhin meditation the high frequency component decreased (MK: 13.5 ms). In contrast, the low frequency variations were approximately the same during sitting and mental task (S: 38.1 ms, T: 26.9 ms) and increased considerably during Zazen and Kinhin meditation (MZ: 61.1 ms, MK: 69.5 ms), cf. Figure 3B. Again, the balance is approximately the same during sitting and mental task (S: 1.7, T: 1.5) and increases during Zazen meditation (3.2) and is largest during Kinhin meditation (4.8), cf. Figure 3C. The extent of RSA is approximately the same during sitting and mental task (S: 67.9 ms, T: 55.6 ms) and considerably increases during Zazen and Kinhin meditation (MZ: 134.6 ms, MK: 168.3 ms), cf. Figure 3D.

Discussion

The investigation of different kinds of meditation has gained attention in recent years. On a psychosomatic level the meditation techniques may be used to calm down the patient and to direct the awareness to distinct processes, e.g. the process of breathing, that are usually carried out without much attention, or to the present moment. Thus, meditation may change the significance of every day activities. This way the coping with stress and problems (arising e.g. from a specific disease) may by enhanced, i.e. so-called salutogenetic processes may be improved, and a healthier state may result (Antonovsky 1987). This may also lead to benefits on a physiological level.

The impact of meditation on physiological parameters may also be investigated directly because most meditation techniques make use of specific procedures which also influence the breathing frequency (e.g. by focussing on breathing during Zen meditation). In this study, cardiorespiratory interaction has been analyzed in nine subjects (one teacher of Zen meditation and eight first-time meditators) practicing two different kinds of Zen meditation. Zazen and Kinhin meditation both led to a highly synchronized interaction between heart rate fluctuations, i.e. respiratory sinus arrhythmia (RSA), and respiration. Zazen meditation drastically slowed down the breathing frequency (approx. 8 breaths per minute) and, hence, led to a pronounced and in-phase RSA. Although the heart rate was increased during Kinhin meditation the extent of synchronization was slightly higher than during Zazen meditation because this kind of meditation slowed down the breathing frequency even more (approx. 6 breaths per minute). On the contrary, sitting in a chair with spontaneous breathing led to an almost completely de-synchronized cardiorespiratory interaction. During the mental task exercise the extent of cardiorespiratory synchronization was slightly increased compared to spontaneous breathing. With respect to the extent of cardiorespiratory synchronization during quiet sitting (spontaneous breathing) and Zazen meditation our results are in accordance with previous findings (Peng et al. 2004).

The origin of this kind of cardiorespiratory synchronization is the respiratory sinus arrhythmia , i.e. the modulation of heart rate by respiration (Angelone and Coulter 1964). The magnitude of RSA depends on the frequency and the amplitude of the breathing oscillations. Some basic dependencies that have to be taken into account are described in the following. The extent of RSA increases as the tidal volume increases and the breathing frequency is constant (Hirsch and Bishop 1981). If the tidal volume is kept constant, breathing oscillations modulate heart rate strongest for frequencies below 0.15 Hz (Hirsch and Bishop 1981; Brown et al. 1993; Hayano et al. 1994; Pitzalis et al. 1998; Bernardi et al. 2000; Stark et al. 2000). On the other hand, mental effort decreases the extent of RSA (Bernardi et al. 2000). Hypercapnia, which may result from a low breathing frequency, is counterbalanced by adjusting the tidal volume appropriately and by an improved pulmonary gas exchange resulting from RSA (Hayano et al. 1996; Giardino et al. 2003).

These facts have to be taken into account to assess the effects of the different exercises appropriately. During both kinds of meditation the breathing frequency was apparently decreased and led to an increase of low frequency heart rate variation and the extent of RSA. The low frequency breathing pattern produced regular excitatory and inhibitory effects of the central respiratory generators on vagal and sympathetic outflow. The local maximum of the cardiorespiratory transfer function at low frequencies (approx. 0.1 Hz) suggests that this effect is especially pronounced at these frequencies (Berntson et al. 1993). As a result, cardiorespiratory synchronization occurs. During sitting and mental task the breathing frequency was increased compared to the meditation exercises. The transfer function decays strongly at these frequencies and, hence, the regular excitatory and inhibitory effects of the central respiratory generators on vagal and sympathetic outflow is diminished. As a consequence, cardiorespiratory interaction was almost fully de-synchronized. Nevertheless, this increase was associated with a slight increase of the extent of cardiorespiratory interaction.

