# Information Dynamics in Cardiorespiratory Analyses: Application to Controlled Breathing*

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*Abstract*— **Voluntary adjustment of the breathing pattern is widely used to deal with stress-related conditions. In this study, effects of slow and fast breathing with a low and high inspiratory to expiratory time on heart rate variability (HRV) are evaluated by means of information dynamics. Information transfer is quantified both as the traditional transfer entropy as well as the cross entropy, where the latter does not condition on the past of HRV, thereby taking the highly unidirectional relation between respiration and heart rate into account. The results show that the cross entropy is more suited to quantify cardiorespiratory information transfer as this measure increases during slow breathing, indicating the increased cardiorespiratory coupling and suggesting the shift towards vagal activation during slow breathing. Additionally we found that controlled breathing, either slow or fast, results as well in an increase in cardiorespiratory coupling, compared to spontaneous breathing, which demonstrates the beneficial effects of instructed breathing.**

## I. INTRODUCTION

Mental stress is a growing problem that has been associated with an increased cardiovascular risk [1]. In order to diminish the negative effects of stress-related disorders, people have been trying to cope with this, often by voluntarily adjusting the breathing pattern [2]. Most breathing instructions aim to acquire a shift towards a reduction in sympathetic activation and an increase in vagal activity.

Information regarding cardiac autonomic control is typically assessed via heart rate variability (HRV). One of the main modulators of HRV is respiration, a phenomenon that is called respiratory sinus arrhythmia (RSA) and that is linked to vagal outflow and leads to an increase in heart rate during inspiration and a decrease during expiration [3]. Seeing that RSA is strongly dependent on the frequency and depth of breathing [4], it is interesting to investigate whether adaptation of the breathing pattern alters the autonomic balance and evaluate whether this can be used to reduce the negative stress-related effects on autonomic control. Most breathing instructions to enhance vagal activation include a reduction in breathing frequency and increase in tidal volume. It is however unclear to which extent other features of the breathing pattern, such as the ratio between inspiratory and expiratory phase (i/e ratio), contribute to the beneficial effects of slow breathing. We therefore aim to investigate the effects of controlled breathing on the autonomic balance, manipulating both breathing frequency and i/e ratio.

Analyses of these manipulations already revealed that slow breathing is accompanied by higher tidal volumes and that a lower i/e ratio results in a higher heart rate, but that the heart rate is not influenced by the breathing frequency, as reported in [5]. In addition, as expected, RSA is higher when breathing at 6 compared to 12 breathing cycles per minute (cpm). An increased RSA is also found in a low compared to high i/e ratio, yet only when breathing at 6 cpm.

In this study, we aim to assess autonomic behaviour during controlled breathing by means of information-theoretic measures that quantify information storage and transfer of HRV and respiration. Information theory has proven to be useful to evaluate directional interactions in cardiorespiratory data [7], and gives other insights than the traditional HRV analyses and analyses of cardiorespiratory coupling by means of e.g. correlation, coherence and synchronisation methods.

## II. METHODS

### A. Data Acquisition and Preprocessing

*1) Participants:* In the context of a study concerning the effects of respiratory rate and i/e ratios on self-reported relaxation states, and on RSA and HRV, 30 students (18-22 years; 2 men) have been selected to participate in the experiment [5]. The data are collected at the Faculty of Psychology and Educational Sciences of the KU Leuven (Leuven, Belgium). The study is approved by the local ethical committee. All participants provided written informed consent.

*2) Instrumentation:* The LifeShirt System (Vivometrics Inc., Ventura, CA) is used to measure the electrocardiogram (ECG, sampling frequency $f_s$ = 200 Hz) and respiration ($f_s$ = 50 Hz). Respiration is recorded by means of inductive

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plethysmography around the abdomen and rib cage. Based on those two displacements, an estimation of the tidal volume is made, which is further used as respiratory signal. In order to take possible delays between respiratory drive and the recorded tidal volume into account, thereby affecting the causality relation, a time lag of 0.5 $s$ is included in the recorded respiratory signal [6].

*3) Experimental Protocol:* First, baseline recordings are measured for 7 minutes while sitting quietly and breathing spontaneously. Next, the participants practiced four different breathing patterns, each for 45 $s$; at first, a pattern of 12 cpm is instructed with an inspiratory time of 1.5 $s$ and an expiratory period of 3.5 $s$ (i/e ratio = 0.42). The second breathing pattern is also at 12 cpm, but with a reversed i/e ratio (= 2.33; 3.5 $s$ in- and 1.5 $s$ exhalation time). In the third case, a respiratory rate of 6 cpm is imposed, again with an i/e ratio of 0.42 (3 $s$ in- and 7 $s$ exhalation time). The last pattern comprises a rate of 6 cpm with an i/e ratio of 2.33 (7 $s$ in- and 3 $s$ exhalation time). These four patterns will further be referred to by their breathing frequency of 6 (slow) or 12 cpm (fast breathing), and a low or high i/e ratio. After this practice period, the recordings during the various breathing patterns started. The participants are asked to follow each breathing pattern during 5 minutes, while being assisted by breathing videos. The 24 possible presentation orders of the breathing patterns are counterbalanced across the participants.

*4) Preprocessing:* The tachogram is constructed after R peak detection using the Pan-Tompkins algorithm. In order to obtain an accuracy of 1 $ms$ when constructing the tachogram, parabolic interpolation using 5 samples around the detected peak is performed. Next, both tachogram and respiratory signal are resampled at 2 Hz using cubic spline interpolation and both signals are high-pass filtered with a cut-off frequency of 0.05 Hz in order to remove baseline wander. Additionally, the first 10 $s$ of each breathing pattern are removed to reduce transient behaviour. From the baseline period of spontaneous breathing, a 5 minute segment is randomly selected to match the data size of the controlled breathing periods.

### *B. Information Dynamics*

*1) Information Decomposition:* Consider a system that is composed of two interacting processes $X$ and $Y$, then the predictive information $P_Y$ measures how much information carried by the present sample $Y_n$ can be predicted by the knowledge of the past of $X$ and $Y$, written as $\boldsymbol{V}_n^{X,Y}$:

$$P_Y = H(Y_n) - H(Y_n|\boldsymbol{V}_n^{X,Y}), \tag{1}$$

with $H(Y_n)$ the Shannon entropy.

The predictive information of $Y$ can also be written as the sum of the transfer entropy $T_{X\to Y}$ and the self entropy $S_Y$, with

$$T_{X\to Y} = H(Y_n|\boldsymbol{V}_n^{Y}) - H(Y_n|\boldsymbol{V}_n^{X,Y}) \tag{2}$$

$$S_Y = H(Y_n) - H(Y_n|\boldsymbol{V}_n^{Y}). \tag{3}$$

The transfer entropy $T_{X\to Y}$ indicates how much information that is carried by $Y_n$, that was not already predicted by the past of $Y$, can be predicted by the past of $X$, while the self entropy $S_Y$ is a measure of information storage that quantifies how much of the information carried by $Y_n$ can be predicted by the knowledge of its own past. When the information transfer between several interacting processes is assessed, transfer entropy is typically used [7].

Alternatively, we can decompose the predictive information as the sum of the cross entropy $C_{X\to Y}$ and the conditional self entropy $S_{Y|X}$, with

$$C_{X\to Y} = H(Y_n) - H(Y_n|\boldsymbol{V}_n^{X}) \tag{4}$$

$$S_{Y|X} = H(Y_n|\boldsymbol{V}_n^{X}) - H(Y_n|\boldsymbol{V}_n^{X,Y}). \tag{5}$$

The cross entropy $C_{X\to Y}$ is a measure of information transfer and quantifies how much information that is carried by $Y_n$ can be predicted by the past of $X$. The conditional self entropy $S_{Y|X}$ quantifies information storage by assessing how much of the information carried by $Y_n$ can be predicted by the knowledge of its own past, conditioned to the knowledge of the past of $X$.

Let $X = r$ be the respiratory signal and $Y = R$ the RR interval series, then both $T_{r\to R}$ and $C_{r\to R}$ are measures of information transfer, indicating cardiorespiratory coupling. Information storage of HRV is quantified by $S_R$ and $S_{R|r}$.

*2) Computation of Conditional Entropy:* Entropy is computed according to $H(Y_n) = -\sum p(y_n)\ln p(y_n)$, which requires the estimation of the probability function $p(\cdot)$. When conditional entropy, e.g. $H(Y_n|\boldsymbol{V}_n^{X,Y})$, needs to be estimated, first we need to determine the conditioning vector $\boldsymbol{V}_n^{X,Y}$. In this application, a non-linear model-free approach with non-uniform embedding is used. In this procedure, the conditioning vector $\boldsymbol{V}_n^{X,Y}$ is built by selecting terms from an initial candidate set $\widehat{\boldsymbol{V}}_n^{X,Y} = [X_{n-1}, \ldots, X_{n-L}, Y_{n-1}, \ldots, Y_{n-L}]$ that includes lags up to $L = 10$, such that the conditional entropy $H(Y_n|\boldsymbol{V}_n^{X,Y})$ is minimized and as such, the description of the target series $Y$ is optimized. When there is no significant decrease in conditional entropy, as determined by a randomization test [8], the selection procedure of terms for the conditioning vector ends. Note that delays between the cardiorespiratory time series, possibly induced by the controlled breathing protocol, are taken into account by the high number of lags (up to 5 $s$) that are included in the candidate set. The entropies in Eqs. (1-5) are estimated using the histogram with 6 quantization levels. A more detailed description of this procedure can be found in [7]. All entropies were computed using the MuTE toolbox (http://users.ugent.be/~dmarinaz/MuTE.html).