Interestingly, the heart rate variability reveals a difference between both types of meditation. During the Kinhin meditation the high frequency variations were smallest and the low frequency variations were largest. Thus, during Kinhin meditation the balance was even higher than during Zazen meditation, i.e. the Kinhin meditation transfers slightly more oscillatory impact from the high frequency band to the low frequency band than the Zazen meditation. This effect is even more remarkable if the orthostasis and the slight physical effort of this kind of meditation is taken into account. Furthermore, it is interesting to note that these physiological effects appeared in unexperienced meditators. This suggests that the physiological benefits from practicing meditation appear regardless of any prior experience in meditation.

The cardiorespiratory synchronization may be associated with findings of positive signs of recovery: an increase of arterial oxygen saturation SaO_2 during breathing at a frequency of 6 breaths per minute (Bernardi et al. 1998), an increased arterial baroreflex sensitivity as a favourable long term prognostic factor in cardiac patients (Bernardi et al. 2002), and a decrease of systolic blood pressure (Grossman et al. 2001). Although meditation is often associated with some kind of (mental) relaxation the different physiological implications of meditation suggest a more detailed picture: a rather pronounced heart rate variability which is well coordinated with other oscillations, e.g. respiration. The latter characteristic seems to be essential to make the exercises comfortable (in the sense of calm) although some physiological functions are at least partially more active (Peng et al. 2004). Since many different meditation techniques make use of breathing patterns with low frequencies, cardiorespiratory synchronization may also appear during other kinds of meditation. More generally, this feature may occur whenever the breathing frequency is low, e.g. during recitation of the rosary prayer (Bernardi et al. 2001) or the ‘OM’-mantra (Telles et al. 1995). However, an increased mental activity may reduce the extent of cardiorespiratory synchronization.

Limitations

The study design is a balanced design using longitudinal and cross-sectional elements. Thus, it was possible to achieve reliable results with a relatively low number of participants and it was not necessary to introduce any kind of randomization. As pointed out in (Bettermann et al. 2002) this kind of design is especially ‘well suited in the field of creative arts therapy research’. This statement also applies for the present study because the creative arts therapy investigated in the cited study also deals with different breathing modalities.

Another point is concerned with the question whether subjects practicing Zen meditation for the first time experience the same effects (and / or benefits) than experienced Zen meditators do. This study unambiguously reveals that with respect to cardiorespiratory interaction the Zen meditation shows similar effects in the teacher of Zen meditation and in first-time meditators. Thus, we conclude that this kind of physiological impact does not require long time training in Zen meditation. However, there might be other levels of impact, e.g. different states of mind (or awareness), that probably are not attainable by first-time meditators (Büssing 2005). Hence, it may be possible that other physiological effects, e.g. a specific signature in the electroencephalogram as a physiological representation of the state of mind (Lutz et al. 2004), are not attainable by first-time meditators. Such questions deserve future investigations, but they were not topic of this investigation.

In conclusion, Zen meditation synchronizes the cardiorespiratory interaction with respect to breathing oscillations and the heart rate variations induced by respiration (RSA). Furthermore, it drastically increased low frequency variations of heart rate. Spontaneous breathing patterns hardly showed any cardiorespiratory synchronization and during mental activity the cardiorespiratory synchronization was decreased compared to both types of Zen meditation. It remains to be shown that this kind of cardiorespiratory synchronization is advantageous for the gas exchange in the respiratory tract. Furthermore, this study indicates that this kind of religious practice has immediate physiological effects on cardiorespiratory interaction without the need of special long-term training.