### *C. Statistical Analysis*

After testing for normality and equal variances, a two-way within-subject ANOVA is conducted on the four controlled respiratory patterns, with breathing frequency, i.e. 6 or 12 cpm, and i/e ratio, i.e. low or high as factors. A $p < 0.05$ is considered statistically significant.

## III. RESULTS

Fig. 1 displays the predictive information during spontaneous breathing and the four controlled breathing patterns.

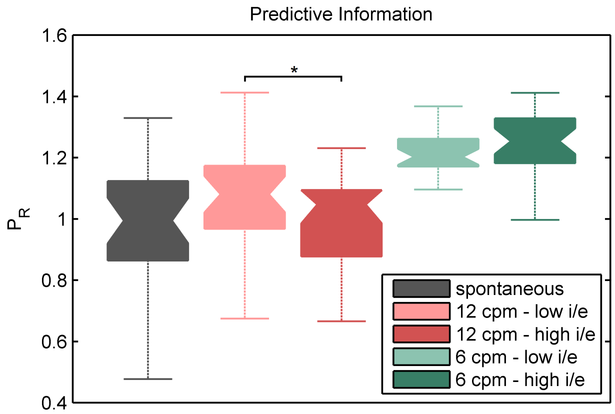


Fig. 1. Boxplot of the predictive information $P_R$ during spontaneous breathing, breathing at 12 and 6 cpm with i/e ratios of 0.42 (low) and 2.33 (high). * indicates significant differences between a low and high i/e ratio.

There is a significant effect of breathing frequency, where slow breathing is accompanied by an increase in $P_R$. No effect of i/e ratio is found, but a significant interaction effect indicates that only at 12 cpm, a low i/e ratio results in a higher $P_R$ than a high i/e ratio. It is also interesting to note that $P_R$ is lower during spontaneous breathing than during controlled breathing.

The decomposition of predictive information in transfer and self entropy is given in Fig. 2. $T_{r\to R}$ and $S_R$ exhibit significant effects of breathing frequency, with a higher $T_{r\to R}$ and lower $S_R$ during fast compared to slow breathing. Although both in $T_{r\to R}$ and $S_R$, no effect of i/e ratio is found, a significant interaction effect is observed in $S_R$, showing also that at 12 cpm, a low i/e ratio results in a higher self entropy than a high i/e ratio.

The alternative decomposition of predictive information using cross and conditional self entropy is given in Fig. 3. In terms of information transfer and storage, exactly the opposite trends as in the traditional decomposition are found; $C_{r\to R}$ is significantly lower at 12 cpm than at 6 cpm, while $S_{R|r}$ is higher during fast than slow breathing. The i/e ratio does not alter $C_{r\to R}$ or $S_{R|r}$. Spontaneous breathing results in a lower $C_{r\to R}$ than controlled breathing, while the conditional self entropy exhibits the opposite.

## IV. DISCUSSION

### A. Information Transfer and Storage

The two different decompositions of predictive information into a component related to information storage and another component related to information transfer lead to entirely opposite results; while $S_{R|r}$ and $T_{r\to R}$ are higher during fast than slow breathing, $S_R$ and $C_{r\to R}$ are precisely lower when breathing at 12 cpm.

The opposing results can be explained by the different mechanisms of information storage; information storage as traditionally defined by $S_R$ not only includes internal memory mechanisms in the target process $R$, but also memory in the target process that originates from the driving process $r$ [9]. In this traditional decomposition, the information storage is in fact favoured at the expense of the information transfer, because we first condition on the past of the target series. However in doing so, the measured storage may also reflect part of the information transfer, thereby underestimating $T_{r\to R}$. The alternative decomposition does not have this problem because we subserve the information transfer by first conditioning on the past of the driving respiratory process, but it has the limitation that $C_{r\to R}$ is not a measure of causality in the Granger sense since it can be nonzero in the absence of causality. However, by exploiting the highly unidirectional relation between respiration and HRV, this limitation is circumvented. Moreover, in accordance to the reduction in RSA during fast breathing that was reported in [5], the information transfer as quantified by $C_{r\to R}$ is lower compared to slow breathing. Note however that the information transfer is a measure of cardiorespiratory coupling, but is not necessarily correlated to RSA amplitude.