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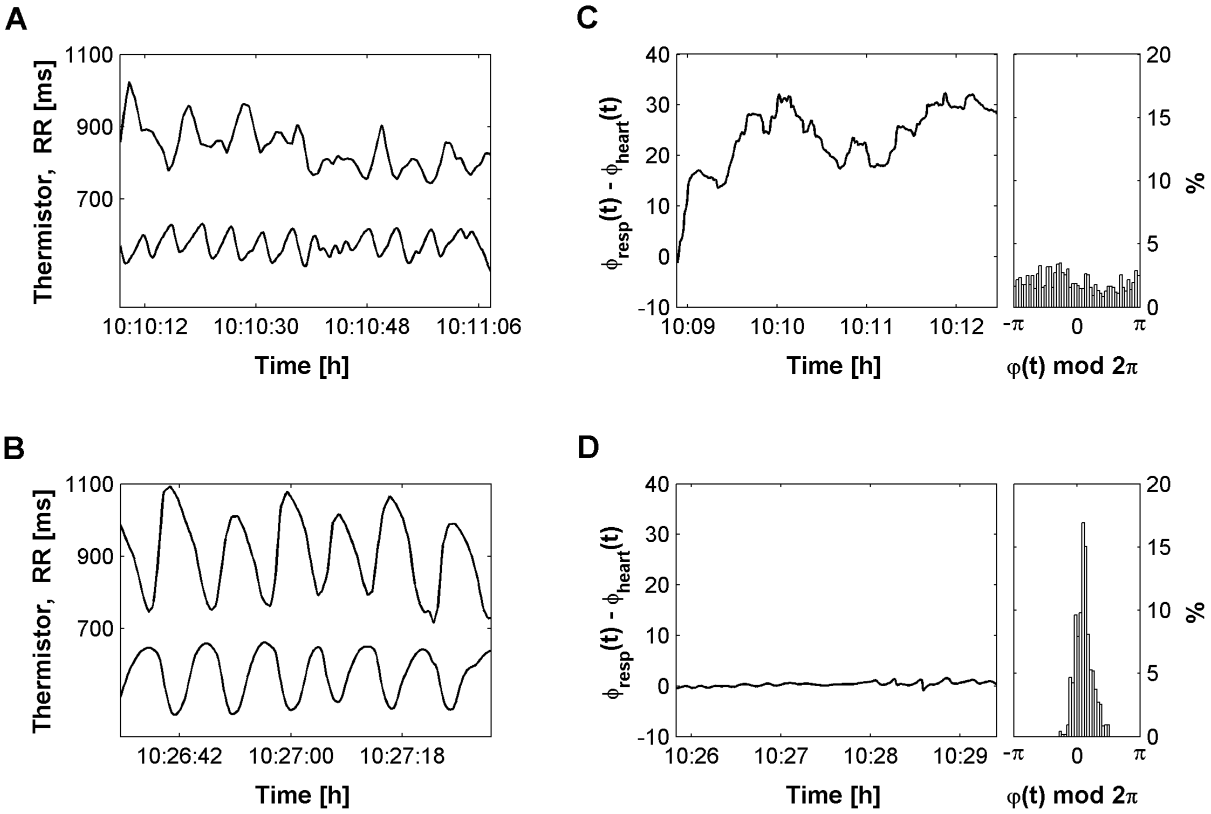

Figure 1: (A) During spontaneous breathing instantaneous heart rate (upper trace) and simultaneous air flow (lower trace) are desynchronized. (B) During Zazen-meditation cardiorespiratory interaction is synchronized. (C) and (D) illustrate the accompanying phase difference $j(t) = f_{resp}(t) - f_{heart}(t)$ and the distribution of $j(t) \bmod 2p$ between heart rate and respiration. In a synchronized state the phase difference is almost constant and the distribution shows a distinct maximum.