Information storage is related to the self predictability of the tachogram and is typically associated with an unhealthier cardiovascular system as this indicates a reduced flexibility to respond to bodily demands [10]. Again, the alternative definition of information storage, i.e. $S_{R|r}$ which we can consider as the residual (free from respiration) self predictability, seems more suitable as its reduction, in contrast to the increase of $S_R$, during slow breathing also corresponds to the expected shift in autonomic balance.

These results motivate the use of cross entropy and conditional self entropy in cardiorespiratory applications as they exploit the directional knowledge between respiration and heart rate. Transfer entropy underestimates the true information transfer from respiration to HRV, while self entropy overestimates the information storage.

### B. Breathing Patterns

The cross entropy is higher during slow than fast breathing, indicating an increased cardiorespiratory coupling, which is probably related to the shift in autonomic balance towards vagal activity as previous findings reported. Although RSA significantly differed between a high and low i/e ratio during slow breathing [5], this was not perceived in $C_{r\to R}$, demonstrating that the cross entropy is related to cardiorespiratory coupling, but not as such RSA amplitude. It is also interesting to note that during spontaneous breathing the cross entropy is significantly lower than during all controlled breathing patterns. This suggests that only the imposition of following a certain breathing pattern, already results in an increase in cardiorespiratory coupling, and possibly RSA, and thus shows the potential of instructed breathing to cope with stress-related conditions.

As already mentioned, the conditional self entropy can be associated with the ability of the autonomic nervous system to quickly respond to bodily demands [10]. Fast and spontaneous breathing both result in increased values for $S_{R|r}$, suggesting again the beneficial effects of slow breathing; not only the cardiorespiratory coupling increases during slow breathing, the low values for $S_{R|r}$ also indicate a state of more flexibility in autonomic modulation.

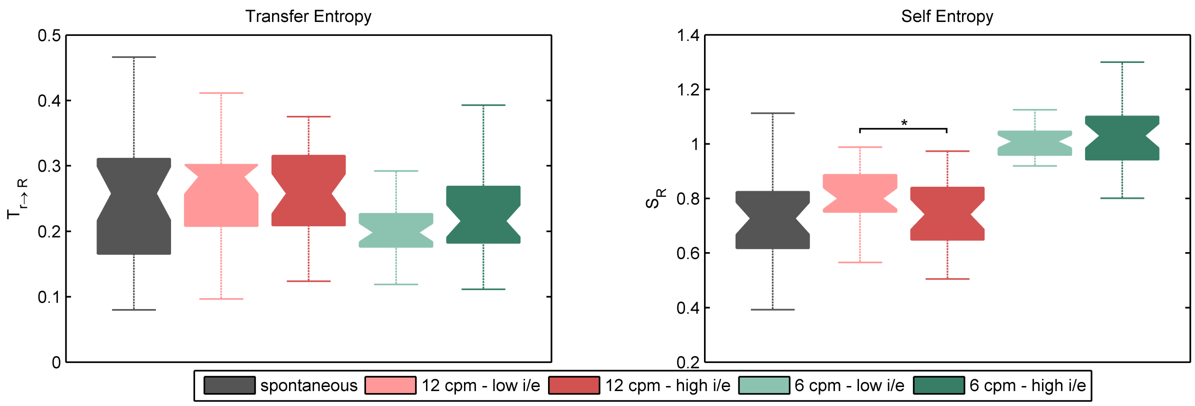


Fig. 2. Boxplot of the transfer entropy $T_{r\rightarrow R}$ (left) and self entropy $S_R$ (right) during spontaneous breathing and breathing at 12 and 6 cpm with i/e ratios of 0.42 (low) and 2.33 (high). * indicates significant differences between a low and high i/e ratio.