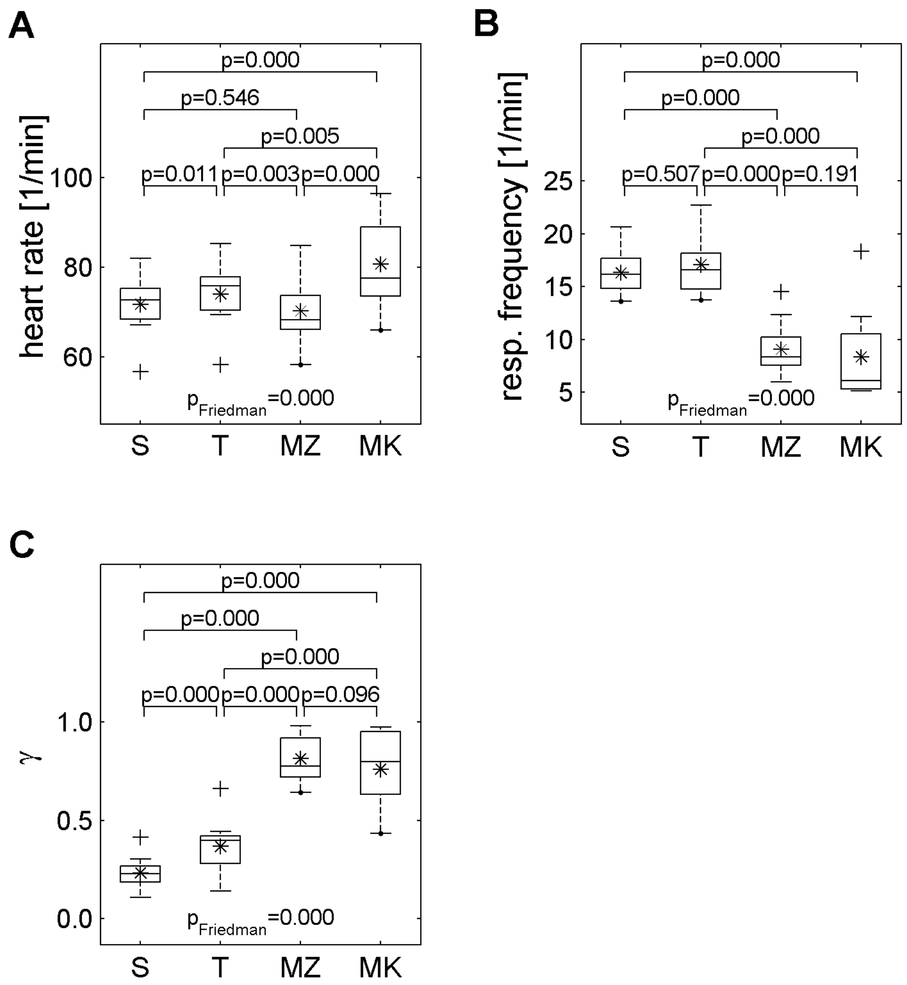

Figure 2: Heart rate and respiratory frequency during the quiet sitting (S), mental task (T), Zazen meditation (MZ) and Kinhin meditation (MK). Low values of $p_{Friedman}$ indicate the likely differences between the exercises. The probability of similar values between the exercises is indicated by the p-values above the box and whisker plots. The box plots show median and quartiles (horizontal lines), average (*), and maximum and minimum values (whiskers).

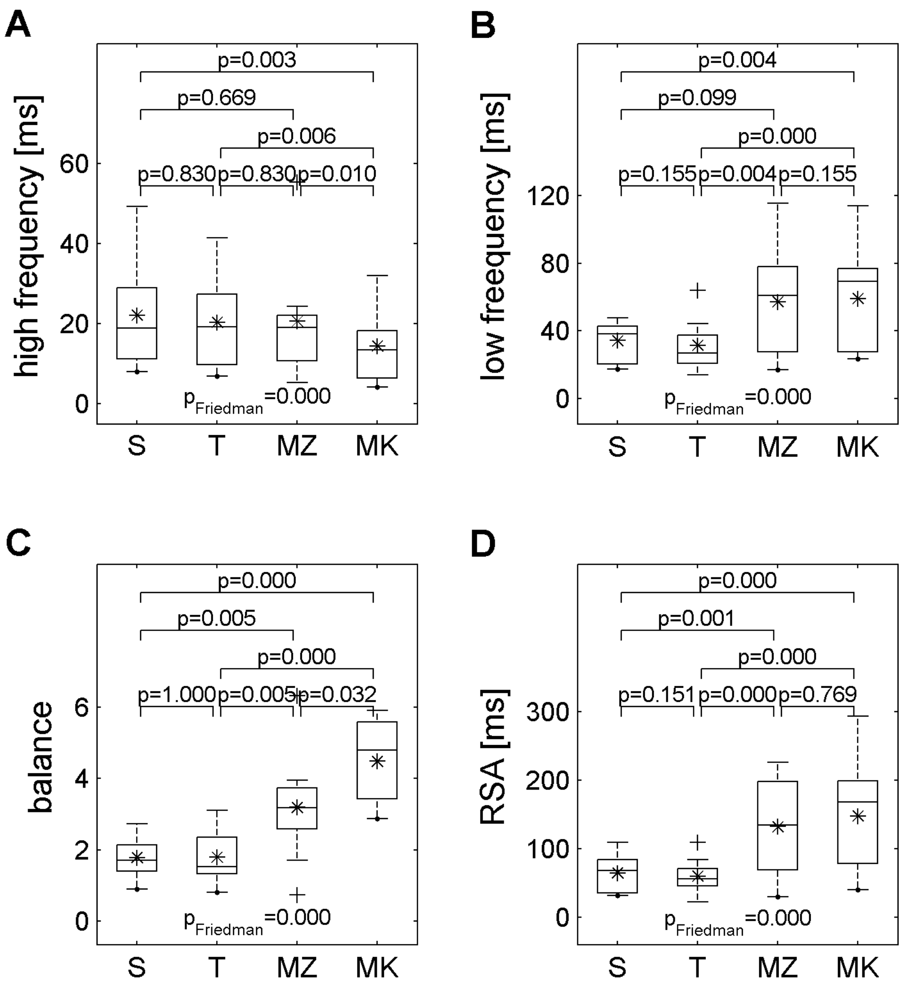

Figure 2: Heart rate variability (high frequency *HF*; low frequency *LF*; balance=*LF*/*HF*; extent of RSA) during the quiet sitting (S), mental task (T), Zazen meditation (MZ) and Kinhin meditation (MK). Low values of $p_{Friedman}$ indicate the likely differences between the exercises. The probability of similar values between the exercises is indicated by the p-values above the box and whisker plots. The box plots show median and quartiles (horizontal lines), average (*), and maximum and minimum values (whiskers).

Exercise:	**Sitting**	**Mental Task**	**Meditation**			**Sitting**
			Zazen	**Kinhin**	**Zazen**	
Duration:	8 min	7 min	11 min	7 min	7 min	10 min

Table 1: Experimental protocol of the study. The experiment was divided into six consecutive exercises. For further details, see text.