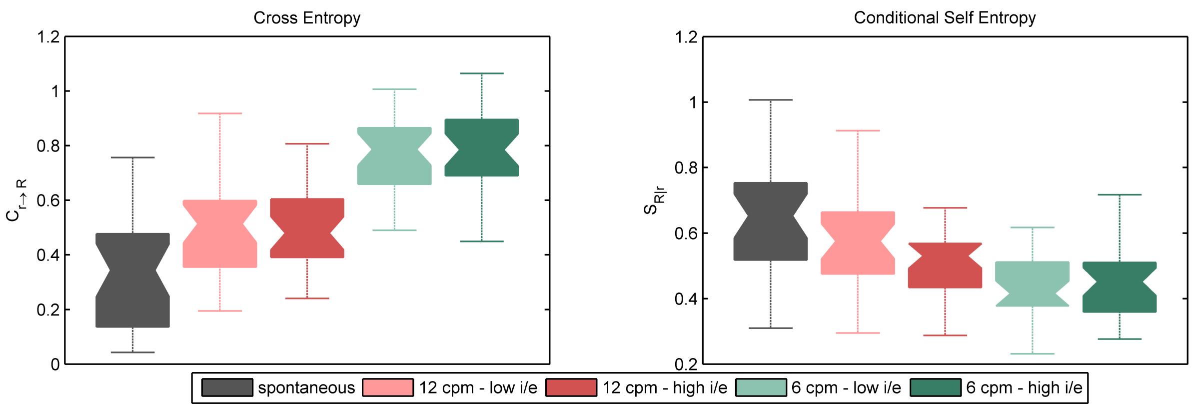


Fig. 3. Boxplot of the cross entropy $C_{r\rightarrow R}$ (left) and conditional self entropy $S_{R|r}$ (right) during spontaneous breathing and breathing at 12 and 6 cpm with i/e ratios of 0.42 (low) and 2.33 (high).

## V. CONCLUSION

This paper evaluated two ways to assess information storage and transfer during controlled breathing. The results revealed that opposed to the traditionally used transfer entropy, in cardiorespiratory applications, the cross entropy is a better way to quantify information transfer as it does not condition on the past of the heart rate, thereby exploiting the causal relation between respiration and heart rate. In addition, we found that slow breathing can be associated with an increased cardiorespiratory coupling and reduced residual self predictability of the tachogram, suggesting why slow breathing is an effective method to enhance vagal activation. Additionally, beneficial effects of controlled breathing can already be observed compared to spontaneous breathing.

## REFERENCES

[1] N. Hjortskov, D. Rissen, A.K. Blangsted, N. Fallentin, U. Lundberg and K. Sogaard, The Effect of Mental Stress on Heart Rate Variability and Blood Pressure during Computer Work, European Journal of Applied Physiology, vol. 92, no. 12, pp. 84-89, 2004.

[2] B. M. Cappo and D. S. Holmes, The Utility of Prolonged Respiratory Exhalation for Reducing Physiological and Psychological Arousal in Non-Threatening and Threatening Situations, Journal of Psychosomatic Research, vol. 28, no. 4, pp. 265-273, 1984.

[3] G. G. Berntson, J. T. Cacciopo and K. S. Quigley, Respiratory Sinus Arrhythmia: Autonomic Origins, Physiological Mechanisms, and Psychophysiological Implications, Psychophysiology, vol. 30, no. 2, pp. 183-196, 1993.

[4] T. Ritz, M. Thöns and B. Dahme, Modulation of Respiratory Sinus Arrhythmia by Respiration Rate and Volume: Stability across Posture and Volume Variations, Psychophysiology, vol. 38, no. 5, pp. 858-862, 2001.

[5] I. Van Diest, K. Verstappen, A. E. Aubert, D. Widjaja, D. Vansteenwegen and E.Vlemincx, Inhalation/exhalation Ratio modulates the Effect of Slow Breathing on Heart Rate Variability and Relaxation, *under revision in Applied Psychophysiology and Biofeedback*.

[6] J. P. Saul, R. D. Berger, M. H. Chen and R. J. Cohen, Transfer function analysis of autonomic regulation II. Respiratory sinus arrhythmia, American Journal of Physiology-Heart and Circulatory Physiology, vol. 256, no. 1, pp. H153-H161, 1989.

[7] L. Faes, G. Nollo and A. Porta, Information Domain Approach to the Investigation of Cardio-Vascular, Cardio-Pulmonary, and Casculo-Pulmonary Causal Couplings, Frontiers in Physiology, vol. 2, pp. 80, 2011.

[8] D. Kugiumtzis, Direct-coupling information measure from nonuniform embedding, Physical Review E, vol. 87, no. 6, pp. 062918, 2013.

[9] M. Wibral, J. Lizier, S. Vögler, V. Priesemann and R. Galuske, Local Active Information Storage as a Tool to Understand Distributed Neural Information Processing, Frontiers in Neuroinformatics, vol. 8, pp. 1, 2014.

[10] A. Voss, S. Schulz, R. Schroeder, M. Baumert and P. Caminal, Methods Derived from Nonlinear Dynamics for Analysing Heart Rate Variability, Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences, vol. 367, no. 1887, pp. 277-296, 2009.